

# N4

# Industrial Electronics



Gateways to Engineering Studies - John Dillon & Chris Brink



**HYBRID  
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# Gateways to Engineering Studies

Industrial Electronics  
N4

John Dillon & Chris Brink

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## Icons used in this book

We use different icons to help you work with this book; these are shown in the table below.

Icon	Description	Icon	Description
	Assessment / Activity		Multimedia
	Checklist		Practical
	Demonstration/ observation		Presentation/ Lecture
	Did you know?		Read
	Example		Safety
	Experiment		Site visit
	Group work/ discussions, role-play, etc.		Take note of
	In the workplace		Theoretical – questions, reports, case studies, etc.
	Keywords		Think about it

# Module 1

## Alternating Current Theory

### Learning Outcomes

On the completion of this module the student must be able to:

- Describe alternating current theory
- Use phasor diagrams and complex number calculations
- Calculate and describe the characteristic curves of Q-factor, bandwidth, maximum power transfer, resonant frequency and circuits

### 1.1 Introduction



Alternating current (AC), is an electric current in which the flow of electric charge periodically reverses direction. This module demonstrates calculations involving AC.

### 1.2 Complex numbers

Complex numbers have two parts to them:

$$Z = a + jb$$

↑ Complex number
↑ Imaginary number
↑ Real numbers


Figure 1.1 Complex numbers


There is the real part,  $a$  and the imaginary part  $b$ . Although  $b$  is a real number, it is referred to as the imaginary part because it is always linked to the imaginary.  $j$ , the imaginary number has a value that cannot be written down accurately unless it is denoted as  $\sqrt{-1}$ .

*The imaginary number written as  $a$  or  $j = \sqrt{-1}$*

Using complex numbers in industrial electronics helps get accurate answers to problems that contain the value  $\sqrt{-x}$ .

An example is shown in **Worked example 1.1**:

	<b>Worked Example 1.1</b>
Find the answer to:	
$\frac{6 \pm \sqrt{-16}}{2}$	
<b>Solution:</b>	
$\frac{6 \pm \sqrt{-16}}{2}$ $= \frac{6 \pm \sqrt{-1} \times \sqrt{16}}{2}$ $= \frac{6 \pm j \times \sqrt{16}}{2}$ $= \frac{6 \pm j \times 4}{2}$ $= 3 \pm 2j$	


	<p><b>Note:</b> It is vital that we can work with square roots. For example:</p> $\sqrt{-16} = \sqrt{16} \times \sqrt{-1}$
---	--

The complex number:  $Z = 3 \pm 2j$  means  $Z = 3 + 2j$  or  $Z = 3 - 2j$

### 1.2.1 The imaginary number

$$j = \sqrt{-1}$$

$$\text{Therefore } j^2 = (\sqrt{-1})^2 = -1$$

	<p><b>Note:</b></p> $(\sqrt{x})^2 = (x)^{\frac{2}{2}} = x$
---	--

$$\text{and } j^3 = (\sqrt{-1})^3 = j^2 \times j = (-1)(j) = -j$$

$$\text{and } j^4 = j^2 \times j^2 = (-1)(-1) = 1$$

$$\text{and } j^5 = (j^2)^2 \times j = (-1)^2(j) = j$$

**Table 1.1** shows the pattern of the first four simplified imaginary numbers and how these are repeated:

Imaginary number	Value
$j^0$	1
$j^1$	j
$j^2$	-1
$j^3$	-j
$j^4$	1
$j^5$	j
$j^6$	-1
$j^7$	-j
$j^8$	1
$j^9$	j
$j^{10}$	-1

Table 1.1 imaginary numbers



### Worked Example 1.2

Simplify:

- $j^{25}$
- $\frac{36 \pm \sqrt{-40}}{6}$

**Solution:**

$$1. \quad j^{25} = (j)^{24} j = (j^2)^{12} \times j = (-1)^{12} (j) = j$$

$$2. \quad \frac{36 \pm \sqrt{-40}}{6}$$

$$\begin{aligned}
 &= \frac{36 \pm \sqrt{40} \cdot \sqrt{-1}}{6} \\
 &= \frac{36 \pm \sqrt{40} j}{6} \\
 &= 6 \pm 1.054 j
 \end{aligned}$$

### 1.2.2 Introduction to phasors

The argand plane is a normal Cartesian plane but it's used in connection with complex numbers.

Take a normal Cartesian plane with X and Y co-ordinates:

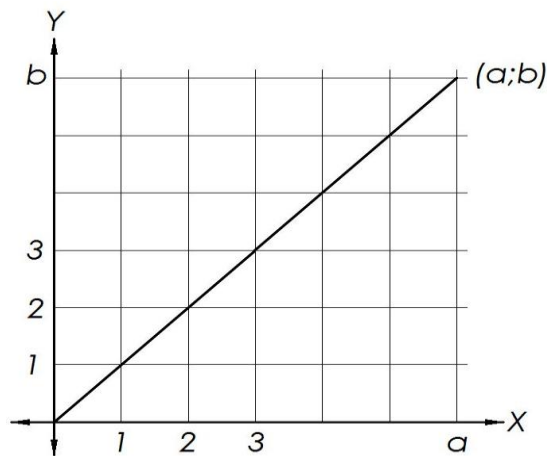


Figure 1.2 Cartesian plane

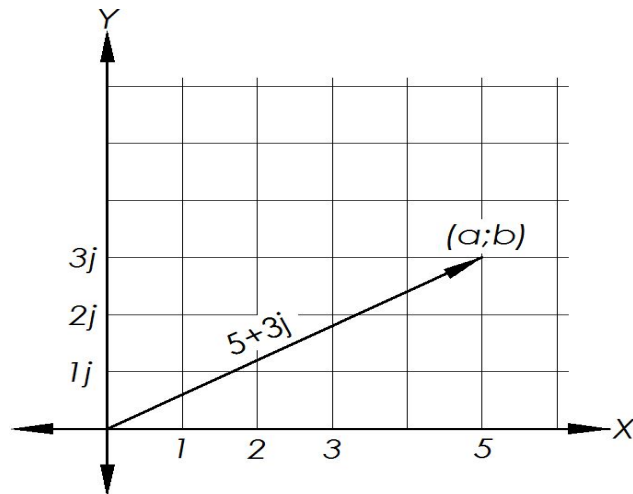
Points along the X axis are:

Point "1" is denoted (1;0) and point "a" is (a ;0)

Points along the Y axis are:

Point "1" is denoted (0;1) and point "b" is (0; b)

For the Argand plane, the X axis denoted real numbers but the Y axis changes to represent imaginary numbers. **Figure 1.3** shows the Argand plane with a vector representing a complex number.

Figure 1.3 Argand plane with vector  $5+3j$ **Note:**

The value of  $j$  on the Y axis is 1 and the value of  $2j$  is 2 and so on.

**Worked Example 1.3**

With the help of a graph, write down the geometrical effect of the following:

1. 1
2.  $3j - 2$

**Solution:**

Multiply the number by  $j$ , then simplify. Then write in the form  $(a;b)$  then make a sketch.

1.

$$1 \times j = j = (0; 1)$$

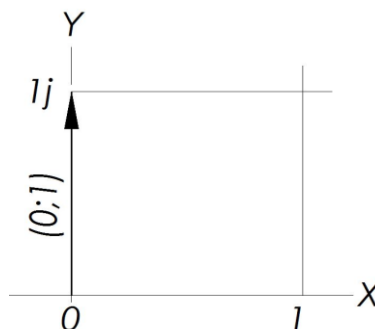


Figure 1.4

2.

$$j \cdot (3j - 2) = 3j^2 - 2j = 3 \cdot (-1) - 2j = (-3; -2)$$

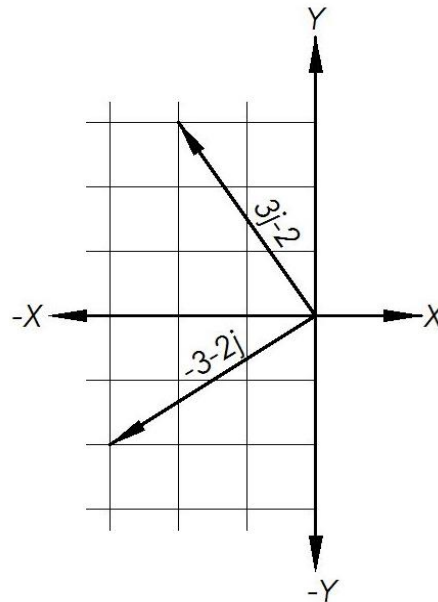


Figure 1.5

**Note:**

As seen by **Worked example 1.3**, any complex number on the argand plane turns through 90 degrees (anti-clockwise) if it is multiplied by  $j$ .

### 1.2.3 The modulus argument or polar form

A complex number can easily be converted to polar form. Look at **Figure 1.6**:

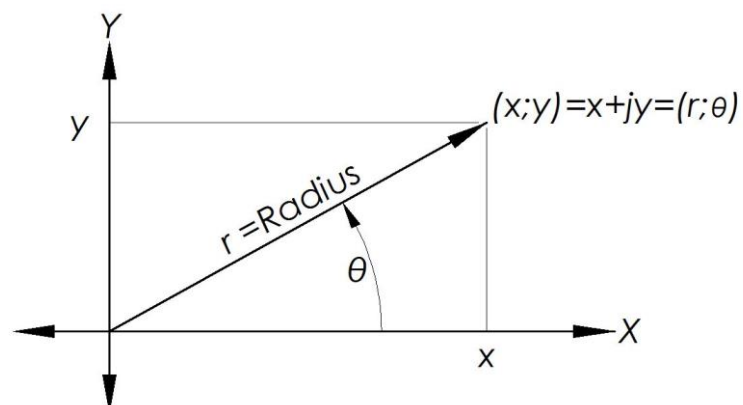


Figure 1.6 Polar form of a complex number

From the basic trigonometrical ratios and looking at the graph:

$$x = r \cos \theta$$

$$y = r \sin \theta$$

$$\frac{y}{x} = \tan \theta$$

From Pythagoras:

$$r = \sqrt{x^2 + y^2}$$



### Worked Example 1.4

Find the polar co-ordinate of  $Z = 1 + j$ :

**Solution:**

First create a sketch.

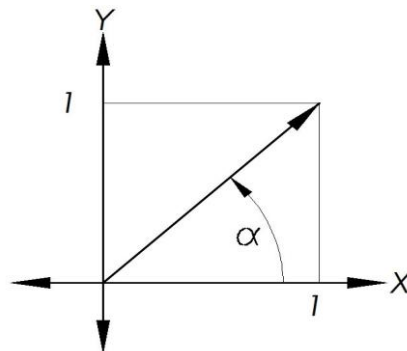


Figure 1.7

$$\text{Auxiliary angle } \alpha = \tan^{-1} \frac{y}{x} = \tan^{-1} \frac{1}{1} = 45^\circ$$

$$\text{But } \theta = \alpha = 45^\circ$$

$$\text{and } r = \sqrt{x^2 + y^2} = \sqrt{2}$$

The polar form is written  $Z = r \text{ cis } \theta$  or  $Z = r [\underline{\theta}]$

$$\text{written } Z = \sqrt{2} \text{ cis } 45^\circ \text{ or } Z = \sqrt{2} [\underline{45^\circ}]$$



### Worked Example 1.5

Write  $Z = -2 + 3j$  in cis-form.

**Solution:**

**Note** that  $Z = (-2; 3)$ . Create a sketch.

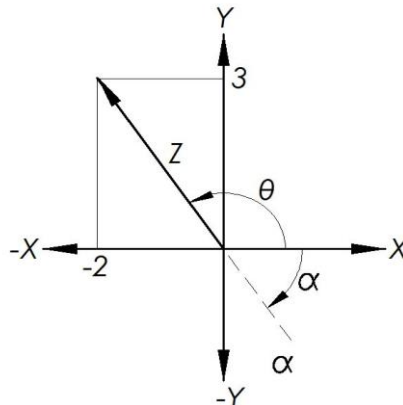


Figure 1.8

$$\text{Auxiliary angle } \alpha = \tan^{-1} \frac{3}{2} = 56.309^\circ$$

Looking at the sketch  $\theta = 180^\circ - \alpha = 123.69^\circ$

$$\text{and } r = \sqrt{(-2)^2 + (3)^2} = \sqrt{13} = 3.61$$

## 1.3 Working with complex numbers

De Moivre used the polar form of complex numbers to find the product, quotient and power of complex numbers.

### 1.3.1 Multiplication of complex numbers

Let  $Z_1 = r_1 \angle \theta_1$  and  $Z_2 = r_2 \angle \theta_2$

$$Z_1 \times Z_2 = r_1 r_2 \angle \theta_1 + \theta_2$$

### 1.3.2 Division of complex numbers

$$\frac{Z_1}{Z_2} = \frac{r_1}{r_2} \angle \theta_1 - \theta_2$$

### 1.3.3 Powers of complex numbers

$$(Z_1)^n = (r_1)^n \angle n\theta_1$$



### Worked Example 1.6

If  $Z_1 = 2\angle 30^\circ$  and  $Z_2 = 3\angle 40^\circ$ , find  $Z_1 \times Z_2$  and  $\frac{Z_1}{Z_2}$

**Solution:**

$$Z_1 \times Z_2 = 2 \times 3 \angle 30^\circ + 40^\circ$$

$$Z_1 \times Z_2 = 6 \angle 70^\circ$$

$$\text{And } \frac{Z_1}{Z_2} = \frac{2}{3} \angle 30^\circ - 40^\circ$$

$$\frac{Z_1}{Z_2} = -\frac{2}{3} \angle -10^\circ$$



### Worked Example 1.7

Write  $\frac{1}{(1-j)^3}$  in rectangular form.

**Solution:**

Take the content of the bracket  $(1 - j)$  and let that =  $Z$

$$\text{Then } \frac{1}{(1-j)^3} = \frac{1}{Z^3}$$

$$(1-j)^{-3} = Z^{-3}$$

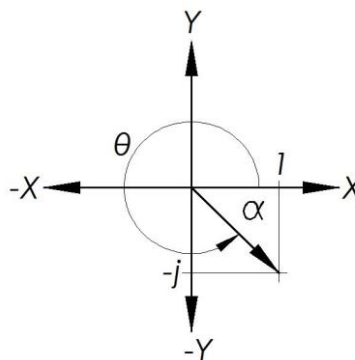


Figure 1.9

From the sketch  $r = \sqrt{2}$  and  $\theta = -45$

Write in polar form  $Z^{-3} = (\sqrt{2} \angle -45^\circ)^{-3}$

$$\begin{aligned}
 \text{Using De Moivre's third formula } (Z_1)^n &= (r_1)^n \angle n\theta_1 \\
 &= (\sqrt{2})^{-3} \angle [-3 \times 45^\circ] \\
 &= 0.3535 \angle 135^\circ \\
 \text{In rectangular form:} &= -\frac{1}{4} + \frac{1}{4}j
 \end{aligned}$$

## 1.4 Phasor representation

### 1.4.1 Frequency and speed

Both the sinus and the cosine waveforms have the same form and a cycle of  $360^\circ$ .

The big difference between the two is that the cosine waveform is moved by  $90^\circ$  before the sinus wave. This means that the cosine wave reaches its maximum value  $90^\circ$  before the sinus wave does.

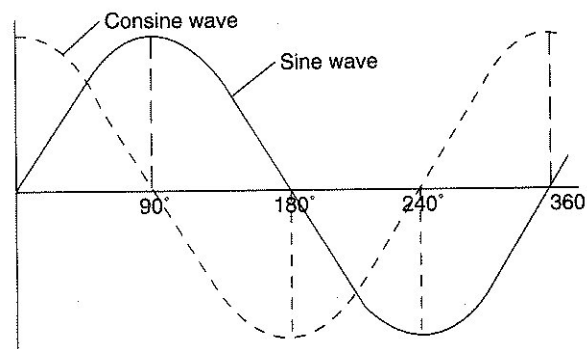


Figure 1.10 A waveform diagram of sinus and cosine waveforms

The sinus wave begins with the value 0 at  $0^\circ$ ,  $180^\circ$  and  $360^\circ$  and reaches a peak value at  $90^\circ$  and minimum value at  $270^\circ$ . The cosine wave begins with a peak value at  $0^\circ$  and has the peak at  $360^\circ$ . The wave crosses the zero line at angles of  $90^\circ$  and  $270^\circ$  with a minimum at  $180^\circ$ .

A cycle can be seen as that part of the waveform before it starts to repeat itself. In the case of the sinus wave this is the part of the signal oscillating to a maximum on the positive side of the time axis, then back to zero on to the maximum negative and back to the zero line.

### 1.4.2 Phase angle

Phase angle: (The angle with which the current leads or lags the voltage.) In practice the current leads or lags the voltage by a small angle.

This angle is referred to as the phase angle  $\Phi$  (phi). In most cases the current lags the voltage as shown in **Figure 1.10**. In a purely resistive circuit the current is in phase with the voltage.

### 1.4.3 The phasor

A phasor, is a complex number representing a sinusoidal function whose amplitude ( $A$ ), angular frequency ( $\omega$ ), and initial phase ( $\theta$ ) are time invariant.

It decomposes a sinusoid into the product of a complex constant and a factor that encapsulates the frequency and time dependence. The complex constant, which encapsulates amplitude and phase dependence, is known as phasor, complex amplitude.

A common situation in electrical networks is the existence of multiple sinusoids all with the same frequency, but different amplitudes and phases. The only difference in their analytic representations is the complex amplitude (phasor). A linear combination of such functions can be factored into the product of a linear combination of phasors (known as phasor arithmetic) and the time/frequency dependent factor that they all have in common.

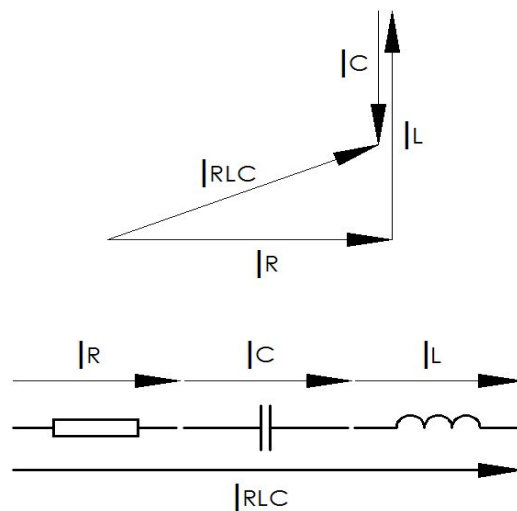


Figure 1.11 The RLC diagram for a specific speed

After the phasors have moved through  $\theta$ , they occupy positions OA1 and OA1 respectively with OB1 leading OB1 with the angle  $\phi$ .

$$\text{Instantaneous EMF } e = E_m \sin(\theta + \phi)$$

$$\text{Instantaneous current } i = I_m \sin \theta$$

### 1.4.4 Phasor addition

Sometimes it is necessary when studying sinusoids to add together two alternating waveforms, for example in an AC series circuit, that are not in-phase with each other.

If they are in-phase that is, there is no phase shift then they can be added together in the same way as DC values to find the algebraic sum of the two vectors.

For example, if two voltages of say 50 volts and 25 volts respectively are together “in-phase”, they will add or sum together to form one voltage of 75 volts.

If, however, they are not in-phase, that is, they do not have identical directions or starting point then the phase angle between them needs to be taken into account so they are added together using phasor diagrams.

Consider two AC voltages,  $V_1$  having a peak voltage of 20 volts, and  $V_2$  having a peak voltage of 30 volts where  $V_1$  leads  $V_2$  by  $60^\circ$ .

The total voltage,  $V_T$  of the two voltages can be found by firstly drawing a phasor diagram representing the two vectors and then constructing a parallelogram in which two of the sides are the voltages,  $V_1$  and  $V_2$  as shown below.

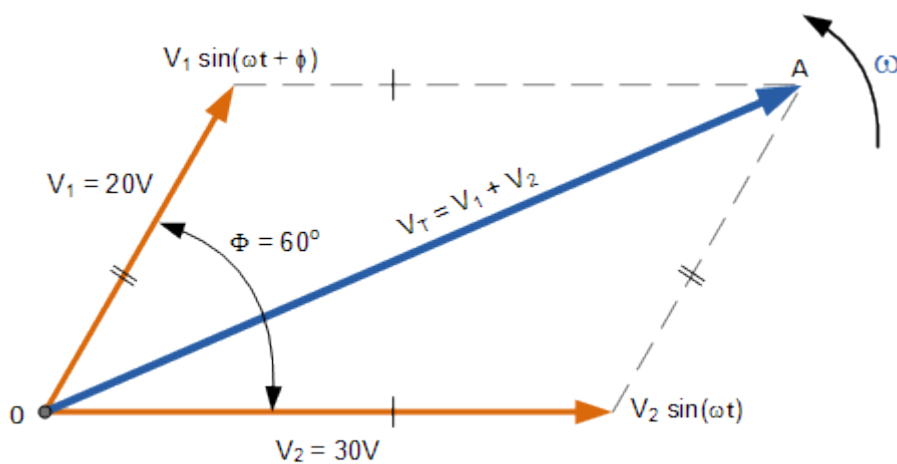


Figure 1.12 Phasor addition of two phases

By drawing out the two phasors to scale onto graph paper, their phasor sum  $V_1 + V_2$  can be easily found by measuring the length of the diagonal line, known as the “resultant r-vector”, from the zero point to the intersection of the construction lines 0-A.

The downside of this graphical method is that it is time consuming when drawing the phasors to scale. Also, while this graphical method gives an

answer which is accurate enough for most purposes, it may produce an error if not drawn accurately or correctly to scale.

Then one way to ensure that the correct answer is always obtained is by an analytical method.

In the rectangular form, the phasor is divided up into a real part,  $x$  and an imaginary part,  $y$  forming the generalized expression  $Z = x \pm jy$ .

This then gives us a mathematical expression that represents both the magnitude and the phase of the sinusoidal voltage.

## 1.5 RCL circuits

### 1.5.1 Resistance

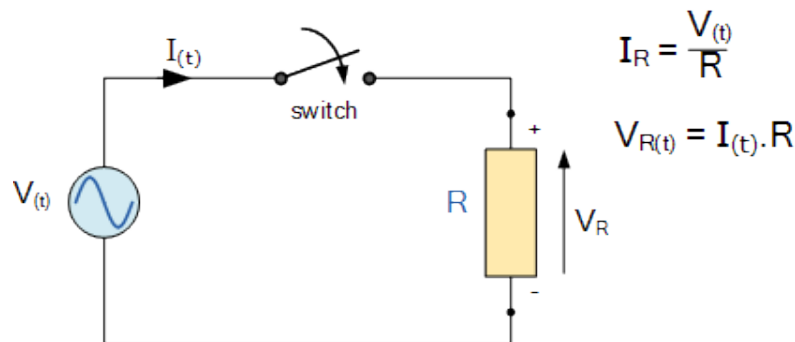


Figure 1.13 Pure resistance in an AC circuit

When the switch is closed, an AC voltage,  $V$  will be applied to resistor,  $R$ . This voltage will cause a current to flow which in turn will rise and fall as the applied voltage rises and falls sinusoidally.

As the load is a resistance, the current and voltage will both reach their maximum or peak values and fall through zero at exactly the same time, i.e. they rise and fall simultaneously and are therefore said to be “*in-phase*”.

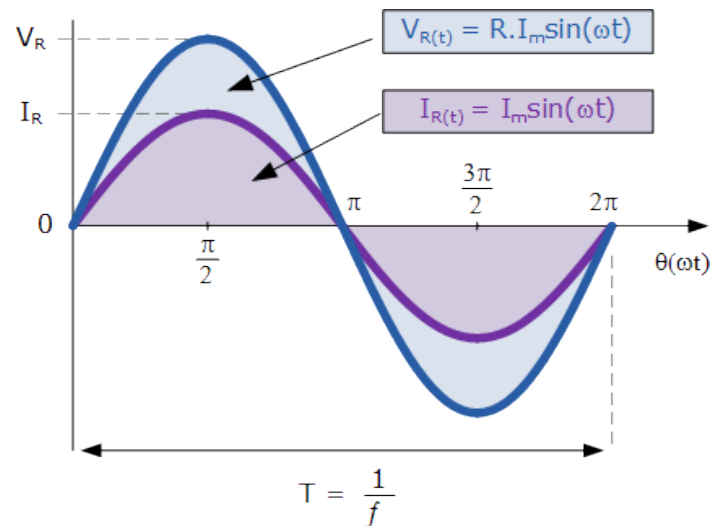


Figure 1.14 Sinusoidal waveforms of an AC circuit

### 1.5.2 Inductance

Inductors do not behave the same as resistors. Whereas resistors simply oppose the flow of electrons through them (by dropping a voltage directly proportional to the current), inductors oppose *changes* in current through them, by dropping a voltage directly proportional to the *rate of change* of current.

In accordance with *Lenz's Law*, this induced voltage is always of such a polarity as to try to maintain current at its present value.

That is, if current is increasing in magnitude, the induced voltage will “push against” the electron flow, if current is decreasing, the polarity will reverse and “push with” the electron flow to oppose the decrease.

The inductance ( $L$ ) is in Henrys, and the instantaneous voltage ( $e$ ), is in volts. To show what happens with alternating current, let's analyze a simple inductor circuit: **Figure 1.15**.

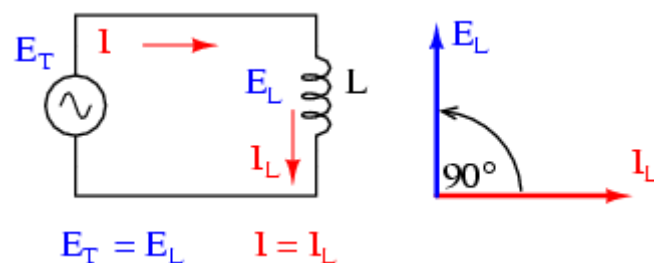


Figure 1.15 Simple inductor circuit

In a pure inductive circuit, The inductor current lags the inductor voltage by  $90^\circ$ .

If we were to plot the current and voltage for this very simple circuit, it would look something like this: **Figure 1.16**.

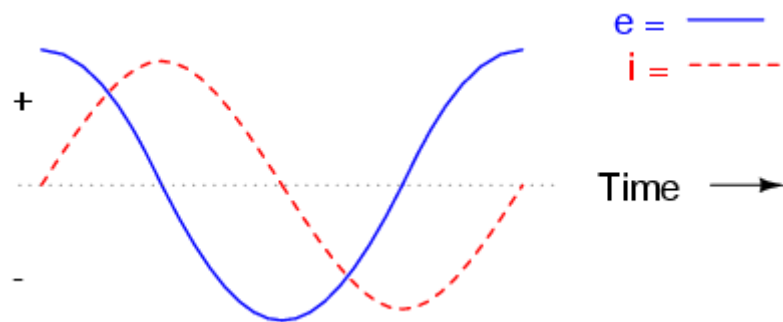


Figure 3.16 Pure inductive circuit, waveforms.

The voltage dropped across an inductor is a reaction against the change in current through it. Therefore, the instantaneous voltage is zero whenever the instantaneous current is at a peak, and the instantaneous voltage is at a peak wherever the instantaneous current is at maximum change.

This results in a voltage wave that is  $90^\circ$  out of phase with the current wave. Looking at the graph, the voltage wave seems to have a “head start” on the current wave, the voltage “leads” the current, and the current “lags” behind the voltage. **Figure 1.17**.

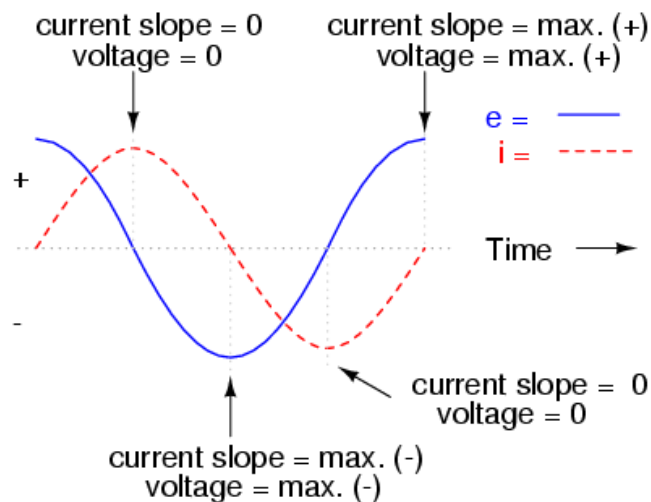


Figure 1.17 Current lags voltage by  $90^\circ$  in a pure inductive circuit.

The power for this circuit **Figure 1.18**:

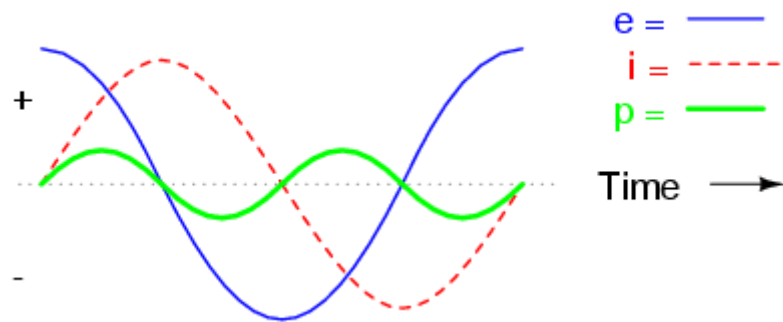


Figure 1.18 In a pure inductive circuit, instantaneous power may be positive or negative

Because instantaneous power is the product of the instantaneous voltage and the instantaneous current ( $p=ie$ ), the power equals zero whenever the instantaneous current or voltage is zero.

Whenever the instantaneous current and voltage are both positive (above the line), the power is positive.

As with the resistor example, the power is also positive when the instantaneous current and voltage are both negative (below the line).

However, because the current and voltage waves are  $90^\circ$  out of phase, there are times when one is positive while the other is negative, resulting in equally frequent occurrences of negative instantaneous power.

### 1.5.3 Capacitance

Capacitors do not behave the same as resistors. Whereas resistors allow a flow of electrons through them directly proportional to the voltage drop, capacitors oppose changes in voltage by drawing or supplying current as they charge or discharge to the new voltage level.

The flow of electrons “through” a capacitor is directly proportional to the rate of change of voltage across the capacitor. This opposition to voltage change is another form of reactance, but one that is precisely opposite to the kind exhibited by inductors.

To show what happens with alternating current, let's analyze a simple capacitor circuit: **Figure 1.19**.

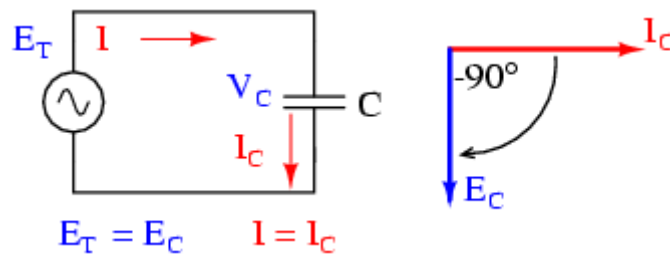


Figure 1.19 In a pure capacitor circuit

In a pure capacitive circuit, the capacitor voltage lags the capacitor current by  $90^\circ$ .

If we were to plot the current and voltage for this very simple circuit, it would look something like this: **Figure 1.20**.

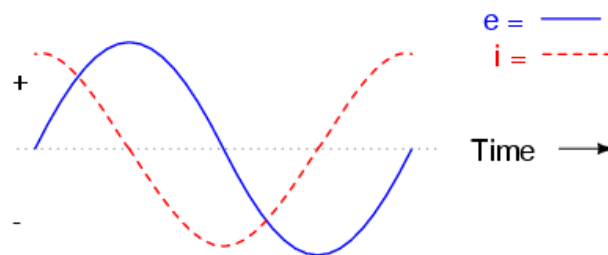


Figure 1.20 Pure capacitive circuit waveforms.

The current through a capacitor is a reaction against the change in voltage across it. Therefore, the instantaneous current is zero whenever the instantaneous voltage is at a peak, and the instantaneous current is at a peak wherever the instantaneous voltage is at maximum change.

This results in a voltage wave that is  $-90^\circ$  out of phase with the current wave. Looking at the graph, the current wave seems to have a “head start” on the voltage wave; the current “leads” the voltage, and the voltage “lags” behind the current. **Figure 1.21**.

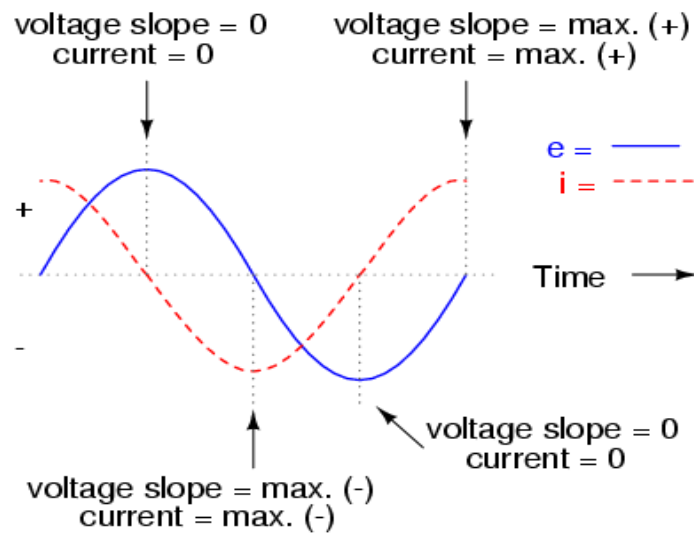


Figure 1.21 Voltage lags current by  $90^\circ$  in a pure capacitive circuit. The same unusual power wave that we saw with the simple inductor circuit is present in the simple capacitor circuit, too: **Figure 1.22**.

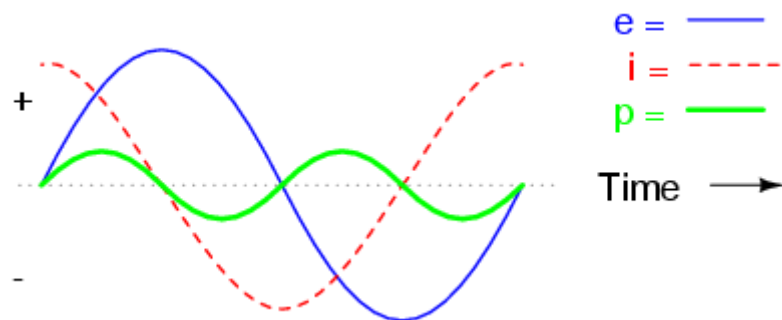


Figure 1.22 In a pure capacitive circuit, the instantaneous power may be positive or negative.

As with the simple inductor circuit, the 90 degree phase shift between voltage and current results in a power wave that alternates equally between positive and negative.

This means that a capacitor does not dissipate power as it reacts against changes in voltage; it merely absorbs and releases power, alternately.

### 1.5.4 Impedance

Electrical impedance is the measure of the opposition that a circuit presents to a current when a voltage is applied.

It is the complex ratio of the voltage to the current in an alternating current (AC) circuit.

The symbol for impedance is usually  $Z$  and it may be represented by writing its magnitude and phase in the form  $|Z|\angle\theta$ . However, Cartesian complex number representation is often more powerful for circuit analysis purposes.



**Definition: Impedance**

Defined as the frequency domain ratio of the voltage to the current. In other words, it is the voltage–current ratio for a single complex exponential at a particular frequency  $\omega$ .

In general, impedance will be a complex number, with the same unit as resistance, for which the SI unit is the ohm ( $\Omega$ ).

For a sinusoidal current or voltage input, the polar form of the complex impedance relates the amplitude and phase of the voltage and current.

In particular:

- The magnitude of the complex impedance is the ratio of the voltage amplitude to the current amplitude.
- The phase of the complex impedance is the phase shift by which the current lags the voltage.

The reciprocal of impedance is admittance (i.e., admittance is the current-to-voltage ratio, and it conventionally carries units of Siemens, formerly called mhos).

$X$  is the difference between  $X_L$  and  $X_C$

If  $X_L$  is greater, the power factor will be lagging

If  $X_C$  is greater, the power factor will be leading.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{R^2 + X^2}$$

### 1.5.5 Power

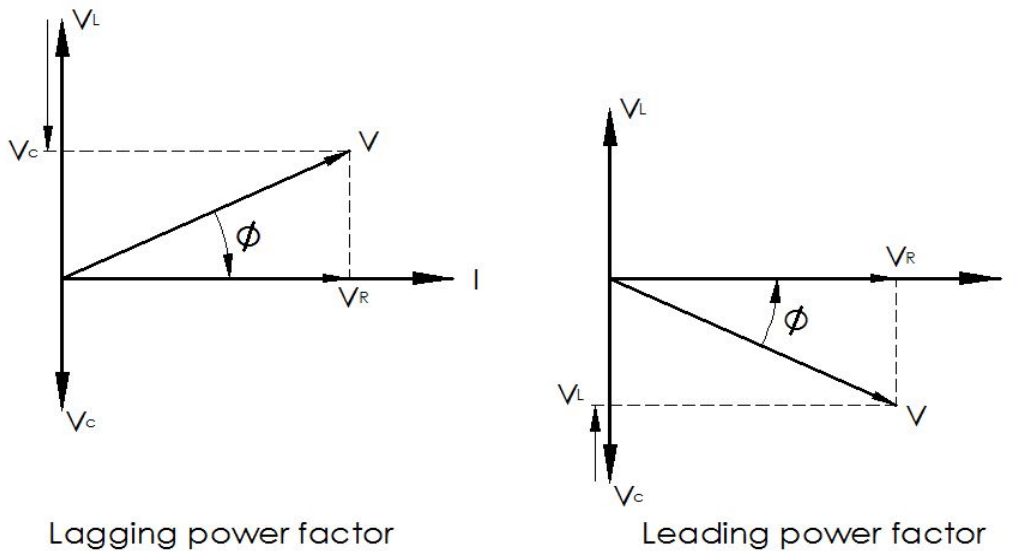


Figure 1.23 Phase angle with lagging and leading power factor

$$\text{Lagging PF } \tan \phi = \frac{V_L - V_C}{V_R}$$

$$\text{Leading PF } \tan \phi = \frac{V_C - V_L}{V_R}$$

$$\text{Lagging PF } \tan \phi = \frac{X_L - X_C}{R}$$

$$\text{Leading PF } \tan \phi = \frac{X_C - X_L}{R}$$

$$\tan \phi = \frac{X}{R}$$

When there is a phase difference between the voltage and current, the actual power is not equal to  $VI$ . It is lower.

$$\text{Power} = PD \times \text{The inphase component}$$

$$\text{True or Actual Power } P = VI \cos \phi$$

$I$  is the in-phase component of the current

$$\text{True Power } P = I^2 R$$

$$\text{Apparent Power } S = VI$$

#### Power factor:

The power factor is a ratio between the true power and the apparent power:

$$\text{Power factor} = \frac{\text{True power}}{\text{Apparent power}}$$

$$\text{Power factor} = \frac{V I \cos \phi}{V I}$$

$$\therefore \text{Power factor} = \cos \phi$$

### 1.5.6 Low power factor

The power factor should be kept as high as possible because this will provide an efficient system.

