

University of Sheffield

Department of Electronic and Electrical Engineering

EEE118: Electronic Devices in Circuits – Circuits Component

2018 - 2019 Edition

Dr. James E Green

Videos of Lectures
Videos of Problem Sheet Solutions
Videos of Extended Material

And

Written Exam Solutions
Written Problem Sheet Solutions
Many past Exam Papers
Past Mid-term Papers

And

Circuit Simulation Files

Are available via MOLE

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The University Of Sheffield.

Electronic & Electrical Engineering.

EEE118 ELECTRONIC DEVICES AND CIRCUITS

Credits: 20

Course Description including Aims

This module introduces the underlying solid-state physical principles that govern the properties of the active and passive circuit components that comprise all electronic and electrical circuits. Issues affecting the practical behaviour of resistors, capacitors and especially diodes and transistors are discussed. The circuit environments in which diodes and transistors are used, and the models describing their internal behaviour and external interactions, are introduced. It is shown how transistors and diodes can be used in both switching circuits and amplifier circuits and the important concept of small signal modelling is introduced in the context of the latter.

The module aims to:

1. describe the key conduction mechanisms - drift and diffusion - in solids and in a vacuum.
2. introduce students to the differences between conductors, semiconductors and insulators.
3 to describe the various technologies of resistor and capacitor manufacture and the relative performance issues associated with them.
4. establish a distinction between mobile charge and space charge in semiconductors and their respective roles in electronic devices.
5. develop in students a thorough understanding of the basic mechanisms of the p-n junction.
6. show students how to use their knowledge of semiconductors to create models that relate physical mechanisms in semiconductors to the terminal characteristics of electronic devices, in particular transistors.
7. introduce the idea of non-linear circuit elements and how to handle them.
8. present piecewise linear models and standard circuit symbols used to represent active circuit elements such as p-n junctions, BJTs, JFETs and MOSFETs.
9. explore the application areas of p-n junction diodes and examine their behaviour in a range of circuit contexts.
10. introduce the notion of electronic switches and the application of BJT and MOSFET devices as switches in various circuit environments.
11. introduce the idea of amplification and explain the need for biasing and the concept and use of small signal modelling.
12. introduce the ideal op-amp and basic op-amp circuits and to examine the effects of finite gain.

Outline Syllabus

Electrons in a Vacuum : force on electron in an electric field, energy, velocity, current and current density. **Electrons in Solids :** transport mechanisms, drift, diffusion. Resistivity of metals and physical origin, temperature coefficient. **Insulators :** breakdown strength, dielectrics and relative permitivity, different types of capacitors and their uses. **Semiconductors :** intrinsic and extrinsic, doping, charge carriers, holes, basic relationships of J for bulk semiconductors. **PN Junctions :** structure, junction potential, forward bias behaviour, charge injection, diode equation. Idea of space charge, Poisson's equation, internal fields, reverse breakdown mechanisms. Diode characteristics and temperature effects.

Transistors : JFETs and MOSFETs, basic mechanisms and characteristics, transconductance. BJT, transport mechanisms, charge control model, characteristics, simple circuits to obtain gain. Simple equivalent circuits. **Basic Diode Behaviour** : large and small signal diode models. **Diode Applications** : rectifiers, capacitor input smoothing, ripple, zener diode regulators. Clipping, clamping, voltage doublers, voltage multipliers. **Transistors :** BJT, JFET and MOSFET characteristics, similarities and differences. **Switching Applications** : on-state and off-state behaviour, drive considerations for BJT and MOSFET, inductive loads and back emf, switching AC power, bridge topologies for motor control. **Amplifier Applications** : amplification, biasing, designing dc conditions, thermal stability. Small signal ideas, generation of simple model (g_m based), equivalent circuits, coupling and decoupling, mid-frequency examples. **Operational Amplifiers** : advantages of - ideal performance. Basic circuit shapes, idea of feedback, follower circuits, virtual earth circuits, effect of finite gains. Use of superposition to handle multiple source amplifiers.

Time Allocation

48 lectures, 24 problem classes and 124 hours of independent study

Recommended Previous Courses

entry qualifications

Assessment

mid term test (January) - 9%, homework (continuous) 8%, exam (June) answer 4 questions from 6 in 3 hours - 83%

Recommended Books

Horowitz & Hill	The Art of Electronics 3rd Ed	Cambridge
Sedra & Smith	Microelectronics	Oxford
Millman & Grabel	Microelectronics	McGraw Hill
Streetman & Banerjee	Solid State Electronic Devices	Prentice Hall
Laszlo Solymar, Donald Walsh & Richard R. A. Syms	Electrical Properties of Materials	Oxford
John Allison	Electronic Engineering Materials and Devices	McGraw Hill

Objectives

"By the end of the unit, a candidate will be able to"

1. determine the differences of electron motion in a vacuum and in solids (drift and diffusion).
2. outline the properties and uses of metals, semiconductors and insulators.
3. identify the physical processes which are important in semiconductor electronic devices.
4. describe the p - n junction and the concept of electron and hole current.
5. appreciate the use of a diode for the emission and detection of light.
6. identify the physical mechanisms within the JFET and BJT that lead to the transconductance and output characteristics.
7. identify under what conditions a diode will conduct and what its effect will be on the behaviour of the circuit as a whole.
8. design simple capacitor input filtered power supplies, understand the significance of the approximations involved and specify voltage ratings for the components used.
9. predict the behaviour of circuits containing resistors, capacitors and diodes such as voltage doublers, peak detectors and differentiators.
10. discuss the similarities and differences between the characteristic behaviour of BJTs, JFETs and

MOSFETS.

11. determine key operational parameters of a simple switching circuit and design simple circuits - including ones with inductive loads - to achieve specified goals.
12. analyse and synthesise the two practically useful bias circuits used in BJT amplifiers.
13. apply small signal model ideas to complete circuits and make quantitative estimates of a circuit's small signal performance.
14. calculate circuit gain for inverting, non-inverting operational and multiple input amplifier circuits for both ideal operational amplifiers and ones with a finite gain.

Detailed Syllabus

1. Force on electrons in an electric field, equations of motion, velocity, energy.
2. Formal definitions of current and current density, vacuum devices (just as illustration).
3. Solids - insulators, conductors, semiconductors.
4. Conduction mechanisms in solids, drift, diffusion.
5. Resistivity in conductors, temperature coefficient in metals and intrinsic semiconductors.
6. Insulators, breakdown strength, dielectrics, relative permittivity.
7. Capacitors - different types and uses.
8. Semiconductor conduction, intrinsic and extrinsic.
9. Doping, electrons and holes, p-type and n-type, drift and diffusion.
10. Conductivity, mobility, drift velocity.
11. Recombination effects, diffusion length.
12. P-n junction, space charge and mobile charge, Poisson's equation.
13. Junction potential, internal field, space charge, capacitance, voltage dependence.
14. Charge injection, diffusion, recombination, forward current.
15. Reverse characteristics, breakdown, Zener and avalanche.
16. Diode characteristics, relation to semiconductor characteristics, temperature dependence.
17. Junction field-effect transistor, current control, channel depletion.
18. Current saturation, qualitative explanation of characteristics.
19. Derivation of drain current versus voltage below saturation.
20. Operation as an amplifier, small signal equivalent circuit, uses.
21. MOSFET, simple explanation, enhancement and depletion modes, characteristics, uses.
22. Bipolar transistor, physical explanation of operation, biasing of junctions.
23. Junctions linked by narrow base, diffusion length, base current components, current gain.
24. Charge control model, output characteristics, small signal equivalent circuit.
25. What the course is about, what sort of ideas it is intended to transmit, what skills students should begin to have attained by the end of it. Books, review of booklist, how to use books. Assumed background knowledge. Beginning of an introduction to diode behaviour.
26. Piecewise linear diode models, identification of conduction state of a diode in a circuit.
27. Clipping circuits. Purpose of this type of circuit, action of basic clipping circuit. Protection applications. Shaping circuits or soft clipping, application in function generators; triangle to sine converters.
28. Clipping and clamping with R-C circuits. Behaviour of first order R-C circuits handout and discussion.
29. Peak detector applications, low power rectifier, effect of time constant on ability to respond to some frequencies but not to others; a.m. detector applications. Clamping circuits, purpose, top level clamps, bottom level clamps, description of behaviour.
30. Differentiating circuit. Combinations of clipping and clamping circuits, peak to peak detector (voltage doubler). Voltage multipliers.

31. Half wave rectifier circuit shapes - nature of output signal, average value. Full wave circuit shapes starting with centre tapped secondary and two diodes, ending with full wave bridge. Average value of full wave output with sinusoidal drive.
32. Smoothing - necessity of smoothing for most equipment - purpose of smoothing filter, idea of ripple. Capacitor input smoothing - basic circuit shape and description of ideal behaviour. Design models for capacitor input filters. Objectives of the model for choosing C - statement of assumptions and their justification - evaluation of C and general comments.
33. Regulation and stabilisation, definition of terms which are used quite loosely. Purpose of a regulator. Zener diode as simplest form of regulator - characteristics - typical circuit, explanation of its operation and application of basic principles to the circuit to enable design.
34. Power dissipation in circuit components of a zener diode regulator. Effect of zener diode regulator on ripple - idea of using a small signal equivalent representation of the zener to work out ripple attenuation. Other comments ---- behaviour of knee for voltages above and below 6.2V, temperature coefficient.
35 Introduction to transistors using a handout giving the characteristics of BJTs, JFETs and MOSFETs. Transconductance characteristic, output characteristic.
36. Ideal switches, mechanical versus electronic switches, advantages and shortcomings. Transistors as switches, driving BJT and MOSFET switches (not including transient effects).
37. Simple switching circuit topologies, switching AC power, bridge switching topologies. Switching inductive loads, back emfs, freewheeling diodes.
38. Explanation of amplification taking a graphical approach based on the device characteristics, including the need for biasing.
39. Setting up the bias conditions for a BJT. The two realistic bias circuits and their analysis and synthesis - the control of collector current by negative feedback - usefulness of the "0.7V drop".
40. Idea of small signal models. Generation of a simple g_m based small signal model (suitable for all devices) for a BJT together with the BJT specific notion of current gain.
41. Applying the small signal model - drawing the small signal equivalent circuit of a real transistor circuit. The notion that the power supply is a ground point to small signals. SS analysis to find key circuit parameters like gain.
42. Operational amplifiers as ideal circuit elements. Basic circuit connections, inverting circuit connections. Concept of a virtual earth and its justification.
43. Non-inverting circuit connections. The voltage follower. The effects of finite gain (treated quantitatively).
44. Amplifiers with multiple inputs. Use of superposition to analyse multiple input summers and subtractors.

Homework

Homework solutions are NOT available

EEE118 Homework and Problem Sheets

Homework is (supposed to be) the "easy bit". Homework is – in theory – a gentle introduction to the problem sheets. The homeworks are collectively worth nothing at all in terms of module marks. No credit is awarded. Students are not obliged to submit completed homwork assignments for the circuits part of EEE118. It is optional. If you submit homework, I will remember, and you will be a "good egg". That said, in July when the exam results come out there will be a causal relationship between exam grade and effort at doing homeworks.

If a student submits homework then feedback will be returned to them. This feedback is not a mark (there is no mark). The feedback will tell you where you went wrong and your senior demonstrator, in the problem classes, should be able to explain what is written in the feedback until you are satisfied that you understand it and are ready to attempt those parts of the homework that were done incorrectly again and then to move to the problem sheets. If you are still uncertain, email me or find me in the problem classes.

Problem sheets have easy questions which are about the same strength as the homework, medium questions which are about the same strength as the exam and hard questions which are so tricky and fiendish that if you can do them, without looking at the answers, you'll certainly be able to get a very high mark on the exam. If you can do the first half of all the problem sheets reliably, without looking at the answers, there's a good chance you'll pass the exam. (It would certainly help to practice past exam papers too...) If you can do all of the sheets flawlessly then you probably don't do much except work and should get out a bit more.

No one will be checking up on if you do the problem sheets or not, there are no marks available for doing them and you do not submit your solutions to them. That said, in July when the exam results come out there will also be a causal relationship between exam grade and effort at doing problem sheets. About 3/10 people will need another attempt at the exam in August having failed it in May. The main reason (ignoring factors beyond your control such as illness) for this is lack of practice at the questions in the problem sheets.

Submission of Homework

If you submit homework for marking it must be *handwritten* and have your registration number on it. Scan it using the university's IT facilities and then email it to me. **Do not** take a photo of your homework on your phone and send that, I will ignore it. Your submission must be handwritten – the exam will be handwritten. You should do the homework with a pen and paper, preferably several colours of pen. All the best engineering starts with an idea a pen and the back of an envelope/beer mat.

Submission of Problem Sheets

You do not submit your solutions to the problem sheets.

EEE118 Homework 1

This homework is not 'due in', you are not required to do it. There is a slide in the lectures that says "Homework X is now possible".

Question 1: Thévenin and Norton

Part a Find the Thévenin equivalent circuit for Fig. 1.

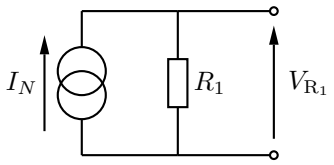


Figure 1: Question 1a.

Part b Find the Norton equivalent circuit for Fig. 2.

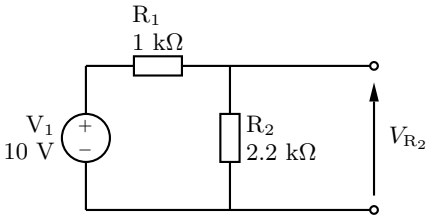


Figure 2: Question 1b.

Question 2: Time Domain Response of L and C

Part a Sketch the inductor current resulting from the impressed voltage in Fig. 3. The objective here is to think about the shape of the resulting graph and *not* to worry about any numbers.

Part b Sketch the capacitor current resulting from the impressed voltage in Fig. 4.

Note: To answer the question appropriately it is necessary to sketch the impressed voltages (above) on the same sketch as your solution.

Question 3: Diode Conduction State

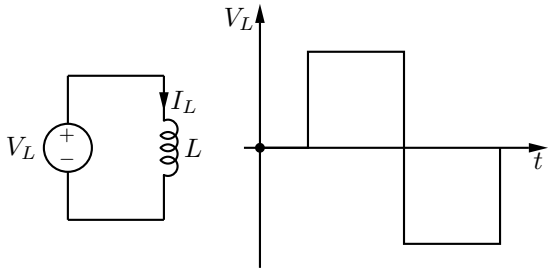


Figure 3: Question 2a.

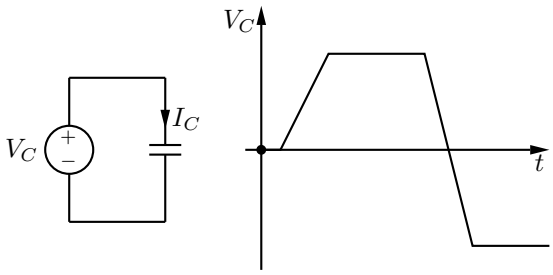


Figure 4: Question 2b.

This question requires you to show the method of determining the conduction state of a diode in a circuit. If you choose to solve by loop or nodal analysis please show at least one circuit in which the diode is assumed not conducting and if it turns out to be necessary show a further circuit in which the diode is conducting. For solutions presented using the principle of superposition please show all your partial circuits.

Part a, warm up. Determine if the diode in Fig. 5 is conducting or not. If it is conducting find the anode current. If it is not conducting find the reverse bias voltage. Begin by assuming that the diode is not conducting.

Part b Determine if the diode in Fig. 6 is conducting or not. If it is conducting find the anode current. If it is not conducting find the reverse bias voltage. Begin by assuming that the diode is not conducting.

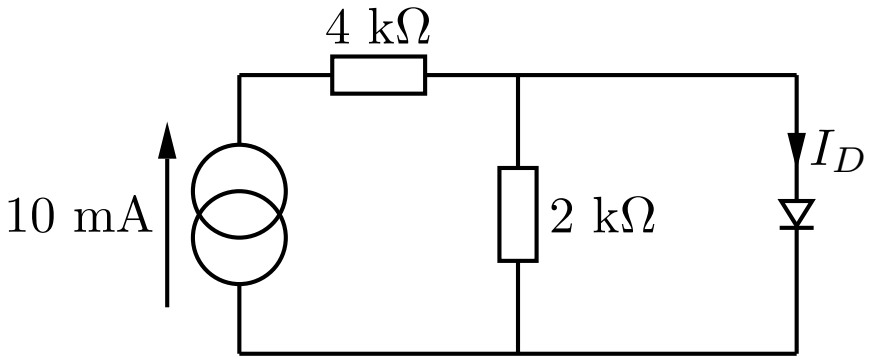


Figure 5: Question 3a.

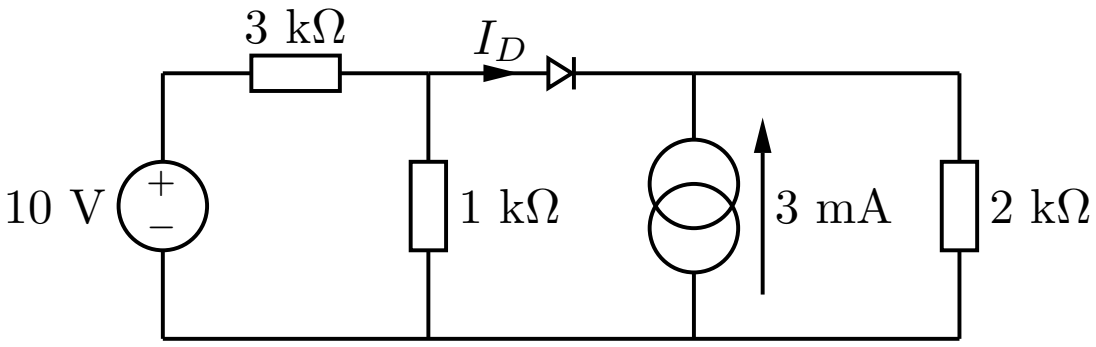


Figure 6: Question 3b.

EEE118 Homework 2

This homework is not 'due in', you are not required to do it. There is a slide in the lectures that says "Homework X is now possible".

Question 1: Diode Circuits with Pulses

Part a Construct a set of axes and sketch (i.e. free hand on normal writing paper *not* graph paper) the input voltage to the circuit in Fig. 1. *On the same axis* sketch the output voltage, V_O, as a function of time. Assume that the diode has a forward voltage drop of 0.7 V and is otherwise ideal.

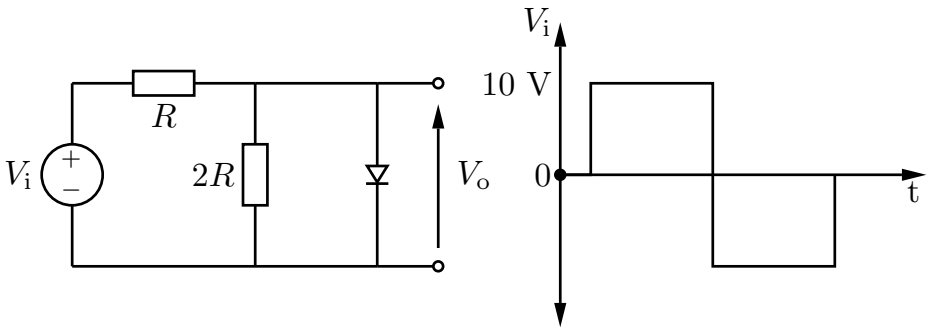


Figure 1: Question 1a.

Part b Inspect the diode, resistor & capacitor circuit shown in Fig. 2 in which the diode has a forward voltage drop of 0 V and no series resistance (it is ideal). Construct a set of axes and sketch (i.e. free hand, and on writing paper - *not* graph paper) the input voltage, V_i, output voltage, V_{C_1}, and the capacitor current, I_{C_1}, waveforms as a function of time. Ensure that all relevant voltages, times and time constants are noted on your solution. *Hint: begin by assuming that the circuit has been switched off for a long time, and therefore the capacitor is initially discharged.*

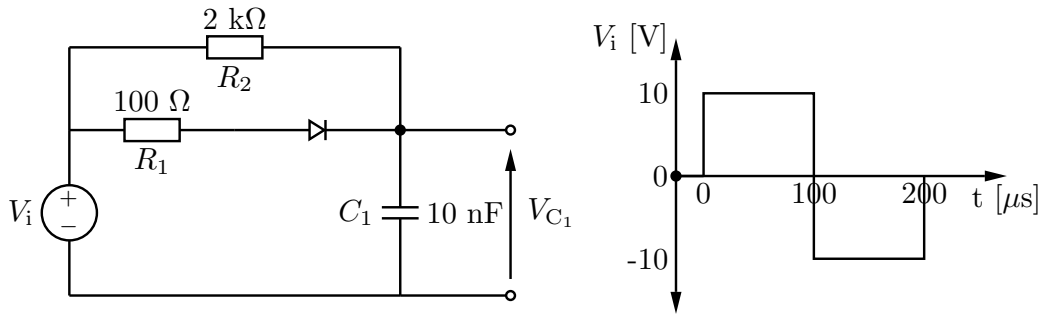


Figure 2: Question 1b.

Question 2: A Standard Diode Circuit

Consider the circuit in Fig. 3. Construct a set of axes and sketch (i.e. free hand and on standard writing paper - *not* graph paper) several cycles of,

1. the input voltage, $V_\mathrm{i} = 10\,\sin(\omega\,t)$.
2. the voltage across the resistor, V_{R_1}.
3. the diode current, I_{D_1}.

Label any significant voltages, times or time constants. Assume that the time constant $R_1 \cdot C_1$ is much greater than the period of the signal you choose.

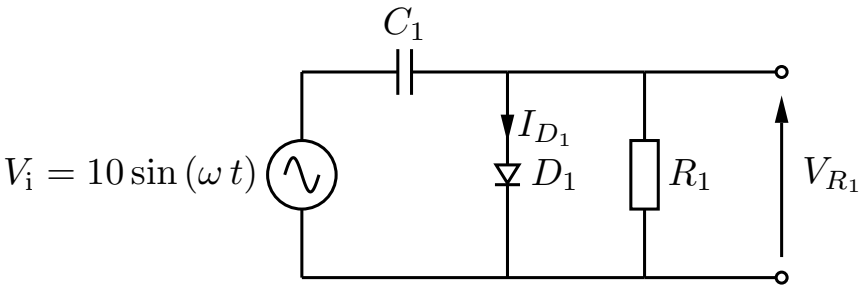


Figure 3: Question 2.

EEE118 Homework 3

This homework is not 'due in', you are not required to do it. There is a slide in the lectures that says "Homework X is now possible".

Question 1: Linear Power Supply

Part a The circuit shown in Fig 1 is a full wave bridge rectifier.

1. Draw a circuit diagram showing the current path through the diode bridge and load resistor when the secondary voltage, V_s, is much greater than zero.
2. Draw a second circuit diagram showing the current path through the diode bridge and load resistor when the secondary voltage, V_s, is much less than zero.

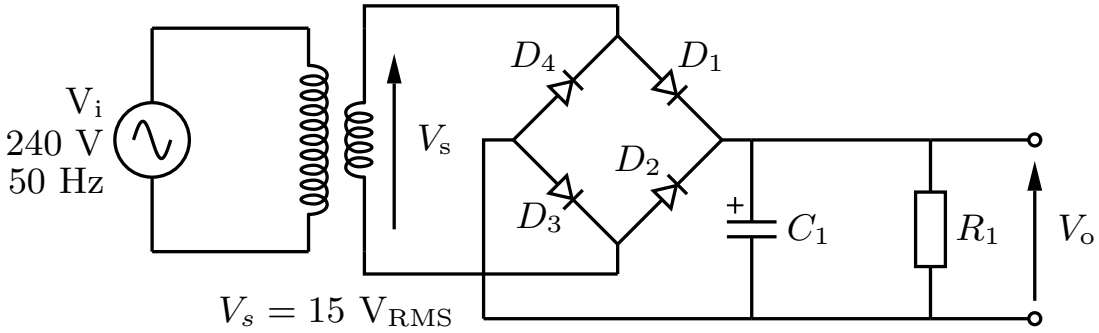


Figure 1: Question 1a.

Part b Still considering the circuit in Fig. 1,

1. calculate the voltage across the smoothing capacitor, C_1, if the diodes have a forward bias voltage drop of 0.7 V but are otherwise ideal and assuming there is no load ($R_1 = \infty$).
2. calculate the period of ripple waveform that will appear across the output when R_1 is added ($R_1 < \infty$).
3. the supply is designed to have a maximum ripple of 2 $V_{\text{pk-pk}}$. Assuming that the ripple waveform is triangular, sketch a graph showing *both* the secondary voltage and voltage ripple experienced by the load resistance, R_1, note any significant voltages and times on the graph.
4. If $R_1 = 1$ kΩ, calculate the minimum value C_1 must be to meet the ripple requirement.

Don't forget to state your assumptions!

Question 2: A Zener Diode Regulator

The linear power supply in Question 1 is being used to power a vintage spring reverb unit which unfortunately is susceptible to induced "hum" due to ripple on its power supply lines. The power supply can be improved by adding a Zener diode shunt regulator. In Fig. 2, the reverb circuit is represented by a resistance, R_1. The reverb circuit requires 15 V and will draw 15 mA under normal circumstances. The Zener diode requires 3.73 mA to operate properly.

1. Draw a circuit diagram of the regulator similar to Fig. 2 showing the information given in the question and including any information you think is needed from Question 1.

2. With the help of your diagram, calculate the largest value of R_S that will allow the regulator to function as designed.

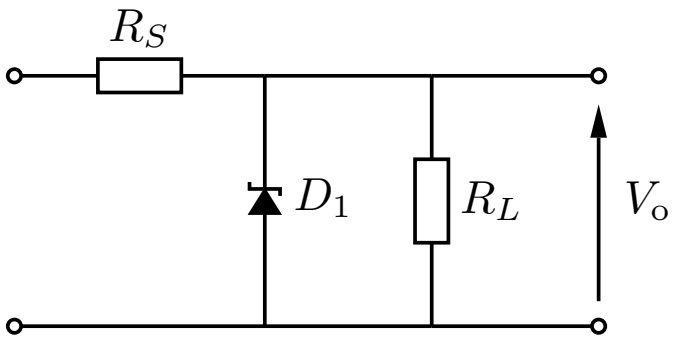


Figure 2: Question 2.

EEE118 Homework 4

This homework is not 'due in', you are not required to do it. There is a slide in the lectures that says "Homework X is now possible".

Question 1: Transistor Characteristics

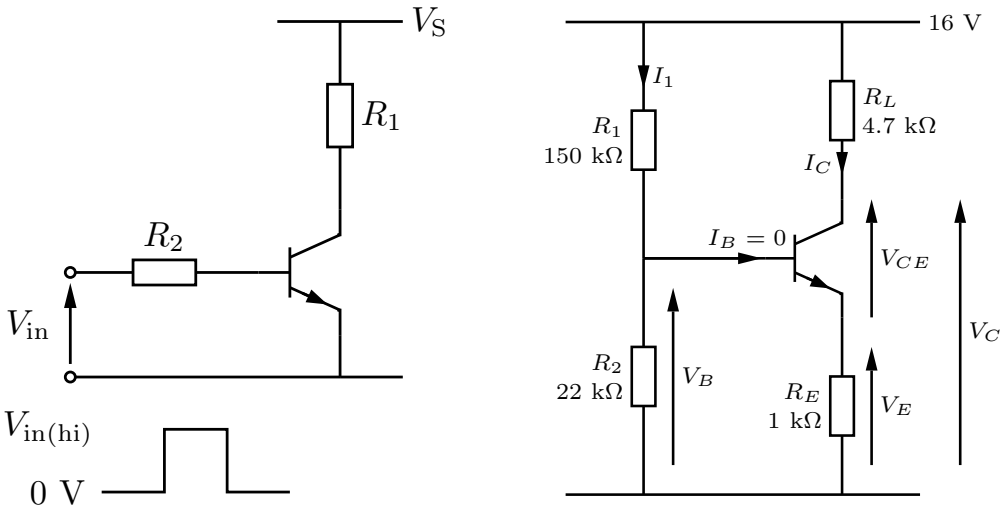
The purpose of this question is to encourage you to think about how the graphs that describe transistor relate to the circuit's operation without any numbers. It is important to develop a strong conceptual understanding of how the transistor behaves and the laws that govern it. This understanding will give you the confidence to tackle new, interesting and useful circuits.

Part a Sketch an *output characteristic* for a BJT showing a number of different values of v_{be} or i_b.

1. Draw a resistive 'load line' on the characteristics.
2. Mark on the point where the transistor is switched off.
3. Mark on the point where the transistor is switched on.
4. Mark on the point where the transistor is dissipating the maximum power for this load line.
5. Note the "saturation region" with an arrow.
6. Mark on $V_{CE(sat)}$, What is the physical significance of this voltage?

Part b Sketch a *transfer characteristic* for a BJT.

1. Choose – and mark with a dot – a suitable "operating point" to use the transistor as an amplifier.
2. Note on the graph an algebraic equation for the transfer characteristic.
3. Sketch a sinusoidal input, $v_{be} = A\,sin(\omega\,t)$ on suitably positioned and rotated set axes.
4. Sketch the output resulting from the input waveform on a second suitably positioned set of axes,.
5. Note on the transfer characteristic an algebraic expression for the transconductance of the amplifier at your chosen "operating point".



(a) Question 2.

(b) Question 3.

Figure 1: Circuits for Questions 2 and 3.

Question 2: Transistor Switch Circuit

Consider the switching circuit in Fig. 1a and express algebraically,

1. the collector current (don't forget $V_{CE(sat)}$) when the transistor is switched on.
2. the power dissipated in the load, R_1.
3. the power dissipated in the transistor.
4. the largest value of R_2 that will still allow proper operation.

Question 3: Transistor Amplifier Circuit

Part a For the amplifier circuit in Fig. 1b calculate the DC conditions including, I_{R_L}, I_1, I_E, V_B, V_E, V_C.

Part b Assuming a sinusoidal input and output sketch several cycles of I_1, I_C, V_B, V_E, V_C, V_{R_L} and V_{CE}. Pay attention to the DC magnitude and the phase of the signals. Experts might like to include numerical values for the AC magnitudes, but it is not mandatory. The question is most easily answered by sketching the currents first, then working out what happens to the voltages using Ohm's law where applicable. Figure out V_{CE} last.

EEE118 Homework 5

This homework is not 'due in', you are not required to do it. There is a slide in the lectures that says "Homework X is now possible".

Question 1: The Opamp

Part a Draw the circuit symbol for an opamp, label the: non-inverting input, inverting input, output, positive power supply input, negative power supply input.

Part b State the opamp equation and define the terms.

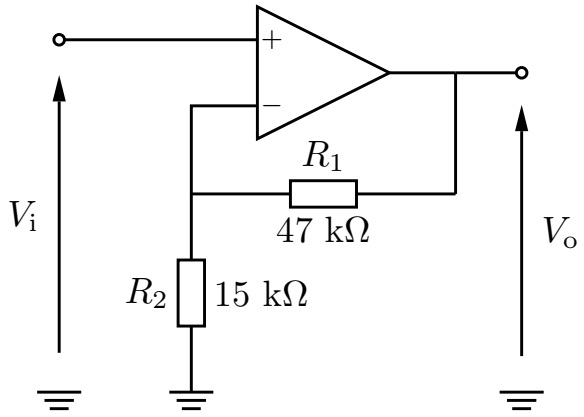


Figure 1: An Opamp amplifier circuit.

Question 2: Amplifier Circuit

Consider the opamp amplifier circuit in Fig. 1,

Part a Is this circuit inverting or non-inverting?

Part b Assuming the open loop gain, A_v, is infinite,

1. What key assumption can we make about the inputs of this opamp?
2. Derive an algebraic expression for the gain of the amplifier, $V_\mathrm{o}/V_\mathrm{i}$.
3. Find the numerical value for the gain.

Part c Assuming $A_v < \infty$,

1. Derive an algebraic expression for the gain of the amplifier.
2. Find a numerical value for the gain of the amplifier if $A_v = 500$.

Problem Sheets

(Some) Video Solutions On-Line at

https://www.youtube.com/user/IceAmplifiers

Written Solutions available via MOLE

The University of Sheffield

Department of Electronic and Electrical Engineering

EEE118 Problem Sheet

Background Knowledge Exercises

1 Work out in symbolic terms the Thevenin equivalent circuit of figure 1.

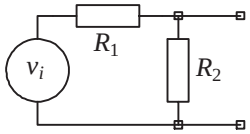


Figure 1

2 Analyse figure 2 using loop analysis and superposition and hence evaluate I_1 and V_3. Calculate the Norton equivalent circuit components that will represent figure 2. What value of V_2 would make $I_1 = 0$? (0.706A, 7.88V, $I_N = 5.58$, $R_N = 1.41\Omega$, 15V)

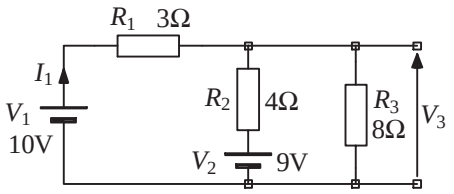


Figure 2

3 Analyse figure 3 using loop analysis and superposition and hence evaluate I_1 and V_3. Calculate the Thevenin equivalent circuit components that will represent figure 3. What value of I would make $V_3 = 0$? (3A, -6V, V_{TH} = -6V, $R_{TH} = 2.4\Omega$, 1.25A)

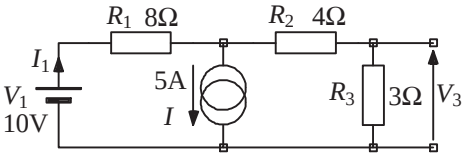


Figure 3

4 In the following equations Z represents impedance, R_X (or r_x) represents resistance, C_X represents capacitance, L_X represents inductance and ω is angular frequency. I_X is current, V_X is voltage and $_X$ is any subscript. By checking dimensional consistency, identify those equations that must be incorrect together with the term(s) causing the problem.

(i) $$I_B = \frac{V_1 - V_2}{R_4} + \frac{V_S - V_2}{R_{17} - R_9} + \frac{I_5}{R_6} + \frac{I_4}{2}$$

(ii) $$V_O - I_2 R_6 = 6V_3 + \frac{I_3 (R_1 + R_2) + I_4 (R_8 + 1)}{\frac{R_7}{R_6} + \frac{R_5}{R_4} + R_3}$$

(iii) $$r_o = \frac{\frac{(\beta + 1) R_E}{r_{be} + (\beta + 1) R_E} \cdot \frac{R_B // r_{it}}{R_S + R_B // r_{it}}}{\frac{(\beta + 1)\, R_B // r_{be}}{r_{be}\,(R_S + R_B // r_{be})}}$$ where β is a constant.

(iv) $v_i\,(j\omega)^2 C_1C_2R_1R_2 = v_o\,(1+ j\omega C_2R_1 + j\omega\,(C_1+C_2)R_2 + (j\omega)^2 C_1C_2R_1R_2 + j\omega C_2R_1R_2)$

(v) $$\frac{v_o}{v_i} = \frac{-j\omega C_2R_1}{1+ j\omega(C_1+C_2)R_2^2 + (j\omega)^2 C_1R_2C_2R_1}$$

(vi) $$Z = 1 + \frac{j\omega L}{1+ j\omega CR}$$

(vii) $$Z = \frac{R_1 - \omega^2 LCR_2 + j\omega(L + C\,R_1R_2)}{1 - \omega^2 LC + j\omega C\,(R_1 + R_2)}$$

5 (i) The capacitor in figure 5 is initially contains zero charge. Sketch a graph to show how the capacitor voltage varies as a function of time if the current generator has the waveform shown.

(ii) How much charge is in the capacitor at t = 8ms? (1μC)

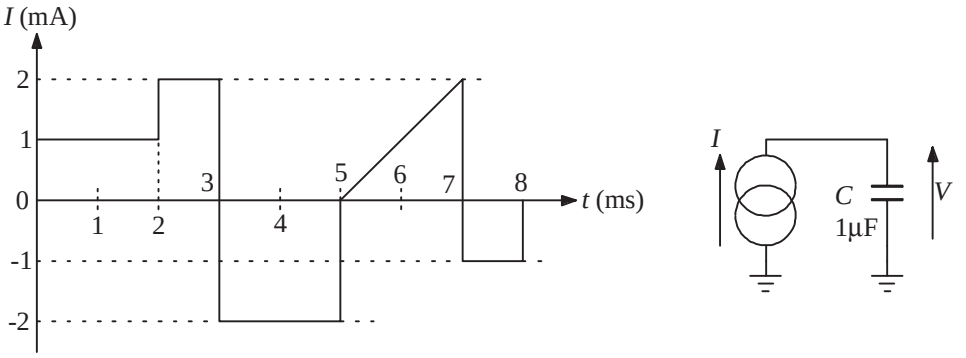


Figure 5

AND FOR EXPERTS .....

6 Draw a graph to show how capacitor current *I* in figure 6 varies with time. Work out the area and polarity of any impulsive currents. (-3μC @ 2ms, +2μC @ 6ms, -2μC @ 7ms)

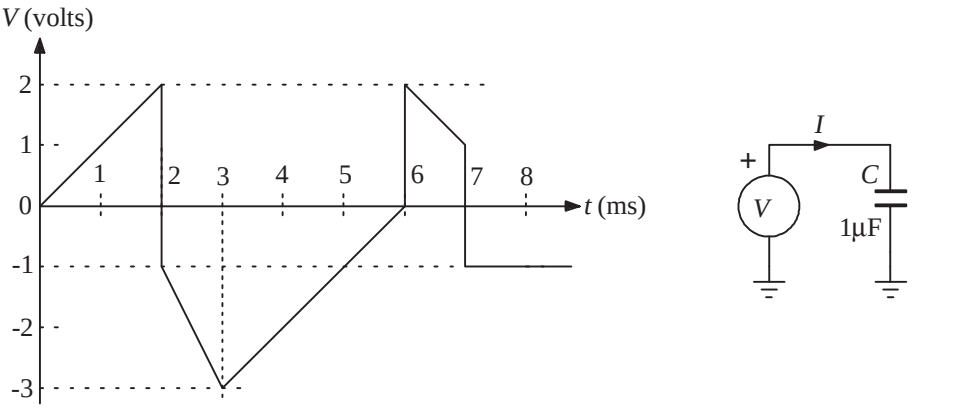


Figure 6

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EEE118 Problem Sheet

Diode Conduction State

Q1 For the circuits of figure 1, identify the conduction state of the diode and calculate either the reverse bias voltage or the forward bias current, as appropriate. Assume that the diodes perfectly block current flow for all anode - cathode voltages less than 0.7V (the reverse bias state) and conduct perfectly if the circuit tries to make the anode - cathode voltage greater than 0.7V. *Note that the answers give the magnitude of the reverse bis voltage or forward current as appropriate. Since answers will let you avoid the guess stage, only some answers are given.*

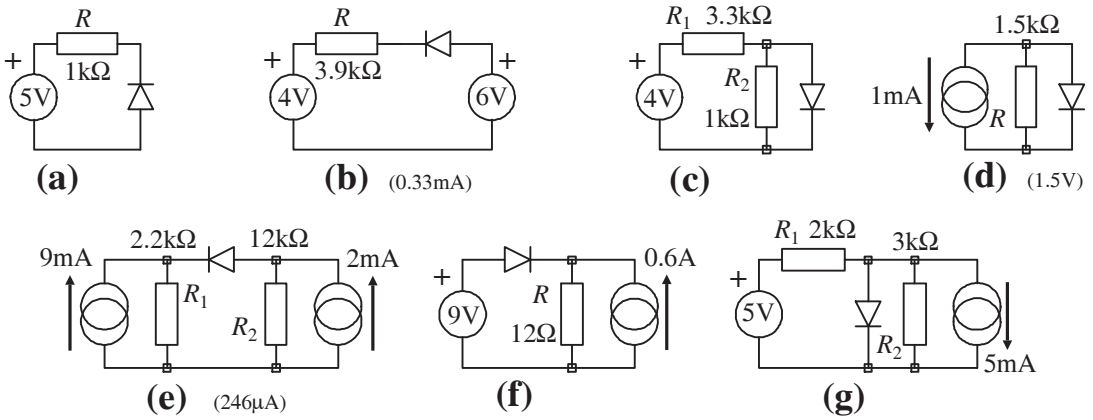


Figure 1

Q2 The circuits of figure 2 are the same as figure 1 except that the source (or one of the sources) has been changed from a fixed value to a variable one. Find the value of the variable source at which the diode changes from a conducting to a non-conducting state.

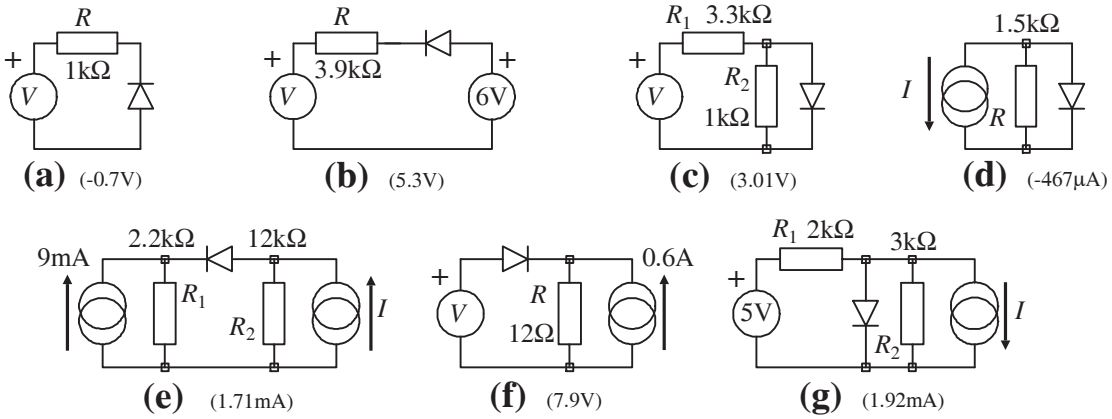
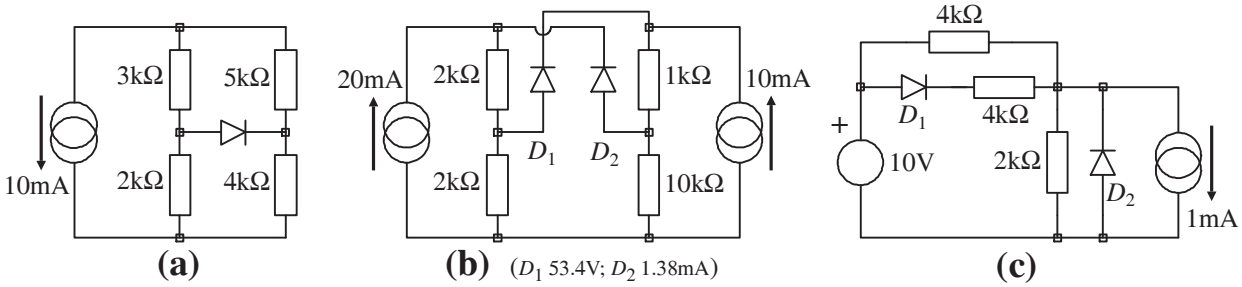


Figure 2

AND FOR EXPERTS

Q3 The circuits in figure 3 are more complicated than those in figure 1. Identify the conduction state of the diode(s) and calculate either the reverse bias voltage or the forward bias current, as appropriate. Assume that the diodes perfectly block current flow for all anode - cathode voltages less than 0.7V (the reverse bias state) and conduct perfectly if the circuit tries to make the anode - cathode voltage greater than 0.7V. *Note: In circuits with two diodes there are in principle four possible combinations of conduction state. Start by making a guess for both diodes and proceed as for a single diode to find out whether your guesses were right.*



(a) **(b)** (D_1 53.4V; D_2 1.38mA) **(c)**

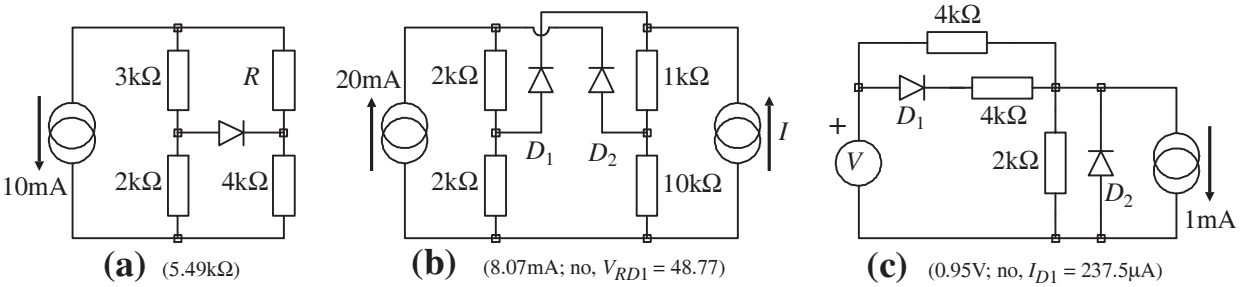
Figure 3

Q4 The circuits of figure 4 are the same as figure 3 except that a source or component has been changed from a fixed value to a variable one. Find

(i) the value of R in figure 4a at which the diode is on the point of changing from a conducting to a non-conducting state.

(ii) the value of I in figure 4b at which D_2 changes from a conducting to a non-conducting state. Has the state of D_1 changed under these new conditions?

(iii) the value of I in figure 4c at which D_2 changes from a conducting to a non-conducting state. Has the state of D_1 changed under these new conditions?



(a) (5.49kΩ) **(b)** (8.07mA; no, V_{RD1} = 48.77) **(c)** (0.95V; no, I_{D1} = 237.5μA)

Figure 4

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EEE118 Problem Sheet

Diode, Resistor and Capacitor Circuits.

NOTE: A pulse described as "long" has a width that is many times the biggest time constant in the circuit of interest. All the pulses used as inputs in this problem sheet have infinitely fast rising and falling edges.

Q1 For the circuit of figure 1, sketch the V_O - V_i and I_D - V_i characteristics that you would expect to observe over the range V_i = -10V to V_i = +10V if the diode has a forward voltage drop of 0.7V.

Q2 For the circuit of figure 2, sketch the waveshape that you would expect to observe if V_i was a triangular waveshape with a peak value of 10V (ie, a positive peak of 10V and a negative peak of -10V) and the diode had a forward voltage drop of 0.7V.

What is the largest value of forward current through the diode?

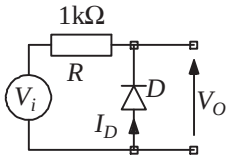


Figure 1

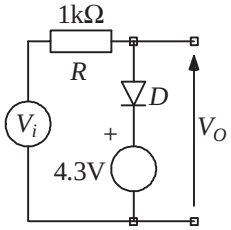


Figure 2

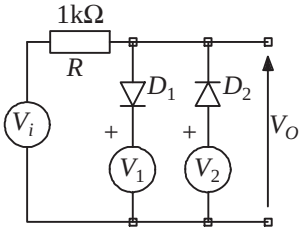


Figure 3

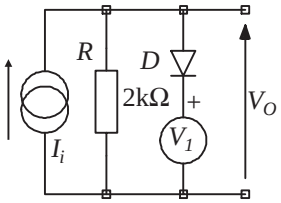


Figure 4

Q3 In the circuit of figure 3, V_i is a triangular wave of 10V peak whose frequency is to be measured by a system that requires its input signals to lie within the range 0V to 3.3V if damage to the system is to be avoided. Assuming the diodes have forward bias voltage drops of 0.7V, choose values for V_1 and V_2 that will clip those parts of the triangular V_i that are higher in voltage than 3.3V and lower in voltage than 0V.

Q4 In figure 4, V_1 = -2V. Sketch V_O as a function of I_i over the range I_i = -3mA to +3mA.

Q5 Design a soft clipping circuit that will realise the V_O-V_i characteristic of figure 5 using diodes that have a turn on voltage of 0.7V. (*Base your design on the circuit of figure 3; keep the 1kΩ resistor, add a series resistor into each of the diode arms and work out suitable values for V_1, V_2 and the two series resistors.*)

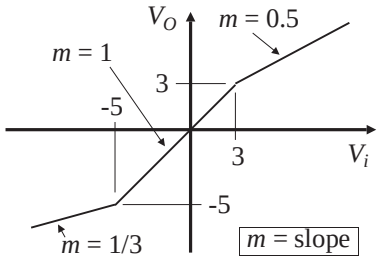


Figure 5

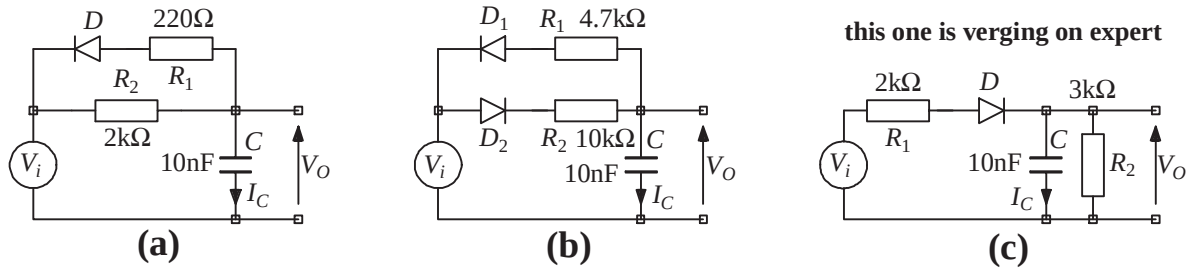


Figure 6

Q6 For each of the circuits of figure 6, sketch the response of V_O and I_C to a 0V to 10V input pulse with a duration of 100µs. You should assume that the diodes are ideal (ie, 0V forward voltage drop) and take care to label your sketch with salient features such as time constants and aiming levels. In the case of figure 6b you will need to work out the voltage reached by V_O at the end of the pulse.

In each case write down the exponential form of the rising and falling edge responses and calculate the width of the output pulse, measured in figure 6a and 6c at half its height and measured in 6b at 5V. *(In one of the three circuits the output pulse height is not the same as the input pulse height.)*

AND FOR EXPERTS

Q7 The circuits of figure 7 are slightly more subtle in their behaviour than those of figure 6. Each circuit is driven by a 0V to 10V input pulse of 100µs duration and uses diodes that can be assumed to be ideal (ie, 0V forward voltage drop).

For figure 7a, sketch the response of V_O and I_C to the input pulse.

For figures 7b and 7c, sketch the response of V_O to the input pulse.

For figure 7c, calculate the time for which V_O is below 2.5V *after* the falling edge of the input pulse.

As in question 6, be sure to label all the salient features of your sketches.

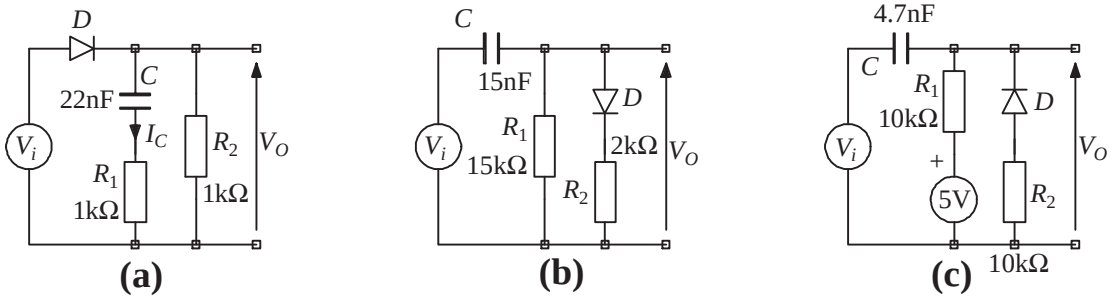


Figure 7

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EEE118 Problem Sheet

Rectifiers and Smoothing

Note: All a.c. voltages are r.m.s. quantities unless otherwise stated and unspecified frequencies are 50Hz.

Q1 In the half wave rectifier circuit of figure 1 both the diode and the transformer are ideal (ie, *D* conducts with zero voltage drop for forward bias and is an infinite resistance for reverse bias and the transformer has zero series resistance).

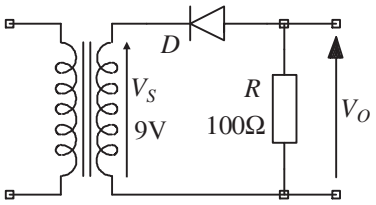


Figure 1

(i) Sketch the shape of the voltage V_O as a function of time for at least one period of V_S.

(ii) What is the peak value of V_O? (-12.73V)

(iii) What is the average value of V_O? (-4.05V)

(iv) What is the r.m.s. value of V_O? (6.36V)

(v) What is the power dissipated in *R*? (405mW)

If the transformer has a total effective resistance of 10Ω in series with its secondary winding.

(vi) What is the new peak value of V_O? (-11.57V)

(vii) What is the new power dissipated in *R*? (335mW)

Q2 What value of smoothing capacitor is required across the 100Ω load of figure 1 in order to achieve a ripple voltage of 0.3V peak to peak? What assumptions have been made in order to arrive at an answer? Estimate the power dissipated in the 100Ω load with this value of *C* connected. Assume that transformer and diode are ideal. (8500mF, 1.58W)

Q3 For the circuit of figure 3 what are the peak values of the voltage differences:

(a) $V_B - V_A$? (25.5V)

(b) $V_A - V_C$? (25.5V)

(c) $V_C - V_B$? (-51V)

Is the rectifier a full wave or a half wave type? *Note: The answers given ignore the diode forward voltage drop.*

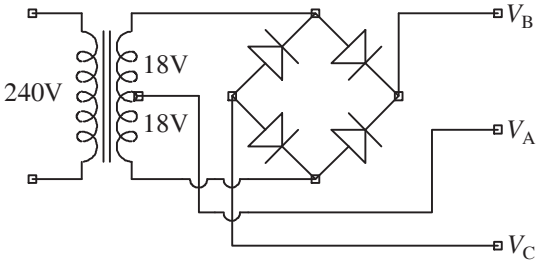


Figure 3

Q4 The circuit of figure 3 is to be used to supply an amplifier which requires nominally balanced positive and negative power supplies with respect to zero. The amplifier demands a current of 2A and at this current the ripple voltage must be less than 1V pk to pk on each supply rail.

(i) Redraw the circuit to include the capacitors necessary for capacitor input filtering of the rectifier output.

(ii) Estimate a suitable value for each capacitor. (20mF)

(iii) What d.c. component of output voltage will the smoothed supply provide? (24.3V)

(iv) What peak reverse voltage (PIV) must the diodes be capable of handling if reverse breakdown is to be avoided? (51V)

*The answer to part **(iii)** will be very dependent on the assumptions and approximations made. Assume here that all components used are ideal.*

Q5 The preamplifier section (tone controls etc) of the amplifier of question 4 requires a +10V supply at a current that may vary between 20mA and 50mA. This supply is to be derived from the main supply worked out in question 4 using a resistor and a zener diode.

(i) What zener breakdown voltage is required? (10V)

(ii) What value of series resistance is required if the current through the zener diode must be a minimum of 10mA? (230Ω)

(iii) What power rating must the zener diode have if a worst case condition is the disconnection of the preamplifier from its supply? (600mW)

(iv) What power rating must the resistor have if a worst case condition is the short circuiting of the preamplifier supply? (2.72W)

(v) What are the normal operating power dissipations in the resistor and zener diode? (980mW and 400mW respectively - when I_L can vary, worst case normal operating dissipations must be used)

(vi) What is the maximum zener diode slope resistance, r_Z , that can be tolerated if the pk to pk ripple voltage on the preamplifier supply must be ≤ 10mV? (2.3Ω)

AND FOR EXPERTS

Q6 The circuit of figure 6 is sometimes called a full wave voltage doubler. *(The diode clamp - peak detector combination is sometimes called a half wave voltage doubler)*

(i) Sketch the shape of V_O that you would expect to observe, taking special care with the ripple.

(ii) If $V_S = 20\text{V}, I_L = 100\text{mA}$ and the components are ideal, what value of C_1 and C_2 is necessary if the peak to peak ripple must be 5V or less? (400μF)

(iii) What is the average V_O under the conditions of part **(ii)**? (51.6V)

(iv) What PIV must D_1 be able to withstand? (54.1V)

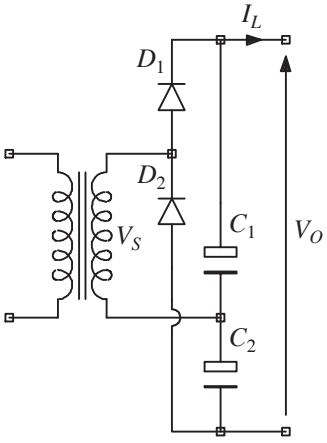


Figure 6

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EEE118 Problem Sheet

Transistors as Switches and Amplifiers

Q1 Why is it important to ensure that a transistor switch is driven on an off properly?

The transistor in the circuit of figure 1 has a large signal static current gain, h_{FE}, of between 70 and 250. When V_i is 10V, the switch must be "on" and when V_i is 0V the switch must be "off". Find,

(i) The "on" state I_C through the switch. (1.25A)

(ii) The worst case (largest) I_B in the "on" state. (17.86mA)

(iii) The value of R_B that will ensure proper switching for all possible values of h_{FE}. You can assume here that the "on" state V_{BE} is 0.7V. (521Ω)

(iv) The power loss in the on state if $V_{CE\,SAT}$ = 250mV. (313mW)

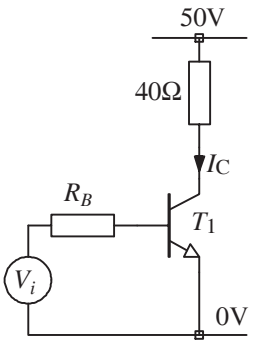


Figure 1

Q2 In addition to the bipolar transistor of figure 1, you have some MOSFETs with an on-state resistance, $r_{DS\,ON}$, of 0.25Ω. Work out the on-state power loss for one of these MOSFETS if it was substituted for T_1 in the circuit of figure 1 and hence decide whether or not it would be a better choice than the BJT in figure 1 from an efficiency point of view. Assume that when V_i = 10V, the MOSFET is switched on properly. (390mW, no)

Q3 The 40Ω load in figure 1 has associated with it a series inductance of 100mH as shown in figure 2.

(i) What is the energy stored in the inductive part of the load if *S* has been on for a long time? (78mJ)

(ii) What is the purpose of *D* and *R*?

(iii) What is the value of I_D immediately after *S* opens? (1.25A)

(iv) What is the decay time constant of I_D if R = 0Ω? (2.5ms)

AND FOR EXPERTS

(v) What is the maximum *R* that can be used if *S* has a maximum voltage rating of 200V? (120Ω)

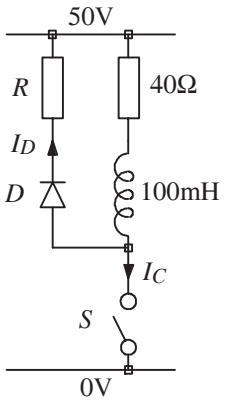


Figure 3

(vi) If R = 100Ω and the switch switches fifty times per second, what is the power dissipation in *R*? (2.8W)

Assume that *D* is ideal and that there is no capacitance associated with the circuit.

Q4 In the circuit of figure 4, the motor rotates in a clockwise direction when the current through it is in the direction shown.

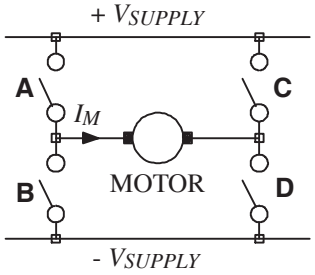


Figure 4

(i) Which two switches must be on to cause clockwise rotation?

(ii) Which two switches must be on to cause anticlockwise rotation.

(iii) Sketch out the circuit to show where idling diodes could be placed to prevent excessive switch voltages due to motor winding inductance. Indicate which diodes would conduct if the motor had just been switched off from a clockwise rotation state.

Q5 The manufacturers data for the BC183 transistor states that the current gain, h_{FE} (= I_C/I_B), may lie anywhere in the range 100 to 850.

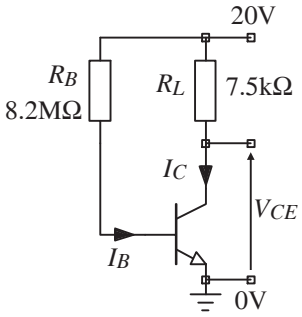


Figure 5

(i) Evaluate I_B in figure 5. (2.35μA)

(ii) Within what range of voltage will the collector voltage, V_{CE}, fall if a BC183 is used in the circuit of figure 5? (5V to 18.2V)

(iii) Why is the circuit of figure 5 a poor bias circuit?

AND FOR EXPERTS

(iv) If the temperature coefficient of h_{FE} is 0.5% per ^oC, what is the temperature coefficient of collector voltage for a particular BC183 with h_{FE} = 450? (-40mV$^oC^{-1}$)

You should assume that a forward biassed p-n junction has 0.7V across its terminals.

Q6 For the circuit of figure 6, V_{BE} = 0.7V and all voltages are measured with respect to 0V.

(i) Work out the d.c. conditions, V_C, V_E and I_C using the assumption that I_B is negligible. (12.3V, 3.22V and 3.22mA)

(ii) Work out r_{be} and g_m for the transistor of figure 6 if β = 500. (4.04kΩ, 0.124A/V)

(iii) Draw a small signal equivalent circuit of the circuit of figure 6.

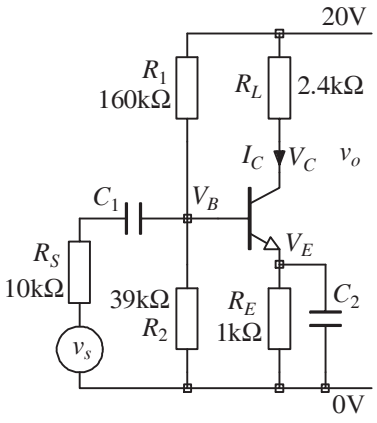


Figure 6

AND FOR EXPERTS

(iv) Estimate the small signal voltage gain, v_o/v_s, of the circuit. (-78.7)

AND FOR REAL EXPERTS

(v) Work out the temperature coefficient of I_C assuming that the transistor of question 5 is used and that h_{FE} is the only temperature dependence in the circuit. (1.16μA $^oC^{-1}$)

Q7 For the circuit of figure 7,

(i) Work out the d.c. conditions, V_C, V_E, I_C and I_F using the assumption that I_B is negligible. (13.5V, 2.55V, 946μA and 108μA)

(ii) Evaluate the small signal transistor parameters g_m and r_{be}. (36.4mA/V, 13.7kΩ)

(iii) Draw the small signal equivalent circuit of figure 7 assuming that all capacitors are small signal short circuits.

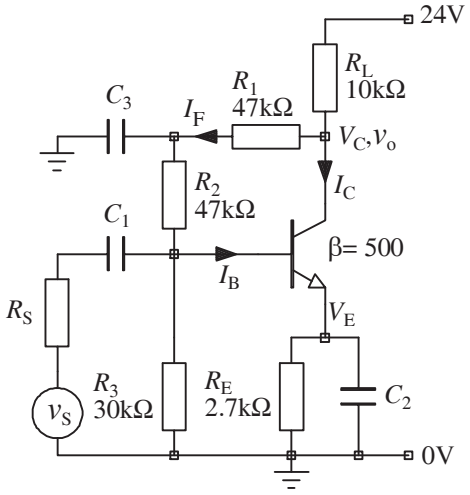


Figure 7

AND FOR EXPERTS

(iv) Work out the small signal voltage gain, v_o/v_s, of the circuit for:

a) $R_S = 0$ (-300)
b) $R_S = 10\text{k}\Omega$ (-132)

AND FOR REAL EXPERTS

(v) What would the small signal voltage gain be if C_3 was omitted from the circuit and $R_S = 10\text{k}\Omega$? (-8.85)

You should assume that a forward biassed p-n junction has a forward voltage drop of 0.7V across its terminals.

You may find some of the following relationships and definitions useful:

$$g_m = \frac{eI_C}{kT} \qquad r_{be} = \frac{\beta}{g_m} \qquad h_{FE} = \frac{I_C}{I_B} \qquad \beta = \frac{\Delta I_C}{\Delta I_B} = \frac{i_c}{i_b} \qquad \tau = RC$$

$$I = C\frac{dV}{dt} \qquad \omega = 2\pi f \qquad V(t) = (V_{START} - V_{FINISH})\exp\left(\frac{-t}{\tau}\right) + V_{FINISH}$$

$V_{AVE} = \frac{V_P}{\pi}$ for a half wave rectified sinusoid $\qquad V_{rms} = \frac{V_P}{\sqrt{2}}$ for a sinusoid

$$v_o = A_v\,(v^+ - v^-) \qquad \frac{kT}{e} = 0.026\text{V}$$

unit multipliers: p = x10^{-12}, n = x10^{-9}, μ = x10^{-6}, m = x10^{-3}, k = x10^{3}, M = x10^{6} G = x10^{9}

All the symbols have their usual meanings

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EEE118 Problem Sheet

Operational Amplifiers

Q1 If $R_2 = 75\text{k}\Omega$ and $R_1 = 15\text{k}\Omega$ and $A_v \Rightarrow \infty$, evaluate the gain of the non-inverting amplifier circuit of figure 1. (6)

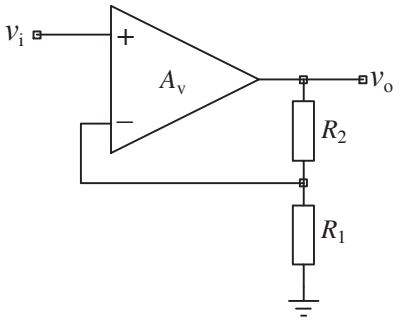


Figure 1

Q2 Show that for the circuit of figure 1, the effect of A_v on gain is given by:

$$\frac{v_o}{v_i} = \frac{1}{\left[\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}\right]} = K$$

Under normal circumstances, one would assume that since the op-amp gain, A_v, is very large, the circuit gain, K, is controlled only by the resistors R_1 and R_2. If $A_v = 10^5$V/V, estimate the percentage error in gain caused by using the above assumption for:

a) $R_2 = 9R_1$ (ie. a nominal gain of 10V/V). (0.01%)

b) $R_2 = 299R_1$ (ie. a nominal gain of 300V/V). (0.3%)

Q3 Show that providing $A_v \Rightarrow \infty$ can be assumed, the gain of the inverting amplifier circuit of figure 3 is $\frac{v_o}{v_i} = -\frac{R_F}{R_1}$. What is a virtual earth point and why does it exist? At which node is the virtual earth point in figure 3?

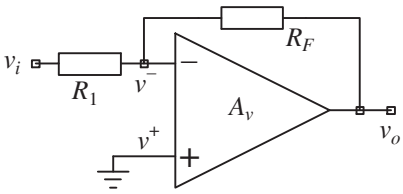


Figure 3

Q4 For the subtractor circuit of figure 4 show that:

$$v_o = \frac{R_2}{R_1}(v_2 - v_1) \qquad \text{for } A_v \Rightarrow \infty$$

(Use superposition to work out first v_o due to v_1, then v_o due to v_2, then add the two to get total v_o and rearrange to get the form given)

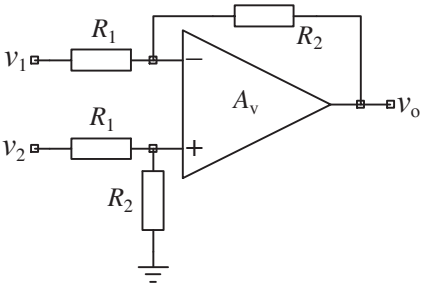


Figure 4

Q5 The three input voltages for the circuit of figure 5 are:

$v_1 = 0\text{V}$
$v_2 = 5\text{V}$
$v_3 = (15 \sin \omega t + 10)\text{V}$

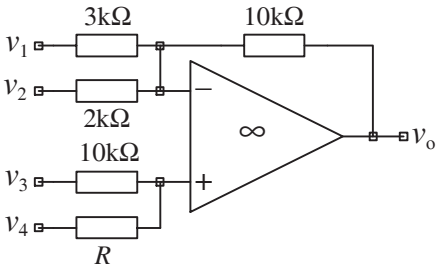


Figure 5

(i) Find values for R and the d.c. voltage v_4 that will give $v_o = (5 \sin \omega t + 0)\text{V}$. ($R = 370\Omega$, $v_4 = +2.4\text{V}$)

AND FOR EXPERTS

(ii) If v_2 and v_3 have the values specified and v_4 and R are as calculated in part **(i)**, what are the upper and lower limits to the range of voltage allowed for v_1 if $|v_o| \leq 10\text{V}$ must be satisfied at all times? ($v_1 = \pm 1.5\text{V}$)

(Once again, superpostion is a useful tool here for part (i). You can also consider the ac and dc parts of the problem separately. It is easier to start by considering the ac part of the problem since this is affected by R but not by the dc voltage v_4. The dc behaviour, on the other hand, is affected by both R and v_4.)

(The experts can fathom out part (ii) for themselves!)

Handouts

(The Course Notes)



Diodes

Introduction

A diode is a two terminal circuit element that allows current flow in one direction only. Diodes are thus non-linear circuit elements because the current through them is not proportional to the potential difference (voltage) across them and this makes them quite different from linear elements like resistors, inductors and capacitors.

There are several technologies that can be used to make diodes. The first really effective diode, the vaccuum diode, was invented in 1904 by J A Fleming and was the workhorse of diode applications until the mid 1950s when semiconductor diodes began to take over. Today, diodes are almost exclusively based on semiconductors and by far the most common form is the "silicon p-n junction" diode. Other materials and stuctures are sometimes used for special purposes - eg LEDs use compound semiconductors such as gallium arsenide - but their basic behaviour is similar to that of silicon diodes.

Silicon p-n junction diodes

The structure, circuit symbol and current-voltage (*I-V*) characteristic of a p-n juction diode is shown in figures 1(a), 1(b) and 1(c).

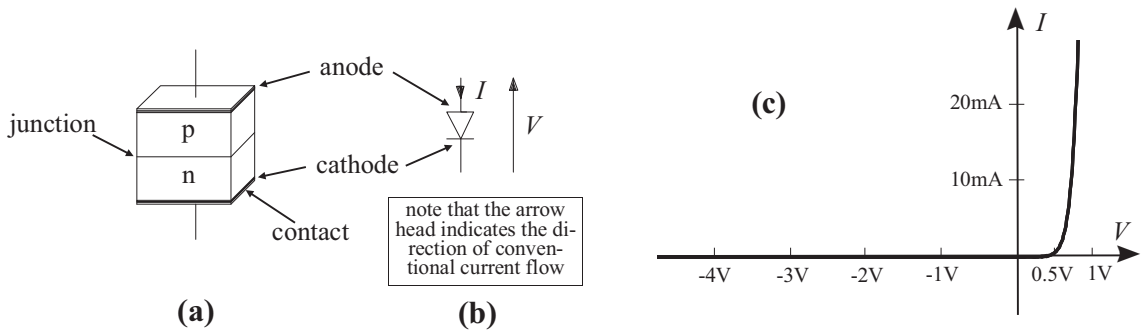


Figure 1 **(a)** *a simplified representation of diode structure,* **(b)** *the diode circuit symbol and* **(c)** a *typical I-V plot for a silicon p-n junction diode*.

Structure

The diode consists of two bits of semiconductor, one p-type and one n-type, in contact with one another. N-type semiconductor is pure semiconductor with added impurities that make it easy for negative charges (electrons) to move around. P-type material, on the other hand, is pure semiconductor with added impurities that make it easy for positive charges (holes) to move around. (A hole is really an absence of an electron where one might be expected but it behaves like a particle for most practical purposes.) The region where the two materials meet is called the junction and the outside edges of the p and n regions are covered with a conducting material, often a metal such as gold, that allows connection to other circuit elements. A diode one might buy in a shop will be packaged in a protective envelope of plastic, glass or metal with connecting wires or terminals protruding from the package. Most diodes are made from silicon.

Circuit Symbol

The diode is drawn in circuit diagrams using the symbol of figure 1b. ***The arrow gives the direction of conventional forward current flow*** so if you see a diode in a circuit you can tell immediately the direction in which it will conduct current. The correspondence between structure and symbol is indicated in figures 1a and 1b.

Characteristic Behaviour

(i) forward bias

When a positive voltage, V, is applied to the p region (or anode) with respect to the n region (or cathode), the device is said to be "forward biassed" and a current, I, called the "forward current", can flow through the device. A certain value of applied voltage is necessary before an observable current flows but once this value is reached, very small increases in applied voltage lead to very large increases in current flow. For a silicon diode the current begins to increase noticeably when the applied voltage is between 0.6V and 0.7V as can be seen in figure 1c. For this reason it is often said that silicon diodes have a "turn on voltage" of 0.7V - this is a useful figure to remember. (In fact the diode turns on over a range of voltages in the region of 0.7V but the assumption of a 0.7V turn on voltage is a very good approximation for most purposes.) The turn on voltage is sometimes called the "diode drop" or the "forward voltage drop".

(ii) reverse bias

When a negative voltage is applied to the anode with respect to the cathode, there is no current flow. (Actually there is a very very small current flowing but it is not important for most applications.) The diode is said to be "reverse biassed" and in this state it behaves very nearly like an open circuit - ie, infinite resistance. If the reverse bias is steadily increased, it will eventually reach a value, the reverse breakdown voltage, that is sufficient to cause failure of the device. The failure mechanism, which is usually destructive, is very similar to the physical mechanism that causes air to change from an insulating to a conducting state during a lightning strike.

Diode Models

The diode equation

The "diode equation", which is derived fom considerations of the device physics and accurately describes the relationship between current through and voltage across the diode, is

$$I = I_0 \left(\exp\left(\frac{eV}{nkT} \right) - 1 \right)$$

where
I is the conduction current
I_0 is a constant
e is electronic charge
V is applied bias
n is a constant with a value between 1 and 2 (often taken as 1)
k is Boltzmann's constant
T is absolute temperature

The diode equation shows that the current through the diode is exponentially related to the voltage across it. Computer simulators that work numerically use the diode equation to model the behaviour of diodes but exponential relationships can be difficult to deal with from a human analytical point of view - especially where sinusoids or transients are involved. To get around this difficulty, piecewise linear approximations are commonly used by engineers for simple estimates of performance.

Piecewise linear models

Piecewise linear models are usually created by observing a device characteristic and representing it as two or more straight line approximations. Taking this approach with the diode suggests the use of two linear regions, one for forward bias when the diode is conducting and one for reverse bias when it is not conducting. Possible forms of such a model are shown in figures 2a, 2b and 2c.

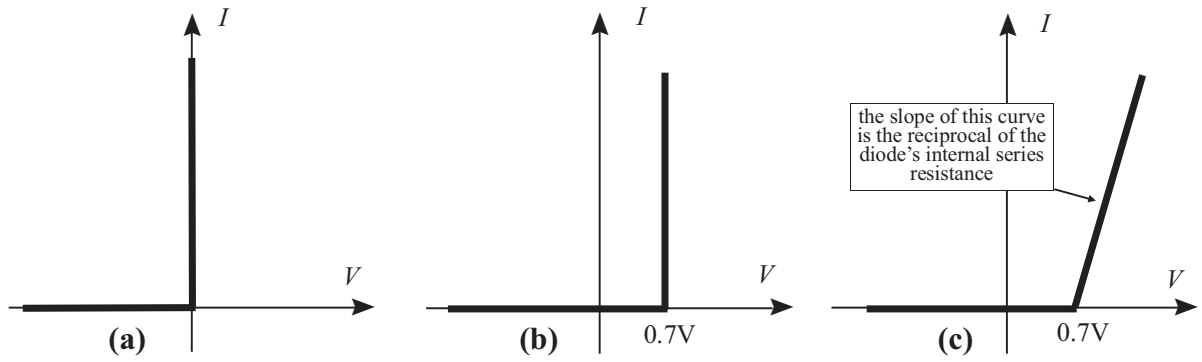


Figure 2: *Piecewise linear diode models.* **(a)** *the ideal diode*, **(b)** *diode with a turn on votage of 0.7V but otherwise ideal and* **(c)** *diode with a turn on voltage of 0.7V and internal series resistance.*

The model of figure 2a assumes that the diode conducts zero current, ie blocks perfectly, when reverse biassed and conducts perfectly when forward biassed. It is a useful starting point when trying to interpret a circuit containing diodes and gives numerically accurate predictions of circuit behaviour when the voltages in circuits are large compared to 0.7V. The model of figure 2b is similar to that of figure 2a except for the inclusion of the 0.7V forward drop which makes it more useful for circuits with voltage differences that cannot be assumed to be large compared to 0.7V. Figure 2c adds a further refinement that allows for the effect of series internal resistance, a parasitic effect present in all diodes but one that can be ignored for the purposes of this module.

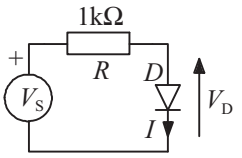


Figure 3
A simple diode circuit

To get a feel for the effect of the difference between the models of figures 2a and 2b on numerical estimates, consider the circuit of figure 3. The driving source, V_S, is in such a direction that positive V_S will tend to forward bias the diode. The current, I, is then given by

$$I = \frac{\text{voltage across } R}{R} = \frac{V_S - V_D}{R}$$

Thus if V_S = 100V, the model of figure 2a gives I = 100mA and that of figure 2b gives I = 99.3mA; if V_S = 10V and then 2V, the corresponding currents are for 10V, I = 10mA and I = 9.3mA and for 2V, I = 2mA and I = 1.3mA. The error only becomes serious for the 2V case.

If the problem was to estimate the power dissipation in the diode, of the models of figures 2a and 2b, 2b is the only sensible choice. This is because the power dissipated is $V_D I$ so it makes no sense to choose a model that approximates V_D to zero. The most important thing about using a model is to be aware of the approximations implicit in it.

How to work out a diode's conduction state

In order to use a piecewise linear model, one must identify the points at which behaviour changes from one piecewise linear mode to another. In the context of a diode in a circuit with dc driving sources this amounts to identifying whether the diode is conducting or not conducting. In circuits where sources can vary, the conditions that will put the diode at the boundary between conduction and non-conduction must be identified.

(i) with fixed sources

In circuits containing only fixed dc sources, the conduction state of the diode can be identified as follows.

1 Make an assumption about the state of the diode - ie, conducting or not conducting.

2 Replace the diode with a circuit element appropriate for the choice made in step 1 - this would be an infinite resistance (open circuit) for "not conducting" or a 0.7V source, with its positive end at the position of the diode anode, for "conducting". [*Note that this assumes the model of figure 2b is being used. If the model of figure 2a is used, a conducting diode behaves like a short circuit - ie a zero ohm link.*]

3 Work out, as appropriate, the voltage across or the current through the element representing the diode.

4 Test the result of your calculation for physical sensibility. A conducting diode would give a positive I flowing through the 0.7V source from its "+" end to its "-" end. A non conducting diode would give a voltage difference between the circuit nodes to which the anode and cathode were connected that was less than 0.7V. [*Notes: The voltage difference must be in the direction* $V_{anode\ node} - V_{cathode\ node}$. *The use of 0.7V assumes the model of figure 2b is being used; less than 0V would be the critical test for the model of figure 2a.*]

5 Since there are only two options, conducting or non conducting, if one is incorrect, the other must be correct. If the guess in step 1 was wrong, replace the diode by the correct representation and repeat step 3 to find either the reverse bias voltage or forward current as appropriate.

(ii) with varying sources

In circuits with varying source(s), the diode may change its conduction state as the source(s) change over their operating range of output. The task here is to identify the value of source at which the diode is on the point of changing from one state to another. Essentially the question that needs to be answered is

> "what source voltage or current conditions will put a voltage $V_{\text{anode}} - V_{\text{cathode}}$ of 0.7V across the diode with a current through it of zero?".

In some circuits it is fairly easy to identify the value of source at which the diode will change state but for others it is necessary to use analysis.

As an example of the easier form of problem, consider the circuit of figure 3. If the diode is replaced by an infinite resistance and the source varied, the diode will be in a non conducting state for all V_S that results in a V_D *l*ess than 0.7V. For V_S = 0.7V and V_D = 0.7V, the diode is on the point of changing state (although the current through it would still be zero because there would be no voltage drop across R). For V_S greater than 0.7V the diode will be forward biassed and the infinite resistance must be replaced by a 0.7V fixed source so that the diode current can be calculated.

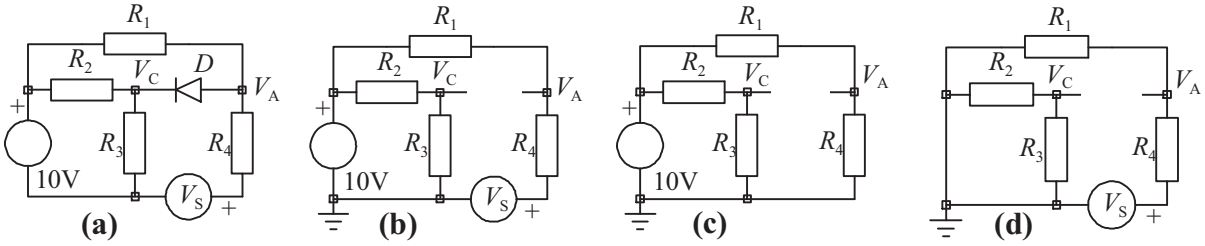


Figure 4: **(a)** *the full circuit*, **(b)** *with diode replaced by an infinite resistance and a reference point added,* **(c)** *with the* V_S *source replaced by a short circuit and* **(d)** *with the 10V source replaced by a short circuit.*

For the circuit of figure 4a, identification of the value of V_S at which the diode will change from a non conducting to a conducting state is more difficult and some analysis is necessary as follows.

1 Make an assumption about the state of the diode - let us assume that it is not conducting.

2 Replace the diode by the appropriate circuit element for the choice in 1 - in this case an open circuit.

3 Choose a reference point with respect to which all voltages will be measured and choose an appropriate analysis method.

The decisions so far leave a modified circuit of figure 4b where the bottom of R_3 has been chosen as a suitable reference node and the diode has been replaced by an infinite resistance.

4 Work out V_A - V_C in terms of circuit components and sources. The following process uses the superposition principle as the analysis method .....

First, work out V_A and V_C due to the 10V source with V_S replaced by its Thevenin equivalent impedance - ie, a short circuit. The partial circuit is shown in figure 4c.

V_A and V_C are a potential divisions of the 10V source through (R_1 and R_4) and (R_2 and R_3) respectively

$$V_{A\,(10)} = \frac{10R_4}{R_1 + R_4} \text{ and } V_{C\,(10)} = \frac{10R_3}{R_2 + R_3}$$

Second, work out V_A and V_C due to V_S with the 10V source being replaced by a short circuit. This partial circuit is shown in figure 4d.

V_A is a potential division of V_S through R_4 and R_1 (note that it is the voltage across R_1 that gives V_A w.r.t. the reference point). V_C must be zero because both R_2 and R_3 are connected to the reference point, so

$$V_{A\,(V_S)} = \frac{V_S R_1}{R_1 + R_4} \text{ and } V_{C\,(V_S)} = 0$$

Then add the various contributions together

$$V_A - V_C = (V_{A\,(10)} + V_{A\,(V_S)}) - (V_{C\,(10)} - V_{C\,(V_S)}) = \frac{10R_4}{R_1 + R_4} + \frac{V_S R_1}{R_1 + R_4} - \frac{10R_3}{R_2 + R_3} - 0$$

If the component values are known, the point at which the diode is on the point of conducting

can be evaluated. For example, if R_1 = 1kΩ, R_2 = 2kΩ, R_3 = 3kΩ and R_4 = 4kΩ,

$$V_A - V_C = \frac{10 \times 4}{5} + \frac{V_S \times 1}{5} - \frac{10 \times 3}{5} = 2 - \frac{V_S}{5}$$

and equating this to 0.7V will give the V_S at which the diode is on the boundary between its two piecewise linear states. In this example, the diode will be on the point of changing state when V_S = 6.5V. If V_S is bigger than this value it will try to make V_A - V_C bigger than 0.7V so the diode will conduct a forward current.

Other types of diode

Although the silicon p-n junction diode is by far the most commonly used diode, there are other types made for special purposes and sometimes made from other materials that you should be aware of. A brief description of the more commonly used ones follows.

Light emitting diodes

Light emitting diodes (LEDs) are diodes that emit light when they are forward biassed. The light is emitted when energetically excited electrons lose their energy and return to their resting energy state. The physics of silicon makes it much more likely that energy will be lost as heat than as a photon emission so LEDs are made from compound semiconductors such as gallium arsenide (GaAs), gallium phosphide (GaP) and gallium nitride (GaN) where optical emission is a very probaable energy loss mechanism. (The advantages that would be gained if silicon could be made to emit photons are significant so there is a significant research effort aimed at identifying impurities that might be added to silicon to encourage photon emission.)

LEDs obey the diode equation although the constants are different from those appropriate for silicon. The *V-I* characteristic is similar in shape to that of a silicon diode but differs in turn on voltage. A red LED will have a turn on voltage of around 1.5V, a green LED of around 2V and a blue LED of around 3V. UV LEDs will have even higher turn on voltages. Leds are used extensively in applications such as traffic signalling (both roadside and mobile) and instrumentation indicators and are slowly but steadily moving into the space lighting area.

Zener diodes

Zener diodes are silicon diodes that are unusual because they are designed to be operated in the usually destructive reverse breakdown region and they are designed to break down at a well defined reverse voltage. In the reverse breakdown region current flows through a reverse biassed diode and the voltage across the diode is largely unaffected by changes in reverse current through it. This ability to maintain a more or less constant voltage across when current through is changing makes the zener diode useful as a regulating element in simple power supplies. Breakdown voltages from 3V to around 300V at power ratings of a few hundred mW to over 100W are readily available.

Shottky barrier diodes

These are metal semiconductor junction devices. Their characteristics are similar to p-n junction devices except that turn on voltage is a function of the metal used in the juction. Typical turn on voltages range from 0.3V to 0.6V. They have advantages for high speed operation - they have been used for many years as signal detectors at frequencies up to 10^{11} Hz and over recent years have found increasing applications in high efficiency switching power supply circuitry.

First Order Circuits

1 Introduction

There are two forms of first order frequency response, low-pass and high-pass. There is also a third hybrid form which is a linear sum of the low-pass and high-pass cases; this is not really a separate type of response in its own right. The terms high-pass and low-pass relate to the way the circuit gain changes as frequency is varied. A low-pass circuit tends to pass frequencies below a critical value but attenuates increasingly as frequency exceeds this critical value. The high-pass circuit, on the other hand, passes frequencies above some critical value and attenuates increasingly as frequency falls below this critical value. The critical value is usually called the **corner frequency** or the **3dB frequency**. In working out transfer functions it is important to keep j and ω together and replacing $j\omega$ with s is a convenient way of achieving this objective. s is actually the Laplace complex frequency variable which reduces to $j\omega$ for steady state frequency response considerations.

The two forms of first order response can be represented by standard forms and although the hybrid form is a sum of low-pass and high-pass, it is usually convenient to treat it as a third standard form. All first order circuits can be interpreted by forcing their transfer functions into the shape of a standard form and then extracting the relevant parameters by inspection.

2 First order standard forms

A general transfer function will have a **denominator** of the form $a_0 + a_1 s + a_2 s^2 + a_3 s^3 + \ldots$. A transfer function is first order if only the a_0 and $a_1 s$ terms exist. From a frequency response point of view, $s \Rightarrow j\omega$.

The two basic forms of first order transfer function are;

The low-pass
$$\frac{v_o}{v_i} = k \cdot \frac{1}{1 + s\tau} = k \cdot \frac{1}{1 + j\dfrac{\omega}{\omega_o}} = k \cdot \frac{1}{1 + j\dfrac{f}{f_o}} \qquad \textbf{(2.1)}$$

The high-pass
$$\frac{v_o}{v_i} = k \cdot \frac{s\tau}{1 + s\tau} = k \cdot \frac{j\dfrac{\omega}{\omega_o}}{1 + j\dfrac{\omega}{\omega_o}} = k \cdot \frac{j\dfrac{f}{f_o}}{1 + j\dfrac{f}{f_o}} \qquad \textbf{(2.2)}$$

The third form, which is a linear sum of **(2.1)** and **(2.2)**, is often called a "pole-zero" or "lead lag" function.

$$\frac{v_o}{v_i} = k \cdot \frac{1 + s\tau_1}{1 + s\tau_2} = k \cdot \frac{1 + j\dfrac{\omega}{\omega_1}}{1 + j\dfrac{\omega}{\omega_2}} = k \cdot \frac{1 + j\dfrac{f}{f_1}}{1 + j\dfrac{f}{f_2}} \qquad \textbf{(2.3)}$$

The key points about these standard forms are

(i) The denominator is always complex

(ii) Whatever multiplies $j\omega$ **in the denominator** is the system time constant. In frequency domain expressions it is very common to see time constant expressed in terms of a frequency domain constant as in **(2.1)**, **(2.2)** and **(2.3)**.

(ii) The denominator has a real part of unity in all cases.

(iii) The numerator may be real (constant) as in **(2.1)**, imaginary as in **(2.2)** or complex as in **(2.3)**.

(iv) Where the numerator is purely imaginary, the coeficcient of $j\omega$ in the top line should be made to be the same as that of the imaginary part of the denomiator.

(v) Where the numerator is complex, its real part should be forced to unity.

(vi) The form of the numerator indicates the type of first order response -

purely real	$\Rightarrow$	low-pass (or simple integrator)
purely imaginary	$\Rightarrow$	high-pass (or simple differentiator)
complex	$\Rightarrow$	"pole-zero" or "lead-lag" circuit - a linear sum of low-pass and high-pass, each with different k.

3 Getting the transfer function

The transfer function will often be a suitably manipulated potential divider relationship. In order to end up with a result that is easily interpretable, it is desirable to express the transfer function in a particular way. An outline of the steps necessary is as follows with the circuit of figure 1 used as an example.

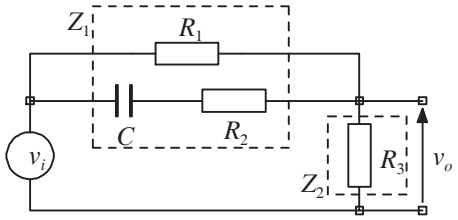


Figure 1

An example first order RC circuit

(i) Work out the impedances Z_1 and Z_2 remembering to keep $(j\omega)$ together. For figure 1 and using s for $j\omega$ they are

$$Z_1 = R_1 \,//\, (R_2 + X_C)$$

$$= \frac{R_1\left(R_2 + \dfrac{1}{sC}\right)}{R_1 + R_2 + \dfrac{1}{sC}} = \frac{R_1(1 + sCR_2)}{1 + sC(R_1 + R_2)} \qquad \textbf{(3.1)}$$

$$Z_2 = R_3 \qquad \textbf{(3.2)}$$

(ii) Write down the potential division relationship. For the circuit of figure 1 it is

$$\frac{v_o}{v_i} = \frac{Z_2}{Z_2 + Z_1} = \frac{R_3}{R_3 + \dfrac{R_1\,(1 + sCR_2)}{1 + sC\,(R_1 + R_2)}} \qquad \textbf{(3.3)}$$

(iii) Manipulate the potential division relationship to end up with a ratio of two polynomials in s. Note that in general the numerator polynomial may be completely real, completely imaginary or complex; the denominator will be complex with a real and an s term. For the circuit of figure 1,

$$\frac{v_o}{v_i} = \frac{R_3\,(1 + sC\,(R_1 + R_2))}{R_3\,(1 + sC\,(R_1 + R_2)) + R_1\,(1 + sCR_2)}$$

$$= \frac{R_3\,(1 + sC\,(R_1 + R_2))}{R_3 + R_1 + sC\,(R_1R_3 + R_2R_3 + R_1R_2)} \qquad \textbf{(3.4)}$$

(iv) Take out factors to force the real parts of the numerator and denominator to unity. This will often result in having to divide the s term in the denominator by the real part of the denominator. The numerator often naturally occurs in the right form (as in this example). For the circuit of figure 1 R_3 is obviously a factor in the numerator. $(R_1 + R_3)$ is the factor that must be removed from the denominator to give a denominator real part of unity. These two factors form a dimensionless frequency independent ratio that multiplies the complex part of the expression.

$$\frac{v_o}{v_i} = \frac{R_3}{R_1 + R_3} \cdot \frac{1 + sC\,(R_1 + R_2)}{1 + sC\,\dfrac{R_1R_2 + R_2R_3 + R_1R_3}{R_1 + R_3}} \qquad \textbf{(3.5)}$$

At each stage of this process you should get into the habit of checking that your equations are dimensionally consistent. It is easy to check dimensions and although dimensional checks will not reveal all errors, they will reveal a significant number.

4 Interpreting the transfer function

Having obtained the transfer function and manipulated it so that it has the shape of a standard form, the next step is to compare the transfer function with the standard form of the same type. Again, using the circuit of figure 1 as an example and comparing **(3.5)** with **(2.1)**, **(2.2)** and **(2.3)**, it is clear that **(3.5)** is of the form of **(2.3)** - the hybrid form - and by comparison of coefficients,

$$k = \frac{R_3}{R_1 + R_3}\,,\ \omega_1 = \frac{1}{C\,(R_1 + R_2)} \text{ and } \omega_2 = \frac{R_1 + R_3}{C\,(R_1R_2 + R_1R_3 + R_2R_3)} \qquad \textbf{(4.1)}$$

Knowledge of these three parameters and the the type of response ((2.1), (2.2), or (2.3)) specifies the shape of the amplitude and phase responses of the circuit as shown in section 5. It is also possible to use the transfer function to identify system gain as frequency approaches very low or very high values - the low frequency gain and the high frequency gain. To do this one must consider how the modulus of the transfer function behaves as frequency becomes very small or very large. Taking the hybrid standard form of **(2.3)**,

$$\left|\frac{v_o}{v_i}\right| = k\,.\left|\frac{1 + j\dfrac{\omega}{\omega_1}}{1 + j\dfrac{\omega}{\omega_2}}\right| = k\,.\left(\frac{1 + \dfrac{\omega^2}{\omega_1^2}}{1 + \dfrac{\omega^2}{\omega_2^2}}\right)^{\frac{1}{2}} \qquad \textbf{(4.2)}$$

At low frequencies, $\omega << \omega_1$ and $\omega << \omega_2$ so both $\dfrac{\omega^2}{\omega_1^2}$ and $\dfrac{\omega^2}{\omega_2^2}$ are $<< 1$ and $\left|\dfrac{v_o}{v_i}\right| \approx k\,.$ **(4.3)**

At high frequencies, $\omega >> \omega_1$ and $\omega >> \omega_2$ so both $\dfrac{\omega^2}{\omega_1^2}$ and $\dfrac{\omega^2}{\omega_2^2}$ are $>> 1$ and $\left|\dfrac{v_o}{v_i}\right| \approx k\ \dfrac{\omega_2}{\omega_1}.$ **(4.4)**

5 Response shapes

There are three response shapes that correspond to the three standard forms of **(2.1)**, **(2.2)** and **(2.3)**. **All** first order transfer functions will fall into one of these three categories. Amplitude responses are usually plotted with gain in dB; phase is usually plotted on a linear scale. Both amplitude and phase are usually plotted with a logarithmic frequency axis.

5.1 Low-Pass

(a) Amplitude response

The low-pass amplitude response shape can be worked out by considering the modulus of **(2.1)** for frequencies well below, well above and in the region of, ω_0.

$$\left|\frac{v_o}{v_i}\right| = k\,.\,\left|\frac{1}{1+j\dfrac{\omega}{\omega_0}}\right| = k\,.\left(\frac{1}{1+\dfrac{\omega^2}{\omega_0^2}}\right)^{\frac{1}{2}}$$

(i) $\omega << \omega_0$

Under this condition $\dfrac{\omega^2}{\omega_0^2}$ is much smaller than unity so $\left|\dfrac{v_o}{v_i}\right| \approx k\,.$ $(\equiv 20\log k$ dB)

(ii) $\omega = \omega_0$

Under this condition $\dfrac{\omega^2}{\omega_0^2} = 1$ so $\left|\dfrac{v_o}{v_i}\right| \approx \dfrac{k}{\sqrt{2}}\,.$ $(\equiv 20\log k$ dB $- 3$dB)

(iii) $\omega >> \omega_0$

Under this condition $\dfrac{\omega^2}{\omega_0^2}$ is much larger than unity so $\left|\dfrac{v_o}{v_i}\right| \approx k\,\dfrac{\omega_0}{\omega}$. Thus the circuit gain is inversely proportional to frequency; if ω increases by a factor of 10, gain decreases by a factor of 10. A factor of 10 reduction in gain is a reduction of 20 dB so the slope of the amplitude response in this frequency region will approach −20dB for every decade increase in frequency.

A good approximation to the amplitude response (known as the Bode approximation) draws the response as two straight lines - a horizontal line at the low frequency gain from 0Hz to ω_0 and a -20dB per decade line from ω_0 upwards. The low-pass amplitude response is shown in figure 2.

(b) Phase response

The phase of the low-pass response of **(2.1)** is calculated from $\varphi = -\tan^{-1}\dfrac{\omega}{\omega_0}$ and as in the amplitude case, its shape can be deduced by considering three frequency conditions,

(i) $\omega << \omega_0$

Under this condition, as $\omega \Rightarrow 0$, $\varphi \Rightarrow 0^o$.

(ii) $\omega = \omega_0$

Under this condition, $\varphi = -\tan^{-1}\dfrac{\omega}{\omega_0} = -\tan^{-1} 1 = -45^o$

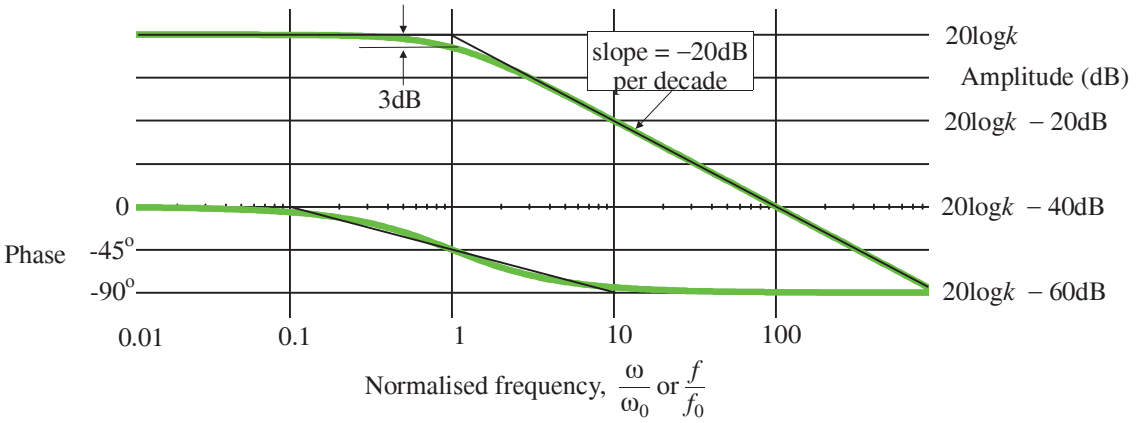
(iii) $\omega >> \omega_0$

Under this condition, $\varphi = -\tan^{-1}\dfrac{\omega}{\omega_0} \Rightarrow -\tan^{-1}[\text{a large number}] \Rightarrow -90^{\circ}$

The Bode approximation for the phase response is a straight line starting from 0° at $\omega = 0.1\omega_0$, going through -45° at $\omega = \omega_0$ and reaching -90° at $\omega = 10\ \omega_0$. Its slope is therefore -45° per decade. The phase response is shown in figure 2.

Figure 2

Low-pass amplitude and phase response



5.2 High-Pass

(a) Amplitude response

The high-pass transfer function of **(2.2)** has a magnitude response that is a mirror image of the low-pass response about the vertical line $\omega/\omega_0 = 1$. The response plot for high-pass function can be written as

$$20\log\left|\frac{v_o}{v_i}\right| = 20\log\left(k\,.\left|\frac{j\dfrac{\omega}{\omega_0}}{1+j\dfrac{\omega}{\omega_0}}\right|\right) = 20\log k + 20\log\left|j\frac{\omega}{\omega_0}\right| + 20\log\left|\frac{1}{1+j\dfrac{\omega}{\omega_0}}\right|$$

and this makes it clear that on a logarithmic amplitude plot, the response consists of a sum of three components.

$20\log k$ is a constant.

$20\log\left|j\dfrac{\omega}{\omega_0}\right|$ is a straight line with a slope of +20 dB per decade that goes through 0 dB when $\omega = \omega_0$

$20\log\left|\dfrac{1}{1+j\dfrac{\omega}{\omega_0}}\right|$ is the low pass response shape, without the k, considered in section 5.1.

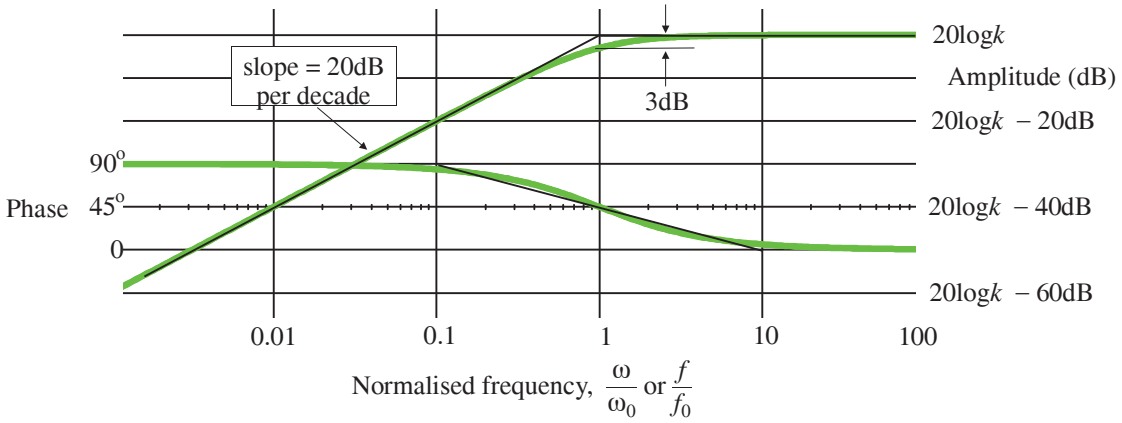
The high-pass amplitude response is shown in figure 3.

(b) Phase response

The phase response of the high-pass function is the same shape as that of the low-pass function but at all frequencies the high-pass phase is 90° higher than the low-pass phase. The difference arises because there is a j term but no real term in the numerator and that j term acts as a 90° phase shift operator. The phase response of the high-pass function is shown in figure 3.

Figure 3

High- pass amplitude and phase response



5.3 Pole-Zero or Lead-Lag

(a) Amplitude response

Using the same approach as in section 5.2, the log of the modulus of **(2.3)** can be expressed as the sum of simpler logarithmic components

$$20\log\left|\frac{v_o}{v_i}\right| = 20\log\left(k\,.\left|\frac{1+j\dfrac{\omega}{\omega_1}}{1+j\dfrac{\omega}{\omega_2}}\right|\right) \text{ or}$$

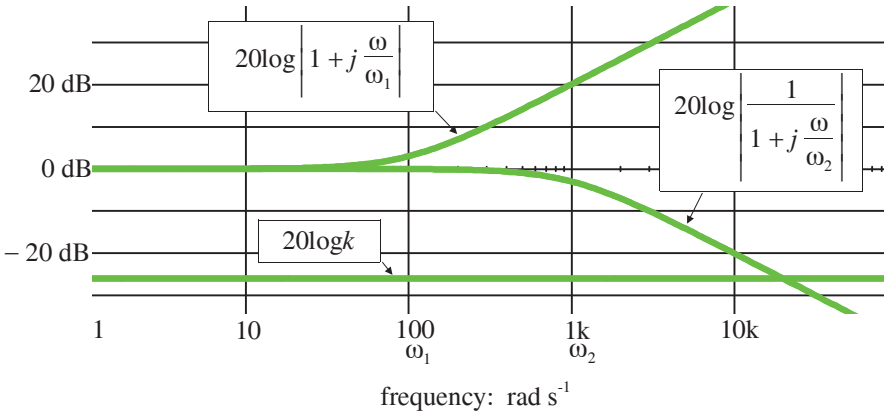
$$20\log\left|\frac{v_o}{v_i}\right| = 20\log k + 20\log\left|1+j\frac{\omega}{\omega_1}\right| + 20\log\left|\frac{1}{1+j\dfrac{\omega}{\omega_2}}\right| \qquad \textbf{(5.1)}$$

The only new part here is the second term. Since $20\log\left|1+j\dfrac{\omega}{\omega_1}\right| = -20\log\left|\dfrac{1}{1+j\dfrac{\omega}{\omega_1}}\right|$, the response of the second term is the inverse of the first order low pass response of section 5.1. In other words for the second term, the gain is 0 dB at 0 Hz, rises to + 3 dB at $\omega = \omega_1$ and rises at 20 dB per decade for frequencies greater than ω_1.

If $\omega_1 < \omega_2$, the overall gain rises as frequency increases between ω_1 and ω_2 before flattening off when $\omega > \omega_2$. If $\omega_1 > \omega_2$, the overall gain falls as frequency increases between ω_2 and ω_1 before flattening off when $\omega > \omega_1$. Figure 4a shows the gain components of **(5.1)** and figure 4c shows the overall sum of those components, together with the overall phase response.

Figure 4a

The three log magnitude components of ***(5.1)****. In this example,* ω_1 *is 100 rad* s^{-1} *and* ω_2 *is 1000 rad* s^{-1}*.*



(b) Phase response

For a function such as **(2.3)** the phase is given by

$$\varphi = \tan^{-1}\frac{\omega}{\omega_1} - \tan^{-1}\frac{\omega}{\omega_2} \qquad \textbf{(5.2)}$$

There is no phase shift associated with the constant k. Both parts of the phase expression have a phase that approaches 0^o at low frequencies and approaches 90^o for high frequencies. Since the two subtract, the high frequency phase shift will also be zero. In the region of ω_1 and ω_2, the phase will be a positive going or negative going hump depending upon whether $\omega_1 < \omega_2$ or vice versa. Figure 4b shows the contribution to phase made by each of the components of **(5.2)** and figure 4c shows the sum of these components.

Figure 4b

The three phase components of ***(5.2)****. In this example,* ω_1 *is 100 rad* s^{-1} *and* ω_2 *is 1000 rad* s^{-1}*.*

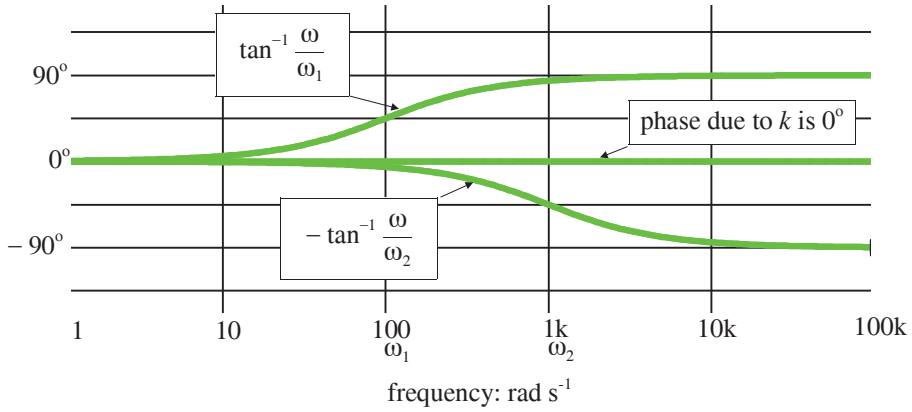
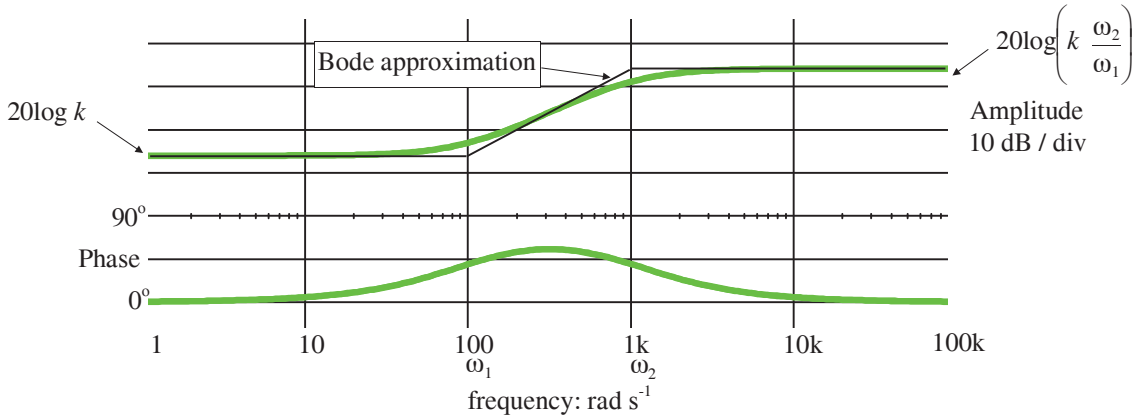


Figure 4c

Overall response of a pole-zero circuit such as ***(2.3)*** *with* $\omega_1 = 100$ *rad* s^{-1} *and* $\omega_2 = 1000$ *rad* s^{-1}. *The amplitude response is the sum of the components of shown in figure 4a and the phase response is the sum of the components shown in figure 4b.*



Note that in general ω_1 can be smaller than or larger than ω_2. The response shown here is for ω_1 smaller than ω_2. If ω_2 had been smaller than ω_1, gain and phase would have started falling because of the effects of ω_2 before they flattened out because of the effects of ω_1. The phase response would then be a downwards going hump and the amplitude response would have a higher value at low frequencies than at high frequencies.

For the circuit of figure 1, ω_1 is lower than ω_2 for all possible component value combinations.

6 Checking by inspection

It is quite easy to identify high frequency gain, low frequency gain and time constant by inspection. Identifying these parameters is a useful check on the accuracy of your algebraic manipulations; if the time constant is different depending on how you calculated it, there is an error somewhere. The following section outlines the steps in the checking process using the circuit of figure 1 as an example.

(i) Low frequency (l.f.) gain

The low frequency gain is the gain that is approached as $f \Rightarrow 0$. To work it out, replace capacitors with a very high impedance. Capacitors then dominate the impedance of series *RC* combinations but are of negligible effect in parallel *RC* combinations. In most cases the capacitors are simply removed from the circuit. Thus the low frequency equivalent circuit of figure 1 is given in figure 5 and the gain is easily written down as

$$\frac{v_o}{v_i} = \frac{R_3}{R_1 + R_3}$$

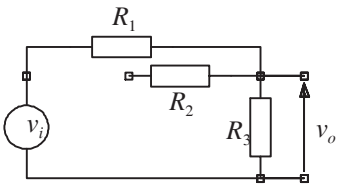


Figure 5

The low-frequency equivalent circuit of figure 1. Note that C has been replaced by an open circuit.

(ii) High frequency (h.f.) gain

The high frequency gain is the gain that is approached as $f \Rightarrow \infty$. In this case capacitors have a very low reactance so the impedance of series *RC* combinations is dominated by *R* and that of parallel combinations is dominated by *C*. The high frequency equivalent circuit of figure 1 is

shown in figure 6. Again, the gain can be easily written down as

$$\frac{v_o}{v_i} = \frac{R_3}{R_1 // R_2 + R_3} = \frac{R_3\,(R_1 + R_2)}{R_1R_2 + R_1R_3 + R_2R_3}$$

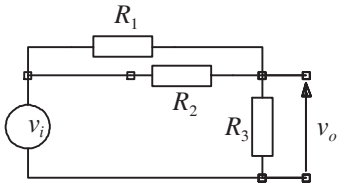


Figure 6

A high frequency equivalent circuit of figure 1. Note that C has been replaced by a short circuit.

(iii) Time constant

To identify the system time constant one must look at the circuit from the capacitor's point of view. First replace all sources by their Thevenin equivalent impedances - 0Ω for a voltage source and ∞Ω for a current source. Then imagine that you can inject some charge into the capacitor and ask yourself what is the resistance of the discharge path. C multiplied by the discharge path resistance is the system time constant and this should be the same as the coefficient of $j\omega$ in the denominator of the transfer function.

Figure 7 shows figure 1 with v_i replaced by a short circuit. Charge in C must flow through R_2. After passing through R_2, the current is faced with R_1 and R_3 in parallel giving a time constant

$$\tau = C\,(R_2 + R_1 // R_3) = C\,\frac{R_1R_2 + R_1R_3 + R_2R_3}{R_1 + R_3}$$

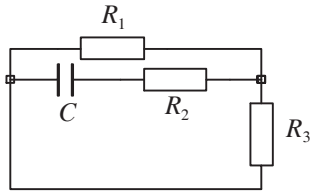


Figure 7

Equivalent circuit of figure 1 for identifying time constant

7 Step response

A step input is an instantaneous change in input voltage from one voltage to another. The instant at which the change occurs is usually taken as $t = 0$ although it doesn't have to be there. A unit step input is a change from 0V to 1V.

Step inputs are very useful test signals because many circuit applications deal with signals that change state suddenly from one value to another. The step response of a circuit, ie the output that arises as a result of a step at the input is therefore a useful response to be able to predict.

For first order circuits, the step response will in general consist of a step followed by an exponential. The magnitude of the step can be calcuated from the gain terms and the exponential can be written

$$V(t) = (V_{START} - V_{FINISH})\,e^{-t/\tau} + V_{FINISH} \qquad \textbf{(7.1)}$$

The numbers needed to define V_{START}, V_{FINISH} and τ can be found from the input step magnitude, the low frequency ($f \Rightarrow 0$) gain, the high frequency ($f \Rightarrow \infty$) gain and the system time constant - all these can be found by inspection as described in section 6 and they apply here as follows.

- The high frequency gain operates on the instantaneous step
- The low frequency gain operates on the dc voltage that exists before the step occurs - this is often 0V - and defines the voltage that will be reached as $t \Rightarrow \infty$

As an example, consider the circuit of figure 1, redrawn for convenience as figure 8 with component values added and a step input going from –2 V to + 8 V at $t = 0$.

The low frequency gain of the circuit is

$$A_{LF} = \frac{1\text{k}\Omega}{1\text{k}\Omega + 10\text{k}\Omega} = 90.9\text{x}10^{-3}$$

This defines the voltage from which any step on the output begins - in this case it is

$$-2\text{V}\text{x}90.9\text{x}10^{-3} = -0.18\text{V}$$

and also the voltage aimed for as $t \Rightarrow \infty$ which is

$$8\text{V}\text{x}90.9\text{x}10^{-3} = 0.73\text{V}$$

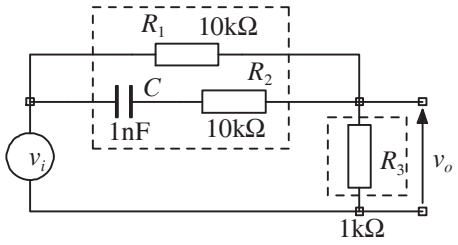


Figure 8

The first order RC circuit of figure 1 with values added. v_i is a step defined by $v_i = -2V$ for $t < 0$ and $v_i = 8V$ for $t > 0$

The high frequency gain of the circuit is

$$A_{HF} = \frac{1\text{k}\Omega}{10\text{k}\Omega//10\text{k}\Omega + 1\text{k}\Omega} = 0.167$$

and this, when multiplied by the height of the input step defines the height of the output step as

$$0.167\text{x}(8\text{V} - (-2\text{V})) = 1.67\text{V}$$

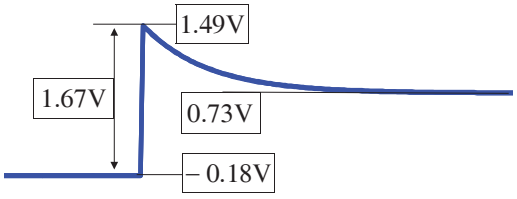


Figure 9

The step response associated with figure 8

The overall response is shown in figure 9 with the key voltages labelled. The exponential decay has $V_{START} = 1.49\text{V}$, $V_{FINISH} = 0.73\text{V}$ and $\tau = 10.9\mu\text{s}$ so using **(7.1)**, the exponential part of the response is $V(t) = (1.49 - 0.73)\, e^{-t/10.9\text{x}10^{-6}} + 0.73$.

8 An example

Identify the behaviour of the circuit of figure 10.

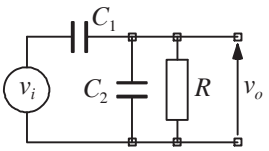


Figure 10

An example circuit

(i) By inspection

At low frequency the reactance of C_1 is much larger than the impedance of the C_2R combination so in the limit of $f \Rightarrow 0$, l.f. gain = 0

At high frequency the reactances of both capacitors are small compared with R and C_2 dominates the C_2R combination. As $f \Rightarrow \infty$, the gain is determined by the capacitive potential division between C_1 and C_2 so h.f. gain is

$$\frac{\dfrac{1}{j\omega C_2}}{\dfrac{1}{j\omega C_1} + \dfrac{1}{j\omega C_2}} = \frac{C_1}{C_1 + C_2} \qquad \textbf{(8.1)}$$

The time constant will be $R(C_1 // C_2)$ which is $R\,(C_1 + C_2)$ **(8.2)**

(ii) By analysis

The transfer function is a potential division between C_1 and the parallel combination C_2R.

$$\frac{v_o}{v_i} = \frac{\dfrac{\dfrac{R}{j\omega C_2}}{R + \dfrac{1}{j\omega C_2}}}{\dfrac{1}{j\omega C_1} + \dfrac{\dfrac{R}{j\omega C_2}}{R + \dfrac{1}{j\omega C_2}}} = \frac{\dfrac{R}{1 + j\omega C_2 R}}{\dfrac{1}{j\omega C_1} + \dfrac{R}{1 + j\omega C_2 R}} = \frac{j\omega C_1 R}{1 + j\omega C_2 R + j\omega C_1 R}$$

$$= \frac{j\omega C_1 R}{1 + j\omega (C_2 + C_1) R} = \frac{C_1}{C_1 + C_2} \cdot \frac{j\omega (C_1 + C_2) R}{1 + j\omega (C_2 + C_1) R} \equiv k \cdot \frac{j\dfrac{\omega}{\omega_c}}{1 + j\dfrac{\omega}{\omega_c}} \qquad \textbf{(8.3)}$$

The analysis of **(8.3)** has five steps. Step 1 is the raw potential divider expression that is successively simplified to step 4. Step 4 is clearly a high pass response because of the purely imaginary numerator but the standard form of **(2.2)** (repeated as a sixth term in **(8.3)**) requires that the coefficient of $j\omega$ in the numerator is forced to that in the denominator. This can be easily achieved at the expense of introducing a constant multiplier term consisting here of a capacitive potential divider. The l.f. gain, h.f. gain and time constant obtained from **(8.3)** are consistent with those obtained by inspection in section 6.

(iii) Step response

Assume an input step from 0 V to V_1 V at $t = 0$

The l.f. gain $\Rightarrow$ 0 as $\omega \Rightarrow 0$ rad s^{-1} so as $t \Rightarrow \infty$, $v_o \Rightarrow 0$.

The h.f. gain $\Rightarrow \dfrac{C_1}{C_1 + C_2}$ as $f \Rightarrow \infty$ so the step size is $V_1 \times \dfrac{C_1}{C_1 + C_2}$

The output waveshape is therefore a voltage step from 0 V to $V_1 \times \dfrac{C_1}{C_1 + C_2}$ V followed by an exponential of the form $V(t) = (V_1 \times \dfrac{C_1}{C_1 + C_2})\, e^{-t/\tau}$ where $\tau = R\,(C_1 + C_2)$.

Remember that the start voltage for the exponential is always the voltage at the end of any step arising at the output because of the transient change of input. Low-pass transfer functions (i.e., those of the same shape as **(2.1)**) do not have an output step in their step response whereas high-pass and pole-zero responses (i.e, **(2.2)** and **(2.3)**) always do.

9 Concluding comments

All the discussion here has been in terms of passive *RC* circuits. First order behaviour is also exhibited by *LR* circuits and by active circuits such as op-amp based amplifiers. The three standard forms apply to all manifestations of first order frequency dependent behaviour.

RCT 9/07

Rectifier and Power Supply Applications of Diodes

Introduction

One of the commonest applications of diodes is the conversion of an alternating current into a unidirectional current. This conversion process occurs in the signal detector parts of radio based systems and in power supplies designed to convert power from an alternating current distribution system (such as the UK's 50Hz land based power distribution system or the 400Hz distribution systems found in marine and airborne applications) into a good quality direct current source for electronic circuitry. Signal based applications of rectifiers will be discussed first.

Detectors and clamps

Peak detectors are circuits that have an output voltage that is (ideally) equal to the peak value of an input signal. Diode clamp circuits clamp one extreme of a signal (ie, either its positive peak or its negative peak) to a defined potential.

Peak detectors

The circuit diagram of a peak detector is shown in figure 1. The key elements of source, diode and capacitor are connected in series and it is quite common to find a resistor in parallel with the capacitor. The source may be a transformer secondary as is common in radio circuits or an amplifier output as is more typical of instrumentation systems. The idea is simple; when V_i is positive, D conducts and C charges to (V_i - 0.7V) as current flows from V_i through D to C. For high values of R, ie, values that allow only a small fraction of the charge put into C to be lost in one periodic time of V_i, V_O remains more or less constant during a cycle time.

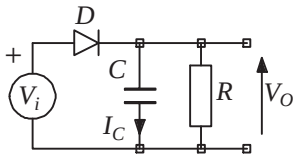


Figure 1

Peak detector circuit

The action of the peak detector circuit and the effect of R on its behaviour is illustrated in figures 2a and 2b. In figure 2a, the sinusoid is switched on at t = 0. Since the first half cycle is negative (ie, the wave is actually -sin ωt), the diode is reverse biassed for this half cycle and no

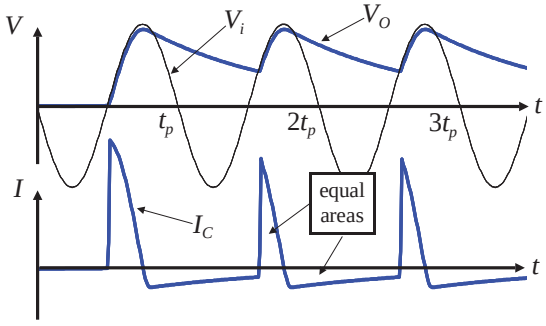


Figure 2a

Input voltage, output voltage and capacitor current in a peak detector circuit.

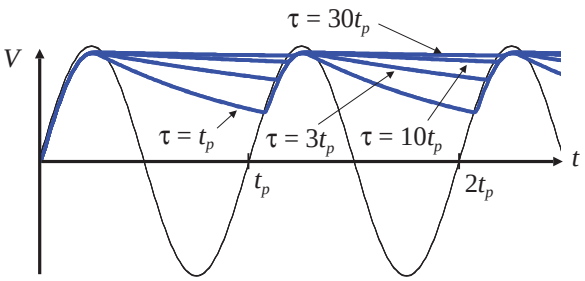


Figure 2b

Effect of RC on the output voltage of the peak detector

current flows. When $t = t_p/2 + \Delta t$, where Δt is the usually negligible time taken for the positive half cycle to rise to 0.7V, the diode begins to conduct and current flows from the source through C and R. The charge put into C is the amount needed to change its voltage from 0 to $V_{i\ \text{peak}}$ - 0.7V. The current rises quickly to a maximum and falls more slowly to zero as the source voltage approaches its positive peak (where the rate of change of source voltage equals zero).

The capacitor does not lose its charge straight away, instead it loses it slowly in the form of a current through R. This means that the source voltage, V_i, very soon becomes less than 0.7V higher than the capacitor voltage and consequently the diode ceases to conduct. Peak detectors are usually designed to ensure that the capacitor voltage does not fall too far in one source period so when the source voltage once again exceeds the capacitor voltage by 0.7V, only the charge lost through R need be replaced and the current pulse is correspondingly smaller in area than for the first charging event after switch on.

The effect of R on the rate at which the capacitor voltage falls is shown in figure 2b where there are waveshapes for four different values of R giving time constants of $RC = t_p$, $RC = 3t_p$, $RC = 10t_p$ and $RC = 30t_p$. If R were removed there would be no mechanism by which C could lose charge and the voltage across C would be $V_{i\ \text{peak max}}$ - 0.7V where $V_{i\ \text{peak max}}$ is the highest value of source voltage that had ever occurred.

Signal detectors

Peak detector circuits are often used to extract the information content from amplitude modulated radio signals. In this application the choice of RC is a compromise between a value large enough to give a small value of ripple at the carrier frequency and a value small enough to allow the capacitor voltage to follow the modulation envelope. Figures 3a to 3d illustrate this compromise in the context of a 100kHz carrier that is amplitude modulated by a 5kHz modulating signal. These conditions are approximately those relevant to the BBC Radio 4 long wave radio transmission at the upper limit of its signal bandwidth.

Notice that V_i, the modulated carrier, has an average value of zero whereas V_O has a non-zero average and a periodicity that is related mainly to the modulation envelope rather than the carrier. In figure 3a, $RC = 30t_p$, where t_p is the carrier frequency period. Although the carrier ripple is small, C cannot lose charge through R fast enough to allow its terminal voltage to follow the modulation shape. The remaining parts of figure 3 have RC products of $RC = 10t_p$, $RC = 3t_p$ and $RC = t_p$ for figures 3b, 3c and 3d respectively. Notice how the carrier ripple increases as V_O follows the modulation envelope more closely.