To keep it high, the current should be brought as near into phase with the voltage as possible.

If the current is far out of phase with the voltage, the following negative effects will manifest themselves:

- An increase in resistance losses that will lessen the efficient of the equipment and supply.
- The output of generators and transformers are limited.
- Causes a greater fall in terminal voltage across power lines and equipment.

### 1.5.7 Series RLC circuit

For the series RLC circuit **Figure 1.24**, this can be shown as:

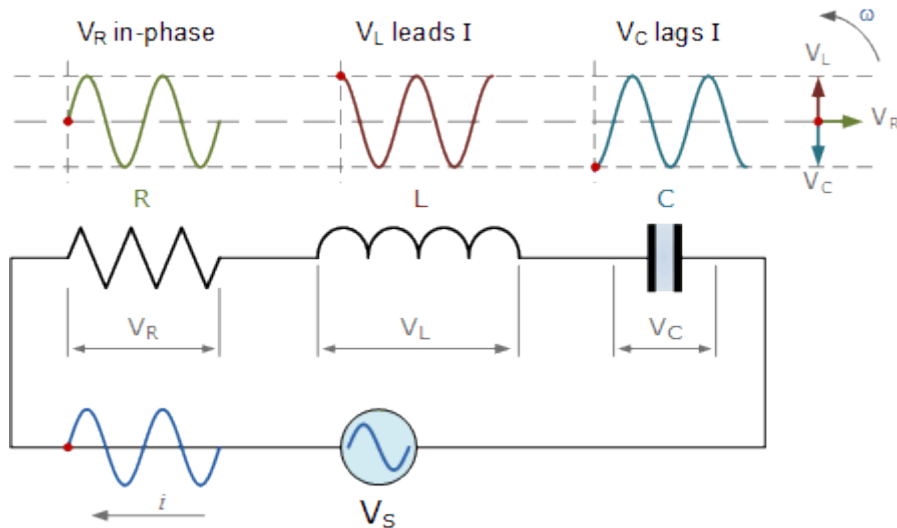


Figure 1.24 Series RLC circuit.

The amplitude of the source voltage across all three components in a series RLC circuit is made up of the three individual component voltages,  $V_R$ ,  $V_L$  and  $V_C$  with the current common to all three components. The vector diagrams will therefore have the current vector as their reference with the three voltage vectors being plotted with respect to this reference as shown **Figure 1.25**:

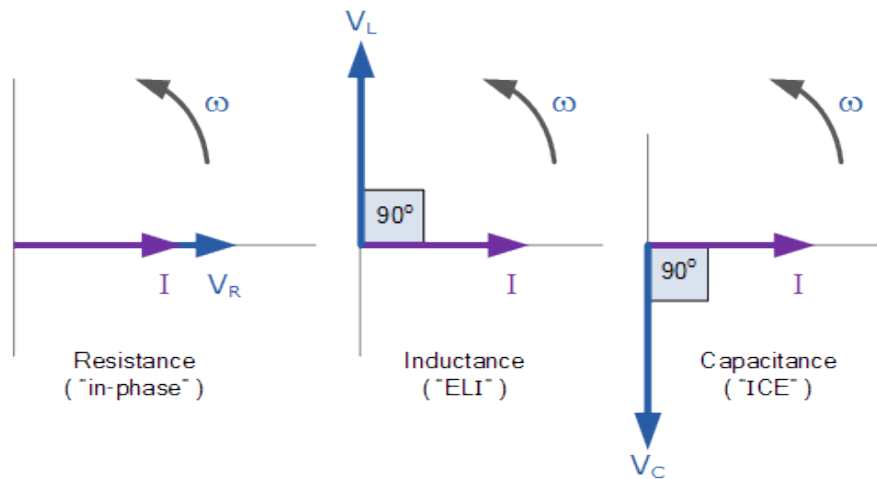


Figure 1.25 Series RLC circuit.

This means then that we cannot simply add together  $V_R$ ,  $V_L$  and  $V_C$  to find the supply voltage,  $V_S$  across all three components as all three voltage vectors point in different directions with regards to the current vector.

Therefore, we will have to find the supply voltage,  $V_S$  as the **Phasor Sum** of the three component voltages combined together as vectors.

Kirchhoff's voltage law ( KVL ) for both loop and nodal circuits states that around any closed loop the sum of voltage drops around the loop equals the sum of the EMF's.

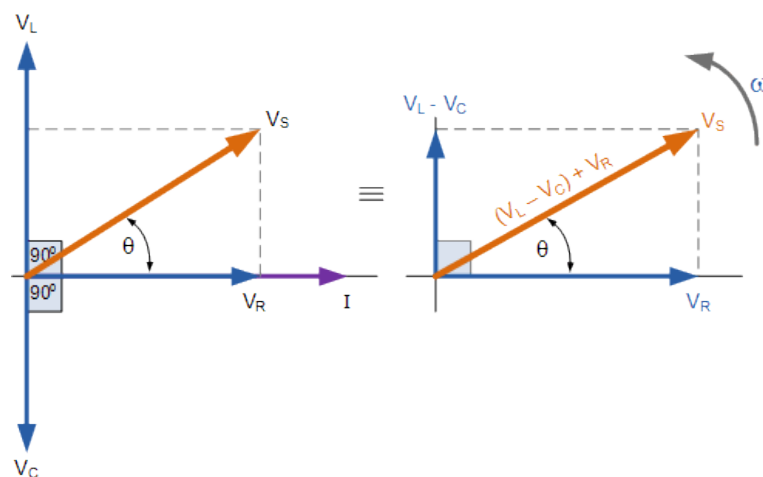


Figure 1.26 Instantaneous Voltages for a Series RLC Circuit

### 1.5.8 Parallel RLC circuit

The Parallel RLC Circuit is the exact opposite to the series circuit. Although some of the previous concepts and equations still apply.

This time instead of the current being common to the circuit components, the applied voltage is now common to all so we need to find the individual branch currents through each element.

The total impedance,  $Z$  of a parallel RLC circuit is calculated using the current of the circuit similar to that for a DC parallel circuit, the difference this time is that admittance is used instead of impedance. Consider the parallel RLC circuit **Figure 1.27**.

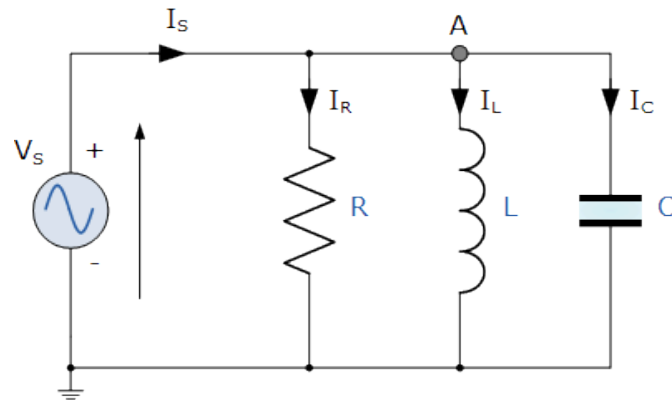


Figure 1.27 Parallel RLC circuit

In the above parallel RLC circuit, the supply voltage,  $V_s$  is common to all three components whilst the supply current  $I_s$  consists of three parts. The current flowing through the resistor,  $I_R$ , the current flowing through the inductor,  $I_L$  and the current through the capacitor,  $I_C$ .

But the current flowing through each branch and therefore each component will be different to each other and to the supply current,  $I_s$ . The total current drawn from the supply will not be the mathematical sum of the three individual branch currents but their vector sum.

Like the series RLC circuit, we can solve this circuit using the phasor or vector method but this time the vector diagram will have the voltage as its reference with the three current vectors plotted with respect to the voltage. The phasor diagram for a parallel RLC circuit is produced by combining together the three individual phasors for each component and adding the currents as vectors.

Since the voltage across the circuit is common to all three circuit elements we can use this as the reference vector with the three current vectors drawn relative to this at their corresponding angles.

The resulting vector  $I_s$  is obtained by adding together two of the vectors,  $I_L$  and  $I_C$  and then adding this sum to the remaining vector  $I_R$ . The resulting angle obtained between  $V$  and  $I_s$  will be the circuit's phase angle as shown **Figure 1.28**.

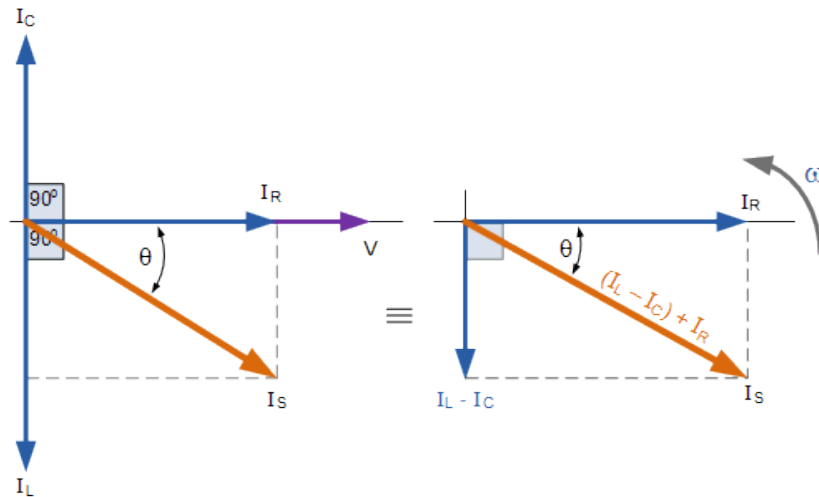


Figure 1.28 Circuits phase angle

We can see from the phasor diagram on the right hand side above that the current vectors produce a rectangular triangle, comprising of hypotenuse  $I_S$ , horizontal axis  $I_R$  and vertical axis  $I_L - I_C$

this forms a Current Triangle and we can therefore use Pythagoras's theorem on this current triangle to mathematically obtain the magnitude of the branch currents along the x-axis and y-axis and then determine the total current  $I_S$  of these components as shown.

### Impedance of a parallel RLC circuit

A parallel RLC circuit produces complex impedance's for each parallel branch as each element becomes the reciprocal of impedance,  $(1/Z)$  with the reciprocal of impedance being called Admittance.

In parallel AC circuits it is more convenient to use admittance, symbol  $(Y)$  to solve complex branch impedance's especially when two or more parallel branch impedance's are involved.

The total admittance of the circuit can simply be found by the addition of the parallel admittances. Then the total impedance,  $Z_T$  of the circuit will therefore be  $1/Y_T$  Siemens.



### Worked Example 1.8

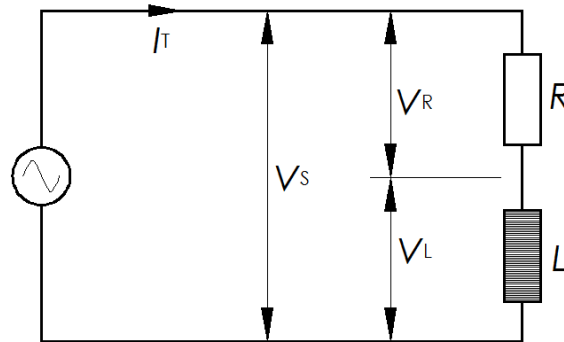


Figure 1.29

Draw the phasor diagram of the series RL circuit above

**Solution:**

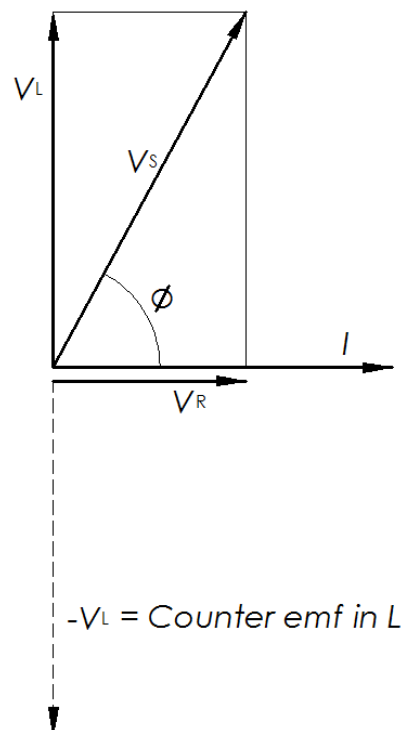


Figure 1.30



### Worked Example 1.9

Draw the phasor diagram of the parallel RLC circuit below when:

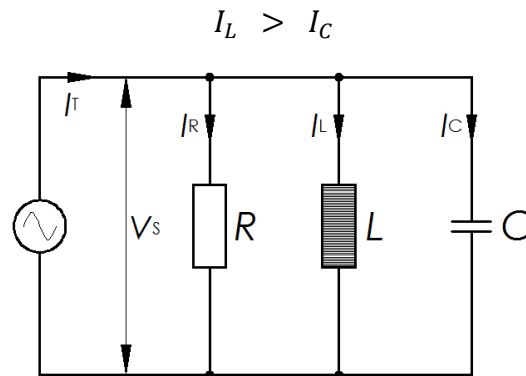


Figure 1.31

**Solution:**

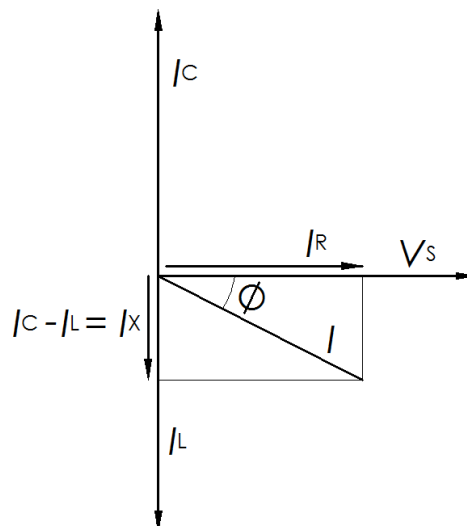


Figure 1.32

## 1.6 Resonance

Consider a RLC circuit in which the resistor, inductor and capacitor are connected in series across a voltage supply.

This series RLC circuit has a distinguishing property of resonating at a specific frequency called resonant frequency.

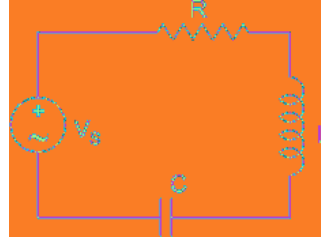


Figure 1.33 RLC circuit

In this circuit containing inductor and capacitor, the energy is stored in two different ways:

- When a current flows in an inductor, energy gets stored in magnetic field.
- When a capacitor is charged, energy gets stored in static electric field.

The magnetic field in the inductor is built by the current, which is provided by the discharging capacitor.

Similarly, the capacitor is charged by the current produced by collapsing magnetic field of the inductor and this process continues on and on, causing electrical energy to oscillate between the magnetic field and the electric field.

In some cases, at a certain frequency called resonant frequency, the inductive reactance of the circuit becomes equal to the capacitive reactance which causes the electrical energy to oscillate between the electric field of the capacitor and the magnetic field of the inductor.

This forms a harmonic oscillator for current. In a RLC circuit, the presence of a resistor causes these oscillation to die out over a period of time and is called the damping effect of resistor.

### 1.6.1 Application of Series RLC Resonant Circuit

Since resonance in a series RLC circuit occurs at a particular frequency, it is used for filtering and tuning purpose as it does not allow unwanted oscillations that would otherwise cause signal distortion, noise and damage to the circuit to pass through it.

For a series RLC circuit at a certain frequency called the resonant frequency, the following points must be remembered.

#### For the Resonance frequency:

- Inductive reactance  $X_L$  is equal to capacitive reactance  $X_C$ .
- Total impedance of circuit becomes minimum which is equal to  $R$ .

$$ie\ Z = R$$

- Circuit current becomes maximum as the impedance reduces.

$$I = \frac{V}{R}$$

- Voltage across the inductor and capacitor cancels each other, so voltage across the resistor  $V_r$ :

$$V_r = V = \text{Supply voltage}$$

- Since net reactance is zero, circuit becomes purely resistive circuit and hence the voltage and the current are in same phase, so the phase angle between them is zero.
- Power factor is unity.
- Frequency at which resonance in series RLC circuit occurs is given by:

$$\frac{1}{2\pi\sqrt{LC}} = f_r \text{ unit is } H_z$$

Where:

$L$  is the inductance

$C$  is the capacitance

$f_r$  is the frequency

### 1.6.2 Frequency effect on circuit impedance

The reactance due to inductance and the reactance due to capacitance has the following effect on a series RLC circuit.

$$X_L = 2\pi fL$$

$$X_C = \frac{1}{2\pi fC}$$

$$\therefore \text{Impedance } Z = R + j(X_L - X_C)$$

### 1.6.3 Current at resonance

The current in a RLC circuit is determined from:

$$I = \frac{V}{R + j(X_L - X_C)}$$

**Figure 1.34** shows a typical curve of current verse frequency for a series RLC circuit.

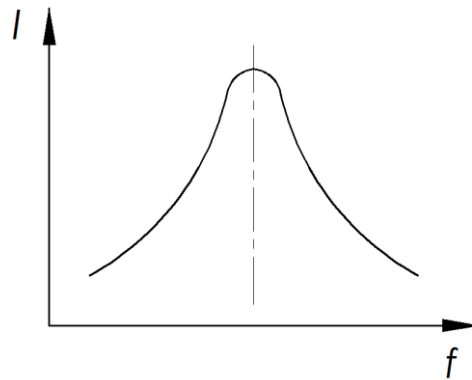


Figure 1.34 Current verse frequency in a RLC circuit

### 1.6.4 Resonance frequency

This is the frequency at which resonance occurs:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

The current reaches a maximum value at the resonance frequency and falls off sharply at frequencies above and below the resonance frequency.

### 1.6.5 Resonance rise in voltage

At resonance frequency, the voltage across the resistance is:

$$V_R = \text{The supply voltage}$$

The voltage across the capacitor is:

$$V_C = IX_C$$

The voltage across the inductor is:

$$V_L = IX_L$$

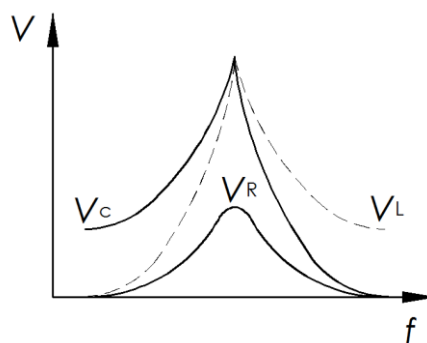


Figure 1.35  $V_C$ ,  $V_L$  and  $V_R$  plotted verses frequency

### 1.6.6 The quality of resonance (Q factor)

A measure of the quality of a resonance circuit is the ratio of the voltage developed across the capacitor at resonance to the supply voltage. This is termed the Q-factor.

The Q-factor:

$$Q = \frac{1}{R} \sqrt{\frac{L}{C}}$$

$$Q = \frac{X_L}{R}$$



#### Worked Example 1.10

A series RLC circuit produces the following readings:

It resonates at 500 kHz

L = 100 milli H

R = 25 ohms

C = 1000 pF

Determine the Q-factor of the circuit.

**Solution:**

$$Q = \frac{1}{R} \sqrt{\frac{L}{C}}$$

$$Q = \frac{1}{25} \sqrt{\frac{100}{1000}}$$

$$Q = 12.6$$

OR:

$$X_L = 2\pi fL$$

$$X_L = 2\pi 500 \times 100 \times 10^{-3}$$

$$Q = \frac{X_L}{R}$$

$$Q = \frac{314.159}{25} = 12.6$$

### 1.6.7 Bandwidth

**Figure 1.26** shows that the current reaches maximum  $I_m$  at resonance, but the frequency close to resonance is close to the maximum current value. Therefore, the resonance circuit selects a band of frequencies rather than just one frequency.

The lowest frequency of the band is  $f_1$  and the highest frequency of the band is  $f_2$ . The bandwidth is  $\Delta f$ :

$$\Delta f = f_2 - f_1$$

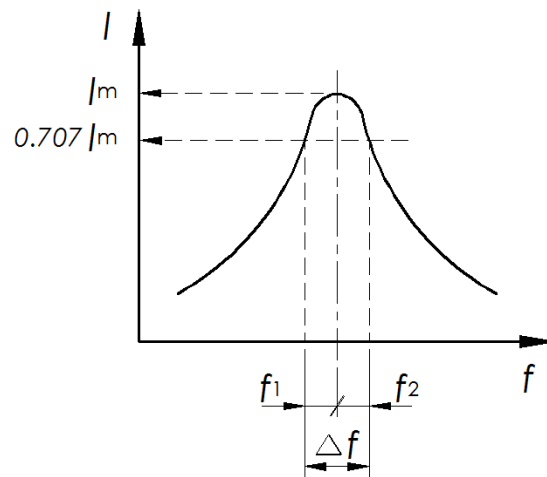


Figure 1.36 Bandwidth of a series resonance circuit

$$\Delta f = \frac{R}{2\pi L}$$

$$\Delta f = \frac{f_r}{Q}$$

### 1.7 Ideal parallel resonance circuit

When the supply frequency in an ideal parallel circuit is adjusted so that:

$$X_L = X_C$$

The admittance becomes:

$$Y = \frac{1}{R_p}$$

The circuit impedance becomes:

$$Z = R_p$$

The current taken from the supply:

$$I = \frac{V}{R_P}$$

### 1.7.1 Ideal parallel resonance circuit

An inductor is not reactive only but has a winding resistance. Capacitors can be assumed to be purely reactive. The impedance of a parallel LC circuit:

$$Z = \frac{L}{CR_S}$$

### 1.7.2 The Q-factor for a parallel LC circuit

The total current drawn from the supply is in phase with the voltage and is much less than  $I_C$  and  $I_L$ . Therefore, with the parallel resonant LC circuit there is current magnification which corresponds to the voltage magnification.

The Q-factor can be determined as the ratio of  $I_L$  to the supply current.

$$Q = \frac{I_L}{I} = \frac{X_L}{R_S}$$

$$Q = \frac{\omega L}{R_S}$$

### 1.7.3 Resonance frequency for a parallel LC circuit

$$\Delta f = \frac{f_r}{Q}$$



#### Activity 1.1

1. Define the following terms:
  - 1.1 Q-factor
  - 1.2 Band width
2. Consider the phasor diagram in **Figure 1.37** and calculate the values of  $Z_A$ ,  $Z_B$  and  $Z_C$  if the supply voltage is given as 120 V.

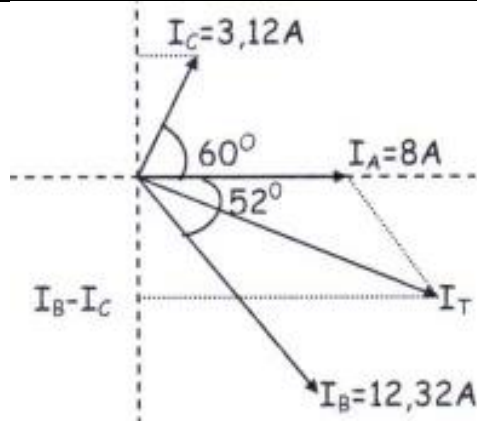


Figure 1.37

3. Consider **Figure 1.38** and, using complex numbers, calculate the following:
- 3.1 The total impedance of the circuit.
  - 3.2 The current flowing in the circuit.
  - 3.3 The voltage drop across the inductor.
  - 3.4 The voltage drop across the capacitor.

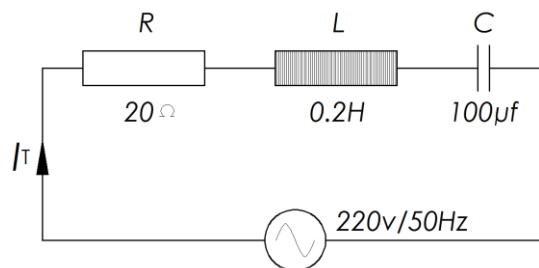


Figure 1.38

4. A coil of  $20\Omega$  resistance and  $100\mu\text{H}$  inductance are connected in parallel with a variable capacitor across a  $5\text{V}$ ,  $1\text{MHz}$  AC supply. Calculate the following:
- 4.1 The capacitance of the capacitor when the supply current is at minimum.
  - 4.2 The dynamic impedance.
  - 4.3 The supply current.
5. Consider **Figure 1.39** and calculate the following:
- 5.1 The value of the capacitor to give resonance
  - 5.2 The dynamic impedance

5.3 The Q-factor of the circuit

5.4 The total resistance of the circuit

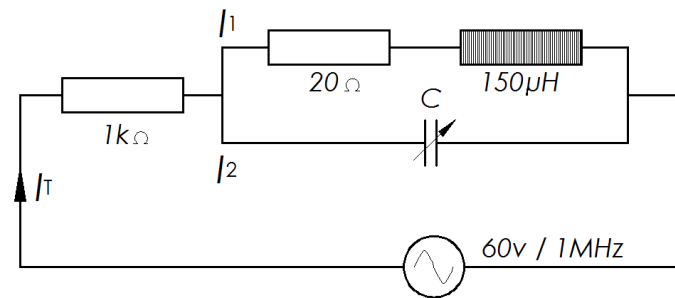


Figure 1.39

6. The following values were calculated from an RLC circuit. Draw a neat, labelled phasor diagram of the circuit.

6.1  $I_1 = 20,85 \angle -30^\circ \text{A}$

6.2  $I_2 = 15 \angle 110^\circ \text{A}$

6.3  $I_T = 12,64 \angle 16^\circ \text{A}$

7. How much current will flow in a 50 Hz series RLC circuit if  $V_S = 10 \text{V}$ ,  $R_T = 60 \Omega$  and  $X_T = 50 \Omega$ ?

8. What is the current-phase angle for a parallel-RLC circuit when  $I_L = 2,162 \text{A}$ ,  $I_C = 5 \text{A}$  and  $I_R = 3 \text{A}$ ?

9. The Q-factor of a circuit will be .... If  $X_L = X_C = 1500 \Omega$  and the resistor value is 15.

10. A circuit consists of two branches connected in parallel. A total voltage of  $120 \angle 10^\circ \text{V}$  is applied to this circuit. The current in the respective branches are  $15 \angle 20^\circ \text{A}$  and  $20 \angle 30^\circ \text{A}$ .

Calculate the following:

10.1 The total impedance of each branch

10.2 The total impedance of the circuit

10.3 The total current of the circuit

11. Study **Figure 1.40** and calculate the following:

11.1  $I_A$

11.2  $Z_A$

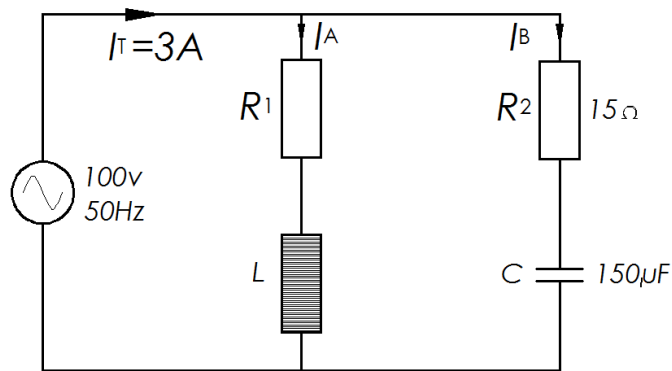


Figure 1.40



### Activity 1.1

#### Answers:

1. :
  - 1.1 Q-factor is the ratio of the reactance of the inductor or capacitor to its equivalent resistance
  - 1.2 Bandwidth is the range of frequencies centred around  $f_r$ , between  $f_H$  and  $f_L$ .
2.  $Z_A = 15 \angle 0^\circ \Omega$   $Z_B = 9,74 \angle 52^\circ \Omega$   $Z_C = 38,462 \angle -60^\circ \Omega$
3. :
  - 3.1 36,903  $57,2^\circ \Omega$
  - 3.2 5,962  $57,2^\circ \text{ A}$
  - 3.3 374,652  $32,8^\circ \text{ V}$
  - 3.4 189,753 –  $147,2^\circ \text{ V}$
4. :
  - 4.1  $C = 253,2 \text{ pF}$
  - 4.2  $I_T = \frac{V}{Z_D}$
  - 4.3 253,  $\mu\text{A}$
5. :
  - 5.1 168,825  $\text{pF}$
  - 5.2 50 000  $\Omega$

5.3	0,943
5.4	5,901 M
6.	:
7.	[0.128]
8.	[1°]
9.	[100]
10.	:
10.1	$Z_1 = 8 \angle -10^\circ \Omega$ $Z_2 = 6 \angle -20^\circ \text{ A}$
10.2	$3,442 \angle -15,7^\circ \Omega$
10.3	$34,869 \angle 25,7^\circ \text{ A}$
11.	:
11.1	$3,234 \angle -76,1^\circ$
11.2	$30,921 \angle 76,1^\circ \Omega$



### Self-Check

#### I am able to:

- |  | Yes | No |
|--|-----|----|
| • Describe alternating current theory  |     |    |
| • Use phasor diagrams and complex number calculations  |     |    |
| • Calculate and describe the characteristic curves of Q-factor, bandwidth, maximum power transfer, resonant frequency and circuits |     |    |

If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.

# Module 2

## Direct Current Theory

### Learning Outcomes

On the completion of this module the student must be able to:

- Calculate voltage, current and power by using the following network theorems:
  - Super position
  - Kirchhoff
  - Thevenin

### 2.1 Introduction



Current that flows in a single direction is called Direct Current, or DC. This module demonstrates calculations using DC Theory.

### 2.2 Super position theorem

The strategy used in the Superposition Theorem is to eliminate all but one source of power within a network at a time, using series/parallel analysis to determine currents within the modified network for each power source separately.

Then, once currents have been determined for each power source working separately, the values are all “superimposed” on top of each other (added algebraically) to find the actual currents with all sources active.



#### Worked Example 2.1

Determine the current by apply Superposition Theorem to it:

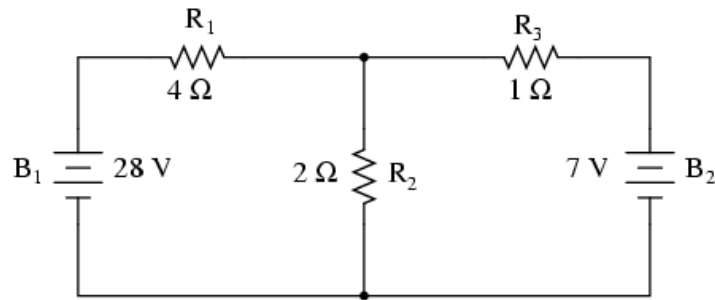


Figure 2.1

**Solution:**

Since we have two sources of power in this circuit, we will have to calculate two sets of values for currents, one for the circuit with only the 28 volt battery in effect. . .

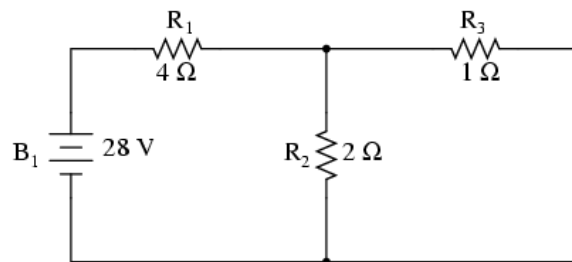


Figure 2.2

. . . and one for the circuit with only the 7 volt battery in effect:

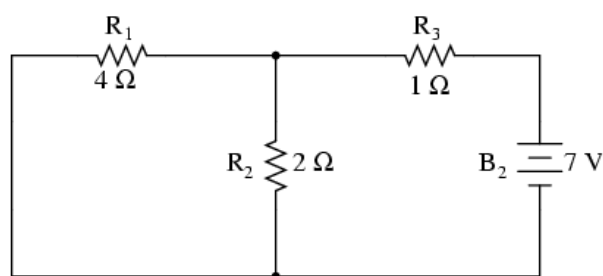


Figure 2.3

When re-drawing the circuit for series/parallel analysis with one source, all other voltage sources are replaced by wires (shorts), and all current sources with open circuits (breaks).

Since we only have voltage sources (batteries) in our example circuit, we will replace every inactive source during analysis with a wire.

Analyzing the circuit with only the **28 volt battery**, we obtain the following values for voltage and current:

	$R_1$	$R_2$	$R_3$	$R_2 // R_3$	$R_1 + R_2 // R_3$ Total	
E	24	4	4	4	28	Volts
I	6	2	4	6	6	Amps
R	4	2	1	0.667	4.667	Ohms

Figure 2.4

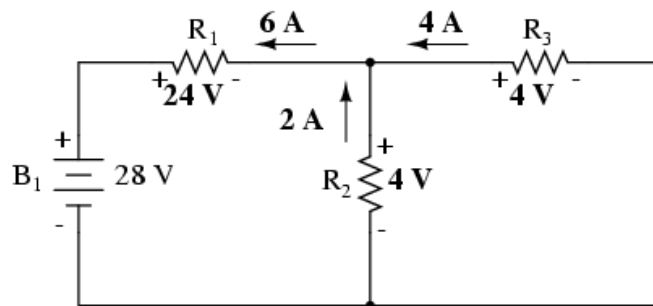


Figure 2.5

Analyzing the circuit with only the **7 volt battery**, we obtain another set of values for voltage and current:

	$R_1$	$R_2$	$R_3$	$R_1 // R_2$	$R_3 + R_1 // R_2$ Total	
E	4	4	3	4	7	Volts
I	1	2	3	3	3	Amps
R	4	2	1	1.333	2.333	Ohms

Figure 2.6

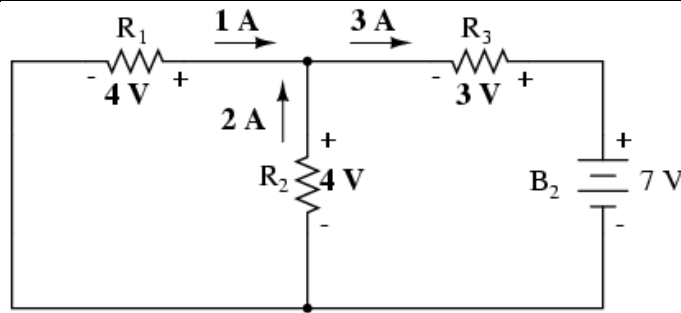


Figure 2.7

When superimposing these values of voltage and current, we have to be very careful to consider polarity (voltage drop) and direction (electron flow), as the values have to be added algebraically.

With 28 V battery	With 7 V battery	With both batteries
$24\text{ V}$  $E_{R1}$	$4\text{ V}$  $E_{R1}$	$20\text{ V}$  $E_{R1}$ $24\text{ V} - 4\text{ V} = 20\text{ V}$
 $E_{R2}$ $4\text{ V}$	 $E_{R2}$ $4\text{ V}$	 $E_{R2}$ $8\text{ V}$ $4\text{ V} + 4\text{ V} = 8\text{ V}$
$4\text{ V}$  $E_{R3}$	$3\text{ V}$  $E_{R3}$	$1\text{ V}$  $E_{R3}$ $4\text{ V} - 3\text{ V} = 1\text{ V}$

Figure 2.8

Applying these superimposed voltage figures to the circuit, the end result looks something like this:

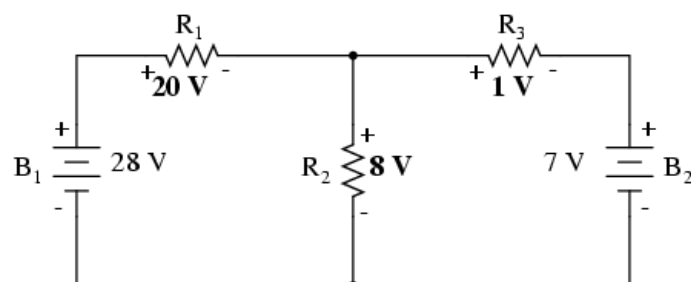


Figure 2.9

Currents add up algebraically as well, and can either be superimposed as done with the resistor voltage drops, or simply calculated from the final voltage drops and respective resistances ( $I=E/R$ ).

Either way, the answers will be the same. Here I will show the superposition method applied to current:


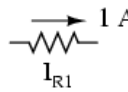
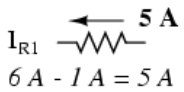

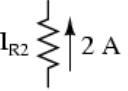



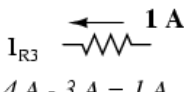
With 28 V battery	With 7 V battery	With both batteries
 $I_{R1}$	 $I_{R1}$	 $I_{R1}$ $6 A - 1 A = 5 A$
 $I_{R2}$	 $I_{R2}$	 $I_{R2}$ $2 A + 2 A = 4 A$
 $I_{R3}$	 $I_{R3}$	 $I_{R3}$ $4 A - 3 A = 1 A$

Figure 2.10

Once again applying these superimposed figures to our circuit:

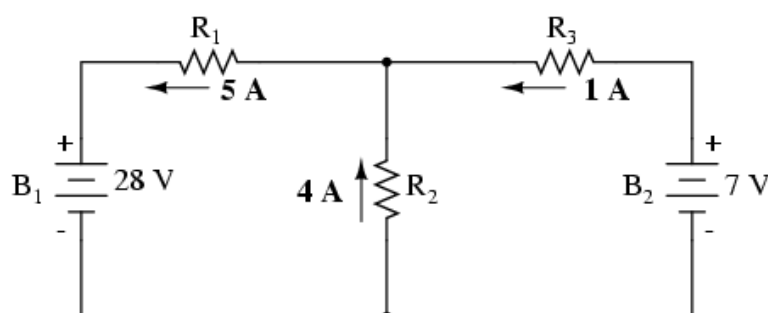


Figure 2.11



**Note:**

It must be noted, though, that the Superposition Theorem works only for circuits that are reducible to series/parallel combinations for each of the power sources at a time.