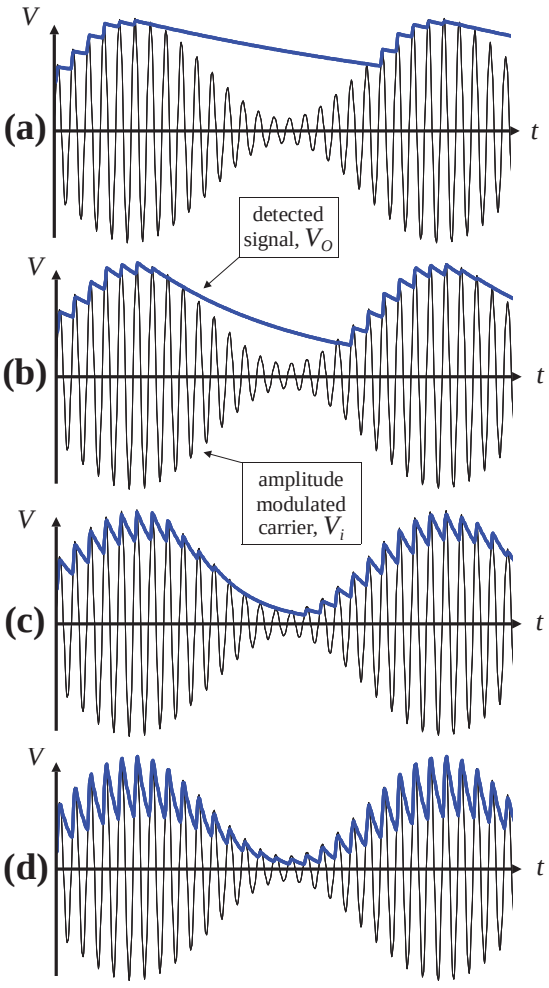


Figure 3

Effect of different time constants on a peak detector's performance.

Diode clamps

A diode clamp is a circuit that fixes or "clamps" either the positive or negative extreme of a waveform to a defined voltage level. There are some signals that transmit dc level information as part of the signal. The output of a signal detector is simply a waveshape consisting of a dc component and a superimposed signal waveshape. A clamping circuit discards the dc component and defines the dc level of either the positive or the negative signal peaks. Because clamping circuits resore the correct dc levels contained in signals, they are sometimes called "dc restoration circuits" and this term is used frequently in the context of analogue television video signals.

A basic diode clamp circuit is shown in figure 4. It contains the same components as the peak detector of figure 1 but they are put together in a different order. Figure 5 shows the input voltage output voltage and diode current that arise when the circuit of figure 4 is driven by a sinusoid switched on at $t = 0$. The action of the circuit is as follows.

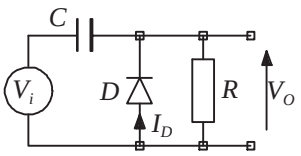


Figure 4
Diode clamp circuit

The first half cycle after switch on, $t = 0$ to $t = t_p/2$, is positive. The rising V_i will try and drive current through C towards the output. The diode will not conduct current in this direction so the only current that can flow in the circuit is through R. Since R is very large, the current is not large enough to affect sinificantly the charge stored in C. Thus there is a negligible change of charge in C, hence negligible *change* of voltage across it, and V_O follows V_i.

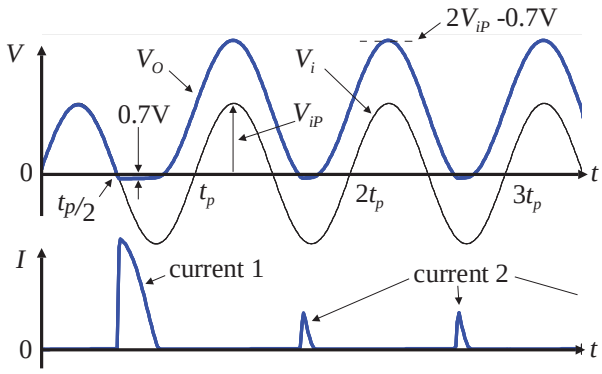


Figure 5
Voltage and current waveforms associated with the diode clamp of figure 4.

In the first half of the second half cycle, which begins at $t = t_p/2$, V_i continues to fall. V_O follows until it reaches -0.7V at which point D becomes forward biassed and begins to conduct (current 1 in figure 5). D conducts for the first half of the half cycle and thus holds the voltage on the output side of C at -0.7V. By the time V_i has reached its negative peak a charge of C ($V_iP - 0.7$) has been stored in C.

In the last quarter of the first cycle, V_i begins to increase again. This rising voltage once more tries to drive a current through C from the input side to the output side. As for the first half cycle, D will not support current flow in this direction so there is only a very small change of voltage across C because of the small current through R. Thus V_O follows the rise in V_i until the positive peak of V_i half a cycle later when $V_O = 2V_{iP} - 0.7$V and, because V_O is higher than -0.7V, continues to follow V_i as it falls back towards its negative peak one and three quarter cycles after the start.

When V_i gets close to its negative peak, V_O reaches -0.7V and a current flows once more through D into C. This current is replacing the charge lost by C because of the small current flowing through R for all the time V_O was above 0V. It is clear from figure 5 that this current (labelled as current 2) is much smaller than the current in the first half of the second half cycle (labelled as current 1). If R was infinitely large, current 2 would be zero because C would have lost no charge.

Notes:

1 V_i can be superimposed on any dc voltage without affecting the circuit behaviour. The practical limit to any such dc voltage is the votage rating of the capacitor C. In figure 5 V_i is drawn with an average value of zero because it is useful to have the waveshapes close to each other.

2 In practice C must be able to lose charge slowly so that the circuit can adapt to sources with slowly changing signal amplitudes. This means that R must be finite. It is usually the case though that R is sufficiently large to make charge loss per cycle a small fraction of the charge injected by current 1.

3 If the diode is turned round, the positive peaks of V_i are clamped to +0.7V and the output goes negative from there. The action is a mirror image of the action described here.

Peak to peak detector (voltage doubler)

A peak to peak detector is essentially a diode clamp followed by a peak detector. The diode clamp takes a sinusoid and clamps its negative peaks to -0.7V and the peak detector peak detects the positive peaks to give an output voltage approximately twice what it would have been without the clamp.

A peak to peak detector circuit is shown in figure 6. C_1 and D_1 form the diode clamp and D_2 and C_2 form the peak detector. R is effectively the circuit load. The circuit is used both in signal applications and in low power power supply applications.

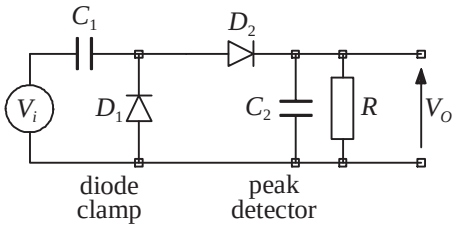


Figure 6

A peak to peak detector circuit.

The circuit is really one of a class of circuits called "diode pump" circuits or "charge pump" circuits. V_i is a driving force that is more or less equivalent to the reciprocating action needed to operate a pump such as a bicycle pump. When V_i is low, charge flows through D_1 into C_1 as described in the diode clamp explanation and when V_i goes high, that charge is tipped through D_2 into C_2. C_2 is essentially a charge reservoir from which charge continually drains away in the form of a current through R. If C_2 is a to be an effective charge reservoir, the constant leakage of charge through R should cause only a very small fall in voltage across it. Another way of putting this condition is RC_2 must be very much greater than the period of V_i. The output voltage is then determined by the equilibrium condition, charge pumped from C_1 to C_2 per second equals the charge lost through R per second.

Assuming that C_2 is an effective reservoir, C_1 affects the equilibrium output voltage and the time it takes the output to reach equilibrium. A C_1 that is small compared to C_2 will only be able on each cycle to transfer a small fraction of the charge needed to fill C_2. Thus charge will build up in C_2 over many input cycles (hence V_O will build up over many cycles) and because the rate at which charge is entering C_2 is small, V_O is sensitive to small current drains such as that through R because of the need to maintain an equilibrium between the charge flowing into and that flowing out of C_2. A C_1 that is large compared to C_2 can pump a large charge per cycle into C_2 so V_O rises rapidly and is relatively insensitive to R.

The voltage multiplier circuit

The peak to peak detector circuit can be extended to obtain higher output voltages using the circuit of figure 7. Let V_i be a sinusoid with a peak value V_{iP} big enough for the 0.7V drop associated with the diodes to be neglected.

C_1, D_1, C_2 and D_2 form a peak to peak detector that generates a voltage across C_2 of approximately $2V_{iP}$ as described in the previous section.

C_3, D_3, C_4 and D_4 form another peak to peak detector. In this second circuit, D_3 clamps the negative peak of the signal at node **B** to the top of C_2 - ie to a voltage of $2V_{iP}$. The positive peak of the voltage at node **B** is $2V_{iP}$ above its clamped negative peak giving a peak detected voltage across C_4 of $2V_{iP}$.

C_5, D_5, C_6 and D_6 form yet another peak to peak detector. This time the signal at node **C** is clamped to the voltage at the top of C_4, ie, $4V_{iP}$. As a result, the positive peak at node **C** is at a voltage of $6V_{iP}$ and this is peak detected by D_6 and C_6 to give $2V_{iP}$ across C_6.

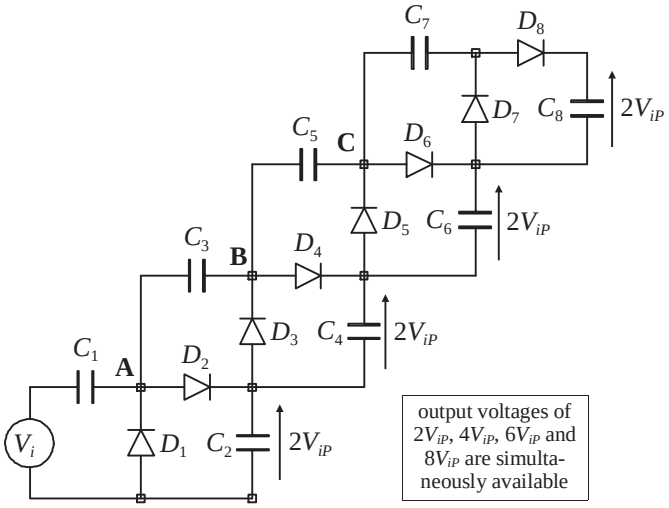


Figure 7

A votage multiplier circuit made from a cascade of peak to peak detectors

C_7, D_7, C_8 and D_8 form yet another peak to peak detector. The action is similar to the previous cases and the result is a voltage of $2V_{iP}$ across C_8. Thus there is a voltage of $8V_{iP}$ between the top of C_8 and the bottom of C_2; V_{iP} has been multiplied.

If the circuit is stretched out and redrawn it appears in the form of figure 8 and this is how it is usually presented in circuit diagrams. The circuit is exactly the same as that of figure 7

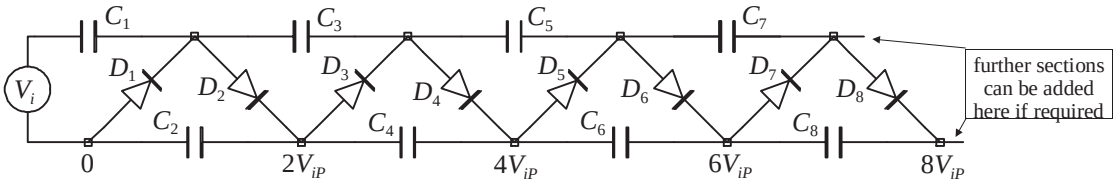


Figure 8

An alternative way of drawing the voltage multiplier circuit of figure 7

This circuit is used commonly in colour cathode ray tube based displays where it is used to multiply pulses of approximately 6kV in amplitude by a factor of around 4 to obtain the 24kV or so required to accelerate the electron beam towards the screen. It is also used in integrated form to multiply 5V pulses up to around 100V to drive the small plasma displays often found on CD and cassette tape players. It has been used in experimental physics research to obtain extremely high voltages - of the order of MV - for electric discharge studies and in such applications, multiplications of several hundred may be used. All these applications require low currents - typically a few tens of μA. The circuit is not suitable for high currents.

Rectifier circuits

The term "rectifier" is usually used in the context of the conversion of ac voltage into a unipolar voltage that is usually of the form of a dc component with a superimposed ac component. The dc component is always the *average* value of the rectifier output voltage and the superimposed ac component, which is rarely sinusoidal, is called the ripple voltage. In what follows, the ripple voltage will always be the peak to peak value of the superimposed ac component.

Rectifier circuits are often divided into two categories "half wave" and "full wave". In fact, full wave circuits can be looked at as two or more half wave circuits connected together and that is the approach used here. Other descriptive terms applied to rectifier circuits are "single phase" and "three phase" and these terms relate to the nature of the ac power supply - most high power industrial circuits (kilowatts and above) will be supplied by a three phase ac power source while low power industrial applications are more likely to be supplied by a single phase source. Domestic dwellings are supplied by a single phase source.

Single phase half wave rectifier

Figure 9 shows a single phase half wave rectifier circuit. The transformer can be considered as an ideal voltage source producing an rms voltage V_S across its secondary. (In fact, real transformers are not ideal in rectifier circuits as we will see later. All the calculations used in this module will, however stick to the ideal assumption.) The primary voltage V_P is derived from the local power system, eg 230V 50Hz for the UK, 115V 60Hz for the USA and 115V 400Hz for marine and airborne applications.

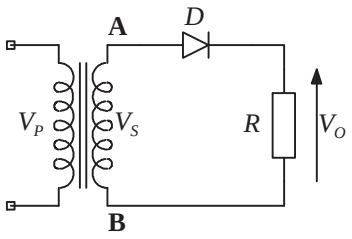


Figure 9

A half wave rectifier circuit.

It is important to remember that the voltage ratings of transformers designed for use with normal ac power distribution systems are given as rms voltages. Since the waveshape is sinusoidal, the peak value of voltage is $V_{\text{rms}}\sqrt{2}$ so in the case of figure 9, the voltage of node **A** with respect to node **B** will have a maximum value of $V_S\sqrt{2}$ and a minimum value of $-V_S\sqrt{2}$. The diode will conduct whenever node **A** is more than 0.7V positive with respect to node **B** and thus positive half cycles are transmitted to *R* but negative half cycles are blocked. The output voltage, V_O, from the circuit of figure 9 is shown in figure 10. Note that if the direction of *D* in figure 9 was reversed, the polarity of V_O would be reversed because *D* would conduct when node **A** was negative with respect to node **B**.

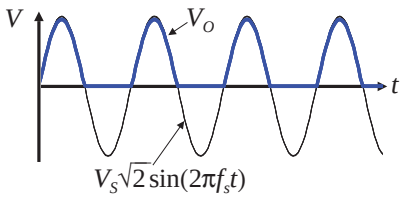


Figure 10

The output waveshape from the circuit of figure 9

There is a limited range of power supply applications for a waveshape such as that of V_O in figure 10. Most electronic equipment requires a relatively smooth supply voltage that approximates to the dc one might expect from a battery. V_O in figure 10 is clearly unipolar (ie, all positive in this case) and has a positive average (or dc) value but the magnitude of the superimposed ripple is too great. In particular the value of V_O is zero for the duration of alternate half cycles. For the circuit to be useful as a dc power source for electronic circuitry, the output needs to be "smoothed" or "filtered" in order to reduce significantly the amplitude of the superimposed ripple voltage.

Half wave rectifier with smoothing

There are various ways in which smoothing can be achieved - all rely on energy storage devices that are capable of filling in the gaps and smoothing out the peaks of the unfiltered waveform. The simplest of these is a capacitor connected as shown in figure 11. This smoothing process is called "capacitor input" filtering but in essence the circuit is a peak detector designed for relatively large voltages and currents and C stores energy which it uses to fill in the gaps in the waveform of figure 10.

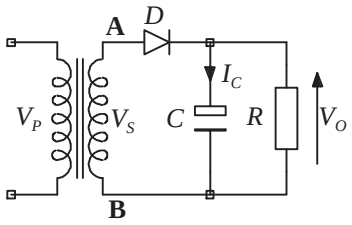


Figure 11

A half wave rectifier circuit with "capacitor input" filtering.

The waveshapes of V_S, V_O and I_C are shown in figure 12. These graphs were simulated using a real diode model but the transformer and capacitor are ideal. C is charged in the vicinity of the peak of every positive half cycle and provides current for the load inbetween the positive peaks. The charge lost by C inbetween peaks must equal the charge gained by C at the peaks if the average dc output voltage remains constant.

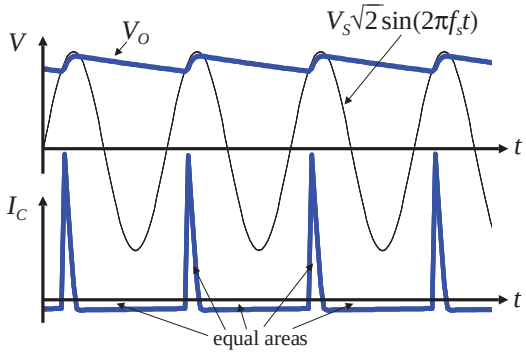


Figure 12

The waveshapes associated with the circuit of figure 11. All voltages are measured with respect to node B.

Note:

(i) The ripple is a very good approximation to a triangle - this fact will be useful when constructing a simplified model

(ii) The current waveform has large amplitude charging pulses of short duration. The pulse amplitude is some fifteen times the load current (which is equal to the magnitude of the negative capacitor current). Pulses like this are a nuisance for a number of reasons - their rms value to average value ratio is high (implies excessive losses due to I^2R heating in the circuit), the utilities are supplying all the energy used at one point on a cycle (sets up impulsive mechanical loads in the utility machinery) and rapid rates of change of current with time can cause radiative interference problems.

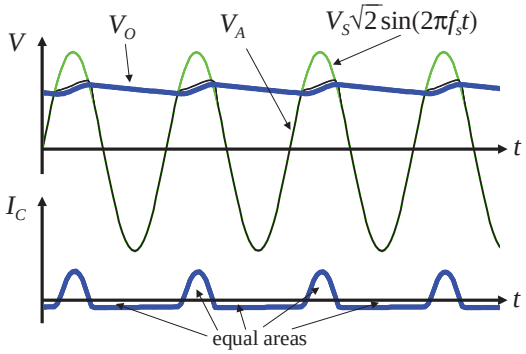


Figure 13

The waveshapes associated with the circuit of figure 11 when a realistic transformer impedance is included. All voltages are measured with respect to node B

In reality, the transformer and, indeed, the main supply have a series impedance that helps to mitigate the problems associated with charging C, at the expense of output voltage. Figure 13 shows the same waveforms as figure 12 with a series impedance appropriate for a 6VA transformer added between transformer and diode. In the simulation, the circuit is delivering less than 1W to the load and this is well within the transformer's capability. $V_S\sqrt{2}\sin(2\pi f_s t)$ is the ideal transformer secondary voltage and V_A is the voltage actually appearing at the diode anode.

Notice that the series impedance means that a large impulsive charging current is no longer

possible. The waveform is effectively clipped at a value significantly below its peak and this has two main consequences; firstly the output voltage is somewhat lower than in the ideal case of figure 12 and secondly because charge cannot get into *C* at the rate shown in figure 12, the charging pulses are broader and smaller in amplitude than (albeit of similar area to) those in figure 12. ***Notice, though, that the ripple voltage is still triangular in shape.***

Manufacturers do not give figures for the impedance of their transformers and even if they did, the calculation of the effects of that impedance would be very difficult. The message here is that the output voltage from a simple power supply with capacitor input filtering is poorly defined and in practice will be lower than ideal estimates. Consequently the use of simplified models for design and prediction of behaviour can easily be justified.

Choosing a capacitor to meet a ripple specification

The model usually used in order to describe the behaviour of a circuit such as that of figure 11 is based on the triangular nature of the ripple as shown in figure 14. In figure 14, the solid line represents the triangular ripple such as that in figures 12 and 13. It is common to assume, as a further simplification, that the capacitor discharges throughout the charging cycle and charges instantaneously at the peak of each charging cycle. Instantaneous charging implies infinitely high charging current pulses and is thus an inappropriate model for any consideration of diode or transformer current. Assumptions usually used are:

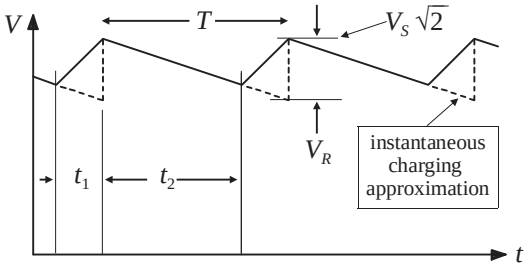


Figure 14

A simplified model of the output voltage from a capacitor input filtered rectifier circuit.

(i) The transformer and power source are ideal (ie, zero seies impedance)

(ii) Diode forward voltage drop is negligible

(iii) Load current is constant

(iv) Discharge occurs for the whole interval between charging peaks

Using the instantaneous charging model, the voltage across $_C$ reduces at a constant rate over the interval T as load current I_L is drawn from C. Thus

$$I_L = C\,\frac{dV}{dt} = C\,\frac{V_R}{T} \qquad \textbf{(1)}$$

since I_L is constant. Since this is a half wave rectifier

$$T = \frac{1}{f_s} \qquad \textbf{(2)}$$

where f_s is the supply frequency and if the load is a resistance R, as in figure 11,

$$I_L = \frac{V_{O\,peak}}{R}\,. \qquad \textbf{(3)}$$

Note that the V_O used in equation **(3)** is the peak value, $V_S\sqrt{2}$. This will give the largest possible value of I_L so will always overestimate C for a given ripple requirement. Equations **(1)**, **(2)** and **(3)** can be combined and manipulated in a number of ways to get the answer required depending on the information given.

The key is to understand the model and how equation **(1)** relates to it.

Single phase full wave rectifier circuits

In terms of their circuit shapes, single phase full wave circuits can be thought of as combinations of half wave rectifier circuits.

One of the oldest full wave circuit shapes is shown in figure 15. In this circuit V_{S1} and V_{S2} are 180^o out of phase - ie, when node **A** is at $V_S\sqrt{2}$, node **B** is at $-V_S\sqrt{2}$ and vice versa. V_{S1} and D_1 form one half wave rectifier and V_{S2} and D_2 form another. The outputs of these two half wave rectifiers are combined before being applied to the load. Because of the 180^o phase shift between V_{S1} and V_{S2}, V_{S2} and D_2 are active when V_{S1} and D_1 are not and there is an output across R on every half cycle as shown in figure 16.

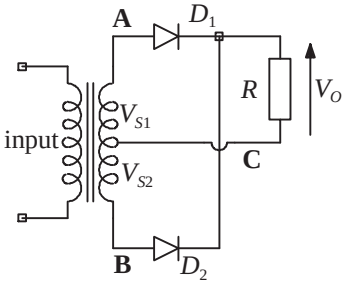


Figure 15

A two diode full wave rectifier circuit.

If the diodes in figure 15 were reversed, V_O would be negative - ie an upside down version of V_O in figure 16. In fact, there is no reason why reversed versions of D_1 and D_2 should not be connected to nodes **A** and **B** of figure 15 in order to obtain a simultaneous positive and negative output with respect to node **C**. Such a circuit, shown in figure 17, consists of four half wave rectifiers connected together to form a full wave rectifier. The circuit is more commonly drawn as shown in figure 18 and in this form is called a "full wave bridge rectifier".

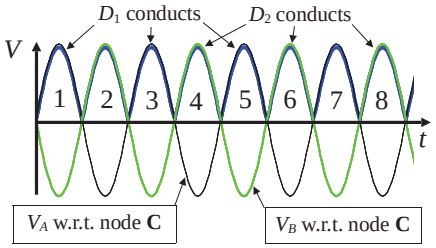


Figure 16

The output from a full wave rectifier. D_1 conducts on half cycles labelled 1, 3, 5, 7, etc and D_2 conducts on half cycles 2, 4, 6, 8, etc.

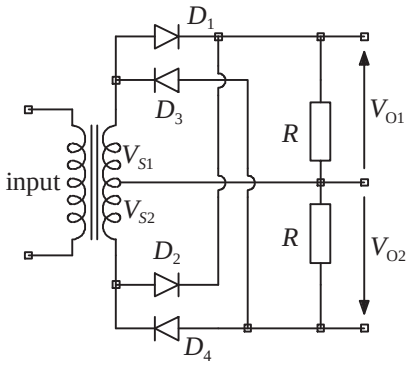


Figure 17

Four half wave rectifiers arranged to give a dual output full wave rectifier circuit

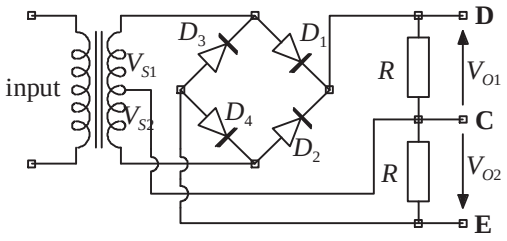


Figure 18

Figure 17 redrawn in a recognisable full wave bridge circuit shape.

In figures 17 and 18, diodes D_1 and D_2, the top R and V_{O1} are exactly the same as in figure 15.

The outputs from figures 17 and 18 can be used in various ways. If node **C** is the reference point, node **D** is a positive output and node **E** is a negative output. If node **E** is the reference point, both nodes **C** and **D** are positive with **D** having twice the magnitude of node **C**. If node **D** is the reference point, both nodes **C** and **E** are negative with node **E** having twice the magnitude

of node **C**. The two most common applications are firstly a positive and negative output with respect to node **C** (often called a "centre zero" power supply and used extensively for audio amplifiers) and secondly a single output of node **D** with respect to node **E** (as would normally be found in a low cost car battery charger). In the latter case, the connection between the centre of the transformer secondary and the mid-point of the *R*s is often omitted.

When deciding the output voltage from circuits like figure 17 and 18 it is important to take note of the way the transformer seconary voltage is specified. Transformers with a centre tap on their secondary winding are often specified as, say, 12-0-12 and in the context of figure 18 this would mean that $V_{S1} = V_{S2} = 12$Vrms. Very occasionally a secondary like this might be described as "24V centre tapped".

Smoothing a full wave rectifier

Smoothing a full wave rectifier output is very similar to smoothing a half wave circuit. The main difference is

the half wave rectifier charges the smoothing capacitor ***once*** per input cycle.

the full wave rectifier charges the smoothing capacitor ***twice*** per input cycle.

In all other respects the behaviour is the same and the model of figure 14, together with equations **(1)**, **(2)** and **(3)** that follow from it can be used to choose a capacitor to meet ripple requirements or to estimate ripple given the circuit values and operating conditions. The ripple frequency from a single phase full wave rectifier is a twice the input frequency.

Three phase full wave rectifiers (not examinable)

Most power systems that handle more than a few kW are three phase. A three phase power system has three live conductors (instead of the single live conductor in most domestic systems) that each carry power at the same frequency, but displaced in phase from one another by 120^o. There are many reasons why three phase power systems are attractive and some of them are connected with the fact that when one phase is going through zero, the other two are not, so power is continuously available from somewhere. (There are many other advantages that are irrelevant here.)

Figure 19 shows the circuit diagram of a three phase full wave rectifier and figure 20 shows its unsmoothed output. If one compares figure 20 with the unsmoothed full wave output of

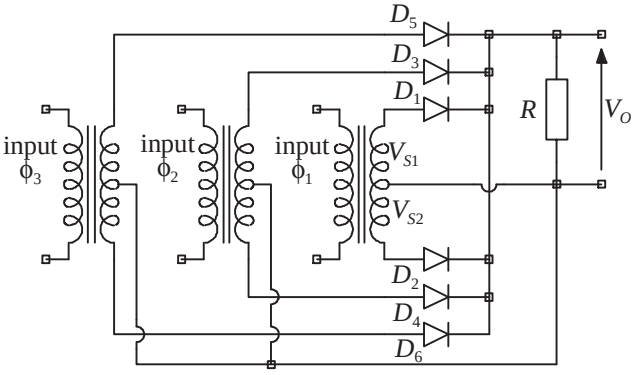


Figure 19
A three phase full wave rectifier circuit. Each transformer is the same as that in figure 15.

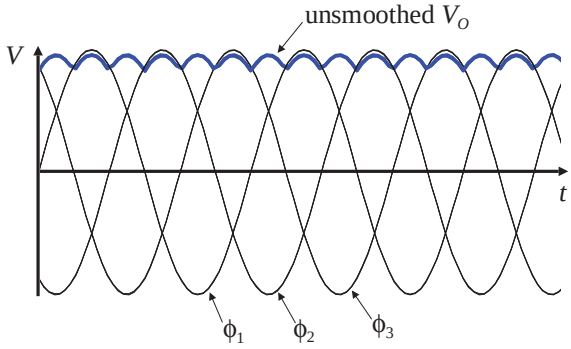


Figure 20
Output from a three phase full wave rectifier. Note that even with no smoothing the ripple is small.

figure 16, a couple of key points are immediately obvious:

(i) There is a large dc component of output voltage, $V_{DC} = 0.955V_P$, in the unsmoothed output waveform.

(ii) The peak to peak ripple voltage of the unsmoothed output waveform is $0.133V_P$ (compared to a value of V_P for single phase full wave and half wave rectifier circuits).

(iii) The fundamental frequency of the ripple is six times the input frequency (compared to the input frequency and twice the input frequency for single phase half wave and full wave rectifiers respectively).

These three points mean that for many applications smoothing is not necessary but when it is necessary, it is easier to achieve than in single phase circuits both because of the intrinsically smaller ripple voltage and because of the higher ripple frequency.

Stabilisation and regulation

The output from a rectifier and smoothing circuit is rarely of sufficient quality to supply an electronic circuit directly. There are many reasons for this

- The effects of finite supply and transformer impedance make it difficult accurately to predict the dc component in the output waveform (as illustrated in figure 13)
- The permitted range of supply voltage (in the UK, a nominal 230V with an upper limit of 253V (a + 10% rise) and a lower limit of 116V (a - 6% fall) that allows the utilities to manage load to ensure a constant supply frequency).
- The ripple voltage - very small ripple voltages demand very large smoothing capacitors. (bulky and expensive)
- The dependency of output dc voltage and ripple voltage on load current.

These problems have historically been divided into the two categories; **stabilisation** - the process of making the output independent of changes in supply voltage, and **regulation** - the process of making the output independent of load current changes. Although in the early days of electronics, the methods used to achieve good regulation were different from those used to achieve good stabilisation, good regulation and stabilisation are now simultaneously achieved by circuits that are usually called regulator circuits.

Regulator circuits

There are two types of regulator circuit; series regulators and shunt regulators. These can be further subdivided depending on their mode of operation but here the interest is in the basic forms shown in figures 21a and 21b. In both cases the unregulated dc input must be bigger than the required output voltage by some defined margin - and this must be true at the lowest instantaneous value of input, ie, the instant of the ripple negative peak.

The series regulator is connected in series with the load and works in the same way as a water tap or gas regulator by restricting the flow of current from input to output in such a way as to maintain a constant V_O across the load.

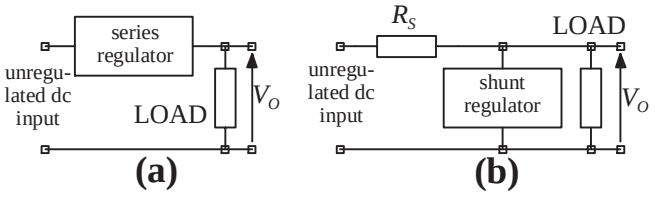


Figure 21

Organisation of a series regulator (figure 21a) and a shunt regulator (figure 21b).

The shunt regulator is in parallel with the load and works in conjunction with a series resistor R_S. It works by altering the current it draws, and thus the voltage drop across R_S, in such a way as to maintain a constant V_O across the load.

It is the shunt regulator that is of interest in this module.

Zener diode regulators

The simplest form of shunt regulator exploits the characteristic of a special type of silicon p-n junction diode called a "Zener" diode - named after its inventor. In a forward bias direction the Zener diode behaves in the same way as any other p-n junction diode. Its special properties lie in its reverse bias region, in particular, its reverse breakdown region. Once reverse breakdown in a p-n junction occurs, large increases in reverse current cause only small increases in reverse voltage and this property is exploited by Zener diodes which are special in that they are designed to break down at a particular well defined voltage. Devices are available with reverse breakdown voltages in the range 3V to 300V and the breakdown voltage is specified to an accuracy of typically ±5%.

A Zener diode characteristic is shown in figure 22 together with the symbol for this diode variant. The direction of current and voltage indicated are consistent with a forward bias being regarded as positive. The diode is always used in its reverse biassed direction so in a circuit environment, its reverse bias current is usually taken as positive. Once the diode has broken down in a reverse direction, an increase in reverse bias, ΔV will lead to an increase in reverse current ΔI. The ratio $\Delta V/\Delta I$ is known as the "**Zener slope resistance**" and is usually given the symbol r_Z (the lower case r indicates an inremental rather than a static resistance). The slope of the reverse breakdown characteristic is much steeper than drawn in figure 22 and typical r_Z for a typical low power device is 5Ω to 10Ω.

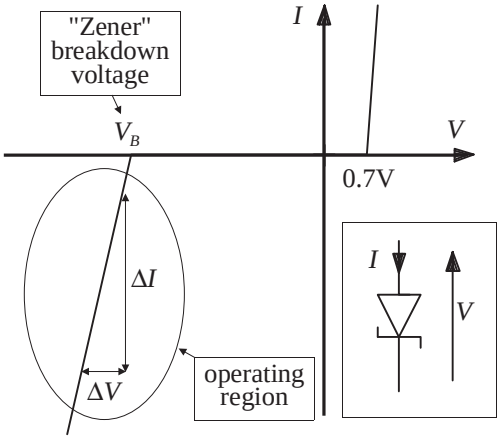


Figure 22

The I-V characteristic of a Zener diode. The diode symbol is shown in the inset diagram. The arrow head in the symbol has the same significance as for any other p-n junction

A Zener diode regulator circuit is shown in figure 23. V_i is an unregulated dc supply that may come from a battery or may come from a rectifier circuit and have a waveshape such as that in figure 14. The circuit output voltage will be close to V_Z, the so called "Zener voltage" (which is the same as V_B, the diode breakdown voltage), providing that the diode is biassed in its operating region (shown in figure 22). If the diode is to be biassed in its operating region, $I_Z > 0$ at all times. The operation is as follows.

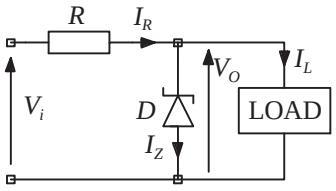


Figure 23

A Zener diode regulator circuit

First let I_L be constant but let V_i change. A reduction in V_i of ΔV_i will cause a change of voltage across R of ΔV_i and hence a reduction in I_R of $\Delta V_i/R$. This will tend to reduce V_O slightly which will in turn reduce I_Z. Only a small change in V_O is required to cause a large change in I_Z because of the steepness of the Zener diode characteristic in the operating region. Thus, the reduction in I_R is compensated by an almost equal reduction in I_Z leaving V_O and I_L more or less

unchanged.

If V_i remains constant but I_L changes, the action is very similar. An increase in I_L would also tend to lower V_O. Again a small drop on V_O causes a relatively large drop in I_Z so effectively the extra I_L has come from a reduction in I_Z and I_R is essentially unchanged.

design of a zener diode regulator

From a design point of view the circuit must be set up so that it can work as described above. At the cathode node of the diode

$$I_R = I_L + I_Z \qquad \textbf{(4)}$$

I_R can be written in terms of V_i, V_O and R, $I_R = \dfrac{V_i - V_O}{R}$ **(5)**

I_L will be defined either by V_O and the resistance of the load or, if the load is not a resistance, by a specified value or range of values that the load may draw.

I_Z is the variable that must be set by the designer to keep the diode in its operating region under all input voltage and load current conditions. In many cases Zener diode manufacturers will specify a minimum value of I_Z, $I_{Z\,MIN}$, that must be maintained for proper device operation.

The design proceeds by considering the conditions most likely to violate the minimum I_Z condition that must be satisfied. A moment's thought should lead to the conclusion that the circumstances most likely to threaten the minimum I_Z condition are when V_i is at its smallest, $V_{i\,MIN}$, and when I_L is at its largest, $I_{L\,MAX}$. Combining **(4)** and **(5)** and the appropriate worst case conditions,

$$\frac{V_{i\,MIN} - V_O}{R} = I_{L\,MAX} + I_{Z\,MIN} \qquad \textbf{(6)}$$

from which a suitable value of R can be found. Note that equation **(6)** is using the conditions most likely to make I_Z too small. If a value of R larger than that suggested by equation **(6)** were used, there would be insufficient I_R to satisfy the worst case demands of $I_{L\,MAX}$ and $I_{Z\,MIN}$. Thus, the R calculated in equation **(6)** is the largest value that can be used.

ripple considerations

To calculate the effect of the Zener diode regulator on ripple, a ripple equivalent circuit is used. If the circuit has been properly designed, the diode will be operating as intended and the incremental resistance of the reverse current region in conjuction with R will give the relationship between the input and output ripple voltages. The ripple equivalent circuit is shown in figure 24 where V_R is the ripple component of the input voltage and v_r is the output ripple. The relationship between input and output ripple is given by the potential division between R and r_Z,

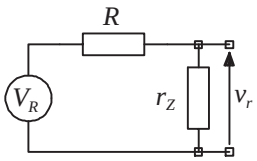


Figure 24

The ripple equivalent circuit of a Zener diode regulator

$$v_r = V_R \frac{r_Z}{R + r_Z} \qquad \textbf{(7)}$$

The load has been ignored in equation **(7)** but any load resistance will appear in parallel with r_Z and give a v_r smaller than that predicted.

Transistor Characteristics

Introduction

Transistors are the most recent additions to a family of electronic current flow control devices. They differ from diodes in that the level of current that can flow through them is controlled by a control input (which unfortunately has different names in different devices) and in this sense they act like the control valves one might find in an hydraulic or pneumatic system. Indeed, the very first active devices consisted of systems of electrodes in an evacuated glass envelope and these were given the name "valves".

The detailed operation of these devices is not of interest in this module. Unlike water or gas which are fluids made of charge-neutral molecules, the moving particles (called electrons) that constitute an electric current carry an electric charge. In transistors and valves, control of flow is achieved by manipulating the electric field environment through which the electrons must travel in order to make it easier or harder for flow to occur. The devices are generally three terminal devices with one terminal common to the current flow path and the control input.

From an application point of view, transistors (and valves) are described by performance characteristics and there are two of these that are important in understanding device operation: The ***transconductance characteristic*** (the relationship between input control voltage and output (controlled) current) and the ***output characteristic*** (the relationship between output (controlled) current and the voltage across the current flow path terminals). After looking at transconductance and output characteristics in general terms, each of the three main transistor families will be introduced.

Transconductance characteristics

The transconductance characteristic of a transistor (or vacuum tube) is the relationship between the input (control) voltage to and the output (controlled) current through the device. It is a measure of the effectiveness of the control mechanisms within the device; a high value of transconductance means that small changes in the input (control) variable give rise to large changes in the output (controlled) variable.

Typical transconductance characteristics of a "bipolar junction transistor" (BJT), a "junction field effect transistor" (JFET) and an "enhancement mode MOSFET" are shown in figure 1a and relate to the circuits of figure 1b in which both the circuit symbol of each device and the variables used in figure 1a are given. I_C (I_D) is the controlled current and V_{BE} (V_{GS}) is the control voltage for the BJT (FET of either type). There are a few points to notice about the curves of figure 1a and the symbols of figure 1b.

(i) The transconductance curves are all basically the same shape - ie they all have some threshold after which the controlled current increases with increasing control voltage.

(ii) The BJT has a much steeper slope than the FETs - ie the control process is most effective with a BJT and least effective with a JFET.

(iii) The emitter (source) is the BJT (FET) terminal that is common to controlled current and control voltage.

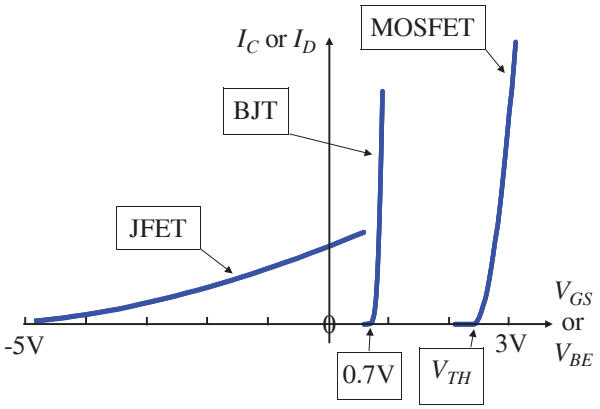


Figure 1a

Transconductance curves for a JFET, a BJT and a MOSFET.

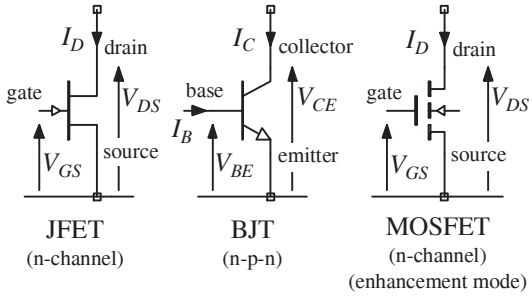


Figure 1b

The circuit symbols, terminal names and variable definitions for a JFET, a BJT and a MOSFET

(iv) The MOSFET has an extra terminal called the "substrate". In the majority of cases this is connected either to the source or to the most negative part of the circuit (ie the negative side of the power supply. Some MOSFETS, particularly power MOSFETS have source and substrate connected internally by the manufacturing process.

The slope of the transconductance characteristic is called the "transconductance" or "mutual conductance" of the device. It is given the symbol $\boldsymbol{g_m}$ and plays an important role in signal amplification.

Output Characteristics

The output characteristics are important because they indicate the degree of independence between output (controlled) current and the voltage difference imposed by the external circuit on the output terminals of the device. Transistors are often used as amplifiers or switches and in both applications a small input voltage change gives rise to a large change in voltage across the output terminals. Ideally the output (controlled) current will be determined entirely by the (control) input voltage.

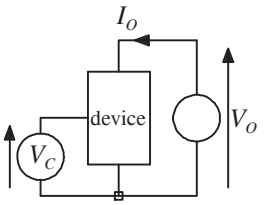


Figure 2a

definition of variables in the output characteristic of figure 2b.

Figure 2b shows an output characteristic typical of a transistor or vacuum tube labelled as "device" in figure 2a. The output characteristics usually take the form of a family of curves that show the V_O I_O relationship for a number of different control inputs, V_C. The slope of the output characteristic, $\Delta I_O/\Delta V_O$, is small and ideally zero; it depends mainly on device internal geometry. There is an obvious change in the behaviour at low values of V_O that arises because the insides of the device need a certain voltage across them before they start working as desired. The size of this low voltage

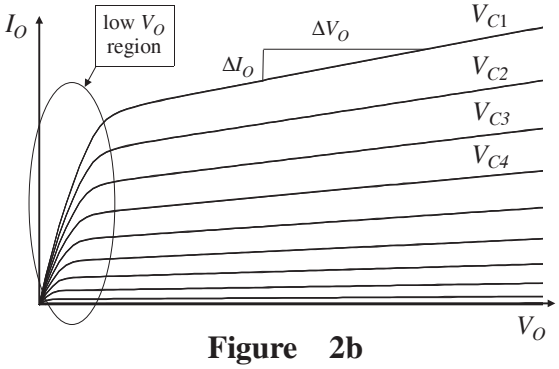


Figure 2b

A typical output characteristic. This one is for a JFET

region (which unfortunately has different names in different devices) is different for different device types and more detail is given in the discussion of each transistor type. There are a number of key points about output characteristics:

(i) The output characteristic curves are all basically the same shape - they all have a low voltage region after which the controlled current is substantially independent of V_O.

(ii) The BJT has a much smaller low voltage region than the FETs (a couple of hundred mV rather than a couple of V) and vacuum tubes.

(iii) The slope of the output characterisic at high V_O increases with increasing I_O.

About the transistors

Three transistor types have been included in figure 1b. There are actually many more types of transistor in existence but most of these are variations designed for relatively specialised applications. The three already mentioned cover most application areas.

BJTs

BJTs are the oldest of the transistors. First demonstrated in 1949 it is now a very mature technology. Early devices were made of germanium and had maximum operating frequencies of about 10kHz. The frequency was limited by the technology, not the material. Silicon became the material of choice in the 1960s and by the end of that decade devices that would work up to 5GHz were becoming available. Bipolar transistors can now operate at frequencies in excess of 100GHz. Small signal transistors are designed to operate at currents of mA and a few 10s of volts whilst some power transistors can cope with 1000s A at around 1000V. Some transistors are made from materials other than silicon but most BJTs are made from silicon.

There are two main types of BJT structure; n-p-n and p-n-p, the names indicating the ordering of semiconductor material polarities (n-type or p-type) that make up the device. The BJT in figure 1b is an n-p-n structure in which a thin layer of p-type material (the base) is sandwiched between two layers of n-type material called the emitter and collector. (The p-n-p structure consists of a thin n-type base sandwiched between a p-type emitter and a p-type collector.) There is a p-n junction between base and collector and base and emitter. The base-collector junction is usually reverse biassed whilst the base-emitter junction is usually forward biassed. It is between the base and emitter that the control voltage is applied and this means that V_{BE} is always in the region of 0.7V.

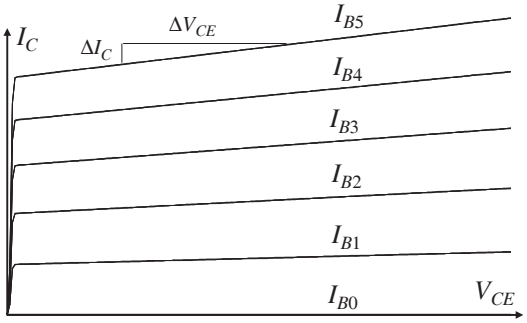


Figure 3
A BJT output characteristic.

The output characteristic of an n-p-n BJT is shown in figure 3. I_C is exponentially related to V_{BE} but is related to I_B by a constant, h_{FE}, called the "static current gain". Thus in output characteristic plots, base current (rather than base voltage) is increased in equal increments.

The thing to notice here is that the **collector current is mainly controlled by the base current (or base-emitter voltage)** although there is also a small dependence of I_C upon V_{CE}.

In other words as far as the circuit connected to the collector is concerned, the collector of

the transistor looks like a Norton equivalent circuit with a current source (whose magnitude is controlled by I_B or V_{BE}) in parallel with a resistance $\Delta V_{CE}/\Delta I_C$.

The characteristics of a p-n-p transistor are shown in figure 4. Notice that the shapes are the same as those for the n-p-n but the characteristics have been rotated by 180° about their origins. The characteristics of p-n-p devices are sometimes described as complementary to those of n-p-n devices and pairs of devices with matched characteristic shapes are sometimes called "complementary pairs".

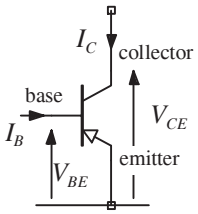


Figure 4a

The symbol for a p-n-p BJT. Note that the arrow on the emitter points towards the base.

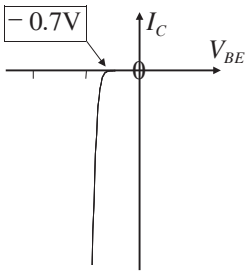


Figure 4b

The transconductance characteristic of a p-n-p BJT. Note that VBE is typically -0.7V

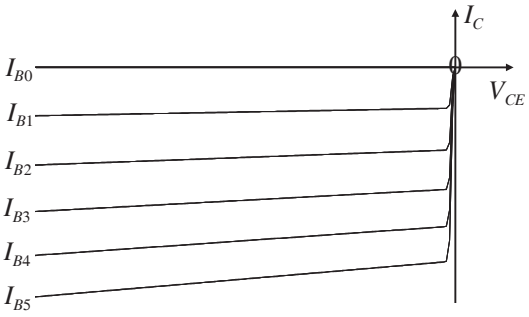


Figure 4c

The output characteristic of a p-n-p BJT. Note that I_{B1} to I_{B5} will be negative since I_B will be in a direction opposite to that shown in figure 4a.

The BJT differs from other transistors in that its transconductance characteristic is accurately defined by the behaviour of electrons in semiconductors and is relatively independent of device geometry. The relationship between I_C and V_{BE} is given by

$$I_C = I_{C0}\left(\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right) \qquad \textbf{(1)}$$

For forward bias of the base emitter junction, the normal operating mode for amplifier applications, the exponential term is much larger than unity and equation **(1)** can be approximated by

$$I_C \approx I_{C0}\exp\left(\frac{eV_{BE}}{kT}\right). \qquad \textbf{(2)}$$

The dc or static current gain of the transistor is usually written symbolically as h_{FE} and is simply the ratio of collector to base current. h_{FE} is slightly dependent on I_C, being lower at the extremes of low and high I_C than it is for middle values of I_C. h_{FE} is very dependent on process variations and geometry (particularly the base layer thickness) and a range of 100 to 400 is not unusual in BJTs of the same nominal type designed for small signal amplifier applications. The relationship between I_C, I_B and h_{FE} is

$$h_{FE} = \frac{I_C}{I_B} \qquad \textbf{(3)}$$

Summing currents into the BJTs in both figures 1b and 4a leads to $I_B + I_C = I_E$ where I_E is the current flowing out of the emitter of the BJT. Since I_C is typically very much greater than I_B, this relationship can usually be approximated by $I_C \approx I_E$.

MOSFETS

MOSFETS (the name is an acronym made from Metal-Oxide-Semiconductor Field Effect Transistors) first appeared in the mid 1960s as small signal amplifiers and as small scale logic ICs but really took off at the end of the 1970s when the power MOSFET appeared. Power MOSFETS offered qualities that made them attractive alternatives to BJTs in many switching applications - especially in the 100s kHz range. Also in the late 1970s, MOSFETS entered the computer processor and memory arena in the form of large scale integrated circuits. They now dominate the computer arena.

The control electrode of a MOSFET is called the "gate", a metallised rectangle on the surface of the semiconductor that is insulated from it by a thin layer of insulator (usually silicon dioxide). This means that in principle no current is drawn through the control input and the device is a true field effect device. In practice there is always a tiny current, usually of the order of pA, flowing into the control input because no insulator is perfect. A conducting channel is induced on the surface of the semiconductor underneath the gate by applying a postive voltage to the gate with respect to the source, V_{GS}. One end of the gate overlaps the drain and the other overlaps the source and the channel, when formed, connects drain and source and forms the controlled current path. The channel begins to form at a particular V_{GS} known as the "threshold voltage" V_{TH}, and gets wider (more conductive) as V_{GS} increases above V_{TH}.

The output characteristics of MOSFETs are very similar in appearance to those of BJTs. They are usually plotted in the form of a family of curves of drain-source current, I_D, against drain-source voltage, V_{DS}, for a number of equal increments in the control input, V_{GS}, as shown in figure 5. The voltage increments have been added here to show the effect of threshold voltage - nothing happens in this particular MOSFET until V_{GS} gets somewhere between 2V and 2.5V. Other MOSFETS would have a different V_{TH} so activity would start at a different V_{GS}. The effect of V_{TH} can also be seen on the transconductance characteristic of figure 1a. The main difference between the characteristics of the BJT (figure 3) and the MOSFET (figure 5) is that in figure 5 the region at low V_{DS} where I_D is very dependent on V_{DS} extends over a couple of volts whereas in figure 3 this region extends typically over tens of mV to a couple of hundred mV.

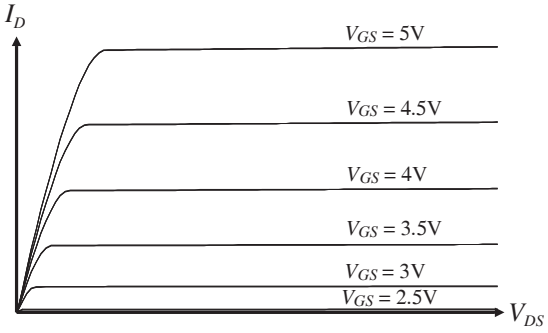


Figure 5

The output characteristics of a MOSFET

The slope of the characteristic at high V_{DS} is a function of the geometrical design of the MOSFET and a wide range of slopes can be observed from different devices. The Norton model of controlled current source in parallel with a large resistor that represents the behaviour of a BJT collector is also appropriate to model the behaviour of the drain of a MOSFET.

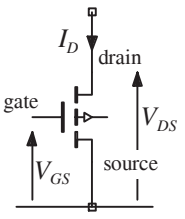


Figure 6

The symbol for a p-channel MOSFET.

As for BJTs, there are two main types of MOSFET; n-channel and p-channel. The p-channel device is the complement of the n-channel device and the relationship between the characteristics of n-channel and p-channel MOSFETS is similar to that between n-p-n (shown in figures 1a and 3) and p-n-p (shown in figures 4b and 4c) BJTs. The symbol for a p-channel MOSFET is shown in figure 6 - note that the arrowhead on the substrate

connection points away from the p-channel.

The MOSFET is governed by a square law transconductance equation rather than the exponential law that governs a BJT. The drain current is given by

$$I_D = a(V_{GS} - V_{TH})^2 \quad \textbf{(4)}$$

"a" is a constant set mainly by device geometry. The square law relationship of equation **(4)** is much less steep than the exponential relationship for a BJT and this is why the MOSFET has a lower transconductance per unit device area than the BJT. The notion of current gain is meaningless in the context of a MOSFET because input current is ideally zero. When the MOSFET is fully conducting and the drain source voltage is close to zero, the device behaves like a resistance, $r_{DS\,ON}$, whose value (which is specified by manufacturers for devices designed for switching applications) depends upon device geometry.

JFETs

Although JFETs (the name comes from Junction Field Effect Transistor) were conceived before BJTs, technological difficulties delayed their realisation for a decade after the invention of the BJT. The terminal names are the same for the JFET as for the MOSFET (except that JFETs would not normally have a substrate connection). The JFET consists of a layer of semiconductor (the channel) with drain at one end and source at the other. If the channel is n-type, the gate is a p-type deposition on the channel surface, placed between source and drain, and thus the gate-channel combination forms a p-n junction. A V_{GS} of zero, gives maximum channel conductivity and reverse biassing the gate with respect to the source reduces the channel conductivity.

The reverse biassed gate-source junction control modality gives the JFET a high gate source resistance. The transconductance is low (see figure 1a) so getting high circuit gains is difficult. Parameter spread between devices of the same type is large and this makes circuit design a relatively difficult process. As discrete devices JFETs are now only used in specialised applications but they are often used as the input transistors in IC amplifiers where their high input impedance and relative (to a MOSFET) insensitivity to static electricity are attractive.

The JFET is governed by a square law transconductance relationship similar in nature to the MOSFET but with a different constant. Its output characteristics are qualitatively similar to the MOSFET and the BJT and the drain can be modelled using a Norton circuit. As for MOSFETS, both p-channel and n-channel devices exist, the characteristics of the two types having the same relative properties as those of the two BJT or MOSFET polarities. The symbol for a p-channel JFET is the same as the n-channel one except that the arrowhead direction is reversed. Occasionally a JFET symbol in which the arrowhead is on the source lead is used. In such cases, the arrowhead points away from the gate for the n-channel device and towards the gate for the p-channel device.

Vacuum tubes

Vacuum tubes are now used only in very specialised areas; guitar amplifiers, high end audio systems, high power (10kW to MW) continuous wave and pulsed radio frequency and microwave sources for communications and long range RADAR systems. From a characteristic point of view the signal amplifying types used in audio applications behave in a very similar way to JFETs except that whereas JFETs require a supply voltage of around 10V to 20V, tubes require a couple of hundred volts.

Transistors As Amplifiers

This discussion will concentrate on bipolar junction transistors (BJTs) in amplifier applications because BJTs are by far the most commonly used amplifying device. Remember though that all amplifying devices operate in a similar way so the same principles that govern the way BJTs amplify govern the use of JFETs, MOSFETs and valves as amplifiers.

A Word About Amplifiers

The purpose of an amplifier is to increase the amplitude of a signal. If one thinks purely in terms either of voltage or of current then it is possible to change the amplitude of a signal by using a transformer. However a transformer offers no possibility of power gain – if a weak signal enters the primary of a transformer it will be at best equally weak when it emerges from the secondary. Imagine voltage is increased by a ratio of five to one. Current will be reduced by a similar ratio and the power of the signal entering the primary will be equal to the sum of the power of the signal leaving the secondary and any power lost in the transformer. The crucial factor about an amplifier is its ability to offer *power gain*. At low frequencies, one is usually more interested in the factor by which the signal (voltage or current) amplitude has been magnified than in the signal power gain which tends to be a more important parameter at higher frequencies (> 50 MHz). Several measures of gain are available:

Voltage Gain is the ratio of the output voltage amplitude and input voltage amplitude. It is used when the parameter of interest is the signal voltage amplitude. It is used at low frequencies (100 MHz or less). An ideal voltage amplifier has infinite input resistance (i.e. it draws zero current from the signal source driving it) and has zero output resistance (i.e. it can supply unlimited current to its load).

Current Gain is the ratio of the output current amplitude and input current amplitude. It is used when the parameter of interested in is the signal current amplitude. It is also used at low frequencies. An ideal current amplifier has zero input resistance (i.e. there is no signal voltage at the input) and infinite output resistance (i.e. it can supply unlimited voltage to its load).

Power Gain is the ratio of the output signal power to the input signal power. Power gain is used at high frequencies in "impedance matched" systems where the effects of electromagnetic propagation in the circuit cannot be ignored. In an impedance matched system all output impedances are equal to all impedances at a value known as the "characteristic impedance". $50\ \Omega$ is a common characteristic impedance in communications and radar applications, television systems use $75\ \Omega$.

Note that in an impedance matches system knowledge of any one of these three gains automatically defines the other two.

There are two other kinds of gain that are of interest in special applications; transconductance and transresistance. Transconductance is the ratio of the output signal current to the input signal voltage and is measured in Amps per Volt (or Siemens but occasionally written as Mhos as well). Transconductance is an important concept for all amplifying devices. Transresistance is the ratio of output voltage to input current and is measured in Volts per Amp or Ohms.

The Mechanism of Amplification

All amplifying devices can be regarded as circuit elements that have their output current controlled by an input voltage. The characteristic that describes this behaviour is known as the transconductance characteristic (or occasionally mutual characteristic) because it relates output current to input voltage. The transconductance characteristics for various devices are shown in Fig. 1. If a signal is regarded as a small change or "perturbation" around some average value (often zero), there are obvious problems with these characteristics from an amplification point of view. For example, a signal with an average value of zero applied to a BJT would cause no change in I_C for all signal voltages below 0.7 V. In other words the signal voltage below 0.7 V would effectively be lost. This is usually not an acceptable state of affairs and consequently the signal is added to a d.c. voltage, known as a bias voltage, to ensure that I_C can respond to the whole of the signal.

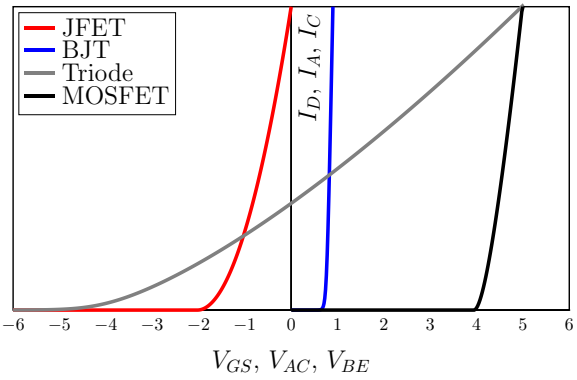


Figure 1: Example transconductance curves for, JFET (red), triode (grey), BJT (blue), MOSFET (black).

The situation is shown in the diagram of Fig. 2. If ΔV_{BE}, the signal, was applied with no bias, i.e. with its average value equal to zero there would be no change of I_C and so $\Delta I_C = 0$. If, on the other hand, a bias voltage, V_{BEB}, is added to the signal, there is a substantial change in I_C as a result of the signal. The same arguments hold for all the other devices although the best choice of bias voltage will be different for each.

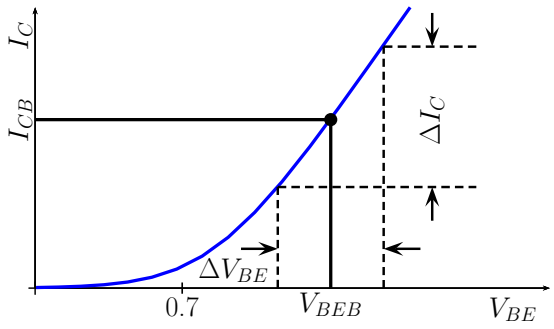


Figure 2: A BJT transconductance curve with quiescent (no siganl or d.c.) conditions shown (solid lines) and the extent of signal swing shown (dashed lines)

The relationship between ΔI_C and the signal that caused it, ΔV_{BE} is the "small signal transconductance", g_m, of the device being used. g_m is the slope of the transconductance characteristic at the bias point (V_{BEB}, I_{CB}). Since the transconductance characteristic is not a straight line, g_m, varies with V_{BEB} and indeed within ΔV_{BE} if ΔV_{BE} is not sufficiently small. It is usually assumed that ΔV_{BE} is sufficiently small for the transconductance characteristic to be approximated as a straight line over the range of V_{BE}.

In Fig. 3, the changes in collector current, ΔI_C, are converted into an output signal voltage using a resistor, R_L. An input voltage of (1),

$$V_{IN} = V_{BEB} \pm \frac{\Delta V_{BE}}{2} \tag{1}$$

will give a collector current change of (2),

$$I_C = I_{CB} \pm g_m \frac{\Delta V_{BE}}{2} \tag{2}$$

remember,

$$g_m \equiv \frac{\Delta I_C}{\Delta V_{BE}} \tag{3}$$

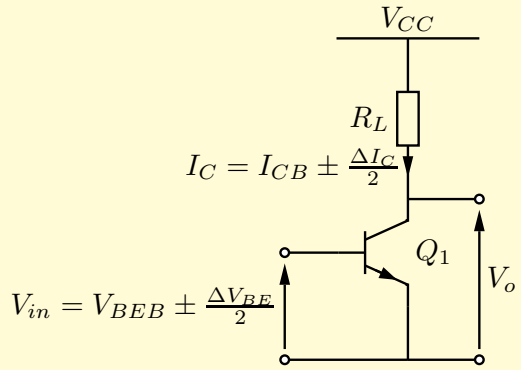


Figure 3: A one transistor amplifier including DC and AC voltages and currents.

for a BJT, and this will in turn give rise to a change in collector voltage of,

$$V_O = V_{CC} - I_C R_L \tag{4}$$

$$= V_{CC} - I_{CB} R_L \mp g_m R_L \frac{\Delta V_{BE}}{2} \tag{5}$$

$$\equiv V_{OB} \pm \frac{\Delta V_O}{2} \tag{6}$$

where V_{OB} is the output voltage obtained when the signal is zero,

$$V_{OB} = V_{CC} - I_{CB} R_L \tag{7}$$

and $\frac{\Delta V_O}{2}$ is the component of the output voltage due to the signal perturbation,

$$\frac{\Delta V_O}{2} = -g_m R_L \frac{\Delta V_{BE}}{2} \tag{8}$$

By using the relationship between ΔV_O and ΔV_{BE} it is possible to estimate the voltage gain of the amplifier,

$$\Delta V_O = -g_m R_L \Delta V_{BE} \tag{9}$$

or

$$\frac{\Delta V_O}{\Delta V_{BE}} = -g_m R_L = \text{gain} \tag{10}$$

Note that:

1. The bias conditions V_{BEB}, I_{CB} and V_{OB} do not explicitly appear in the expression for gain although it must be remembered that g_m is a function of V_{BEB}.

2. The gain is negative. This simply means that an increase in input voltage leads to a decrease in output voltage and vice versa. In signal terms it implies inversion of a 180° phase shift.

Point 1 above is very important because it suggests that the bias conditions and the signal conditions can be considered separately. Defining a stable set of bias condition is one of the primary objectives of amplifier circuit design.

BJT Biassing

BJTs are the odd ones out in the family of amplifying devices because they need to draw an input current in order to operate. A given collector current I_C will require a base current I_B to support it and the two are related by,

$$\frac{I_C}{I_B} = h_{FE} \tag{11}$$

see Fig. 4. h_{FE} is the large signal static current gain of the BJT. It is approximately independent of I_C but it varies with temperature and there is a large spread of values (typically a factor of five) from device to device of the same type. Control of the bias conditions must not therefore fall to the transistor but should be accomplished by well defined circuit elements such as resistors.

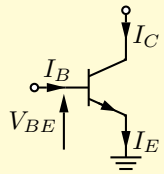
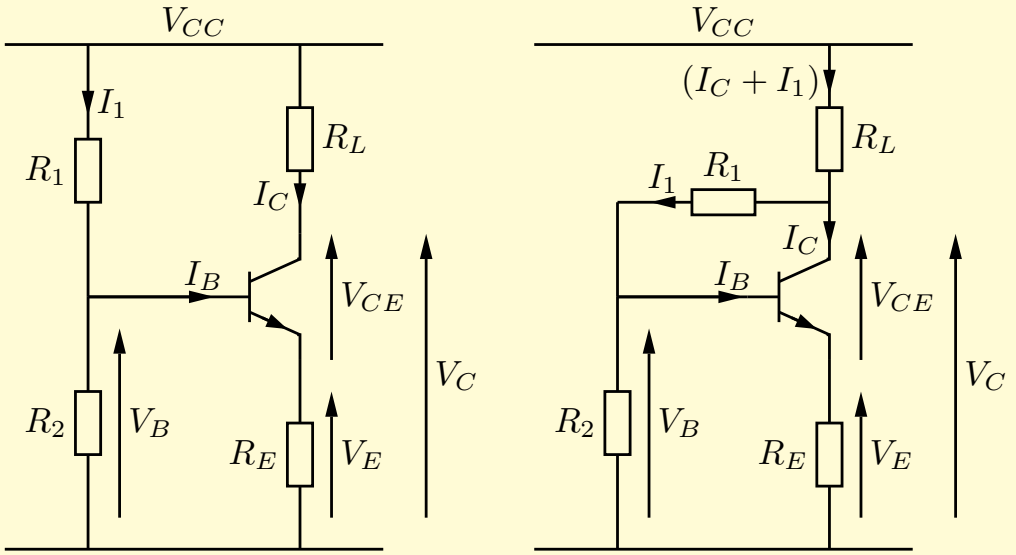


Figure 4: BJT terminal currents & voltages

Two types of bias circuit are suitable for single transistor BJT amplifiers (Fig. 5). The objective of both of these bias circuits is to control the collector current, I_C.

In both cases this control is achieved by negative feedback. In circuit 1 the voltage V_B defined by V_{CC}, $R_1 + R_2$, is made up of $V_E + V_{BE}$. If V_E is made large compared to changes expected in V_{BE} (either as a result of temperature changes or device to device variation) the V_E, and hence I_C is substantially constant. In circuit 2 R_E provides negative feedback as in circuit 1 but there is a second source of negative feedback from V_C via R_1 and R_2. I_C will tend to reduce V_C, hence reducing V_B and counteracting the increase in I_C. Circuit 1 will not operate satisfactorily with $R_E = 0$ because under such a condition, all negative feedback has been removed. Circuit 2 will operate with $R_E = 0$ because there still remains the negative feedback path from V_C via R_1 and R_2. It is usual in the analysis of both circuit 1 and circuit 2 to assume that I_B is negligible and it is usual in design to make sure that the assumption is valid.



(a) Circuit 1 (b) Circuit 2

Figure 5: Two one transistor amplifiers, showing components important for DC opperation.

Working Out the Bias Conditions

Circuit 1 – Assume I_B is negligible, $V_{BE} \approx 0.7$ V and $h_{FE} >> 1$ (i.e. $I_C \approx I_E$).

$$V_B = \frac{V_{CC}\, R_2}{R_1 + R_2} \text{ by potential division} \tag{12}$$

$$V_B = V_E + 0.7 = V_E + V_{BE} \text{ by Kirchhoff's Voltage Law} \tag{13}$$

$$I_E \approx I_C = \frac{V_E}{R_E} = \frac{V_B - 0.7}{R_E} = \frac{1}{R_E}\left[\frac{V_{CC}\, R_2}{R_1 + R_2} - 0.7\right] \tag{14}$$

$$V_C = V_{CC} - I_C\, R_L \text{ by } \mathbf{K}\text{irchhoff's } \mathbf{V}\text{oltage } \mathbf{L}\text{aw (K.V.L)} \tag{15}$$

Circuit 2 – Assume I_B is negligible, $V_{BE} \approx 0.7$ V and $h_{FE} >> 1$ (i.e. $I_C \approx I_E$).

$$I_1\, R_2 + I_1\, R_1 + (I_1 + I_C)\; R_L = V_{CC} \text{ (K.V.L)} \tag{16}$$

$$\text{or } V_{CC} = I_C\, R_L + I_1\, (R_L + R_1 + R_2) \tag{17}$$

$$I_1\, R_2 = V_E + V_{BE} = V_E + 0.7 \text{ (K.V.L)} \tag{18}$$

$$\text{or } I_1\, R_2 = I_C\, R_E + 0.7 \tag{19}$$

either I_1 or I_C may be eliminated from (17) using (19) for example, eliminating I_1 gives,

$$V_{CC} = I_C\, R_L + \frac{I_C\, R_E + 0.7}{R_2}\,(R_L + R_1 + R_2) \tag{20}$$

$$\text{or } I_C = \frac{V_{CC} - \dfrac{0.7\ (R_L + R_1 + R_2)}{R_2}}{R_L + \dfrac{R_E\,(R_L + R_1 + R_2)}{R_2}} \tag{21}$$

This result for I_C can be used in (19) to find I_1. V_C is found using,

$$V_C = V_{CC} - (I_C + I_1)\ R_L \tag{22}$$

Notes

- It is not the results that are important, but the application of the basic circuit rules that lead to them.
- The only transistor voltage drop that should appear in equations is V_{BE}. V_{CB} and V_{CE} do not and should not appear in equations for amplifiers.
- The assumption "I_B is negligible" really says that the existence of I_B does not disturb the potential at the transistor base significantly.
- Always check that the solution to equations (17) and (19) in circuit 2 is self consistent.

Design of Bias Circuits

The design process for single transistor amplifiers involves choosing one of the two circuits and deciding on appropriate values of node voltages and transistor collector current and then working out sensible component values. The choice of circuit depends to some extent on the application area. For low frequency applications, either circuit 1 or circuit 2 can be used. For high frequency applications, circuit 2 with $R_E = 0$ tends to be used.

The value of I_B must be considered during the design process to ensure that the design will satisfy the criterion "I_B is negligible". The case most likely to violate the criterion is *smallest* h_{FE}. Remember that the manufacturer will specify a maximum and minimum value of h_{FE} for a particular transistor. Remember also that the purpose of the bias circuit is to control I_C. Thus, $I_{B_{max}} = \frac{I_C}{h_{FE_{min}}}$

and $I_{B_{max}}$ is usually taken to be negligible if I_1, the current at the top of the biasing chain $\geq 10\, I_{B_{max}}$.

The value of I_C, V_C, V_E and V_B are a little more complicated to decide on because they will affect the signal properties of the amplifier. A few of the compromises are:

1. The value of collector voltage will affect the output voltage swing available. For example in cirucit 1, V_C can lie anywhere between V_{CC} and V_E. To maximise output voltage swing for a symmetrical signal like a sinusoid, V_C should be placed halfway between V_{CC} and V_E. i.e.

$$V_C = \frac{V_{CC} + V_E}{2} \text{ for max symmetrical swing} \tag{23}$$

2. Clearly both V_{CC} and V_E will affect the max symmetrical swing, which is $V_{CC} - V_E$. V_{CC} is usually set by what is available within the rest of the system, V_E can be chosen.

3. Larger V_E gives more precise control of I_C. For a BJT it is unwise to let V_E fall below 1 V in a circuit such as number 1.

4. I_C is chosen by considering the nature of the load, but it also affects the effective input resistance of the transistor[1] and output resistance of the amplifier. In general one would aim for a condition $R_L << $ [input resistance of the next stage].

5. R_1 and R_2 should be as large as possible consistent with the maintenance of the appropriate relationship between $I_{B_{max}}$ and I_1.

To visualise how the supply voltage will be divided up between the various parts of the circuit, it is helpful to draw a chart such as Fig. 6. This makes it clear that increasing V_E reduces the range of voltage that can be occupied by V_C and that the best position for V_C with symmetrical signals is halfway through the available range. Note that in this chart the minimum available value of V_C is V_B whereas in the comments above it is V_E. Most amplifier transistors will work satisfactorily with V_C as low as a few hundred mV above V_E but there are good reasons for saying that ideally V_C should not fall below V_B.

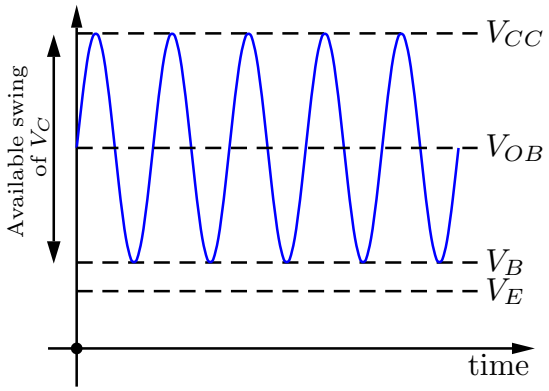


Figure 6: The transistor electrode voltages in the one transistor amplifier circuits.

[1] because I_C controls g_m via $g_m = (e\, I_C)/(k\, T)$ and $r_{be} = \beta/g_m$ so r_{be} and I_C are linked.

Notes

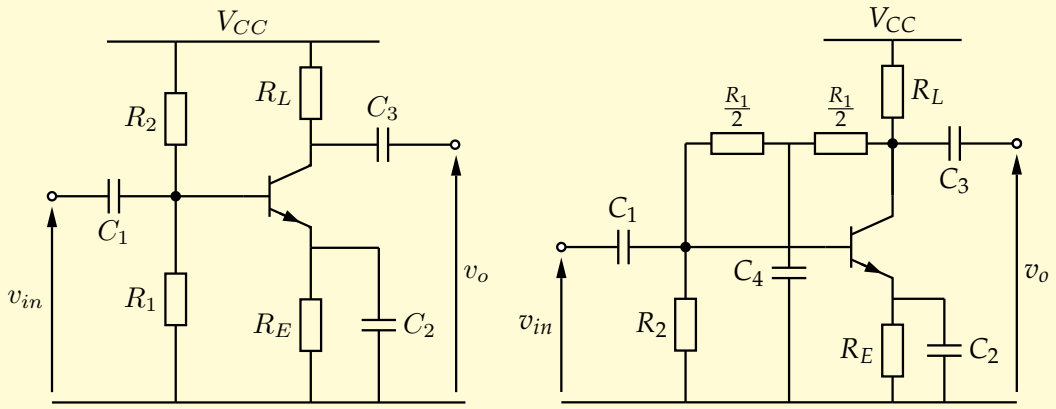
1. The design process is a compromise.
2. No two designers would make identical decisions.
3. Never specify component values more tightly than is necessary.
4. Use "preferred" (E12, E24 etc.) values.

Coupling and Decoupling

Transmitting signals from one place to another in a circuit is called "coupling". Removing signals from nodes in the circuit is called "decoupling". Capacitors or transformers can be used for coupling leading to so called "R-C" and "transformer coupled" amplifiers. Amplifiers that are required to amplify d.c. signals, such as strain gauge amplifiers or thermocouple amplifiers, cannot use transformers or capacitors – instead they must be "direct coupled" or "d.c." coupled. Direct coupled amplifiers use many transistors and will not be considered further at this point. Transformer coupling is attractive at high frequencies or in tuned amplifiers where resonant circuits are used. Capacitor coupling is used at lower frequencies. For example, an audio amplifier will be a combination of d.c. and capacitor coupling; a radio or TV I.F. amplifier will be transformer coupled.

Circuits 1 and 2 are shown in Fig. 7 with coupling and decoupling capacitors included. For the purposes of this discussion, a capacitor may be regarded as an open circuit (infinite impedance) to d.c. and a short circuit (zero impedance) to signals. Note that in Fig. 7 the signal voltage, v_{in} and v_o are in lower case v whereas the bias conditions are in upper case V. In both cases,

- C_1 couples the signal from the signal source to the transistor base without allowing the source to affect the bias conditions or the bias conditions to affect the source.
- C_2 decouples the emitter node of the transistor. In other words C_2 short circuits the emitter node of the transistor to ground as far as signals are concerned. This prevents R_E having the same stabilising effect on the signals as it has on the d.c. conditions. by removing the negative feedback caused by R_E. The circuit voltage gain $\frac{v_o}{v_i}$ is much larger if C_2 is incuded in the circuit than it would be if R_E was not bypassed by a capacitor.
- C_3 couples the signal from the output (collector node) to the load without allowing disturbance of the bias conditions or the imposition of a d.c. voltage accross the load.



(a) Circuit 1 (b) Circuit 2

Figure 7: Two one transistor amplifiers.

In circuit 2,

- C_4 decouples the mid point of R_1. Since R_1 is also a negative feedback path it will reduce the circuit gain if a.c. as well as d.c. voltages can be transmitted via R_1 to the base. C_4 short circuits the mid point of R_1 to ground as far as a.c. (signal) voltages are concerned hence eliminating any effects of the negative feedback via R_1 on circuit gain.

How the Transistor Interacts with Signals

The transistor is characterised by non-linear characteristic curves (see notes on characteristics). The rest of the amplifier circuit consists of standard circuit elements such as resistors and capacitors so it is convenient to represent the behaviour of the transistor towards the signal in standard circuit terms. A circuit representation of how the transistor behaves towards a signal is called a "small signal model" – it assumes that the signal represents only a small deviation from the bias conditions. All amplifying devices can be represented by a small signal model.

A Small Signal BJT Model

The underlying process of amplification involves the device "transconductance" – i.e. the amplifying device can be considered as a current source whose magnitude is controlled by the input voltage. For small signals it is the slope of the transconductance characteristic at the bias point which is of interest (see Fig. 8). For a BJT,

$$I_C = I_{CO}\left(\exp\left(\frac{e\,V_{BE}}{k\,T}\right) - 1\right) \qquad (24)$$

and the slope at the bias point is,

$$\frac{\mathrm{d}I_{CB}}{\mathrm{d}V_{BEB}} = I_{CO}\,\frac{e}{k\,T}\,\exp\left(\frac{e\,V_{BE}}{k\,T}\right) = g_m \qquad (25)$$

for a conducting diode,

$$\exp\left(\frac{e\,V_{BE}}{k\,T}\right) >> 1 \qquad (26)$$

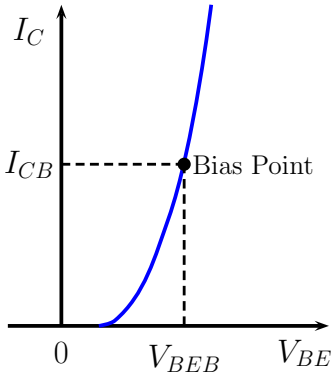


Figure 8: A BJT transfer characteristic showing the bias or quiescent point. The characteristic (blue line) is expressed by (24).

so

$$I_C = I_{CO}\left(\exp\left(\frac{e\,V_{BE}}{k\,T}\right) - 1\right) \approx I_{CO}\exp\left(\frac{e\,V_{BE}}{k\,T}\right) \qquad (27)$$

substituting,

$$\therefore \frac{\mathrm{d}I_C}{\mathrm{d}V_{BE}} = I_{CO}\,\frac{e}{k\,T}\,\exp\left(\frac{e\,V_{BE}}{k\,T}\right) = \frac{e\,I_C}{k\,T} = g_m \qquad (28)$$

$g_m = \frac{e\,I_C}{k\,T}$ where I_C is the quiescent or d.c. collector current. It is one of the fundamental BJT relationships and should be remembered. At room temperature, $\frac{e}{k\,T} \approx 40$ This transconductance consideration leads to the simplest BJT model, shown in Fig. 9. It is a good low frequency model for JFETs, MOSFETs and valves (although these devices and the BJT would probably have a resistor in parallel with the current source to take account of the slope on the output characteristics).

The BJT, however, is unique in having an input resistance that can rarely be ignored. The input resistance if found by working out the slope of the input characteristic, at the operating or quiescent point, in an indirect way,

$$r_{be} = \frac{\mathrm{d}V_{BE}}{\mathrm{d}I_B} = \frac{\mathrm{d}I_C}{\mathrm{d}I_B}\cdot\frac{\mathrm{d}V_{BE}}{\mathrm{d}I_C} \qquad (29)$$

$$\frac{\mathrm{d}I_C}{\mathrm{d}I_B} = \beta = \text{ small signal current gain} \qquad (30)$$

$$\frac{\mathrm{d}V_{BE}}{\mathrm{d}I_C} = \frac{1}{g_m} \text{ from (28)} \qquad (31)$$

$$\therefore r_{be} = \frac{\beta}{g_m} \qquad (32)$$

another vital BJT relationship.

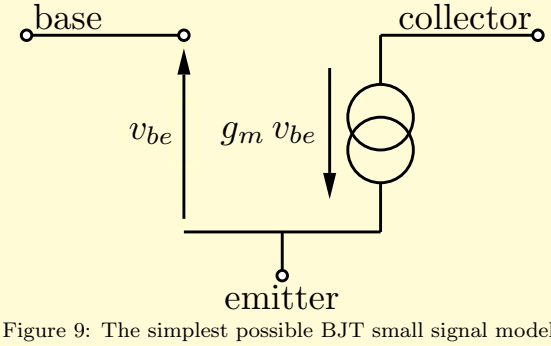


Figure 9: The simplest possible BJT small signal model.

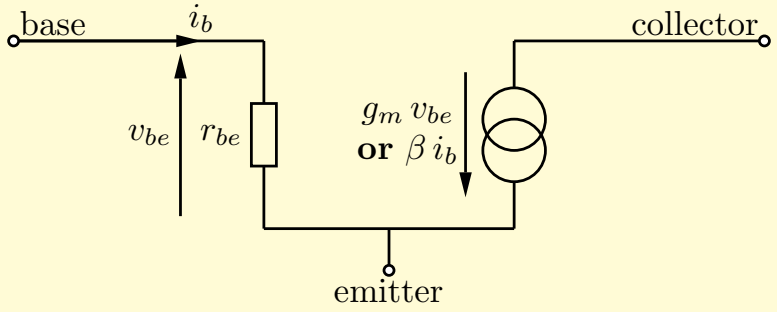


Figure 10: A simple BJT smal signal model including r_{be}.

Note that $\mathrm{d}V_{BE}$, $\mathrm{d}I_B$, $\mathrm{d}I_C$ are the small changes to the bias conditions and could be represented at small signal quantities v_{be}, i_b and i_c,

$$r_{be} = \frac{\beta}{g_m} = \frac{\mathrm{d}V_{BE}}{\mathrm{d}I_B} = \frac{v_{be}}{i_b} \tag{33}$$

$$\text{so } g_m\, v_{be} = \beta\, i_b \tag{34}$$

This is an interesting result because it says that the output current generator in the BJT model may be thought of as being controlled by the current through r_{be} or by the voltage across r_{be}. People get very worked up over the question "is a BJT a current or transconductance amplifier?" The answer really is that it doesn't matter – use whichever is more convenient for any particular problem. The discussion of the BJT in transconductance terms is helpul because the transconductance viewpoint is common to all three terminal amplification devices. No other device can be looked at as a current amplifier. Including r_{be} in the model leads to Fig. 10.

Notes

- Usually $\beta \neq h_{FE}$. β is a small signal parameter and h_{FE} is a large signal parameter.
- β is sometime given as h_{fe}. h_{fe} is derived from a different modelling system and except at high frequencies they can be taken as equal.
- There are other elements one could add to this model to explain details of behaviour. One example is a resistor in parallel with the current generator to model the slope on the output characteristic. The simple model in Fig. 10 consisting of input resistance and output current source is reasonable for a wider range of applications and will be used for the rest of this course.

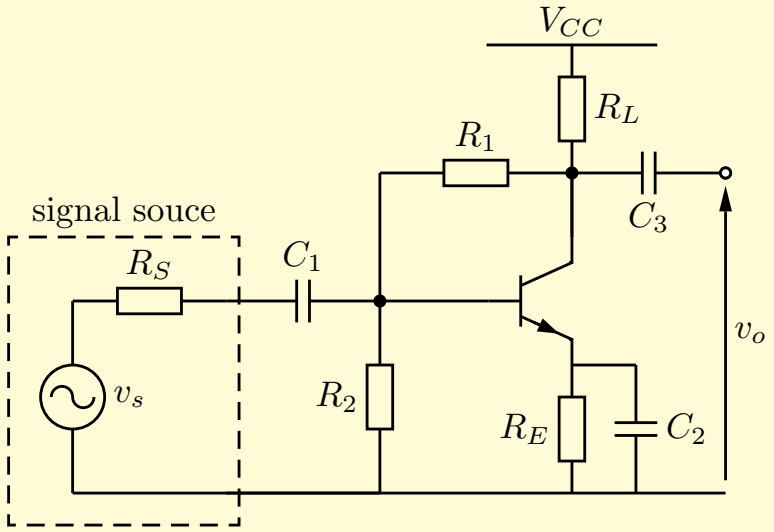


Figure 11: Circuit 1 with AC and DC feedback via R_1 and DC feedback via R_E.

The Small Signal Equivalent Circuit

In principle this is a straightforward task – it is a matter of drawing a circuit which describes what a signal in the circuit would experience, so it is necessary to look at the circuit from the signal's point of view. There are two important consequences of being interested only in the signal's interaction with the circuit.

1. All d.c. voltage sources (such as power supplies are replaced by their Thévenin equivalent impedance (i.e. 0 Ω – a short circuit).

2. All d.c. current sources are replaced by their Thévenin equivalent impedance, i.e. ∞ Ω – an open circuit.

In addition, since for the purposes of this course capacitors are considered as open circuit at d.c. adn short circuits to a.c., all capacitors are replaced by short circuits. The transistor is replaced terminal for terminal by its small signal model. Consider circuit 2, without decoupling R_1, which has the circuit diagram shown in Fig. 11. This circuit has the small signal model shown in Fig. 12. This small signal model can be tidied up to form Fig. 13.

Note that the small signal equivalent circuit will vary according to the circuit it is derived from. Do not attempt to learn the result – attempt instead to acquire the skill of deriving the small signal model for any circuit.

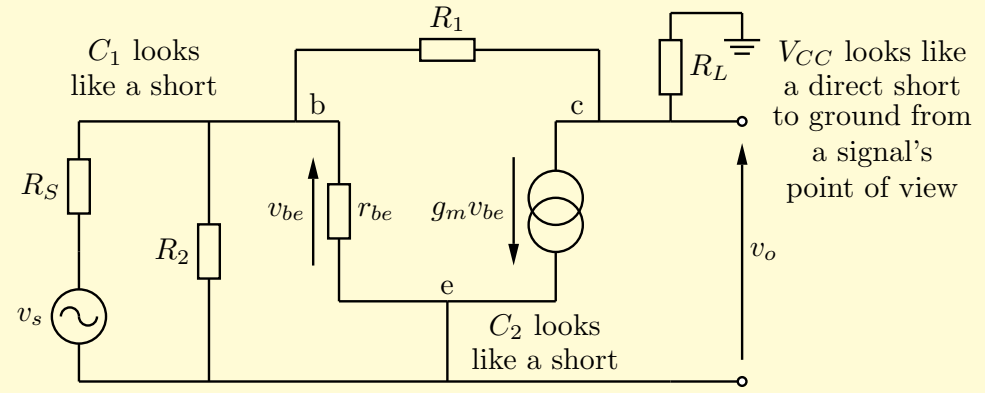


Figure 12: A "terminal for terminal" small signal model of the circuit in Fig. 11

Once the equivalent circuit is obtained, normal circuit analysis methods can be used to evaluate performance. For example, to obtain the overall voltage gain, $\frac{v_o}{v_s}$, one would begin by summing the currents (applying Kirchhoff's current law) at the output note,

$$\frac{v_o}{R_L} + \frac{(v_o - v_{be})}{R_1} + g_m\, v_{be} = 0 \tag{35}$$

summing currents (K.C.L) at the input node,

$$\frac{(v_s - v_{be})}{R_S} + \frac{(v_o - v_{be})}{R_1} = \frac{v_{be}}{R_2} + \frac{v_{be}}{r_{be}} \tag{36}$$

Equations (35) and (36) can be transposed to yield respecively,

$$v_{be} = -\frac{v_o\,(R_1 + R_L)}{g_m\, R_1\, R_L - R_L} \approx -\frac{v_o}{g_m\, R_1 // R_L} \tag{37}$$

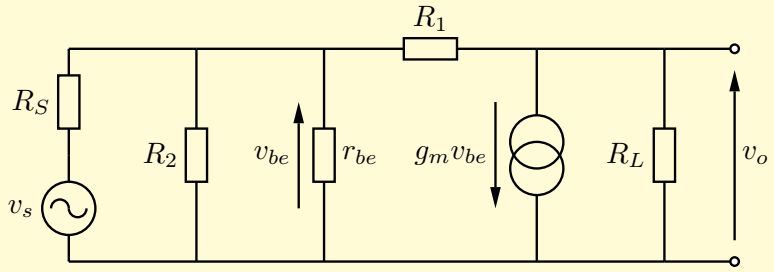


Figure 13: A tidied up version of small signal circuit diagram in Fig. 12

and

$$v_{be} = -\frac{\dfrac{v_s}{R_S} + \dfrac{v_o}{R_1}}{\dfrac{1}{R_2} + \dfrac{1}{r_{be}} + \dfrac{1}{R_s} + \dfrac{1}{R_1}} \tag{38}$$

$$= \frac{v_s\,(R_2//r_{be}//R_S//R_1)}{R_S} + \frac{v_o\,(R_2//r_{be}//R_S//R_1)}{R_S} \tag{39}$$

Eliminating v_{be} and transposing to obtain the voltage gain, $\frac{v_o}{v_s}$, required gives,

$$\frac{v_o}{v_s} = -\frac{R_1}{R_S} \cdot \frac{1}{1 + \dfrac{R_1}{g_m\,R_L\,(R_2//r_{be}//R_S)}} \tag{40}$$

and since R_1 is very large the $R_1\,/\,(g_m\,R_L\,(R_2//r_{be}//R_S))$ term will dominate the denominator giving,

$$\frac{v_o}{v_s} = -\frac{R_1}{R_S} \cdot \frac{1}{\dfrac{R_1}{g_m\,R_L\,(R_2//r_{be}//R_S)}} = -g_m\,R_L \cdot \frac{R_2//r_{be}}{R_S + R_2//r_{be}} \tag{41}$$

This expression consists of a gain term, $g_m\,R_L$ and an input potential division $(R_2//r_{be})/(R_S + R_2//r_{be})$. Note that the circuit gain is now directly dependent on the transistor parameters g_m and r_{be}; the negative feedback effects of R_1 have been eliminated. In removing R_1, the circuit is being changed from a small signal point of view, from circuit 2 in to circuit 1 with the emitter decoupled. The R_1 in circuit 1, which is necessary for correct biasing of the transistor, appears in small signal terms in parallel with R_2, hence altering the effective value of R_2 but not the form of the result.

Each circuit shape will produce its own result for gain and other performance measures so memorising this result would be unhelpful. The desirable outcome is for the student to practice the skill of deriving small signal circuit diagrams and equations until they can do it for any circuit and then to be able to interpret the results of their analysis.

Switches

These notes discuss mechanical, electromechanical and electronic switches concentrating on bipolar junction transistors (BJTs) and MOSFETs. The concept of an ideal switch is first introduced and each type of switch is evaluated agains the ideal as a mechanism of comparison. Real switches are discussed in terms of their useful life, isolation of the controlled and controlling parameter and switching speed.

Similar arguments apply to JFETs, IGBTs and Valves as apply to MOSFETs and BJTs however they are not discussed. Phase controlled switches (Triacs, Thyristors etc.) can be found in later modules.

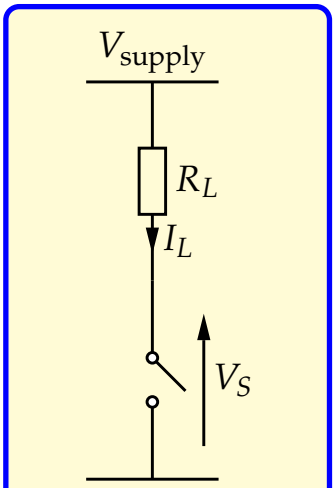


Figure 1: A generic switching circuit.

Ideal Switches

The purpose of a switch is to control power in a load in and "on"/"off/" sense.

When "on" $I_L = \frac{V_{supply}}{R_L}$
When "off" $I_L = 0$
When "on" $V_s = 0$
When "off" $V_s = V_{supply}$

The product of V_s and I_L in both switch states is zero so no power is dissipated in the switch. The "on" state current is determined by the external circuit (i.e. the load resistor), not by the switch. The ideal switch has no "leakage" current (a current that flows even when the switch is off). The idea switch also has no voltage or current limits.

Real Switches

Real switches have some series resistance and some leakage in the "off" state. In most cases, R_P (Fig. 2), the "off" state leakage can be neglected. R_s, the series resistance, usually has to be included because it is responsible for power dissipation in the switch. Power dissipation leads to the generation of heat, which the designer must account for. For a real switch

$$I_{on} = \frac{V_{supply}}{R_{Load} + R_s} \tag{1}$$

Switch Types

There are three switch types discussed in this course, mechanical, electromechanical and electronic.

Mechanical switches are characterised by

- A mechanical force brings two metal contacts together each of these is connected to a conductor. This is exemplified by toggle switches and push switches etc.
- A design current in the range 10^{-3} to 10^{+7} A.
- Very low contact resistance (R_s).
- Very low leakage resistance (high R_p).
- The requirement for mechanical force to be applied to a linkage between the switch and the operator.
- Inertia and elasticity limit the switching rate to a few hundred Hz.

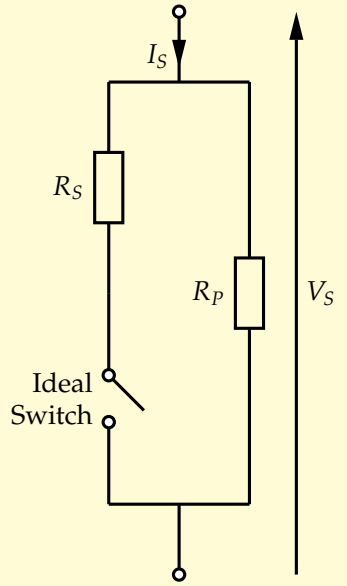


Figure 2: A model of a real switching circuit.

Electromechanical switches (relays) are characterised by

- A mechanical force brings two metal contacts together each of these is connected to a conductor and the mechanical force is provided by an electromagnet. This is exemplified by relays.
- A design current in the range 10^{-3} to 10^{7} A.
- Very low contact resistance (R_s).
- Very low leakage resistance (high R_p).
- The possibility of remote operation due to the electromagnet drive scheme while maintaining the advantages of mechanical contacts.

Note that in both mechanical and electromechanical switches, the switch contacts can be, and usually are, electrically insulated from the control linkages or electromagnet!

Electronic switches are characterised by

- A great variety of types of switch.
- Ones of interest here are based on MOSFET and BJT transistors.
- Fast switching. More than 10^9 switching cycles per second. (Most mechanical switches are incapable of more than 10^5 mechanical operations.

- Much higher losses than in mechanical switches (generally speaking).
- The control input being electrically connected to one of the main current path terminals.
- Support of current flow in only one direction.

These last two points are somewhat inconvenient. However the advantages and functionality that can be gain by using electronic switches are so great that designers have devised a number of ways to get round the problems.

MOSFET and BJT Switches

The device is put into a circuit like Fig. 3. V_s is the supply voltage, V_i is the control voltage and V_{sw} is the voltage across the switch. V_{sw} and I_{sw} are related by

$$I_{sw} = \frac{V_s - V_{sw}}{R_L} \qquad (2)$$

There is also a second relationship between V_{sw} and I_{sw} defined by the output characteristics of the transistor. Both transistor types have the same shape of output characteristics

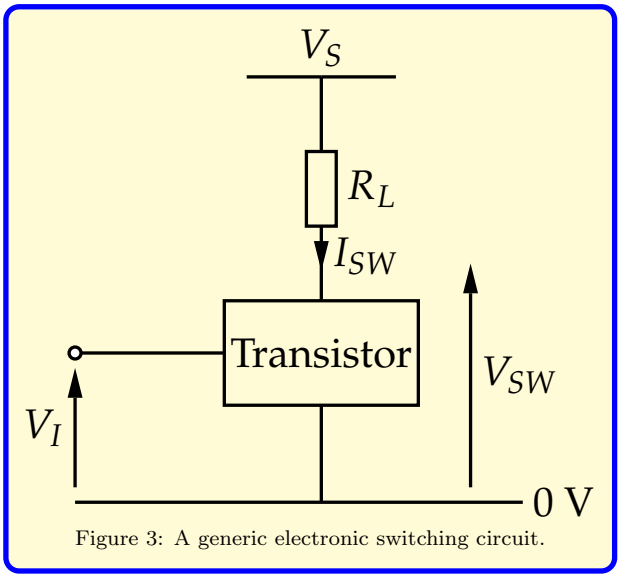


Figure 3: A generic electronic switching circuit.

The switch is controlled by V_i. Point C is the "off" stage point. If V_i is increased, I_{sw} will increase and V_{sw} will decrease until, eventually point B is reached. Point B is the real "on" state working point. Point A is the ideal "on" state working point so point B should be close to point A. In the region between points B and C, there is a significant VI product being dissipated within the switch and designers go to considerable lengths to keep the devices either at point B or at Point C and when moving between B and C the switching circuit is designed to allow the switch to chance I_{sw} as fast as possible in order to minimise power dissipation in the switch.

For example a ZTX653 bipolar transistor is capable of dissipating 1 W, can switch up to 2 A at up to 100 V i.e. it can control 200 W in a load. The instantaneous VI product at the mid point between B and C would be 50 W which is enough to destroy the transistor in considerably less than 1 second. Therefore the working point must not be allowed to linger between B and C. Designers ensure that the transistors survive by switching rapidly (usually in less

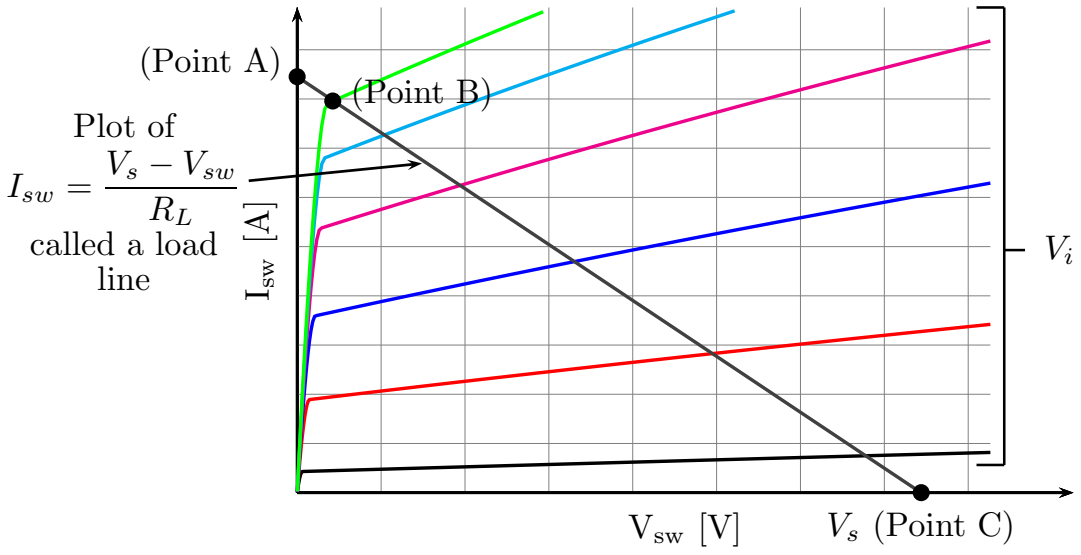


Figure 4: Example of Transistor Output Characteristics.

than 1 μs) between states. This makes the average energy dissipated in the switch small.

MOSFET Switches

The MOSFET behaves like a resistance when fully on (i.e. at point B). Manufacturers specify this resistance as $r_{ds(on)}$. The expression for the load line becomes,

$$I_D = \frac{V_s}{R_L + r_{ds(on)}} \tag{3}$$

when in the "on" state and, since leakage is usually negligible, $I_D \approx 0$ in the "off" state.

The effect of $r_{DS(on)}$ on load power is usually small (may be 1 or 2%) but the effect on the transistor may be important because the power disipated in it is,

$$P_{sw} = I^2_{D(on)}\, r_{DS(on)} \tag{4}$$

and the switch must be capable of dissipating this energy. To be sure that a MOSFET is fully "on", the manufacturers datasheet should be consulted but, for most MOSFETs in the $I_{D(max)} = 1 - 20$ A range and $V_{DS(max)} = 10 - -1000$ V range, a V_{GS} of 10 V will

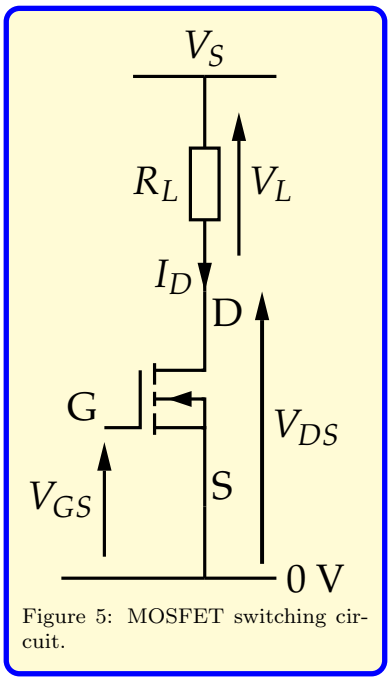


Figure 5: MOSFET switching circuit.

turn the device fully on and a V_{GS} of 0 V will turn it fully off. Since te gate terminal is insulated, no current is require to *maintain* the gate voltage drive. Note though that the gate has capacitance associated with it which complicates transient (switching) conditions. A more thorough discussion of switching circuits will be undertaken in later modules.

BJT Switches

When a BJT is fully "on" (i.e. at point B) the voltage across it is $V_{CE(sat)}$, the saturated on-state voltage drop. $V_{CE(sat)}$ is approximately constant for a constant ratio of I_C/I_B and its magnitude depends upon the particular transistor. For a 100 V, 2 A device $V_{CE(sat)}$ would be a couple of hundred millivolts. For a 1000 V 20 A device it would be around 1 V.

$$I_{C(on)} = \frac{V_s - V_{CE(sat)}}{R_L} \tag{5}$$

and $I_{C(off)} \approx 0$ because leakage is small. The on-state power dissipated in the switch is $I_{C(on)}\, V_{CE(sat)}$ and the device must be capable of dissipating this energy. To be sure the BJT is fully on, the designer must ensure that sufficient I_B is driven in to the transistor base. The BJT has a parameter called "static current gain", I_C/I_B which is given the symbol h_{FE}. This tells the designer the base current required to support a particular collector current. So for a BJT the design process would be

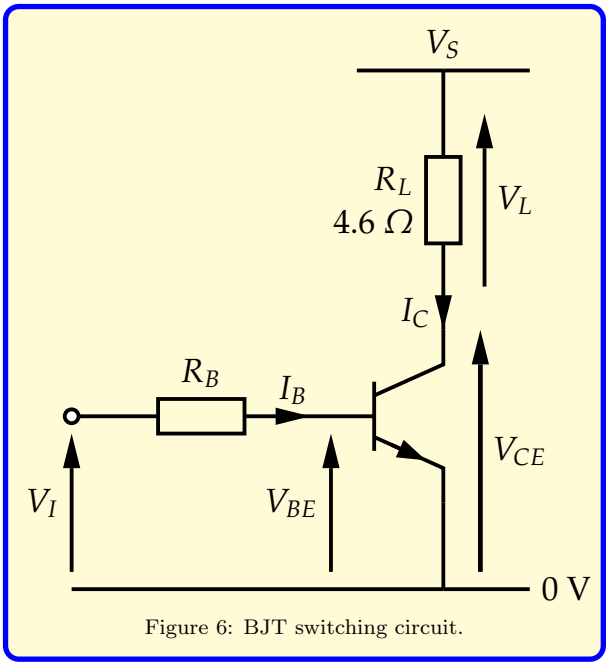


Figure 6: BJT switching circuit.

$$I_C = \frac{V_s - V_{CE(sat)}}{R_L} \tag{6}$$

$$\therefore \text{ minimum } I_B \text{ needed } = \frac{I_C}{h_{FE}} = \frac{V_s - V_{CE(sat)}}{h_{FE}\, R_L} \tag{7}$$

This current is controlled by R_B according to

$$I_B = \frac{V_i - V_{BE}}{R_B} \tag{8}$$

where V_i this the input drive voltage and V_{BE} is the voltage drop associated with a forward biased p-n junction - i.e. 0.6 - 0.7 V. Usually a designer will make I_B two or three times the minimum value in order to be user the transistor is switched on properly under all circumstances.

Electronic Switches with AC

Often current must be controlled in AC systems. Examples are numerous including for example heating and air handling applications. In the circuit of Fig. 7 the diode, D_1 ensures that the switch is not reverse biassed during negative half cycles. However the control is only half wave - the load can never by energised when V_S is in the negative half cycle. Therefore half of the potential load dissipation is unavailable, which is highly undesirable.

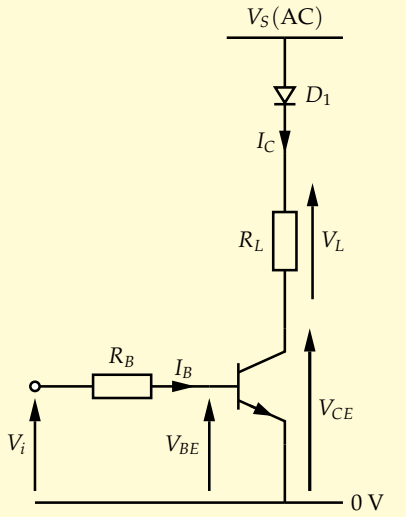
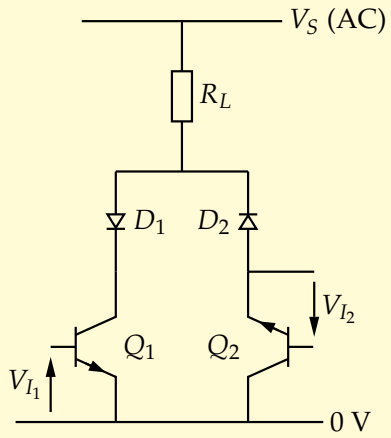
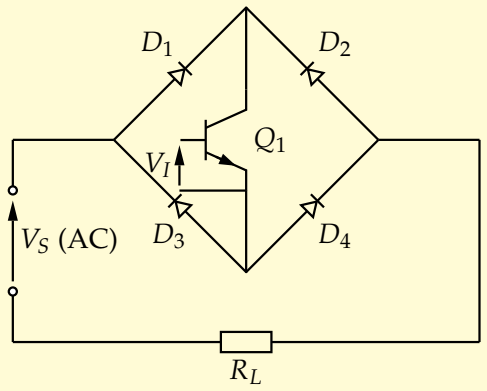


Figure 7: Half Wave Rectifying BJT AC Switching Circuit

We could add a second diode as in Fig 8a. Here D_1 and Q_1 will operate when $V_{s(AC)}$ is positive and D_2 and T_2 will operate when $V_{s(AC)}$ is negative. The control input to Q_2 is somewhat complicated but it is not impossible to devise an appropriate control circuit. Often, especially in mains or 3ϕ equipment opto-isolators or pulse transformers are used to electrically isolate the drive circuit from the switching transistor. An alternative full



(a) Two transistor AC switching circuit.



(b) Diode bridge switching circuit.

Figure 8: Two Full Wave AC Switching Circuits.

wave approach is to use the four diode bride with a single switch showin in Fig. 8b. The diode bridge ensures that whatever the instantaneous polarity of V_S, I_C is always in the same direction. The current through R_L alternates. This circuit has similar difficulties with the control input terminals, but a suitable control circuit is relatively straightforward.

H-Bridge Circuits

H-Bridge circuit are often used to control d.c. motors from a d.c.

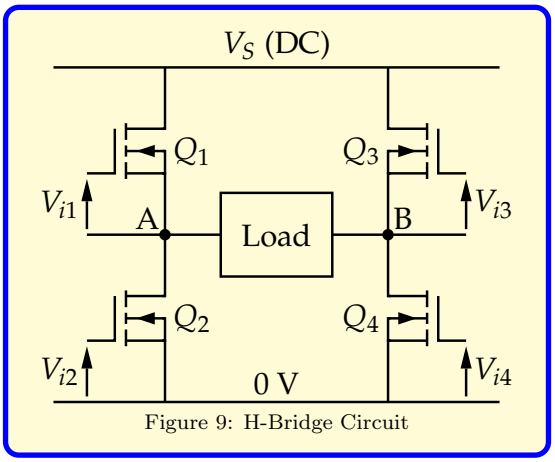


Figure 9: H-Bridge Circuit

- The H-bridge consist of four switches in an "H" shape. The load forms the cross bar of the H.
- For electric car applications V_S may be in the region of 600 V dc and peak currents may reach 50 A.
- By controlling switches appropriately, current can be made to flow in either direction through the load. Therefore d.c. motors can be made to run in both directions. The average load power can also be controlled by using pulse width modulation techniques. This allows maximisation of torque while controlling speed.

To understand the operation imagine Q1 and Q4 are "on". Current will flow through Q1 to A, through the load to B and then through Q4. Current can be made to flow from B to A by switching "off" Q1 and Q4 and switching "on" Q3 and Q2. Note if Q1 and Q2 or Q3 and Q4 are ever permitted to be on simultaneously, a large "shoot-through" current will flow and, if there is nothing else to limit the current, the switches will be destroyed, usually very violently.

Switching Inductive Loads

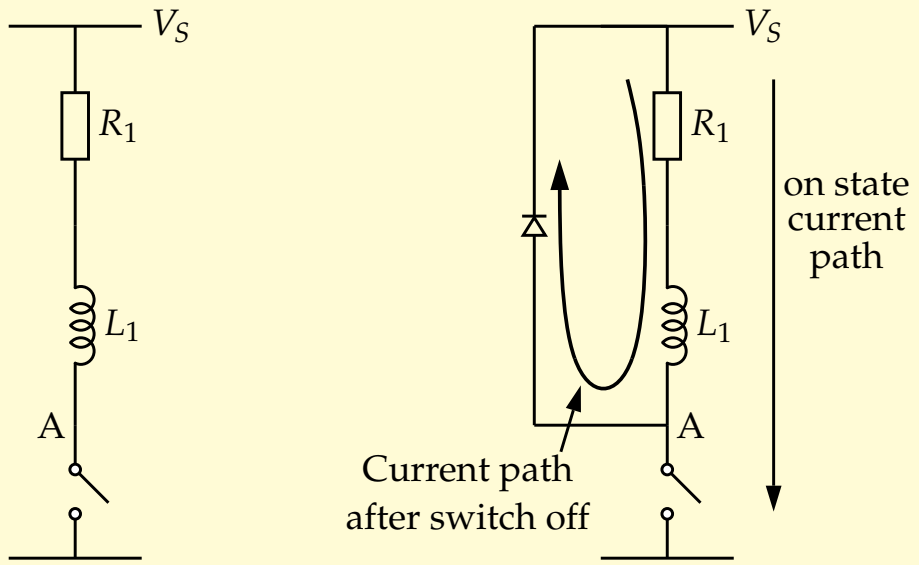
Inductors always try to keep current flowing in them or more precisely inductors generate a voltage across their terminals which acts to oppose any change in current through the inductor. Since

$$V_L = L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{9}$$

if one tries to switch off a current, i.e. make $\mathrm{d}i/\mathrm{d}t \to \infty$, $V_L \to \infty$. Effectively what happens is as follows:

- When the switch is "on", a current V_s/R_L flows in the circuit.
- When the switch turns "off", L keeps pushing current into node A... so charge builds on node A very rapidly.

- Node A has only a small capacitance (this is stray or parasitic capacitance between the node and the other parts of the circuit) so a small amount of charge yields a big voltage ($I = C\mathrm{d}V/\mathrm{d}t$) which is sometimes called a "back emf spike".
- Peak voltage can easily reach several kilovolts in a system driven by 12 V. The voltage spikes can damage or destroy the switch and other components.
- The effect can be controlled by providing an alternative pathway for current leaving the inductor when the switch turns "off". One way is to use an "idling" or "free wheeling" diode that is reverse biassed while the switch is on by conducts if the voltage on node A rises above V_S.
- Immediately after switch "off", the current through D is the same as in the "on" stage immediately before switch "off". The current then falls exponentially with a time constant of L/R_T where R_T is the total resistance of the idling current pathway.



(a) Switch circuit with inductive load. (b) Inductive load and free wheeling diode.

Figure 10: Switch circuits with and without "back emf" protection.

In some applications, these back emf spikes are useful. Examples include car ignition, electric fences, flyback converters (a kind of switched mode power supply), and CRT and VFD display power supplies. In most applications however attempts are made to control them.

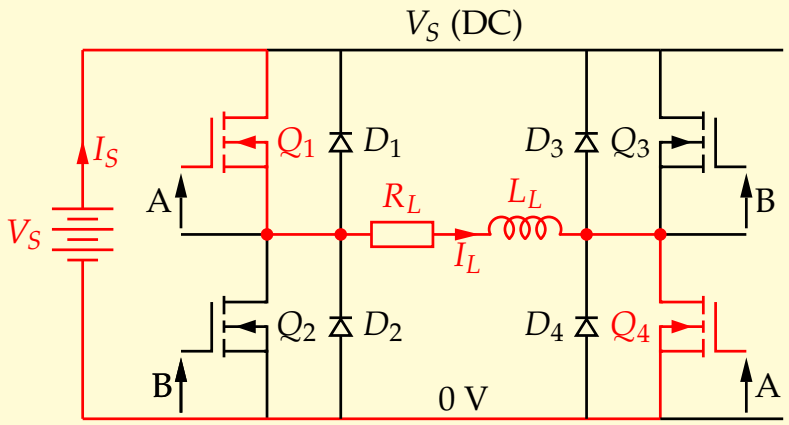


Figure 11: H-bridge with free wheeling diodes, switches conducting.

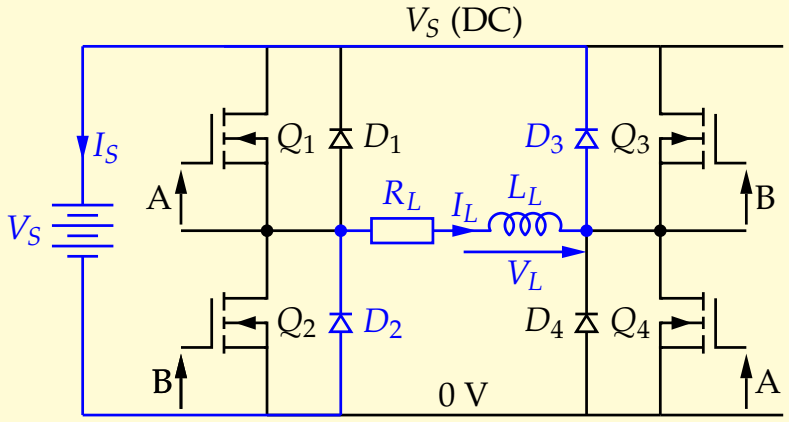


Figure 12: H-bridge with free wheeling diodes, diodes conducting.

The energy stored in the inductor drives the "back emf" process and in the simple idling diode circuit of Fig. 10b this energy is dissipated in D_1 and R_T. In an H-bridge circuit, energy stored in the load is returned to the supply. For example if Q_1 and Q_4 have been on for a long time and Q_2 and Q_3 are off and stay off, the on state and idling current paths are shown in Figs. 11 and 12, note that the idling current acts to charge up the power supply (either a battery or a bench power-supply etc.)

Operational Amplifiers

These notes introduce operational amplifiers. Classical feedback systems are considered briefly and comparisons are drawn with operational amplifiers. The necessity to supply d.c. power to the opamp is discussed before analysis of several common operational amplifier circuits is presented both using an infinite open loop gain approach and considering a finite gain defect. This discussion leads directly into the discussion of transistor and operational amplifier circuits in EEE225.

Operational amplifiers are the most commonly used analogue "building block". They have been around since the 1930s, the first were constructed using thermionic valves, they were big, heavy and power hungry - about the size of a briefcase in fact. For more details on the background of opamps you'll need to do some digging but a profitable place to start is Jung, W., "The Opamp Applications Handbook", Newnes, 2004. The first opamps formed the basis of analogue computers. Early and modern operational amplifiers differ somewhat in various aspects so here we limit ourselves to modern opamps (i.e. 1968 onwards after the design of the μA741). Modern opamps are designed to have,

- A differential input.
- very high input resistance ($> 10^9\ \Omega$).
- very low output resistance ($< 50\ \Omega$).
- very high gain ($> 10^5$)

The opamp relies on feedback to operate effectively as an amplifier and it can be considered in terms of a classical feedback system.

Classical Feedback Systems

The classical feedback system is shown in Fig. 1. It is possible to use the classical feedback system to see why the properties of the opamp listed above are desirable.

If the output voltage is v_o, a fraction, $H\,v_o$ is fed back to the input stage where it is subtracted from v_i. This leaves $(v_i - H\,v_o)$ at the input of the gain stage G, so

$$v_o = G\,(v_i - H\,v_o) \tag{1}$$

$$\frac{v_o}{v_i} = \text{ system gain } = \frac{G}{1 + G\,H} \tag{2}$$

If G is very large, then $G\,H >> 1$ and

$$\frac{v_o}{v_i} \approx \frac{G}{G\,H} = \frac{1}{H} \tag{3}$$

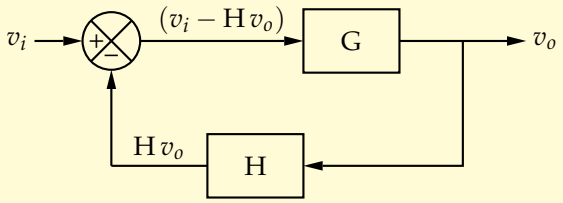
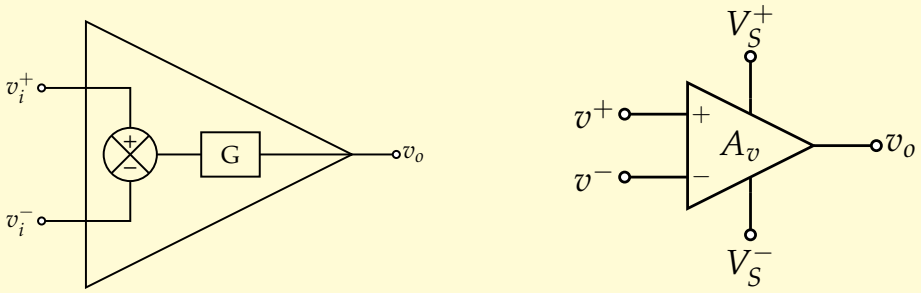


Figure 1: A classical feedback system.

This is a very useful result because it tells the designer that if G is made large enough, system gain is dependent only on the feedback fraction H. H is usually defined by well behaved components – resistors and capacitors – although in this module only resistors will be used.

The Opamp

The opamp integrates two parts of this classical feedback system shown in Fig. 2a.



(a) Opamp parts of a feedback system. (b) Opamp drawn *with* power pins.

Figure 2: Representations of the opamp.

- The input resistances must be high so that the v^- input does not affect the network that defines H and so that the v^+ input does not affect the signal source.
- The output resistance must be low so that the system can drive a load without v_o being affected and so that the system can drive the network defining H without being affected.
- The reason for the differential input and the high gain are evident from the (3). We want H, which is defined by resistors under our control, to set the gain of the amplifier.

- The opamp is usually drawn as shown in Fig. 2b.
- V_s^+ and V_s^- are the power supplies. They are often not included on circuti diagrams but must be connected in the real circuti. v_o cannot move outside the range $V_s^+ > v_o > V_s^-$.
- v^+ is called the "non-inverting" input of the opamp. It is identified by a "+" next to the input line, inside the opamp triange.
- v^- is called the "inverting" input of the opamp. It is identified by a "-" next to the input line, inside the opamp triange.
- the output, v_o, comes from the point of the amplifier symbol.
- A_v is the voltage gain (equivalent of G) which relates the output and intpu by the opamp equation. A_v operates on the *difference* between v^+ and v^- to produce v_o.

$$v_o = A_v \left(v^+ - v^-\right) \tag{4}$$

Opamp Circuits

There are many different circuits that are used with opamps but these are two that are far more common than any others "non-invertin amplifier" and "inverting amplifier".

Non-Inverting Amplifier

When designing an opamp circuit it is usual to initially assume that $A_v \to \infty$. This means that the circuit behaviou is completely controlled by the feedback. If $A_v \to \infty$, for finite v_o, $v^+ \approx v^-$ and this makes working out the circuit behaviour quite straightforward.

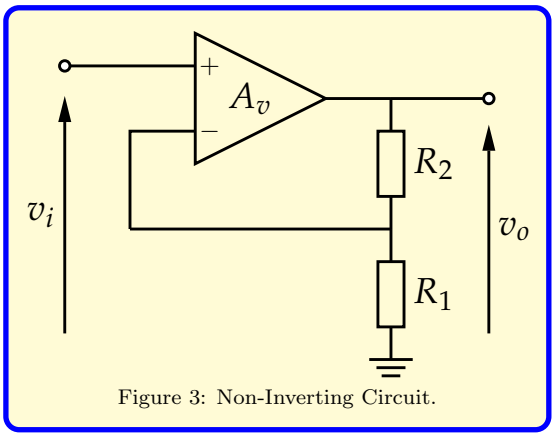


Figure 3: Non-Inverting Circuit.

$$v^- = v_o \frac{R_1}{R_1 + R_2} \text{ by potential division} \tag{5}$$

$$v^+ = v_i \text{ connected by a wire} \tag{6}$$

$$\therefore \text{ if } A_v \to \infty,\ v^+ \approx v^- \tag{7}$$

$$\text{substituting yields } v_i = v_o \frac{R_1}{R_1 + R_2} \tag{8}$$

$$\text{or } \frac{v_o}{v_i} = \frac{R_1 + R_2}{R_1} \tag{9}$$

Notice that the feedback is returned to the input at the "inverting" (v^-) input.

Inverting Amplifier

In the inverting amplifier connection v^+ is grounded and v_i is applied to R_1. Again if $A_v \to \infty$, $v^+ \approx v^-$ and since v^+ is connected to zero v^- must also be very close to zero. The v^- node in this case is called a "virtual earth" because the potential is always close to zero bat the node is not actually connected to zero. The virtual earth exists because of the negative feedback arrangement in this circuit, because A_v is very large and because the opamp subtracts its inputs i.e. obeys the opamp equation. All of these are required for the virtual earth to exist. To work out the gain, start by summing currents at the v^- node...

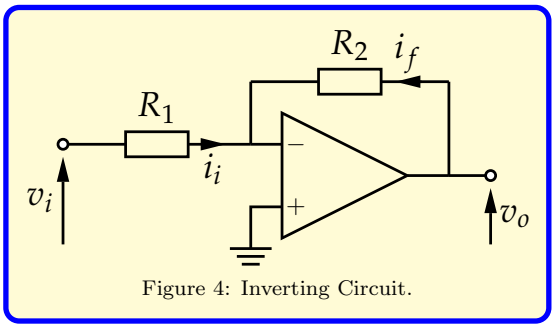


Figure 4: Inverting Circuit.

$$i_i + i_f = 0 \tag{10}$$

substituting via Ohm's law

$$\frac{v_i - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0 \tag{11}$$

and since $v^- = 0$

$$\frac{v_i}{R_1} + \frac{v_o}{R_2} = 0 \tag{12}$$

transposing for voltage gain

$$\frac{v_o}{v_i} = -\frac{R_2}{R_1} \tag{13}$$

Notice the "-" sign. This means that the signal is inverted (i.e. the phase is shifted by 180°) as well as being amplified. Two inverting amplifiers in series would give rise to an overall non-inverting amplifier – the first stage would invert the signal and the second would invert it back to its original phase.

The Effects of Finite Open Loop Gain

Very occasionally it may be necessary for a designer to estimate the effect of finite opamp open loop gain on the overall circuit gain.

Non-Inverting Amplifier

When considering the effects of finite gain the $v^+ \approx v^-$ approximation can not be used. Instead the analysis must use the opamp equation (4) at a suitable point. The analysis proceeds as follows:

$$v^- = v_o \frac{R_1}{R_1 + R_2} \text{ as before} \tag{14}$$

$$v^+ = v_i \text{ as before} \tag{15}$$

Now the opamp equation must be used to relate v^+, v^- and v_o.

$$v_o = A_v \left(v^+ - v^-\right) = A_v \left(v_i - v_o \frac{R_1}{R_1 + R_2}\right) \tag{16}$$

transposing for v_i

$$v_o \left[\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}\right] = v_i \tag{17}$$

then the gain is

$$\frac{v_o}{v_i} = \frac{1}{\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}} \tag{18}$$

Note that if $A_v \to \infty$, $1/A_v$ becomes negligible and (18) becomes (9).