This theorem is useless for analyzing an unbalanced bridge circuit, and it only works where the underlying equations are linear (no mathematical powers or roots).

The requisite of linearity means that Superposition Theorem is only applicable for determining voltage and current, not power.

Power dissipations, being nonlinear functions, do not algebraically add to an accurate total when only one source is considered at a time. The need for linearity also means this Theorem cannot be applied in circuits where the resistance of a component changes with voltage or current.

Hence, networks containing components like lamps (incandescent or gas-discharge) or varistors could not be analyzed.

Another prerequisite for Superposition Theorem is that all components must be “bilateral,” meaning that they behave the same with electrons flowing either direction through them.

### 2.3 Thevenin’s Theorem

Thevenin’s Theorem states that it is possible to simplify any linear circuit, no matter how complex, to an equivalent circuit with just a single voltage source and series resistance connected to a load.

The qualification of “linear” is identical to that found in the Superposition Theorem, where all the underlying equations must be linear (no exponents or roots).

If we’re dealing with passive components (such as resistors, and later, inductors and capacitors), this is true. However, there are some components (especially certain gas-discharge and semiconductor components) which are nonlinear: that is, their opposition to current changes with voltage and/or current.

As such, we would call circuits containing these types of components, nonlinear circuits.

Thevenin’s Theorem is especially useful in analyzing power systems and other circuits where one particular resistor in the circuit (called the “load” resistor) is subject to change, and re-calculation of the circuit is necessary with each trial value of load resistance, to determine voltage across it and current through it.



#### Worked Example 2.2

Determine the current by apply Thevenin’s Theorem to it:

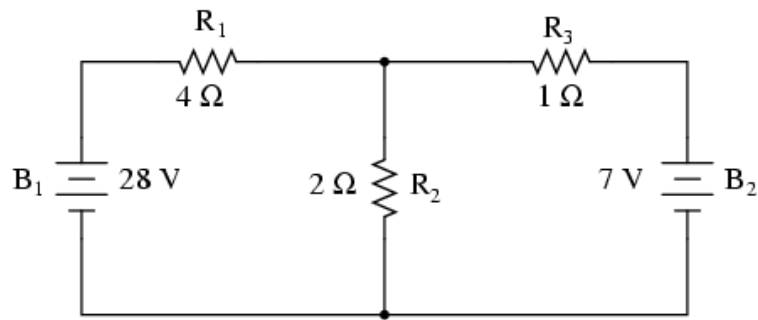


Figure 2.12

**Solution:**

Thevenin's Theorem makes this easy by temporarily removing the load resistance from the original circuit and reducing what's left to an equivalent circuit composed of a single voltage source and series resistance.

The load resistance can then be re-connected to this "Thevenin equivalent circuit" and calculations carried out as if the whole network were nothing but a simple series circuit:

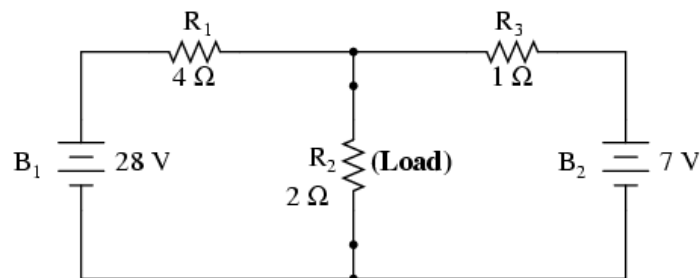


Figure 2.13

after Thevenin conversion . . .

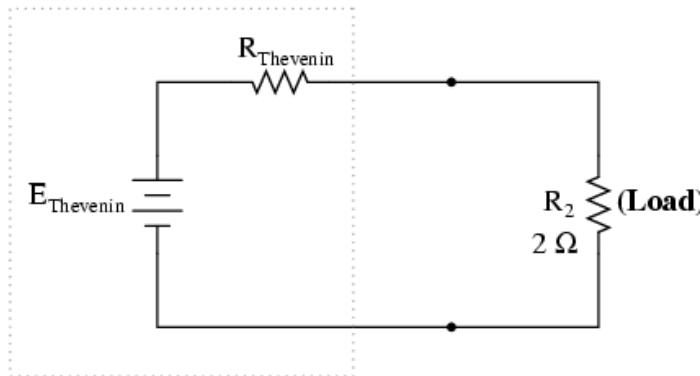
*Thevenin Equivalent Circuit*

Figure 2.14

The “Thevenin Equivalent Circuit” is the electrical equivalent of  $B_1$ ,  $R_1$ ,  $R_3$ , and  $B_2$  as seen from the two points where our load resistor ( $R_2$ ) connects.

The Thevenin equivalent circuit, if correctly derived, will behave exactly the same as the original circuit formed by  $B_1$ ,  $R_1$ ,  $R_3$ , and  $B_2$ . In other words, the load resistor ( $R_2$ ) voltage and current should be exactly the same for the same value of load resistance in the two circuits.

The load resistor  $R_2$  cannot “tell the difference” between the original network of  $B_1$ ,  $R_1$ ,  $R_3$ , and  $B_2$ , and the Thevenin equivalent circuit of  $E_{\text{Thevenin}}$ , and  $R_{\text{Thevenin}}$ , provided that the values for  $E_{\text{Thevenin}}$  and  $R_{\text{Thevenin}}$  have been calculated correctly.

The advantage in performing the “Thevenin conversion” to the simpler circuit, of course, is that it makes load voltage and load current so much easier to solve than in the original network.

Calculating the equivalent Thevenin source voltage and series resistance is actually quite easy. First, the chosen load resistor is removed from the original circuit, replaced with a break (open circuit):

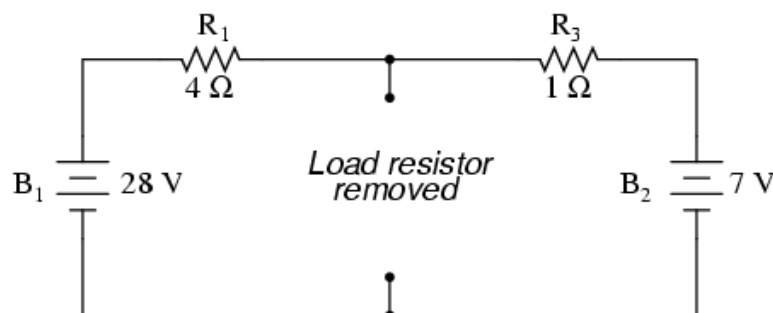


Figure 2.15

Next, the voltage between the two points where the load resistor used to be attached is determined. Use whatever analysis methods are at your disposal to do this.

In this case, the original circuit with the load resistor removed is nothing more than a simple series circuit with opposing batteries, and so we can determine the voltage across the open load terminals by applying the rules of series circuits, Ohm's Law, and Kirchhoff's Voltage Law:

	$R_1$	$R_3$	Total	
E	16.8	4.2	21	Volts
I	4.2	4.2	4.2	Amps
R	4	1	5	Ohms

Figure 2.16

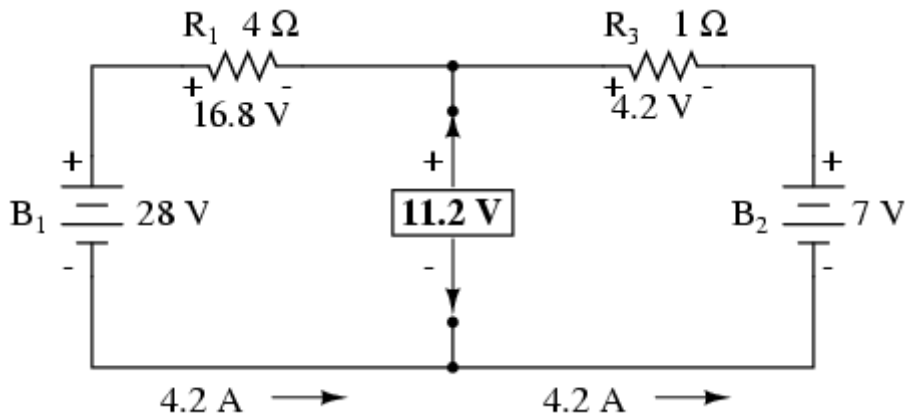


Figure 2.17

The voltage between the two load connection points can be figured from the one of the battery's voltage and one of the resistor's voltage drops, and comes out to 11.2 volts.

This is our "Thevenin voltage" ( $E_{Thevenin}$ ) in the equivalent circuit:

*Thevenin Equivalent Circuit*

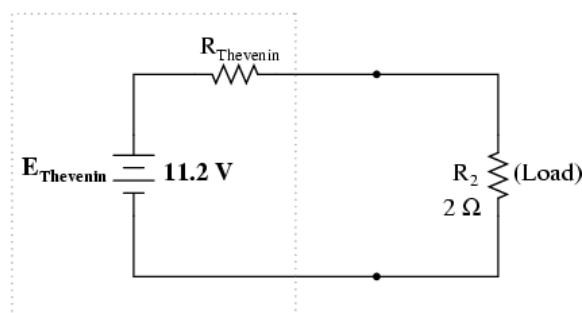


Figure 2.18

To find the Thevenin series resistance for our equivalent circuit, we need to take the original circuit (with the load resistor still removed), remove the power sources (in the same style as we did with the Superposition Theorem: voltage sources replaced with wires and current sources replaced with breaks), and figure the resistance from one load terminal to the other:

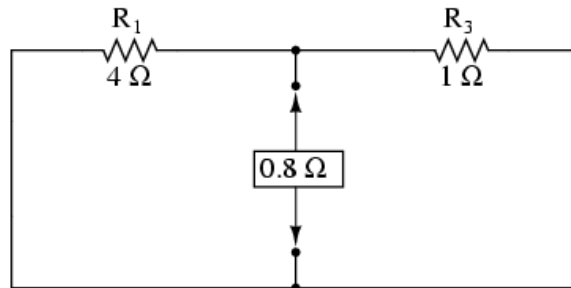


Figure 2.19

With the removal of the two batteries, the total resistance measured at this location is equal to  $R_1$  and  $R_3$  in parallel:  $0.8 \Omega$ . This is our “Thevenin resistance” ( $R_{Thevenin}$ ) for the equivalent circuit:

*Thevenin Equivalent Circuit*

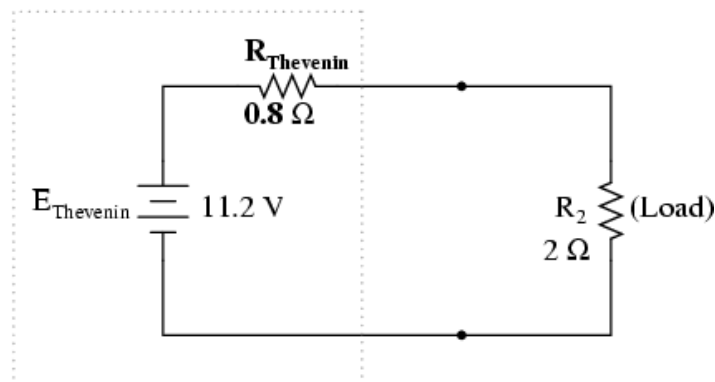


Figure 2.20

With the load resistor ( $2 \Omega$ ) attached between the connection points, we can determine voltage across it and current through it as though the whole network were nothing more than a simple series circuit:

	$R_{Thevenin}$	$R_{Load}$	Total	
E	3.2	8	11.2	Volts
I	4	4	4	Amps
R	0.8	2	2.8	Ohms

Figure 2.21

Notice that the voltage and current figures for  $R_2$  (8 volts, 4 amps) are identical to those found using other methods of analysis.

Also notice that the voltage and current figures for the Thevenin series resistance and the Thevenin source (total) do not apply to any component in the original, complex circuit. Thevenin's Theorem is only useful for determining what happens to a single resistor in a network: the load.

The advantage is that you can quickly determine what would happen to that single resistor if it were of a value other than  $2\ \Omega$  without having to go through a lot of analysis again.

Just plug in that other value for the load resistor into the Thevenin equivalent circuit and a little bit of series circuit calculation will give you the result.

## 2.4 Kirchhoff's theorem

Kirchhoff's circuit laws are two equalities that deal with the current and potential difference in the lumped element model of electrical circuits.

This generalized the work of Georg Ohm and preceded the work of Maxwell. Widely used in electrical engineering, they are also called Kirchhoff's rules or simply Kirchhoff's laws.

Both of Kirchhoff's laws can be understood as corollaries of the Maxwell equations in the low-frequency limit. They are accurate for DC circuits.



### Worked Example 2.3

Use Kirchhoff's method to determine the current flowing through  $5\ \Omega$ .

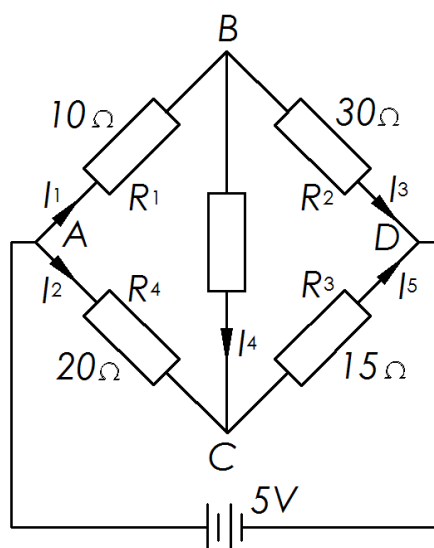


Figure 2.22

**Solution:**

Consider loop ABCA

$$0 = 10I_1 + 5I_2 - I_3 - 20I_2$$

$$0 = 10I_1 + 5I_2 - I_3 - 20I_2 \dots\dots\dots (1)$$

Consider loop BDCB

$$0 = 30I_3 - 15(I_1 - I_3) - (I_1 - I_3)$$

$$0 = 30I_3 - 5I_2 + 15I_3 - 15I_2 - 5I_1 + 15I_3$$

$$0 = 20I_1 + 15I_2 - 50I_3 \dots\dots\dots (2)$$

Consider loop ABDA

$$5 = 10I_1 + 30I_3$$

$$10I_1 = 5 - 30I_3$$

$$I_1 = 0,5 - 3I_3 \dots\dots\dots (3)$$

$$(1) \times 15: 0 = 225I_1 - 300I_2 - 75I_3 \dots\dots\dots (4)$$

$$(2) \times 20: 0 = 400I_1 + 300I_2 - 1000I_3 \dots\dots\dots (5)$$

$$(4) + (5): 0 = 625I_1 - 1075I_3 \dots\dots\dots (6)$$

$$\text{Subst } I_1 \text{ in (6): } 0 = 625(0,5 - 3I_3)$$

$$I_3 = 0,106 \text{ A}$$

$$I_1 = 0,5 - 3(0,106)$$

$$I_1 = 0,182 \text{ A}$$

$$\begin{aligned} I_4 &= I_1 - I_3 \\ &= 0,182 - 0,106 \\ &= 0,076 \text{ A} \end{aligned}$$

**Activity 2.1**

1. Use Thevenin's theorem to calculate the current flowing through the 10 ohm resistor.

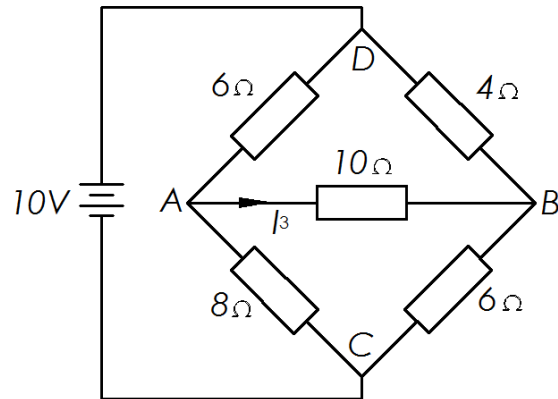


Figure 2.23

2. Use Thevenin's method to determine the current flowing through  $R_4$ .

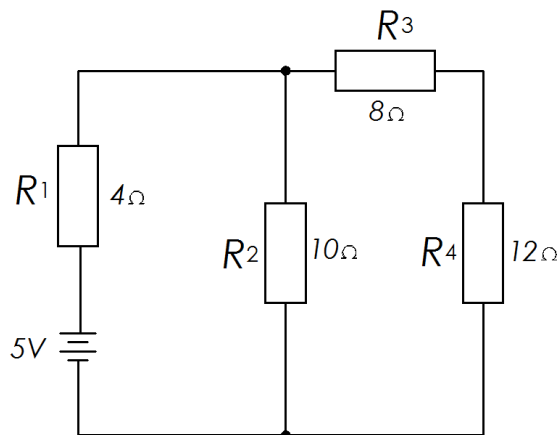


Figure 2.24

3. Use the Superposition method to calculate the current flowing through a  $15\ \Omega$  resistor.

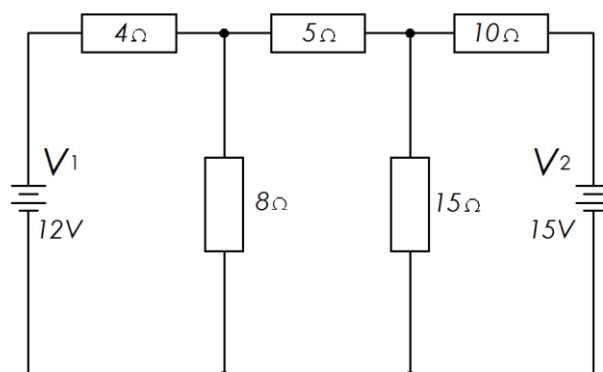


Figure 2.25

4. Use Kirchoff's law to calculate the current flowing through  $R_L$ .

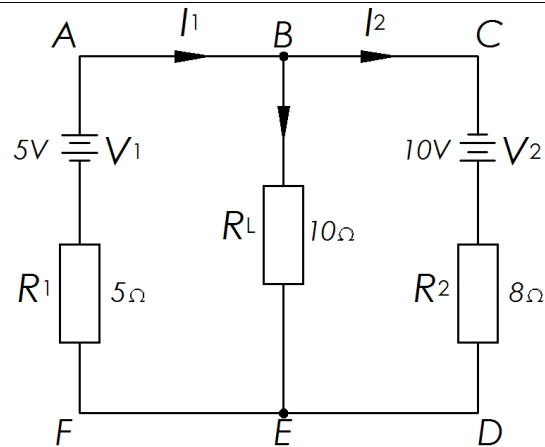


Figure 2.26

5. Use Thevenin's theorem to calculate the current flowing through the load resistor.

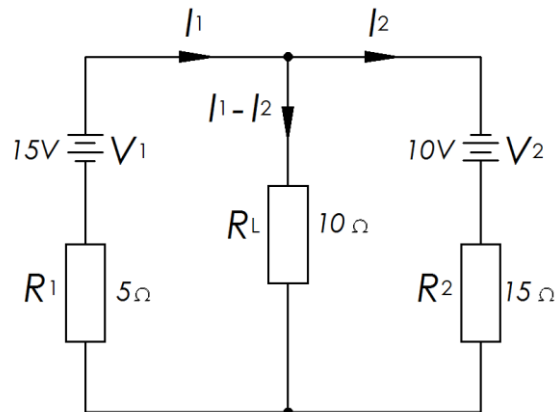


Figure 2.27

6. Use the superposition method to calculate the current flowing through the  $8\ \Omega$  resistor for the circuit.

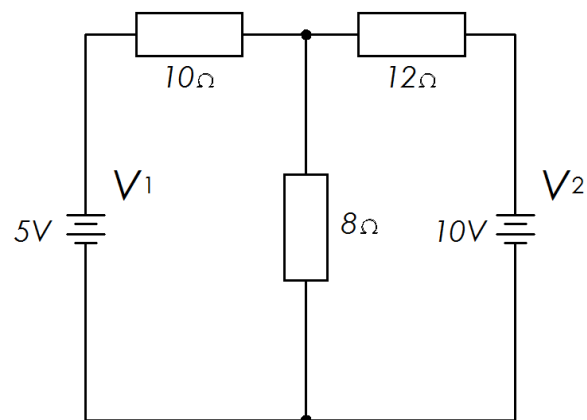


Figure 2.28



### Activity 2.1

#### Answers:

1. 0,126 A
2. 0,156 A
3. 0,571 A
4. -0,059 A
5. 0,636 A
6. 0,558 A



### Self-Check

#### I am able to:

- |  | Yes | No |
|--|-----|----|
| <ul style="list-style-type: none"> <li>• Calculate voltage, current and power by using the following network theorems:               <ul style="list-style-type: none"> <li>○ Super position</li> <li>○ Kirchhoff</li> <li>○ Thevenin</li> </ul> </li> </ul> |     |    |

If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.

# Module 3

## Semi-conductors - Diodes

### Learning Outcomes

On the completion of this module the student must be able to:

- Calculate the forward- and reverse saturation current and forward voltage by using the diode equation
- Calculate the forward resistance of a PN junction diode
- Calculate the voltage, current and resistance values of a simple voltage regulator
- Describe the properties and characteristic curves of:
  - Tunnel diode
  - Varactor diode
  - Zener diode

### 3.1 Introduction



A diode is a two-terminal electronic component that conducts primarily in one direction; it has low resistance to the flow of current in one direction, and high resistance in the other. A semiconductor diode, the most common type today, is a crystalline piece of semiconductor material with a p-n junction connected to two electrical terminals.

### 3.2 Properties and characteristic curves

#### 3.2.1 The tunnel diode

The Tunnel diode is one of the most commonly used negative conductance devices. It is also known as Esaki diode after L. Esaki for his work on this effect.

With this diode, the p-n junction is abrupt. For this reason, the depletion layer width is very small. In the current voltage characteristic of the tunnel diode, we can find a negative slope region when forward bias is applied.

Quantum mechanical tunneling is responsible for this phenomenon and thus this device is named as tunnel diode.



#### Definition: Fermi level

The term used to describe the top of the collection of electron energy levels at absolute zero temperature.

### Characteristics of a Tunnel diode:

When reverse bias is applied the electron energy level of the p - side becomes higher than the electron energy level of the n-side. Hence, the tunneling of electrons from the balance band of the p-side to the conduction band of the n-side takes place.

The tunnel current is very large compared to the normal junction current.

When the forward bias is increased, the tunnel current is increased up to certain limit.

When the forward bias is raised further, normal p-n junction current is obtained which is exponentially proportional to the applied voltage. The V - I characteristics of the tunnel diode is given,

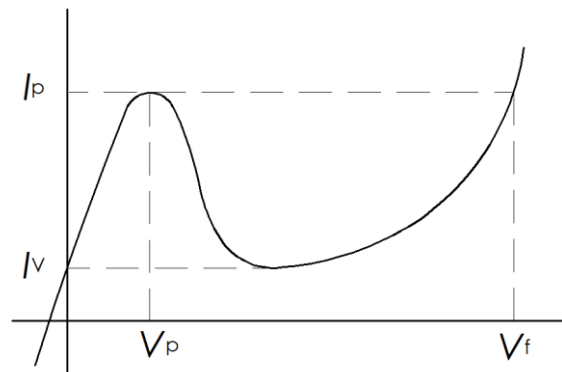


Figure 3.1 V - I characteristics of the tunnel diode

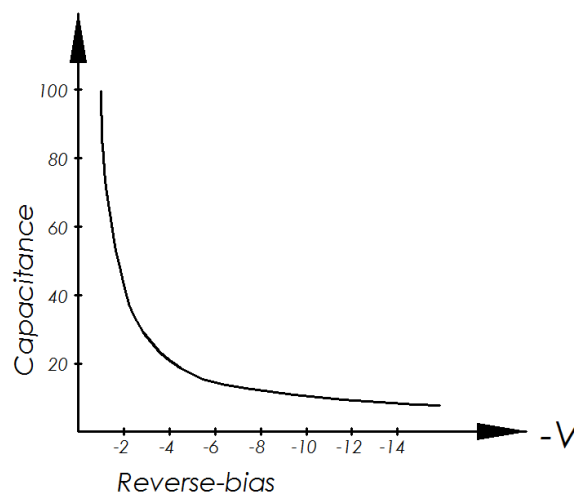


Figure 3.2 V - C reverse-bias characteristics of the tunnel diode

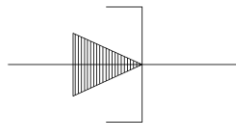
**Tunnel diode symbol:**

Figure 3.3 Symbol for the tunnel diode

**Tunnel diode applications:**

The tunnel diode is a type of SC diode which is capable of very fast and in microwave frequency range. It was the quantum mechanical effect which is known as tunneling.

It is ideal for fast oscillators and receivers because of its negative slope characteristics. But it cannot be used in large integrated circuits – that's why its applications are limited.

When the voltage is first applied, the current increases with the increase of voltage. Once the voltage rises to a certain high level, the current starts increasing again and the tunnel diode starts behaving like a normal diode.

Because of this unusual behavior, and the fact that they are resistant to nuclear radiation, resistant to the effects of magnetic fields and high temperature, they can be used in a number of special applications stated below:

- High frequency oscillators
- Microwave circuits
- Modern military equipment
- Satellite communication equipment

**3.2.2 The varactor diode**

Varactor Diode is a reverse biased p-n junction diode, whose capacitance can be varied electrically. As a result, these diodes are also referred to as varicaps, tuning diodes, voltage variable capacitor diodes, parametric diodes and variable capacitor diodes.

The operation of the p-n junction depends on the bias applied which can be either forward or reverse in characteristic. It is also observed that the span of the depletion region in the p-n junction decreases as the voltage increases in case of forward bias.

**Characteristics of a varactor diode:**

On the other hand, the width of the depletion region is seen to increase with an increase in the applied voltage for the reverse bias scenario. Under such condition, the p-n junction can be considered to be analogous to a capacitor, where the p and n layers represent the two plates of the capacitor while the depletion region acts as a dielectric separating them.

Thus one can apply the formula used to compute the capacitance of a parallel plate capacitor to the varactor diode.

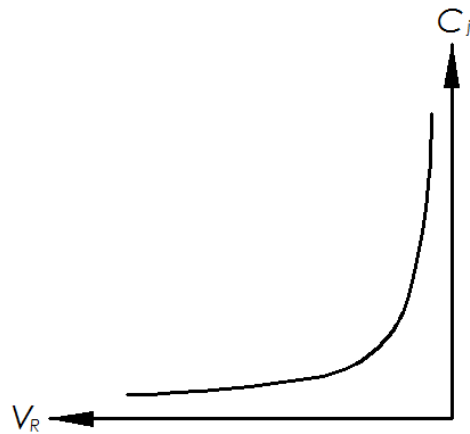


Figure 3.4 Characteristics of the varactor diode

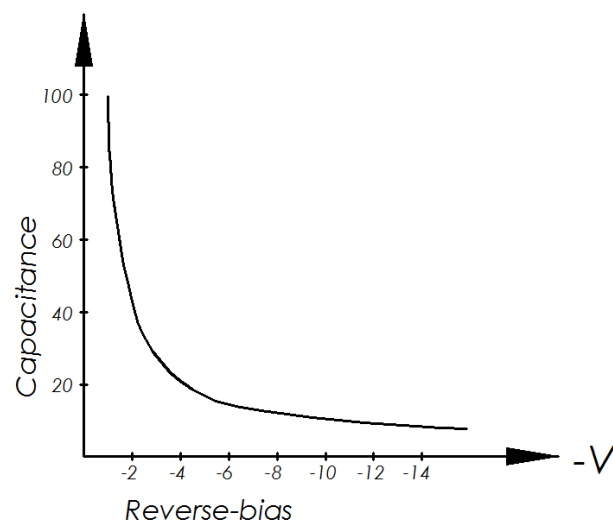


Figure 3.5 Characteristics of reverse-bias of the varactor diode

#### Varactor diode symbol:

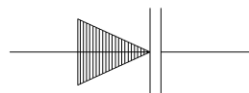


Figure 3.6 Symbol for the varactor diode

#### Varactor diode applications:

These varactor diodes are advantageous as they are compact in size, economical, reliable and less prone to noise when compared to other diodes.

Hence, they are used in:

- Tuning circuits to replace the old style variable capacitor tuning of FM radio
- Small remote control circuits
- Tank circuits of receiver or transmitter for auto-tuning as in case of TV
- Signal modulation and demodulation.
- Microwave frequency multipliers as a component of LC resonant circuit
- Very low noise microwave parametric amplifiers
- AFC circuits
- Adjusting bridge circuits
- Adjustable bandpass filters
- Voltage Controlled Oscillators (VCOs)
- RF phase shifters
- Frequency multipliers

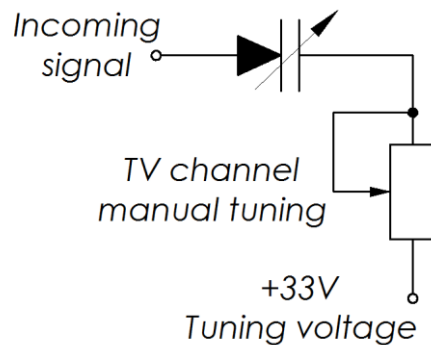


Figure 3.7 A varactor diode used in a tuning circuit application

### 3.2.3 The zener diode

The zener diode is basically like an ordinary PN junction diode but normally operated in a reverse biased condition. But ordinary PN junction diode connected in reverse biased condition is not used as Zener diode practically. A Zener diode is a specially designed, highly doped PN junction diode.

When a PN junction diode is reverse biased, the depletion layer becomes wider. If this reverse biased voltage across the diode is increased continually, the depletion layer becomes more and more wider.

At the same time, there will be a constant reverse saturation current due to minority carriers. After a certain reverse voltage across the junction, the minority carriers get sufficient kinetic energy. This is due to the strong electric field.

Free electrons with sufficient kinetic energy collide with stationary ions of the depletion layer and knock out more free electrons. These newly created

electrons also get sufficient kinetic energy due to the same electric field, and they create more free electrons by continued collision.

Due to this commutative phenomenon, a large amount of electrons will be created in the depletion layer, and the entire diode will become conductive. This type of breakdown of the depletion layer is known as avalanche breakdown, but this breakdown is not sharp.

There is another type of breakdown in the depletion layer which is sharper compared to avalanche breakdown, and this is called Zener breakdown.

The voltage at which this breakdown occurs is called zener voltage. If the applied reverse voltage across the diode is more than the zener voltage, the diode provides a conductive path to the current through it, hence, there is no chance of further avalanche breakdown in it.

Theoretically, zener breakdown occurs at lower voltage levels than avalanche breakdown in a diode which is specially doped for zener break down.

### Characteristics of a zener diode:

Looking at the graphical representation of the operation of the zener diode. The V-I characteristics are shown for a p - n junction diode.

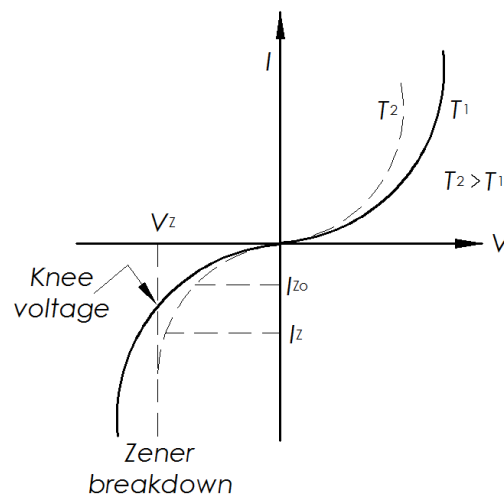


Figure 3.8 Characteristics of the zener diode

The above diagram shows the V-I characteristics of the zener diode. When the diode is connected in forward bias, this diode acts as a normal diode but when the reverse bias voltage is greater than a predetermined voltage, zener breakdown voltage takes place.

To make the breakdown voltage sharp and distinct, the doping is controlled and the surface imperfections are avoided. In the V-I characteristics  $V_z$  is the

zener voltage, it is also the knee voltage because at this point the current is very rapid.

### Zener diode symbol:

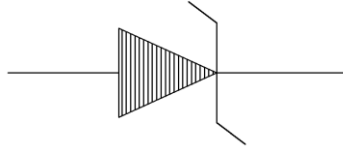


Figure 3.9 Symbol for the zener diode

### Zener diode applications:

The main application of this type of diode is the voltage regulator, over voltage protector and voltage references.

Overvoltage protection is done by using Zener diodes because there is current flowing through the diode after the reverse bias voltage exceeds a certain value.

This circuit protects the equipment connected at the terminals. Because of a fault in the circuit, the current may exceed the maximum allowable limit. A SCR is used and the output voltage is quickly cut out and a fuse blows which disconnects the input source power.

Voltage references determines that power, current or voltage remains constant. This is done with the help of a Zener diode.

To avoid unstable performance, zener diodes are used where voltage reference is required like ohmmeters, ammeters and voltmeters.

### Zener Diode as Voltage Regulator:

The term regulator means that which regulates or controls. A zener diode can work as a voltage regulator when it is introduced in a circuit. The output across the diode will be constant. It is driven by a current source.

If the voltage across the diode exceeds a certain value it would draw excessive current from the supply.

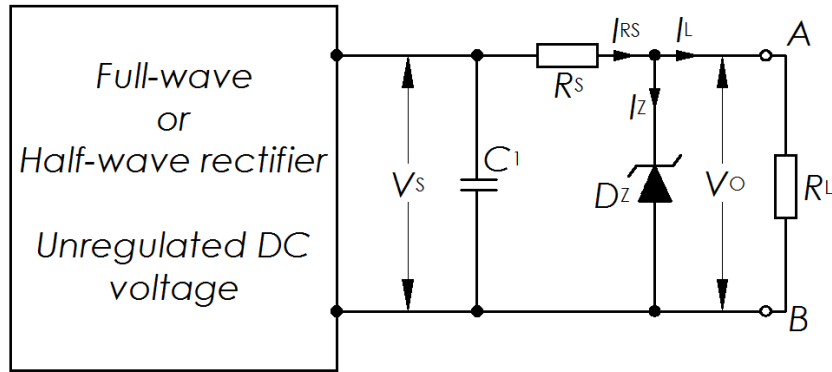


Figure 3.10 Zener diode voltage regulator

#### Output load regulation:

If the load current through  $R_L$  increase, the Zener current will fall with the corresponding amount.

If the load current through  $R_L$  decreases, the Zener current will increase with the corresponding amount.

### 3.3 The Diode

A diode is a device which allows current to flow in one direction only.

A diode blocks current in the reverse direction only while the reverse voltage is within a limited range.

#### The PN junction DIODE:

The diode acts as a valve in an electronic circuit. A PN junction is the simplest form of the diode which behaves as a short circuit when it is in forward biased and an open circuit when it is in the reverse biased.

Beside simple PN junction diodes, there are different types of diodes although the fundamental principle is more or less same. So a particular arrangement of **diodes** can convert AC to pulsating DC, and hence, it is sometimes also called as a rectifier.



Figure 3.11 Diode

#### 3.3.1 Pulse and waveforms

A pulse wave is a kind of non-sinusoidal waveform that is similar to a square wave, but does not have the symmetrical shape associated with a perfect square wave.

It is a term common to synthesizer programming, and is a typical waveform available on many synthesizers. The exact shape of the wave is determined by the duty cycle of the oscillator.

The pulse wave is also known as the rectangular wave.

### Electron charge:

Electron charge, (symbol  $q$ ), is a fundamental physical constant expressing the naturally occurring unit of electric charge, equal to  $1.6021765 \times 10^{-19}$  coulomb,

In addition to the electron, all freely existing charged subatomic particles thus far discovered have an electric charge equal to this value or some whole-number multiple of it.

$$\text{Electron charge} = 1,6 \times 10^{-19} \text{C}$$

### Boltzmann constant:

The Boltzmann constant ( $k$ ), named after Ludwig Boltzmann, is a physical constant relating energy at the individual particle level with temperature.

The Boltzmann constant has the dimension energy divided by temperature, the same as entropy. The accepted value in SI units is  $1.38064852 \times 10^{-23}$  J/K.

$$\text{Boltzmann's constant} = 1,38 \times 10^{-23} \text{J/k}$$

### Voltage regulation:

$$V_{rms} = 0,707 V_m$$

$$V_{rms} = 0,637 V_m$$

$$V_{dc} / V_{gs} = 0,637 V_m$$

$$V_{dc} / V_{gs} = 0,318 V_m$$

$$V_{rms} / V_{wgk} = 0,385 V_m$$

$$PIV = V_m \text{ or } 2 V_m$$

$$V_{rms} / V_{wgk} = \frac{V_r(p-p)}{\sqrt[2]{3}}$$

$$V_{dc} / V_{gs} = V_m - \frac{V_r(p-p)}{2}$$

$$V_{rms} / V_{wgk} = \frac{V_{dc} / V_{gs}}{R_L \sqrt[2]{3} FC}$$

$$V_{dc} / V_{gs} = V_m \frac{I_{dc} / I_{gs}}{2FC}$$

$$VR = \frac{I_{NL} - V_{FL}}{V_{FL}}$$

$$i = I_s \left( e^{\frac{qv}{kT}} - 1 \right)$$

### Full wave power supply:

Output DC voltage of capacitor:

$$V_{dc} = V_m - \frac{I_{dc}}{4FC}$$

$$V'_{dc} = \frac{R_L \times V_{dc}}{R_L + R}$$

Output ripple voltage:

$$V_{rms}/V_{Wgk} = \frac{X_c}{\sqrt{R^2 + X_c^2}} \times \frac{V_{rms}/V_{Wgk}}{1}$$

Output ripple factor:

$$r' = \frac{V_{r'(RMS)}}{V'_{dc}}$$

### Current flow through a diode:

$T = 273.t$  measured in Kelvin

$$\text{Current flow } I = \frac{KT}{Rq}$$

Were:

$R$  is the forward resistance

### Output voltage of an LC – $\pi$ – filter:

The output voltage  $V'_{dc}$ :

$$V'_{dc} = \frac{R_L \times V_{dc}}{R_L + R}$$

Were:

$R_L$  is the load resistance

$V_{dc}$  is the voltage across the input capacitor



### Worked Example 3.1

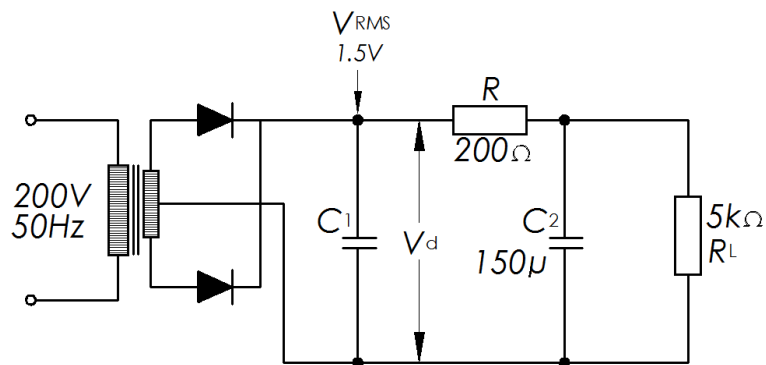


Figure 3.12

Consider the circuit diagram shown in **Figure 3.12** and calculate the following:

1. The output DC voltage
2. The output ripple voltage
3. The output ripple factor

**Solution:**

$$\begin{aligned}
 1. \quad V'_{dc} &= \frac{R_L}{R_L + R} \times V_{dc} \\
 &= \frac{5000}{5000 + 200} \times 15 \\
 &= 14,423 \text{ V}
 \end{aligned}$$

$$\begin{aligned}
 2. \quad V_{r(rms)} &= X_c \times \frac{V_{r(rms)}}{\sqrt{R^2 + X_c^2}} \text{ but } \frac{1}{4\pi \times 50 \times 150 \times 10^{-6}} = 10,609 \Omega \\
 &= \frac{10,609}{\sqrt{200^2 + 10,609^2}} \times 1,5 \\
 &= 0,079 \text{ V}
 \end{aligned}$$

$$\begin{aligned}
 3. \quad r' &= \frac{V_{r(rms)}}{V'_{dc}} \\
 &= \frac{0,079}{14,423} \\
 &= 0,006
 \end{aligned}$$



### Worked Example 3.2

The output voltage across the second capacitor of a half-wave LC- $\pi$ -filter is 60 V DC.