Inverting Amplifier

Start as before by summing the current at the inverting (v^-) node.

$$i_i + i_f = 0 \text{ or } \frac{v_i - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0 \tag{19}$$

which can be transposed to give v^-

$$v^- = v_i \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2} \tag{20}$$

the circuit diagram makes clear that

$$v^+ = 0 \tag{21}$$

Now use the opamp equation (substitute (20) and (21) into (4))

$$v_o = A_v \left(0 - \left[v_i \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2}\right]\right) \tag{22}$$

separating v_o and v_i

$$v_o \left[\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}\right] = -v_i \frac{R_2}{R_1 + R_2} \tag{23}$$

and finally the gain is

$$\frac{v_o}{v_i} = -\frac{\dfrac{R_2}{R_1+R_2}}{\dfrac{1}{A_v}+\dfrac{R_1}{R_1+R_2}} \tag{24}$$

Again if $A_v \to \infty$, v_o/v_i is given by (13).

Circuit Input Resistance

The input to the non-inverting circuit goes directly to the opamp so the circuit input resistance is the same as that of the opamp i.e. very high. The inverting circuit is slightly different. Taking the $A_v \to \infty$ case, and i_i of v_i/R_1 flows from the source. Input resistance is the ration of applied signal current drawn i.e. $v_i/i_i = R_1$. this is typically likely to be a few kΩ which makes inverting amplifiers unsuitable as amplifiers of signal derived from sources with a large Thévenin resistance.

The Unity Gain Buffer

The unity gain buffer is a special case of the non-inverting amplifier. Here $v^- = v_o$ so the opamp equation becomes

$$v_o = A_v\left(v^+ - v^-\right) = A_v\left(v_i - v_o\right) \tag{25}$$

transposing for voltage gain

$$\frac{v_o}{v_i} = \frac{1}{\dfrac{1}{A_v}+1} = \frac{A_v}{1+A_v} \tag{26}$$

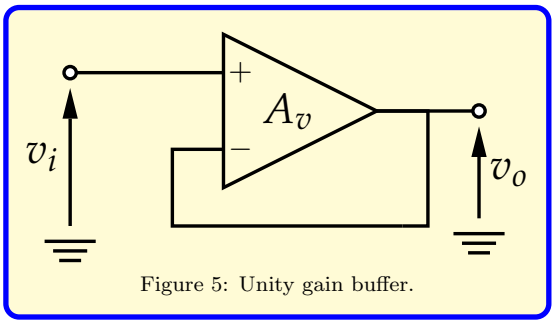


Figure 5: Unity gain buffer.

If A_v is large. v_o/v_i is very close to unity. The circuit is used to isolate high impedance sources from low impedance loads; it has a high power gain.

Circuits with Multiple Inputs

Operational amplifier circuits can have many inputs, limited only by the practicality of connections and space. Multiple input circuits considered in this course are a kind of summing amplifier and a kind of subtractor or difference amplifier. A general method for multiple input circuits will be given. When considering opamp circuits with more than one input in this course we will assume $A_v \to \infty$.

Summing Amplifier

Many analogue audio "mixers" use the circuit shape shown in Fig. 6. It is superior in several respects to a summing amplifier based on a non-inverting topology. The nature of the superiority is left as an exercise for the curious mind - it's to do with impedances. Assume $A_v \rightarrow \infty$ so $v^- \rightarrow$ virtual earth i.e 0 V. This assumption is always valid in a practically sensible multiple input circuit. Then,

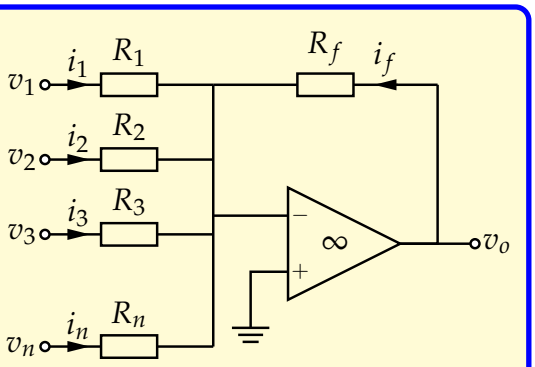


Figure 6: Summing amplifier.

$$i_f + i_1 + i_2 + i_3 + \cdots + i_n = 0 \quad (27)$$

using Ohm's law

$$\frac{v_o}{R_F} + \frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} + \cdots + \frac{v_n}{R_n} = 0 \quad (28)$$

transposing for v_o

$$v_o = -\left[v_1\frac{R_F}{R_1} + v_2\frac{R_F}{R_2} + v_3\frac{R_F}{R_3} + \cdots + v_n\frac{R_F}{R_n}\right] \quad (29)$$

Subtractors or Difference Amplifiers

The subtractor shown in Fig. 7 can be solved by several methods. Since $A_v \rightarrow \infty$, $v^+ = v^-$ so here we will work out v^+ and v^- and then equate them to get v_o in terms of v_1 and v_2. Summing currents at the v^- node

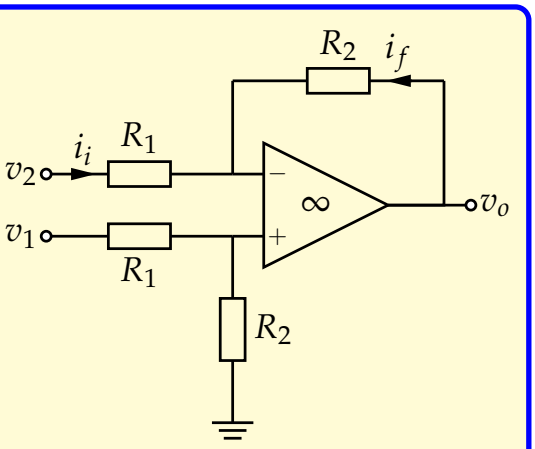


Figure 7: Subtracting amplifier.

$$i_i + i_f = 0 \quad (30)$$

Using Ohm's law

$$\frac{v_2 - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0 \quad (31)$$

and this can be transposed to give

$$v^- = v_2\frac{R_2}{R_1 + R_2} + v_o\frac{R_1}{R_1 + R_2} \quad (32)$$

v^+ is a potentially divided version of v_1

$$v^+ = v_1 \frac{R_2}{R_1 + R_2} \tag{33}$$

equating v^+ and v^-

$$v_2 \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2} = v_1 \frac{R_2}{R_1 + R_2} \tag{34}$$

transposing for terms in v_o on the left

$$v_o \frac{R_1}{R_1 + R_2} = v_1 \frac{R_2}{R_1 + R_2} - v_2 \frac{R_2}{R_1 + R_2} \tag{35}$$

cancelling

$$v_o = \frac{R_2}{R_1} (v_1 - v_2) \tag{36}$$

Note that the accuracy of the subtraction depends upon the matching of the tow R_1s and R_2s.

General Multiple Input Circuits

The subtractor circuit can be generalised to allow more than two inputs. Such a circuit is shown in Fig. 8. It could be analysed by finding v^+ and v^- and equating them or by using the principle of superposition. Superposition has the advantage that at each stage the circuit is reduced to a familiar single input circuit. Consider first the output due to v_1. In this case v_2, v_3 and v_4 are grounded the circuit becomes that of Fig. 9a

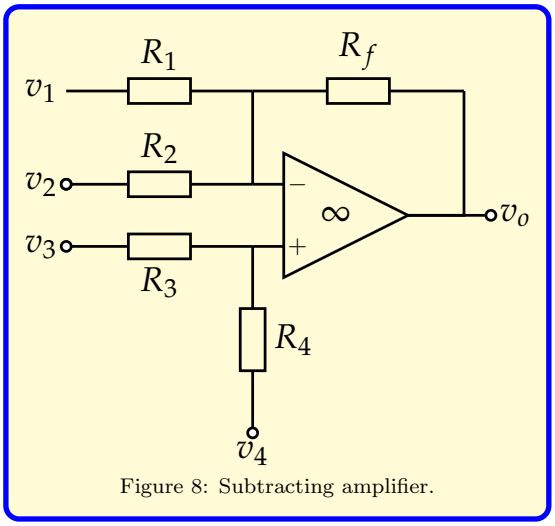


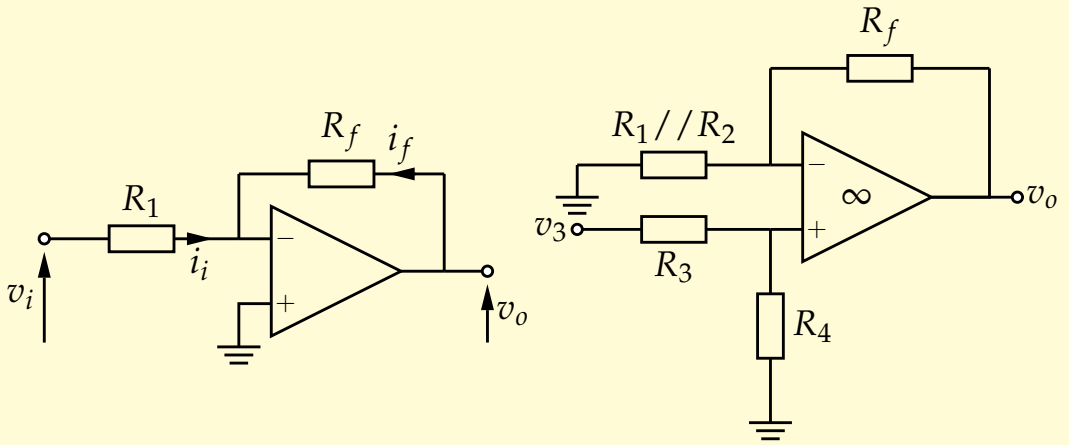
Figure 8: Subtracting amplifier.

Note that since both v_3 and v_4 are zero, v^+ is zero and v^- is a virtual earth. since v^- is a virtual earth, no current flow through R_2 so it has no effect on the circuit.

$$v_o|_{v_1} = v_1 \left(-\frac{R_F}{R_1} \right) \tag{37}$$

By a very similar argument

$$v_o|_{v_2} = v_2 \left(-\frac{R_F}{R_2} \right) \tag{38}$$



(a) Partial circuit for superposition of v_1.(b) Partial circuit for superposition of v_3.

Figure 9: Partial circuits for superposition of the multiple input opamp circuit.

The output due to v_3 leads to a more complicated partial circuit shown in Fig. 9b. Here $v_1 + v_2$ are grounded so R_1 is effectively in parallel with R_2. v^+, the non-inverting amplifier input is a potentially divided version of v_3 so

$$\frac{v_o}{v^+} = \frac{R_F + R_1//R_2}{R_1//R_2} \tag{39}$$

this is just the non-inverting opamp gain. And potential division

$$\frac{v^+}{v_3} = \frac{R_4}{R_3 + R_4} \tag{40}$$

defines the relationship between v^+ and v_3. Bringing the two together

$$\frac{v_o}{v_3} = \frac{v_o}{v^+} \cdot \frac{v^+}{v_3} = \frac{R_4}{R_3 + R_4} \cdot \frac{R_F + R_1//R_2}{R_1//R_2} \tag{41}$$

v_o due to v_3 is then

$$v_o|_{v_3} = v_3 \frac{R_4}{R_3 + R_4} \cdot \frac{R_F + R_1//R_2}{R_1//R_2} \tag{42}$$

By a very similar argument

$$v_o|_{v_4} = v_4 \frac{R_3}{R_3 + R_4} \cdot \frac{R_F + R_1//R_2}{R_1//R_2} \tag{43}$$

The total output voltage is the sum (superposition) of the results so far

$$v_{o(\text{total})} = v_o|_{v_1} + v_o|_{v_2} + v_o|_{v_3} + v_o|_{v_4} \tag{44}$$

Remember that if any of the inputs have d.c. and a.c. parts, those two parts can be treated as separately due also to the superposition principle.

Handouts

(The Lecture Slides)



EEE118: Electronic Devices and Circuits

Lecture I

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

EEE118. "Electronic Devices and Circuits"

Part 1

- Lectures 1 & 2. Passive Components and Circuit Theorems
- Lecture 3. Diodes I
- Lecture 4. Conduction State Problems in Diodes
- Lecture 5. Pulse Circuits Containing Diodes.
- Lectures 6 & 7. Five Common Diode Circuits
- Lectures 8 & 9. Rectification and Stabilisation

This Lecture

1. Introduction
   - Aims & Objectives
2. Books
3. Problem Sheet
4. Circuits Terminology
5. Units
6. Passive Components
   - Resistors
   - Resistor Colour Codes
   - Capacitors
7. Review
8. Bear

Aims & Objectives[1]

To begin our description of the operation, analysis and design of electronic components and circuits.

These circuits are formed from,

- Active elements
  - Diodes
  - Transistors (e.g. BJT, JFET & MOSFET)
  - Integrated Circuits (ICs)
- Passive elements
  - Resistors
  - Capacitors
  - Inductors

[1] See the course descriptor in the Handbook or on MOLE.

How is this different from the other stuff?

In Dr. Groom's part of the course the objective is

to understand how electronic devices work

What happens inside devices? Where do the electrons and holes go? Why?

In this part of the course the objective is

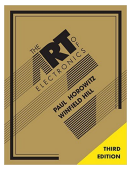
to understand how to make electronic devices work

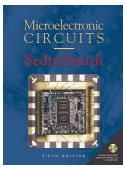
Can I use what I know about electron device operation and circuit design to build an (amplifier/oscillator/mixer/VCA etc.)?

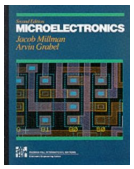
What to expect...

- Slides & Notes
- The Handout Pack (Don't leave without one...)
- Older Handouts & past exams + solutions available on MOLE
- Videos of the lectures available on-line
- Videos of lectures from past years also on-line
- Problem sheets & problem classes (solutions online)
- Information Commons and Diamond Library

Books







- Horowitz, P. and Hill, W., "The Art of Electronics", Cambridge University Press, 3rd ed., 2015.
- Sedra, A. S., and Smith, K. C., "Microelectronics", Oxford University Press, 5th ed., 2006.
- Millman, J., and Grabel, A., "Microelectronics", McGraw-Hill Higher Education, 2nd ed. 1988.

Background Skills Problem Sheet

It should be possible to fully attempt the background skills problem sheet now.

Voltage & Current

The properties of circuits are described by two important quantities.

Voltage, has the units volts and symbol V. Also called "potential difference"
It is the energy required to move a quantity of charge between two potentials.
One joule of energy is required to "raise" one coulomb of charge by one volt.
Voltage is always measured *across* two *nodes*.

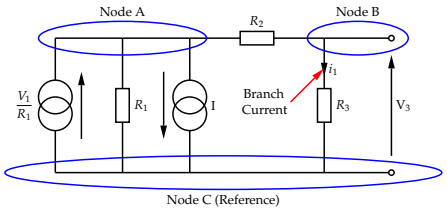
Current, has the units amperes and symbol A.
It is the rate of flow of electric charge (coulombs per second).
At the atomic level it relates to the flow of electrons where 1 electron has a charge of 1.6×10^{-19} C
1 A $= 6.241 \times 10^{18}$ electrons per second
Current flows *through* a circuit *branch* .

Nodes and Branches

A *Node* is "A point in a circuit where two or more components are electrically connected."

A *Branch* is "A pathway in a circuit through which current may flow."

We talk about "node voltages" and branch "currents".



Engineering Units

Engineers and Pure Scientists often use a modified scientific notation called "engineering units".

Prefix	Symbol	Multiplier
Peta	P	$\times 10^{15}$
Tera	T	$\times 10^{12}$
Giga	G	$\times 10^{9}$
Mega	M	$\times 10^{6}$
kilo	k	$\times 10^{3}$
		$\times 10^{0}$
Milli	m	$\times 10^{-3}$
Micro	μ	$\times 10^{-6}$
Nano	n	$\times 10^{-9}$
Pico	p	$\times 10^{-12}$
Femto	f	$\times 10^{-15}$

Writing in engineering units makes the magnitude of the unit easier to understand.

107 μV is preferable to 1.07×10^{-4} V

20.6 nA is easier than 0.0000000206 A

10 MV is clearer than 10×10^{6} V

Significant Figures & Decimal Places

In calculations use the full available precision until the final solution is reached.

Non-zero digits are significant

Zeros between two non-zero digits are significant.

Leading zeros are not significant.

Trailing zeros in a number containing a decimal point are significant.

Trailing zeros in a number not containing a decimal point are ambiguous.

91 has 2 s.f. and 0 d.p.

123.45 has 5 s.f. and 2 d.p.

0.00052 has 2 s.f. and 5 d.p.

0.000122300 has 7 s.f and 9 d.p.

12.2300 has 6 s.f. and 4 d.p.

91000 has 2 - 5 s.f. and 0 d.p.

In engineering we prefer to use significant figures not decimal places.

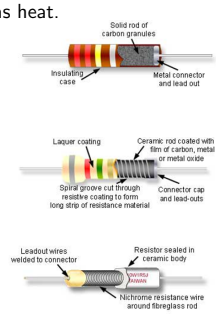
Time Domain Relationship Between Current and Voltage

Depends on the component.

Resistors	I is linearly proportional to V. $I = \frac{V}{R}$ (Ohm's Law)
Capacitors	I is the derivative of V. $I = C\frac{\mathrm{d}V}{\mathrm{d}t}$ V is the integral of I. $V = \frac{1}{C}\int I\,\mathrm{d}t.$
Inductors	I is the integral of V. $I = \frac{1}{L}\int V\,\mathrm{d}t.$ V is the derivative of I. $V = L\frac{\mathrm{d}I}{\mathrm{d}t}$

Resistor Construction & Technology

Resistors are two terminal circuit elements which dissipate energy as heat.



Carbon Composition Finely powdered carbon is mixed with a filler. The more carbon this mix contains the lower the resistance.

Carbon/Metal Film A layer of carbon or metal film is coated on a ceramic rod. The resistance is trimmed by cutting a helix.

Wire Wound A thin nichrome wire is wound onto a ceramic rod.

Carbon Composition

- Generally poor tolerance specification (± 20 %).
- More expensive than in prior times as production volumes are lower, other technologies becoming more dominant.
- Excellent for high energy pulse applications (protection circuits etc.) as the whole volume conducts current approximately evenly and the resistor has a high "thermal mass" for its volume.
- High "excess noise"[2] compared to other types of resistor $V_n >> \sqrt{4\,k\,T\,R\,B}$
- High temperature coefficient $\sim 1,000$ ppm per °C.
- £0.07 per unit when buying 100 units.

[2] Excess resistor noise is often a function of the voltage drop across the resistor. k is Boltzmann's constant, T is the absolute temperature, R is the resistance and B is the measurement bandwidth.

Carbon Film

- Tolerance specification (± 5 % – ± 1 %).
- Relatively inexpensive due to high production volumes (1 kΩ 0.25 W, £0.0078 per unit at 1,000 units).
- Moderately low "excess noise" compared to other types of resistor $V_n \approx (4\,k\,T\,R\,B)^{0.5}$
- Pulse power dissipation is low because the conducting media is a helix not the whole volume of the part.
- Continuous power dissipation up to a few watts.



Metal Film

- Excellent tolerance specification (± 0.05 %) possible.
- Still generally slightly more expensive than carbon film (1 kΩ 0.25 W, £0.0189 per unit at 1,000 units)
- Generally composed of nichrome, tin oxide or tantalum nitride.
- Good excess noise characteristics $V_n = (4\,k\,T\,R\,B)^{0.5}$ (more or less).
- Typical applications: bridge circuits, RC oscillators and active filters.
- Temperature coefficients ranging between 10 and 100 ppm per °C.
- Similar power ratings as carbon film.

Wire Wound

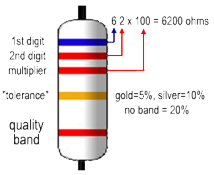
- Excellent tolerance specification (± 0.05 %).
- More expensive than all others.
- Generally composed of nichrome wire wound round a ceramic former.
- Negligible excess noise characteristics $V_n = (4\,k\,T\,R\,B)^{0.5}$.
- Typical applications: high power dissipation loads, current balancing resistors.
- Temperature coefficients ranging between less than 10 ppm per °C.
- Power ratings up to several kW.



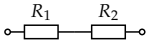
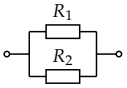
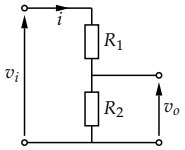
Resistor Colour Codes

Three, four and five band resistors are produced. For the three band resistor, bands 1 and 2 are the two most significant digits. Band 3 is the power of 10 *after* the second most significant digit. Band 4 is the tolerance (e.g. ±5%).

Bands 1, 2, (3 & 4)	Tolerance
Black = 0	Brown = 1 %
Brown = 1	Red = 2 %
Red = 2	Gold = 5 %
Orange = 3	Silver = 10 %
Yellow = 4	No Band = 20 %
Green = 5	
Blue = 6	
Violet = 7	
Grey = 8	
White = 9	



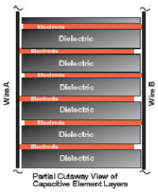
Some Simple Resistor Circuits

Series		$R = R_1 + R_2$
Parallel		$R = \frac{R_1 \cdot R_2}{R_1 + R_2}$
Potential Divider		$v_o = i \cdot R_2$ $i = \frac{v_i}{R_1 + R_2}$ $v_o = v_i \cdot \frac{R_2}{R_1 + R_2}$

Capacitor Construction & Technology

- Capacitors are two terminal electrical components which store energy in an electric field.
- They are composed of pairs of electrical conductors separated by a dielectric (insulator).
- In the simplest type; two metal plates are separated by an air gap forming a "parallel plate" capacitor.





Electrolytic Capacitors

- Made from a liquid soaked electrolyte sandwiched between Aluminium foil.
- Electrolytics are polarised (directional).
- Tolerance is poor (+20/-10%).
- High self discharge (leakage).
- Degrade quickly with temperature (85 °C and 105 °C).
- The capacitance of SMT electrolytics tends to fall with applied DC voltage.
- High capacitance in small volume (up to 200 mF).
- Make a mess when they explode.

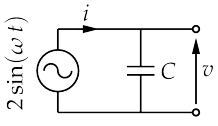


Tantalum, Polymer & Ceramic

Tantalum	Electrolytic, uses Tantalum metal which forms its own dielectric, tantalum oxide.	
Polymer	High quality polymer film with metal coated on either side. Good quality, tolerance and stability but limited values. Un-polarised.	
Ceramic	Alternating layers of metal and ceramic. Used in low-precision coupling and filtering applications. Suitable for high frequencies, but can have a high dissipation factor. Also capacitance depends on applied voltage.	

Mica, Glass & Super Capacitors

Mica	Type of ceramic. Expensive, but excellent RF properties. Higher capacitance than glass. High stability. Low Tempco ∼ +50 ppm/°C. Oscillators, Filters etc.	
Glass	Bigger units usually filled with oil. Common in very high voltage applications. Low capacitance. Excellent RF properties. Expensive.	
Super Caps	Usually based on porous amorphous carbon. Very high capacitance (up to several thousand Farads). Usually only 1 – 3 V operating voltage.	



$v = 2\sin(\omega t)$

$i = C\frac{dv}{dt}$

$i = 2\omega C\cos(\omega t)$

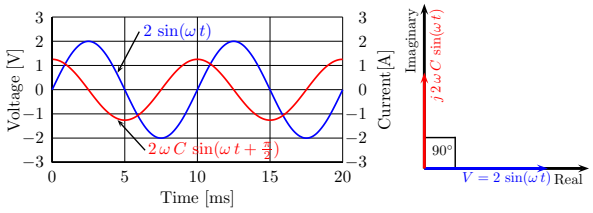
$i = 2\omega C\sin(\omega t + \pi/2)$

$v = 2\sin(\omega t)$

$x_c = 1/(j\omega C)$

$i = v/x_c$

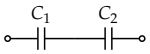
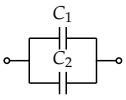
$i = j2\omega C\sin(\omega t)$



Red: Capacitor Current, Blue: Capacitor Voltage. i leads v by 90°.

Simple Capacitor Circuits

Voltage can be applied and current can flow, like resistors, but ideal capacitors do not dissipate power because the phase of the current leads the voltage by 90°. $P = I\,V\cos(\phi)$ Where ϕ is the phase angle between voltage and current. $cos(\phi)$ is the *power factor*.

Series		$C = \frac{C_1 \cdot C_2}{C_1 + C_2}$
Parallel		$C = C_1 + C_2$

Review

- Stated the Aims and Objectives of the course
  How electronic devices (diodes, transistors et al. work in circuits
- Introduced some Circuit Terminology (Voltage, Current, Node, Branch)
- Introduced Engineering Units
  units use powers of three. 100 nA, 1 uA, 10 uA, 100 uA, 1 mA, 10 mA etc.
- Discussed two Passive Components, their physical construction (Resistors and Capacitors), relative price and performance.
- Considered the relationship between current and voltage in R & C in the time domain.



EEE118: Electronic Devices and Circuits

Lecture II

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Last Lecture: Review

- Stated the Aims and Objectives of the course
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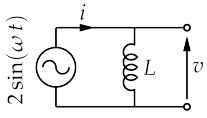
Outline

1. Passive Components
   - Inductors
2. Sources
   - Voltage and Current Sources
   - Internal Resistance of Perfect Sources
3. Source Transformation Theorems
   - Thévenin
   - Norton
4. Circuit Theorems
   - Superposition
   - Power Transfer
5. Review
6. Bear

Inductor Construction and Technology

- Inductors are two terminal electrical components which store energy in a magnetic field.
- Composed of one or more electrical conductors wound onto a ring of magnetic material.
- Or one or more insulated electrical conductors wound onto plastic/cardboard former and possibly slid onto an iron or ferrite core to form a magnetic circuit.
- Several inductors may be wound so the magnetic flux is coupled between them to form a transformer.





$$i = \frac{1}{L}\int v\,\mathrm{d}t.$$

$$i = \frac{1}{L}\left[\frac{-\cos(\omega\, t)}{\omega}\right]$$

$$i = \frac{\sin(\omega\, t - \pi/2)}{\omega\, L}$$

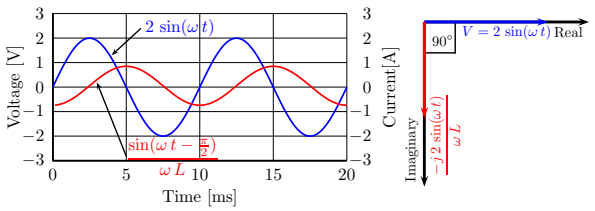
$$x_L = j\,\omega\, L$$

$$i = v/x_L$$

$$i = \frac{2\,\sin(\omega\, t)}{j\,\omega\, L}$$

$$1/j = -j$$

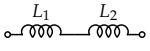
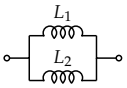
$$i = \frac{-j\,2\,\sin(\omega\, t)}{\omega\, L}$$



Red: Inductor Current, Blue: Inductor Voltage. i lags v by 90°.

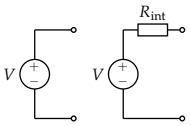
Simple Inductor Circuits

Voltage can be applied and current can flow, like resistors, but ideal inductors do not dissipate power because the phase of the current lags the voltage by 90°. $P = I\,V\cos(\phi)$ Where ϕ is the phase angle between voltage and current. $cos(\phi)$ is the *power factor*.

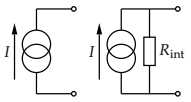
Series		$L = L_1 + L_2$
Parallel		$L = \frac{L_1 \cdot L_2}{L_1 + L_2}$

Voltage and Current Sources

An ideal voltage source is a two terminal circuit element supplying a fixed voltage and having zero internal resistance. A real voltage source can only supply a finite current and behaves as an ideal source with a resistance in series. It has non-zero internal resistance *in series* with the ideal voltage source.

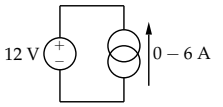


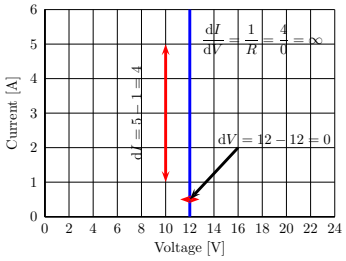
An ideal current source is a two terminal circuit element supplying a fixed current and having infinite internal resistance. A real current source can only supply the specified current over a range of terminal voltages. It has a finite internal resistance *in parallel* with the ideal current source.



Voltage Source Internal Resistance

What is the internal resistance of a perfect voltage source? Force a known current into a perfect voltage source and observe the change in voltage, then use Ohm's law to find the internal resistance.

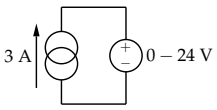


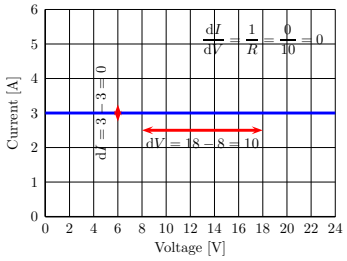


$\frac{1}{\infty} = 0\ \Omega$, so the internal resistance of a perfect voltage source is zero.

Current Source Internal Resistance

What is the internal resistance of a perfect current source? Force a known voltage across a perfect current source and observe the change in current, then use Ohm's law to find the internal resistance.



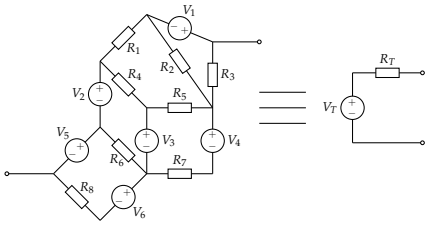


$\frac{?}{0} = \infty\ \Omega$, so the internal resistance of a perfect current source is infinite.

Thévenin

Theorem

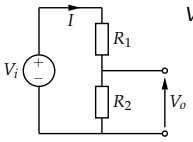
Any network of resistance elements and energy sources can be replace by a series combination of an ideal voltage source V_T and a resistance R_T where V_T is the open-circuit voltage of the circuit and R_T is the ratio of the open circuit voltage to the short circuit current.



Thévenin Method

- Find V_T by measurement or calculation of the voltage across the nodes of interest without anything connected (open-circuit)
- Find by measurement or calculation the current (I_{sc}) that flows when the nodes of interest are connected together (short-circuit).
- Divide V_T by I_{sc} to yield R_T.

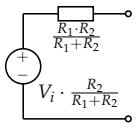
For example,



$$V_T = V_o = V_i \cdot \frac{R_2}{R_1 + R_2}$$

$$I_{sc} = \frac{V_i}{R_1}$$

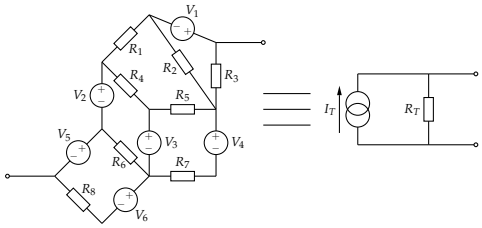
$$R_T = \frac{R_1 R_2}{R_1 + R_2}$$



Norton

Theorem

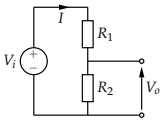
Any network of resistance elements and energy sources can be replace by a parallel combination of an ideal current source I_T and a resistance R_T where I_T is the shot-circuit current of the circuit and R_T is the ratio of the open circuit voltage to the short circuit current.



Norton Method

- Find I_N by measurement or calculation the current that flows from one node to the other when they are short-circuit (connected together)
- Find by measurement or calculation the voltage (V_{oc}) that appears across the nodes of interest when nothing is connected between them (open-circuit)
- Divide V_{oc} by I_N to yield R_N.

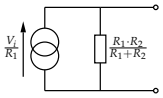
For example,



$$I_N = \frac{V_i}{R_1}$$

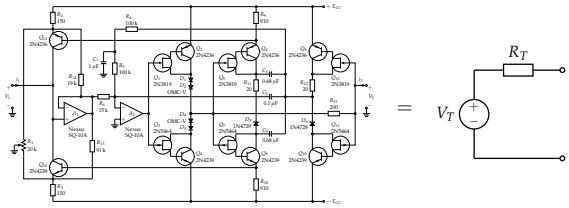
$$V_{oc} = V_i \cdot \frac{R_2}{R_1 + R_2}$$

$$R_N = \frac{R_1 R_2}{R_1 + R_2}$$



Source Transformations Summary

Active and passive circuits can be treated as a "black box" and thought of in terms of their Thévenin equivalent voltage and series resistance or Norton equivalent current and parallel resistance.



Superposition

Theorem

If a circuit consists of linear components (or components that can be considered linear over a small range of voltage and current), the combined effect of several energy sources on the circuit is equal to the sum of the effects of each source acting alone.

The theorem implies that the sources should be considered independently, but does not say what to do with the ones we are not considering!

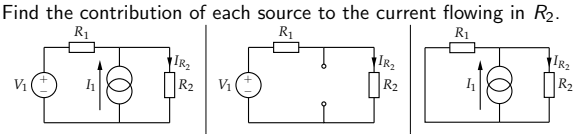
Consider the internal resistance of perfect voltage and current sources (look back at the earlier slides).

Current sources are replaced by an infinite resistance open circuit.

Voltage sources are replaced by zero resistance short circuit.

Superposition Example

Find the contribution of each source to the current flowing in R_2.



Both Sources	Voltage Source	Current Source
??	$I_{R_2} = V_1 \cdot \frac{1}{R_1+R_2}$	$I_{R_2} = I_1 \cdot \frac{R_1}{R_1+R_2}$

Also by inspection the two expressions for I_2 have current flowing in the same direction so they are summed to yield,

$$I_{R_2} = V_1 \cdot \frac{1}{R_1 + R_2} + I_1 \cdot \frac{R_1}{R_1 + R_2}$$

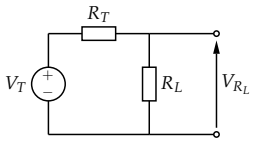
See Smith, R. J., and Dorf, R. C., *Circuits Devices and Systems* 5th ed., Wiley, 1992, pp. 56, dd. 621.3

Power Transfer

Consider an imperfect voltage source, where the internal resistance is not zero. Is there an optimum resistance to transfer the maximum power from the source into the circuit?

Two methods,

1. Trial and error with example numbers
2. Mathematical derivation

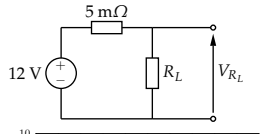


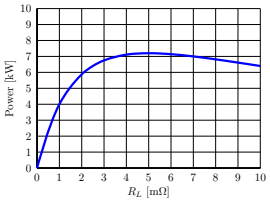
$$P = I\,V \text{ and } P = \frac{V^2}{R} \text{ and } P = I^2\,R$$

Trial and Error

Let R_L be,

1. 2.5 mΩ
   $V_{R_L} = 12 \cdot \frac{2.5}{2.5+5}\ \text{m}\Omega = 4\ \text{V}.$
   $P = \frac{V^2}{R} = \frac{4^2}{2.5\times10^{-3}} = 6.4\ \text{kW}$
2. 5 mΩ
   $V_{R_L} = 12 \cdot \frac{5}{5+5}\ \text{m}\Omega = 6\ \text{V}.$
   $P = \frac{V^2}{R} = \frac{6^2}{5\times10^{-3}} = 7.2\ \text{kW}$
3. 7.5 mΩ
   $V_{R_L} = 12 \cdot \frac{7.5}{7.5+5}\ \text{m}\Omega = 7.2\ \text{V}.$
   $P = \frac{V^2}{R} = \frac{7.2^2}{7.5\times10^{-3}} = 6.9\ \text{kW}$





The maximum power transfer seems to occur when $R_L = R_T$.
A more rigorous approach is desirable however.

Derivation of Maximum Power Transfer Condition

$$P_{R_L} = \frac{V_{R_L}^2}{R_L} \quad V_{R_L} = \frac{V_T\, R_L}{R_L + R_T}$$

Substituting,

$$P_{R_L} = \frac{V_T^2\, R_L}{(R_L + R_T)^2}$$

Differentiating with respect to R_L,

$$\frac{\mathrm{d}P_{R_L}}{\mathrm{d}R_L} = \frac{V_T^2}{(R_L + R_T)^2} - \frac{2\, V_T^2\, R_L}{(R_L + R_T)^3}$$

Set equal to zero (to find the turning point) and solve for R_L,

$$R_L = R_T$$

Review

- Finished discussed of Passive Components with inductors their physical construction, relative price and performance.
- Considered perfect and imperfect voltage and current sources
- **Perfect current sources have infinite parallel resistance**
- **Perfect voltage sources have zero series resistance**.
- Introduced the Thévanin and Norton theorems of source transformation. And gave a simple example of each.
- Introduced the Superposition theorem and gave a simple example.
- Considered the conditions required for maximum power transfer from a Thévanin source ($R_L = R_T$). This result will be used again in EEE225 when studding electronic noise. Could you derive for Norton on your own?



EEE118: Electronic Devices and Circuits

Lecture III

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Last Lecture: Review

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Outline

1. Terminology
   - Active and Passive Components, Bias and Signals
2. Diodes
   - Forward Bias Characteristics
   - Reverse Bias Characteristics
3. Conduction State Definitions
4. General Method for Diode Conduction State Problems
   - Series Resistance + Diode Analysis
5. A Comprehensive Conduction State Example
6. Review
7. Bear

Signal

A voltage, current or other measurable quantity which carries useful information.

Bias

A constant voltage or current which is used to set up favourable quiescent conditions in a circuit containing active components.

Passive Component

One which requires no external energy (other than the signal) to operate.

Active Component

One which requires external energy (bias) to set the quiescent conditions so that the circuit containing the active component(s) will perform some useful function.

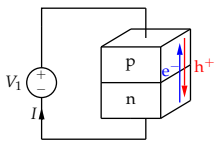
Diodes

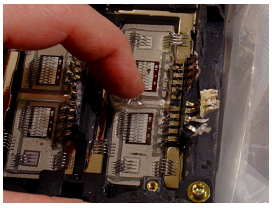
- A diode is a two terminal electronic device that allows current flow in one direction only.
- Diodes are non-linear circuit elements. The current through a diode is not *linearly* proportional to the voltage across it.
- Diodes are active components.
- Diodes can be produced using several technologies, including thermionic valves, semiconductor-metal junctions and semiconductor-semiconductor junctions.





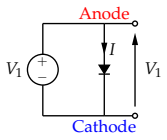
By far the most common is the silicon p-n junction diode. It is formed by two pieces of semiconductor, one doped n-type and another p-type in close metallurgical contact. The n-type material is doped with impurities to add additional electrons and the p-type doped to add additional holes. An alloy of metals are deposited on the surfaces of the n and p-type semiconductors. Fine gold or aluminium wires are bonded to the contacts and to the package body. The package is hermetically sealed.

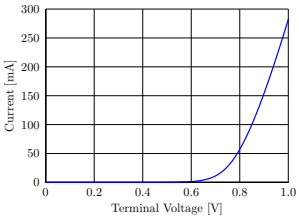




Forward Bias Characteristics

Under forward bias the diode obeys the Shockley - or diode equation - $I = I_0\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$, where I is the total current, I_0 is the saturation current, q is the electron charge, V is the terminal voltage, k is Boltzmann's constant and T is the absolute temperature. Diodes can be tested for polarity using a "multimeter" and can be fully investigated using a curve tracer which produces a plot of the diode's characteristic.



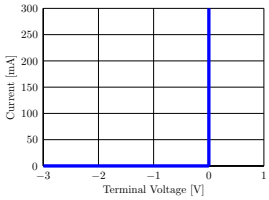


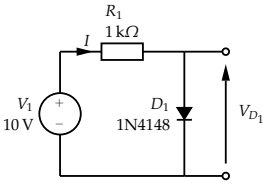
- When a positive voltage, V_1, is applied to the p region (anode) with respect to the n region (cathode), the device is forward biased and a current, I, flows through the device.
- A certain value of applied bias voltage is necessary before an observable current flows, but once this value is reached, very small increases in applied voltage lead to exponential increases in current.
- For a silicon diode the current begins to increase when the applied voltage is $\approx$0.7 V.
- The voltage at which the current begins to rise is the turn on voltage. It is also called the forward voltage drop. It's an approximation, but a good one for most purposes.
- Turn on voltage is a function of band-gap. In other materials (specialist diodes, LEDs etc.) it could be higher or lower e.g. for a GaN "blue" LED it is $\sim$ 3 V.

The diode equation is difficult to use in circuit analysis. A piecewise linear model is preferable. The simplest practical model of a diode only addresses the direction of current flow.

First Linear Model

Assume that the diode conducts perfectly in the forward direction without any voltage drop. If the diode is forward biased the current flowing is limited only by the circuit elements surrounding it.



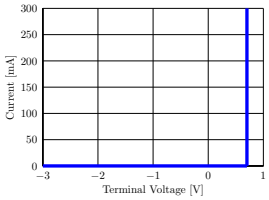


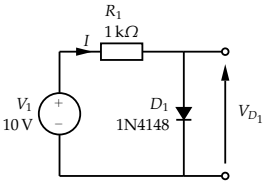
In this diode resistor circuit the resistor limits the current to 10 mA. In this model, the diode is incapable of dissipating power!

The simple model can be improved easily by the addition of a 0.7 V source to model the turn on voltage of the diode.

Improved Linear Model

Assume that the diode conducts perfectly in the forward direction with a constant 0.7 V drop. If the diode is forward biased the current flowing is limited only by the circuit elements surrounding it.

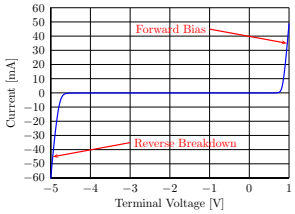




In this simple series diode resistor circuit the diode will limit the current to 9.3 mA. This improved model is often used.

Reverse Bias Characteristics

When the cathode voltage is greater than the anode the diode is reverse biased. The diode can be approximated by an open circuit. The current flowing is I_s - the saturation current. If the reverse bias voltage is sufficiently large *impact ionisation* occurs and the diode conducts a reverse current. This effect is used to produce Zenner diodes. The maximum reverse voltage that can be sustained by a diode is the repetitive reverse maximum or peak inverse voltage.



Conduction State Definitions

A diode in conduction

A diode is conducting if the magnitude of the current flowing in the diode is greater than zero. A diode ceases to be in a conducting state when the current falls to zero.

A diode on the point of conduction

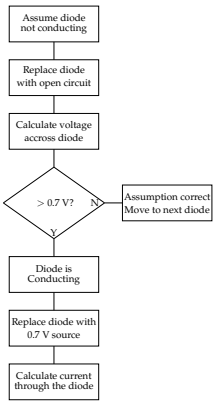
A diode is on the point of conduction if the anode voltage is 0.7 V greater than the cathode. No current flows on the point of conduction.

The beginning of conduction

Conduction begins when the anode voltage is *more* than 0.7 V greater than the cathode.

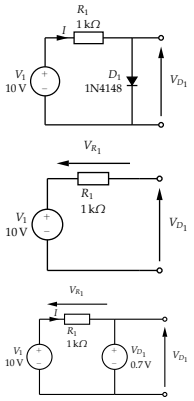
A general method for deciding if a diode is conducting in any circuit is desirable.

General Method for Conduction State Problems



This flow diagram assumes the diode is not conducting. It is equally acceptable to assume that the diode is conducting and construct a slightly different flow diagram. In circuits containing more than one diode, the order in which they are analysed may be important. It is necessary to check that each prior diode every time one is found to change state.

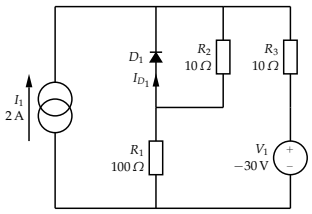
Simple Conduction State Example



1. Assume the diode is not conducting.
2. Replace it with an open circuit. No current flows in R_1 and so no voltage is dropped across R_1. Therefore all of V_1 appears across the diode (V_{D_1}). The diode will enter conduction $V_{a-c} = 10$ V, (> 0.7).
3. Replace the open circuit with a 0.7 V perfect voltage source. $V_{R_1} = 10 - 0.7 = 9.3$ V. By Ohm's law $I = 9.3$ mA.

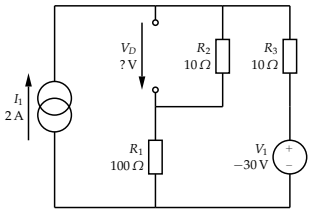
Example Question, Part A.

In the circuit below determine if the diode, D_1, is conducting. If D_1 is conducting find the current, I_{D_1} flowing through it. If D_1 is not conducting find the magnitude of the reverse bias voltage across it.



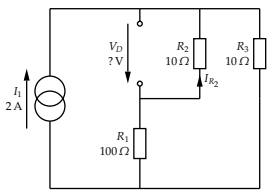
The node voltage and loop current methods and superposition theorem can be used. In this example Ohm's law and superposition will be used.

Follow the flow diagram in an earlier slide. Assume the diode is not conducting and is therefore replaced with an open circuit.



Use the superposition theorem to find the voltage across this open circuit. If the voltage is greater than 0.7 V then the non-conducting assumption is invalid. If the voltage is less than 0.7 V the non-conducting assumption is valid and we can state the reverse bias voltage. If the voltage is exactly 0.7 V the diode will be on the point of conduction and *no current will flow*.

Since superposition is being used, each of the sources must be considered individually and then their effects are combined. Choose to consider the current source, I_1, and switch off the voltage source, V_1. Replace it with a short circuit.



$$I_{R_2} = -I \cdot \frac{R_3}{R_1 + R_2 + R_3} \quad (1)$$

$$I_{R_2} = -2 \cdot \frac{10}{100 + 10 + 10} \quad (2)$$

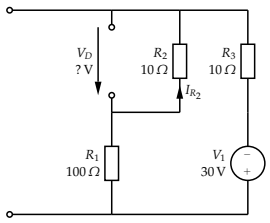
$$I_{R_2} = -0.166\dot{6} \text{ A} \quad (3)$$

$$V_{R_2} = I_{R_2} \cdot R_2 \quad (4)$$

$$V_{R_2} = -1.66\dot{6} \text{ V} \quad (5)$$

Note that R_2 is in parallel with the open circuit. Note also that this is a current divider circuit and is analogous to a potential divider.

The voltage source, V_1, which was previously replaced with a short circuit (its internal impedance) is now considered alone. The current source is replaced by an open circuit (its internal impedance).



$$I_{R_2} = \frac{V_1}{R_1 + R_2 + R_3} \quad (6)$$

$$I_{R_2} = \frac{30}{100 + 10 + 10} \quad (7)$$

$$= 0.25 \text{ A} \quad (8)$$

$$V_{R_2} = I_{R_2} \cdot R_2 \quad (9)$$

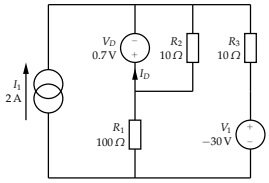
$$V_{R_2} = 0.25 \cdot 10 = 2.5 \text{ V} \quad (10)$$

This is a potential divider circuit containing three resistors. The voltage is shared according to the magnitude of the resistances.

Summing the voltage across the open circuit due to both the current and voltage sources (I_1 & V_1) we have

$$V_D = 2.5 + (-1.666\dot{6}) = 0.83\dot{3}\ \text{V}.$$

The assumption that the diode is not conducting is invalid!



The open circuit must be replaced with a 0.7 V perfect voltage source. Each of the three sources (I_1, V_1 and V_D) must be considered individually and superposition used to find the current, I_D, flowing in the forward biased diode.

Review

- Defined some terminology (Bias, Signals, Passive and Active components)
- Introduced Diodes as active components having a non linear relationship between voltage and current.
- Briefly considered how a diode is constructed from semiconducting materials
- Considered the effect of "forward" and "reverse" biasing a diode.
- Constructed two linear models of the diode action under forward bias.
- Defined three distinct states of conduction and non-conduction for a diode
- Provided a general method for solving conduction state problems in diode circuits.
- Started working through an example of a conduction state problem.



EEE118: Electronic Devices and Circuits

Lecture IIII

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

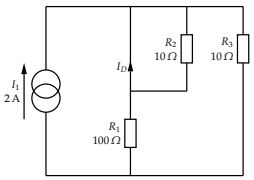
Last Lecture: Review

1. Defined some terminology (Bias, Signals, Passive and Active components)
2. Introduced Diodes as active components having a non linear relationship between voltage and current.
3. Briefly considered how a diode is constructed from semiconducting materials
4. Considered the effect of "forward" and "reverse" biasing a diode.
5. Constructed two linear models of the diode action under forward bias.
6. Defined three distinct states of conduction and non-conduction for a diode
7. Provided a general method for solving conduction state problems in diode circuits.
8. Started working through an example of a conduction state problem.

Outline

1. A Comprehensive Conduction State Example Part A – Continued
2. A Comprehensive Conduction State Example Part B
3. Homework 1
4. Other Types of Diodes
   - Light Emitting Diodes
   - Zener Diodes
   - Schottky Diodes
5. Review
6. Bear

Since superposition is being used, each of the sources must be considered individually and then their effects are combined. As before, choose to consider the current source, I_1, and switch off the voltage sources, V_1 and V_D. Replace both with short circuits.



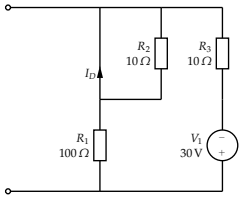
$$I_D = -I_1 \cdot \frac{R_3}{R_1 + R_3} \quad (1)$$

$$I_D = -2 \cdot \frac{10}{100 + 10} \quad (2)$$

$$I_D = -0.181\dot{8}\ \text{A} \quad (3)$$

This is a slightly easier current divider problem than before. In potential dividers, larger resistances = larger share of the voltage. Potential dividers are series circuits driven by voltage sources.
In current dividers, smaller resistors = larger share of the current. Current dividers are parallel circuits driven by current sources.

The voltage source, V_1, which was previously replaced with a short circuit (its internal impedance) is now considered alone. I_1 and V_D are replaced by there internal resistances (open and short circuit, respectively).



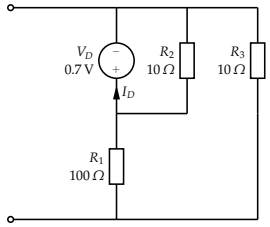
$$I_D = \frac{V_1}{R_1 + R_3} \quad (4)$$

$$I_D = \frac{30}{100 + 10} \quad (5)$$

$$I_D = 0.27\dot{2}\dot{7}\ \text{A} \quad (6)$$

This is a potential divider circuit containing two resistors. The voltage is shared according to the magnitude of the resistances. R_2 *is shorted, no current flows in it.*

The voltage source, V_D, which was previously replaced with a short circuit (its internal impedance) is now considered alone. I_1 and V_1 are replaced by there internal resistances (open and short circuit, respectively).



$$-I_D = \frac{V_D}{R_2} + \frac{V_D}{R_1 + R_3} \quad (7)$$

$$-I_D = \frac{0.7}{10} + \frac{0.7}{110} \quad (8)$$

$$-I_D = 70 + 6.36\dot{3}\dot{6}\ \text{mA} \quad (9)$$

If R_1 and R_3 are combined (summed because they are in series), this problem reduces to two cases of Ohm's law.

The contribution to current flow in the diode can be summed from the three circuit problems (one from each source I_1, V_1 & V_D) to yield the total current, I_D.

$$I_D = 0.27\dot{2}\dot{7} + (-0.18\dot{1}\dot{8}) + (-76.36\dot{3}\dot{6} \times 10^{-3}) \quad (10)$$

$$I_D = 14.54\dot{5}\dot{4}\ \text{mA} \quad (11)$$

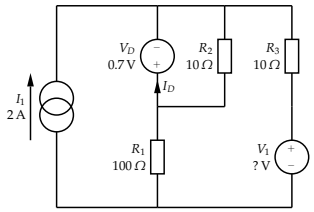
The negative signs are due to the direction of current as drawn on the diagrams. Remember that in power sources current flows in the same direction that the voltage faces but in other elements the direction of voltage and current oppose each other.

Part B.

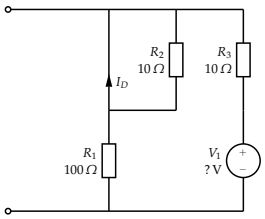
What magnitude would V_1 have to be changed to in order that the diode would be on the point of conduction (0.7 V across but no current flowing)?

Part B.

What magnitude would V_1 have to be changed to in order that the diode would be on the point of conduction (0.7 V across but no current flowing)?



The solution of this problem requires the use of the on the point of conduction definition is used. The diode will have 0.7 V across it in the forward bias direction *and* no current will flow.



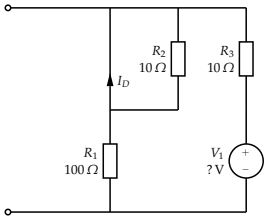
Superposition is used as before, but two of the results are already known.

I_D due to I_1 $\quad -0.18\dot{1}\dot{8}$ A

I_D due to V_D $\quad -76.36\dot{3}\dot{6}$ mA

I_D due to $V_1 = \left(0.18\dot{1}\dot{8} + 76.36\dot{3}\dot{6}\right)$ A

Having decided the current that V_1 must provide just enough current to yield $I_D = 0$ A we can work backwards to find the magnitude of the voltage required.



$$I_D = \frac{V_1}{R_1 + R_3} \quad (12)$$

$$V_1 = I_D\,(R_1 + R_3) \quad (13)$$

$$= \left(0.18\dot{1}\dot{8} + 0.076\dot{3}\dot{6}\right) \cdot (100 + 10) \quad (14)$$

$$= -28.4\ \text{V} \quad (15)$$

To yield 0.7 V forward bias across the diode and 0 A through the diode requires V_1 to have the value -28.4 V. Before leaving the question **consider if the answer to part B is consistent with the answer to part A**. The minus sign is required because the current - as we have defined it - is flowing into the source (+)

Homework 1

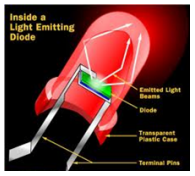
It is possible to fully attempt Homework 1 now.

It is also possible to begin attemptting the Diode Conduction State problem sheet now.

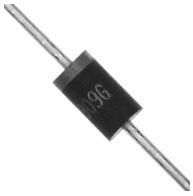
Other Types of Diode

The silicon pn junction diode is the most commonly used diode. Several other types exist however, including:

1. Light Emitting Diodes (LEDs)
2. Zener Diodes
3. Schottky Diodes







Light Emitting Diodes

LEDs are found in many applications including indicators (on electronic equipment) and also in power applications such as room lighting. LEDs emit light when they are forward biased by a process known as electroluminescence. The electrons which are promoted into the conduction band in the n-type material recombine in the p-type material loosing their energy as photons. An LED is just a junction diode, but not made from silicon.





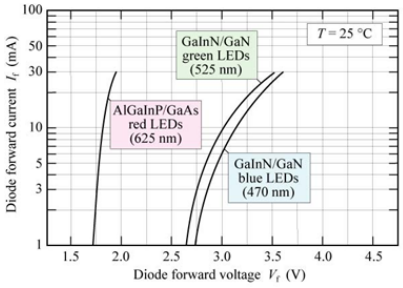
Because silicon is an indirect band-gap material electrons loosing energy must also undergo a change in momentum, this requires a phonon interaction. Both energy loss and momentum shift must happen simultaneously - it is very rare. Other quantum mechanical interactions are *much* more likely. In Si electrons tend to loose their energy without producing photons.

Direct band-gap materials including gallium arsenide (GaAs) gallium phosphide (GaP) and gallium nitride (GaN) among others[1] are used to produce light emitting diodes. In these materials no shift in momentum is required for the electrons to loose energy as they recombine and photons are a likely result of the recombination process. **LEDs obey the diode equation** but with differing constants from silicon.

[1] `http://www.oksolar.com/led/led_color_chart.htm`

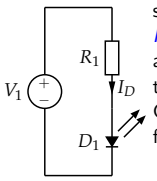
LED Current Voltage Characteristics

Current - voltage (IV) characteristics for several material systems are shown below[2]. It is common to limit the current (and hence power) dissipated in an LED by adding a resistance in series.



[2] see `http://www.lightemittingdiodes.org`

LED Example



Obtain the forward current (I_D) required to deliver the specified luminous output, and the forward voltage drop (V_D) from the device datasheet. The diode *is* conducting, replace it with a perfect voltage source, V_D. Compute the voltage remaining across R_1. Choose R_1 based on the desired current (I_D) by applying Ohm's law. Assume 600 mA is required and the forward voltage drop is 13 V (Sharp P/N: GW5BQF50K03, £10.50 + VAT) the module will run from a 24 V supply (V_1) which is already available.

$$V_R = V_S - V_D = 24 - 13 = 11 \text{ V} \quad (16)$$

$$R_1 = \frac{V_R}{I_R} = \frac{11}{0.6} = 18.3\dot{3} \ \Omega \quad (17)$$

$$P_{R_1} = I^2 R = 0.6^2 \cdot 18.3\dot{3} = 6.6 \text{ W} \quad (18)$$

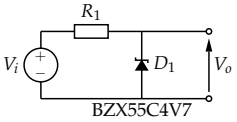
Zener Diodes

Zener diodes are designed to be operated in reverse breakdown (but can also operate in forward bias). They are designed with a particular breakdown voltage and are sold accordingly. Having broken down the reverse voltage increases very little as reverse current increases. The usual diode model applies but where V_D is replaced with the breakdown voltage. The Zener diode is often used as a voltage reference and in circuits where stabilisation of a DC supply is required.



Breakdown voltage from 3 V to 300 V at power ratings of ∼mW to 100 W are available. Breakdown voltage tolerance of 5% is common.

The Zener (Clarence Zener, 1905 – 1993) effect is another name for quantum mechanical (QM) tunnelling, however most Zener diodes do not operate by QM tunnelling but rather by impact ionisation (II). The Zener effect is dominant in devices where the breakdown voltage is below 5 V and impact ionisation is dominant in devices which breakdown at higher voltages. The temperature coefficient of breakdown voltage is negative for the QM tunnelling and positive for II (in Si). In devices with a breakdown voltage of 4.7 - 6 V the two temperature coefficients nearly cancel. Engineering a circuit design to make use of this particular breakdown voltage range is wise in situations where the circuit performance as a function of temperature is critical.



Schottky Diodes

- Metal - semiconductor junction devices.
- Construction is different to pn devices but circuit characteristics are similar.
- The metal semiconductor junction usually has a lower turn on voltage than pn diodes, values from 0.2 V to 0.6 V are common.
- Schottky[3] diodes use only one type of semiconductor (usually n-type). This allows them to switch faster and sustain greater current densities.
- Radio frequency circuits, up to 100 GHz, where high speed is critical.
- High efficiency applications (e.g. switch mode power supplies)
- Fast voltage clamp circuits, for prevention of transistor saturation.

[3] Walter H. Schottky, 1886 – 1976

Review

1. Finished the diode conduction state example question from lecture four.
2. Introduced the Light Emitting Diode (LED) and direct *vs.* indirect band-gap.
3. Performed a calculation to set the operating point of the LED.
4. Introduced the Zener Diode and considered the Zener effect and Impact Ionisation.
5. Very briefly considered a voltage regulating circuit using a Zener diode. (more later)
6. Introduced the Schottky Diode.



EEE118: Electronic Devices and Circuits

Lecture V

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Last Lecture: Review

1. Finished the diode conduction state example question from lecture four.
2. Introduced the Light Emitting Diode (LED) and direct *vs.* indirect band-gap.
3. Performed a calculation to set the operating point of the LED.
4. Introduced the Zener Diode and considered the Zener effect and Impact Ionisation.
5. Very briefly considered a voltage regulating circuit using a Zener diode. (more later)
6. Introduced the Schottky Diode.

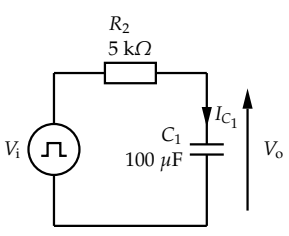
Outline

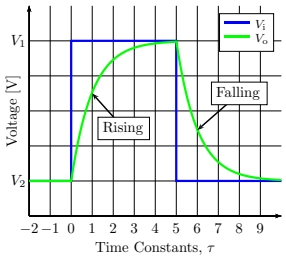
1. Pulse Circuits with Resistors & Capacitors
   - Pulse Circuit: "Low Pass" RC Example
2. Pulse Circuits with Diodes, Resistors & Capacitors
   - Pulse Circuits with Diodes Example Question
   - Pulse Circuits with Diodes Example Solution
3. Five Diode Circuits
   - Peak Detector
4. Review
5. Bear

Pulse Circuits with Resistors & Capacitors

- These sort of circuits are found in measurement systems for timing and can be used to help retrieve information from noisy systems (phase sensitive detection) and in digital systems (clock distribution etc.) and in high frequency applications such as radar systems.
- In this course we're interested in understanding what goes on in the circuit and doing some calculations rather than derivations. Derivation is on the handout.
- All first order RC circuits have a transient or time domain response that involves $e^{\left(\frac{-t}{\tau}\right)}$ where τ is dependent on the circuit not on the properties of the pulse and t is time.
- τ (greek: *tau*) is the time constant which has units of seconds. $\frac{volts}{amps}\frac{coluombs}{volts} = \frac{coulombs}{\frac{coulombs}{seconds}} = seconds$

Pulse Circuit: "Low Pass" RC Example





Rising: $V_o(t) = (V_1 - V_2)\left(1 - \exp\left(-\frac{t}{\tau}\right)\right) + V_2$, t = 0 at the start of the pulse

Falling: $V_o(t) = (V_2 - V_1)\left(\exp\left(-\frac{t}{\tau}\right)\right) + V_2$, t = 0 at the end of the pulse

$V_2 - V_1$ is the aiming voltage, the exponential gives the shape and V_2 is the offset

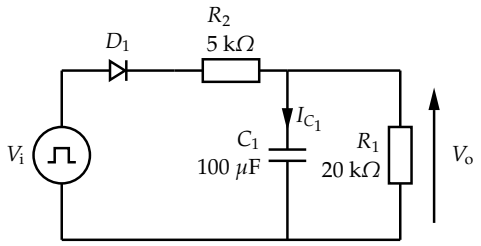
Pulse Circuits

- Often circuits which operate using pulses have several capacitances in them as well as resistors and diodes.
- In some cases the capacitance is used intentionally. In other cases the capacitance is "stray" or "parasitic" i.e. it is not desirable.
- In many cases there are several capacitances and the problem is taxing, however it can often be reduced to just a single dominant capacitance.
- An excellent example of a pulse circuit problem without a diode is the 10:1 oscilloscope probe circuit, but that will have to wait for EEE225 and the second year Amplifiers Laboratory.
- Problem Sheet 3 is devoted to these sorts of circuits[1].