The ripple voltage across the first capacitor is 10 V at a frequency of 100 Hz.

When  $L = 3\text{ H}$ ,  $R = 200\ \Omega$ ,  $C_2 = 5\ \mu\text{F}$  and  $R_L = 5\ \text{k}\ \Omega$ , calculate the following:

1. The output voltage across the first capacitor
2. The ripple voltage across the second capacitor

#### Solution:

$$1. \quad V'_{dc} = \frac{V_{dc}}{R_L + R}$$

$$60 = \frac{5000}{5000 + 200} \times V_{dc}$$

$$V_{dc} = 62,4\ \text{V}$$

$$2. \quad V_{r(rms)} = X_C \times \frac{V_{r(rms)}}{4\pi^2 f^2 LC}$$

$$= \frac{10}{4\pi^2 100^2 \times 3 \times 5 \times 10^{-6}}$$

$$= 1,689\ \text{V}$$



### Activity 3.1

1. Explain the following:
  - 1.1 PN-junction diode
  - 1.2 Varactor diode
  - 1.3 Tunnel diode
  - 1.4 Zener diode
2. A diode has a forward resistance of 0,11 ohm. Calculate the current flow through the diode at a room temperature of 30 °C.
3. Calculate the output voltage of an LC- $\pi$ -filter with a resistance of 200 ohms and a 1,5 k  $\Omega$  load resistance. The voltage across the input

capacitor is 200 V.

4. Draw a simple Zener diode voltage-regulator circuit and explain how the output load will be regulated.
5. A 12 V full-wave power supply operates from a 50 Hz supply. If a load draws a 15 mA current from the supply, calculate the output DC voltage if a 100  $\mu F$  capacitor is used.
6. Draw a circuit diagram of a varactor diode used in tuning circuits and give three of its areas of application.
7. The output voltage across the first capacitor of a LD- $\pi$ -filter half-wave rectifier is 120 V DC with an 8 ripple at a frequency of 110 Hz. Calculate the output ripple factor of the filter if  $L = 5 H$ ,  $R = 200 \Omega$  and  $C_2 = 6 \mu F$ . The filter is connected to a 6 k  $\Omega$  load.
8. Calculate the PIV of a half wave rectifier that has an input voltage of 220 Vrms.
9. Name two advantages and three disadvantages of an LC filter.
10. Draw a neat symbol and a characteristic curve of a tunnel diode. Name also one of its applications.
11. State five differences between a bridge-rectifier circuit and two diodes with a centre-tap transformer circuit.
12. Answer the following questions on the varactor diode:
  - 12.1 State two of its uses
  - 12.2 Draw its characteristic curve
  - 12.3 Explain its operation
13. Consider **Figure 3.13** and calculate the following:
  - 13.1 The value of the series resistor ( $R_S$ )
  - 13.2 The value of the load resistor ( $R_L$ )

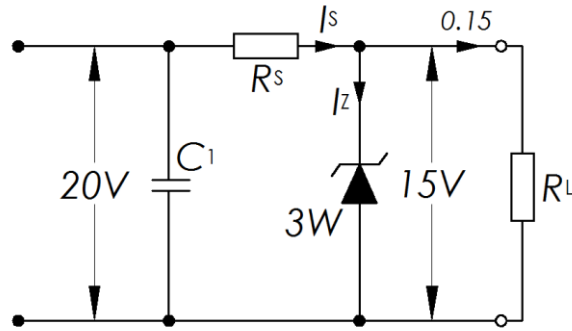


Figure 3.13

14. Give two disadvantages of a half-wave rectifier

15. Give the names of the diodes that match the following descriptions:

- 15.1 It permits current to flow in the forward bias direction but it will also flow in the reverse bias when the voltage is above breakdown voltage.
- 15.2 It has heavily doped p-type and n-type regions separated by an intrinsic region.
- 15.3 Its operation depends on the capacitance that exists at the PN-junction which is reverse biased.
- 15.4 It has a negative resistance region where an increase in terminal voltage results in reduction in current of the diode.
- 15.5 One of its areas of application is the parametric amplifier

16. A half-wave rectifier has an input voltage of 200 Vrms applied to it.

Calculate the following:

- 16.1  $V_{max}$
- 16.2  $V_{dc}$
- 16.3 PIV



### Activity 3.1

#### Answers:

1. :

- 1.1 has heavily doped p-type and n-type regions separated by an intrinsic region.

- 1.2 its operation depends on the capacitance that exists at the PN-junction which is reverse biased.
- 1.3 has a negative resistance region where an increase in terminal voltage results in reduction in diode current.
- 1.4 permits current to flow in the forward bias direction but it will also flow in the reverse bias when the voltage is above breakdown voltage.

- 2. 0,238 V
- 3. 176,471 V
- 4. :

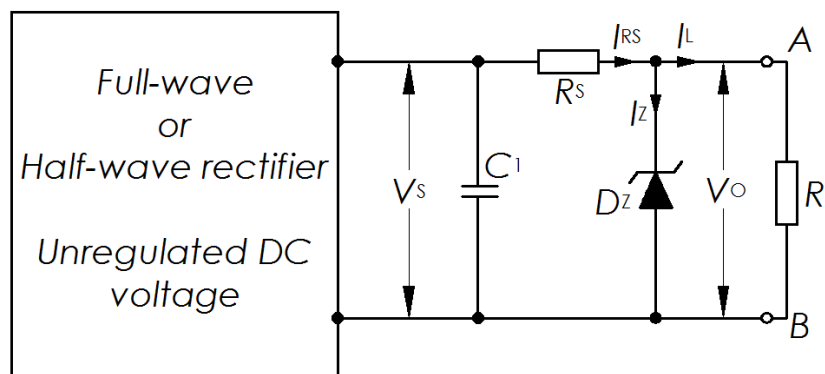
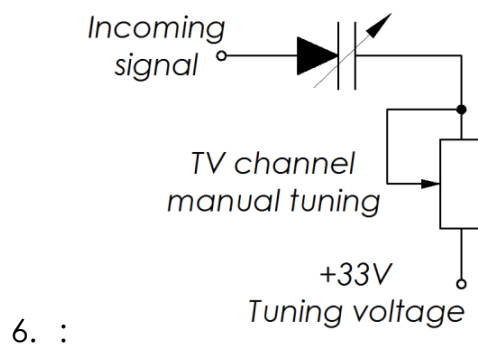


Figure 3.14

If the current through  $R_L$  increases, the Zener current will fall with the corresponding amount.

If the load current through  $R_L$  decreases, the Zener current will increase with the corresponding amount.

- 5. 11,25 V



- 6. :

Figure 3.15

- Automatic frequency control
- Adjustable band pass filters
- FM modulators
- Parametric amplifiers

7. 0,005

8. 311,174

9. *Advantages:*

- Very good smoothing action compared to other filters.
- Better ripple reduction.
- High output voltage.
- Most popular.

*Disadvantages:*

- Lower output voltage due to voltage drop across the resistor.
- Ripple increases with the load current.
- The regulation is worse.

10.:

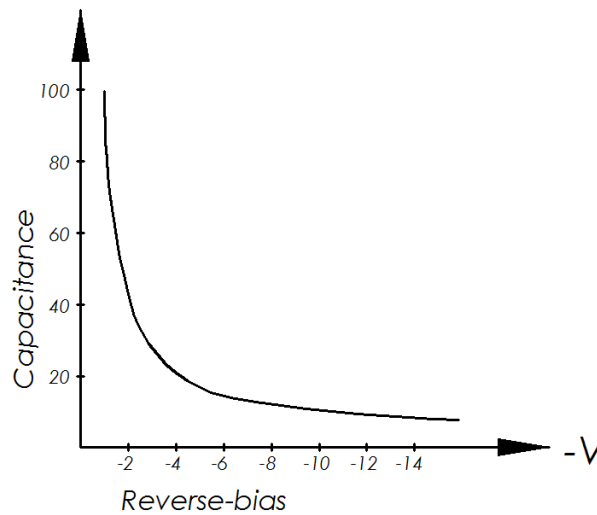


Figure 3.16

11.:

Bridge rectifier circuit	Centre-tap circuit
Four diodes	Two diodes
Forward voltage drop is double that of centre-tape	Forward voltage drop is half that of a bridge
PIV is equals maximum voltage	PIV is twice the maximum voltage

Full wave is achieved without a centre-tap	Need a centre-tap to achieve full wave
Can be directly supplied from the ac	The supply is always via the centre-tap transformer

Table 3.1

12.:

- FM modulators
- Automatic frequency-control devices
- Adjustable band-pass filters
- Tuning circuit

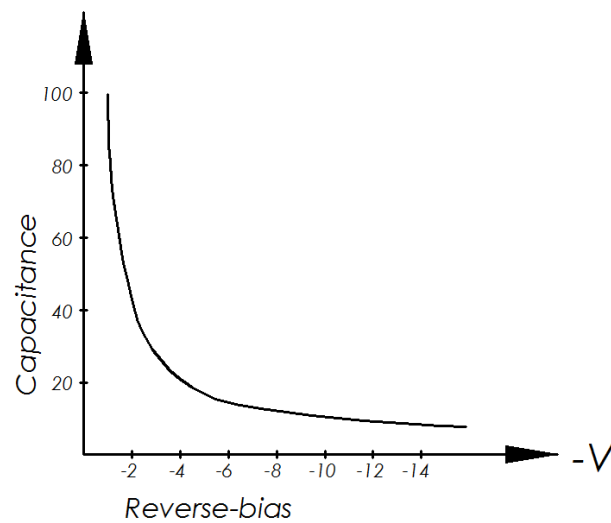


Figure 3.17

The more the reverse-bias potential, the more the width of the depletion region increases and the lesser the capacitance becomes.

13.:

13.1 14,286  $\Omega$ 13.2 100  $\Omega$ 

14.:

- It has excessive ripple of 121%
- Poor efficiency of 40%

15.:

15.1 Zener diode

15.2 PN-junction diode

15.3 Varactor diode

15.4	Tunnel diode
15.5	Varactor
16.:	
16.1	282,8 V
16.2	90,006 V
16.3	282,8 V



### Self-Check

I am able to:	Yes	No
• Calculate the forward- and reverse saturation current and forward voltage by using the diode equation		
• Calculate the forward resistance of a PN junction diode		
• Calculate the voltage, current and resistance values of a simple voltage regulator		
• Describe the properties and characteristic curves of:		
○ Tunnel diode		
○ Varactor diode		
○ Zener diode		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

# Module 4

## Power Supplies

### Learning Outcomes

On the completion of this module the student must be able to:

- Describe the types of transformers and their applications
- Calculate using transformer ratio equations
- Describe circuit diagrams, operation, waveforms of diode rectification
- Calculate current, RMS value, efficiency, ripple factor, PIV.
- Describe capacitor filter, RC filter and LC filter

### 4.1 Introduction



A power supply is an electronic device that supplies electric energy to an electrical load. The primary function of a power supply is to convert one form of electrical energy to another and, as a result, power supplies are sometimes referred to as electric power converters.

### 4.2 Principle of operation of a transformer

**Figure 4.1** shows a coil wound around a "closed" iron core. When a current flows through the coil, all (except for a very small amount of leakage flux) the magnetic lines of force (flux) pass through the *closed magnetic circuit*.

It works with alternating current so the magnetic lines of force (flux) reverse direction at the same rate as the current one of the useful applications of this phenomenon is the transformer.

The coils are electrically separate, i.e. they are insulated from each other. The coils are magnetically coupled by means of a laminated iron core.

When an alternating voltage is applied to the primary winding:

- an alternating current flows through it,
- this sets up an alternating flux in the iron core,
- which links with the secondary winding
- Inducing in it an electromotive force (EMF) of the same
- Frequency (this is known as mutual induction).

If a load is connected to the secondary winding a current will flow. Electrical energy is transferred entirely magnetically from the primary winding to the secondary winding.

Standard transformers are used to step a voltage up or down with a corresponding decrease or increase in current.

#### 4.2.1 Advantages

- Their construction is simple.
- Their efficiency at full load is high,  $\pm 97\%$ .
- Because they have no moving parts their operation is silent.

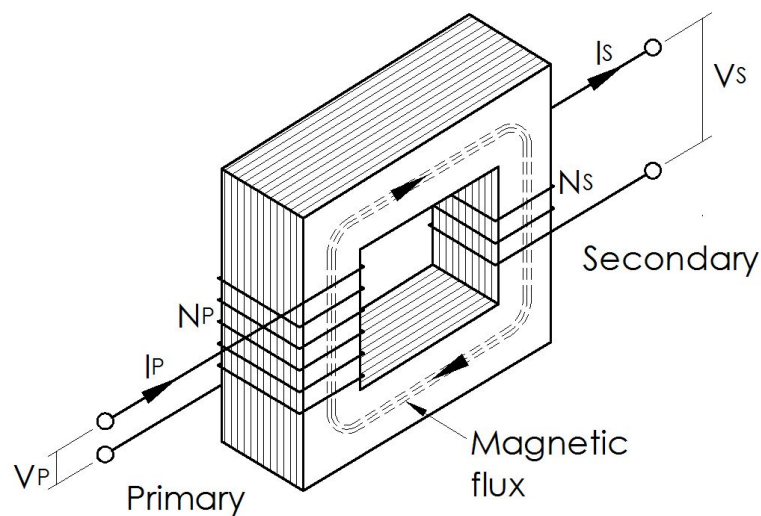


Figure 4.1 Principle of operation of a transformer

Relation of voltage to turns:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

Relation of voltage to current:

$$\frac{I_S}{I_P} = \frac{V_S}{V_P}$$

Relation of current to turns:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

$$\frac{E_P}{E_S} = \frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P}$$

$$\begin{aligned} \text{Average EMF induced in each turn} &= 4 \Phi_m f \\ \text{R. M. S. EMF induced in each turn} &= 1.11 \times 4 \Phi_m f \end{aligned}$$

$$\text{No-load current } I_o = \sqrt{I_c^2 + I_{mag}^2}$$

$$V_{rms} = 0,707 V_m$$

$$V_{ave} = 0,637 V_m$$

$$V_{dc} / V_{gs} = 0,637 V_m$$

$$V_{dc} / V_{gs} = 0,318 V_m$$

$$V_{rms} / V_{r_{wgk}} = 0,385 V_m$$

$$PIV = V_m \text{ or } 2 V_m$$

$$V_{rms} / V_{r_{wgk}} = \frac{V_r(p-p)}{\sqrt{3}}$$

$$V_{dc} / V_{gs} = V_m - \frac{V_r(p-p)}{2}$$

$$V_{rms} / V_{r_{wgk}} = \frac{V_{dc} / V_{gs}}{R_L \sqrt{3} FC}$$

$$V_{dc} / V_{gs} = V_m \frac{I_{dc} / I_{gs}}{2 FC}$$

$$VR = \frac{I_{NL} - V_{FL}}{V_{FL}}$$

### Half-wave rectifier:

Transformer secondary peak voltage:

$$V_{dc} / V_{gs} = V_m - \frac{V_r(p-p)}{2}$$

Transformer average output voltage:

$$V_{dc} / V_{gs} = 0,318 V_m$$

Transformer secondary RMS voltage:

$$V_{rms} = 0,707 V_m$$

### 4.3 Single phase transformer

Transformers are made up from primary and secondary coils (called windings) that are made from turns of insulated wire.

The coils are arranged on a core of magnetic material that increases the amount of magnetic flux set up by one coil and will make sure that most of it links with the other coil; in this way mutual inductance is increased.



Figure 4.2 A simple transformer

The single-phase voltage transformer has two coils or windings, a primary winding and a secondary winding that are not in electrical contact with each other.

When an electric current passed through the primary winding, a magnetic field is developed which induces a voltage into the secondary winding as shown in **Figure 4.3**.

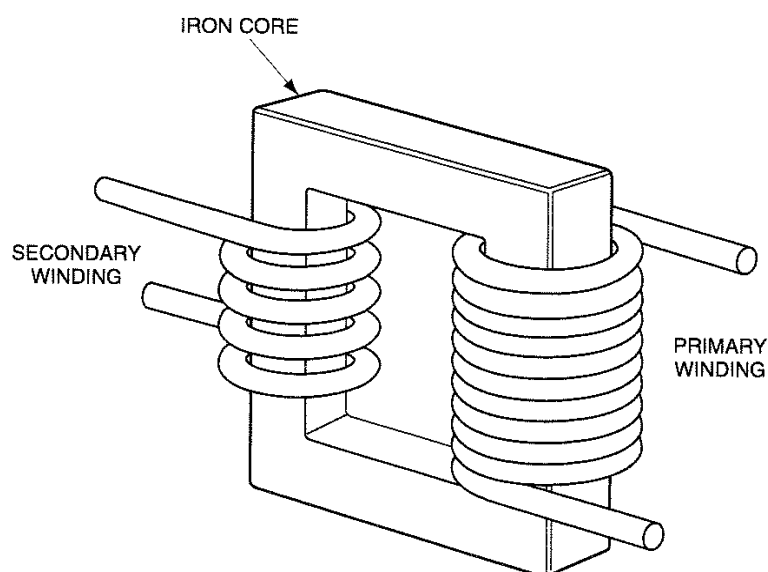


Figure 4.3 Simple transformer

A single phase transformer consists of a primary and secondary winding, electrically separate from each other, but magnetically coupled by means of a laminated iron core.

### 4.4 The Auto Transformer

The auto transformer uses one single winding which acts as the primary winding as well as the secondary winding. Normally transformers have two different windings, one primary and one secondary.

**Figure 4.4** shows an auto transformer with one winding where AB is the primary winding and CB the secondary winding.

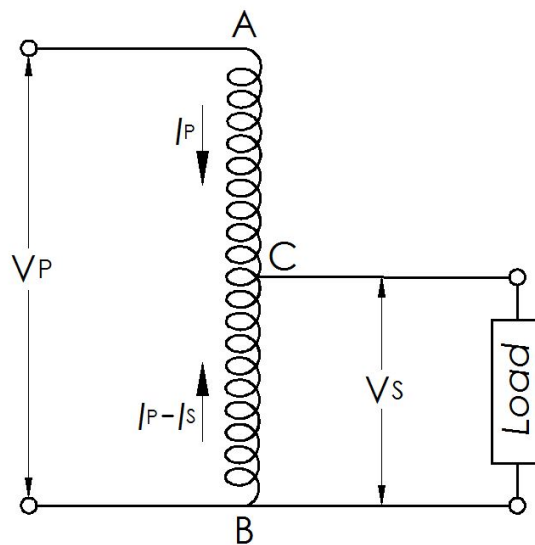


Figure 4.4 The auto transformer

The uniqueness of auto transformers is listed in **Table 4.1** below:

Single phase transformer	Auto transformer
Mutual induction	Self induction
No electrical connection	There are connections
Step-up or down	Step-down only
Primary and secondary windings apart	Primary and secondary have same winding

Table 4.1

#### 4.4.1 Applications of The auto transformer

- Testing a repaired electronic device.  
After performing a repair on a piece of electronic equipment, it is best to slowly power up the device to avoid burning up the replaced parts. You will often discover multiple part failures one at a time. Using the auto

transformer to slowly power up the repaired unit can prevent damaging the replacement parts.

- Powering up an old radio or amplifier.  
When powering up an old radio or amplifier that has not been used for an extended period of time, it is best to apply reduced voltage power to the unit in stages in order to re-condition the electrolytic capacitors.
- Adjusting the temperature of a resistance-type heater.  
Resistance-type heating elements can be adjusted by varying the AC power applied.
- Dimming incandescent lighting.  
Incandescent lights may be dimmed by varying the applied AC voltage. This is not possible with newer LED or fluorescent lamps.
- Changing fan speed over a narrow range.  
The speed of some types of small AC motors may be varied over a narrow range by changing the applied AC voltage. A problem with this application is that the torque of the motor is also reduced which may result in the fan or motor stalling out. Also note that this technique cannot be used with all electric motors.
- Compensating for line voltage drop in AC power applications.  
Long power line runs can often result in voltage drops across the lines, especially in high current draw applications like hot tubs or spas. You can use an auto transformer to compensate for this voltage loss.
- High-current unregulated DC power supply.  
A high-current adjustable unregulated DC power supply can be constructed using an auto transformer, high current rectifier, and filter capacitor. Do not attempt this without being aware of the possible safety concerns when using an auto transformer. Since an auto transformer is not isolated from the AC power lines, the AC power is directly accessible. The ideal configuration would use an isolation transformer to isolate the AC power mains from the application.
- Adjusting the voltage of an AC power supply.  
The output of an AC power supply, such as an electric train transformer, can be adjusted with an auto transformer.

## 4.5 Instrument Transformer

Instrument transformers are high accuracy class electrical devices used to isolate or transform voltage or current levels. Two types of instrument transformers are the current transformer and the voltage or potential transformer.

### 4.5.1 Current transformers (CT):

Current transformers are a series connected type of instrument transformer.

They are designed to present negligible load to the supply being measured and have an accurate current ratio and phase relationship to enable accurate secondary connected metering.

### 4.5.2 Voltage transformers (VT):

Voltage transformers, also called potential transformers (PT), are a parallel connected type of instrument transformer.

They are designed to present negligible load to the supply being measured and have an accurate voltage ratio and phase relationship to enable accurate secondary connected metering.

### 4.5.3 Applications of The instrument transformer

- The most common usage of instrument transformers is to operate instruments or metering from high voltage or high current circuits, safely isolating secondary control circuitry from the high voltages or currents.
- The primary winding of the transformer is connected to the high voltage or high current circuit, and the meter or relay is connected to the secondary circuit.
- Instrument transformers may also be used as an isolation transformer so that secondary quantities may be used in phase shifting without affecting other primary connected devices.

## 4.6 Filters

### 4.6.1 LC filter

An LC circuit, also called a resonant circuit, is an electric circuit consisting of an inductor, represented by the letter L, and a capacitor, represented by the letter C, connected together.

The circuit can act as an electrical resonator, an electrical analogue of a tuning fork, storing energy oscillating at the circuit's resonant frequency. LC circuits are used either for generating signals at a particular frequency, or picking out a signal at a particular frequency from a more complex signal.

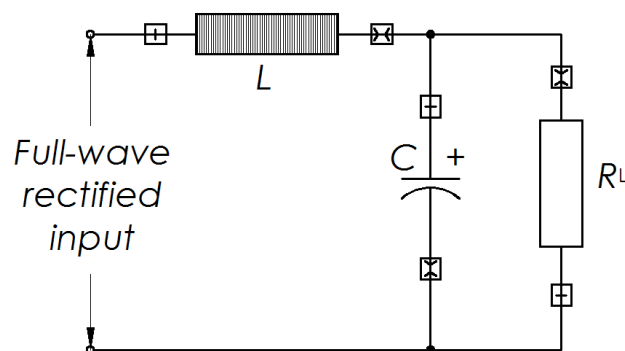


Figure 4.5 Circuit of a LC filter

They are key components in many electronic devices, particularly radio equipment, used in circuits such as oscillators, filters, tuners and frequency mixers.

#### Applications of a LC filter:

- Tuning radio transmitters and receivers.
- A series resonant circuit provides voltage magnification.
- A parallel resonant circuit provides current magnification.
- Both parallel and series resonant circuits are used in induction heating.

#### 4.6.2 RC filter

A RC filter or RC network, is an electric circuit composed of resistors and capacitors driven by a voltage or current source. A first order RC circuit is composed of one resistor and one capacitor and is the simplest type of RC circuit.

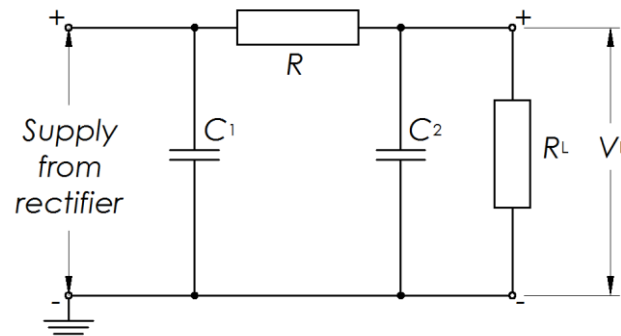


Figure 4.6 Circuit of a RC filter

#### Applications of a RC filter:

RC circuits can be used to filter a signal by blocking certain frequencies and passing others.

#### 4.6.3 capacitor filter

The capacitor-input filter is also called the pi filter. Filter circuits are used to remove unwanted or undesired frequencies from a signal.

A simple pi filter, containing a pair of capacitors, an inductor, and a load.

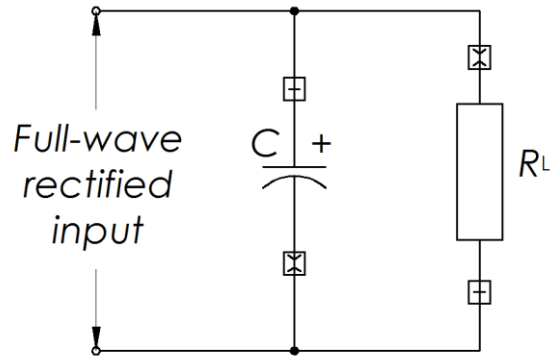


Figure 4.7 Circuit of a capacitor filter

A typical capacitor input filter consists of a filter or reservoir capacitor  $C_1$ , connected across the rectifier output, an inductor  $L$ , in series and another filter or smoothing capacitor,  $C_2$ , connected across the load,  $R_L$ .

A filter of this sort is designed for use at a particular frequency, generally fixed by the AC line frequency and rectifier configuration. When used in this service, filter performance is often characterized by its regulation and ripple.

#### The capacitor-input filter operates in three steps:

- The capacitor  $C_1$  offers low reactance to the AC component of the rectifier output while it offers infinite resistance to the DC component. As a result, the capacitor shunts an appreciable amount of the AC component while the DC component continues its journey to the inductor  $L$ .
- The inductor  $L$  offers high reactance to the AC component but it offers almost zero resistance to the DC component. As a result, the DC component flows through the inductor while the AC component is blocked.
- The capacitor  $C_2$  shunts the AC component which the inductor had failed to block. As a result, only the DC component appears across the load  $R_L$ .
- Tuning radio transmitters and receivers.



#### Worked Example 4.1

The no-load current of a single-phase transformer is 10 A at a power factor of 0,707 lagging. Calculate the value of the magnetising current and the value of the core loss current.

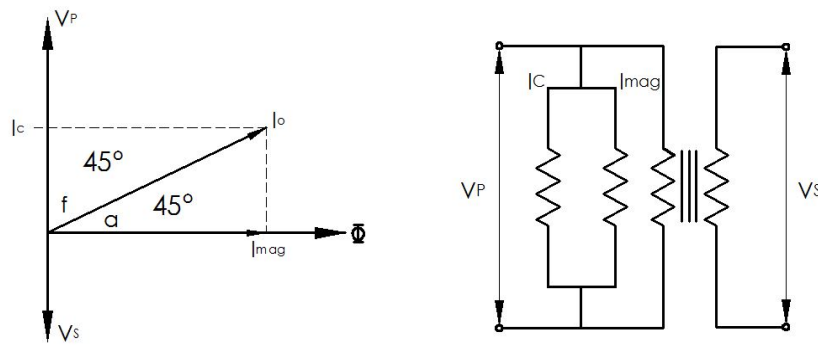
**Solution:**

Figure 4.8

$$\Phi_0 = \cos^{-1} 0,707 = -45^\circ = 90 - 45^\circ = 45^\circ$$

$$I_0 = 10 \angle 45^\circ = 7,07 + j7,07$$

$$I_{mag} = 7,07A$$

$$I_c = 7,07A$$

**Worked Example 4.2**

A 30 kVA single-phase transformer has a maximum core flux of 1,8018 mWb with 250 primary and 50 secondary winding.

Calculate the following:

1. Secondary voltage if the primary voltage is 100 V
2. Primary full-load current
3. Frequency in Hz

**Solution:**

$$1. \quad V_2 = \frac{N_2 V_1}{N_1} = \frac{100 \times 50}{250} = 20 \text{ V}$$

$$2. \quad I_1 = \frac{S}{V} = \frac{30\,000}{100} = 300 \text{ A}$$

$$3. \quad f = E / 4,44 \Phi_m N = \frac{100}{250} \times 1,8018 \times 10^{-3} \times 4,44 = 50 \text{ Hz}$$



### Worked Example 4.3

Draw a neat, labelled circuit diagram of a power supply using the following components:

- A centre-tap transformer
- Two diodes
- Two capacitors
- A resistor
- A load resistor

**Solution:**

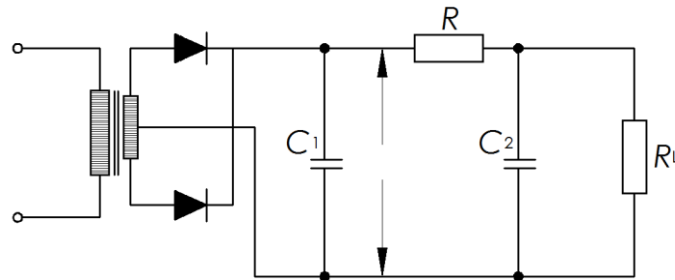


Figure 4.9



### Worked Example 4.4

The input voltage of a 100 kVA transformer is 2 000 V and the output voltage is 500 V at a frequency of 50 Hz.

If the transformer has 110 secondary windings, calculate the following:

1. The primary current
2. The secondary current
3. The primary turns

**Solution:**

1. 
$$I_p = \frac{P}{V_p} = \frac{100 \times 10^3}{2000}$$
$$= 50 \text{ A}$$
2. 
$$PI_s = \frac{100}{V_s} = \frac{10^3}{500}$$
$$= 200 \text{ A}$$
3. 
$$N_p = \frac{N_s V_p}{V_s} = \frac{110 \times 2000}{500}$$
$$= 440 \text{ turns}$$



### Worked Example 4.5

Figure 4.10 shows a waveform obtained from a half-wave rectifier.

Calculate the following:

Transformer's secondary peak voltage

Transformer's average output voltage

Transformer's secondary RMS voltage

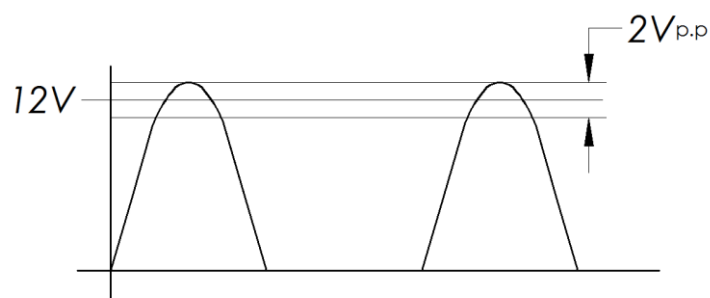


Figure 4.10

**Solution:**

1. 
$$V_m = 12 + \frac{2(p-p)}{2}$$
$$= 13 \text{ V}$$

$$\begin{aligned}
 2. \quad \text{Wave} &= 0,318 \times V_m \\
 &= 0,318 \times 13 \\
 &= 4,134 \text{ V} \\
 3. \quad V_{rms} &= 0,707 \times V_m \\
 &= 0,707 \times 13 \\
 &= 9,191 \text{ V}
 \end{aligned}$$



### Activity 4.1

1. Give two advantages of a transformer.
2. Name the windings of a transformer.
3. What is the core of a transformer made from?
4. With reference to a transformer, what is a breather and what is its function?
5. Mention two main methods of cooling transformers.
6. What do you understand by mutual induction?
7. With the aid of a neat labelled sketch explain the construction and operation of a single-phase transformer.



### Activity 4.2

1. A single-phase transformer has 350 windings on the primary coil which is connected to a 210 V supply. The secondary voltage and current is 42 V and 8 A respectively.  
Calculate the following:
  - 1.1 The number of windings on the secondary side
  - 1.2 The primary circuit
  - 1.3 The rating of the transformer in VA
2. A single-phase transformer has 49 turns on the secondary winding and is

connected to a 240 V supply. The output voltage is 80 V and the primary current is 0,218 A.

Determine the primary number of turns.

3. A transformer with an input of 110 V has a turns ratio of 2:4. Determine the secondary voltage and primary current if the secondary current must be 22 millisecond-amperes.
4. A single phase transformer has 380 windings on the primary coil and 190 windings on the secondary coil. Determine the output voltage if the input voltage is 220 V.
5. A single phase transformer has a primary voltage of 220 V and a output voltage of 12 V. The output current is 0.8 amperes. What is the input current?



### Activity 4.1

**Answers:**

1. [70; 1.6; 336]
2. [147]
3. [220; 44]
4. [110]
5. [14.7]



### Self-Check

I am able to:	Yes	No
• Describe the types of transformers and their applications		
• Calculate using transformer ratio equations		
• Describe circuit diagrams, operation, waveforms of diode rectification		
• Calculate current, RMS value, efficiency, ripple factor, PIV.		
• Describe capacitor filter, RC filter and LC filter		

If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.

# Module 5

## Transistors and Amplifier Devices

### Learning Outcomes

On the completion of this module the student must be able to:

- Describe the operation and properties of PNP and NPN transistors
- Describe circuit diagrams and characteristic curves of:
  - Common emitter amplifier
  - Common collector amplifier
  - Balance amplifier
- Calculate current gain, voltage gain, power gain and emitter amplifier
- Describe H-parameter equivalent circuits
- Calculations using the approximation method
- Describe unijunction transistors (UJT)
- Apply UJT to trigger a SCR
- Describe a J-FET, MOS-FET and a C-MOS
- Calculate gain, circuit diagrams and wave forms of:
  - Inverter
  - Non-inverter
  - Adder
  - Differentiator
  - Comparator
  - Integrator

### 5.1 Introduction



A transistor is a semiconductor device used to amplify or switch electronic signals and electrical power. It is composed of semiconductor material usually with at least three terminals for connection to an external circuit. An amplifier, electronic amplifier or (informally) amp is an electronic device that can increase the power of a signal.

## 5.2 Transistors

### 5.2.1 PNP Transistor

The PNP transistor is a bipolar junction transistor. In a PNP transistor, the first letter P indicates the polarity of the voltage required for the emitter. the second letter N indicates the polarity of the base.

The working of PNP transistor is the exact opposite to the NPN transistor. In this type of transistor, the majority charge carriers are holes. Basically, this transistor works the same as the NPN transistor.

The materials which are used to construct the emitter, base and collector terminals in the PNP transistor are different from those used in the NPN transistor. The PNP transistor bias setup is shown in the below figure.

The base-collector terminals of the PNP transistor are always reversed biased, then the negative voltage must be used for the collector. Therefore, the base terminal of the PNP transistor must be negative with respect to the emitter terminal, and the collector must be negative than the base.

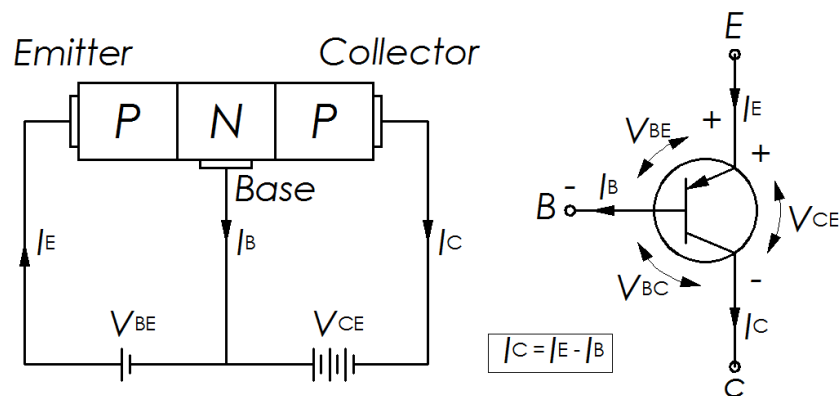


Figure 5.1 PNP transistor

The voltage sources are connected to a PNP transistor, which is shown in the figure. The emitter is connected to the  $V_{CC}$  with the  $R_L$ . this resistor limits the max current flowing through the device, which is connected to the collector terminal.

The base voltage  $V_B$  is connected to the base resistor  $R_B$ , which is biased negative with respect to the emitter. To cause the base current to flow during a PNP transistor, the base terminal must be more negative than the base terminal by approx. 0.7volts or a Si device.

The fundamental difference between a PNP and a PN transistor is the proper biasing of the transistor junctions; the current directions and the voltage polarities are always opposite to each other.

### 5.2.2 NPN Transistor

The NPN transistor is a bipolar junction transistor, In a NPN transistor, the first letter N indicates a negatively charged layer of material and a P indicates a positively charged layer. These transistors have a positive layer, which is located in-between two negative layers.

NPN transistors are generally used in circuits for switching, amplifying the electrical signals that pass through them. These transistors comprise three terminals namely, base, collector and emitter and these terminals connect the transistor to the circuit board.

When the current flows through the NPN transistor, the transistor base terminal receives the electrical signal, the collector makes a stronger electric current than the one passing through the base, and the emitter passes this stronger current on to the rest of the circuit. In this transistor, the current flows through the collector terminal to the emitter.

Generally, this transistor is used because it is so easy to produce. For an NPN transistor to work properly, it needs to be formed from a semiconductor material, which carries some electric current, but not the maximum amount as very conductive materials like metal.

Silicon is one of the most commonly used semiconductor, and NPN transistors are the easiest transistors to make out of silicon. The application of an NPN transistor is on a computer circuit board.

Computers need all their information to be translated into binary code, and this process is accomplished through a plethora of small switches flipping on and off on the computers circuit boards.

NPN transistors can be used for these switches. A powerful electric signal turns the switch on, whereas a lack of a signal turns the switch off.

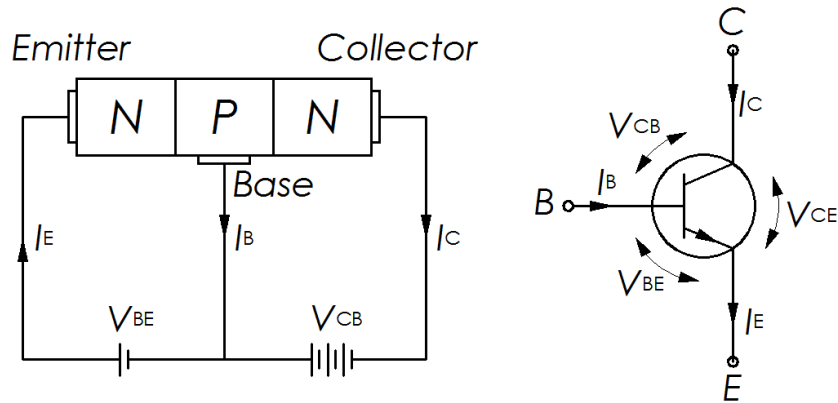


Figure 5.2 NPN transistor

The transistor is a current operated device. When the transistor is switched on, the large current  $I_C$  flows between the collector and emitter within the transistor. However, this only happens when a small biasing current  $I_B$  flows through the base terminal of the transistor.

A bipolar NPN transistor. the current is the ratio of these two currents ( $I_C/I_B$ ), called the DC current gain of the device and it is denoted with the symbol "hfe" or nowadays beta. The value of beta can be large up to 200 for standard transistors, and it is this ratio between  $I_C$  and  $I_B$ , which makes the transistor a useful amplifier.

When this transistor is used in an active region, then  $I_B$  provides the input and  $I_C$  provides the output. Beta has no units as it is a ratio.

The current gain of the transistor from the collector to the emitter is called alpha that is,  $I_C/I_E$ , and it is a function of the transistor itself. As the emitter current  $I_E$  is the sum of a small base current and large collector current, the value of the alpha is very close to unity, and for a typical low power signal transistor this value ranges from about 0.950 to 0.999.

### 5.2.3 The difference between the PNP and NPN transistors

- Both PNP and NPN transistors are composed of different materials and current flow of these transistors is also dissimilar.
- In an NPN transistor, the current flows from the collector (C) to the Emitter (E), whereas in a PNP transistor, the current flows from the emitter to the collector.
- PNP transistors are made up of two layers of P material with a sandwiched layer of N. The NPN transistors are made up of two layers of N material and sandwiched with one layer of P material.
- In an NPN transistor, a positive voltage is given to the collector terminal to produce a current flow from the collector to For PNP transistor, a positive

voltage is given to the emitter terminal to produce current flow from the emitter to collector.

- The working principle of an NPN transistor is such that when you increase current to the base terminal, then the transistor turns ON and it conducts fully from the collector to emitter. When you decrease the current to the base terminal, the transistor turns ON less and until the current is so low, the transistor no longer conducts across the collector to emitter, and shuts OFF.
- The working principle of a PNP transistor is such that when the current exists at the base terminal of the transistor, then the transistor shuts OFF. When there is not current at the base terminal of the PNP transistor, then the transistor turns ON.

### 5.2.4 Common Emitter Amplifier

In a Bipolar Transistor there are different ways to connect a transistor but the most common circuit configuration for an NPN transistor is that of the Common Emitter Amplifier.

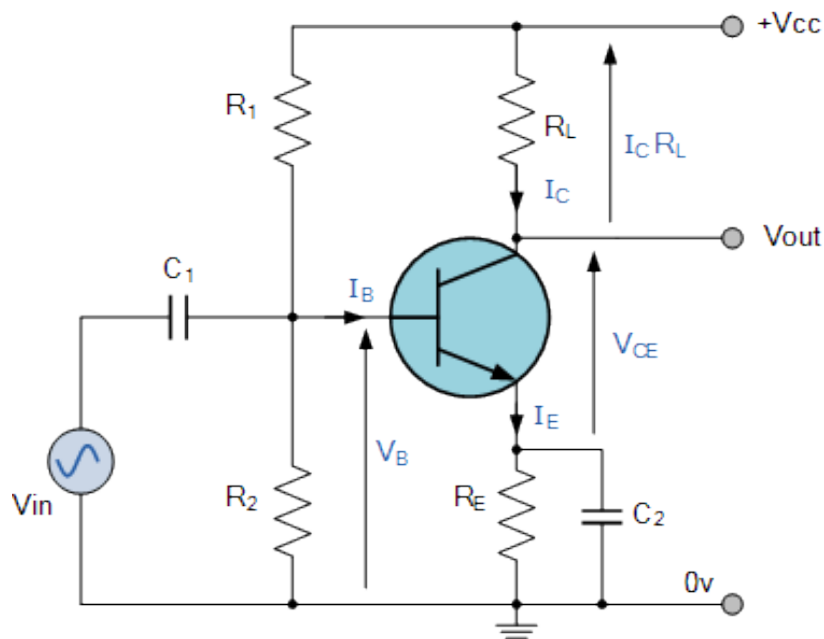


Figure 5.3 Common Emitter Amplifier

### 5.2.5 The Common Emitter Amplifier Circuit

The single stage common emitter amplifier circuit shown above uses what is commonly called “Voltage Divider Biasing”.

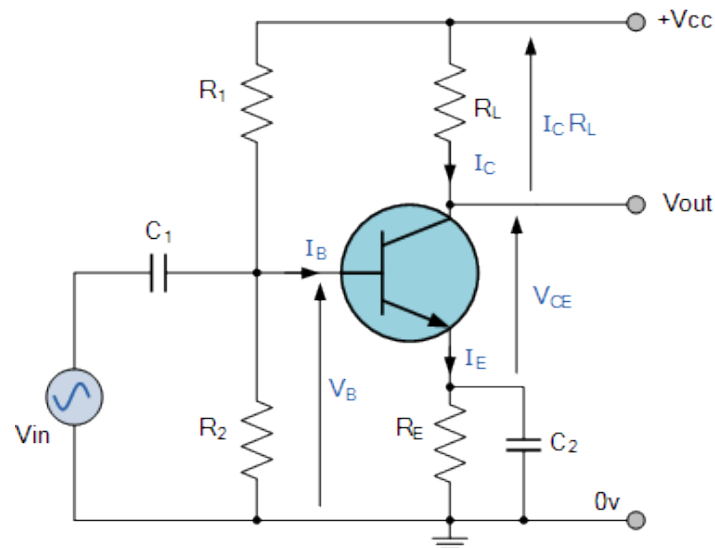


Figure 5.4 Common Emitter Amplifier circuit

This type of biasing arrangement uses two resistors as a potential divider network across the supply with their center point supplying the required Base bias voltage to the transistor.

Voltage divider biasing is commonly used in the design of bipolar transistor amplifier circuits.

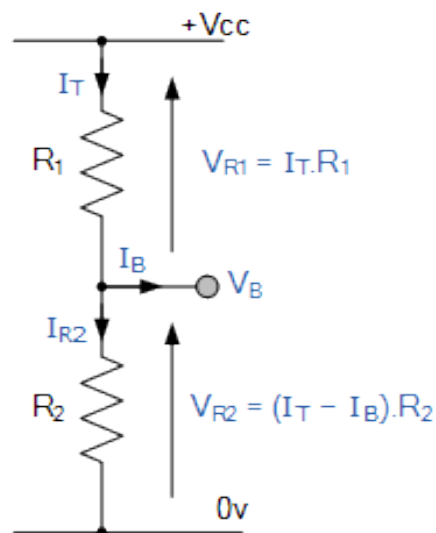


Figure 5.5 Voltage divider biasing

This method of biasing the transistor greatly reduces the effects of varying Beta, ( $\beta$ ) by holding the Base bias at a constant steady voltage level allowing for best stability.

The quiescent Base voltage ( $V_b$ ) is determined by the potential divider network formed by the two resistors,  $R_1$ ,  $R_2$  and the power supply voltage  $V_{cc}$  as shown with the current flowing through both resistors.

Then the total resistance  $R_T$  will be equal to  $R_1 + R_2$  giving the current as

$$i = V_{cc}/R_T.$$

The voltage level generated at the junction of resistors  $R_1$  and  $R_2$  holds the Base voltage ( $V_b$ ) constant at a value below the supply voltage. Then the potential divider network used in the common emitter amplifier circuit divides the supply voltage in proportion to the resistance.

### 5.2.6 Voltage Gain ( $\Delta v$ )

The voltage gain is obtained by dividing the output by the input voltage.

$$\Delta v = V_{out} / V_{in}$$



#### Worked Example 5.1

An amplifier has a current gain of 500 ( $\Delta i = 500$ ) and an input current of 10  $\mu A$ . If the load of the amplifier is a 200 ohms resistor. What will be the voltage?

#### Solution:

The output current:  $I_{out} = \Delta i \times I_{in} = 500 \times 10 \mu A = 5000 \mu A = 5 \text{ mA}$

The load voltage will be: (using the Ohm's law)

$$V_{out} = 200 \times I_{out} = 200 \text{ ohms} \times 5 \text{ mA} = 1000 \text{ mV} = 1 \text{ volt}$$

### 5.2.7 Power Gain ( $\Delta p$ )

The power gain is obtained by dividing the power delivered at the output terminals by the power received at the input terminals. Voltage.

$$\Delta p = P_{out} / P_{in}$$



#### Worked Example 5.2

Using the above example and assuming that at the input of the amplifier we deliver 0.1  $\mu W$  (microwatts). What will the power gain be?

**Solution:**

We have the input power, now we will find the output power:

The output power is:

$$P_{out} = V * I = 1 \text{ Volt} \times 5 \text{ mA} = 5 \text{ mW (milliwatts)}$$

**Worked Example 5.3**

Study the characteristic curves in **Figure 5.6**.

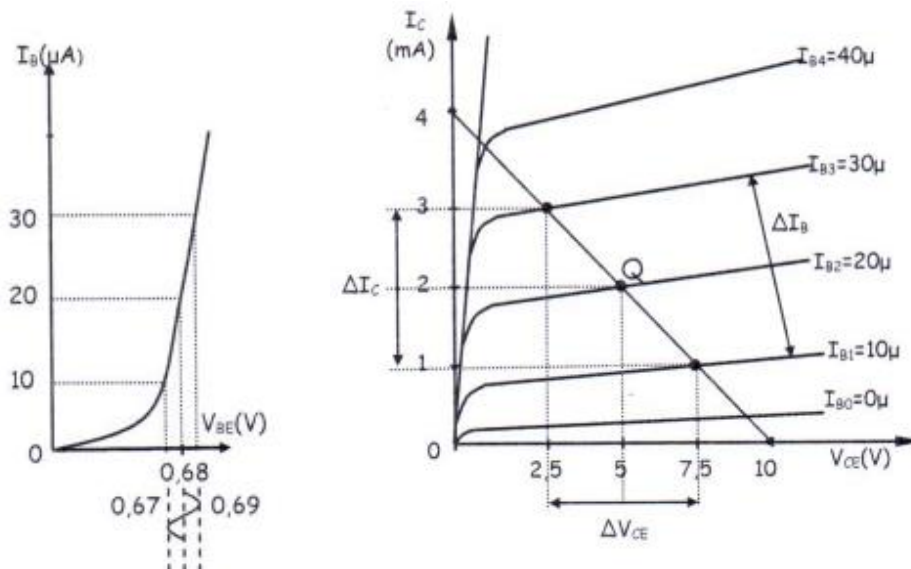


Figure 5.6

Using H-parameters, calculate the following dynamic values:

1. The input impedance
2. The reverse voltage gain
3. The forward current gain
4. The output impedance

**Solution:**

$$\begin{aligned}
 1. \quad h_{ie} &= \frac{\Delta V_{be}}{\Delta I_b} = \frac{0,69 - 0,67}{(30 - 10) \times 10^{-6}} \\
 &= 1 \text{ k}\Omega
 \end{aligned}$$

$$\Delta V_{be} \quad 0,69 - 0,67$$

$$2. \quad h_{re} = \frac{\Delta V_{be}}{\Delta V_{ce}} = \frac{0,69 - 0,67}{7,5 - 2,5}$$

$$= 0,004$$

$$3. \quad h_{fe} = \frac{\Delta I_c}{\Delta I_b} = \frac{(3-1) \times 10^{-3}}{(30-10) \times 10^{-6}}$$

$$= 100$$

$$4. \quad \frac{1}{h_{oe}} = \frac{\Delta V_{ce}}{\Delta I_c} = \frac{7,5 - 2,5}{(3-1) \times 10^{-3}}$$

$$= 2\,500 \, \Omega$$



### Worked Example 5.4

Draw a neat push-pull amplifier circuit which uses two NPN transistors. Clearly show the output wave forms.

**Solution:**

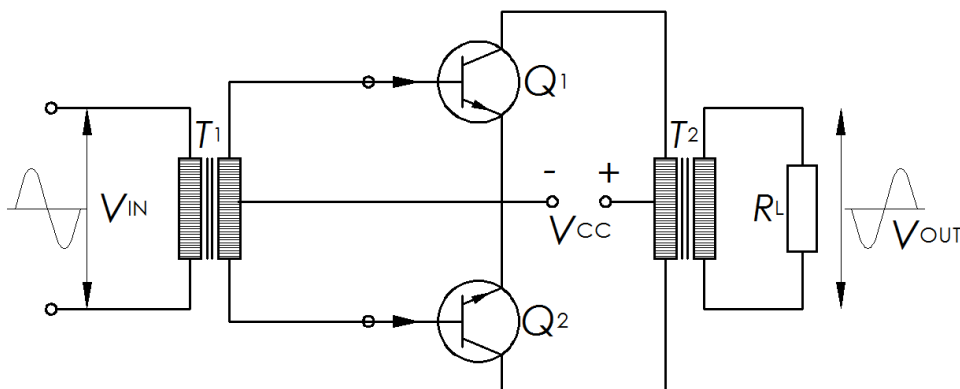


Figure 5.7



### Worked Example 5.5

Draw a neat labelled symbol and characteristic curve of P-channel depletion MOSFET.

**Solution:**

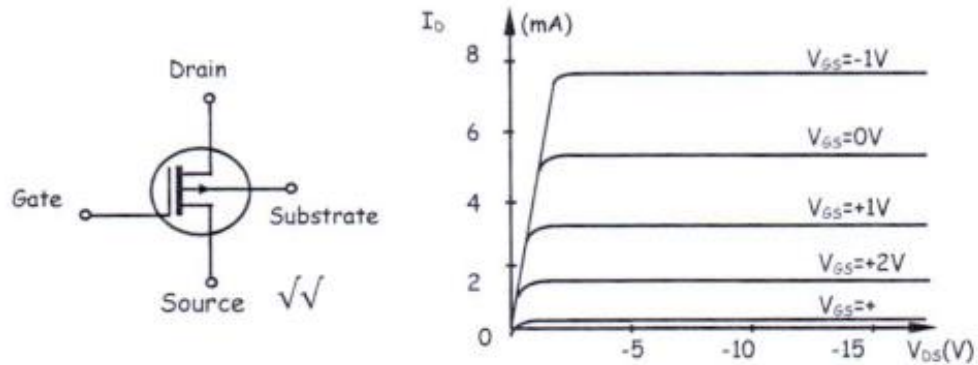


Figure 5.8



### Worked Example 5.6

Draw a neat sketch showing the basic connection of a CMOS device by means of enhancement of PMOS and NMOS transistors. Also state where it is being widely used.

**Solution:**

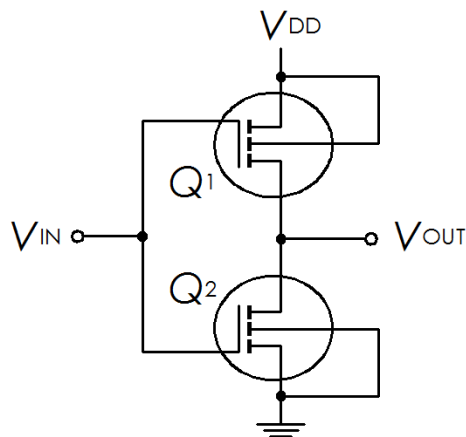


Figure 5.9

It is widely used in battery operated applications.



### Worked Example 5.7

Draw a circuit diagram to illustrate how a UJT can be used to trigger an SCR.

**Solution:**

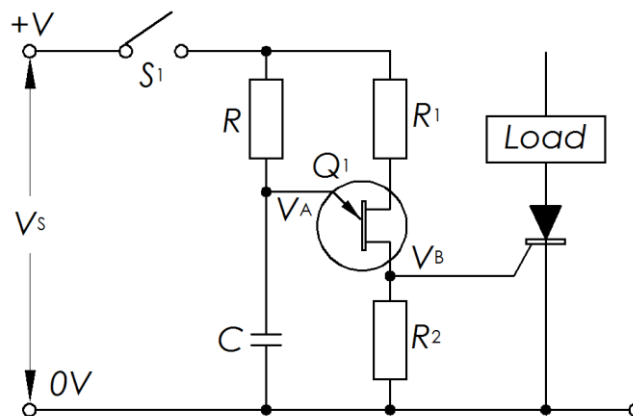


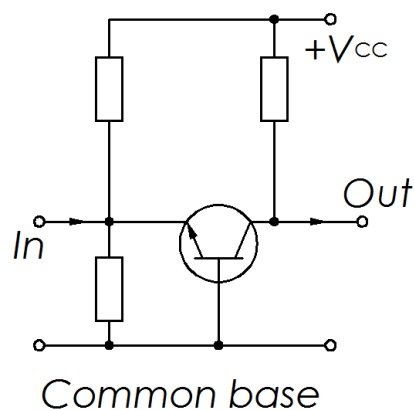
Figure 5.10



### Worked Example 5.8

Demonstrate, by means of neat, labelled diagrams the three different transistor configurations.

**Solution:**



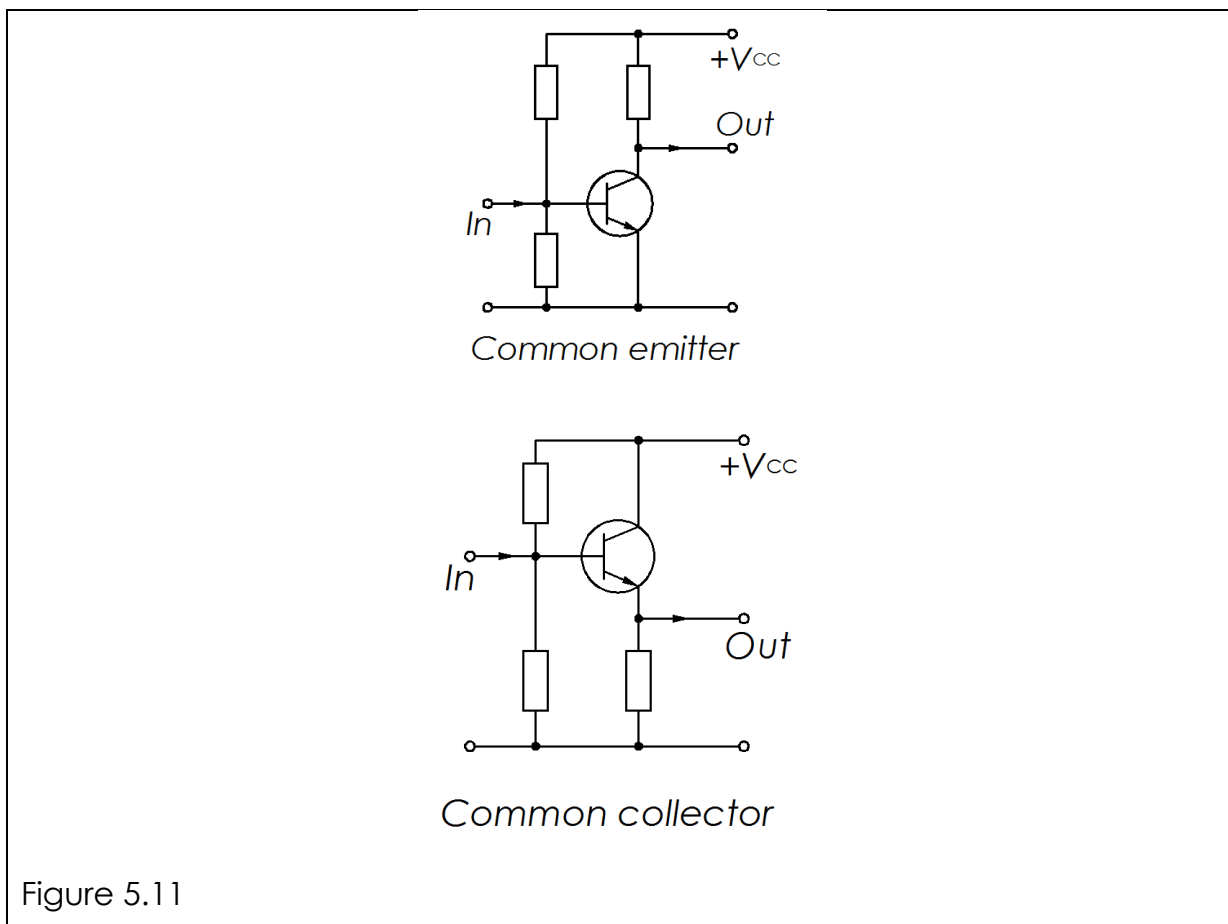


Figure 5.11

### 5.3 Operational amplifiers

An operational amplifier (op-amp) is a DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output.

In this configuration, an op-amp produces an output potential (relative to circuit ground) that is typically hundreds of thousands of times larger than the potential difference between its input terminals.

Operational amplifiers had their origins in analog computers, where they were used to perform mathematical operations in many linear, non-linear and frequency-dependent circuits.

The popularity of the op-amp as a building block in analog circuits is due to its versatility. Due to negative feedback, the characteristics of an op-amp circuit, its gain, input and output impedance, bandwidth etc. are determined by external components and have little dependence on temperature coefficients or manufacturing variations in the op-amp itself.

### 5.3.1 Inverter

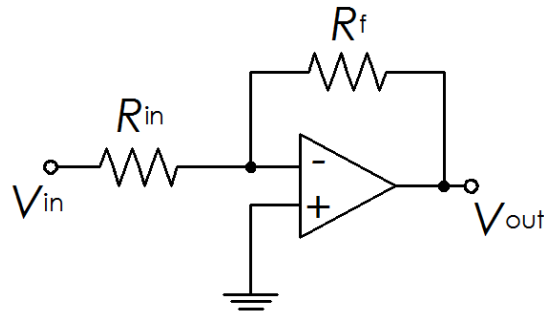


Figure 5.12 Inverting amplifier

An inverting amplifier is a special case of the differential amplifier in which that circuit's non-inverting input  $V_2$  is grounded, and inverting input  $V_1$  is identified with  $V_{in}$  above. The closed-loop gain is  $R_f / R_{in}$ , hence:

$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

The simplified circuit above is like the differential amplifier in the limit of  $R_2$  and  $R_g$  very small. In this case, though, the circuit will be susceptible to input bias current drift because of the mismatch between  $R_f$  and  $R_{in}$ .

To intuitively see the gain equation above, calculate the current in  $R_{in}$ :

$$I_{in} = \frac{V_{in}}{R_{in}}$$

then recall that this same current must be passing through  $R_f$ , therefore (because  $V_- = V_+ = 0$ ):

$$V_{out} = -I_{in}R_f = -V_{in} \frac{R_f}{R_{in}}$$

A mechanical analogy is a seesaw, with the  $V_-$  node (between  $R_{in}$  and  $R_f$ ) as the fulcrum, at ground potential.

$V_{in}$  is at a length  $R_{in}$  from the fulcrum;  $V_{out}$  is at a length  $R_f$ .

When  $V_{in}$  descends "below ground", the output  $V_{out}$  rises proportionately to balance the seesaw, and vice versa.

### 5.3.2 Non-Inverter

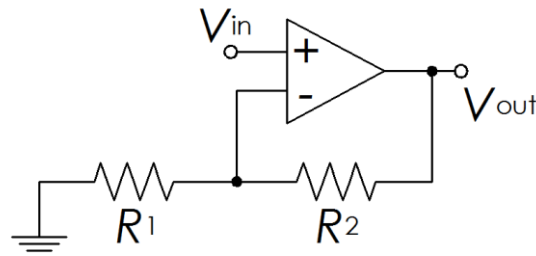


Figure 5.13 Non-inverting amplifier

A non-inverting amplifier is a special case of the differential amplifier in which that circuit's inverting input  $V_1$  is grounded, and non-inverting input  $V_2$  is identified with  $V_{in}$  above, with  $R_1 \gg R_2$ . Referring to the circuit immediately above,

$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

To intuitively see this gain equation, use the virtual ground technique to calculate the current in resistor  $R_1$ :

$$I_1 = \frac{V_{in}}{R_1}$$

then recall that this same current must be passing through  $R_2$ , therefore:

$$V_{out} = V_{in} + I_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

Unlike the inverting amplifier, a non-inverting amplifier cannot have a gain of less than 1.

### 5.3.3 Adder

In the inverting operational amplifier that the inverting amplifier has a single input voltage, ( $V_{in}$ ) applied to the inverting input terminal.

If we add more input resistors to the input, each equal in value to the original input resistor,  $R_{in}$  we end up with another operational amplifier circuit called a Summing Amplifier, or a "voltage adder" circuit as shown below.

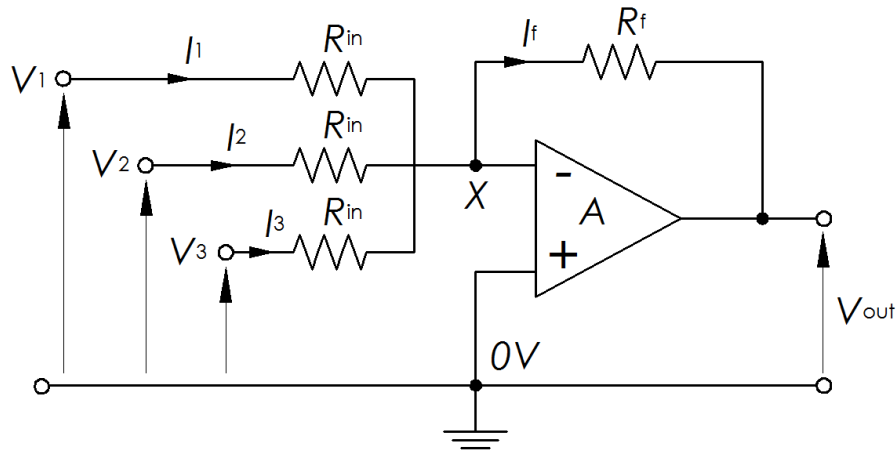


Figure 5.14 Voltage adder

In this simple summing amplifier circuit, the output voltage, ( $V_{out}$ ) now becomes proportional to the sum of the input voltages,  $V_1$ ,  $V_2$ ,  $V_3$ , etc. Then we can modify the original equation for the inverting amplifier to take account of these new inputs:

$$I_f = I_1 + I_2 + I_3 = - \left[ \frac{V_1}{R_{in}} + \frac{V_2}{R_{in}} + \frac{V_3}{R_{in}} \right]$$

$$\text{Inverting equation } V_{out} = - \frac{R_f}{R_{in}} V_{in}$$

$$\text{Then } -V_{out} = \frac{R_f}{R_{in}} V_1 + \frac{R_f}{R_{in}} V_2 + \frac{R_f}{R_{in}} V_3$$

However, if all the input impedances, ( $R_{in}$ ) are equal in value, we can simplify the above equation to give an output voltage of:

$$-V_{out} = \frac{R_f}{R_{in}} [V_1 + V_2 + V_3]$$

### 5.3.4 Differentiator

Here, the position of the capacitor and resistor have been reversed and now the reactance,  $X_c$  is connected to the input terminal of the inverting amplifier while the resistor,  $R_f$  forms the negative feedback element across the operational amplifier as normal.

This operational amplifier circuit performs the mathematical operation of Differentiation, that is it “produces a voltage output which is directly proportional to the input voltage’s rate-of-change with respect to time“.

In other words the faster or larger the change to the input voltage signal, the greater the input current, the greater will be the output voltage change in response, becoming more of a “spike” in shape.

As with the integrator circuit, we have a resistor and capacitor forming an RC Network across the operational amplifier and the reactance ( $X_c$ ) of the capacitor plays a major role in the performance of a Op-amp Differentiator.

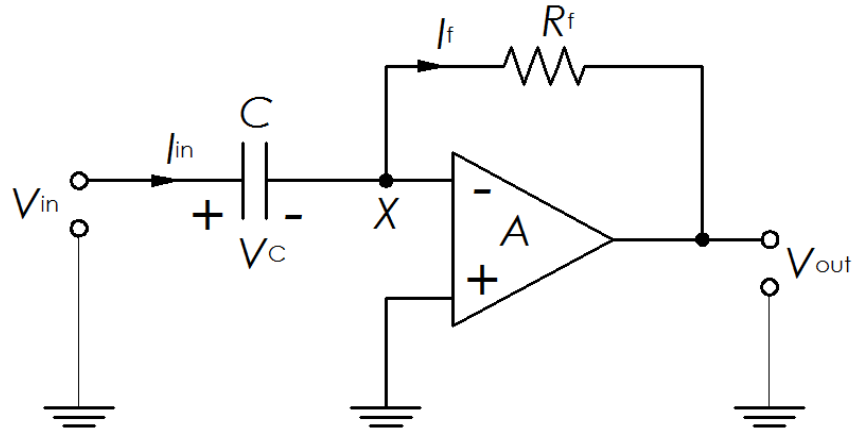


Figure 5.15 Differentiator circuit

The input signal to the differentiator is applied to the capacitor. The capacitor blocks any DC content so there is no current flow to the amplifier summing point, X resulting in zero output voltage.

The capacitor only allows AC type input voltage changes to pass through and whose frequency is dependent on the rate of change of the input signal.

At low frequencies the reactance of the capacitor is “High” resulting in a low gain ( $R_f/X_c$ ) and low output voltage from the op-amp. At higher frequencies the reactance of the capacitor is much lower resulting in a higher gain and higher output voltage from the differentiator amplifier.

Since the node voltage of the operational amplifier at its inverting input terminal is zero, the current,  $i$  flowing through the capacitor will be given as:

$$I_{in} = I_f \text{ and } I_f = -\frac{V_{out}}{R_f}$$

The charge on the capacitor equals Capacitance x Voltage across the capacitor:

$$Q = C \times V_{in}$$

The rate of change of this charge is:

$$\Delta Q = C \frac{dV_{in}}{d_t}$$

$$V_{out} = -R_f C \frac{dV_{in}}{d_t}$$

### 5.3.5 Integrator

Change the purely resistive (  $R_f$  ) feedback element of an inverting amplifier to that of a frequency dependent impedance, (  $Z$  ) type complex element, such as a Capacitor,  $C$ .

By replacing this feedback resistance with a capacitor we now have a RC network connected across the operational amplifiers feedback path producing another type of operational amplifier circuit commonly called an Op-amp Integrator circuit as shown below.

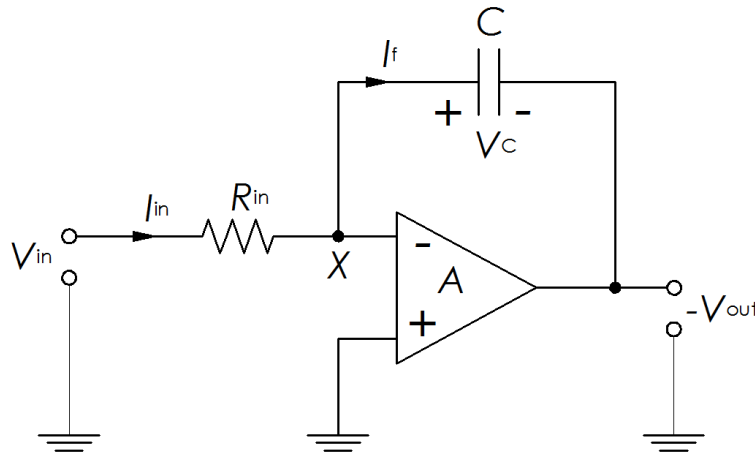


Figure 5.16 Integrator circuit

As its name implies, the Op-amp Integrator is an operational amplifier circuit that performs the mathematical operation of Integration, that is we can cause the output to respond to changes in the input voltage over time as the op-amp integrator produces an output voltage which is proportional to the integral of the input voltage.

If we apply a constantly changing input signal such as a square wave to the input of an Integrator Amplifier then the capacitor will charge and discharge in response to changes in the input signal.

This results in the output signal being that of a saw-tooth waveform whose output is affected by the RC time constant of the resistor/capacitor combination because at higher frequencies, the capacitor has less time to fully charge. This type of circuit is also known as a Ramp Generator and the transfer function is given below.

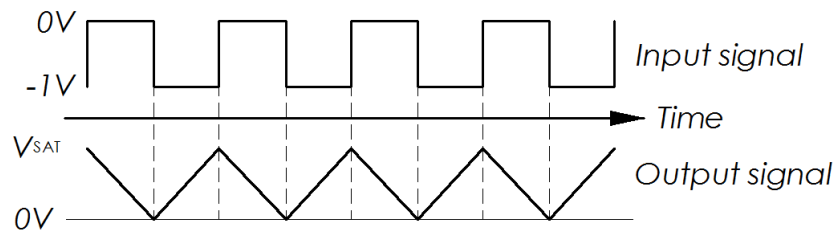


Figure 5.17 Op-amp Integrator Ramp Generator

We know from first principals that the voltage on the plates of a capacitor is equal to the charge on the capacitor divided by its capacitance giving  $Q/C$ .

Then the voltage across the capacitor is output  $V_{out}$  therefore:

$$-V_{out} = Q/C.$$

If the capacitor is charging and discharging, the rate of change of voltage across the capacitor is given as:

$$V_{out} = -\frac{1}{R_{in} \cdot C} \int_0^t V_{in} dt = -\int_0^t V_{in} \frac{dt}{R_{in} \cdot C}$$



### Worked Example 5.9

Draw a neat, labelled circuit symbol of a comparator amplifier.

**Solution:**

Comparator

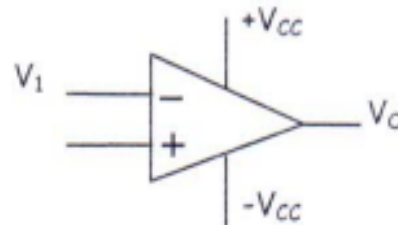


Figure 5.18



### Worked Example 5.10

Draw the operational amplifiers that comply with the following requirements:  
The output voltage is related to the rate at which the input voltage changes at a particular instant.

**Solution:**

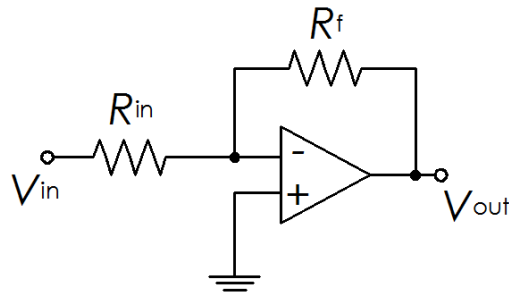


Figure 5.19



### Worked Example 5.11

Draw the operational amplifiers that comply with the following requirements:  
The rate at which the output voltage is related to the value of the input voltage at that instant.

**Solution:**

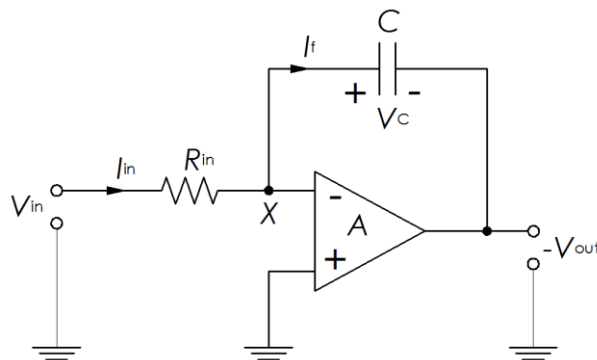


Figure 5.20



### Worked Example 5.12

Three different input voltages must be added by means of a single operational amplifier.

Draw a labelled circuit that would illustrate how this is done.

**Solution:**

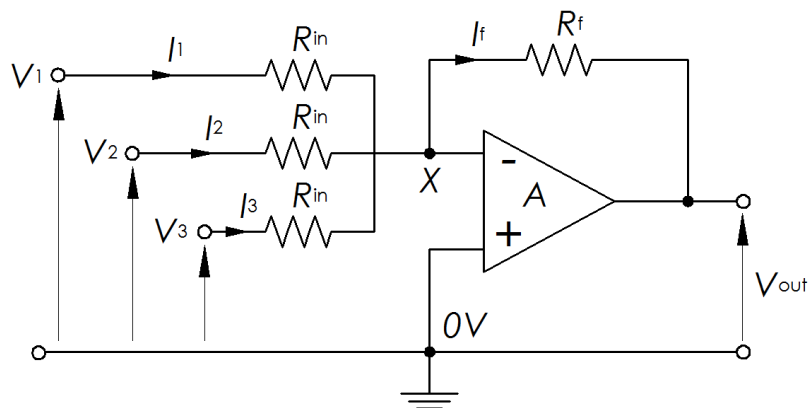


Figure 5.21



### Worked Example 5.13

Draw the expected waveform if the input waveform shown in **Figure 5.22** is fed into the comparator operational amplifier. Also draw the symbol for the amplifier.