The example here appears somewhere in the first year...

[1] For more, see Millman and Taub, "Pulse and Digital Circuits", 1956 or "Pulse, Digital and Switching Waveforms", 1965

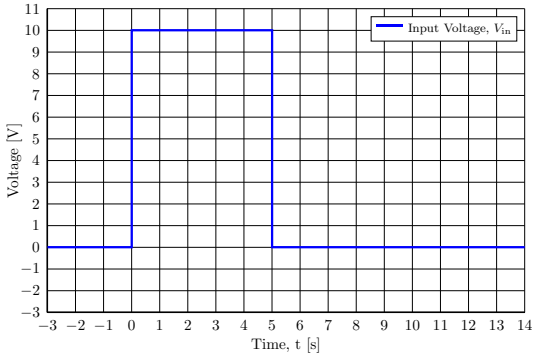
Pulse Circuit Example



Assumptions:

- When D_1 is conducting it has 0 V across it (*not* 0.7 V)
- D_1 has no series resistance.
- C_1 is initially discharged so V_o is initially 0 V, unless the question says otherwise.

The input, V_i, is a single 0 to 10 V pulse of 5 seconds duration. A graph may or may not be provided so it's a good idea to learn how to interpret a description of the waveform.



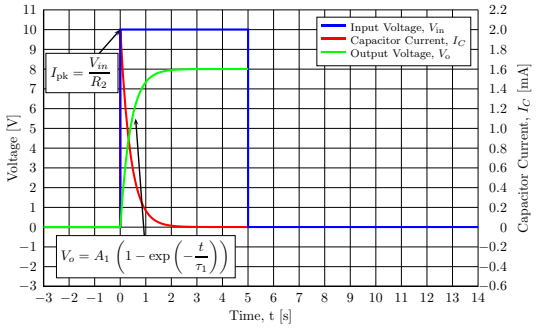
Description of Operation

$t \geq 0$ & $t \leq 5$ seconds

$V_{in} = 10$ V, the diode is forward biassed. C_1 is charged by V_{in} through R_2 causing V_o to rise exponentially towards a maximum or aiming voltage. I_{C_1} is initially a maximum value at $t = 0$, it then falls exponentially towards zero. Some of the current in R_2 flows in R_1 complicating the problem!

$t > 5$ seconds

The pulse has ended, $V_{in} = 0$. The capacitor is now the source of energy in the circuit. The diode is reverse biased. It stops conducting when the current in it falls to zero at t = 5 s. The capacitor can not discharge through R_2 because the diode is high impedance. C_1 discharges through R_1 only. Because R_1 is larger than $R_2//R_1$ we should expect C_1 to take longer to discharge than to charge.

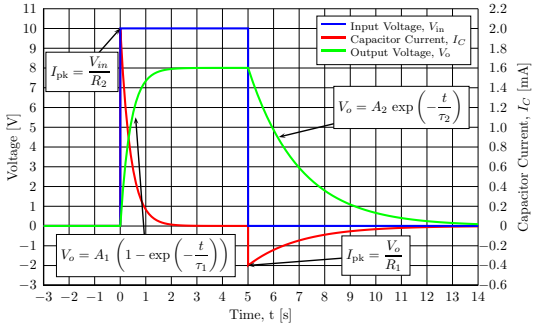


A_1 is 8 V in this case and I_{pk} is 2 mA. τ_1 the time constant is determined by the components involved $\tau_1 = (R_2//R_1)\ C_1$. The expressions for exponential rise to maximum and exponential decay are derived in the handout.

$t \geq 0$ & $t \leq 5$ seconds

- C_1 charges up from V_{in}, current flows from V_{in} through R_2 into C_1 and R_1
- V_o rises exponentially towards a maximum.
- I_C starts at a maximum and falls exponentially as the voltage across R_2 falls due to the voltage across C_1 getting larger.
- Since C_1 is initially (at $t = 0$) discharged, $V_o = 0$ V so the biggest value of I_{C_1} is at $t = 0$ and is given by Ohm's law $\frac{V_{in} - V_o}{R_2}$.
- The aiming voltage of V_o is the voltage that would exist across the capacitor if it had been charged up for a long time and the voltages and currents had reached a steady state. In this case the capacitor can not charge to a voltage greater than the potential division of V_{in} by R_2 and R_1.

  $A_1 = V_{in}\frac{R_1}{R_1 + R_2}$



I_C changes direction, hence negative values. τ_2 is larger than τ_1. The negative peak current is given by Ohm's law using the voltage across C_1 at $t = 5$ s and R_1. $I_{pk} = -\frac{7.999}{20\times10^3} = -399.95\ \mu$A.

$t > 5$ seconds

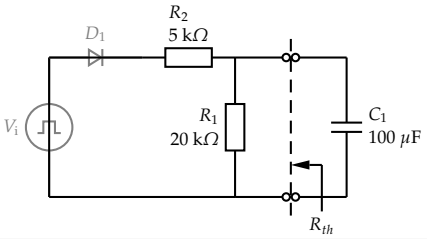
- At the end of the pulse $t = 5$ s, V_o has reached ≈ 8 V
  $V_o = 8\left(1 - \exp\left(-\frac{5}{4\times10^3\cdot100\times10^{-6}}\right)\right) = 7.999$ V)
- I_{C_1} has fallen to nearly zero
  $I_{C_1} = 2\times10^{-3}\exp\left(-\frac{5}{4\times10^3\cdot100\times10^{-6}}\right) = 7.453$ nA
- V_i falls to zero, I_{R_2} falls to zero, and the diode switches off.
- The circuit becomes C_1 and R_1 in parallel, all else can be ignored.
- C_1 is the source of energy and this energy is lost as heat in R_1 as C_1 discharges to zero.
- The time constant for this discharge is $\tau_2 = R_1\,C_1$.

Derivations for exponential expressions can be found in most undergraduate circuit's books e.g. Smith & Dorf, "Circuits Devices and Systems".

Puzzle

Why is $\tau_1 = (R_1//R_2)\,C_1$?

Use Thévenin's theorem. We are not interested in the Thévenin voltage (it's A_1). What resistance does the capacitor "see" looking back into the circuit. This is the resistance in the time constant and the Thévenin resistance. Replace all sources by their internal resistances. The diode has no internal resistance (it's ideal).



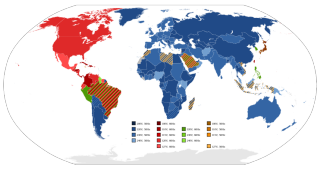
Five Diode Circuits

Five common circuits consisting of resistors capacitors and diodes will be examinable in this course, including:

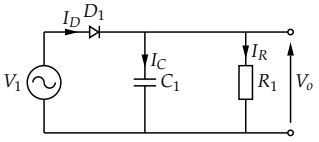
1. Peak detector
   - e.g. AM radio demodulator
2. Voltage clamp
   - e.g. Preventing switching transistor saturation, distorting guitars etc.
3. Voltage multiplier
   - AC to DC conversion with doubling, many specialist PSU applications.
4. Diode rectifier circuit (three types of power supply)
   - Half-wave (one diode)
   - Full-wave (two diode)
   - Bridge (four diode)
5. Zener diode voltage regulator
   - Stabilise DC voltages having a small AC component or ripple

Peak Detector

One of the commonest applications of diodes is the conversion of an alternating current into a unidirectional current. This conversion process occurs in the signal detector parts of radio based systems and in power supplies designed to convert power from an alternating current distribution system - such as the UK's 50 Hz land based power distribution system or the 400 Hz distribution systems found in marine and airborne applications - into a good quality direct current source for electronic circuitry. Signal based applications of rectifiers will be discussed first.



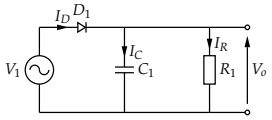
Peak Detector



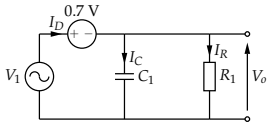
The key elements of source, V_1, diode, D_1, and capacitor, C_1, are connected in series and it is quite common to find a resistor, R_1, in parallel with the capacitor. The source may be a transformer secondary as is common in radio circuits or an amplifier output as is more typical of instrumentation systems. The circuit has two distinct states based on the conduction or non-conduction of the diode.

1. The diode is conducting (above), capacitor charges
2. The diode is not-conducting (shortly), capacitor discharges

Peak Detector - Diode Conducting

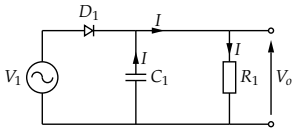


Since the diode is conducting, replace with 0.7 V source.

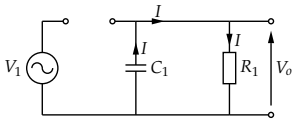


The diode current charges C_1, and dissipates power in R_1. The charging current is limited by the diode series resistance. The voltage on C_1 can not increase above $V_1 - 0.7$.

Peak Detector - Diode Not Conducting

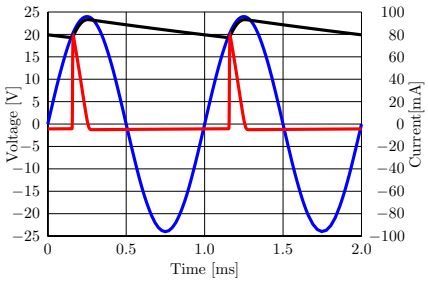


Since the diode is not conducting, replace with open circuit



C_1 discharges through R_1. Voltage across C_1 falls as discharge proceeds. The shape of V_o is often a good approximation to a triangular waveform.

Peak Detector Graph



V_1: Blue, V_o: Black, I_{C_1}: Red

The integral of the capacitor current (area under the graph) sums to zero in one whole cycle.

Review

1. Introduced circuits driven by pulses.
2. Noted that, in EEE118 we are concerned with how to treat the circuit operation rather than how to solve differential equations (we will use the solutions without derivation).
3. Developed the idea of a time constant.
4. Looked at a low pass filter driven by a square pulse.
5. Worked through an "exam strength" pulse circuits question.
6. Introduced five diode circuits driven by sinusoids or waveforms derived from sinusoids. These form the basis of discussion from now until after the holidays.
7. Begun a description of operation for the peak detector circuit by thinking about the diode's conduction state as a function of time. A technique we will return to in the future.



EEE118: Electronic Devices and Circuits

Lecture VI

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Last Lecture: Review

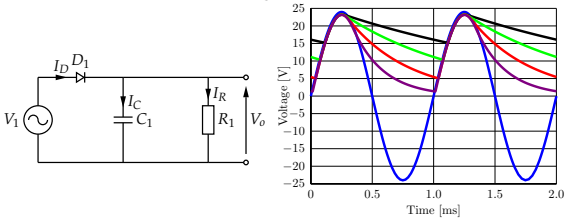
1. Introduced circuits driven by pulses.
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Outline

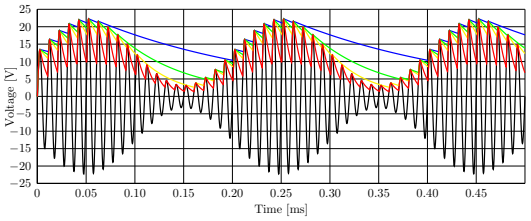
1. Peak Detector
   - Signal Detectors
2. Voltage Clamp
3. Voltage Doubler
4. Voltage Multiplier
5. Homework 2
6. Review
7. Bear

Peak Detector Continued

The time constant $R_1\,C_1$ determines how effective the peak detector is at maintaining the peak signal voltage. It is common to arrange $R_1\,C_1 >> t_p$ where t_p is the period of the waveform. When $t_p = R_1\,C_1$ (green line) the peak detector fails to maintain the peak voltage for the majority of the cycle. As $R_1\,C_1$ is decreased further the exponential nature of the voltage decay becomes apparent and the triangular ripple assumption is broken.



Peak detectors extract information from AM radio signals. RC is a compromise between a value large enough to give a small value of ripple at the carrier frequency and a value small enough to allow the capacitor voltage to follow the modulation envelope.



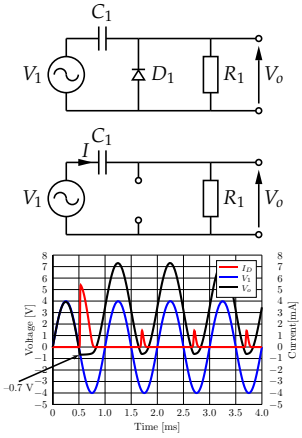
Notice that V_1 (Black), the modulated carrier, has an average value of zero whereas the peak detector output has a non-zero average and a periodicity that is related mainly to the modulation envelope rather than the carrier.

Voltage Clamp

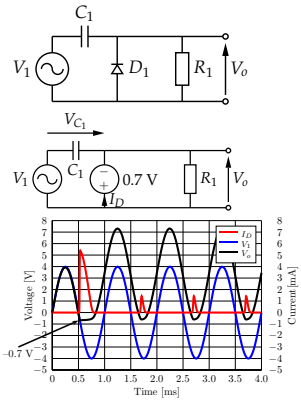
Clamp Description

A circuit that fixes or "clamps" either the positive or negative extreme of a waveform to a defined voltage level.

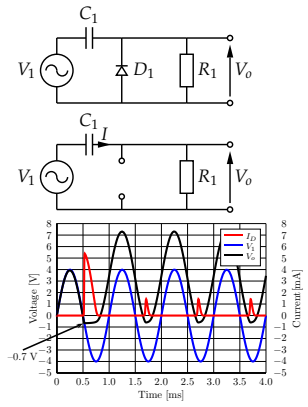
There are some signals that transmit DC level information as part of the signal. The output of a signal detector is simply a waveshape consisting of a DC component and a superimposed signal waveshape. A clamping circuit discards the DC component and defines the DC level of either the positive or the negative signal peaks. Because clamping circuits restores the correct DC levels contained in signals, they are sometimes called "DC restoration circuits" and this term is used frequently in the context of analogue television video signals.



- For the first $^1/_2$ cycle from 0 to 0.5 ms V_1 is positive. The rising V_1 will drive current through C_1 towards the output.
- The diode does not conduct, so current only flows through R_1
- Since R is large, the current flowing does not significantly charge C_1
- There is negligible change of charge in C_1 and so negligible change of voltage across it. So V_o follows V_1

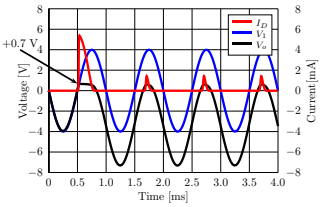


- In the second half cycle V_1 falls and V_o follows until it reaches -0.7 V
- The diode conducts from 0.5 ms - $\sim$ 0.75 ms and holds the voltage at -0.7 V. By the time V_1 has reached its negative peak at 0.75 ms a charge of $C_1 \cdot (V_{1_{pk}} - 0.7)$ has been stored
- The voltage across C_1 is now $V_{1_{pk}} - 0.7$.



- In the last quarter of the first cycle, V_1 begins to increase again. This rising voltage tries to drive a current through C_1.
- D_1 does not support current flow in this direction. A small discharge current flows from C_1 through R_1 (which is high valued).
- C_1 is not significantly discharged so V_{C_1} remains approximately constant.

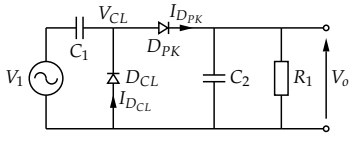
- V_1 could have any additional DC voltage superimposed without affecting the circuit behaviour. The only limit is the voltage rating of the capacitor, C_1
- In practice C_1 must be able to loose charge slowly so that the circuit can follow slowly changing signal amplitudes. R_1 must be finite. But must be sufficiently large to make the charge loss per cycle relatively small
- If the diode is turned around, the positive peaks of V_1 are clamped to $+0.7$ V and the output goes negative.



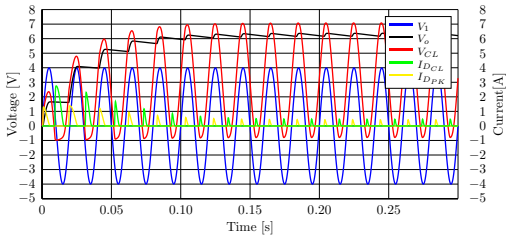
Voltage Doubler

A voltage doubler is a voltage clamp *followed by* a peak detector, also called a peak to peak detector.
The diode clamp takes a sinusoidal signal and clamps the negative peaks to -0.7 V. The peak detector detects the positive peaks to give an output voltage approximately twice what would be expected without the clamp.

C_1 and D_{CL} form the diode clamp and D_{PK} and C_2 form the peak detector. R_1 is the load.



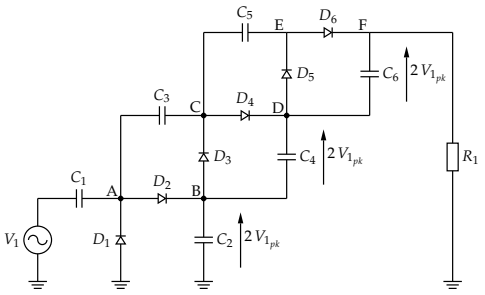
The peak to peak detector is used in signal applications and in low power, power supply applications. The circuit is one of a class of "diode pump" circuits.



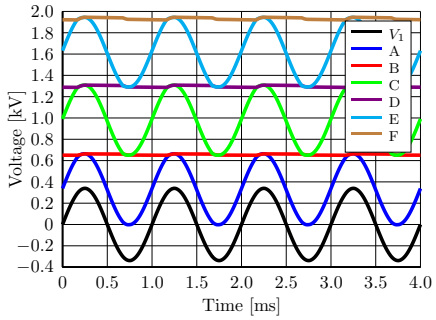
- When V_1 is low, charge flows through D_1 into C_1 as described in the diode clamp explanation.
- When V_1 goes high, that charge is tipped through D_1 into C_2, C_2 is essentially a charge reservoir which is slowly depleted by R_1.
- If C_2 is to be effective, the current in R_1 should yield a small fall in voltage across C_2.

- The output voltage is then determined by the equilibrium condition; charge pumped from C_1 to C_2 per second equals the charge lost through R_1 per second.
- Assuming that C_2 is an effective reservoir, C_1 affects the equilibrium output voltage and the time it takes the output to reach equilibrium.
- If C_1 is small compared to C_2 it will only be able to transfer a small fraction of the charge needed to fill C_2 on each cycle. Charge will build up in C_2 over several input cycles (hence V_o will build up over several cycles) and because the rate at which charge is entering C_2 is small, V_o is sensitive to small current drains such as that through R_1 because of the need to maintain an equilibrium between the charge flowing into and out of C_2 .
- A value of C_1 that is large compared to C_2 can pump a large charge per cycle into C_2 so V_o rises rapidly and is relatively insensitive to current drain through R_1.

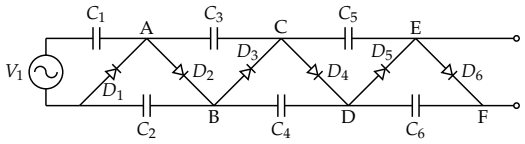
The peak to peak detector circuit can be extended to obtain higher output voltages. C_1, D_1, C_2 & D_2 form a peak to peak detector that generates a voltage across C_2 of $2\,V_{1_{pk}}$. C_3, D_3, C_4 and D_4 form another peak to peak detector. D_3 clamps the negative peak of the signal to a voltage of $2\,V_{1_{pk}}$.



The positive peak of the voltage at B is $2\,V_{1_{pk}}$ above its clamped negative peak (-0.7 V) giving a peak detected voltage across C_4 of $2\,V_{1_{pk}}$. Each peak to peak detector provides an additional $2\,V_{1_{pk}}$. A total of $6\,V_{1_{pk}}$ exists across R_1. $V_{1_{pk}}$ has been multiplied 6 times.



The circuit is normally presented slightly differently.



Applications,

- Cathode ray tube based displays 25 kV. A *flyback converter* (EEE223/EEE307) sometimes used instead
- In integrated form to multiply 5 V pulses up to around 100 V to drive the small plasma displays often found on automotive and 'high-end' CD players
- In experimental physics research to obtain extremely high voltages - of the order of MV - for electric discharge studies. Also electron microscopy

All these applications require low currents - typically a few tens of μA. The circuit is not suitable for high currents.

Homework 2

It should be possible to fully attempt Homework 2 now.

It should be possible to fully attempt the Diode, Resistor and Capacitor Circuits problem sheet as well.

Review

1. Finished looking at the peak detector circuit.
2. Considered the use of the peak detector in AM radio demodulation
3. Introduced and described the operation of the diode voltage clamp circuit. The clamp can be broken down into,
   - 0° - ∼ 180° - Diode not conducting, negligible charging of C through R.
   - 180° - ∼ 270° - Diode conducts C charges through D.
   - 270° - ∼ 360° - Diode not conducting, small discharge current flows from C through R.
   - All following cycles - Diode briefly conducts around ∼ 270° to recharge C
4. Connected a peak detector to a voltage clamp to form a peak to peak detector

Review Continued

- Considered the equilibrium condition that defines how ideally the peak to peak detector acts as a voltage doubler
- Developed a three stage voltage doubler and looked at the voltage on the clamp and peak detector at each stage.
- Observed that the voltage doubler is often drawn as a ladder in which capacitors are the "edges" and diodes are the "rungs"



EEE118: Electronic Devices and Circuits

Lecture VII

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

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- Considered the equilibrium condition that defines how ideally the peak to peak detector acts as a voltage doubler
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Outline

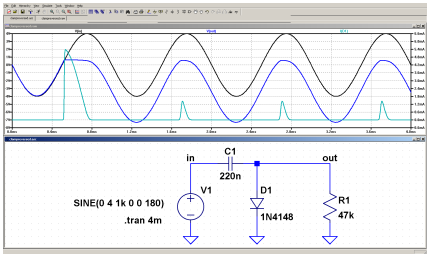
1. Simulation Programs
   - SPICE
   - QsapecNG
2. Rectifiers: Linear Power Supplies
3. Single and Three Phase Supply
4. Half Wave Rectifier
5. Capacitive Smoothing
   - Choosing a Capacitor
6. Review
7. Bear

Simulation Program with Integrated Circuit Emphasis

An open source **numerical** circuit simulation tool that was developed at the of University of California. Linear technology released LTSpice

`http://www.linear.com/designtools/software/#LTspice`

Example files from this course will be available on MOLE

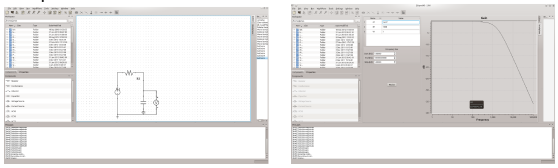


Qt-based Symbolic Analysis Program for Electric Circuits (New Generation)

An open source **analytical** (i.e. symbolic) linear circuit simulation tool that is being developed at the University of Florance

`http://qsapecng.sourceforge.net/`

Example files from this course will be available on MOLE



Linear Power Supplies

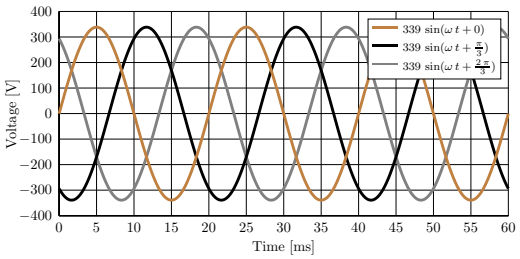
Rectification

Conversion of AC voltage into a unipolar voltage that is usually of the form of a DC component with a superimposed AC component.

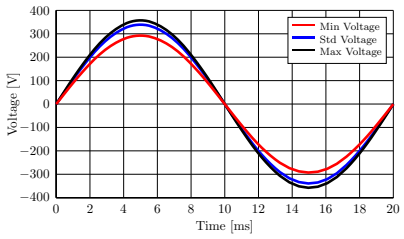
- The DC component is always the average value of the rectifier output voltage and the superimposed AC component, which is rarely sinusoidal, is called the ripple voltage.
- In this course the ripple voltage will always be the peak to peak value of the superimposed AC component.

Rectifier circuits are often divided into two categories half wave and full wave. In fact, full wave circuits can be looked at as two or more half wave circuits connected together.

Other descriptive terms applied to rectifier circuits are single phase and three phase. These terms relate to the nature of the AC power supply. Most medium/heavy industry (kilowatts and above) is supplied by a three phase AC power source while light industrial applications are more likely to be supplied by a single phase source. Domestic dwellings are supplied by a single phase source. Only single phase circuits are examinable.



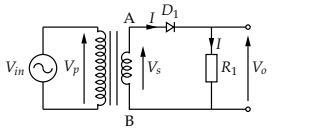
Single phase in the UK is 240 V RMS, 50 Hz. The standard gives 230 V ±10% at 50 Hz ±0.5 Hz (BS 7671)[1,2]. In practice 230 V is quoted so the UK conforms with western Europe, but since 240 V falls within the permissible limits the UK has not changed its generation voltage.

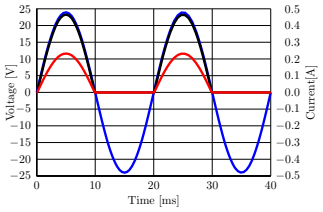


[1] Kitcher, C., *Practical guide to inspection, testing and certification of electrical installations : conforms to 17th edition IEE Wiring Regulations (BS 7671:2008) and Part P of Building Regulations*, Oxford: Newnes, 2009, 621.31924 (K)

[2] http://www.tlc-direct.co.uk/Book/1.1.htm

Half Wave Rectifier





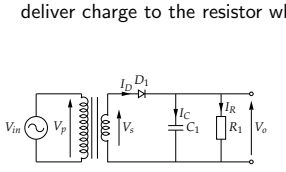
Red: I, Black: V_o, Blue: V_{in}

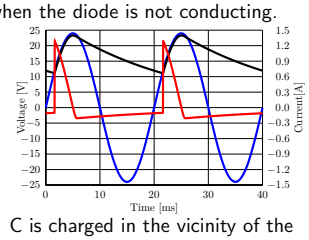
- The diode conducts when the voltage at A is more than 0.7 V positive with respect to B.
- Positive half-cycles of the secondary winding current pass through the diode. Negative half-cycles are blocked.
- If the orientation of the diode was reversed the negative half cycles would pass and the positive ones would be blocked.

- There is a limited range of power supply applications in which this wave shape is acceptable.
- Most electronic equipment requires a relatively smooth supply voltage that approximates continuous DC (e.g. a battery)
- V_o for the half-wave rectifier is unipolar (no negative part, only positive in this case).
- The average value (the DC component) is positive, but the ripple (AC component) is large.
- For the circuit to be useful as a DC power source for most electronic circuits, the output may be *smoothed* to reduce the amplitude of the AC component or "ripple voltage"
- There are various ways in which smoothing can be achieved. Each requires the storage of energy so that it can be redistributed more evenly across the cycle - essentially filling in the gaps.

Capacitive Smoothing

The simplest method is to use a capacitor in parallel with the load resistance to store charge when the diode is conducting, and deliver charge to the resistor when the diode is not conducting.



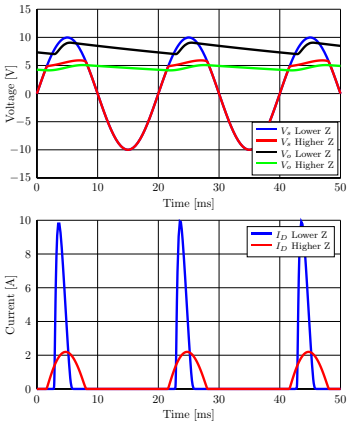


This is a peak detector circuit. C is charged in the vicinity of the peak of every positive half cycle and provides current for the load in between the positive peaks. Note the remaining ripple (somewhat exaggerated in the diagram) is a good approximation to a triangle - this will simplify calculations later.

The current waveform has large amplitude charging pulses of relatively short duration. The peak pulse amplitude can be many times greater than the load current. These may be troublesome for several reasons,

1. The rapid $\mathrm{d}I/\mathrm{d}t$ can cause radiative interference problems (EMI) - more in EEE6010.
2. The external supply is delivering most of the energy used at one point in the cycle. This can set up impulsive mechanical loads in the utility machinery.
3. These pulses develop proportionately high $I^2\,R$ losses, unnecessarily heating the circuit, and lowering efficiency.

Fortunately in most situations the series impedance associated with transformers and the utility supply mean that the impulsive currents are not as troublesome as they would be under ideal conditions.



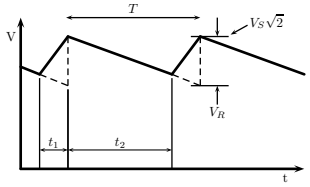
These graphs show voltage and current for the secondary V_s and the output V_o for a small transformer. The series impedance has been exaggerated somewhat in the graphs to make the effect clear. Note that the ideal secondary voltage is $V_s\sqrt{2}\sin(2\pi f_s t)$ neither of the shown V_s lines agree perfectly with the ideal, but the data representing the lower impedance situation comes quite close.

- The series impedance means that a large impulsive charging current is no longer possible.
- The resulting green output voltage waveform is somewhat lower in voltage than the nearly ideal black case. Because C_1 can not charge quickly enough the charging pulses are broader and smaller in amplitude - and area - to the ideal case.
- Note that the ripple voltage is still triangular in shape.
- Manufacturers do not give figures for the impedance of a transformer. If this information was available it would be of little value as the calculations involved are taxing. Regulation information is available, but it relates to the transformer only. Generally bigger VA leads to better regulation.
- The output voltage from a simple linear power supply with capacitor smoothing is poorly defined, will often be lower than ideal estimates and will be a function of the load resistance.

Choosing a Capacitor to Meet a Ripple Specification

Assumptions:

1. The ripple is triangular
2. The capacitor discharges throughout the charging cycle and charges instantaneously at the peak of each charging cycle
3. The transformer and power source are ideal (i.e. zero series impedance)
4. The load current is constant
5. Discharge occurs for the whole interval between charging peaks



Using the instantaneous charging model the voltage across C_1 reduces at a constant rate over the interval T as the load current I_R is drawn from C_1.

$$Q = C\,V\,, I = \frac{dQ}{dt} = C\,\frac{dV}{dt} = C\frac{V_R}{T}$$

Since this is a half-wave rectifier $T = \frac{1}{f_s}$ where f_s is the supply frequency (UK: 50 Hz, USA: 60 Hz JPN: both!). If the load is purely resistive (as shown several slides ago) then,

$$I_L = \frac{\sqrt{2}\,V_s}{R_L}$$

For example

A half wave rectifier power supply is loaded by a power amplifier which is driving an AC machine. The load can modelled by a 5 Ω resistance. Find the ripple voltage if the smoothing capacitor bank has a total capacitance of of 68,000 μF and the transformer secondary voltage (V_s) is 80 V RMS.

Solution

Find the peak load current,

$$I_L = \frac{\sqrt{2}\,V_s}{R_L} = \frac{\sqrt{2}\cdot 80}{5} = 22.6274\ \mathrm{A} \qquad (1)$$

Find the time over which the smoothing capacitor is discharged (the period of the waveform)

$$T = \frac{1}{f_s} = \frac{1}{50} = 20\ \mathrm{ms} \qquad (2)$$

Transpose the capacitor equation $I = C\,(\mathrm{d}V/\mathrm{d}t)$ to obtain the solution.

$$I_L = C\,\frac{V_R}{T}\,, V_R = \frac{I_L\,T}{C} = \frac{22.6274\cdot 0.02}{68\times 10^{-3}} = 6.66\ \mathrm{V} \qquad (3)$$

In many cases this is an overestimate. But an overestimate is more desirable than an underestimate!

Review

1. Noted the existence of two useful - in terms of designing circuits and understanding them - programs for numerical and analytical simulation of electronic circuits.
   - LTSpice - Numerical simulation of linear and non-linear circuits
   - QsapecNG - Analytical (i.e. algebraic) simulation of linear circuits
2. Introduced the idea of linear power supplies
3. Briefly discussed some differences between single phase and three phase supplies
4. Considered the half wave rectifier in detail
5. Used a peak detector circuit to smooth the output voltage of the peak detector
6. Developed a simple model to find a suitable capacitor value for a power supply filter



EEE118: Electronic Devices and Circuits

Lecture VIII

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

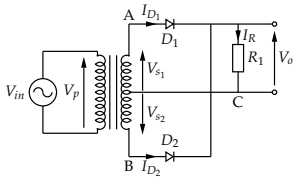
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Outline

1. Full Wave Rectifier
2. Full Wave Bridge Rectifier
3. Smoothing a Full Wave Rectifier
4. Three Phase Full Wave Rectifiers
5. Linear Power Supplies: Summary
6. Stabilisation and Regulation of DC Power Supplies
7. Zener Diode Linear Shunt Regulator
8. Review
9. Bear

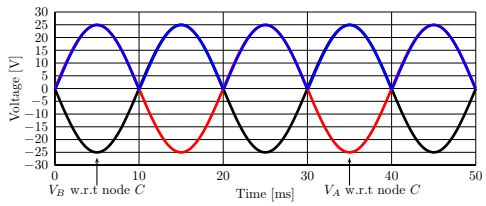
Full Wave Rectifier

The full wave rectifier is essentially the combination of two half wave circuits.



In this circuit V_{s_1} and V_{s_2} are 180° out of phase i.e. when node A is at $\sqrt{2}\,V_s$, node B is at $-\sqrt{2}\,V_s$. V_{s_1} and D_1 form one half wave rectifier and V_{s_2} and D_2 form another. The outputs of these two half wave rectifiers are combined before being applied to the load.

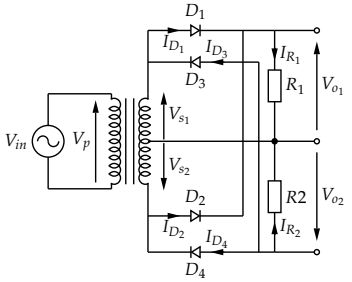
Because of the 180° phase shift between V_{s_1} and V_{s_2}, V_{s_2} and D_2 are active when V_{s_1} and D_1 are not active. Therefore there is a current flowing in R_1 for every half cycle



Blue: V_o, Black: V_{s_1} Red: V_{s_2}

If the diodes in the full wave circuit were reversed, V_o would be negative, (i.e. upside down). Is it possible to add reversed versions of D_1 and D_2 to nodes A and B in the full wave circuit? Could this then provide a simultaneous positive and negative output with respect to node C?

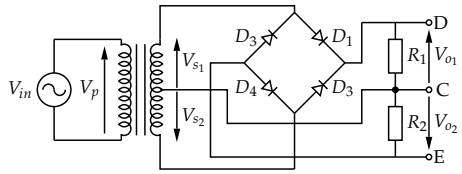
This circuit consists of four half wave rectifiers connected to rectify the full wave.



V_{s_1} and V_{s_2} face opposite directions because the transformer centre tap is the reference. Re-arranging this circuit the standard version of this circuit is obtained, where the diodes are drawn to form a *bridge*. This circuit is known as a full wave bridge rectifier.

Full Wave Bridge

In these figures the diodes D_1 and D_2, R_1 and V_{o_1} are exactly the same as the simple full wave (two diode) case. The outputs from the bridge rectifier can be used in various ways. If node C is the reference point, node D is a positive output voltage and node E is a negative output.



Or if node E is the reference point, both nodes C and D are positive with D having twice the magnitude of node C.

Applications

Yet another possibility is that node D is the reference and both C and E are negative with E having twice the magnitude of C.

Applications

- A positive and negative output with respect to node C. This is used extensively in analogue systems where bipolar signals centred on zero are used, e.g. audio amplifiers. It is often called a "centre zero" power supply.
- A single output of node D with respect to node E This is the low cost version e.g. for a car battery charger. In this case the connection between the centre tap of the transformer and node C is often omitted.

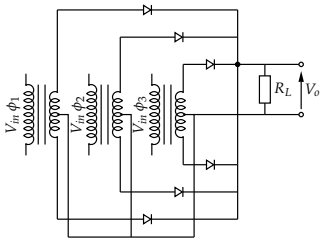
Smoothing a Full Wave Rectifier

- Smoothing a full wave rectifier output is very similar to smoothing a half wave circuit. The main difference is that the half wave rectifier charges the smoothing capacitor *once per input cycle*, whilst a full wave rectifier charges the smoothing capacitor *twice per input cycle*.
- In all other respect the behaviour is the same.
- Because of this the prior equations can be used to choose a capacitor to meet the ripple voltage requirements or to estimate the ripple given the circuit values and operating conditions.
- When calculating capacitances for full wave power supplies remember that the capacitance is replenished at 100 Hz. Not 50 Hz as is the case with the half wave circuit.

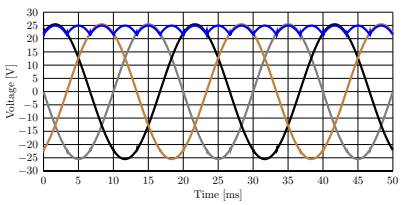
Three Phase Full Wave Rectifiers

- Most power systems that handle more than a few kW are three phase systems
- A three phase power system has three live conductors instead of the single live conductor in most domestic systems
- The three live conductors carry power at the same frequency, but are displaced in phase from one another by 120°.
- The main advantage of three phase is that power is continuously available and never drops to zero. Two phases are always have non-zero voltage at any time.
- The phase currents tend to cancel each other, summing to zero in the case of a linear balanced load. This makes it possible to eliminate or reduce the size of the neutral conductor

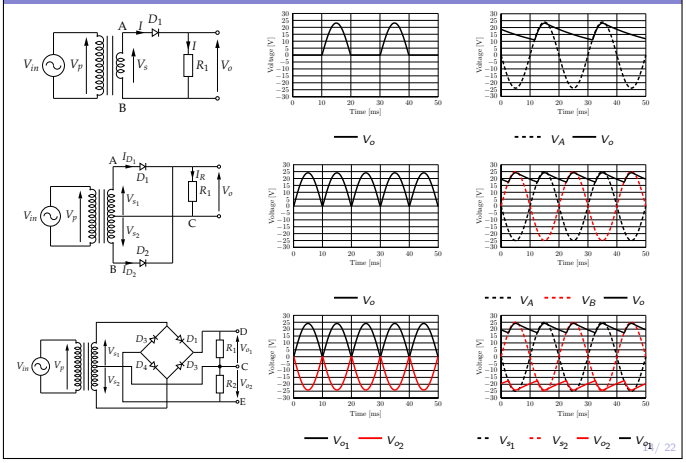
- All the phase conductors carry the same current and so can be the same size, for a balanced load.
- Power transfer into a linear balanced load is constant, which helps to reduce generator and motor vibrations.
- Three-phase systems can produce a magnetic field that rotates in a specified direction, which simplifies the design of some types of electric motor/generator.



- There is a large DC output voltage, $V_{DC} = 0.955\ V_{s_{pk}}$, in the un-smoothed output waveform.
- The peak to peak ripple voltage of the un-smoothed output waveform is 0.133 $V_{s_{pk}}$. This is compared to a value of $V_{s_{pk}}$ for single phase full wave and half wave rectifier circuits.



- The fundamental frequency of the ripple is six times the input frequency e.g. 300 Hz for 50 Hz input. This should be compared to twice the input frequency for single phase half wave and full wave rectifiers respectively.
- Because of this, the un-smoothed three phase output is significantly "better" than single phase.
- For many three phase applications it is therefore not necessary to use smoothing.
- Where smoothing is needed, it is easier to achieve than in single phase circuits because
  - The intrinsic ripple voltage is smaller 0.133 $V_{s_{pk}}$ *vs.* $V_{s_{pk}}$.
  - The ripple frequency is higher, so the time between replenishing the smoothing capacitor is reduced. Consequently, for a given ripple specification the smoothing capacitance can be a smaller value. High capacitance electrolytics are expensive especially when higher voltage specification is required e.g EVOX RIFA 6800 μF, 385 V, £84.80 + VAT



Stabilisation and Regulation of DC Power Supplies

- The output from a rectifier and smoothing circuit is not often of sufficient quality to supply an electronic circuit directly. (although exceptions do exist in e.g. power electronics / electrical machines).
- The effects of finite supply and transformer impedance make it difficult accurately to predict the DC component in the output waveform, and make the DC and ripple components of the power supply dependent on the load.
- The supply voltage can vary. Although we say a 240 V RMS supply in the UK the regulation states that this can have a large tolerance. The current regulation is that it should be 230 V $\pm$10% (207 - 253 V). This just covers the same voltage range as continental Europe. The utility companies use this tolerance to manage the load and ensure the frequency specification is maintained.

- The ripple voltage can also be a problem, introducing noise (hum) into circuits. To have a very small ripple voltage requires high smoothing capacitance, which is expensive and bulky - often impractical.

To mitigate the short-comings of these circuits regulation and stabilisation are required.

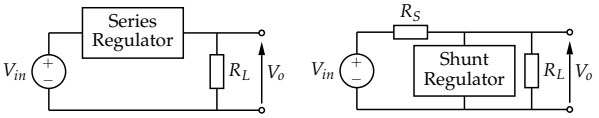
Stabilisation

The process of making the output independent of changes in utility supply voltage.

Regulation

The process of making the output voltage independent of the load current.

Regulation and stabilisation are achieved simultaneously by circuits called regulator circuits of which there are two types series regulators and shunt regulators.



These types can be further subdivided depending on their principle of operation. In EEE118 only the Zener diode shunt linear regulator will be covered. See EEE340 or the EEE118 course books for a more general appraisal. In both series and shunt linear regulators the lowest value of the unregulated DC input voltage must be greater than the required output voltage by a defined margin which is dependant on the particulars of the circuit design. In prior times rectification, regulation and stabilisation was achieved by other methods [1,2,3].

[1] Smith, F. L. (editor), *Radiotron Designers Handbook*, RCA Victor, 4th edition, 1954, Chapters 30 – 34
[2] Terman, F. E., *Electronic and Radioengineering*, McGraw Hill, 4th edition, 1957, Chapter 20
[3] Williams E., *Thermionic Valve Circuits*, Sir Isaac Pitman & Sons, 4th edition, 1961, pp. 237 onwards

Series Regulator Operation

The series regulator restricts the flow of current from the input to the output in such a way as to maintain a constant V_o across the load.

Shunt Regulator Operation

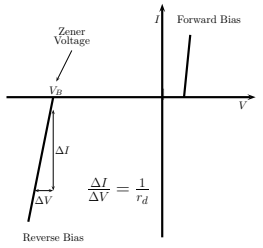
The shunt regulator restricts or increases its own current demand in such a way as to maintain a constant voltage across itself by dropping a varying voltage across R_s. Since the regulator is in parallel with the load, the load voltage is regulated as well.

To construct a shunt regulator an electronic device or component is required which can draw a varying current while dropping as, nearly as possible, a constant voltage. Essentially a current sink.

Zener Diode Linear Shunt Regulator

The simplest form of shunt regulator is constructed with a Zener diode. Where the Zener diode acts as a variable current sink. The Zener diode is a pn junction diode in which both N and P regions are highly doped. Their forward bias characteristics are similar to "normal" diodes but their reverse bias characteristics are engineered so that the diode will break down at a specified voltage. This breakdown behaviour is achieved by virtue of the high doping which gives rise to a large peak electric field when the diode is reverse biased. The high doping is also responsible for the very thin depletion width. Depending on the specified breakdown voltage the Zener diode will either breakdown by quantum mechanical tunnelling ($V_B < 4\ V$), by impact ionisation ($V_B > 6\ V$) or by both processes ($4\ V < V_B < 6\ V$).

The breakdown gives the Zener diode a very abrupt or "sharp" breakdown characteristic. When broken down a small increase in the applied voltage will yield a large increase in current.



Note that it is assumed that the I-V curve in the breakdown region is linear. This is not very realistic, so generally the dynamic resistance, r_d is thought of as the tangent of the curve at a particular breakdown current.

Under normal Zener operation in a shunt regulator the dynamic resistance varies in order to conduct enough current through the diode so that the voltage across the load is held constant by dropping the rest of the supply voltage across R_s.

Review

- Considered full wave and bridge rectifiers as an extension to the half wave principle
- Noted that in the full wave circuit the smoothing capacitor is replenished at double the line frequency
- Observed that the output voltage polarity available is only a function of where the reference is placed
- Discusses the differences between three phase and single phase systems more fully.
- Concluded the section on linear power supplies with a review of the circuits.
- Introduced stabilisation and regulation of power supplies.
- Briefly noted the existence of series and shunt regulators
- Discussed the usefulness of the Zener diode as a shunt regulator



EEE118: Electronic Devices and Circuits

Lecture IX

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

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EEE118. "Electronic Devices and Circuits"

Part 2

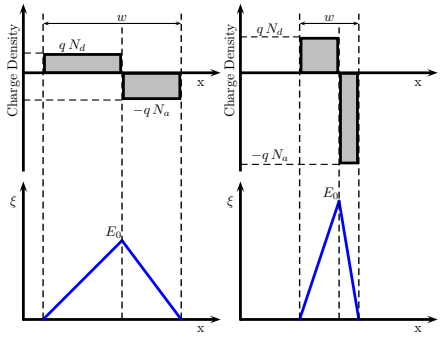
- Lecture 9. (Today) A last word on Diode Regulators
- Lecture 10. Small Signals in Diode Circuits & Introduction to Transistors
- Lectures 11. & 12. Transistor Characteristics Graphs & Switching Applications of Transistors
- Lectures 13. & 14. Transistor circuits for Switching AC & Inductive Loads. & Amplifying Applications of Transistors
- Lectures 15. Two Single Transistor Amplifier Circuits & Small Signal Modelling
- Lectures 16 & 17. Operational Amplifiers
- Lectures 18 & 19. Review and Past Exam Run-through.

Outline

1 Impact Ionisation
2 Zener Diode from a Circuit Perspective
3 Zener Diode Regulator Design Method
  - The Regulator's Effect on Ripple
4 Homework 3
5 All Signals Great and Small
6 Large Signal Diode Circuit Example
7 Review
8 Bear

Zener Diodes - Impact ionisation

There are more zener diodes with $V_B > 6$ V than $V_B < 6$ V so the Zener effect, which is dominant in the lower voltage devices will be ignored for the moment. A pn diode is designed with a doping level in the P and N type material which will yield the "critical electric field" at a particular terminal voltage. Electric field is measured in V/m so what about the meters? It transpires that the wider the depletion region is the more voltage is required to reach the critical field. Consequently a Zener diode can be designed to break down at a particular voltage by controlling the doping density in the P and N regions. In Si the critical field is approximately 40 V/μm, but it is influenced somewhat by the doping densities. Some high voltage Zener diodes will have a pin structure where an lightly doped intrinsic region is sandwiched between the highly doped P and N regions. This acts to increase the depletion distance requiring a higher voltage to yield the critical electric field.



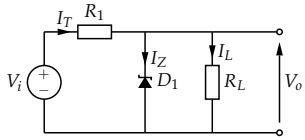
Two pn diodes one with lower doping density (left). Observe that the maximum field E_0, is lower at a given applied voltage in this case than in the higher doping density case (right).

Zener Diodes from a Circuit Perspective

- Since a Zener diode is normally used in reverse bias, it will be assumed that the the cathode will be positive w.r.t anode from now on.
- Zener diodes are only effective regulators if they are biased above their reverse breakdown voltage.
- Once the diode has broken down in a reverse direction, an increase in reverse bias ΔV will lead to an increase in reverse current ΔI
- The ratio of the *small change in V* against the *small change in I* is the dynamic or small signal[1] resistance of the reverse biased diode. It is variable and depends on the biasing conditions. It cannot be computed by dividing the breakdown voltage by the current. It is the change in V and the change in I over a small portion of the breakdown characteristic that is important. dv/di.

[1] small and large signals will be treated fully shortly.

A Zener Diode Shunt Regulator Circuit



In this circuit V_i is the output from any of the rectifier circuits that have been discussed in this course.

- The output voltage V_o will be close to V_B provided the diode is biased above its breakdown voltage. If $V_{C-A} > V_B$ the current is always greater than zero.
- Assume the load current, I_L, is constant but V_i is variable - due to ripple or utility variations.
- A reduction in V_i of ΔV_i will cause a reduction in voltage across R_1 of ΔV_i and hence a reduction in the output voltage.
- However the falling output voltage acts to slightly switch off the Zener diode causing the Zener current, I_Z, to fall by just enough to prevent V_o changing.

- The reduction in the total current I_T due to the falling voltage drop across R_1 is compensated by a similar reduction in I_Z such that I_L (and therefore V_o) are unaffected.
- Similarly if V_i remains constant but I_L changes the increasing I_L tends to lower V_o. A small decrease in V_o tends to switch off the Zener diode slightly, reducing its current and alowing I_L to increase such that V_o remains unchanged.

Design Approach,

- Work out or choose, based on your knowledge of the load, the maximum load current, I_L.
- Choose a Zener diode based on the required output voltage V_o (e.g. BZX55C25 - 25 V)
- Use the diode's manufacturers data sheet to find the minimum current required for proper operation (smallest I_Z that still yields the correct breakdown voltage).

- Consider the conditions that are most likely to cause the regulator to switch off i.e. minimum input voltage and maximum load current; find a value for R_1. The maximum required load current and minimum required Zener current must be able to flow even when the input voltage is at a minimum.

$$\frac{V_{i_{min}} - V_o}{R_1} = I_{L_{max}} + I_{Z_{min}} \qquad (1)$$

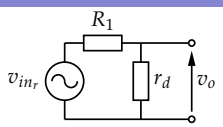
If the value of R_1 is larger than that given by (1), there would be insufficient current under the worst case of input voltage to satisfy the requirements of the load and the regulator. Therefore (1) represents the largest acceptable value of R_1. Of course if R_1 is made smaller than this value its power dissipation will be unnecessarily high.

- Calculate the worst case power dissipation in R_1. (hint: Max input voltage, full load current)
- Calculate the worst case power dissipation in the Zener diode (hint: Max input voltage, no load current). Check the Zener you chose is capable of dissipating the required power, if not select a higher power Zener diode.

Effect on the ripple,

- To calculate the effect of the Zener diode regulator on the ripple an equivalent circuit can be used which models the small changes in Zener resistance that occur to due small fluctuations in the input voltage (or load current).
- If the regulator has been well designed the diode will be broken down in the reverse direction. From the perspective of the ripple signal the diode can be thought of as a small signal (or dynamic) resistance which is equal to the inverse of the slope of the tangent of the breakdown characteristic at the operating point.

In the ripple equivalent circuit only the effect of the small ripple is considered, hence the input is AC. The DC has been neglected.



The output ripple voltage, v_o is obviously a potential division of the input ripple voltage v_{in_r} in the ratio of R_1 and the small signal (dynamic) resistance of the Zener diode. The load resistance (if it is connected) appears in parallel with the dynamic resistance of the Zener and the two may be paralleled using the usual formula. Hence the value of v_o calculated without the load is the worst case ripple voltage. If r_d is lower than R_1 (almost always true) there can be a significant reduction in output ripple. Limitations,

- The voltage is not adjustable.
- The Zener and R_1 may have high power dissipation.
- The dynamic resistance of the Zener is low, but it is not as low as transistor based linear regulators.

Homework 3

It should be possible to fully attempt the Homework 3 now.

It should also be possible to fully attempt the Rectifiers and Smoothing problem sheet.

Signals

In circuits that include active devices (diode, transistors etc.), signals may be considered "large" or "small".
In this course,

Large Signal

If the signal amplitude is the same order of magnitude as the turn on voltage of an active device the signal is "large".

Small Signal

If the signal amplitude is much smaller than the turn on voltage of an active device the signal is "small".

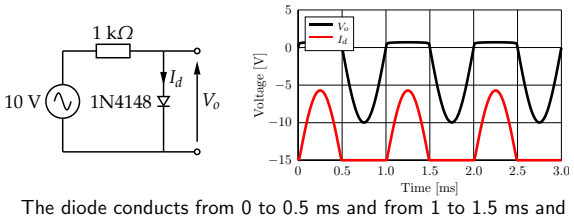
Consider a silicon diode which begins conducting at 0.7 V...

Example of a Circuit with a Large Signal

- The amplitude ("height") of the signal determines how the circuit is analysed.
- If the active devices behave nearly linearly over the range of signal excursion, the circuit can be *linearised* into a single circuit. This means that all the non-linear components (diodes etc.) can be replaced by a single value of dynamic resistance (r_d) which will act on the signal irrespective of the signal amplitude.
- If the active devices behave non-linearly over the range of signal excursion, the circuit may be linearised into several different circuits each having different model parameters (values of didoe dynamic resistance) for each of the the active device(s). The model used will depend on the amplitude of the signal as a function of time.

Typical Conduction State Problem

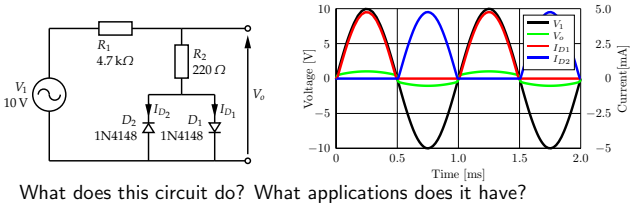
So far we have looked at conduction or non-conduction only. In the circuit below the diode enters conduction when the 10 V source rises above +0.7 V. Otherwise the diode is not conducting.



The diode conducts from 0 to 0.5 ms and from 1 to 1.5 ms and again from 2 to 2.5 ms but is not conducting at other times. This can be seen clearly in the current waveform (red).

Conduction State (large signal) Problems with AC Sources

Some circuits are driven by large amplitude signals. Occasionally the circuit conditions vary so greatly depending on the signal that diodes are switched on and off by the effects the signal has on the surrounding circuit. This is sometimes called large signal analysis. Because the signals are sufficiently large to adjust the operating point or quiescent conditions.



What does this circuit do? What applications does it have?

Applications of this Circuit

This is a kind of limiting circuit. It is one of the simplest in a class of wave-shaping circuits.

Description of Operation

The voltage at the output is limited to the sum of the voltage drop of the forward biased diode and the voltage dropped across R_2 due to the current flowing in it. Provided the input voltage is greater than +0.7 V or less than -0.7 V, one of the diodes will be conducting.

Assuming V_1 is a good approximation to Button V_o will sound something like Button .
Increasing the amplitude of the input signal causes the limiting to become more pronounced. Increasing the value of R_1 or reducing the value of R_2 would have similar overall results.

Review

- Reviewed the principle of operation of Zener diodes (impact ionisation).
- Used the device (diode) characteristic to examine the operating point and linearity of a circuit.
- Introduced the Zener diode shunt regulator circuit.
- Provided a method for designing the component values of the regulator.
- Introduced the idea of small signals and large signals.
- Considered the effects of distortion that large signals experience due to the non-linear nature of the diode characteristic with an audio example.

All of this builds towards analysis of transistor circuits.



EEE118: Electronic Devices and Circuits

Lecture X

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

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- Provided a method for designing the component values of the regulator.
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Outline

1 Linearising Circuits
- Internal Resistance
- Improved Diode Model

2 Example Small Signal Diode Application

3 How does it look on the Characteristics?

4 The Transistor

5 Bipolar Junction Transistor

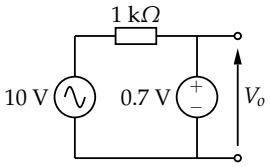
6 Numbering Systems
- JEDEC
- Pro Electron

7 Review

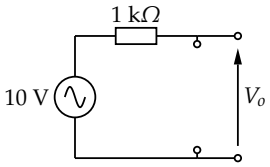
8 Bear

Circuit Linearisation

Diode Conducting:



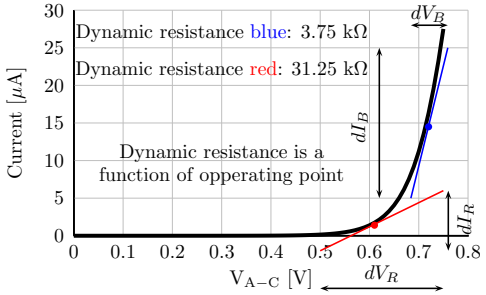
Diode Not Conducting:



In this model the diode is a perfect voltage source (0.7 V) with no internal resistance. The model can be improved by the addition of a resistance in series with the voltage source - remember Thévenin...

Diode with Internal Resistance

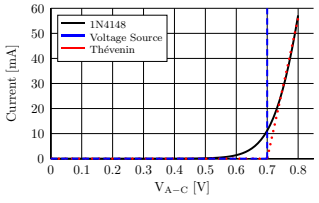
The diode has an internal series resistance, which is proportional to the slope of its characteristic.

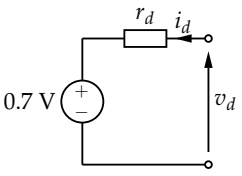


The internal series resistance depends on the current flowing through the diode. The series resistance is changing *continuously*,

Diode with Internal Resistance Model

Adding a constant resistance in series with the voltage source improves the accuracy of the diode model, but the diode resistance changes with diode current so many different values of resistor may be needed. We use a fixed resistor based on the operating point or quiescent conditions. It is important that the signal is *small* with respect to the quiescent conditions otherwise the use of a single value of resistor will not accurately represent the diode operation.

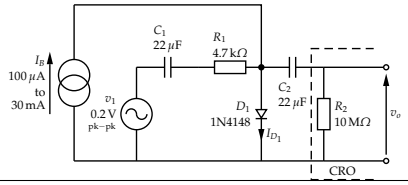




Example Small Signal Diode Application

Problem

Your friend is watching TV in the next room. You can hear the TV all the time but the adverts are louder than the normal programming. It's the adverts that are disturbing your thoughts while attacking a particularly difficult EEE118 problem sheet. Your friend is unwilling to turn the TV down, so you decide to build a circuit to automatically control the volume of the TV to a constant level.



The Components

Name	Purpose
I_B	Sets the operating point of the diode.
v_1	The TV audio output.
C_1	A capacitor to block any DC voltage from the TV which might bias the diode.
R_1	The upper resistor in a potential divider.
D_1	The lower (small signal) resistor in a potential divider.
C_2	A capacitor to block the ∼0.7 V across the diode from passing a current into the oscilloscope (CRO).
R_2	A simple approximation to an oscilloscope probe.

How Does It Work?

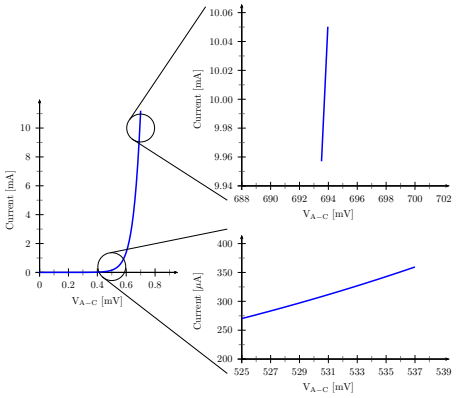
The diode dynamic or incremental or small signal resistance (r_d) varies according to the current flowing through the diode (D_1). The quiescent current in the diode is simply I_B. We aim to make the signal current small with respect to I_B in order that r_d will vary only with I_B. A voltage will appear across D_1 which is sufficient to sustain the current flowing in it. It will be approximately 0.7 V. The value of I_B should be set by the average amplitude of the TV output (perhaps by using a peak detector with a long time constant, but this is ignored, for now...). When the TV volume is "loud" I_B will be larger and so r_d will be smaller and will drop a smaller share of the TV's sound signal. Since r_d is the lower leg of the potential divider - across which the output is taken - the volume will be reduced. This is an example of feedback.

Two Operating Points

We will inspect two examples at different values of I_B to observe the effect on the value of r_d and the output of the circuit. The total diode current is the sum of the quiescent current (I_B) and the current flowing in the potential divider due to v_1.

The linearisation of the circuit requires that the signal current due to v_1 does not change the total current so much that the exponential shape of the diode's IV characteristic becomes significant. To ensure the Thévenin model of the diode holds the diode characteristic must approximate a straight line.

Example Diode Characteristic at Two Operating Points



I_B Small: Calculate Some Important Parameters

We would like to know the small signal resistance of the diode,

$$\frac{\Delta I}{\Delta V} = \frac{1}{r_d} \tag{1}$$

$$\frac{1}{r_d} = \frac{360\ \mu\text{A} - 271\ \mu\text{A}}{538\ \text{mV} - 525\ \text{mV}} \tag{2}$$

$$r_d = 146\ \Omega \tag{3}$$

And the total *signal* current,

$$r_{total} = 4.7\ \text{k}\Omega + 146\ \Omega \tag{4}$$

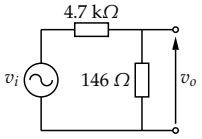
$$= 4846\ \Omega \tag{5}$$

$$i = \frac{v}{r} = \frac{0.2}{4846} \tag{6}$$

$$= 41.2\ \mu\text{A}_{\text{pk-pk}} \tag{7}$$

I_B Small: Small Signal Equivalent Circuit

The small signal equivalent circuit is a circuit diagram which shows only the circuit components that influence what happens to the signal. It is how the signal "sees" the circuit.



$$\frac{v_o}{v_i} = \frac{146}{4700 + 146} \tag{8}$$

$$\approx 0.03 \ \frac{\text{V}}{\text{V}} \tag{9}$$

I_B Large: Calculate Some Important Parameters

We would like to know the small signal resistance of the diode,

$$\frac{\Delta I}{\Delta V} = \frac{1}{r_d} \tag{10}$$

$$\frac{1}{r_d} = \frac{10.8 \text{ mA} - 9.2 \text{ mA}}{698 \text{ mV} - 690 \text{ mV}} \tag{11}$$

$$r_d = 5 \ \Omega \tag{12}$$

And the total *signal* current,

$$r_{total} = 4.7 \text{ k}\Omega + 5 \ \Omega \tag{13}$$

$$= 4705 \ \Omega \tag{14}$$

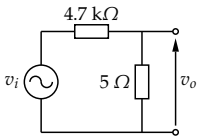
$$i = \frac{v}{r} = \frac{0.2}{4705} \tag{15}$$

$$= 42.5 \ \mu\text{A}_{\text{pk-pk}} \tag{16}$$

Note, making R_1 much larger than r_d controls r_{total} and so keeps the peak to peak value of i almost constant.