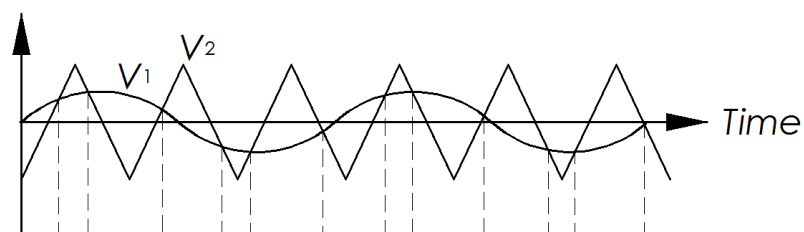


Figure 5.22

**Solution:**

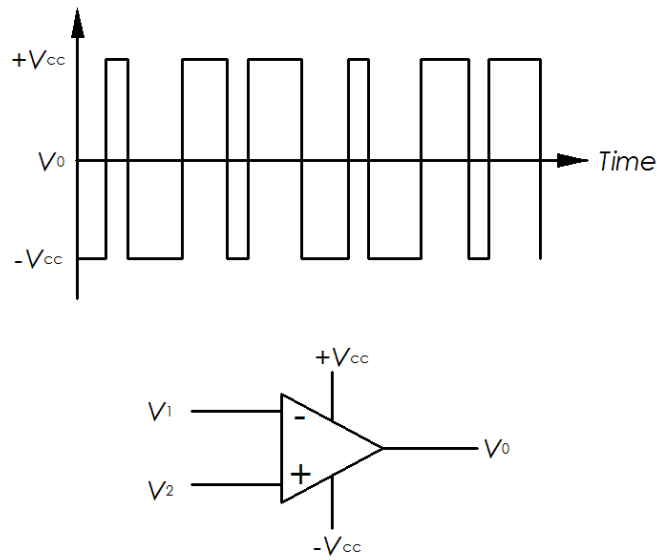


Figure 5.23



**Worked Example 5.14**

Draw a neat, labelled pin layout for a 741 DIL -pin operational amplifier.

**Solution:**

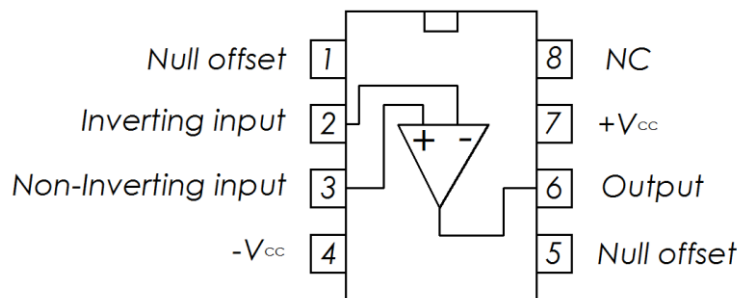


Figure 5.24



### Worked Example 5.15

Consider **Figure 5.25** and answer the questions:

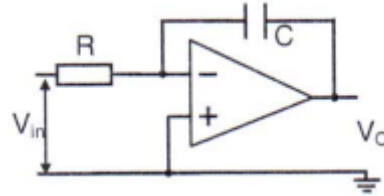


Figure 5.25

1. Identify the operational amplifier
2. Draw a 360° input sin wave form and the expected output waveform

#### Solution:

1. Integrator

2.

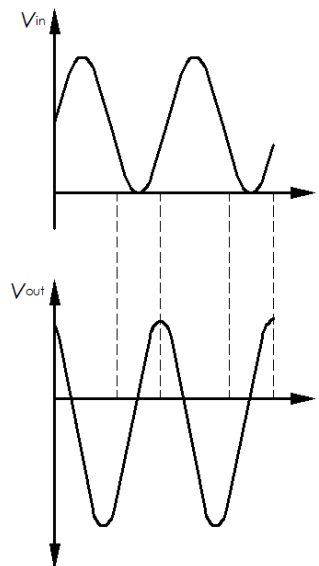


Figure 5.26



### Worked Example 5.16

Draw the functional diagram of an operational amplifier connected as a differentiator. Also draw a  $720^\circ$  input sine wave and its expected output wave form.

**Solution:**

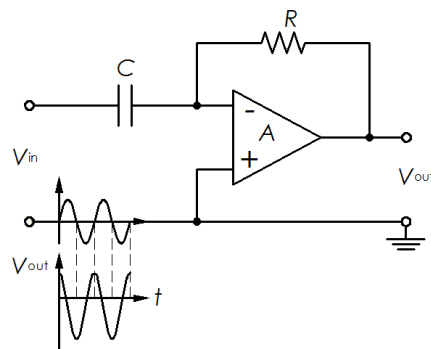


Figure 5.27



### Activity 5.1

Answer 1 to 14 true or false:

1. When transistor voltage and current are constant, the transistor is operating in its dynamic condition.
2. When the transistor operates in the active region its base-emitter junction is reverse biased and base-collector junction is forward biased.
3. Power amplifiers are designed to handle large signals.
4. The uni-junction transistor is a single junction device, which has negative resistance characteristics.
5. Field-effect transistors are relatively unaffected by radiation.
6. UJT possesses a negative resistance.
7. MOSFET: insulated gate field effect transistor.
8. BJT: current-controlled amplifier device.
9. FET: voltage-controlled device.
10. Field Effect Transistors have no offset voltage when used as a switch.
11. The operation of MOSFET under forward bias is called the enhancement mode.
12. The depletion mode MOSFET can be operated only with negative gate voltage.
13. Cross over distortion cannot be eliminated.
14. Uni-junction transistors can be used in a timing circuit.



## Activity 5.2

1. Calculate the values of  $V_{cc}$ ,  $R_{in}$  and  $R_{out}$  if the following information is given:
  - $R_c = 1k\Omega$
  - $V_{be} = 0,68 V$
  - $I_c = 3mA$
  - $V_{ce} = 15 V$
  - $I_b = 20 \mu A$
  
2. The following dynamic values of a common emitter amplifier are given:
  - $V_{be} = 0,67 V$  and  $0,69 V$
  - $I_c = 1 mA$  and  $3mA$
  - $V_{ce} = 5 V$  and  $15 V$
  - $I_b = 20 \mu A$  and  $30 \mu A$
 Calculate the following:
  - 2.1 The dynamic forward current gain
  - 2.2 The dynamic input impedance
  - 2.3 The dynamic reverse voltage gain
  - 2.4 The dynamic output impedance
  
3. Name five points that can be affected by negative feedback to improve the performance of a circuit.
  
4. The following information is given for an amplifier:
  - Input power =  $500 mW$
  - Input voltage =  $15 V$
  - Output power =  $450 W$
  - Output impedance =  $15 \Omega$
 Calculate the following:
  - 4.1 Power gain in dB
  - 4.2 Voltage gain in dB
  - 4.3 Current gain in dB
  
5. A common emitter amplifier produces an output voltage of  $8 V$  with an

input voltage of 6 V. The output current changes with 6 mA by means of 4  $\mu\text{A}$  input current.

Calculate the following:

- 5.1 The input impedance
  - 5.2 The forward-current gain
  - 5.3 The output impedance
6. Give five advantages of the field effect transistor.
7. A common base amplifier produces an output current change of 5 mA with an input current change of 3  $\mu\text{A}$ . The output voltage changes with 5 V by means of a 3 V input change.

Calculate the following:

- 7.1  $h_{ie}$
  - 7.2  $h_{re}$
  - 7.3  $h_{fe}$
  - 7.4  $h_{oe}$
8. Explain what you understand by cross-over distortion in amplifiers.



### Activity 5.3

1. Indicate the properties of an ideal operational amplifier.
2. Explain how the internal gain of an operational amplifier can be changed.
3. Calculate the rate of change of the output voltage for an integrator amplifier if  $C = 100 \mu\text{F}$ ,  $R_{in} = -15 \text{ k}\Omega$  and  $V_{in} = 3 \text{ volts}$ .
4. Calculate the gain and expected output voltage for an amplifier whose output voltage is  $180^\circ$  out of phase with the input voltage if:
  - Feedback resistance =  $100 \text{ k}\Omega$
  - Input resistance =  $200 \text{ k}\Omega$
  - Input voltage =  $20 \text{ mV}$
5. State five main advantages of an operational amplifier.
6. Calculate the gain and output of an operational amplifier whose output voltage is in phase with input voltage, if the following information is

available:

- Input voltage - 0,5 V
- Feedback resistance = 20 k  $\Omega$
- Input resistance = 2 k  $\Omega$

7. Calculate the resistance if  $C = 15 \mu\text{F}$ ,  $V_{\text{in}} = 10 \text{ V}$  and the rate of change of the output voltage = 0,6 V/sec.

8. Name three operational amplifiers that use negative feedback.

9. Three different input voltages of 1,5 V 2 V and 3 V and input resistance of 100 k  $\Omega$ , 150 k  $\Omega$  and 300 k  $\Omega$  respectively, must be added by means of a single operational amplifier. A feedback resistor of 200 k  $\Omega$  is used.

Draw a labelled circuit of the operational amplifier and calculate the output voltage.

10. The input voltage of a non-inverting amplifier is 0,5 V and the output voltage is 4 V. Calculate the value of the feedback resistance needed to be connected if the input resistance is 2 k  $\Omega$ .

11. Name five characteristics of an ideal operational amplifier.

12. Draw a neat, labelled circuit diagram of an operational amplifier connected as an inverter and calculate the output voltage if the following information is given:

- Feedback resistance = 1 k  $\Omega$
- Input voltage = 1 V
- Input resistance = 500  $\Omega$

13. Give five reasons why operational amplifiers are popular building blocks.

14. Calculate the input resistance for an integrator amplifier if  $C = 10 \mu\text{F}$ ,  $V_{\text{in}} = 5 \text{ V}$  and the rate of change of the output voltage is 10 V/sec.



### Activity 5.1

#### Answers:

1. [False]

2. [False]
3. [True]
4. [True]
5. [True]
6. [True]
7. [True]
8. [True]
9. [True]
10. [True]
11. [True]
12. [False]
13. [False]
14. [True]



### Activity 5.2

#### Answers:

1.  $5\text{k}\Omega$
2. :
  - 2.1 100
  - 2.2  $1\text{k}\Omega$
  - 2.3 0,002
  - 2.4  $5\text{k}\Omega$
3. Reducing noise  
 Reducing distortion  
 Increasing its operation bandwidth  
 Increasing the input impedance and decreasing the output impedance  
 Improving its stability
4. :
  - 4.1 29,542 dB
  - 4.2 14,771

4.3 44,401 dB

5. :

5.1 1,5 M $\Omega$

5.2 1500

5.3 1 333,333  $\Omega$

6. Less noisy than the bipolar transistors

Very high input resistance

Relatively unaffected by radiation

Considerable thermal stability

No offset voltage when used as as switch

7. :

7.1 1 M $\Omega$

7.2 0,6

7.3 1 666,667

7.4 0,001

8. It occurs during the period when one transistor starts to switch off and the other one starts to switch on.



### Activity 5.3

#### Answers:

1. Infinite input impedance

Zero output impedance

Infinite bandwidth

Infinite voltage increase

2. It can be changed by changing the value of a feedback resistor

3. 2 V/sec

4. :

4.1 0,5

4.2 1 mV

5. Cheap

Highly reliable  
 Small size  
 Highly stable  
 Low power consumption

6. :

6.1 11

6.2 5,5 V

7. 13 k $\Omega$

8. Inverting

Summer

Integrator

Differentiator

9. -7,6777 V

10.  $R_f = 14 \text{ k}\Omega$

11. Infinite input resistance

Zero output impedance

Infinite bandwidth

Infinite voltage gain

Perfect balance or zero offset voltage

Its characteristics are not affected by temperature

12.:

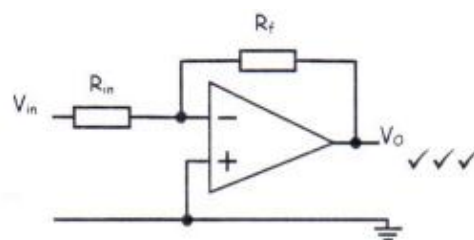


Figure 5.28

2 V

13. Cheap

Small size

Highly stable

Low power consumption

Highly reliable

14.  $R_{in} = 10 \text{ k}\Omega$ **Self-Check**

<b>I am able to:</b>	<b>Yes</b>	<b>No</b>
• Describe the operation and properties of PNP and NPN transistors		
• Describe circuit diagrams and characteristic curves of:		
○ Common emitter amplifier		
○ Common collector amplifier		
○ Balance amplifier		
• Calculate current gain, voltage gain, power gain and emitter amplifier		
• Describe H-parameter equivalent circuits		
• Calculations using the approximation method		
• Describe unijunction transistors (UJT)		
• Apply UJT to trigger a SCR		
• Describe a J-FET, MOS-FET and a C-MOS		
• Calculate gain, circuit diagrams and wave forms of:		
○ Inverter		
○ Non-inverter		
○ Adder		
○ Differentiator		
○ Comparator		
○ Integrator		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

# Module 6

## Electronic Power Control

### Learning Outcomes

On the completion of this module the student must be able to:

- Describe the construction, operation and characteristic curves of:
  - Silicon controlled rectifier
  - Diac
  - Triac
  - Quadrac
  - Light activated SCR
- Describe open and closed loop systems
- Describe single phase motor speed control systems

### 6.1 Introduction



Electronic Power Control deals with routing electric power, controlling its quality, and controlling the devices attached to a power line. A number of technologies have evolved for using the power wiring to turn devices attached to the power line on and off, monitoring attached devices, and similar activities.

### 6.2 Thyristors

#### 6.2.1 The silicon controlled rectifier

A silicon controlled rectifier or semiconductor-controlled rectifier is a four-layer solid-state current-controlling device.

The name "silicon controlled rectifier" is General Electric's trade name for a type of thyristor.

Some define silicon controlled rectifiers as a proper subset of the set of thyristors, those being devices with at least four layers of alternating n- and p-type material.

SCRs are unidirectional devices (i.e. can conduct current only in one direction) as opposed to TRIACs, which are bidirectional (i.e. current can flow through them in either direction).

SCRs can be triggered normally only by currents going into the gate as opposed to TRIACs, which can be triggered normally by either a positive or a negative current applied to its gate electrode.

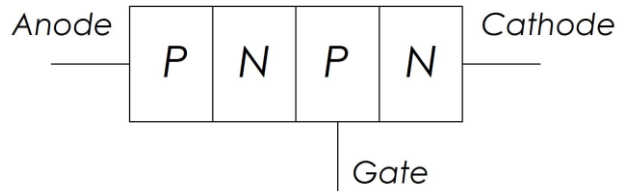


Figure 6.1 Construction of a SRC

### Forward blocking mode

In this mode of operation, the anode is given a positive voltage while the cathode is given a negative voltage, keeping the gate at zero potential i.e. disconnected.

### Forward conduction mode:

SCR can be brought from blocking mode to conduction mode in two ways: either by increasing the voltage across anode to cathode beyond break-over voltage or by applying positive pulse at gate. Once SCR starts conducting, no more gate voltage is required to maintain it in the on state.

### There are two ways to turn it off:

- Reduce the current through it below a minimum value called the holding current and
- With the gate turned off, short out the anode and cathode momentarily with a push-button switch or transistor across the junction.

### Reverse blocking mode:

Usually, the reverse blocking voltage rating and forward blocking voltage rating are the same. The typical application for reverse blocking SCR is in current-source inverters.

### Symbol of a SCR:

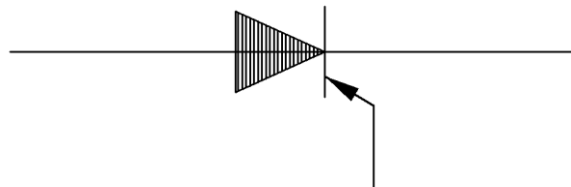


Figure 6.2 Symbol of a SRC

### Characteristic curve of a SCR:

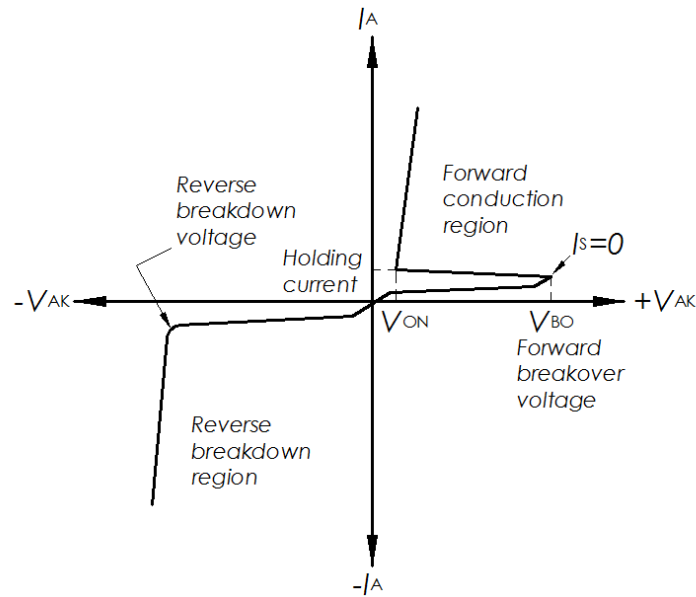


Figure 6.3 Characteristic curve of a SCR

### Applications of the SCR:

- Motor speed control
- Time delay circuits
- Battery charger
- Heater control
- Relay circuit
- Regulated power supplies
- Static switches
- Phase controls

### 6.2.2 The Diac

A diac is a device which has two electrodes. It is a member of the thyristor family. It is mainly used in triggering of thyristor. The advantage of using this device is that it can be turned on or off simply by reducing the voltage level below its avalanche breakdown voltage.

Also, it can be either turned on or off for both the polarity of voltages. This device works when avalanche breakdown occurs.

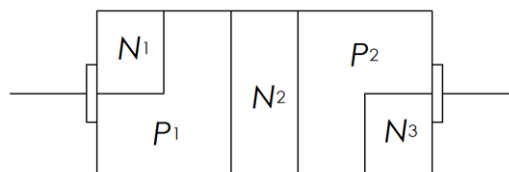


Figure 6.4 Construction of a diac

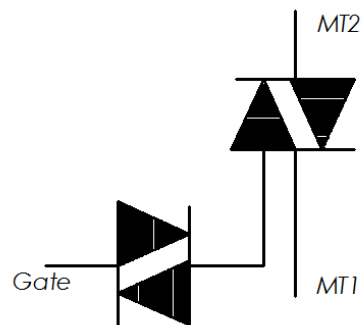
**Symbol of a diac:**

Figure 6.5 Symbol of a diac

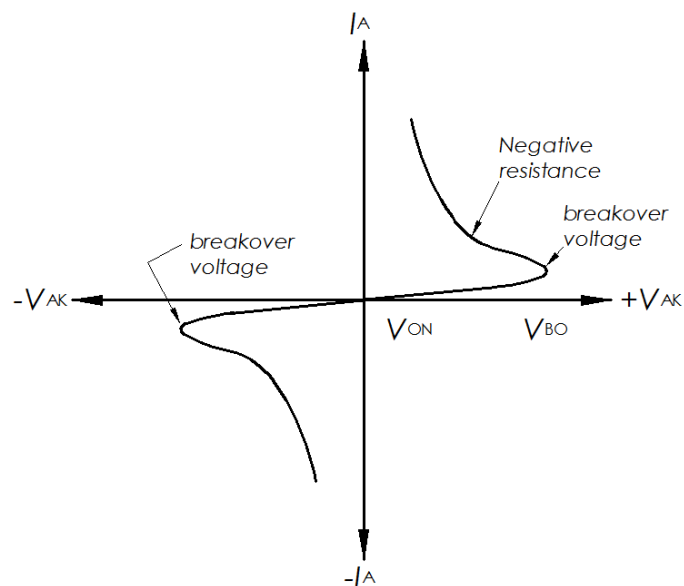
**Characteristic curve of a diac:**

Figure 6.6 Characteristic curve of a diac

**Applications of the diac:**

- It can be used in the lamp dimmer circuit.
- It is used in the heat control circuit.
- It is used in the speed control of a universal motor.
- It is used with triac in series combination for triggering.

**6.2.3 The Triac**

The triac is a three terminal AC switch which is different from the other silicon controlled rectifiers because it can conduct current in both directions. Whether the applied gate signal is positive or negative.

Thus, this device can be used for AC systems as a switch. This is a three terminal, four layer, bi-directional semiconductor device that controls AC

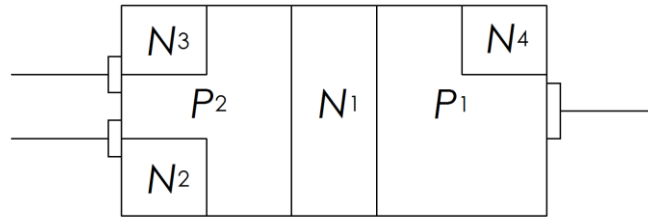


Figure 6.7 Construction of a triac

#### Advantages of Triac:

- It can be triggered with positive or negative polarity of gate pulses.
- It requires only a single heat sink of slightly larger size, whereas for SCR, two heat sinks should be required of smaller size.
- It requires single fuse for protection.
- A safe breakdown in either direction is possible but for SCR protection should be given with parallel diode.

#### Disadvantages of Triac:

- They are not much reliable compared to SCR.
- It has (dv/dt) rating lower than SCR.
- Lower ratings are available compared to SCR.
- We need to be careful about the triggering circuit as it can be triggered in either direction.

#### Symbol of a triac:

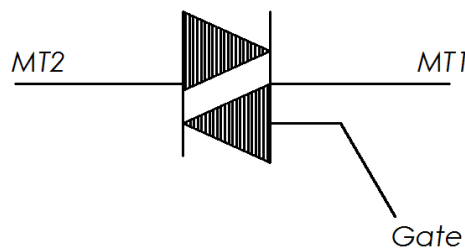


Figure 6.8 Symbol of a triac

#### Characteristic curve of a triac:

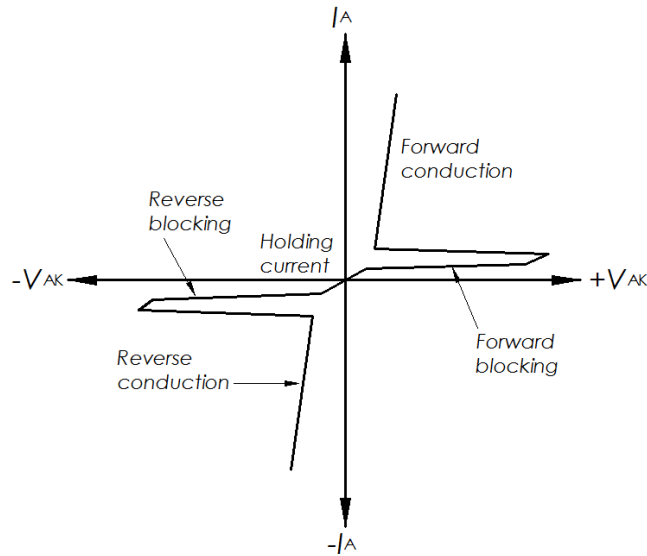


Figure 6.9 Characteristic curve of a triac

#### Applications of the triac:

- They are used in control circuits.
- It is used in High power lamp switching.
- It is used in AC power control.

#### 6.2.4 The Quadrac

Quadracs are a special type of thyristor which combines a "diac" and a "triac" in a single package.

The diac is the triggering device for the triac. Thyristors are four-layer (PNPN) semiconductor devices that act as switches, rectifiers or voltage regulators in a variety of applications.

#### Symbol of a quadrac:

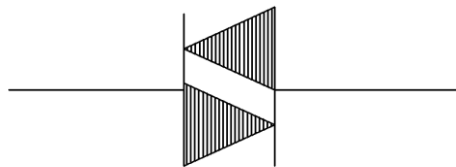


Figure 6.10 Symbol of a quadrac

#### Characteristic curve of a quadrac:

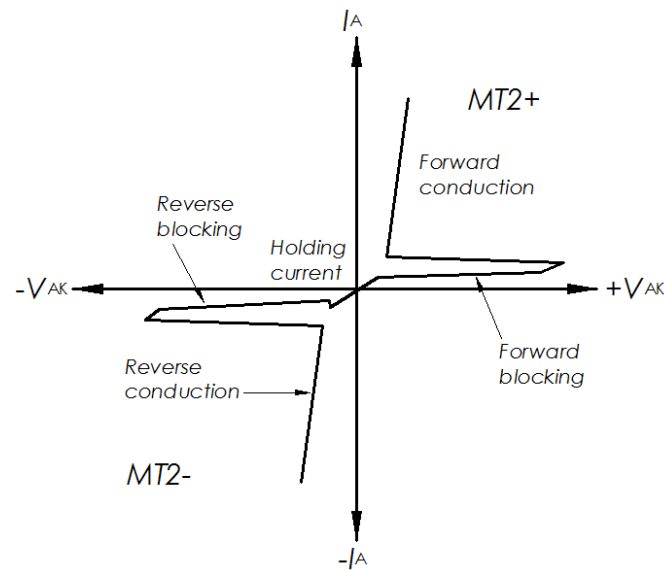


Figure 6.11 Characteristic curve of a quadrac

#### Applications of the quadrac:

- Quadracs are used in lighting control
- Speed control
- Temperature modulation control applications
- They carry performance specifications such as peak repetitive off voltage, peak repetitive reverse voltage, root mean square (RMS) on-state current, and temperature junction.

#### 6.2.5 The LASCR

Light activated SCR (LASCR) or a Photo SCR is just an ordinary SCR except that it can also be light triggered. Most LASCRs also have a gate terminal for being triggered by an electrical pulse just as a conventional SCR.

Many have the light source encapsulated in the same package so that a relay is formed. When the light falling on depletion layers is strong enough, valence electrons are dislodged from their orbits and become free electrons. When these free electrons flow out of the collector of one, transistor into the base of the other.

The positive feedback starts and the LASCR turns on just like a normal SCR, the LASCR will continue to conduct even if the light source is removed. For maximum sensitivity to light, the gate is left open.

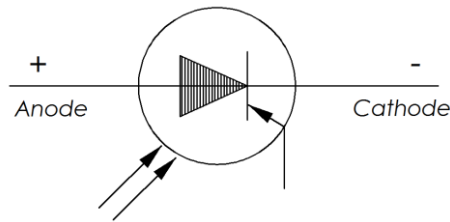
**Symbol of a LASCR:**

Figure 6.12 Symbol of a LASCR

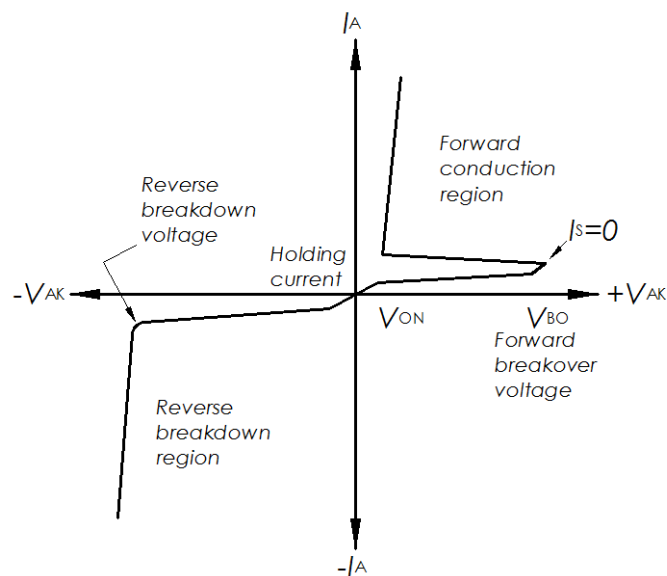
**Characteristic curve of a LASCR:**

Figure 6.13 Characteristic curve of a LASCR

**Applications of the LASCR:**

- Optical light controls
- Relays
- Phase control
- Motor control and a large number of computer applications.

**6.3 Closed and open loop control****6.3.1 Open loop control**

Open loop control means that you send electrical signals to an actuator to perform a certain action, like connecting a motor to a power supply. It often needs human intervention to obtain accurate results.

It needs constantly checking that the velocity of the motor is correct.

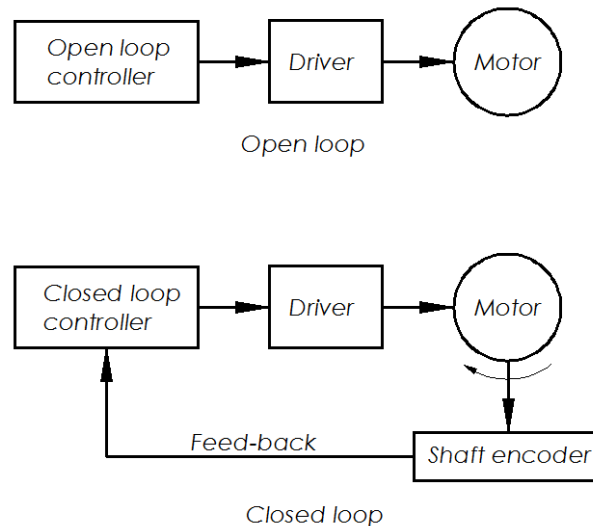


Figure 6.15

### 6.3.2 Closed loop control

Electronic components take over the control of the motor speed. The response time is very short and the accuracy is high.

In order to build a closed loop controller, you need some means of gaining information about the rotation of the shaft like the number of revolutions executed per second, or even the precise angle of the shaft.

This source of information about the shaft of the motor is called “feed-back” because it sends back information from the controlled actuator to the controller.

**Figure 6.15** shows both types of control and they both have a controller that gives orders to a driver, which is a power circuit (usually an H-bridge) that drives the motor in the required direction.

It is clear that the closed loop system is more complicated because it needs a ‘shaft encoder’ which is a device that will translate the rotation of the shaft into electrical signals that can be communicated to the controller.

A closed loop controller will regulate the power delivered to the motor to reach the required velocity. If the motor is to turn faster than the required velocity, the controller will deliver less power to the motor. Controlling the electrical power delivered to the motor, is usually done by Pulse Width Modulation.



### Worked Example 6.1

Draw a neat, labelled block diagram of a closed-loop motor speed-control system and explain the function of a comparator.

**Solution:**

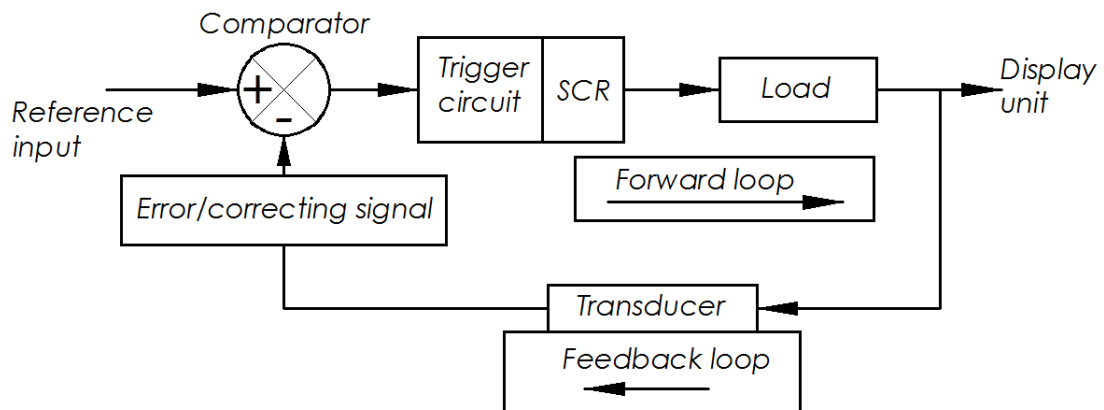


Figure 6.16

The comparator compares the output with the actual condition.



### Worked Example 6.2

Draw a neat, labelled block diagram of an open-loop motor speed-control system and explain the function of each block.

**Solution:**

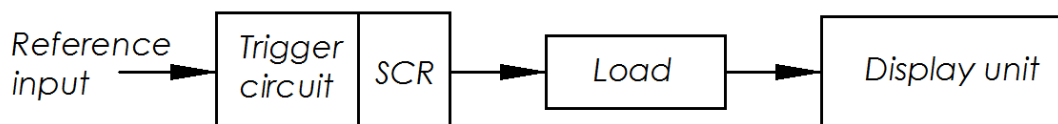


Figure 6.17

- The desired value is set at the reference input.
- The SCR will be triggered by the triggering circuit.

- The output from the load will be measured and displayed in the display unit.



**Worked Example 6.3**

Give three differences between the open-loop and closed-loop control systems.

**Solution:**

OPEN-LOOP CONTROL SYSTEM	CLOSED-LOOP CONTROL SYSTEM
No feedback loop	There is feedback loop
No comparator	There is comparator
The output is not monitored	The output is monitored
It is manually controlled	It is automatic

Table 6.1



**Worked Example 6.4**

Draw a neat, labelled diagram and explain how a diac and a triac can be used to control the speed of a small AC fan motor.

**Solution:**

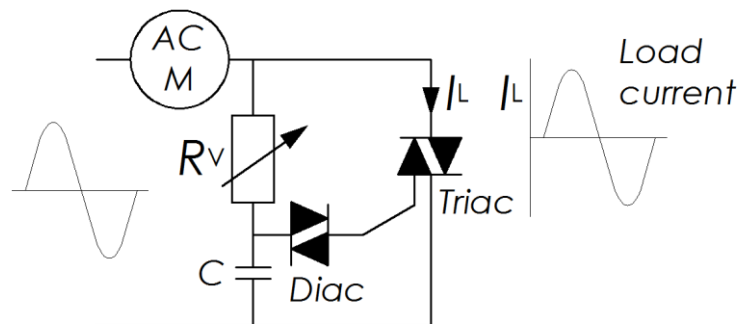


Figure 6.18

- The triac conducts in either direction when turned on.
- Positive or negative gate triggers it into conduction, therefore controlling

the AC motor.

- The conduction angle can be controlled by varying the resistor.



### Worked Example 6.5

Draw the equivalent circuit of an LASCR by transistors. Clearly show all the terminals.

**Solution:**

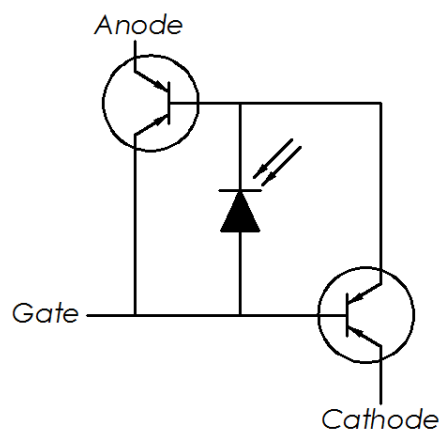


Figure 6.19



### Worked Example 6.6

The LASCR: Explain the operation of the circuit in three points. Include the function of the resistor in the explanation.

**Solution:**

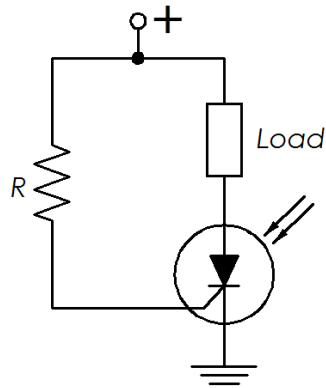


Figure 6.20

When no light is present, the LASCR is off, no current flows through the load. When the light activates the LASCR, it turns on, allowing current to flow through load.

The resistor is used to set the triggering level of the LASCR.



### Activity 6.1

1. Show, with the aid of a labelled characteristic curve, the principle of operation of a SCR.
2. Show, with the aid of a labelled characteristic curve, the principle of operation of a diac.
3. Show, with the aid of a labelled characteristic curve, the principle of operation of a triac.
4. Show, with the aid of a labelled characteristic curve, the principle of operation of a quadrac.
5. Show, with the aid of a labelled characteristic curve, the principle of operation of a LASCR.
6. Draw neat labelled symbols of the following thyristors:
  - SCR
  - Triac
  - LASCR
  - Diac

- Quadrac

**Answers are in found in module 6.**



### Activity 6.2

1. Give two differences between the SCR and the TRIAC.
2. Explain how LASCR can be used in a circuit to replace an SCR.
3. A QUADRAC is basically a triac and a diac combined together in a single package. (True/False)? Motivate your answer.
4. What is the purpose of the diode in the gate of an SCR?
5. :
6. What effect will the gate current have on the anode current after an SCR has been turned on?
7. Explain the following terms:
  - 7.1 Open-loop system
  - 7.2 Closed-loop system
8. Give three applications of an SCR
9. Draw a transistor equivalent circuit of an SCR by means of two transistors. Also show the anode, cathode and the gate.
10. Explain the purpose of each of the following items in relation to the closed-loop control system.
  - 10.1 Reference input
  - 10.2 Comparator
  - 10.3 Trigger circuit
  - 10.4 Feedback loop
  - 10.5 Display unit



### Activity 6.2

**Answers:**

1. SCR conducts during one half cycle while a TRIAC conducts during both

cycles.

SCR controls a small DC motor while a TRIAC controls a small AC motor.

2. The anode must be connected to the positive terminal.  
The cathode must be connected to the negative terminal.  
The gate must be exposed to light.
3. True – it will operate the same way as the triac and diac separately, therefore it has the same characteristics as the triac and diac.
4. It allows only positive pulses to the gate of an SCR and prevents negative pulses from going to the gate.
5. The triac conducts in either direction when turned on.  
Positive or negative signal triggers it into conduction, therefore controlling the AC motor.  
The conduction angle can be controlled by varying the resistor.
6. It will remain on even when the gate is removed in the DC circuit.
7. :
  - 7.1 An amplifier without feedback and it doesn't have a comparator.
  - 7.2 An amplifier with feedback and has a comparator.
8. Relay control  
Heater control  
Battery chargers  
Time-delay circuits  
Regulated power supply  
Static switches
9. :

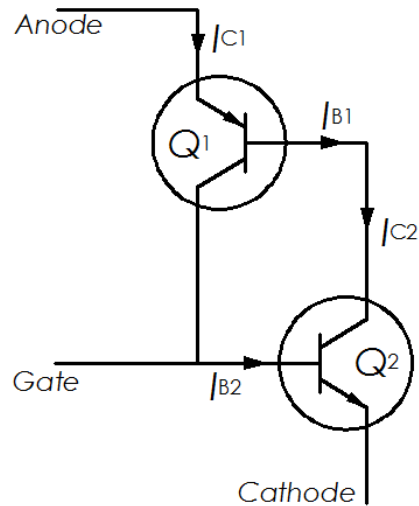


Figure 6.21

- 10. The desired value is set at the reference input.
- Compares the output with the actual conditions.
- Triggers the SCR.
- Detects the process variable.
- Displays the output.



**Self-Check**

<b>I am able to:</b>	<b>Yes</b>	<b>No</b>
• Describe the construction, operation and characteristic curves of:		
○ Silicon controlled rectifier		
○ Diac		
○ Triac		
○ Quadrac		
○ Light activated SCR		
• Describe open and closed loop systems		
• Describe single phase motor speed control systems		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

# Module 7

## Transducers

### Learning Outcomes

On the completion of this module the student must be able to:

- Describe the operating principals and applications of the following resistance transducers:
  - Potentiometer
  - Strain gauge
  - Thermistor
- Describe the circuit diagram configurations of the following resistance transducers:
  - Potentiometer
  - Strain gauge
  - Thermistor
- Describe the operating principals and applications of the following capacitive transducers:
  - Pressure
  - Liquid level
- Describe the circuit diagram configurations of the following capacitive transducers:
  - Pressure
  - Liquid level
- Describe the operating principals and applications of the following inductive transducers:
  - Differential transformer
  - Tachogenerator
- Describe the circuit diagram configurations of the following inductive transducers:
  - Differential transformer
  - Tachogenerator
- Describe the operating principals and applications of the following photo electric transducers:
  - Photodiode
  - Phototransistor
- Describe the circuit diagram configurations of the following photo electric transducers:
  - Photodiode
  - Phototransistor

## 7.1 Introduction



A transducer is a device that converts one form of energy to another. Usually a transducer converts a signal in one form of energy to a signal in another.

Transducers are often employed at the boundaries of automation, measurement, and control systems, where electrical signals are converted to and from other physical quantities (energy, force, torque, light, motion, position, etc.).

## 7.2 Transducers

A transducer is a device that converts one form of energy to another. Usually a transducer converts a signal in one form of energy to a signal in another.

Transducers are often employed at the boundaries of automation, measurement, and control systems, where electrical signals are converted to and from other physical quantities (energy, force, torque, light, motion, position, etc.).

The process of converting one form of energy to another is known as transduction.

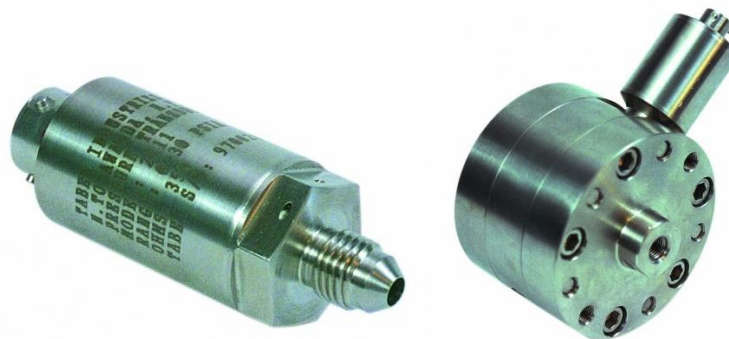


Figure 7.1 Images of transducers

### 7.2.1 Transducer types

#### Active sensors:

Active sensors require an external power sources to operate, which is called an excitation signal. The signal is modulated by the sensor to produce the output signal.

#### Passive sensors:

Passive sensors generate electric signals in response to an external stimulus without the need of an additional energy source. Such examples are a thermocouple, photodiode, and a piezoelectric sensor.

**Actuators:**

An actuator is a device that is responsible for moving or controlling a mechanism or system. It is operated by a source of energy, which can be mechanical force, electrical current, hydraulic fluid pressure, or pneumatic pressure, and converts that energy into motion.

**Bidirectional:**

Bidirectional transducers convert physical phenomena to electrical signals and also convert electrical signals into physical phenomena.

**7.2.2 Transducer applications****Electromagnetic:**

- Antennae – converts propagating electromagnetic waves to and from conducted electrical signals
- magnetic cartridges – converts relative physical motion to and from electrical signals
- Tape head, disk read-and-write heads – converts magnetic fields on a magnetic medium to and from electrical signals
- Hall effect sensors – converts a magnetic field level into an electrical signal

**Electrochemical:**

- pH probes
- Electro-galvanic fuel cells
- Hydrogen sensors
- Air flow sensors
- Load cells – converts force to mV/V electrical signal using strain gauges

**Microelectromechanical systems:**

- Potentiometers (when used for measuring position)
- Pressure sensors
- String potentiometers
- Tactile sensors
- Vibration powered generators

**Electroacoustic:**

- Loudspeakers, earphones – converts electrical signals into sound (amplified signal → magnetic field → motion → air pressure)
- Microphones – converts sound into an electrical signal (air pressure → motion of conductor/coil → magnetic field → electrical signal)<sup>[2]</sup>
- Pickup (music technology) – converts motion of metal strings into an electrical signal (magnetism → electrical signal)
- Gramophone pickups – (air pressure → motion → magnetic field → electrical signal)
- Sonar transponders (water pressure → motion of conductor/coil → magnetic field → electrical signal)

- Ultrasonic transceivers, transmitting ultrasound (transduced from electricity) as well as receiving it after sound reflection from target objects, availing for imaging of those objects.

#### **Electro-optical (Photoelectric):**

- Fluorescent lamps – converts electrical power into incoherent light
- Incandescent lamps – converts electrical power into incoherent light
- Light-emitting diodes – converts electrical power into incoherent light
- Laser diodes – converts electrical power into coherent light
- Photodiodes, photoresistors, phototransistors, photomultipliers – converts changing light levels into electrical signals
- Photodetector or photoresistor or light dependent resistor (LDR) – converts changes in light levels into changes in electrical resistance
- Cathode-ray tubes (CRT) – converts electrical signals into visual signals

#### **Thermoelectric:**

- Resistance temperature detectors (RTD) – converts temperature into an electrical resistance signal
- Thermocouples – converts relative temperatures of metallic junctions to electrical voltage

### **7.2.3 Transducer selection**

#### **Factors influencing selection:**

- What is the physical quantity to be measured?
- Which transducer principle can best be used to measure this quantity?
- What accuracy is required for this measurement?

#### **Some of the factors affecting accuracy are:**

- Fundamental transducer parameters.: type and range of measure and, sensitivity, excitation
- Physical conditions: mechanical and electrical connections, mounting provisions, corrosion resistance
- Ambient conditions: nonlinearity effects. hysteresis effects, frequency response, resolution
- Environmental conditions: temperature effects, acceleration, shock and vibration
- Compatibility of the associated equipment: zero balance provisions, sensitivity tolerance, impedance matching, insulation resistance

## 7.3 Resistance transducers

### 7.3.1 Potentiometer

A potentiometer, informally a pot, is a three-terminal resistor with a sliding or rotating contact that forms an adjustable voltage divider. If only two terminals are used, one end and the wiper, it acts as a variable resistor or rheostat.

#### Operation:

Connect two batteries head to head and tail to tail through a galvanometer.

That means the positive terminals of both batteries are connected together and negative terminals are also connected together through a galvanometer as shown in the **Figure 7.2**.

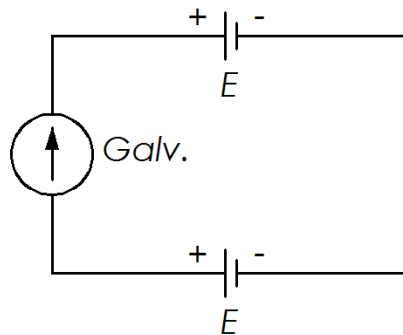


Figure 7.2 Principle of operation of a potentiometer

Because there is no deflection of the galvanometer, the cell voltage is equal. The working principle of potentiometer depends upon this phenomenon.

Take another circuit, where a battery is connected across a resistor via a switch and a rheostat, there will be a voltage drop across the resistor.

As there is a voltage drop across the resistor, this portion of the circuit can be considered as a voltage source for other external circuits. That means anything connected across the resistor will get voltage.

If the resistor has uniform cross section throughout its length, the electrical resistance per unit length of the resistor is also uniform throughout its length. Hence, voltage drop per unit length of the resistor is also uniform.

Suppose the current through the resistor is  $I$  and the resistance per unit length of the resistor is  $R$ . Then the voltage per unit length across the resistor  $V_{PL}$  would be:

$$\text{Voltage drop per unit length } V_{PL} = IR$$

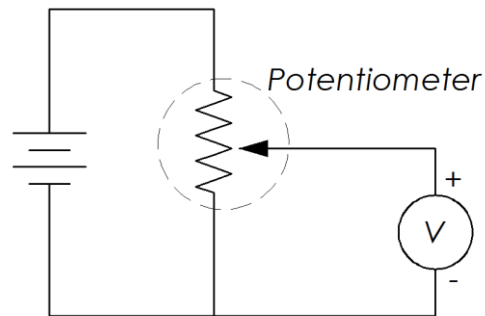


Figure 7.3 Circuit of a potentiometer

### 7.3.2 Strain gauge

A strain gauge is a device used to measure strain on an object. The most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern.

#### Operation:

The gauge is attached to the object by a suitable adhesive, such as cyanoacrylate. As the object is deformed, the foil is deformed, causing its electrical resistance to change.

This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor.

By measuring the change in resistance of an object, the amount of induced stress can be calculated.

The change in resistance normally has very small value, and to sense that small change, strain gauge has a long thin metallic strip arranged in a zig-zag pattern on a non-conducting material called the carrier, as shown in **Figure 7.4**, so that it can enlarge the small amount of stress in the group of parallel lines and could be measured with high accuracy.

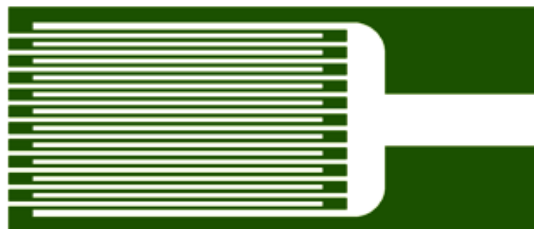


Figure 7.4 Strain gauge where reading is increased

Strain gauge bridge circuit shows the measured stress by the degree of discrepancy, and uses a voltmeter in the center of the bridge to provide an accurate measurement of that imbalance:

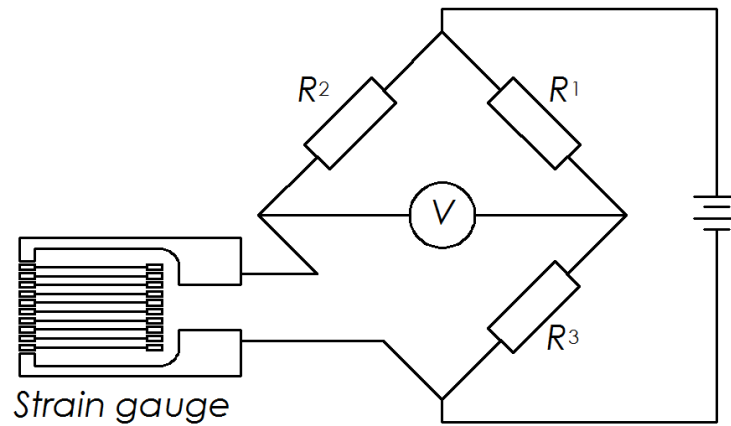


Figure 7.5 Circuit of a strain gauge

In this circuit,  $R_1$  and  $R_3$  are the ratio arms equal to each other, and  $R_2$  is the rheostat arm has a value equal to the strain gauge resistance.

When the gauge is unstrained, the bridge is balanced, and voltmeter shows zero value. As there is a change in resistance of strain gauge, the bridge gets unbalanced and producing an indication at the voltmeter. The output voltage from the bridge can be amplified further by a differential amplifier.

### 7.3.3 Thermistor

A thermistor is a type of resistor whose resistance is dependent on temperature, more so than in standard resistors.

The word is a portmanteau of thermal and resistor. Thermistors are widely used as inrush current limiters, temperature sensors (Negative Temperature Coefficient or NTC type typically), self-resetting overcurrent protectors, and self-regulating heating elements. (Positive Temperature Coefficient or PTC type typically).

#### Thermistors are of two opposite fundamental types:

- With NTC, resistance Decreases as temperature rises to protect against inrush overvoltage conditions. Commonly installed series in a circuit.
- With PTC, resistance Increases as temperature rises to protect against overcurrent conditions. Commonly installed series in a circuit.

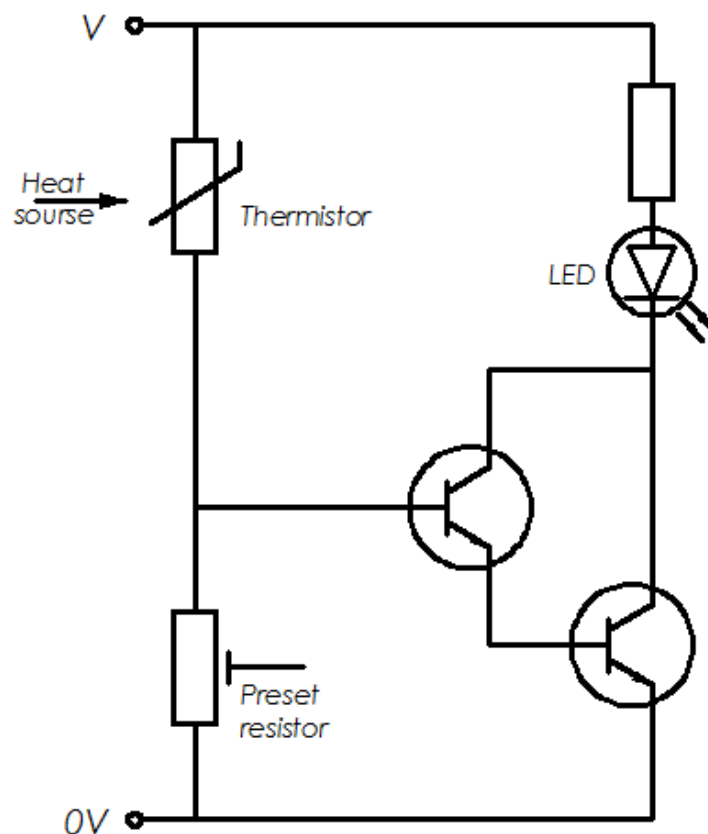


Figure 7.5 Circuit of a thermistor

### Operation:

Thermistor is a temperature sensitive device. If the temperature varies, then the resistance of the thermistor either increases or decreases. By using this property, we can use it as a temperature sensor.

In thermistors, the semiconductor materials are used. The semiconductor materials are prepared from the oxides of chromium, cobalt, nickel, manganese, and sulphides of iron, aluminium or copper.

Because of semiconductor materials, resistance of the thermistor varies significantly with temperature, more than the normal resistance. Thermistor thermometers have high sensitivity but it has nonlinear characteristics.

## 7.4 Capacitive transducers

### 7.4.1 Pressure

A pressure sensor measures pressure, typically of gases or liquids. Pressure is an expression of the force required to stop a fluid from expanding, and is usually stated in terms of force per unit area.

A pressure sensor usually acts as a transducer, it generates a signal as a function of the pressure imposed. Such a signal is electrical.

Pressure sensors are used for control and monitoring in thousands of everyday applications.

**Operation:**

Pressure transducers, when connected to an appropriate electrical source and exposed to a pressure source, will produce an electrical output signal (voltage, current, or frequency) proportional to the pressure.

Most transducers are designed to produce output that is linear with the applied pressure and independent of other system variables - the most important of these being temperature. Most outputs are mV, V, mA, and, sometimes, as a frequency.

Pressure transducers have a sensing element of constant area and respond to force applied to this area by the fluid pressure. This force deflects a diaphragm, bellows, or Bourdon tube. In turn, these deflections, strains, or tensions are converted to electrical outputs through any of a variety of different transduction methods.

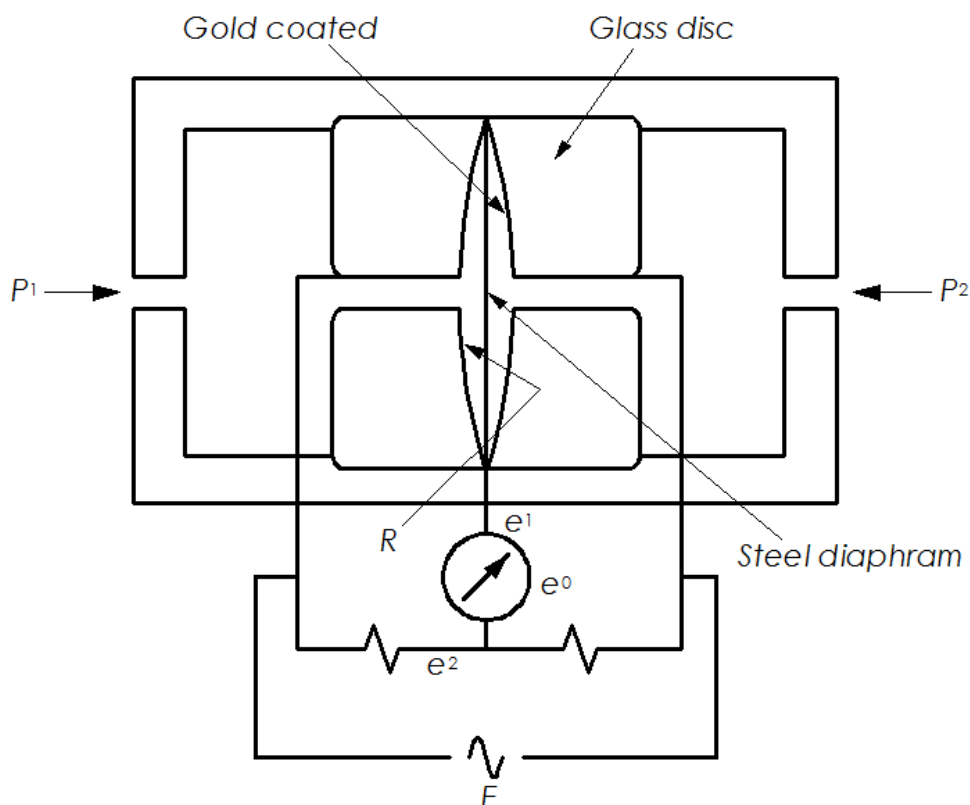


Figure 7.6 Circuit of a capacitor pressure gauge

### 7.4.2 Liquid level

Level sensors detect the level of liquids and other fluids and fluidized solids, including slurries, granular materials, and powders that exhibit an upper free surface. Substances that flow become essentially horizontal in their containers.

The level measurement can be either continuous or point values. Continuous level sensors measure level within a specified range and determine the exact amount of substance in a certain place, while point-level sensors only indicate whether the substance is above or below the sensing point.

#### Operation:

A capacitor is a two terminal device that consists of two conducting bodies separated by a non-conducting (dielectric) material. A simple capacitor consisting of two plates is shown **Figure 7.7**

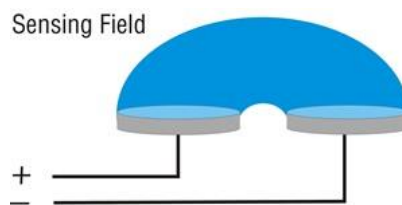


Figure 7.7

To create a more usable geometry for sensors the plates (or electrodes) can be arrayed in a variety of ways. Though this complicates the above expression for capacitance, the overall relationship between the variables remains the same. Shown **Figure 7.8**, the electrodes are arrayed on the same plane. The electric field is projected away from the electrodes.

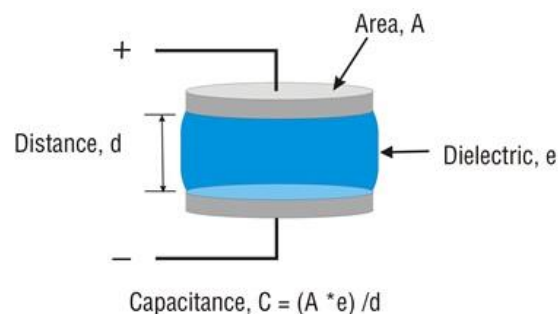


Figure 7.8

If the dielectric remains constant, the capacitance also remains constant. If the dielectric changes, the capacitance naturally also changes. In capacitive proximity sensors, these two electrodes are coupled together, and integrated in a high frequency oscillator.

In the “no target” state the oscillator is tuned to be resting. As a target enters the electric field, increasing the capacitance, oscillation begins. When the amplitude reaches a high enough level, a change in signal state is triggered.

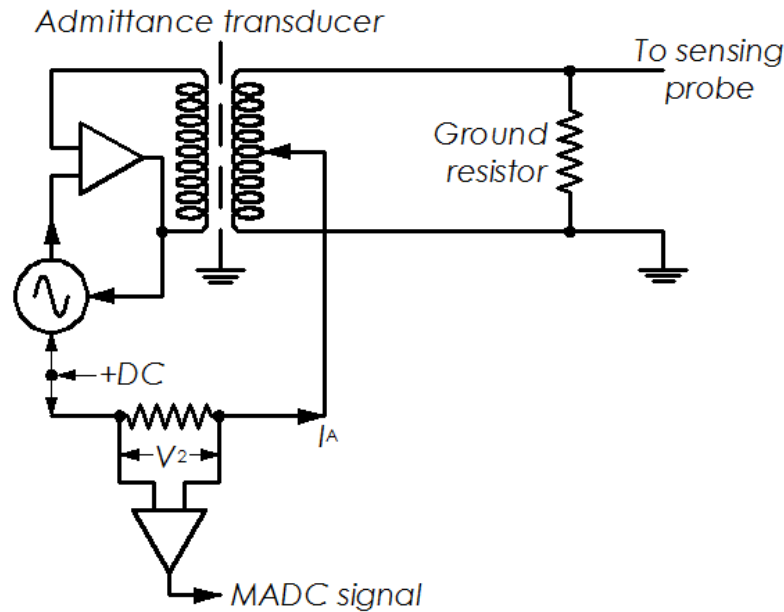


Figure 7.9 Circuit of a capacitor level gauge

## 7.5 Inductive transducers

### 7.5.1 Differential transformer

The linear variable differential transformer (LVDT) is a type of electrical transformer used for measuring linear displacement (position). A counterpart to this device that is used for measuring rotary displacement is called a rotary variable differential transformer (RVDT).

#### Operation:

The linear variable differential transformer has three solenoidal coils placed end-to-end around a tube. The center coil is the primary, and the two outer coils are the top and bottom secondaries.

A cylindrical ferromagnetic core, attached to the object whose position is to be measured, slides along the axis of the tube. An alternating current drives the primary and causes a voltage to be induced in each secondary proportional to the length of the core linking to the secondary.

The frequency is usually in the range 1 to 10 kHz.

As the core moves, the primary's linkage to the two secondary coils changes and causes the induced voltages to change. The coils are connected so that the output voltage is the difference (hence "differential") between the top secondary voltage and the bottom secondary voltage.

When the core is in its central position, equidistant between the two secondaries, equal voltages are induced in the two secondary coils, but the two signals cancel, so the output voltage is theoretically zero.

In practice minor variations in the way in which the primary is coupled to each secondary means that a small voltage is output when the core is central.

When the core is displaced toward the top, the voltage in the top secondary coil increases as the voltage in the bottom decreases. The resulting output voltage increases from zero. This voltage is in phase with the primary voltage.

When the core moves in the other direction, the output voltage also increases from zero, but its phase is opposite to that of the primary. The phase of the output voltage determines the direction of the displacement (up or down) and amplitude indicates the amount of displacement. A synchronous detector can determine a signed output voltage that relates to the displacement.

The LVDT can be used as an absolute position sensor. Even if the power is switched off, on restarting it, the LVDT shows the same measurement, and no positional information is lost.

Its biggest advantages are repeatability and reproducibility once it is properly configured. Also, apart from the uni-axial linear motion of the core, any other movements such as the rotation of the core around the axis will not affect its measurements.

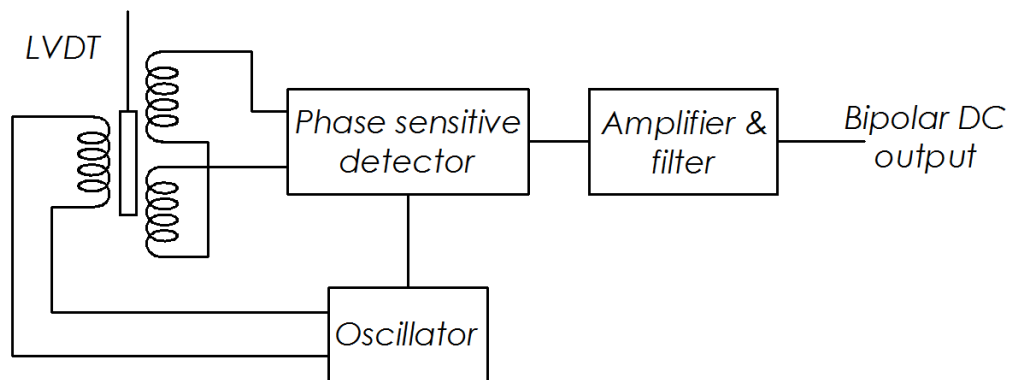


Figure 7.10 Circuit of a differential transformer

### 7.5.2 Tachogenerator

An electromechanical generator is a device capable of producing electrical power from mechanical energy, usually the turning of a shaft.

When not connected to a load resistance, generators will generate voltage roughly proportional to shaft speed. With precise construction and design,

generators can be built to produce very precise voltages for certain ranges of shaft speeds, thus making them well-suited as measurement devices for shaft speed in mechanical equipment.

A generator specially designed and constructed for this use is called a tachometer or tachogenerator.

### Operation:

By measuring the voltage produced by a tachogenerator, you can easily determine the rotational speed of whatever it is mechanically attached to. One of the more common voltage signal ranges used with tachogenerators is 0 to 10 volts.

Obviously, since a tachogenerator cannot produce voltage when it is not turning, the zero cannot be “live” in this signal standard.

Tachogenerators can also indicate the direction of rotation by the polarity of the output voltage. When a permanent-magnet style DC generator's rotational direction is reversed, the polarity of its output voltage will switch.

In measurement and control systems where directional indication is needed, tachogenerators provide an easy way to determine that.

Tachogenerators are frequently used to measure the speeds of electric motors, engines, and the equipment they power: conveyor belts, machine tools, mixers, fans, etc.

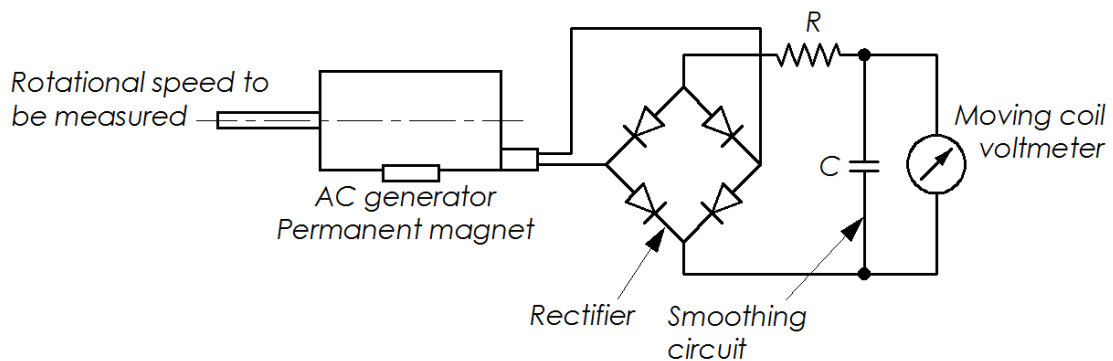


Figure 7.11 Circuit of an electromechanical generator

## 7.6 Photo electric transducers

### 7.6.1 Photodiode

A photodiode is a semiconductor device that converts light into current. The current is generated when photons are absorbed in the photodiode. A small amount of current is also produced when no light is present.

Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas. Photodiodes usually have a slower response time as their surface area increases.

The common, traditional solar cell used to generate electric solar power is a large area photodiode.

Photodiodes are similar to regular semiconductor diodes except that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device.

Many diodes designed for use specifically as a photodiode use a PIN junction rather than a p-n junction, to increase the speed of response. A photodiode is designed to operate in reverse bias.

### Operation:

A photodiode is a p-n junction or PIN structure. When a photon of sufficient energy strikes the diode, it creates an electron-hole pair. This mechanism is also known as the inner photoelectric effect.

If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in electric field of the depletion region.

Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The total current through the photodiode is the sum of the dark current (current that is generated in the absence of light) and the photocurrent, so the dark current must be minimized to maximize the sensitivity of the device.

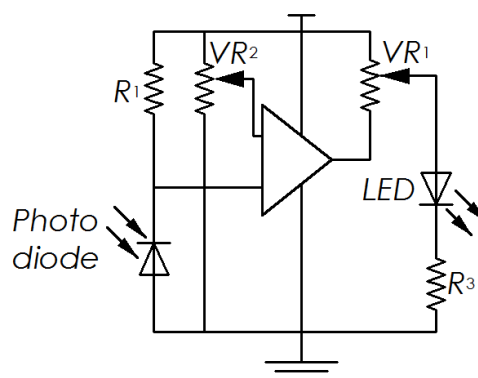


Figure 7.12 Circuit of a photodiode

### 7.6.2 Phototransistor

Phototransistors are either tri-terminal (emitter, base and collector) or bi-terminal (emitter and collector) semiconductor devices which have a light-sensitive base region.

Although all transistors exhibit light-sensitive nature, these are specially designed and optimized for photo applications. These are made of diffusion or ion-implantation and have much larger collector and base regions in

comparison with the ordinary transistors. These devices can be either homojunction structured or heterojunction structured.

In the case of homojunction phototransistors, the entire device will be made of a single material-type; either silicon or germanium. However to increase their efficiency, the phototransistors can be made of non-identical materials (Group III-V materials like GaAs) on either side of the pn junction leading to heterojunction devices. Nevertheless, homojunction devices are more often used in comparison with the hetero junction devices as they are economical.

### **Operation:**

The behavior of phototransistors is identical to that of normal transistors except that the effect brought-about by the base voltage will be experienced due to incident light. This can be made clearer by analyzing the following points:

1. The characteristics of phototransistors are similar to those of normal transistors except that they have base current replaced by light intensity.
2. The phototransistors can be configured in two different configurations viz., common collector and common emitter, depending on the terminal which is common between the input and output terminals, similar to normal transistors.
3. A small reverse saturation current, called dark current, flows through the phototransistor even in the absence of light whose value increases with an increase in the value of temperature, a property identical to that exhibited by the ordinary transistors.
4. Phototransistors are prone to permanent damage due to breakdown if the voltage applied across the collector-emitter junction increases beyond its breakdown voltage, just as in the case of normal transistors.

The output of the phototransistor depends on:

- Wavelength of the incident light
- Area of the light-exposed collector-base junction
- DC current gain of the transistor.
- Luminous sensitivity defined as the ratio of photoelectric current to the incident luminous flux
- Spectral response which decides the longest wavelength which can be used as the sensitivity of the phototransistors is a function of wavelength
- Photoelectric gain which indicates its efficiency of converting light into an amplified electrical signal
- Time constant which influences its response time.

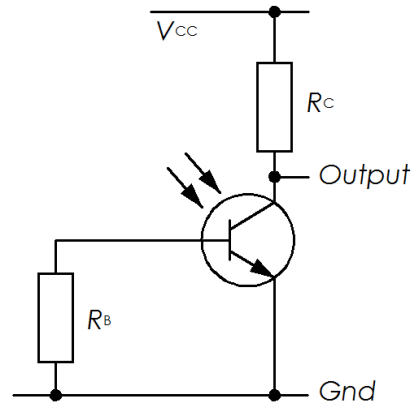


Figure 7.12 Circuit of a Phototransistor

**Worked Example 7.1**

Describe, with the aid of a circuit diagram how strain gauges are used in a Wheatstone bridge.

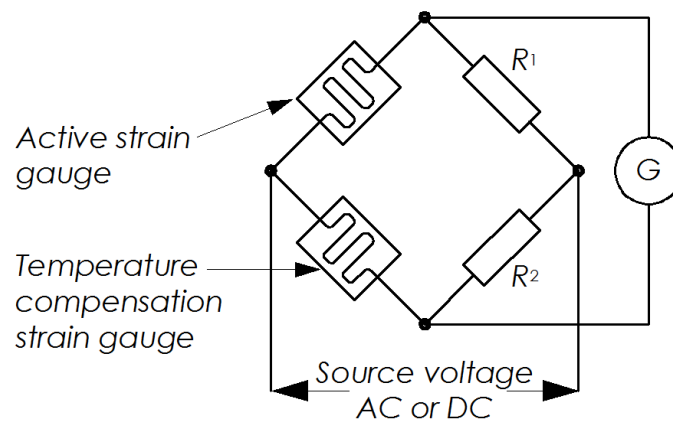
**Solution:**

Figure 7.13

If there is no pressure applied in the active gauge, the bridge is balanced and there is a zero in the galvanometer.

If pressure is applied, the bridge will be out of balance.

The small change in resistance will be amplified and the reading will appear in the galvanometer.

The compensation gauge will prevent false observation due to temperature variation.



### Worked Example 7.2

Discuss, with the aid of a sketch, the operation of a Bourdon tube used to measure angular displacement.

**Solution:**

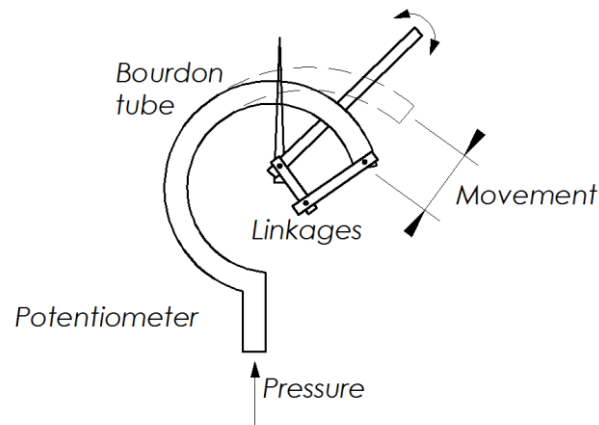


Figure 7.14

When pressure is applied to the bourdon tube, the resulting force will straighten the tube.

The shaft will then turn and the resistance of the tube changes.

The change in resistance is calibrated to read angular displacement.

When pressure is reduced, the bourdon tube returns to its original position.



### Worked Example 7.3

Demonstrate, by means of a neat, labelled sketch of a simple transducer, how you would measure the following:

1. Pressure with bellows
2. Displacement with a potentiometer

**Solution:**

1.

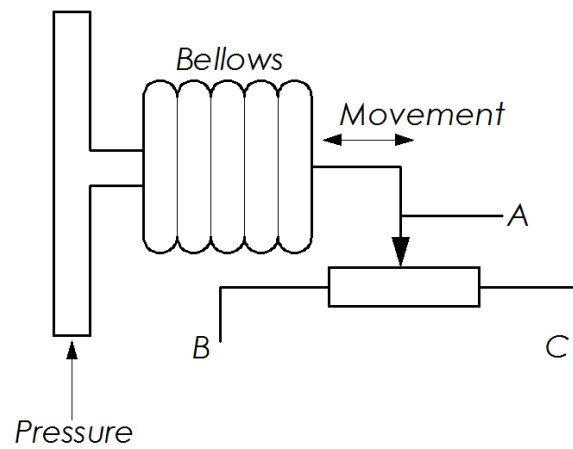


Figure 7.15

2.

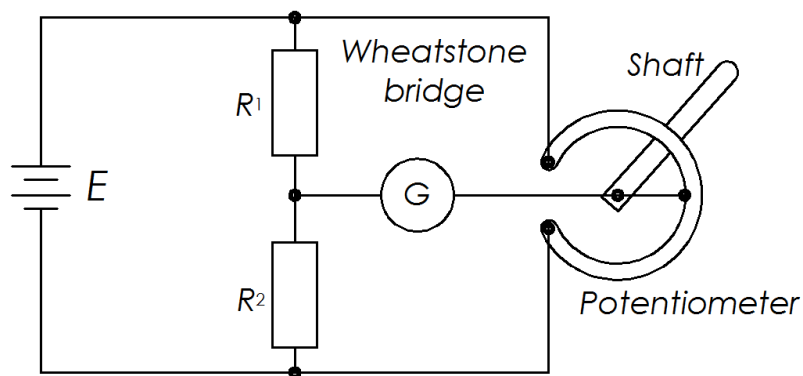


Figure 7.16

**Worked Example 7.4**

Draw and explain the operation of a transducer that is used to monitor the speed of rotation of a shaft.

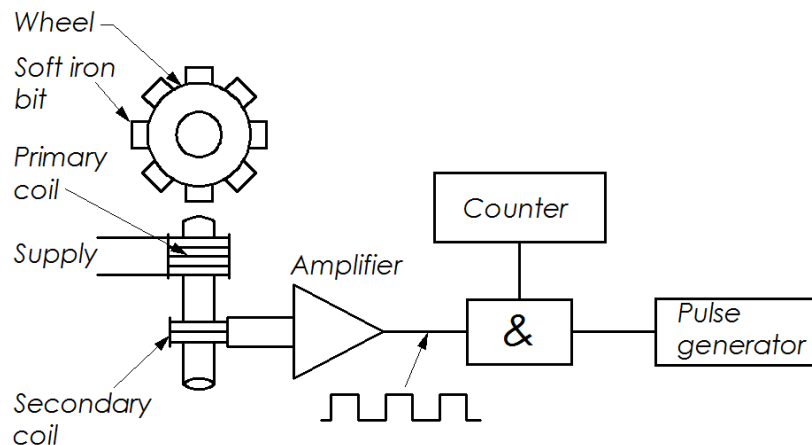
**Solution:**

Figure 7.17

When the primary voltage is applied to the primary coil a magnetic field will be created around it and it will be induced in the secondary coil.