I_B Large: Small Signal Equivalent Circuit

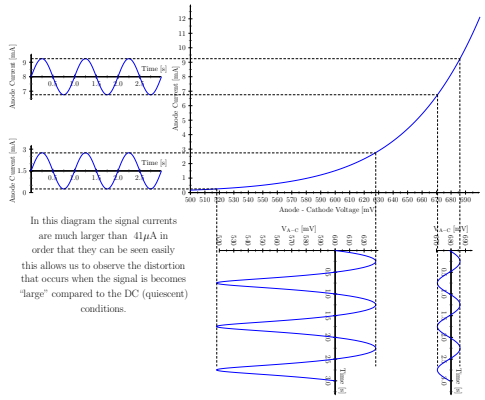
The small signal equivalent circuit has a new value for r_d. Note that the quiescent conditions don't appear in the small signal circuit. Only linear components (R, L, C and Sources) appear in small signal circuits.



$$\frac{v_o}{v_i} = \frac{5}{4700 + 5} \tag{17}$$

$$\approx 0.00106 \ \frac{\text{V}}{\text{V}} \tag{18}$$

Representing Everything on the Characteristic



Transistor Definition

Definition

A transistor is a three terminal semiconductor electronic device which is capable of power amplification.

Different from a transformer or resonant circuit which can only increase the amplitude of current *or* voltage. Several different kinds of transistor exist (BJT, MOSFET, JFET) and Valves.

- BJT is the most common small signal amplifier.
- MOSFETs are more common in large signal applications such as switching power supplies.
- MOSFETs also find use in integrated circuits (producing them on a semiconductor wafer is easy c.f BJT).
- JFETs are found in ICs but are also used as discrete devices.
- Thermionic valves are limited to specialist applications (e.g. high power microwave generation, radio and RADAR transmission, specialist audio applications.)

Bipolar Junction Transistor

The bipolar transistor[1] was invented by John Bardeen, Walter Brattain and William Shockley in the late 1940s at Bell Labs. Read: `http://dx.doi.org/10.1109/5.658752`. They shared the 1956 Nobel Prize. The BJT is a semiconductor device composed of three semiconductor regions N-P-N or P-N-P named Emitter (E), Base (B) and Collector (C). The NPN can be thought of as two diodes with their anodes connected together. The PNP, two cathodes connected.

JEDEC Numbering System

At least three numbering systems exist but not all part numbers apply the rules, JIS, Pro Electron and JEDEC.

- JEDEC the The Joint Electron Devices Engineering Council was formed in 1958 as a part of the Electronic Industries Association (EIA).
- It standardises semiconductor part numbers used in the USA.
- The code is [Number] 'N' [Serial Number] [Suffix Optional].
- Where, 1 - Diode, 2 -Transistor, 3 - Dual-Gate, 4 - Optocoupler (LED + photo diodes), 5 - Optocoupler (LED + Transistor).
- The suffix is optional and is A - low gain, B - medium gain and C - high gain.
- e.g. 2N3904 and 2N2222 are transistors. 1N4148 and 1N4007 are diodes.

Pro Electron Numbering Systems

- European Numbering or "Pro Electron" system. Designated by the European Electronic Component Manufacturers Association of which Pro Electron has been a part since 1983.
- The code is [Letter] [Letter] [Serial Number]
- First letter is A, B, C or R - depends on band-gap
- Second letter indicates device function or application.
- Serial number is an identifier for the device
- e.g. BC182 (Silicon, low power audio frequency transistor) BZX55C4V7 (Zener Diode)
- See handout for full details.

Review

- Introduced the idea of a dynamic resistance or small signal resistance.
- Compared the voltage source model and thévenin model of a diode.
- Considered how capacitors can be used to block quiescent conditions (DC) but pass signals (AC).
- Introduced the idea of a small signal equivalent circuit - How the signal "sees" the circuit.
- Introduced the bipolar transistor.
- Briefly discussed two numbering systems for active devices.



EEE118: Electronic Devices and Circuits

Lecture XI

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

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Outline

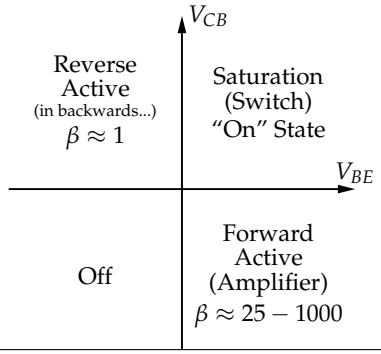
1 Review
2 BJT Modes of Operation
3 Characteristics
- Input Characteristics
- Output Characteristics
- Transfer, Mutual or Transconductance (g_m) Characteristics

4 Large Signal Model of a BJT
5 ZTX653 Large Signal Parameters
6 Large Signal Model of a MOSFET
7 IFR510 Characteristics
8 Switches
9 Switch Types
- Mechanical Switches
- Electro-Mechanical Switches

10 Review
11 Bear

BJT Modes of Operation

There are four possible modes of operation where each of the two junctions is either forward or reverse biased.

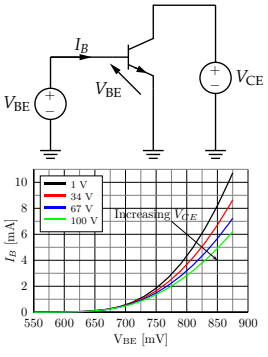


BJT Modes of Operation II

- The forward active region provides amplification of voltage and/or current (both means power amplification ($P = IV$)).
- In the saturation region the transistor appears like a switch which is turned on.
- In the 'off' region the transistor appears like a switch which is turned off.
- The reverse active region is used when the BE and CB junctions are accidentally exchanged (transistor in the circuit backwards). Performance is poor c.f forward active region as transistor designers adjust doping densities and region widths to optimise performance in other regions.

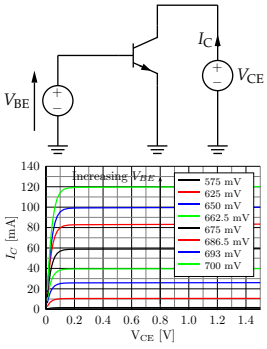
Note: some transistors are designed for amplification (linear) use others are designed for switching use. All transistors can perform both functions but the design of "switching" transistors is optimised for switching applications. Likewise for "amplifier transistors".

Input Characteristics



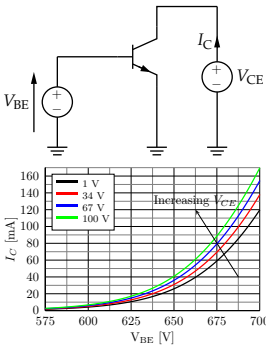
Shape of characteristics essentially governed by the diode equation when $V_{CE} \approx 0$.
$I_B = I_S \left(exp \left(\frac{q V_{BE}}{k T} \right) - 1 \right)$
Increasing V_{CE} with constant V_{BE} decreases the base width, slightly decreasing the recombination of minority carriers in the base region. Note, the base current is incidental, it is the base emitter voltage that is controlling the transistor. But like the compressor from Lecture 9, V_{BE} will rise to whatever is necessary to admit the desired current I_B

Output Characteristics



A family of curves showing effect on the output V_{CE} and I_C as a function of the input V_{BE} (or I_B). When V_{CE} is small the transistor is in saturation both BE and CB junctions forward biased (transistor switched "on") (left of graph). While V_{BE} is too small to cause I_C to rise above the leakage current level, the transistor is off ($y \approx 0$ on the graph). Forward active region is indicated by nearly parallel characteristics.

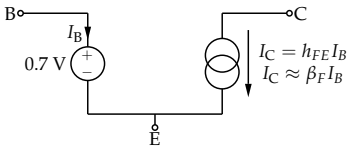
Transfer Characteristics



The transfer characteristic relates the controlling voltage (V_{BE}) to the controlled parameter I_C. V_{BE} is related to I_C for a BJT by $I_C = I_S \left(exp \left(\frac{q V_{BE}}{k T} \right) - 1 \right)$ and by square law expressions for FETs (see handouts). This expression holds over many orders of magnitude while the relationship between base current and collector current changes considerably (h_{FE} not constant). See Horowitz and Hill, second Ed. pp 79 - 81 section 2.10 for full details.

Large signal BJT model

Large signals deal with active devices moving through large *non-linear* regions of their characteristics. A suitable large signal model for the forward active region of a BJT is to replace the base emitter junction with a 0.7 V source (it is a diode after all...) and to replace the reverse biased collector base junction with a current source where the current is controlled by the base current (the two are linked by the large signal current gain h_{FE}[1]) $I_C = h_{FE}\, I_B$.[2]



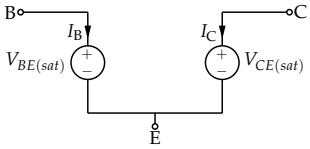
[1] note capital F and capital E means large signal parameters

[2] h_{FE} **h**ybrid model **F**orward, **E**mitter common. Also "Ebers-Moll transistor model", Millman and Grabel second ed. pp. 87 - 114.

- V_{BE} is the controlling variable and I_C is the controlled variable and I_B is incidental (MOSFETs have no equivalent, I_G). However, in the large signal model V_{BE} is fixed at 0.7 V. How can it be the controlling variable if it is fixed?
- In switching applications we want the transistor to change from conducting to non-conducting (and back) as quickly as possible. The load (whatever the collector is connected to) defines the maximum value of I_C.
- The designer ensures that the input to the transistor (whatever the base is connected to) is able to supply whatever base current (I_B) is required to cause the transistor to switch. This makes the exact value of V_{BE} and I_B less important.
- In this way the dependence of the circuit operation on h_{FE} is lessened. This is desirable because h_{FE} varies a great deal even between transistors of the same type.

Large signal BJT model: Saturation (i.e. Switched "On")

A large signal model for the saturation mode of the BJT is two voltage sources representing the saturation voltage between the base and emitter and the collector and emitter. These are given on switching transistor datasheets (e.g. ZTX653 note not Pro E or JEDEC) or the exam question...



In saturation $I_C = h_{FE}\, I_B$ *does not apply*. A model for the transistor when it is off is open circuit between B, C and E. In practice very small leakage currents flow, which are defined on the transistor datasheet.

Finding a Value for h_{FE}, $V_{CE(sat)}$, $V_{BE(sat)}$

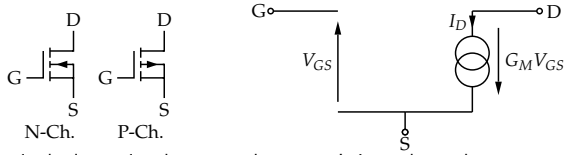
The following parameters of the Large Signal Model may be found on a transistor datasheet.

- h_{FE} - the large signal (capital subscript letters) forward active mode relationship between I_C and I_B.
- $V_{CE(sat)}$ the saturation voltage between collector and emitter.
- $V_{BE(sat)}$ the saturation voltage between base and emitter

All of these parameters are functions of I_C. For the purposes of this course $h_{FE} = 100$ may be assumed if no value is given. The dependence of $V_{CE(sat)}$ and $V_{BE(sat)}$ have also be ignored, but in real design situations (project work etc.) these dependencies should not be forgotten.

MOSFET Large Signal Model

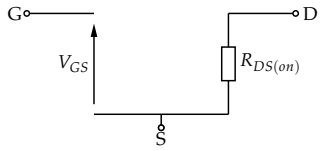
The MOSFET is a three terminal amplifying device like the BJT but the collector has become the drain, base is now gate and emitter changes to source. Also the meaning of saturation is different in BJTs and MOS transistors. "Saturation" in BJT = "Linear Region/Forward Active" in MOS. "Linear Region/Forward Active" in BJT = "Saturation" in MOS! For the N-Ch device to be in saturation V_{GS} must be positive and V_{DG} must be negative. For the P-Ch device to be in saturation V_{GS} must be negative and V_{DG} must be positive.



G_M is the large signal transconductance. It is rarely used.

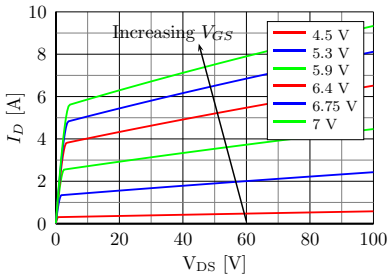
MOSFET Large Signal Model: Switched "On"

Linear because at a constant value of V_{GS} a slight increase in V_{DS} will bring about an *approximately* linear increase in I_D. This is most easily understood by looking at the output characteristics.



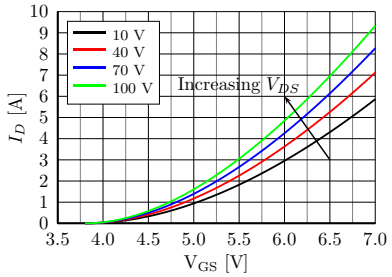
In the linear region the MOSFET behaves like a resistance, $R_{DS(on)}$. The value of $R_{DS(on)}$ is sensitive to temperature (increasing temperature increases $R_{DS(on)}$ however in saturation the dependence is somewhat more complex, based on both the kind of MOSFET (lateral or vertical) and the region of the characteristics it is being operated over.

IRF510 Output Characteristics



Notice V_{GS} is much greater than in the BJT case. In the switching region (left) the curves can be assumed parallel, $R_{DS(on)} \approx$ constant. These characteristics at 25 °C. Very generally speaking $V_{DS(on)} < V_{CE(sat)}$.

IRF510 Transfer Characteristics



The characteristics of MOSFETs are often found in datasheets, because the transconductance depends on device geometry. In BJTs an expression exists independent of device dimensions.

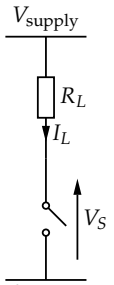
An Ideal Switch

When "on" $I_L = \frac{V_{supply}}{R_L}$

When "off" $I_L = 0$

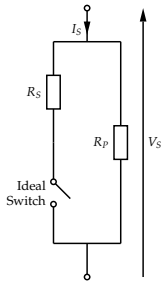
When "on" $V_S = 0$

When "off" $V_S = V_{supply}$



The product of V_S and I_L is zero in both switch states so no power is dissipated in the switch. I_L - the on state current - is determined by the external circuit not the switch.

A Real Switch

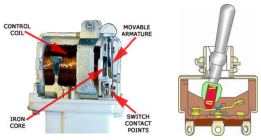


Real switches have some series resistance and some leakage current in the "off state" In most cases, R_P, which represents the "off" state leakage can be neglected. R_S usually has to be considered because it is responsible for the power loss ($I^2 R$) in the switch. For a real switch,

$$I_S = \frac{V_{supply}}{R_L + R_S} \qquad (1)$$

Mechanical Switches

- Mechanical force brings together two metal contacts.
- Easily designed for currents in the range 10^{-3} to 10^{7} A
- Very low contact resistance (R_S)
- Very low leakage (high R_P)
- Requires the application of mechanical for to operate. Elasticity and inertia limits the switching rate to a few hundred Hz.
- The need for mechanical force requires some kind of linkage between the switch and the operator.



Electro-Mechanical Switches

- Similar to mechanical switches except that the mechanical force is provided by an electro-magnet.
- Electro-magnet drive scheme offers possibility of remote operation.
- Advantages of mechanical contacts are maintained i.e. low loss.
- Most small toggle switches are rated for $\sim 10^5$ mechanical operations and 10^6 electrical operations but it depends on the application. A particular kilovac[3] carrying 500 A at 600 V has a *rated* lifetime is about 25 switching cycles. Switching no current it is rated fro 10^6 cycles.

Note that in both theses switch types the switch contacts are usually insulated from the control linkages or electromagnet.

[3] P/N: EV200AAANA see `http://relays.te.com/` or Farnell: 9913971

Review

- Considered the four modes of operation of a BJT.
- Looked at examples of the input, output and transfer characteristics of a BJT.
- Developed a large signal model for a BJT which can be used to solve switching problems.
- Noted some of the limitations of the model in the saturation
- Developed a large signal model of a MOSFET.
- Briefly observed some differences between MOSFET and BJT characteristics.
- Discussed an ideal switch
- Considered the non-idealities of a switch
- Discussed the properties of two classes of 'switch': Mechanical and Electro-Mechanical.



EEE118: Electronic Devices and Circuits

Lecture XII

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

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Outline

1 Switch Types
- Electronic Switches

2 MOSFET an BJT Switches
- Output Characteristics

3 Power Dissipation

4 MOSFET Switches

5 BJT Switches

6 Switching Transistor Example

7 Homework 4

8 Review

9 Bear

Electronic Switches

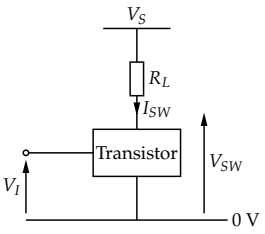
- Many different types (BJT, MOSFET, JFET, Valve, Triac, Thyristor, "Solid State Relay (SSR)"...)
- Interested here in MOSFET and BJT.
- Electronic switches can change state very quickly c.f mechanical switches $> 10^9$ operations *per second* in a modern PC.
- Most mechanical switches would not last 1/1000th of this number of operations!
- Losses in electrical switches considerably greater than mechanical switches.
- The control input is electrically connected to one of the main current path terminals. (Emitter or Source) is common to input network and to output network).
- Most electronic switches support current flow in one direction only (not SSR, it is a compound device).

MOSFET and BJT Switches

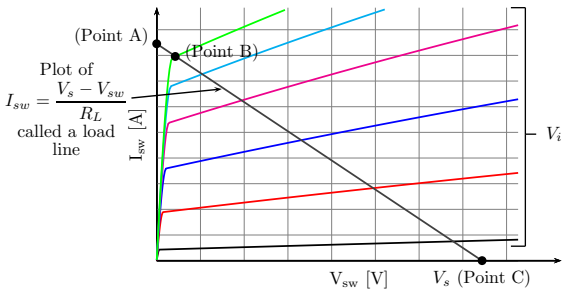
The connection of the control input to the controlled output and the single direction of current flow is inconvenient, however the advantages of electrical switches are so great that designers have developed a number of ways around these problems.

The device is placed into the circuit (right). In which V_S is the supply voltage, V_I is the control voltage and V_{SW} is the voltage across the switch. V_{SW} and I_{SW} are related by

$$I_{SW} = \frac{V_S - V_{SW}}{R_L} \quad (1)$$



There is also a second relationship between V_{SW} and I_{SW} defined by the output characteristics of the transistor.



Notes on the Output Characteristic

- The switch is controlled by V_I (which is equal to V_{BE} in this example).
- Point C is the "off state" point.
- Point B is the real "on state" point.
- Point A is the ideal on state point.
- As V_I is increased, I_C will increase and V_{CE} will decrease until point B is reached.
- The dots on the diagram can be thought of as several different operating points but they are not quiescent conditions as the changes are large compared to the non-linearity of the transistor characteristics.

Notes on the Output Characteristic II

- The operating point moves across a non-linear portion of the characteristics (it's a large signal problem)
- The locus - the path - of the operating point across the output characteristics is called the "load line". It is defined by the load resistance and the supply voltage (V_S).
- The load line is straight - no surprise - it represents a resistance as a function of V and I... Ohm's law.
- In the region between B and C there is a significant $V\,I$ product.
- The designer must keep the transistor at point B or point C and move between them as fast as possible.

Power Dissipation

- The ZTX653 (from Lecture 10) can dissipate 1 W.
- And can carry 2 A...
- At up to 100 V (V_{CE}).
- So it can control 200 W in the load.
- The instantaneous power in the transistor mid-way between B and C would be 50 W.
- Which is sufficient to blow the transistor to pieces.

The designer must ensure the transistor switches quickly to keep the average energy in any switching cycle below the permissible limit. More on this in "EEE340: Analogue and Switching Circuits" now called "EEE223: Energy Management and Conversion".

MOSFET Switches

- From Lecture 10 the MOSFET behaves like a resistance when "on" (linear region) i.e. at point B.
- Manufactures specify $R_{DS(on)}$.
- I_D is given by,

$$I_D = \frac{V_S}{R_L + R_{DS(on)}} \tag{2}$$

when in the "on" state

- $I_D = 0$ in the "off" state.
- The effect of $R_{DS(on)}$ on load power is small (1 – 2% drop).
- The effect on the transistor is

$$P = I_{D(on)}^2 R_{DS(on)} \tag{3}$$

which may be significant.

MOSFET Switches II

- To ensure the MOSFET is fully "on" the datasheet should be consulted or output characteristics obtained by experiment. A V_{GS} of 7 – 10V will probably be sufficient to switch the transistor under most circumstances.
- Since the gate is insulated from the source and drain, no current is required to maintain the gate drive voltage (MOSFETs have no equivalent of I_B).
- Note that the gate has capacitance associated with it and this capacitance complicates transient drive conditions. More in "EEE340: Analogue and Switching Circuits" now called "EEE223: Energy Management and Conversion".

BJT Switches

- When a BJT is fully "on" (i.e. at Point B) the voltage across it is $V_{CE(sat)}$ - the saturated on state voltage drop.
- $V_{CE(sat)}$ is approximately constant for a constant value of h_{FE}
- The value of h_{FE} depends on the particular transistor.

$$I_{C(on)} = \frac{V_S - V_{CE(sat)}}{R_L} \tag{4}$$

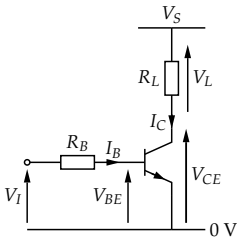
- $I_{C(off)} = 0$ because the leakage is small.
- To be sure the BJT is fully on, the designer must ensure there is sufficient base current available.
- The base current is determined by

$$I_B = \frac{I_C}{h_{FE}} \tag{5}$$

BJT Switch Design Process

First estimate I_C,

$$I_C \approx \frac{V_S}{R_L} \text{ if } V_S >> V_{CE(sat)} \quad (6)$$



then calculate the required base current,

$$\therefore \min I_B = \frac{I_C}{h_{FE}} = \frac{V_S}{h_{FE}\, R_L} \quad (7)$$

I_B is controlled by

$$I_B = \frac{V_I - V_{BE}}{R_B} \quad (8)$$

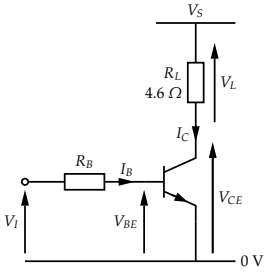
Where V_I is the input voltage and V_{BE} is the voltage associated with the forward biased base emitter junction (0.7 V). Usually it is necessary to make I_B several times the minimum value to make the transistor switch properly under all circumstances.

Switching Transistor Example: Part One

For the following BJT switching circuit find the,

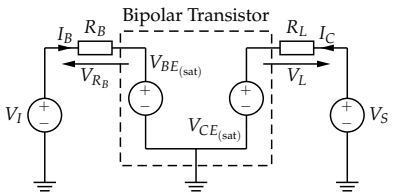
- collector current
- load power
- switch "on" state power loss
- range of possible base currents
- maximum value of R_B

$V_S = 48$ V, $h_{FE} = 35 - 170$, $V_{CE(sat)} = 0.21$ V, $V_{BE(sat)} = 0.7$ V, $V_I = 10$ V.



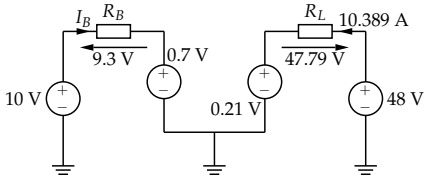
Solution

The "on" state or "saturation" large signal model can be drawn (if necessary)



For the collector current, apply Ohm's law to the collector circuit:

$$I_C = \frac{V_S - V_{CE(\text{sat})}}{R_L} = \frac{48 - 0.21}{4.6} = 10.389 \text{ A} \quad (9)$$



For the load power,

$$P_L = \frac{V_L^2}{R_L} = \frac{(48 - 0.21)^2}{4.6} = 496.49 \text{ W} \quad (10)$$

For the transistor on state power loss,

$$P_T = V_{CE(sat)} \cdot I_C = 0.21 \cdot 10.389 = 2.182 \text{ W} \quad (11)$$

For the minimum I_B (need to use max h_{FE}),

$$I_B = \frac{I_C}{h_{FE(\max)}} = \frac{10.389}{170} = 61.11 \text{ mA} \quad (12)$$

For the maximum I_B (need to use min h_{FE}),

$$I_B = \frac{I_C}{h_{FE(\min)}} = \frac{10.389}{35} = 296.82 \text{ mA} \quad (13)$$

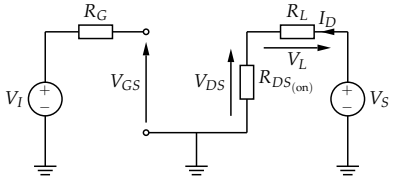
For the max permissible value of R_B (use $I_{B(max)}$),

$$R_B = \frac{V_I - V_{BE(sat)}}{I_{B(max)}} = \frac{10 - 0.7}{296.82 \times 10^{-3}} = 31.33\ \Omega. \quad (14)$$

Always assume worst case h_{FE} in a switching problem.

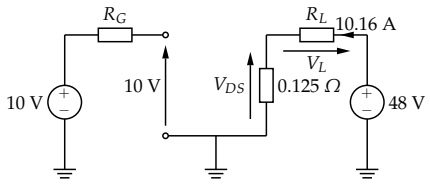
Switching Transistor Example: Part Two

What would the new load power and transistor power be if the BJT was replaced with a MOSFET where $R_{DS(on)} = 0.125\ \Omega$?



For the drain current,

$$I_D = \frac{V_S}{R_{DS(on)} + R_L} = \frac{48}{0.125 + 4.6} = 10.158 \text{ A} \quad (15)$$



The power in the load resistance,

$$P_L = \frac{V_L^2}{R_L} = \frac{\left(V_S - \left(R_{DS(on)}\, I_D\right)\right)^2}{R_L} \tag{16}$$

$$= \frac{\left(48 - \left(0.125 \cdot 10.158\right)\right)^2}{4.6} = 474.72 \text{ W} \tag{17}$$

The power loss in the FET is,

$$P_T = I_D^2\, R_{DS(on)} = 10.158^2 \cdot 0.125 = 12.9 \text{ W} \tag{18}$$

What value of $R_{DS(on)}$ for the MOSFET would yield the same on state loss as the BJT in part one?

Use the *BJT* current and power loss figures to find an equivalent resistance value

$$P_T = 2.181 \text{ W} \tag{19}$$

$$I_D = 10.398 \text{ A} \tag{20}$$

$$R_{DS(on)} = \frac{P_T}{I_D^2} = \frac{2.181}{10.389^2} = 0.0202\ \Omega \tag{21}$$

Homework 4

It should be possible to *start* Homework 4.

It should also be possible to start the Transistors as Switches and Amplifiers problem sheet.

Review

- Discussed the properties of the third class of 'switch': Electronic.
- Considered how the switching action of a transistor is represented on the output characteristics.
- Introduced the idea of a 'load line'.
- Considered power dissipation in the "on" state
- Provided design equations for MOS and BJT switches using a large signal model. Note that in general design work it is often unnecessary to actually draw out this model.
- Performed switching circuit example calculation (exam/tutorial sheet style)



EEE118: Electronic Devices and Circuits

Lecture XIII

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

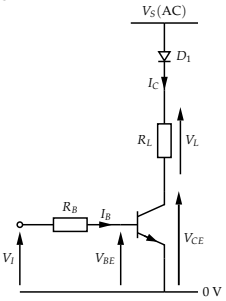
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Outline

1. Review
2. Alternating Current Circuits for Switching Transistors
   - Half Wave
   - Full Wave
   - Full Wave Bridge
3. H-Bridge
4. Switching Inductive Loads
   - Single Transistor Switch with Inductive Load
   - H Bridge with Inductive Load
5. Review
6. Bear

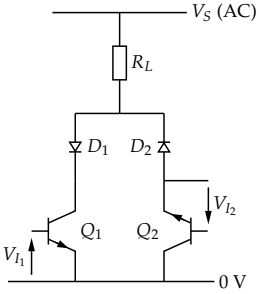
AC Transistor Switching Circuits

The NPN BJT and N-Ch MOSFET should only be operated with conventional current flowing from collector to emitter and drain to source. What about switching voltages that have both positive and negative values?



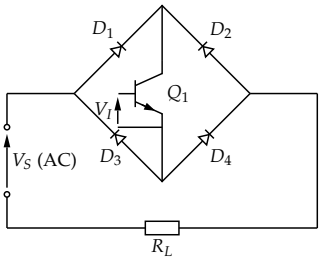
- One option is to include a diode in series with the load.
- When V_S falls below 0 V the diode is reverse biased.
- Only provides half wave rectification.
- On state diode power loss is $0.7 \cdot I_C$

To produce a full wave rectifying AC transistor switching circuit, two NPN transistors can be used together each dealing with one half of the AC cycle.



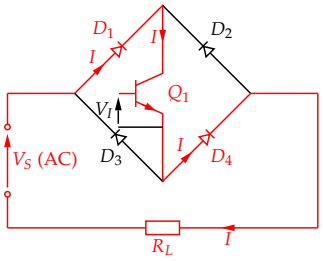
- Q_1 and D_1 are responsible for the current in R_L while $V_S > 0\ V$
- Q_2 and D_2 are responsible for the current in R_L while $V_S < 0\ V$
- The control input for Q_2 is a little inconvenient but it can easily be overcome in practice.

To produce an AC transistor switching circuit with only one switch,



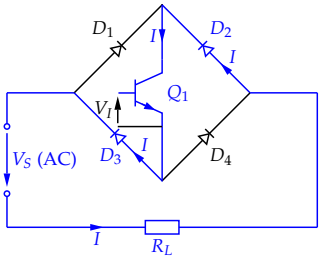
The control voltage is still referenced to a tricky location, but it is not too troublesome.

For one half cycle,



Note that the transistor current is DC, but the load current is AC.

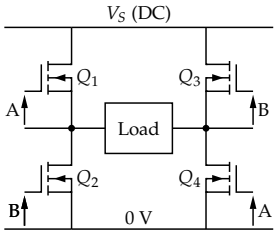
For the other half cycle,



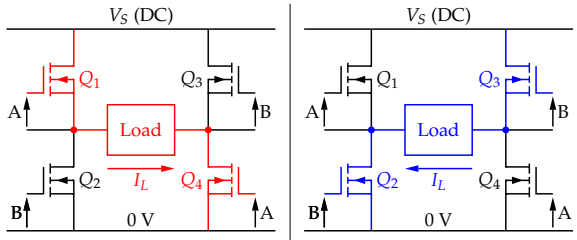
Whatever happens to V_S, I is always flowing into the collector.

H Bridge

Often used for motor control from a DC supply.



- Four switches in an "H" shape. The load is the cross bar.
- For Toyota Prius $V_S \approx 220\ V$, $I \approx 110\ A$
- By controlling the switches current can flow in either direction.
- DC motors can run in both directions.
- Average power can also be controlled.

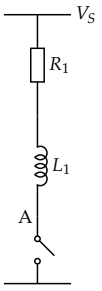


If both "A" and "B" are on together a large 'shoot through' current results, usually destroying the switches. Both "A" and "B" can be time varying which modulates the load current, dissipating a predetermined average power in the load.

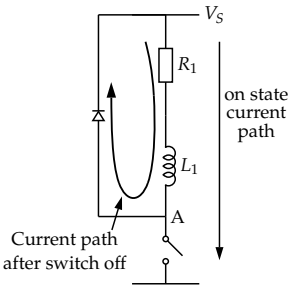
Switching Inductive Loads

Inductors always try to keep current flowing. $V = L\frac{dI}{dt}$. If a switch is opened its current falls to zero very rapidly and $\frac{dI}{dt} \to \infty$. Consequently $V_{L_1} \to \infty$ too.

- When the switch is "on", a current $\frac{V_S}{R_1}$ flows.
- When the switch turns "off", L_1 attempts to maintain the prior "on" current by increasing the voltage across its terminals.
- The charge attempting to leave the inductor as its magnetic field collapses appears at node A, but has no where to go thereafter

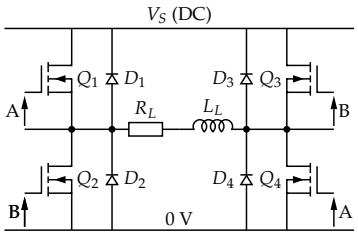


- Node A has some small stray parasitic capacitance due to its physical dimensions.
- The charge arriving on node A charges this stray capacitance according to $Q = C\,V$.
- Since C is small, V must become very large to accommodate even a modest charge, Q.
- The very high voltage spikes which occur may damage any semiconductor switches in the circuit.
- The solution is to provide another path for the charge leaving the inductor to escape from node A.



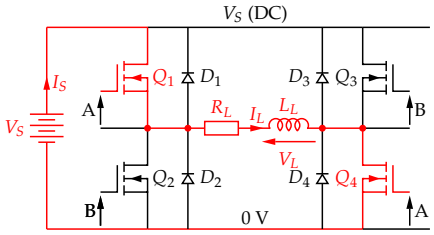
- The diode is reverse biased under normal circumstances. If $V_A > (V_S + 0.7)$ the diode will conduct any charge on A back into the power supply.
- Just after the switch off event, the diode current is equal to the on state inductor current
- After switch off this current falls exponentially with a time constant of $\frac{L_1}{R_T}$ where R_T is the total resistance of the return or "free wheeling" pathway.
- In some applications the "inductive kick" is desirable for example, "boost" and "flyback" converters (types of Switched Mode Power Converter). Also in CRT power supplies and in internal combustion engine ignition systems. Often though, it is highly undesirable and methods to control it are used.

The energy stored in the inductor drives the "back EMF" process. The situation is similar for electrical machines (motors & generators).



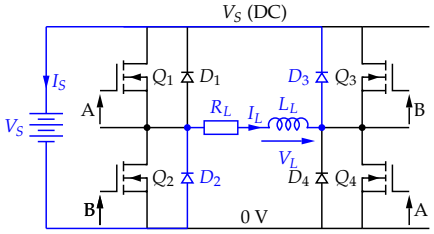
- Operation is as before, Q_1 and Q_4 operate together as do Q_2 and Q_3.
- Now the energy stored in the inductor must be considered.
- As soon as the switches turn off the inductor current must continue.
- There are six interesting states in total, but only four are considered here.

H Bridge with Inductive Load - A switches "on"



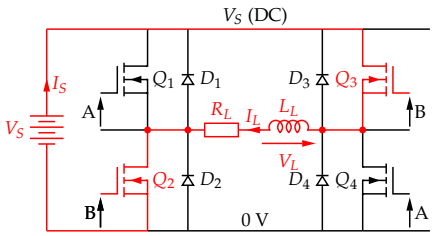
- "A" switches have been on for a long time.
- I_L is constant and flows out of the battery.
- The machine is drawing electrical power from the supply and converting it to mechanical power.

H Bridge with Inductive Load - A switches "off"



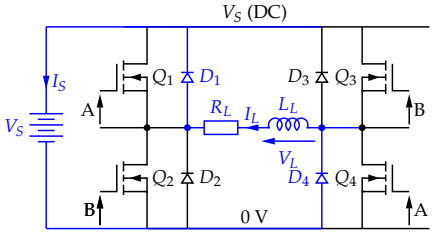
- "A" switches, having been on for a long time, switch off.
- I_L has not yet changed due to the inductive load, note the direction of V_L, I_L and I_S. From a circuit perspective L_L is now a generator.
- The machine is returning electrical power stored in its inductance to the battery.

H Bridge with Inductive Load - B switches "on"



- "B" switches have been on for a long time.
- I_L is constant and flows out of the battery.
- The machine is drawing electrical power from the supply and converting it to mechanical power (rotating in opposite direction).

H Bridge with Inductive Load - B switches "off"



- "B" switches, having been on for a long time, switch off.
- I_L has not yet changed due to the inductive load, note the direction of V_L, I_L and I_S. From a circuit perspective L_L is now a generator.
- The machine is returning electrical power stored in it's inductance to the battery.

Review

- Considered several transistor switching circuits for AC including,
  - Half wave single transistor switch
  - Full wave two transistor switch
  - Bridge full wave single transistor switch
- Introduced the H-bridge as a circuit commonly used to drive electrical machines from a DC supply.
- Considered the effects of inductance in the load of a transistor switch in terms of rate of change of current and provided a diode as an alternate current pathway.
- Applied the parallel diode approach to the H bridge and considered four states of operation.



EEE118: Electronic Devices and Circuits

Lecture XIV

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

- Considered several transistor switching circuits for AC including,
  - Half wave single transistor switch
  - Full wave two transistor switch
  - Bridge full wave single transistor switch
- Introduced the H-bridge as a circuit commonly used to drive electrical machines from a DC supply.
- Considered the effects of inductance in the load of a transistor switch in terms of rate of change of current and provided a diode as an alternate current pathway.
- Applied the parallel diode approach to the H bridge and considered four states of operation.

Outline

1. Review
2. Transistors in Amplifying Applications
   - Gain, Input Impedance and Output Impedance
   - Voltage, Current and Power Amplifiers
   - Transimpedance and Transconductance Gain
3. The Mechanism of Amplification
   - Transconductance Characteristics for Several Amplifying Devices
   - Transconductance Characteristic with Signals
4. Graphical Analysis of a Transistor Amplifier Stage
5. Voltage Gain
6. A Tale of Two Biasing Circuits
7. Review
8. Bear

Transistors in Amplifying Applications

An Amplifier is...

an electronic component, circuit or subsystem which can accept an input signal and output it at a higher *power* level with minimal distortion.

This is different from a transformer which can only increase voltage or current at the expense of decreasing the other. Total power out is always slightly less than total power in. Amplifiers have three figures of "gain"

- Voltage Gain
- Current Gain
- Power Gain

Some more specialist types of amplifier accept an input current and produce an output voltage (transimpedance) or accept an input voltage and produce an output current (transconductance).

Gain

is the ratio of the output variable (voltage, current or power) to the input (voltage, current or power)

Input Impedance

is the ratio of the input voltage to the input current (apply Ohm's law at the input)

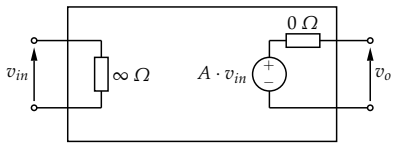
Output Impedance

is the ratio of the Output voltage to the Output current (apply Ohm's law at the output)

An amplifier must possess voltage gain and current gain in order to have power gain ($P = I\,V$...).

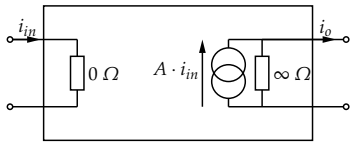
Voltage Amplifiers

- Used at low frequencies (below 30 MHz).
- Gain is $\frac{\text{output voltage}}{\text{input voltage}}$ in which case its units are $\frac{\text{volts}}{\text{volts}}$ i.e. unit-less.
- Should have infinite input impedance i.e. draw no current into its input terminals from the signal source.
- Should have zero output impedance i.e. be able to source an infinite current to the load.



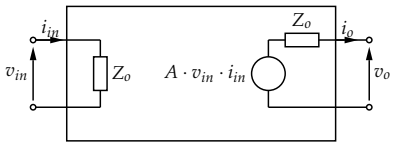
Current Amplifiers

- Used at low frequencies (below 30 MHz).
- Gain is $\frac{\text{output current}}{\text{input current}}$ in which case its units are $\frac{\text{amps}}{\text{amps}}$ i.e. unit-less.
- Should have zero input impedance i.e. can draw infinite current into its input terminals (no signal voltage at the input).
- Should have infinite output impedance i.e. be able to source an infinite voltage to the load.



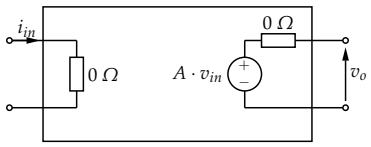
Power Amplifiers

- Used at high frequencies (above 30 MHz) in impedance matched systems where the system has a "characteristic impedance", Z_o (often 50 or 70 Ω)
- Gain is $\frac{\text{output power}}{\text{input power}}$ in which case its units are $\frac{\text{watts}}{\text{watts}}$ i.e. unit-less.
- Should have input impedance equal to Z_0.
- Should have output impedance equal to Z_0.



Transimpedance Gain

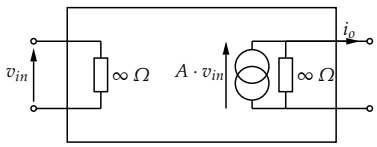
is the ratio of the output voltage to the input current, Gain is measured in Volts per Amp and therefore has the units of Ohms. Input impedance is low and output impedance is low.



This kind of amplifier is sometimes called a current to voltage converter - esp. in DAC/ADC applications. A resistor is a kind of voltage to current or current to voltage converter so it's not difficult to see why the gain of this type of amplifier should have units of Ohms.

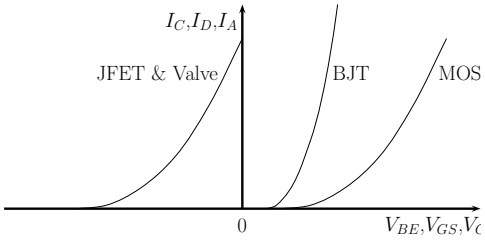
Transconductance Gain

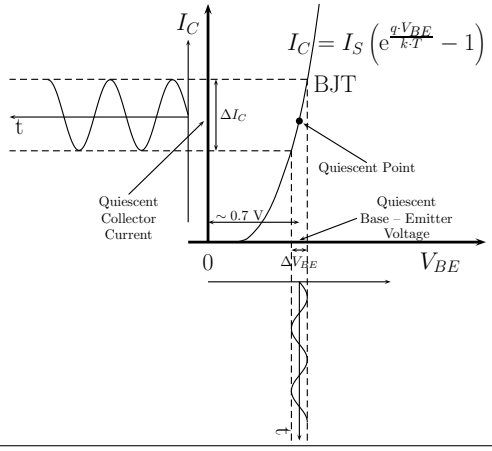
is the ratio of output current to the input voltage, there gain is measured in Amps per Volt and therefore has the units of Siemens or 1/Ohms. Input impedance is high and output impedance is high. **Transconductance is the fundamental mechanism by which transistors operate.**



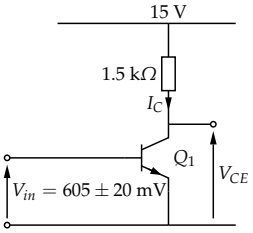
Transistors may be used to make voltage, current, power, transimpedance and transconductance amplifiers.

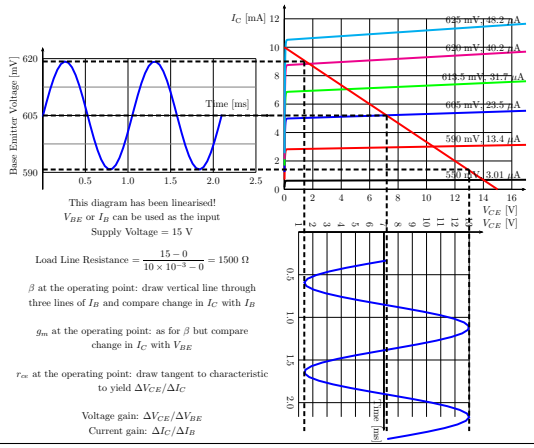
- Bipolar transistors, MOSFETs, JFETs and Valves are all modelled as transconductance devices.
- The relationship between the input voltage and output current is defined by the transconductance characteristics.
- If signals are a small change around an average or quiescent value (often zero) the amplifier will be strongly non-linear.





- Prior to the invention of the BJT all amplifier stages were designed "graphically" using a copy of the characteristics, a pencil, ruler and a slide rule.
- Much can be appreciated about a stage by using the characteristics to design it, however this is not generally done for BJTs nowadays.
- Consider the circuit opposite. Ignore the necessity of biasing for now.
- We can graphically compute the small signal parameters and gain of the stage. β, g_m, r_{be}, voltage and current gain.





- A small signal voltage at the input controls a larger signal current at the output.
- To ensure reasonable linearity, the transistor must be biased to pass a constant quiescent (no signal) current.
- Signals are superimposed onto the quiescent point.
- The relationship between ΔI_C and ΔV_{BE} is called the small signal transconductance (g_m).
- Since the collector current expression is not linear g_m depends on the choice of quiescent point and on the amplitude of the signal.
- Usually it is assumed that ΔV_{BE} is sufficiently small that g_m is constant at the quiescent value i.e. the circuit is assumed linear.
- Usually, the collector current flows through a resistor, which converts the output signal current into a voltage.

An input voltage of,

$$V_{in} = V_{B_Q} \pm \frac{\Delta V_{BE}}{2} \quad (1)$$

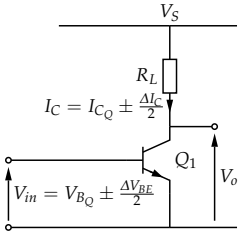
will give rise to a current change of,

$$I_C = I_{C_Q} \pm g_m \frac{\Delta V_{BE}}{2} \quad (2)$$

note,

$$g_m = \frac{\Delta I_C}{\Delta V_{BE}} \quad (3)$$

for a BJT.



This will give rise to a change in collector voltage of,

$$V_O = V_S - I_C R_L \quad (4)$$

$$V_O = V_S - I_{C_Q} R_L \mp g_m R_L \frac{\Delta V_{BE}}{2} \quad (5)$$

$$V_O = V_S - I_{C_Q} R_L \mp g_m R_L \frac{\Delta V_{BE}}{2} \quad (6)$$

$$V_O = V_{O_Q} \pm \frac{\Delta V_O}{2} \quad (7)$$

where V_{O_Q} the the quiescent output voltage, i.e.,

$$V_{O_Q} = V_S - I_{C_Q} R_L \quad (8)$$

and $\frac{\Delta V_O}{2}$ is the component of the output voltage due to the signal. i.e.

$$\frac{\Delta V_O}{2} = -g_m R_L \frac{\Delta V_{BE}}{2} \quad (9)$$

It is possible to estimate the voltgae gain of the amplifier as,

$$\Delta V_O = -g_m R_L \cdot \Delta V_{BE} \quad (10)$$

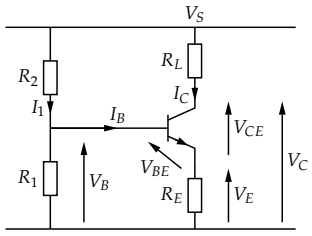
$$\frac{\Delta V_O}{\Delta V_{BE}} = -g_m R_L \quad (11)$$

Some Key Conclusions

1. Because the bias conditions V_{B_Q} and I_{C_Q} and V_{O_Q} do not appear in the gain expression, the gain of the amplifier can be found without *directly* considering the biasing conditions. Note that g_m is a function of I_{C_Q} however, so the gain is indirectly influenced by the choice of quiescent point.
2. The gain is negative. This means that the output signal is 180° out of phase with the input signal. When the input signal is increasing towards a maximum, the output signal is decreasing towards a minimum.

Point 1 allows the calculation of biasing voltages and currents (the quiescent conditions) without having to calculate what will happen to the signal voltages and currents. This is a considerable simplification.

A Tale of Two Biasing Circuits: Circuit One



Circuit 1.
Both circuits aim to control the collector current. In both cases this is achieved by the used of negative feedback.

In this circuit V_B is defined by V_S, R_1 & R_2 and is also formed from $V_E + V_{BE}$.

If V_E is large compared to any changes in V_{BE}, due to temperature or device variation for example, then V_E and therefore I_C are quite constant. Control of I_C has been taken away from the transistor and is now defined by circuit parameters (resistances) which can be easily and repeatably controlled.

Working Out the Biasing Conditions

Assume, I_B is negligible, $V_{BE} = 0.7\ V$, $h_{FE} >> 1 \therefore I_C \approx I_E$ Using potential division,

$$V_B = V_S \frac{R_2}{R_1 + R_2} \tag{12}$$

$$V_B = V_E + 0.7 \tag{13}$$

by Kirchhoff's Voltage Law,

$$V_B = V_E + V_{BE} \tag{14}$$

$$I_E \approx I_C = \frac{V_E}{R_E} = \frac{V_B - 0.7}{R_E} = \frac{1}{R_E}\left[V_S \frac{R_2}{R_1 + R_2} - 0.7\right] \tag{15}$$

also by Kirchhoff's Voltage Law,

$$V_C = V_S - I_C R_L \tag{16}$$

Review

- Introduced some terminology (gain, bias, input, output impedance).
- Introduced three ideal amplifiers in terms of their gain and input and output impedance.
- Considered what happens to signals when applied to an un-biased transistor
- Shown that biasing allows linear operation of an amplifier.
- Derived the voltage gain of a simple transistor amplifier with bias.
- Noted that the biasing terms and signal terms can be separated
- Introduced one of two biasing circuits, which operate using negative feedback, to control collector current nearly independently of device parameters and temperature.



EEE118: Electronic Devices and Circuits

Lecture XV

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

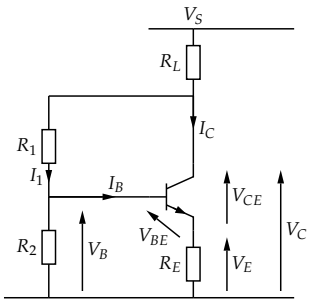
Review

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Outline

1. Review
2. A Tale of Two Circuits... Continued
3. Design of Bias Circuits
   - Compromises in Design
4. Getting Signals in to the and out of the Amplifier
   - Circuit One
   - Circuit Two
5. Small Signal Model of a Transistor Operating as an Amplifier
6. Review
7. Bear

Circuit Two



Circuit 2.

In this circuit R_E provides negative feedback as in circuit one, but negative feedback is also provided from V_C via R_1 and R_2. If the transistor attempts to increase I_C slightly, V_C will be reduced. As a consequence V_B will be reduced as well and the transistor collector current will fall slightly. This circuit will operate without R_E because there is still negative feedback through $R_1 + R_2$. Circuit one will not operate properly without R_E. This circuit is often used at higher frequencies with $R_E = 0$.

Working Out the Biasing Conditions

Assume, I_B is negligible, $V_{BE} = 0.7\ V$, $h_{FE} >> 1 \therefore I_C \approx I_E$ Using KVL,

$$I_1 R_2 + I_1 R_1 + (I_1 + I_C) R_L = V_S \quad (1)$$

or,

$$V_S = I_C R_L + I_1 (R_L + R_1 + R_2) \quad (2)$$

Also by KVL,

$$I_1 R_2 = V_E + V_{BE} = V_E + 0.7 \quad (3)$$

or,

$$I_1 R_2 = I_C R_E + 0.7 \quad (4)$$

Either I_1 or I_C should be eliminated from (2) using (4). For example, eliminating I_1 gives,

$$V_S = I_C R_L + \frac{I_C R_E + 0.7}{R_2} (R_L + R_1 + R_2) \quad (5)$$

or

$$I_C = \frac{V_S - \frac{0.7(R_L+R_1+R_2)}{R2}}{R_L \frac{R_E(R_L+R_1+R_2)}{R_2}} \quad (6)$$

This result for I_C can be used in (4) to find I_1. V_C is found using,

$$V_C = V_S - (I_C + I_1) R_L \quad (7)$$

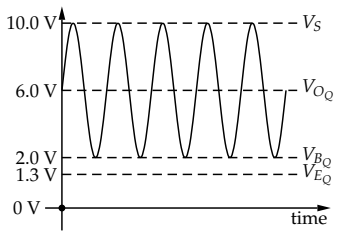
It is not the result that is important. Learning the circuit's skills to get to the result is what counts. No two circuits have the same equations!
Only the transistor V_{BE} can be relied upon. V_{CE} and V_{CB} should *not* appear in your equations.
The assumption that I_B is negligible really means that the existence of I_B does not disturb the voltage on the base significantly.

Designing Bias Circuits

- One of the two circuits must be selected.
- This choice depends on the frequency of operation. At low frequencies circuit one is often selected but at higher frequencies circuit two with $R_E = 0$ is more common.
- The "I_B is negligible" approximation must be considered. It is the smallest value of h_{FE} that yields the largest value of I_B.
- The objective is to control I_C, $I_{B\ (max)} = \frac{I_C}{h_{FE\ (min)}}$. If $I_{B\ (max)} \leq 10 \times I_1$ then I_B is considered negligible.
- The collector current, collector voltage and base voltage have some (indirect) effect on the signal conditions in the circuit so choosing them is often a compromise.

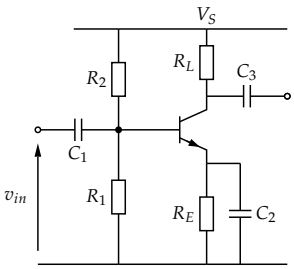
- The collector voltage affects the available output voltage swing. In circuit one V_C can fall between V_S and V_E (although we say V_B for caution's sake).
- To obtain maximum symmetrical swing, $V_C = \frac{V_S+V_B}{2}$.
- Both V_S and V_E affect the max symmetrical swing, which is $V_S - V_E$ (although we say V_B for caution's sake). V_S is often set by external factors, but V_E is often a free choice.
- Larger V_E gives better control over I_C but eats into the available voltage swing. The negative feedback effect of V_E diminishes as V_E approaches V_{BE}. Generally $V_E > 1$ V in the first circuit.
- I_C is chosen by considering the nature of the load, but it also affects the the effective input impedance of the circuit. Generally R_L must be much smaller than the input impedance of whatever is connected to the output of the amplifier.
- $R_1 + R_2$ should be as large as possible (but not violate the $I_1 \sim 10 \times I_B$ rule).

The available voltage in the circuit is shared between the various parts. The transistor must be kept in the forward active region so $V_{BE} = 0.7$ V. A diagram is sometimes helpful.
Increasing V_E reduces the range of voltage that can be occupied by V_O. The optimum position of V_O for maximum signal swing is half way between V_B and V_S.



Most amplifiers will work with V_O swinging down to 200 mV above V_{E_Q}. But there are good reasons to keep V_O above V_{B_Q}.

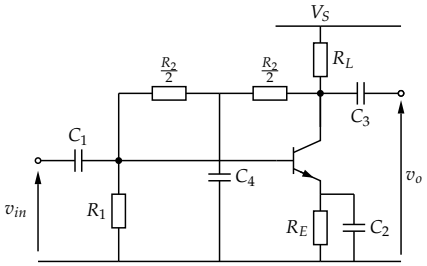
- Passing signals between two points in a circuit is called "coupling".
- Removing signals from a node (to leave only DC) is called "de-coupling".
- As was done for the compressor in lecture 10 "coupling" (or "blocking" capacitors can be used to pass AC signals into the amplifier circuit without the signal source DC conditions affecting the amplifier circuit DC conditions.
- Amplifiers can be coupled with transformers too, this is more common at higher frequencies where the load may be resonant, and in thermionic valve circuits for impedance transformation purposes.
- Amplifiers coupled by capacitors are called "R-C coupled". Amplifiers coupled by transformers are (predictably) "transformer coupled".



C_1 couples the signal from the source to the transistor base without allowing the source to affect the bias conditions, or allowing the bias conditions to affect the source.

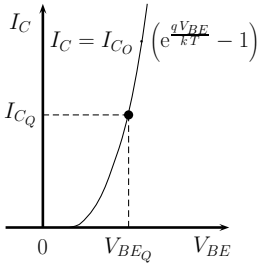
C_2 decouples the emitter node of the transistor. C_2 shorts the emitter node to ground from the signal's point of view. This prevents R_E having the same stabilising effect on the signals as it does on the quiescent conditions. If R_E was not bypassed the voltage gain of the amplifier would be significantly reduced.

C_3 couples the signal from the output to the load without allowing disturbance of the biasing conditions or the imposition of the amplifier's quiescent conditions on the load.



C_4 decouples the mid point of R_2. Since R_2 is also a negative feedback pathway it will reduce the circuit gain is AC as well as DC voltages can be transmitted vie I_B to the base. C_4 shorts the mid point of R_2 to ground as far as signals are concerned, hence eliminating the effect of negative feedback through R_2 on the voltage gain.

Just as large and small signal models were developed for a diode and large signal models were developed for a transistor operated as a switch, a small signal model for a transistor amplifier exists. The fundamental mechanism underpinning "transistor action" is the transconductance - a small change in input voltage elicits a larger change in output current. For small signals it is the slope of the transconductance characteristic that is significant.



$$I_C = I_{C_O}\left(\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)} - 1\right) \tag{8}$$

the slope is,

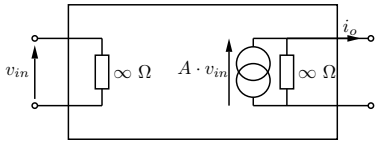
$$\frac{d\,I_C}{d\,V_{BE}} = I_{C_O}\,\frac{q}{k\,T}\,\exp^{\left(\frac{e\,V_{BE}}{k\,T}\right)} \tag{9}$$

For a conducting diode, $\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)} >> 1$ so,

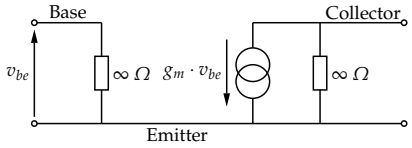
$$I_C = I_{C_O}\left(\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)} - 1\right) \approx I_C = \left[I_{C_O}\,\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)}\right] \tag{10}$$

$$\therefore \frac{d\,I_C}{d\,V_{BE}} = \frac{q}{k\,T}\cdot\left[I_{C_O}\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)}\right] = \frac{q\,I_C}{k\,T} \tag{11}$$

$g_m = \frac{q\,I_C}{k\,T}$ is a fundamental relationship which holds over more than nine orders of magnitude of I_C. Remember it! Looking back at lecture 14, the generalised transconductance amplifier is,



But, the transistor only has three terminals. For the circuits in this course the emitter terminal is common to both the input and output networks. The small signal model of a transistor reduces to,



this is a good low frequency model for JFETs, MOSFETs and Valves. The BJT is special however because there is recombination of carriers in the base region, a base current flows. As a result the resistance looking into the base towards the emitter must be finite (by Ohm's law). The characteristics can be used indirectly to yield the small signal base emitter resistance, r_{be}.

$$r_{be} = \frac{d\,V_{BE}}{d\,I_B} = \frac{d\,I_C}{d\,I_B}\cdot\frac{d\,V_{BE}}{d\,I_C} \tag{12}$$

$$\frac{d\,I_C}{d\,I_B} = \beta = \text{ small signal current gain (see datasheet)} \tag{13}$$

$$\frac{d\,V_{BE}}{d\,I_C} = \frac{1}{g_m} \tag{14}$$

$$\therefore r_{be} = \frac{\beta}{g_m} \tag{15}$$

This is another vital BJT relationship. $d\,V_{BE}$, $d\,I_C$ and $d\,IB$ are the small changes in the bias conditions and may be represented as small signal quantities, v_{be}, i_b and i_c.

$$r_{be} = \frac{\beta}{g_m} = \frac{d\,V_{BE}}{d\,I_B} = \frac{v_{be}}{i_b} \tag{16}$$

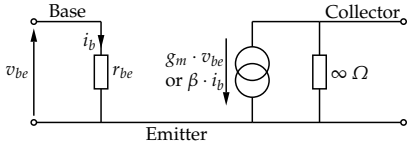
$$r_{be} = \frac{\beta}{g_m} = \frac{v_{be}}{i_b} \tag{17}$$

multiplying through yields,

$$g_m\,v_{be} = \beta\,i_b \tag{18}$$

This means that the BJT can be thought of as a device which accepts an input voltage and outputs a current (transconductance amplifier) or a device that accepts an input current and outputs a current (current amplifier). The choice of how one should think about it depends on the situation. Some circuits are easier to solve if the transistor is thought about in terms of a current amplifier and other circuits are solved more simply by considering the transistor a transconductance device. Only BJTs have the option of two avenues of thought. MOSFETs, JFETS and Valves can only be thought about in terms of transconductance.

Including the effect of a finite r_{be} in the small signal model yields,



- Usually $\beta \neq h_{FE}$. β is a small signal parameter and h_{FE} is a large signal parameter.
- β is sometimes called h_{FE} (notice the lower case subscripts). h_{fe} and β can be assumed equal at low frequencies
- Other circuit elements can be added to more accurately reflect real device performance e.g. the infinite reistance in parallel with the $g_m \cdot v_{be}$ generator is finite and is responsible for the gentle slope of the output characteristics in the forward active region.

Review

- Gave an example of calculation of circuit two's DC conditions.
- Discussed the design of biasing circuits
  - Noted that there is (almost) always some compromise required.
- Looked in detail at coupling and decoupling in the two bias circuits.
  - Coupling - signals in to or out of the circuit.
  - Decoupling - signals shorted to ground where they are unwanted.
- Developed a small signal model for the BJT / MOSFET / JFET / Valve.
  - Looked at the transconductance amplifier / current amplifier duality of BJTs.
  - Derived some key small signal relationships for BJT circuit from the transconductance characteristics.



EEE118: Electronic Devices and Circuits

Lecture XVI

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

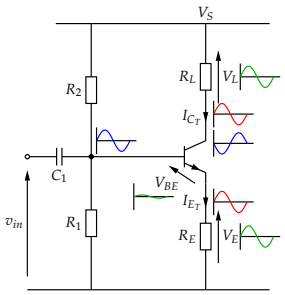
Review

- Gave an example of calculation of circuit two's DC conditions.
- Discussed the design of biasing circuits
  - Noted that there is (almost) always some compromise required.
- Looked in detail at coupling and decoupling in the two bias circuits.
  - Coupling - signals in to or out of the circuit.
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  - Looked at the transconductance amplifier / current amplifier duality of BJTs.
  - Derived some key small signal relationships for BJT circuit from the transconductance characteristics.

Outline

1. Feedback for Quiescent and Signal Conditions
   - Feedback in Amplifiers Without Emitter De-coupling
   - Feedback of Signals in Amplifiers with Emitter De-coupling
   - How the Feedback Operates
2. Drawing the Small Signal Equivalent Circuit
   - Example Small Signal Circuit Problem
3. Homework 4
4. Operational Amplifiers
   - A Classical Feedback System
5. The Opamp
6. Review
7. Bear

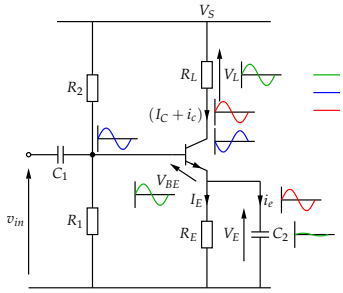
Feedback of Signals in Amplifiers Without Emitter De-coupling



Voltage across a component
Voltage from node to ground
Current through a branch

I_{C_T} and I_{E_T} are formed from a DC component I_C and I_E and an AC (small signal) component i_c and i_e.

Feedback of Signals in Amplifiers with Emitter De-coupling



Voltage across a component
Voltage from node to ground
Current through a branch

1. A signal voltage is impressed on the base with respect to ground (blue)
2. causing a voltage to appear across the base - emitter junction (green)
3. which in turn causes a current in the collector (red)
4. The collector current flows in the emitter also ($i_b = 0$) (red)
5. The emitter resistor drops a voltage, $v = i\,R_E$ (green)
6. Since V_{R_1} is fixed by V_{in} and the ratio of R_1 & R_2, v_{be} must reduce.

The feedback for signals is undesirable so it is removed by de-coupling the emitter resistor ($Z_E = R_E // \frac{1}{2\pi f C_2}$), where C_2 is large enough to dominate Z_E at all frequencies of interest. The feedback for DC conditions is desirable, as it stabilises the operating point. The capacitive de-coupling does not affect the DC conditions because the de-coupling capacitor looks like an open circuit at DC and $Z_E = R_E$.

Drawing the Small Signal Equivalent Circuit

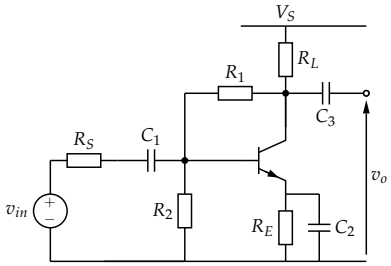
To draw the small signal diagram think about how the signal "sees" the circuit. There are several consequences of considering how the circuit looks to the signal.

- All DC voltage sources (power supplies etc.) are replaced by their Thévenin equivalent impedance (0 Ω).
- All DC current sources are replaced by their Norton equivalent impedance (∞ Ω).
- In small signal problems - in this course - capacitors can often be thought of as open circuit to DC and short circuit to AC.

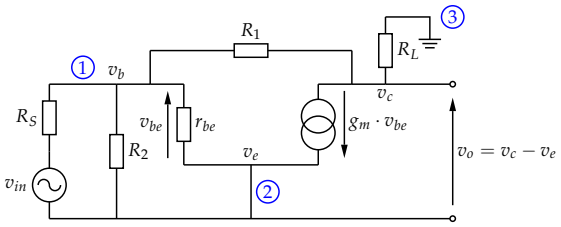
Holding these guidelines in mind, the transistor is replaced terminal for terminal by its small signal model.

An Example Small Signal Circuit Problem

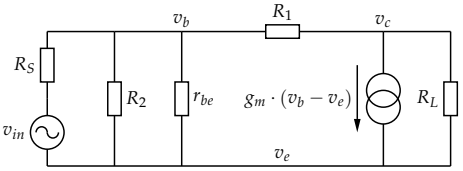
Draw the small signal circuit diagram for the following transistor amplifier,



Solution



1. C_1 looks like a short circuit.
2. C_2 looks like a short circuit, and de-couples R_E.
3. V_S looks like a connection to ground from the signal's point of view.



Remember that the small signal equivalent circuit varies according to the circuit it tries to represent. It is unwise to learn this result. It is wise to learn the skills needed to construct the small signal circuit from the full diagram.

Having arrived at the small signal equivalent circuit, the small signal performance of the circuit can be assessed.

Performance Analysis

What is the voltage gain, $\frac{v_o}{v_{in}}$?
Summing currents at the collector (output) node (note $v_e = 0$!),

$$\frac{v_c - v_e}{R_L} + \frac{v_c - v_b}{R_1} + g_m\,(v_b - v_e) = 0 \qquad (1)$$

Summing currents at the input node,

$$\frac{v_s - v_b}{R_s} + \frac{v_c - v_b}{R_1} = \frac{v_b}{R_2} + \frac{v_b}{r_{be}} \qquad (2)$$

(1) can be transposed to yield,

$$v_b = -\frac{v_c\,(R_1 + R_L)}{g_m\,R_1\,R_L - R_L} \approx -\frac{v_c}{g_m\,R_1 // R_L} \qquad (3)$$

provided $g_m R_1 >> 1$ which is usually true.

(2) can be transposed to yield,

$$v_b = \frac{\frac{v_s}{R_S} + \frac{v_s}{R_1}}{\frac{1}{R_2} + \frac{1}{r_{be}} + \frac{1}{R_S} + \frac{1}{R_1}} \qquad (4)$$

$$= \frac{v_s\,(R_2 // r_{be} // R_S // R_1)}{R_S} + \frac{v_c\,(R_2 // r_{be} // R_S // R_1)}{R_1} \qquad (5)$$

eliminating v_b and transposing to obtain $\frac{v_c}{v_s}$,

$$\frac{v_c}{v_s} = -\frac{R_1}{R_S} \cdot \frac{1}{1 + \frac{R_1}{(g_m R_1 // R_L)(R_2 // r_{be} // R_S // R_1)}} \qquad (6)$$

The value of this result is chiefly that it can tell us how the small signal voltage gain depends on the circuit and transistor parameters. It can be used to estimate gain, but computer simulation packages like SPICE are more suited to this. In this case if $\frac{R_1}{(g_m R_1 // R_L)(R_2 // r_{be} // R_S // R_1)} << 1$ the gain is controlled by the resistors R_1 and R_S, and is largely independent of transistor parameters like g_m and r_{be}.

The feedback caused by R_1 can be removed by setting $R_1 \to \infty$. R_1 disappears from the parallel combinations to yield,

$$\frac{v_c}{v_s} = -\frac{R_1}{R_S}\,\frac{1}{1+\frac{R_1}{g_m R_L(R_2//r_{be}//R_S)}} \tag{7}$$

Since R_1 is very large, the $\frac{R_1}{g_m R_L(R_2//r_{be}//R_S)}$ term will dominate the denominator giving,

$$\frac{v_c}{v_s} = -\frac{R_1}{R_S}\,\frac{1}{\frac{R_1}{g_m R_L(R_2//r_{be}//R_S)}} = -g_m R_L\,\frac{R_2//r_{be}}{R_S + R_2//r_{be}} \tag{8}$$

This expression consists of a gain term, $g_m R_L$ and an input potential division, $\frac{R_2//r_{be}}{R_S+R_2//r_{be}}$. The circuit gain is now dependent on the transistor parameters g_m & r_{be}. The negative feedback effect of R_1 has been removed.

In removing R_1, the circuit has been changed from a small signal equivalent circuit of "circuit two" to "circuit one". The R_1 in circuit one, which is necessary for the correct biasing of the transistor, appears in parallel with R_2 in the small signal model (remember that the V_S rail is small signal ground). Hence adjusting the value of R_1 in circuit one will change the effective value of R_2 (they appear in parallel), but will not change the small signal diagram.

Each circuit shape produces its own result for gain and other performance measures so memorising these results is not wise - learning *how* to derive them and interpret their meaning is...

Some other metrics of performance that can be derived are, input impedance ($\frac{v_s}{i_s}$), output impedance (drive a test current i_t into the collector and find the effect on v_c) and power gain, among others.

Homework 4

It should be possible to *fully* attempt the Homework 4 now.

It should also be possible to fully attempt the Rectifiers and Smoothing problem sheet.

It should also be possible to fully attempt the Transistors as Switches and Amplifiers problem sheet.

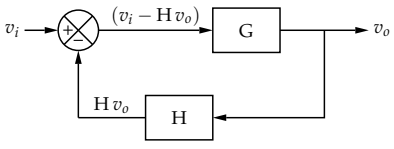
Operational Amplifiers (Opamps)

- An Opamp is an integrated circuit composed of between 10 and ∼50 transistors (BJT, MOS or JFET) which implements certain functionality making it useful as an "analogue building block".
- Opamps have been in use since about 1930, the originals being valve based.
- Opamps are designed to have,
  - differential inputs (two inputs which it subtracts)
  - very high input resistance ($> 10^9\ \Omega$)
  - very low output resistance ($< 50\ \Omega$)
  - very high gain ($\sim 10^5$ is typical)

Opamps are designed to be used with feedback. Therefore, some discussion of feedback is required to understand opamps.

A Classical Feedback System

To understand why the opamp is designed to have the features outlined on the last slide consider a classical feedback system.



- The output voltage is v_o.
- A portion of the output, $H\,v_o$, is fed back to the input.
- This portion is subtracted from v_i,
- leaving $(v_i - H\,v_o)$ at the input of the gain stage, G.

We can write these statements in the form of an equation,

$$v_o = G\,(v_i - H\,v_o) \tag{9}$$

or,

$$\frac{v_o}{v_i} = \text{gain} = \frac{G}{1+G\,H} \tag{10}$$

If G is very large, then $G\,H >> 1$ and,

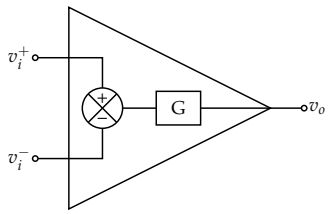
$$\frac{v_o}{v_i} \approx \frac{G}{G\,H} = \frac{1}{H} \tag{11}$$

This is an interesting result because it shows that if G is very large, the system gain depends only on H.

H is usually defined by resistors and capacitors - which the designer has a high degree of control over. Only resistors in EEE118.

The Opamp

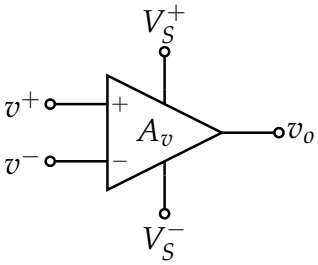
The opamp integrates two parts of the classical feedback system.



- The input resistance must be high so that the v^- input does not affect the network that defines H and so that the v^+ input does not affect the signal source.

- The output resistance must be low so that the system can drive a load without v_o begin affected and so that the system can drive the network defining H without being affected.
- The reason for the differential input and the high gain are shown by (11).

The opamp is usually drawn as,



- V_S^+ and V_S^- are the power supplies. They are often not included on circuit diagrams but *must* be connected in the real circuit. v_o cannot go outside the range $V_S^+ > v_o > V_S^-$
- v^+ is called the "non-inverting" input. It is identified by a "+" next to the input line, inside the opamp triangle.
- v^- is called the "inverting" input. It is identified by a "-".
- The output, v_o, comes from the point of the amplifier symbol.
- A_v is the voltage gain (equivalent to G) which relates the output and input by the opamp equation,

$$v_o = A_v \cdot (v^+ - v^-) \tag{12}$$

A_v operates on the difference between v^+ and v^- to produce v_o.

Review

- Looked at feedback for signals and for DC (quiescent) conditions in a one transistor amplifier with and without emitter decoupling
- The situation where $R_L = R_E$ is called a "phase splitter".
- Looked at the small signal equivalent circuit of a BJT in terms of a one transistor amplifier
- Gave an example of a performance evaluation
- Noted that the value of the small signal circuit is to show which device and circuit affect the gain, not to give a numerical value (although this is possible.)
- Introduced the idea of an "analogue building block" - opamp
- presented the opamp as an implementation of a classical feedback system.
- Derived the opamp equation and presented a circuit symbol for an opamp.



EEE118: Electronic Devices and Circuits

Lecture XVII

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

- Looked (again) at Feedback for signals and for DC (quiescent) conditions in a one transistor amplifier with and without emitter decoupling
- The situation where $R_L = R_E$ is called a "phase splitter".
- Looked at the small signal equivalent circuit of a BJT in terms of a one transistor amplifier
- Gave an example of a performance evaluation
- Noted that the value of the small signal circuit is to show which device and circuit affect the gain, not to give a numerical value (although this is possible.)
- Introduced the idea of an "analogue building block" - opamp
- presented the opamp as an implementation of a classical feedback system.
- Derived the opamp equation and presented a circuit symbol for an opamp.

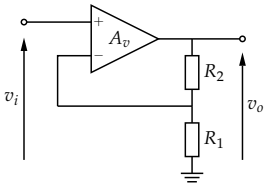
Outline

1. Opamp Circuits
   - $A_v \to \infty$: Non-Inverting
   - $A_v \to \infty$: Inverting
   - $A_v \neq \infty$ Non-Inverting
   - $A_v \neq \infty$ Inverting
2. Special Case: Unity Gain Buffer
3. Circuits with Multiple Inputs
   - Summing Amplifier
   - Subtractor or Difference Amplifier
4. A General Multiple Input Circuit
5. Homework 5
6. Review
7. Bear

Opamp Circuits - Non Inverting

The most common opamp circuits are the "non-inverting amplifier" and the "inverting amplifier".

It is usual to assume initially that $A_v \to \infty$. This means that the circuit behaviour is completely controlled by the feedback. If $A_v = \infty$, for finite v_o then $v^+ \approx v^-$ and this makes the calculation quite straightforward.



$$v^- = v_o \frac{R_1}{R_1 + R_2} \quad (1)$$

$$v^+ = v_i \text{ and } v^+ = v^- = v_i \quad (2)$$

$$v_i = v_o \frac{R_1}{R_1 + R_2} \quad (3)$$

$$\frac{v_o}{v_i} = \frac{R_1 + R_2}{R_1} \quad (4)$$

Opamp Circuits - Inverting

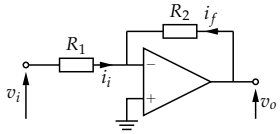
In the inverting amplifier v^+ is grounded and v_i is applied to R_1. If $A_v = \infty$, $v^+ = v^-$ and since v^+ is connected to ground v^- must be very close to ground. It is often called a virtual earth. The potential is always close to zero but the node is *not* actually connected to zero. To obtain the gain sum currents at the v^- node.

$$i_i + i_f = 0 \quad (5)$$

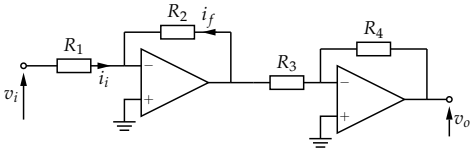
$$\frac{v_i - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0 \quad (6)$$

$v^- = 0$ so $\frac{v_i}{R_1} + \frac{v_o}{R_2} = 0$ (7)

$$\frac{v_o}{v_i} = -\frac{R_2}{R_1} \quad (8)$$



- Notice the "-" sign in the inverting gain formula. This means that the signal is *inverted* i.e. phase shifted by 180° as well as being amplified.
- Two inverting amplifiers in series would give rise to an overall non-inverting amplifier. The first stage would invert the signal and the second would invert it back to its original phase.



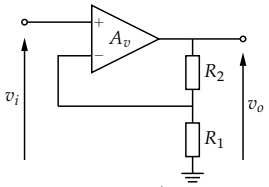
Effects of Finite Gain

Occasionally it is necessary to consider the effect of finite A_v on the overall gain of the circuit. When considering the effects of finite gain the approximation $v^+ \approx v^-$ does not hold.

As before, using potential division at the output,

$$v^- = v_o \frac{R_1}{R_1 + R_2} \quad (9)$$

$$v^+ = v_i \quad (10)$$



But now the opamp equation must be used to relate v^+, v^- and v_o,

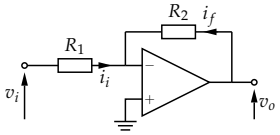
$$v_o = A_v \left(v^+ - v^-\right) = A_v \left(v_i - v_o \frac{R_1}{R_1 + R_2}\right) \quad (11)$$

$$\text{or, } v_o \left[\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}\right] = v_i \quad (12)$$

$$\text{or, } \frac{v_o}{v_i} = \frac{1}{\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}} \quad (13)$$

- Note if $A_v \to \infty$, $\frac{1}{A_v}$ becomes very small and (13) becomes (4).
- A_v is equivalent to G in the classical feedback system.
- It is between several thousand and several hundred thousand in most opamps.
- A_v is actually frequency dependent, but the frequency dependence of A_v is not covered in this course.

For the inverting case start as before, by summing currents at the v^- node,



$$i_i + i_f = 0 \text{ or } \frac{v_i - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0 \quad (14)$$

which can be transposed to yield,

$$v^- = v_i \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2} \quad (15)$$

$$\text{and } v^+ = 0 \quad (16)$$

Using the opamp equation

$$v_o = A_v \left(0 - \left[v_i \frac{R_2}{R_1 + R_2} + v_o \frac{R_1}{R_1 + R_2}\right]\right) \quad (17)$$

$$\text{or } v_o \left[\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}\right] = -v_i \frac{R_2}{R_1 + R_2} \quad (18)$$

$$\text{or } \frac{v_o}{v_i} = \frac{-\frac{R_2}{R_1 + R_2}}{\frac{1}{A_v} + \frac{R_1}{R_1 + R_2}} \quad (19)$$

If $A_v \to \infty$, $\frac{v_o}{v_i}$ reduces to (8).

- Frequency dependent amplifiers (filters) can be produced by using frequency dependent passive components (inductors and, more usually, capacitors) in place of the resistors.
- R_1 and R_2 can become Z_1 and Z_2 and may be arbitrarily complex passive circuits.
- Particular arrangements of resistors and capacitors in opamp circuits can be used to produce circuits which perform mathematical functions such as integration and differentiation.

Input Resistance

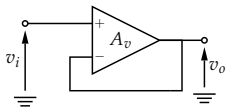
- The input to the non inverting circuit goes directly to the opamp so the circuit input resistance is the same as the opamp - very large ($\sim 10^9$).
- The inverting circuit is slightly different. Taking the $A_v \to \infty$ case, an input current, i_i, of $\frac{v_i}{R_1}$ flows from the source.
- Input resistance is the ratio of the applied signal voltage to the current drawn, i.e. $\frac{v_i}{i_i} = R_1$.
- This is typically a few kΩ which makes inverting amplifiers unsuitable as amplifiers of signals derived from sources with a large thévenin resistance.

Unity Gain Buffer

The unity gain buffer is a special case of the non inverting amplifier, in which $R_2 = 0$ and $R_1 = \infty$. Here $v^- = v_o$ so the opamp equation becomes,

$$v_o = A_v \left(v^+ - v^-\right) = A_v \left(v_i - v_o\right) \quad (20)$$

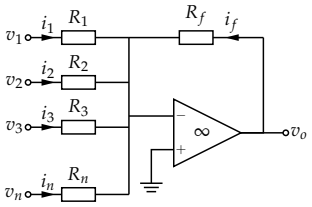
$$\text{or } \frac{v_o}{v_i} = \frac{1}{\frac{1}{A_v} + 1} = \frac{A_v}{1 + A_v} \quad (21)$$



If A_v is large, $\frac{v_o}{v_i}$ is very close to unity. This circuit is used to isolate high impedance sources from low impedance loads; i.e. it has a high power gain.

Summing Amplifier

Assume $A_v \to \infty$ so $v^- \to$ virtual earth (i.e. 0 V)



$$i_f + i_1 + i_2 + i_3 + i_n = 0$$

$$\frac{v_o}{R_f} + \frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} + \frac{v_n}{R_n} = 0$$

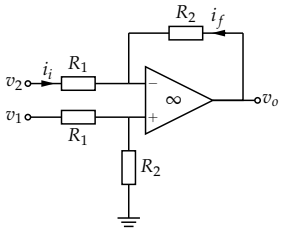
or,

$$v_o = -\left[v_1\frac{R_f}{R_1} + v_2\frac{R_f}{R_2} + v_3\frac{R_f}{R_3} + v_n\frac{R_f}{R_n}\right]$$

Many audio "mixers" use this circuit.

Subtracting Amplifier

Several avenues of solution are available for this circuit. Assume $A_v = \infty$ and so $v^+ = v^-$.



One approach is to work out v^+ and v^- and then equate them to get v_o in terms of v_1 and v_2. Summing currents at the v^- node,

$$i_i + i_f = 0 \text{ or } \frac{v_2 - v^-}{R_1} + \frac{v_o - v^-}{R_2} = 0 \qquad (22)$$

This can be transposed to give,

$$v^- = v_2\frac{R_2}{R1 + R_2} + v_o\frac{R_1}{R_1 + R_2} \qquad (23)$$

v^+ is a potentially divided version of v_1

$$v^+ = v_1\frac{R_2}{R_1 + R_2} \qquad (24)$$

equating v^+ and v^-,

$$v_2\frac{R_2}{R_1 + R_2} + v_o\frac{R_1}{R_1 + R_2} = v_1\frac{R_2}{R_1 + R_2} \qquad (25)$$

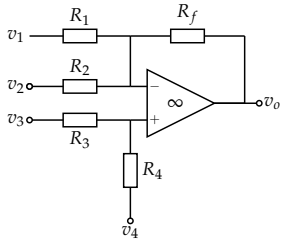
$$\text{or } v_o\frac{R_1}{R_1 + R_2} = v_1\frac{R_2}{R_1 + R_2} - v_2\frac{R_2}{R_1 + R_2} \qquad (26)$$

$$\text{or } v_o = \frac{R_2}{R_1}(v_1 - v_2) \qquad (27)$$

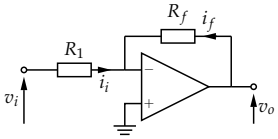
Note that the accuracy of the subtraction depends upon matching the the two R_1's and R_2's.

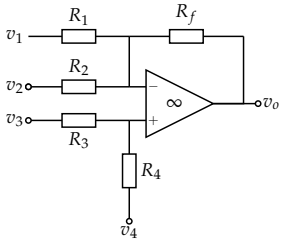
A General Multiple Input Circuit

The subtractor circuit can be generalised to allow more than two inputs. Such a circuit could be analysed by find v^+ and v^- and equating them, or by using the principle of superposition. Superposition has the advantage that at each stage the circuit is reduced to a much simpler single input circuit. For example,



Consider first the output due to v_1. v_2, v_3 and v_4 are grounded. The circuit becomes an inverting amplifier.





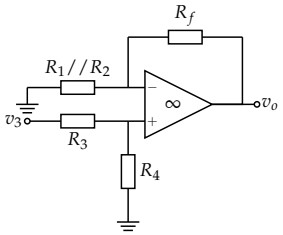
Since both v_3 and v_4 are zero v^+ is zero and v^- is a virtual earth. No current flows through R_2 so it has no effect on the circuit.

$$v_o|_{v_1} = v_1\left(\frac{-R_f}{R_1}\right) \qquad (28)$$

By changing the variable names the output voltage due to v_2 can be found,

$$v_o|_{v_2} = v_2\left(\frac{-R_f}{R_2}\right) \qquad (29)$$

The output due to v_3 leads to a more complex circuit however.



Here v_1 and v_2 are grounded so R_1 is effectively in parallel with R_2. v^+ is a potentially divided version of v_3. So,

$$\frac{v_o}{v^+} = \frac{R_f + R_1//R_2}{R_1//R_2} \qquad (30)$$

$$\frac{v_o}{v_3} = \frac{R_4}{R_3 + R_4} \qquad (31)$$

$$\therefore \frac{v_o}{v_3} = \frac{v_o}{v^+} \cdot \frac{v^+}{v_3} = \frac{R_4}{R_3 + R_4} \cdot \frac{R_f + R_1//R_2}{R_1//R_2} \tag{32}$$

$$\text{or } v_+|_{v_3} = v_3 \frac{R_4}{R_3 + R_4} \cdot \frac{R_f + R_1//R_2}{R_1//R_2} \tag{33}$$

By a similar argument,

$$v_o|_{v_4} = v_4 \frac{R_3}{R_3 + R_4} \cdot \frac{R_f + R_1//R_2}{R_1//R_2} \tag{34}$$

$$v_{o_{\text{total}}} = \frac{v_o}{v_1} + \frac{v_o}{v_2} + \frac{v_o}{v_3} + \frac{v_o}{v_4} \tag{35}$$

Note: if any of the inputs have both a DC and AC component, superposition allows them to be treated separately.

Homework 5

It should be possible to fully attempt the Homework 5 now.

It should also be possible to fully attempt the Operational Amplifiers problem sheet.

Review

Considered circuit diagrams for a common set of opamp circuits and derived results for the output voltage due to one or more inputs:

- Non inverting amplifier with $A_v = \infty$
- Inverting amplifier with $A_v = \infty$
- Non inverting amplifier with $A_v \neq \infty$
- Inverting amplifier with $A_v \neq \infty$
- Unity gain buffer
- Multiple input circuits
  - Summing Amplifier
  - Difference Amplifier (Subtractor)
- General multiple input opamp circuit



(Some) Past Exam Papers

Written Solutions available via MOLE

Data Provided: None

The University Of Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2013-14 (3.0 hours)

EEE118 Electronic Devices & Circuits 1

Answer **FOUR** questions. **No marks will be awarded for solutions to a fifth question.** Solutions will be considered in the order that they are presented in the answer book. Trial answers will be ignored if they are clearly crossed out. **The numbers given after each section of a question indicate the relative weighting of that section.**

You may require the following:

Electronic charge, $e = 1.6\times10^{-19}$C

Permittivity of free space, $\varepsilon_0 = 8.85\times10^{-12}$ Fm^{-1}

Boltzmann's constant, $k = 1.38\times10^{-23}$ JK^{-1}

Planck's constant, $h = 6.6\times10^{-34}$ Js

Energy of a photon $= hc/\lambda$

Poisson's Equation $\dfrac{d^2V}{dx^2} = -\dfrac{ne}{\varepsilon}$

$$E = -\frac{dV}{dx}$$

$$W = \left[\frac{2\varepsilon V_o}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

$$J = eD\frac{dn}{dx}$$

$$J_0 = \frac{eL_e n_p}{\tau_e} + \frac{eL_h p_n}{\tau_h} \quad and \quad J = J_0\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

$$n_p p_p = n_n p_n = n_i^2$$

$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \gamma B$$

$$\partial p = \partial p_0 \exp\left(\frac{-x}{L_h}\right)$$

$$L = \sqrt{D\tau}$$

$$\sigma = ne\mu_e + pe\mu_h \qquad \rho = \frac{1}{\sigma}$$

$$C = \frac{\varepsilon A}{d}$$

$$D = \frac{kT}{e}\mu$$

$$v = \mu E$$

Resistance $R = \rho L/A$

For silicon: relative permittivity $\varepsilon_r = 12$ built-in voltage = 0.7 V

electron mobility = 0.07 m^2/Vs hole mobility = 0.045 m^2/Vs

band gap = 1.12 eV

1. This question is about diodes and some common circuits that contain diodes.

a. The diode in figure 1a has a forward voltage drop of 0.7V but is otherwise ideal.

For the circuit of figure 1a,

i) Show that the diode is conducting. (*Hint: Assume it is not conducting, then use circuit analysis to show your assumption is incorrect*). **(4)**

ii) Find the forward conduction current through the diode. **(3)**

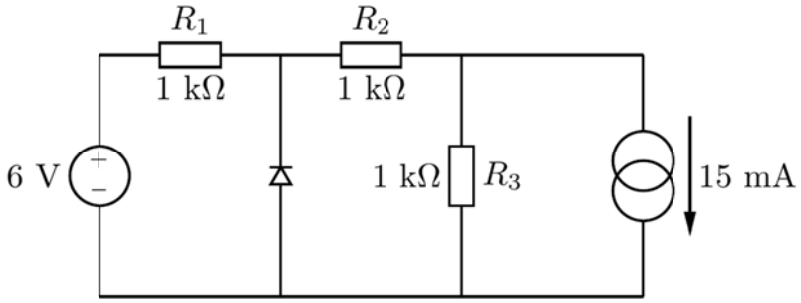


Figure 1a

b. The circuit in figure 1b is a rectifier circuit which will be used to produce a linear power supply.

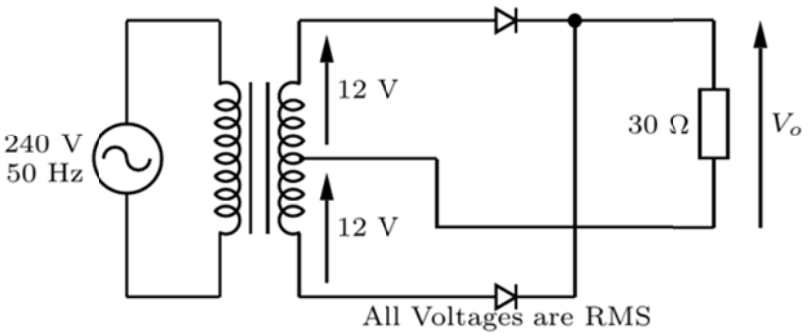


Figure 1b

i) State what kind of rectifier circuit figure 1b shows. **(1)**

ii) Sketch on labelled axes, the load voltage, V_L **(2)**

iii) State the peak magnitude and frequency of the current flowing through the load. **(2)**

iv) A capacitor is added in parallel with the load to smooth the output voltage. Calculate a suitable value for this capacitor if the output voltage ripple must be less than 2 V peak to peak. Assume the ripple voltage waveform is triangular. **(4)**

c The power supply in part 1b is now required to power some measurement circuitry and the output voltage ripple should be reduced using a Zener diode shunt regulator.

The Zener diode has a reverse breakdown voltage of 9 V and requires 4 mA to maintain proper operation. The measurement circuitry requires a minimum of 20 mA in standby mode and a maximum of 500 mA when fully operational.

i) Sketch a suitable Zener diode shunt regulator circuit **(2)**

ii) Find the largest resistor value which will allow proper regulation. **(3)**

iii) Suggest (with calculations) a suitable power rating for the resistor **(2)**

iv) Calculate the power dissipated in the diode when the circuit is on standby and when it is fully operational. **(2)**

2. **a.** Carefully sketch the I/V characteristic of a p-n junction diode showing both the forward and reverse bias and paying attention to the region around zero bias. Identify the reverse leakage current and the forward dynamic resistance in terms of the I/V slope at any particular bias. **(4)**

How does this resistance vary with forward bias? **(2)**

b. A silicon p-n diode forms the emitter-base junction of a p-n-p bipolar transistor and is doped as follows:

$p = 7x10^{25}\ m^{-3}, \quad n = 7x10^{23}\ m^{-3}$

Calculate the emitter injection efficiency. Assume that the current due to each carrier is proportional to the conductivity of the semiconductor from where it originates. **(4)**

Calculate the current gain if the base transport factor, $B = 1$. **(2)**

c. Describe the main contributing mechanism which results in the small reverse leakage current in a p-n junction? **(3)**

Would you expect the reverse biased leakage current to increase or decrease:

i. when using a semiconductor with an increased bandgap or bond strength? **(2)**

ii. at a lower diode temperature? **(2)**

d. The reverse leakage current in a p-n junction at room temperature is 1×10^{-6} A. What applied forward junction voltage will give a current of 1×10^{-2} A? In your calculation assume that the exponential term in the diode equation is >> 1. **(4)**

The actual measured voltage across the diode terminals required to give this current is 25 mV higher than the value calculated above. Explain why this happens? **(2)**

3. This question is about transistors both as switches and amplifiers.

a. Using the information provided in figure 3a find,

i) the load current when the transistor has been on for a long time. **(1)**

ii) the energy stored in the inductor assuming the transistor has been switched on for a long time. **(1)**

iii) the power dissipated in the load. **(1)**

iv) the power dissipated in the switch. **(1)**

v) the base resistance, R_B. **(1)**

vi) the NPN bipolar transistor in figure 3a is replaced with an N-channel MOSFET. What value of $r_{ds(on)}$ would the MOSFET need to have in order to yield the same on-state power dissipation as the bipolar transistor. **(4)**

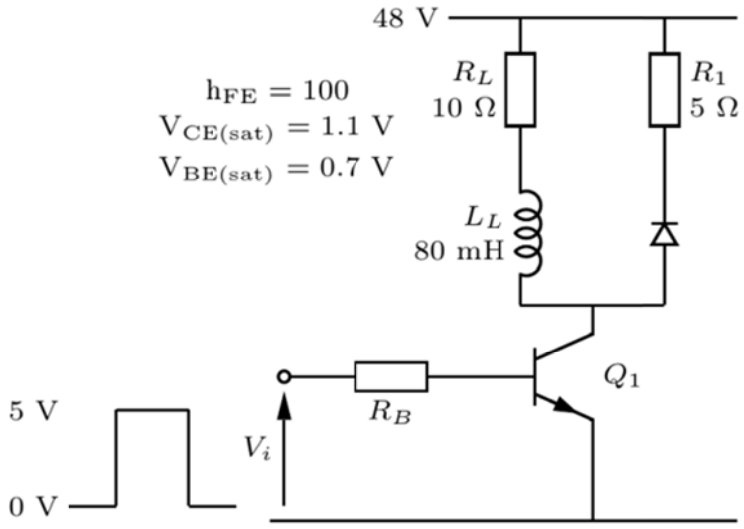


Figure 3a

b. For the amplifier in figure 3b calculate the DC conditions. (*Collector current, load voltage, collector voltage, emitter voltage, base current, emitter current and the current in the base biasing network (I_1)*). Assume that the transistor V_{BE} is 0.7 V in the forward active region and β = 150. State all other assumptions clearly. **(9)**

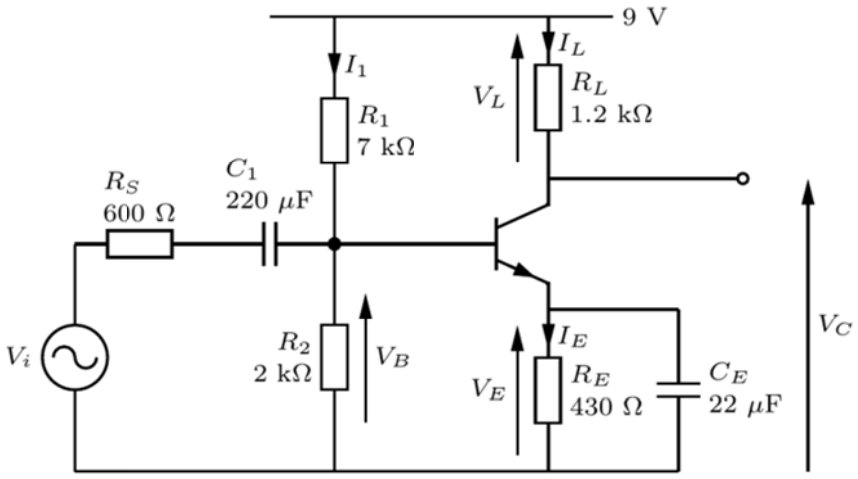


Figure 3b

c. Using a small signal equivalent circuit, find,

i) an expression for the small signal voltage gain for the amplifier in figure 3b. It is acceptable to use // to represent components which appear in parallel. **(5)**

ii) a numerical value for the gain, stating any assumptions. **(2)**

4. **a.** i. Using sketches briefly describe the operation of the n-channel JFET and n-channel MOSFET planar devices. You should highlight the main differences between the two, including how the gate bias controls the drain current in each case. **(14)**

ii. Identify the 'on' and 'off' gate bias conditions for each when operated as a switch. **(4)**

b. i. Using data and equations from page 1 calculate the time it takes for an electron to travel underneath a 1 μm long gate in an n-channel Si MOSFET. You should assume a lateral electric field of 5×10^6 Vm^{-1} under the gate region. **(4)**

ii. Why is this delay time important when designing high frequency or fast switching MOSFETs? **(3)**

5. **a.** Boron (group 3) is used to dope a piece of silicon semiconductor to a concentration of 1 x 10^{24} m^{-3}. Explain on an atomic scale why this results in p-type material with a hole produced for every boron atom introduced into the lattice. **(6)**

b. Will the hole concentration change significantly as the temperature is increased by 50 ^{o}C above room temperature? Under the same temperature increase will the fractional change in charge carriers be higher for intrinsic (undoped) material? Justify your answers. **(4)**

c. Calculate the concentration of minority electrons in this material (n_i =1 x 10^{16} m^{-3} for silicon at room temperature). **(3)**

d. What is the conductivity resulting from this doping? **(3)**

e. Compare this with the conductivity component due to the minority electrons **(3)**

f. Calculate the resistance between opposite faces of a cube of 1 mm edge dimension made from this doped silicon. **(3)**

g. What is the resistance between the end faces of a cube where the edge dimension is doubled? **(3)**

6. a. **i)** Draw a diagram of an inverting opamp circuit **(2)**

ii) Draw an arrow on your diagram pointing to the "virtual earth" **(1)**

iii) State briefly how the "virtual earth" is created and maintained. **(3)**

iv) State the input resistance of the inverting opamp circuit. **(1)**

v) Derive an expression for the gain of the circuit assuming $\boldsymbol{A_v \rightarrow \infty}$. **(3)**

vi) Show that $\frac{v_o}{v_i} = \frac{-R_f}{R_i + \frac{1}{A_v}[R_i + R_f]}$ assuming A_v is finite. **(5)**

b. Consider the multiple input opamp circuit in figure 6b.

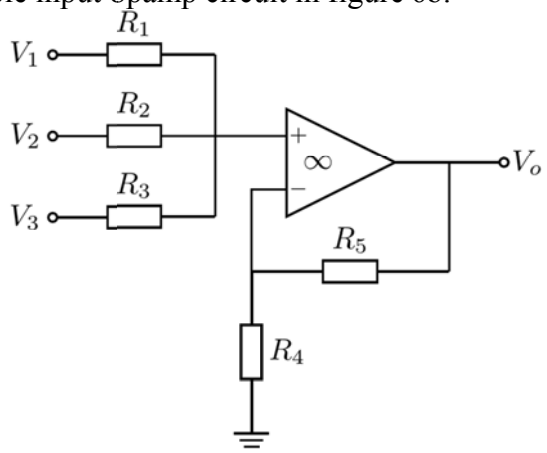


Figure 6b

i) Find the output voltage as a function of the input voltages. **(3)**

ii) Based on your answer to 6. b. i. deduce and state briefly the function of the circuit. **(1)**

c. The opamp circuit in figure 6c is a "subtracting circuit" and is also called a "difference amplifier".

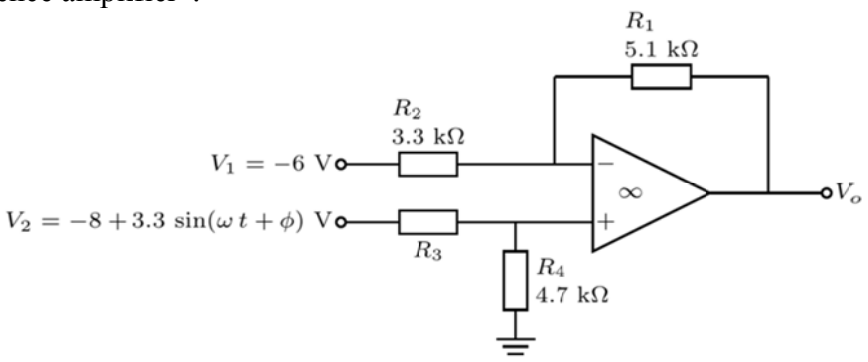


Figure 6c

i) Find, algebraically, the DC output voltage as a function of the input voltages. **(4)**

ii) Hence or otherwise calculate the value of R_3 needed to yield $V_o = 0$ V for the inputs in figure 6. c. **(2)**

PAH / JEG/JPRD

Data Provided: None

The University Of Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2014-15 (3.0 hours)

EEE118 Electronic Devices & Circuits 1

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Permittivity of free space, $\varepsilon_0 = 8.85\times10^{-12}$ Fm^{-1}

Boltzmann's constant, $k = 1.38\times10^{-23}$ JK^{-1}

Planck's constant, $h = 6.6\times10^{-34}$ Js

Energy of a photon $= hc/\lambda$

Poisson's Equation $\dfrac{d^2V}{dx^2} = -\dfrac{ne}{\varepsilon}$

$$E = -\frac{dV}{dx}$$

$$W = \left[\frac{2\varepsilon V_o}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

$$J = eD\frac{dn}{dx}$$

$$J_0 = \frac{eL_e n_p}{\tau_e} + \frac{eL_h p_n}{\tau_h} \quad and \quad J = J_0\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

$n_p p_p = n_n p_n = n_i^2$

$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \gamma B$$

$$\partial p = \partial p_0 \exp\left(\frac{-x}{L_h}\right)$$

$$L = \sqrt{D\tau}$$

$$\sigma = ne\mu_e + pe\mu_h \qquad \rho = \frac{1}{\sigma}$$

$$C = \frac{\varepsilon A}{d}$$

$$D = \frac{kT}{e}\mu$$

Resistance $R = \rho L/A$

$v = \mu E$

For silicon: relative permittivity $\varepsilon_r = 12$ built-in voltage = 0.7 V

electron mobility = 0.07 m^2/Vs hole mobility = 0.045 m^2/Vs

band gap = 1.12 eV

1. This question is about diodes and some common circuits that contain diodes.

a. Figure 1a shows a peak detector circuit. The peak detector is driven by a sinusoidal input of much higher frequency than the time constant $R_1 \cdot C_1$, and has been running for a long time.

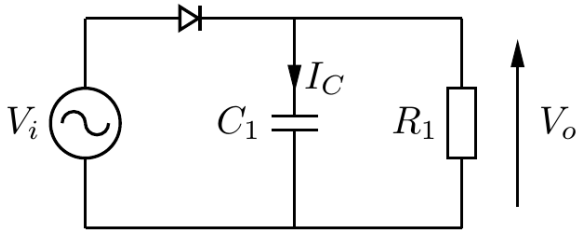


Figure 1a

i) On a single graph sketch, V_i, I_C and V_o over at least one full cycle of the sinusoidal input. **(6)**

ii) Describe the operation of the circuit over one full cycle. *Hint: Pay particular attention to the conduction state of the diode, the direction of current flow in the capacitor.* **(4)**

b. A peak detector can be connected to another circuit and the two combine to form a new circuit which acts as a voltage multiplier.

i) Sketch the circuit diagram of the voltage multiplier and label the components. **(3)**

ii) Name the additional circuit and indicate the components associated with it on the sketch. **(1)**

c. The circuit of figure 1b consists initially of R_1 and C_1. Sketch the V_o you would expect to observe in response to the 0V to 15V pulse input shown. The pulse width is 200 μs. Include on your sketch both the leading and trailing edge responses of the input pulse and label all time constants and peak voltages. **(4)**

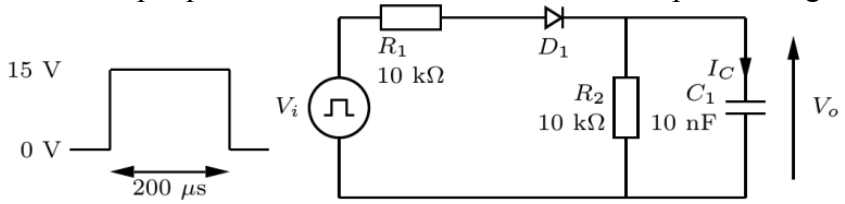


Figure 1b

d. A resistor, R_2 and an ideal diode, D_1 are now added to the circuit to form figure 1b. Sketch the I_C that you would expect to observe in response to the input shown in figure 1b. Label your sketch with peak values and time constants. **(6)**

2. **a.** Carefully sketch the I/V characteristic of a p-n junction diode showing both the forward and reverse bias and paying attention to the region around zero bias. Identify the reverse leakage current and the forward dynamic resistance in terms of the I/V slope at any particular bias. **(4)**

How does this resistance vary with forward bias? **(2)**

b. A silicon p-n diode forms the emitter-base junction of a p-n-p bipolar transistor and is doped as follows:

$p = 7x10^{25}\ m^{-3}, \quad n = 7x10^{23}\ m^{-3}$

Calculate the emitter injection efficiency. Assume that the current due to each carrier is proportional to the conductivity of the semiconductor from where it originates. **(4)**

Calculate the current gain if the base transport factor, $B = 1$. **(2)**

c. Describe the main contributing mechanism which results in the small reverse leakage current in a p-n junction? **(3)**

Would you expect the reverse biased leakage current to increase or decrease:

i. when using a semiconductor with an increased bandgap or bond strength? **(2)**

ii. at a lower diode temperature? **(2)**

d. The reverse leakage current in a p-n junction at room temperature is 1×10^{-6} A. What applied forward junction voltage will give a current of 1×10^{-2} A? In your calculation assume that the exponential term in the diode equation is >> 1. **(4)**

The actual measured voltage across the diode terminals required to give this current is 25 mV higher than the value calculated above. Explain why this happens? **(2)**

3. This question is about transistors both as switches and amplifiers.

a. Using the information provided in figure 3a find,

i) the load current, I_L, when the transistor has been on for a long time. **(1)**

ii) the energy stored in the inductor assuming the transistor has been switched on for a long time. **(1)**

iii) the power dissipated in the load when the switch is on. **(1)**

iv) the power dissipated in the switch when the switch is on. **(1)**

v) I_D, I_L and I_S immediately after the switch turns off. **(3)**

vi) V_{DS} immediately after the switch turns off. **(2)**

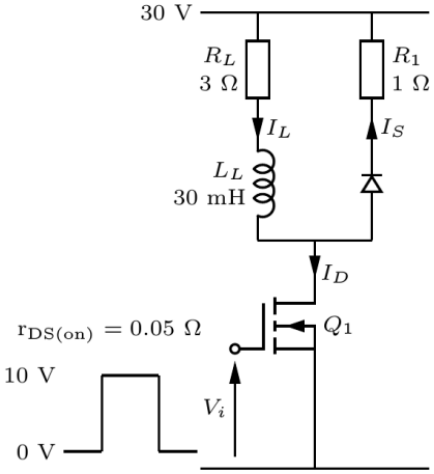


Figure 3a

b. **i)** For the amplifier in figure 3b calculate the quiescent value of V_B, V_C, I_C and the small signal parameters g_m and r_{be}. Assume that the transistor V_{BE} is 0.7 V in the forward active region and β = 700. State any other assumptions clearly. **(5)**

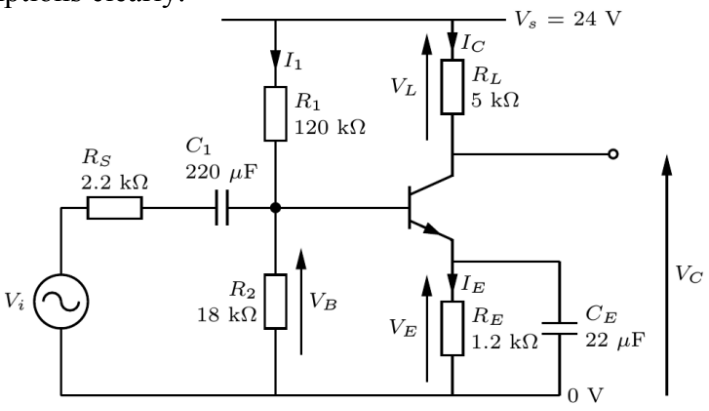


Figure 3b

ii) Sketch a graph showing V_C, V_B, V_E, the power supply voltage and the reference (0 V) over several cycles of the sine wave input siganal. Assume that the amplifier is being driven to the point of 'clipping', where the peak to peak AC voltage swing on the collector, V_C, is as large as possible without significant distortion. **(4)**

iii) Calculate the quiescent V_C for this amplifier which will maximise the possible collector voltage signal swing. **(2)**

c. **i)** Draw a small signal equivalent circuit for the amplifier in figure 3b. **(4)**

ii) Evaluate the input resistance in the 'mid-band' i.e. where all of the capacitors are short circuit. *Hint: R_S is the source resistance and does not form part of the input resistance.* **(1)**

4. **a.** i. Using sketches briefly describe the operation of the n-channel JFET and n-channel MOSFET planar devices. You should highlight the main differences between the two, including how the gate bias controls the drain current in each case. **(14)**

ii. Identify the 'on' and 'off' gate bias conditions for each when operated as a switch. **(4)**

b. i. Using data and equations from page 1 calculate the time it takes for an electron to travel underneath a 1 μm long gate in an n-channel Si MOSFET. You should assume a lateral electric field of 5×10^6 Vm^{-1} under the gate region. **(4)**

ii. Why is this delay time important when designing high frequency or fast switching MOSFETs? **(3)**

5. **a.** Boron (group 3) is used to dope a piece of silicon semiconductor to a concentration of 1 x 10^{24} m^{-3}. Explain on an atomic scale why this results in p-type material with a hole produced for every boron atom introduced into the lattice. **(6)**

b. Will the hole concentration change significantly as the temperature is increased by 50 ^{o}C above room temperature? Under the same temperature increase will the fractional change in charge carriers be higher for intrinsic (undoped) material? Justify your answers. **(4)**

c. Calculate the concentration of minority electrons in this material (n_i =1 x 10^{16} m^{-3} for silicon at room temperature). **(3)**

d. What is the conductivity resulting from this doping? **(3)**

e. Compare this with the conductivity component due to the minority electrons **(3)**

f. Calculate the resistance between opposite faces of a cube of 1 mm edge dimension made from this doped silicon. **(3)**

g. What is the resistance between the end faces of a cube where the edge dimension is doubled? **(3)**

6. **a.** Draw the circuit symbol for an opamp and label,

i) The inverting input. **(1)**

ii) The non-inverting input. **(1)**

iii) The output. **(1)**

iv) The power supplies. **(2)**

b. Draw an opamp circuit containing a "virtual earth". Describe the term and explain how it is maintained. **(6)**

c. The circuit in figure 6a is a transimpedance amplifier.

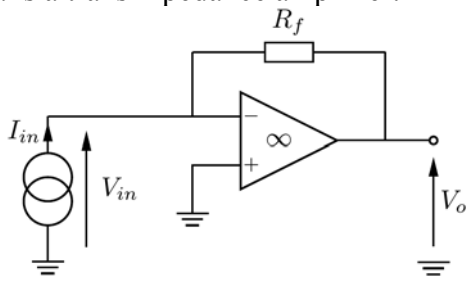


Figure 6a

i) What function does the transimpedance amplifier perform? **(1)**

ii) Derive an expression for $\frac{V_o}{I_{in}}$ assuming A_v is infinite. **(3)**

iii) The input resistance is given by $\frac{V_{in}}{I_{in}}$. Show that $R_{in} = \frac{R_f}{A_v}$ when A_v is finite **(5)**

d. **i)** Show that V_o in figure 6b is given by $V_o = V_2 - V_1$ **(4)**

ii) Suggest a suitable name for this circuit **(1)**

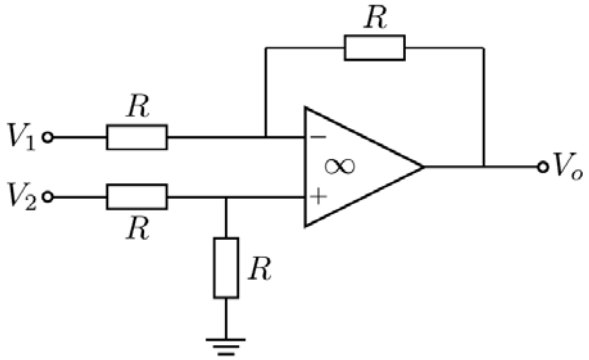


Figure 6b

PAH / JEG/JPRD

Data Provided: None

The University Of Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2015-16 (3.0 hours)

EEE118 Electronic Devices & Circuits 1

Answer **FOUR** questions. **No marks will be awarded for solutions to a fifth or sixth question.** Solutions will be considered in the order that they are presented in the answer book. Trial answers will be ignored if they are clearly crossed out. **The numbers given after each section of a question indicate the relative weighting of that section.**

You may require the following:

Electronic charge, $e = 1.6 \times 10^{-19}$ C

Permittivity of free space, $\varepsilon_0 = 8.85 \times 10^{-12}$ Fm^{-1}

Boltzmann's constant, $k = 1.38 \times 10^{-23}$ JK^{-1}

Planck's constant, $h = 6.6 \times 10^{-34}$ Js

Poisson's Equation, $\frac{d^2V}{dx^2} = -\frac{ne}{\varepsilon}$

Energy of a photon = hc/λ

$$E = -\frac{dV}{dx}$$

$$W_d = \left[\frac{2(V_0 - V)\varepsilon}{e}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

$$J = eD\frac{dn}{dx}$$

$$J_0 = \frac{e\,L_e\,n_p}{\tau_e} + \frac{e\,L_h\,p_n}{\tau_h}$$

$$J = J_0\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

$$n_i = C\,T^{3/2}\exp\left(-\frac{E_g}{2k_B T}\right)$$

$$B = 1 - \frac{1}{2}\left(\frac{l_b}{L_e}\right)^2$$

$$\alpha = \gamma B$$

$$\sigma = ne\mu_e + pe\mu_h$$

$$n_p p_p = n_n p_n = n_i^2$$

$$\beta = \frac{\alpha}{1-\alpha}$$

$$\rho = \frac{1}{\sigma}$$

$$v = \mu E$$

$$C = \frac{\varepsilon A}{d}$$

$$D = \frac{kT}{e}\mu$$

For silicon: relative permittivity $\varepsilon_r = 12$; built-in voltage = 0.7 V; electron mobility = 0.07 m^2/Vs; hole mobility = 0.045 m^2/Vs; band gap = 1.12 eV.

1. This question is about diodes and circuits that contain diodes.

a. Figure 1 shows a linear power supply circuit. The input to the transformer in figure 1 is a 50 Hz sinusoid.

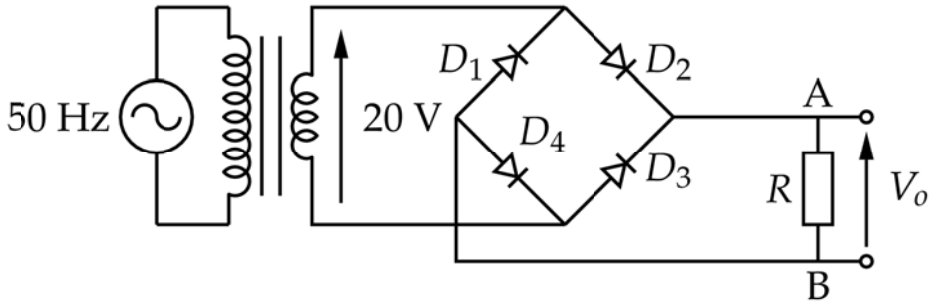


Figure 1

(i) The circuit of figure 1 has a node labelled **A** and another node labelled **B**. Draw the circuit indicating with arrows the current path through the transformer, diodes and resistor when node A is positive with respect to node B. **(1)**

(ii) Sketch the waveform you would expect to see across V_O. Your sketch should contain at least one complete cycle of the input waveform. Label times and amplitudes. **(4)**

(iii) Derive the average value of the waveform of part (ii). **(6)**

(iv) If R = 20 Ω, what is the minimum value of capacitor that can be placed in parallel with R if the ripple voltage component of V_O must not exceed 2 V peak to peak? *(Hint: Some of the marks are given for the derivation of relationships used.)* **(6)**

b. A Zener diode regulator circuit is to be used to derive a 9 V supply from the output of figure 1 which has been smoothed as described in **part d**. The load for the 9 V supply may draw a current anywhere between 5 mA and 10 mA and the Zener diode specifications recommend a minimum current through the diode of 2 mA.

(i) What is the largest value of series resistance that can be used in the regulator circuit? **(5)**

(ii) What ripple voltage would you expect to measure at the output of the regulator if the small signal Zener diode resistance in the breakdown region, r_Z, is 5 Ω and the input ripple to the regulator circuit is 2 V peak to peak? **(3)**

Assume in all parts of the question that the transformer and 50 Hz main supply are perfect and that the diodes D_1 to D_4 have zero series resistance.

2. a.

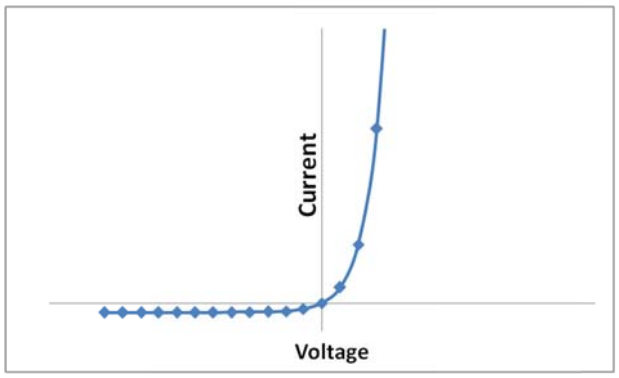


Figure 2

The graph in figure 2 shows the current voltage characteristics of a pn-diode. Draw band alignment diagrams (conduction and valence band) for the diode in:

(i) open circuit

(ii) forward bias

(iii) reverse bias

Use these diagrams to explain qualitatively the diode characteristic in the graph. **(9)**

b. (i) A p^+n diode has a forward bias current of 20 mA at 0.2 V at room temperature. If the reverse bias saturation current density is 9 Am^{-2} what is the cross sectional area of the diode? **(3)**

(ii) The capacitance, C, of the diode is measured as a function of applied voltage. A plot $1/C^2$ versus voltage has a slope of 1.177×10^{19} F^{-2}. Using expressions for the capacitance and depletion width at the beginning of this paper, calculate the density of donors in the n-type region using this information. **(7)**

c. Using equations found at the beginning of this paper, draw a diagram of the dependence of depletion width on donor/acceptor concentration for a symmetric diode, i.e. one where N_a and N_d are equal. **(3)**

d. At a reverse bias larger than that shown in figure 2, the diode enters the Zener breakdown region. Explain Zener breakdown using the band alignment diagrams. Outline why Zener breakdown is more likely in highly doped diodes. **(3)**

3. This question is about circuits containing transistors both as switches and amplifiers.

a. In figure 3a Q_1 is used to switch on a car headlamp, R_L. Q_1 has a static current gain, h_{FE}, of between 50 and 250 and a collector emitter saturation voltage, $V_{CE(sat)}$ of 300 mV and a base emitter saturation voltage, $V_{BE(sat)}$ of 0.7 V. The control input V_i is 12 V when the headlamp is required to be on and 0 V when off.

(i) Calculate the on-state collector current. **(1)**

(ii) Calculate the power dissipation in the load. **(1)**

(iii) Compute the largest value of R_B which will allow switching to occur irrespective of the particular h_{FE}. **(4)**

(iv) Estimate the on-state power loss in Q_1. **(1)**

(v) If Q_1 is replaced by a MOSFET, what $R_{DS(on)}$ would be required for it to dissipate the same power as the BJT? **(3)**

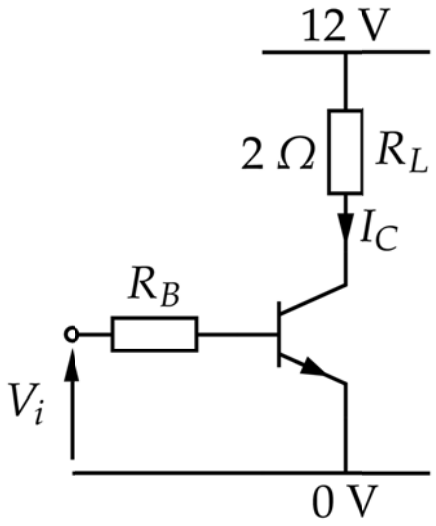


Figure 3a

b. The transistor in figure 3b has a small signal current gain, β, of 400.

(i) Work out the dc conditions V_B, V_C and I_C and the small signal parameters g_m and r_{be} for the circuit of figure 3b. **(5)**

(ii) Draw a small signal equivalent circuit of the circuit of figure 3b, labelling the components. **(4)**

(iii) State the purpose of C_1 and C_2. What effect does C_2 have on the circuit small signal parameters? **(3)**

(iv) Estimate the small signal voltage gain, V_C/V_s. **(3)**

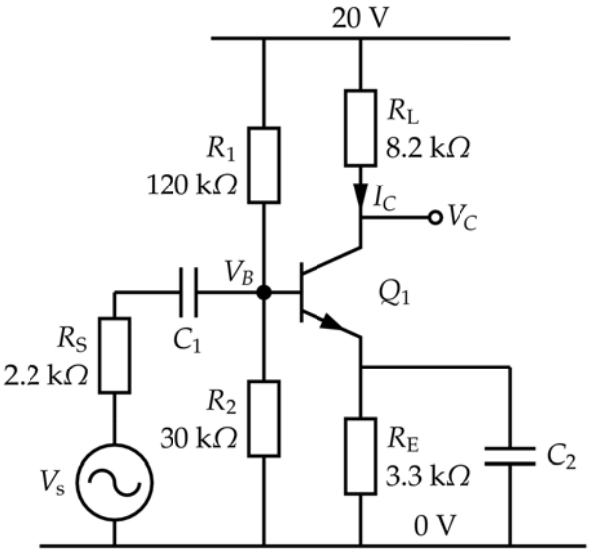


Figure 3b

4. **a.** Describe the bias conditions for the two junctions in a bipolar transistor in order for it to exhibit gain. **(2)**

Using a detailed diagram, indicate the electron and hole current flow in an npn bipolar transistor and describe the effects occurring at the emitter base junction. Indicate what effects in the base region can reduce the current gain of the device. **(6)**

Describe the main design considerations required to maximise the gain in the device. **(2)**

b. A npn bipolar transistor in a common emitter amplifier has its collector connected to a 150 Ω load resistor. If the voltage measured across the load resistor is 45 V when the base current is 3 mA, what is the current gain in the device?

Calculate the base transfer factor and the current transfer ratio in the transistor. **(7)**

c. Due to restrictions on the fabrication process, a semiconductor engineer now has to design the transistor with a base length that is twice that of the original. If the emitter injection efficiency remains the same, $\gamma = 0.997$, calculate the new value for gain in the device. **(8)**

5. **a.** Explain the concepts of the conduction band, valence band and band gap in a semiconductor **(6)**

b. Explain the concept of the hole in a semiconductor and state if it is found in the conduction or valence band **(2)**

c. Explain the difference between an intrinsic and extrinsic semiconductor **(4)**

d. The intrinsic electron density in Silicon at room temperature is 1×10^{16} m^{-3}. What is the electron density at 350 K?

Does the conductivity of the semiconductor increase or decrease with temperature? Why? **(6)**

e. Using the formula given at the beginning of this paper, and assuming the variation of the carrier concentration due to the term $T^{3/2}$ can be neglected, at what temperature would you expect the intrinsic carrier concentration in Silicon to increase by a factor of 1000 over the room temperature value?

By calculating the actual carrier concentration at this temperature using the full formula, estimate the error that was introduced by neglecting the $T^{3/2}$ term. **(7)**

6. This question is about operation amplifiers and circuits made from opamps.

a. (i) Draw the circuit diagram of an amplifier with a voltage gain of -10V/V using only one (ideal) opamp and two resistors. Include suitable component values on your diagram. **(4)**

(ii) Draw the circuit diagram of an amplifier with a voltage gain of +l0V/V using only one (ideal) opamp and two resistors. Include suitable component values on your diagram. **(4)**

b. (i) State the opamp equation and define the terms. **(4)**

(ii) Why is it important for op-amps to have high input resistance, low output resistance and high gain? **(5)**

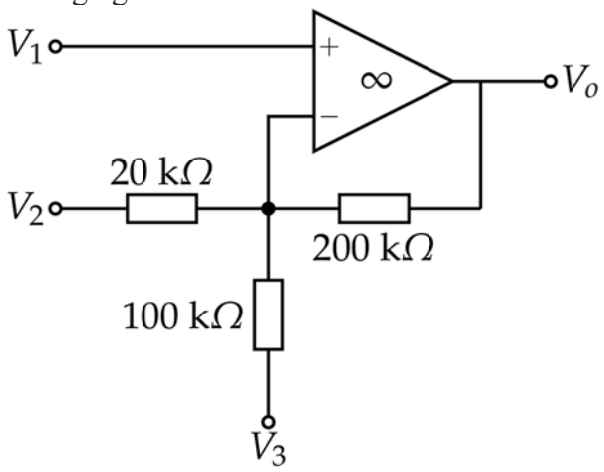


Figure 6.

c. Figure 6 shows an amplifier with three inputs, V_1, V_2 and V_3. V_1 is a d.c. voltage. $V_2 = 0.5 \sin(\omega t)$ V and $V_3 = -6.0$ V

(i) What is the pk - pk value of the a.c. component of the amplifier output voltage? **(3)**

(ii) What value of V_1 will give a d.c. component of output voltage of zero? **(5)**

JEG/JH/MMDS