If a shaft turns the wheel, the soft iron bit increases magnetic coupling through the core. As the magnetic field in the primary coil increases, the soft iron bit passes the magnetic field, it drops producing a pulse at the output of the secondary coil.

The frequency of the pulses is directly proportional to the speed at which the wheel turns. In this way the speed of the wheel can be read off at the counter.

**Worked Example 7.5**

Show by means of a neat, labelled diagram of a transducer how you would measure temperature with a thermistor. Also state the purpose of the compensation gauge used in a circuit.

**Solution:**

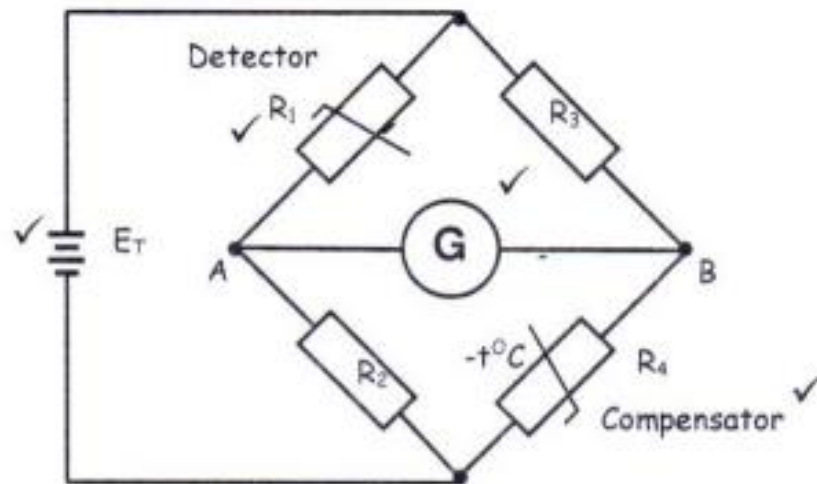


Figure 7.18

The compensation gauge prevents false observation due to temperature variations.



### Worked Example 7.6

Use a circuit diagram to indicate how a photo-diode can be used in an emitter-coupled amplifier to secure a dangerous area.

**Solution:**

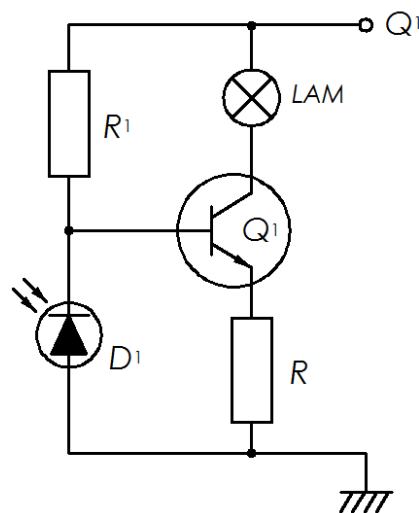


Figure 7.19



### Activity 7.1

Make neat labelled sketched of the following circuit diagrams:

**(Find the answers in module 7)**

1. Potentiometer
2. Strain gauge
3. Thermistor
4. Tachogenerator
5. Capacitor level gauge
6. Photodiode



### Activity 7.2

1. Which formula describes the principle on which a strain gauge operates?
2. Name three factors which will influence the capacitance of a capacitive transducer.
3. What is the function of the compensatopn gauge in the strain gauge?
4. Name the four groups into which transducers can be divided.
5. What is the basic function of a potentiometer as a transducer?
6. Name three convention methods by means of transducers.
7. Explain the basic operating principle of a strain gauge. Also give the formula that describes the principle of its operation.
8. Define the term *transducer*.
9. Name two quantities that can be measured with the aid of a LVDT.
10. Name three aspects that should be considered before a transducer is selected for a particular application.
11. Explain, with the aid of a neat, labelled sketch, how an active stress of strain gauge is measured with a Wheatstone bridge.



## Activity 7.2

### Answers:

1.  $R = \frac{\rho l}{A}$
2. Distance between the plates  
Area of each plate  
Di-electric current
3. The function of the compensating gauge prevents false observation due to temperature variation.
4. Resistive  
Capacitive  
Inductive  
Photo sensitive
5. It converts the shaft position into a resistance that is directly proportional to the shaft angle.
6. Mechanical to electrical  
Light to electrical  
Electrical to mechanical
7. The resistance of a wire is changed by expansion or contraction due to an externally applied stress.  
$$R = \frac{\rho l}{a}$$
8. It is a device that converts non-electrical physical parameters into electrical signal.
9. Force  
Displacement
10. Accuracy required  
The environment in which the transducer will be used  
The physical quantity to be measured  
The type of supply that is available (AC or DC)  
The converting principle which is most suitable

11. If there is no pressure applied to the active gauge, the bridge will be balanced and the output in the galvanometer will be zero.
12. If pressure is applied in the active gauge, the bridge will be out of balance due to the change in length and thus in the area and resistance.
13. The compensation gauge will prevent false observation due to temperature variations.
14. The change that has taken place can now be read in a galvanometer.



### Self-Check

<b>I am able to:</b>	<b>Yes</b>	<b>No</b>
• Describe the operating principals and applications of the following resistance transducers:		
○ Potentiometer		
○ Strain gauge		
○ Thermistor		
• Describe the circuit diagram configurations of the following resistance transducers:		
○ Potentiometer		
○ Strain gauge		
○ Thermistor		
• Describe the operating principals and applications of the following capacitive transducers:		
○ Pressure		
○ Liquid level		
• Describe the circuit diagram configurations of the following capacitive transducers:		
○ Pressure		
○ Liquid level		
• Describe the operating principals and applications of the following inductive transducers:		
○ Differential transformer		
○ Tachogenerator		
• Describe the circuit diagram configurations of the following inductive transducers:		
○ Differential transformer		
○ Tachogenerator		
• Describe the operating principals and applications of the following photo electric transducers:		
○ Photodiode		

○ Phototransistor		
• Describe the circuit diagram configurations of the following photo electric transducers:		
○ Photodiode		
○ Phototransistor		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

# Module 8

## Testing Equipment

### Learning Outcomes

On the completion of this module the student must be able to:

- Describe the following:
  - Cathode ray tube
  - Focus method
  - Deflection method
  - Accelerating anodes
- Describe with the help of diagrams and sketches the oscilloscope
- Describe with the help of diagrams and sketches the function generator
- Describe right angle, sinusoidal and saw tooth wave forms

### 8.1 Introduction



Electronic test equipment is used to create signals and capture responses from electronic devices under test (DUTs). In this way, the proper operation of the DUT can be proven or faults in the device can be traced. Use of electronic test equipment is essential to any serious work on electronics systems.

### 8.2 The cathode ray tube

The cathode ray tube (CRT) is a vacuum tube that contains one or more electron guns and a phosphorescent screen, and is used to display images.

It modulates, accelerates, and deflects an electron beam onto the screen to create the images. The images may represent electrical waveforms (oscilloscope), pictures (television, computer monitor), radar targets, or others.

The CRT uses an evacuated glass envelope which is large, deep (i.e. long from front screen face to rear end), fairly heavy, and relatively fragile. As a matter of safety, the face is typically made of thick lead glass so as to be highly shatter-resistant and to block most X-ray emissions, particularly if the CRT is used in a consumer product.

### 8.2.1 Electrostatic Focusing

We know that the force on an electron is given by:

$$\text{Force of an electron } F_e = qE$$

Where:

$q$  is the charge on the electron ( $q = 1.6 \times 10^{-19}$  C)

$E$  is the electric field intensity

A negative sign shows that the direction of force is in the opposite direction to that of the electric field.

As the beam of electron passes through a plate system, it deflects in the opposite direction to the electric field. The deflection angle can be easily varied by changing the potential of the plates.

### 8.2.2 Electrostatic Deflection

Two plates A and B which are at potential  $+E$  and  $0$  respectively. These plates are also called deflection plates. The field produced by these plates is in the direction of the positive  $y$  axis and there is no force along the  $x$ -axis.

After the deflection plates there is a screen through which we can measure net deflection of the electron beam.

Consider a beam of electrons moving along the  $x$ -axis. The beam deflects at an angle  $A$ , due to the presence of an electric field, the deflection is in the positive direction along the  $y$  axis.

### 8.2.3 Vertical deflection system

The input signal to be examined is fed to the vertical deflection system plates with the help of an input attenuator and a number of amplifier stages.

The main function of these amplifiers is to amplify the weak signals so that the amplified signal can produce the desirable signals.

### 8.2.4 Horizontal deflection system

Like the vertical system, the horizontal system also consists of horizontal amplifiers to amplify the weak input voltage signals but in contrast to vertical deflection system, the horizontal deflection plates are fed by a sweep voltage that provides a time base.

The saw tooth sweep generator is triggered by the synchronizing amplifier when the sweep selector switch is in the internal position and thus the triggered saw tooth generator gives input to the horizontal amplifier by following this mechanism.

**There are four types of sweeps:**

- **Free Running** or Recurrent Sweep. The saw tooth waveform is repetitive i.e. a new sweep is started immediately after the previous sweep.
- Sometimes the waveform to be may not be periodic so the sweep circuit remain inoperative and the sweep be initiated by the waveform under examination. In such cases we use **triggered sweep**.
- Generally a **driven sweep** is used where the sweep is free running but triggered by the signal under test.
- **Non Saw Tooth Sweep** This is used for finding the phase difference between the two voltages. Another important application is that we can compare frequency of input voltages using non saw tooth sweep.

### 8.2.5 Synchronisation

There must be synchronization between the sweep and the signal being measured. Synchronization is done to produce a stationary pattern.

There are three sources of synchronization which can be selected by a synchronization selector and they are:

- **Internal:** This trigger is obtained from the signal being measured through the vertical amplifier.
- **External:** This trigger is when an external trigger source is required.
- **Line:** This method a trigger is obtained by a power supply.

### Intensity Modulation:

Intensity modulation can be done by inserting the signal between the ground and the cathode. Intensity modulation causes the brightening of the display.

### Positioning Controls:

Position can be control by applying a small independent internal direct voltage source to the deflecting plates and with the help of potentiometer (using it as voltage divider) we can control the position of signal.

### Focus Control:

Focus can be controlled by changing the focal length of the focusing electrode which acts like a lens and focal length can be changed by the changing potential of the focusing anode.

### Intensity Control:

The intensity can be varied by changing the grid potential with respect to cathode.

### Calibration Circuit:

Calibrating voltage has a square shape which is usually internally generated of known amplitude.

**Astigmatism:**

By adjusting the focus, the spot can be made sharp in order to avoid the problem of astigmatism.

**8.3 The calibrated oscilloscope**

An oscilloscope, CRO (for cathode-ray oscilloscope), or DSO (for the more modern digital storage oscilloscope), is a type of electronic test instrument that allows observation of constantly varying signal voltages, usually as a two-dimensional plot of one or more signals as a function of time.

Other signals (such as sound or vibration) can be converted to voltages and displayed.

Oscilloscopes are used to observe the change of an electrical signal over time, such that voltage and time describe a shape which is continuously graphed against a calibrated scale.

The observed waveform can be analyzed for such properties as amplitude, frequency, rise time, time interval, distortion and others.

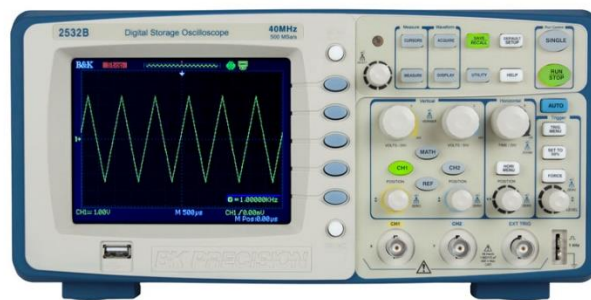


Figure 7.9 The calibrated oscilloscope

Let us discuss the construction of cathode ray tube in order to understand the construction of cathode ray oscilloscope.

Basically the cathode ray tube consists of five main parts and these main parts are written below:

- Electron gun
- Deflection plate system
- Fluorescent screen
- Glass envelope
- Base

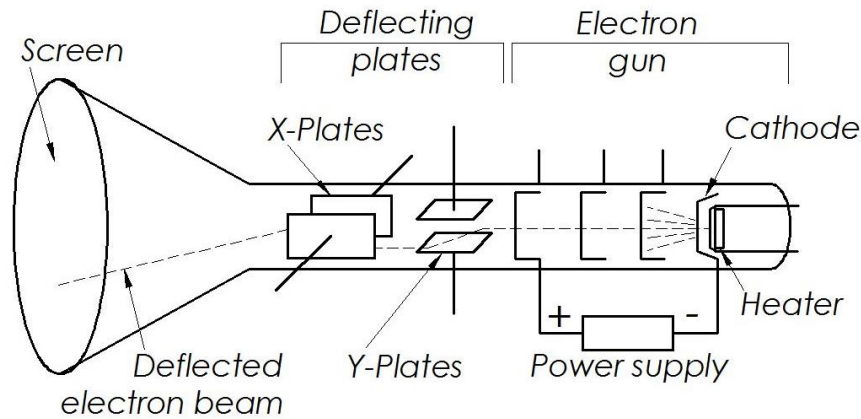


Figure 7.10 The calibrated oscilloscope

### Electron Gun:

It is the source of accelerated, energized and focused beam of electrons. It consists of six parts namely heater, a cathode, a grid, a pre-accelerating anode, a focusing anode and an accelerating anode.

### Deflection plate system:

The beam of the electron passes through this plate system, it deflects in the opposite direction of electric field. The deflection angle can be easily varied by changing the potential of the plates.

**Vertical deflecting:** The input signal is fed to the vertical deflection system plates with the help of an input attenuator and a number of amplifier stages. The main function of these amplifiers is to amplify the weak signals so that the amplified signal can produce the desirable signals.

**Horizontal deflecting:** Like the vertical system, the horizontal system also consists of horizontal amplifiers to amplify the weak input voltage signals but they are fed by a sweep voltage that provides a time base.



**Worked Example 8.1**

Draw a block diagram of an oscilloscope

**Solution:**

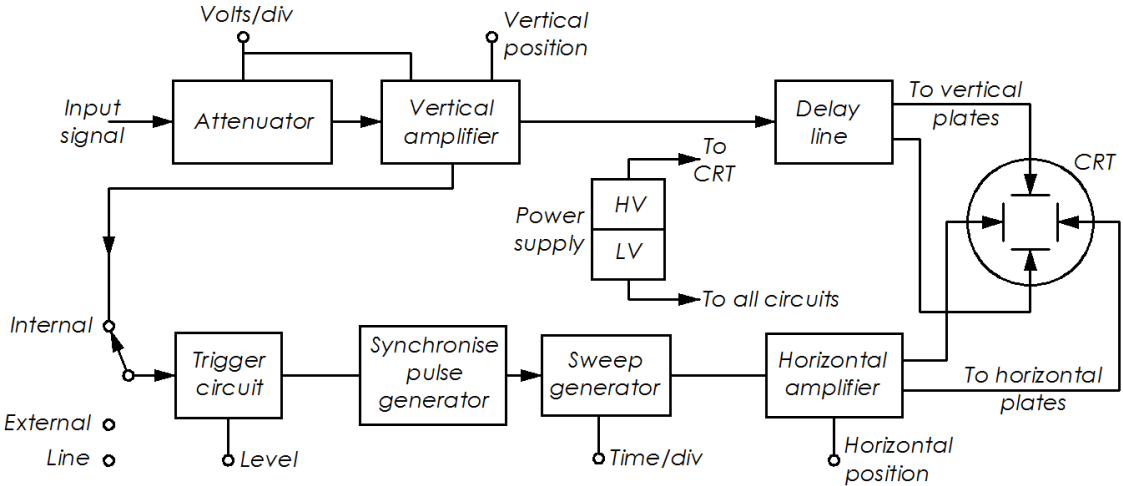


Figure 7.11



**Worked Example 8.2**

Draw a neat, labelled block diagram of a function generator.

**Solution:**

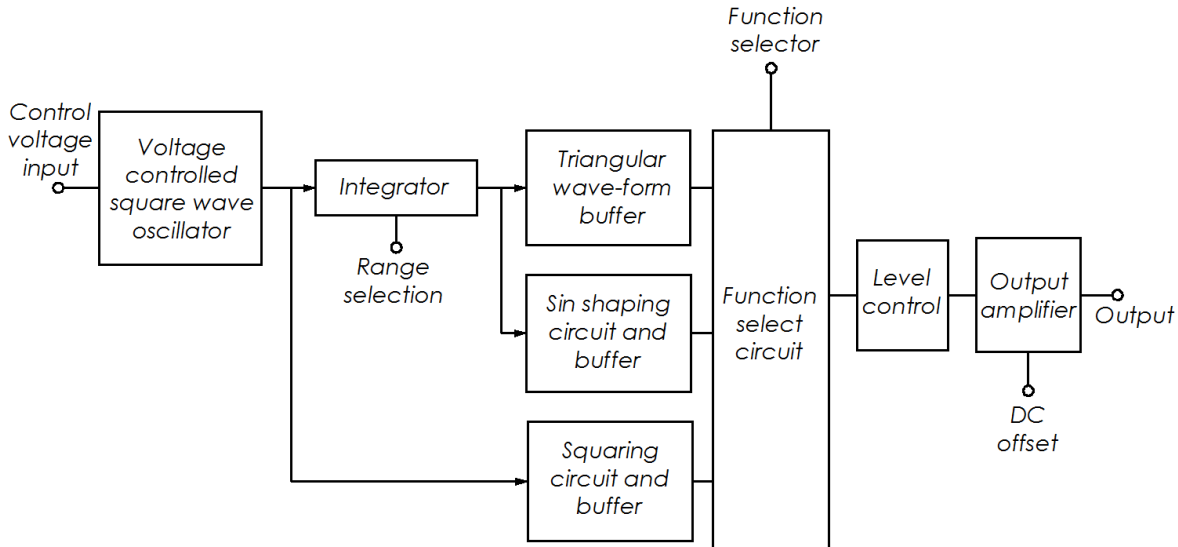


Figure 7.12



### Worked Example 8.3

A square wave pulse is displayed on a CRO screen. The time-base control is set at  $15\mu\text{F}/\text{div}$  and 1 cycle is displayed over 4 cm.

Calculate the following:

1. The period
2. The frequency

**Solution:**

$$\begin{aligned}
 1. \quad \text{Period} &= \text{no of div} \times \text{sec/div} \\
 &= 4 \times 15 \times 10^{-6} \\
 &= 60 \mu\text{sec}
 \end{aligned}$$

$$\begin{aligned}
 2. \quad \text{frequency} &= \frac{1}{t} \times \frac{1}{60 \times 10^{-6}} \\
 &= 16\,666 \text{ Hz}
 \end{aligned}$$



### Worked Example 8.4

An oscilloscope displays a sine wave over 2 vertical divisions and 4 horizontal divisions. The vertical amplifier setting is  $0,3 \text{ V/div}$  and the time-base is at  $2 \mu\text{sec/div}$ .

Calculate the following:

1. The amplitude
2. The peak-to-peak value
3. The average value

**Solution:**

$$\begin{aligned}
 1. \quad \text{Amplitude} &= \text{no of divisions} \times \text{V/div} \\
 &= 2 \times 0,3 \\
 &= 0,6 \text{ V}
 \end{aligned}$$

$$2. \quad V_{p-p} = \text{no of divisions} \times \text{V/div}$$

$$= 4 \times 0,3$$

$$= 1,2 V$$

$$3. \quad V_{ave} = 0,637 \times V_p$$

$$= 0,637 \times 0,6$$

$$= 0,382 V$$



### Activity 8.1

1. Describe the purpose of the following controls that appears in the front panel and main control of an oscilloscope.
  - 1.1 Time/div ( time base control)
  - 1.2 Intensity
  - 1.3 On/off switch
  - 1.4 Volts/div
  - 1.5 Horizontal position
2. Give one application of a saw-tooth wave form.
3. Draw a neat, labelled block diagram of a cathode-ray-tube.
4. With reference to the oscilloscope, which circuit would you investigate if:
  - 4.1 The oscilloscope is turned on and there is no horizontal trace but only a spot of light on the screen?
  - 4.2 There is a horizontal trace on the screen but no vertical deflection when a sine wave is applied?
  - 4.3 It is impossible to stabilise th signal display?
5. Calculate the width of one cycle of the sine wave if the frequency of the signal is 15 kHz in an oscilloscope at the scale setting of  $60 \mu\text{sec}/\text{cm}$ .
6. Indicate whether the following statement is True or False: *One application of a square wave is ion timing circuits in digital electronics.*
7. Describe a power supply.
8. Describe a function generator.
9. Describe a time-base generator.
10. Describe synchronisation.

11. Describe a horizontal amplifier.
12. An oscilloscope with a calibrated time base is used to measure the frequency of an oscillator. If the time/cm control is set at  $100 \mu\text{s}/\text{cm}$  and the width of one cycle of the sine wave is 4 cm, calculate the frequency of the oscillator.
13. What is a cathode-ray oscilloscope (CRO)?
14. What is the function of the time-base generator as used in the oscilloscope?
15. Which wave forms would you see for the following:
  - 15.1 Digital electronic switching
  - 15.2 Transmission of radio signals
16. An oscilloscope displays a sine wave over 6 vertical divisions and 4 horizontal divisions. The vertical amplifier setting is 2 V/div and the time base is at  $15 \mu\text{s}/\text{cm}$ .  
Calculate:
  - 16.1 The amplitude
  - 16.2 The period



### Activity 8.1

#### Answers:

1. :
  - 1.1 It controls the rates at which the spot travels across the screen.
  - 1.2 It determines the brightness of the spot on the display.
  - 1.3 It switches the oscilloscope on or off.
  - 1.4 It adjust the amplitude of the wave-form.
  - 1.5 It moves the trace left or right for easier measurement.
2. Timing circuit  
Scanning circuit in oscilloscope
3. Answer in Module 8.

4. :
  - 4.1 Horizontal and/or vertical deflecting plates.
  - 4.2 Vertical deflecting plates.
  - 4.3 Time-base generator.
5. 1,111 *cm*
6. False
7. A power supply consists of high voltage to operate the CRT and low voltage to supply the other electronic circuitry.
8. A function generator is used to supply waveforms to test the operation of electronic circuits.
9. A time-base generator supplies a saw tooth voltage to the horizontal deflection plates of a CRO.
10. Synchronisation causes the display to drift across the screen making measurement difficult.
11. A horizontal amplifier produces two simultaneous output waveforms and applied to the horizontal plates.
12. 2500 *Hz*
13. A cathode-ray oscilloscope (CRO) is a type of electronic test instrument that allows observation of constantly varying signal voltages using the vertical axis, plotted as a function of time on the horizontal axis.
14. The time-base generator controls the rate at which the spot travels across the screen.
15. :
  - 15.1 Square wave
  - 15.2 Sine wave
16. :
  - 16.1 6 *V*
  - 16.2 60  $\mu/v$



### Self-Check

<b>I am able to:</b>	<b>Yes</b>	<b>No</b>
• Describe the following:		
○ Cathode ray tube		
○ Focus method		
○ Deflection method		
○ Accelerating anodes		
• Describe with the help of diagrams and sketches the oscilloscope		
• Describe with the help of diagrams and sketches the function generator		
• Describe right angle, sinusoidal and saw tooth wave forms		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

# Past Examination Papers



**higher education  
& training**

Department:  
Higher Education and Training  
**REPUBLIC OF SOUTH AFRICA**

**NOVEMBER 2015**

NATIONAL CERTIFICATE

**INDUSTRIAL ELECTRONICS N4**

(8080164)

**2 December 2015 (X-Paper)  
09:00 – 12:00**

**This question paper consists of 7 pages and 1 formula sheet of 2 pages.**

**DEPARTMENT OF HIGHER EDUCATION AND TRAINING  
REPUBLIC OF SOUTH AFRICA  
NATIONAL CERTIFICATE  
INDUSTRIAL ELECTRONICS N4  
TIME: 3 HOURS  
MARKS: 100**

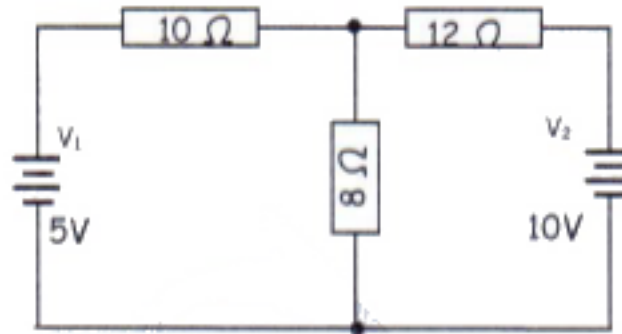
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**INSTRUCTIONS AND INFORMATION**

1. Answer ALL the questions.
  2. Read ALL the questions carefully.
  3. Number the answers according to the numbering system used in this question paper.
  4. Write neatly and legibly.
-

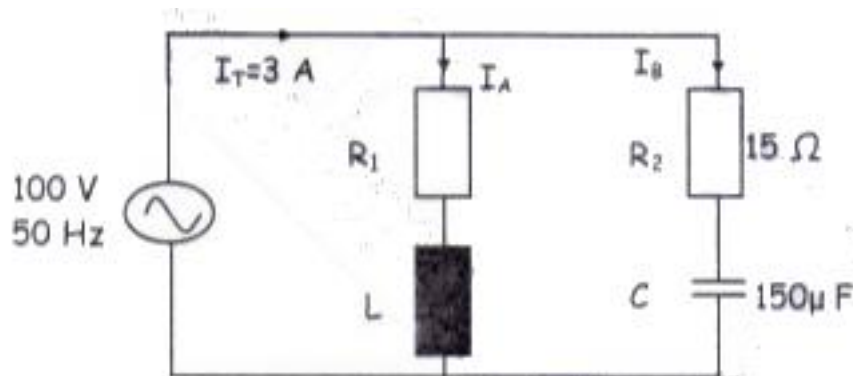
**QUESTION 1:**

- 1.1 Use the superposition method to calculate the current flowing through the  $8\ \Omega$  resistor for the circuit in FIGURE 1 below.

**FIGURE 1****[10]****QUESTION 2:**

Study the circuit diagram below and calculate the following:

- 2.1  $I_A$  (8)  
 2.2  $Z_A$  (2)

**FIGURE 2****[10]****QUESTION 3:**

- 3.1 Give the names of the diodes that match the following descriptions:
- 3.1.1 It permits current to flow in the forward bias direction but it will also flow in the reverse bias when the voltage is above breakdown voltage.
- 3.1.2 It has heavily doped p-type and n-type regions separated by an intrinsic region.
- 3.1.3 Its operation depends on the capacitance that exists at the PN-junction which is reverse biased.
- 3.1.4 It has a negative resistance region where an increase in terminal voltage results in reduction in current of the diode.
- 3.1.5 One of its areas of application is the parametric amplifier. (5 x 1) (5)
- 3.2 Draw a neat, labelled circuit diagram of a power supply using the following components
- A centre-tap transformer
  - Two diodes
  - Two capacitors
  - A resistor
  - A load resistor
- (5 x 1) (5)
- 3.3 A half-wave rectifier has an input voltage of  $200 V_{\text{rms}}$  applied to it.
- Calculate the following:
- 3.3.1  $V_{\text{max}}$  (2)
- 3.3.2  $V_{\text{dc}}$  (2)
- 3.3.3 PIV (1)
- [15]**

#### QUESTION 4:

- 4.1 Give FIVE advantages of the field effect transistor. (5)
- 4.2 A common base amplifier produces an output current change of 5 mA with an input current change of  $3 \mu\text{A}$ . The output voltage changes with 5 V by means of a 3 V input change.
- Calculate the following:
- 4.2.1  $h_{ie}$

4.2.2 hre

4.2.3 hfe

4.2.4 hce

(4 x 2) (8)

- 4.3 Explain what you understand by cross-over distortion in amplifiers. (2)  
[15]

### QUESTION 5:

- 5.1 Give FIVE reasons why operational amplifiers are popular building blocks. (5)

- 5.2 THREE different input voltages must be added by means of a single operational amplifier. (3)

Draw a labelled circuit that would illustrate how this is done.

- 5.3 Calculate the input resistance for an integrator amplifier if  $C=10\ \mu\text{F}$ ,  $V_{in} = 5\ \text{V}$  and the rate of change of the output voltage is  $10\ \text{V/sec}$ . (3)

- 5.4 Draw the operational amplifiers that comply with the following requirements:

5.4.1 The output voltage is related to the rate at which the input voltage changes at a particular instant.

5.4.2 The rate at which the output voltage is related to the value of the input voltage at that instant.

(2 x 2) (4)  
[15]

### QUESTION 6:

- 6.1 Draw a transistor equivalent circuit of an SCR by means of TWO transistors. Also show the anode, cathode and the gate. (5)

- 6.2 Various options are provided as possible answers to the following questions. Choose the answer and write only the letter (A-C) next to the question number (6.2.1-6.2.5) in the ANSWER BOOK.

6.2.1 An application of a(n) ..... is in a lighting system for power interruption.

- A SCR
- B Diac
- C Triac

6.2.2 You need a very efficient thyristor to control the speed of an AC fan motor. A good device to use would be:

- A Diac
- B BJT
- C Triac

6.2.3 The ... can conduct current in either direction and is turned on when a breakdown voltage is exceeded.

- A SCR
- B Diac
- C Quadrac

6.2.4 You have the schematic diagram of several types of circuits.

Which of these circuits most likely uses a triac:

- A An amplifier
- B An AC motor
- C DC motor

6.2.5 You have a need to use a device to trigger an SCR.

A good one to use will be:

- A Diac
- B 4-layer diode
- C LLIF

(5 x 1) (5)

6.3 Explain the purpose of each of the following items in relation to the closed-loop control system.

6.3.1 Reference input

6.3.2 Comparator

6.3.3 Trigger circuit

6.3.4 Feedback loop

6.3.5 Display unit

(5 x 1) (5)  
**[15]**

### QUESTION 7:

7.1 Name THREE aspects that should be considered before a transducer is (3)

selected for a particular application.

- 7.2 Explain, with the aid of a neat, labelled sketch, how an active stress or strain gauge is measured with a Wheatstone bridge. (7)

[10]

**QUESTION 8:**

- 8.1 Describe the purpose of the following controls that appear in the front panel and main control of an oscilloscope.

8.1.1 Time/div (time base control)

8.1.2 Intensity

8.1.3 On/off switch

8.1.4 Volts/div

8.1.5 Horizontal position (5 x 1) (5)

- 8.2 A square wave pulse is displayed on a CRO screen. The time-base control is set at 15 ps/div and 1 cycle is displayed over 4 cm.

Calculate the following:

8.2.1 The period

8.2.2 The frequency (2 x 2) (4)

- 8.3 Give ONE application of a saw-tooth wave form. (1)

[10]

**TOTAL: 100**

## INDUSTRIAL ELECTRONICS N4

## FORMULA SHEET

$$\frac{1}{R_T} = \left( \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n} \right) \quad R_T = \frac{R_1 R_2}{R_1 + R_2} \quad V_2 = \frac{R_2}{R_1 + R_2} \times \frac{V_T}{1}$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad \cos \theta^\circ = \frac{R}{Z} \quad P = I^2 R \quad P = \frac{V^2}{R} \quad P = VI \cos \theta$$

$$P = V \cdot I \quad F_r = \frac{1}{2\pi\sqrt{LC}} \quad Q = \frac{X_L}{R} \quad \text{OF} \quad \frac{1}{R} \sqrt{\frac{L}{C}}$$

$$I_t = \sqrt{I_R^2 + (I_C - I_L)^2} \quad Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_C} - \frac{1}{X_L}\right)^2}} \quad \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

$$V_{rms} = 0,707 V_m \quad i = I_s \left( e^{\frac{qv}{kT}} - 1 \right) \quad R = \frac{kT}{qi} \quad V \cdot R = \frac{V_{SI} - V_{FL}}{V_{FL}}$$

$$V_{av} = 0,637 V_m$$

$$f = \frac{1}{t} \quad \text{Rate of change} = - \frac{V_m}{CR_{in}}$$

$$V_{dc} / V_{gs} = 0,318 V_m$$

$$V_{dc} / V_{gs} = 0,637 V_m$$

$$V_{rms} / V_{r_{wgk}} = 0,385 V_m$$

$$PIV = V_m \quad \text{or/of} \quad 2 V_m$$

$$V_{rms} / V_{r_{wgk}} = \frac{V_r (p - p)}{2\sqrt{3}}$$

$$V_{dc} / V_{gs} = V_m - \frac{V_r (p - p)}{2}$$

$$r = \frac{V_{rms} / V_{r_{wgk}}}{V_{dc} / V_{gs}}$$

$$V_{rms} / V_{r_{wgk}} = \frac{V_{dc} / V_{gs}}{R_L 2\sqrt{3} FC}$$

$$V_{dc} / V_{gs} = V_m \frac{I_{dc} / I_{gs}}{2FC}$$

$$r = \frac{I_{dc} / I_{gs}}{V_{dc} / V_{gs} 2\sqrt{3} FC}$$

$$V_{r_{rms}} / V_{r'_{wgk}} = \frac{X_C}{\sqrt{R^2 + X_C^2}} \times \frac{V_{rms} / V_{r_{wgk}}}{1}$$

$$V'_{dc} / V'_{gs} = \frac{R_L}{R_L + R_S} \times \frac{V_{dc} / V_{gs}}{1}$$

$$V_{r_{rms}} / V_{r'_{wgk}} = \frac{V_{rms} / V_{r_{wgk}}}{(2\pi f)^2 LC}$$

$$R_{in} = \frac{V_{be}}{I_b} \quad R_{out} = \frac{V_{ce}}{I_c} \quad R_c = \frac{V_{cc}}{I_c} \quad V_{out} = R_c C \frac{dv_i}{dt}$$

$$\text{Static current gain} = \frac{I_{out}}{I_{in}}$$

$$\text{Dynamic current gain} = \frac{\Delta I_{out}}{\Delta I_{in}}$$

$$V_{cc} = V_{RC} + V_{ce} \quad V_{ce} = V_{ce} - V_{RC} \quad R = \frac{\rho \ell}{a}$$

$$A_p = 10 \log \frac{P_{out}}{P_{in}} \quad A_v = 20 \log \frac{V_{out}}{V_{in}} \quad A_i = 20 \log \frac{I_{out}}{I_{in}}$$

$$\text{Static voltage gain} = \frac{V_{out}}{V_{in}}$$

$$\text{Dynamic voltage gain} = \frac{\Delta V_{out}}{\Delta V_{in}}$$

$$h_{ie} = \frac{\Delta V_{in}}{\Delta I_{in}} = \frac{\Delta V_{be}}{\Delta I_b} \quad V_{ce} = \text{constant}$$

$$h_{re} = \frac{\Delta V_{in}}{\Delta V_{out}} = \frac{\Delta V_{be}}{\Delta V_{ce}} \quad I_b = \text{constant}$$

$$h_{fe} = \frac{\Delta I_{out}}{\Delta I_{in}} = \frac{\Delta I_c}{\Delta I_b} \quad V_{ce} = \text{constant}$$

$$h_{oe} = \frac{\Delta I_{out}}{\Delta V_{out}} = \frac{\Delta I_c}{\Delta V_{ce}} \quad I_b = \text{constant}$$

$$V_{out} = \frac{R_f}{R_{in}} \times V_{in} \quad V_{out} = - \left( \frac{R_f V_1}{R_1} + \frac{R_f V_2}{R_2} + \dots + \frac{V_n R_f}{R_n} \right)$$

$$V_{out} = \left( 1 + \frac{R_f}{R_{in}} \right) V_{in} \quad V_{out} = - \frac{1}{CR_{in}} \int V_{in}(t) dt$$

Boltzmann's constant =  $1,38 \times 10^{-23} \text{ J/k}$

Electron charge =  $1,6 \times 10^{-19} \text{ C}$

NB: Any applicable formula may be used.

# Marking Guidelines



higher education  
& training

Department:  
Higher Education and Training  
**REPUBLIC OF SOUTH AFRICA**

**NOVEMBER 2015**

NATIONAL CERTIFICATE

**INDUSTRIAL ELECTRONICS N4**

(8080164)

**2 December 2015 (X-Paper)**  
**09:00 – 12:00**

**QUESTION 1**

1.1 Short circuit  $V_1$

$$R_{pA} = \frac{10 \times 8}{10 + 8} = 4,444 \Omega \checkmark$$

$$R_{SA} = 4,444 + 12 = 16,444 \Omega$$

$$I_{TA} = \frac{V_1}{R_{SA}}$$

$$= \frac{5}{16,444}$$

$$= 0,304 \text{ A } \checkmark$$

$$I_{8QA} = \frac{12}{12 + 8} \times 0,304 \checkmark$$

$$= 0,182 \text{ A } \checkmark$$

$$I_{8QT} = 0,182 + 0,376 \checkmark$$

$$= 0,558 \text{ A } \checkmark$$

Short circuit  $V_2$

$$R_{pB} = \frac{8 \times 12}{8 + 12} = 4,8 \Omega \checkmark$$

$$R_{SB} = 4,8 + 10 = 14,8 \Omega$$

$$I_{TB} = \frac{V_2}{R_{SB}}$$

$$= \frac{10}{14,8}$$

$$= 0,676 \text{ A } \checkmark$$

$$I_{8QB} = \frac{10}{10 + 8} \times 0,676 \checkmark$$

$$= 0,376 \text{ A } \checkmark$$

[10]

## QUESTION 2

$$2.1 \quad X_C = \frac{1}{2\pi fC} = \frac{1}{2 \times \pi \times 50 \times 150 \times 10^{-6}} \checkmark$$

$$= 21,218 \, \Omega \checkmark$$

$$Z_B = R - jX_C$$

$$= 15 - j21,218 \checkmark$$

$$= 25,985 \angle -54,7^\circ \checkmark$$

$$I_B = \frac{V_T}{Z_B} = \frac{100 \angle 0^\circ}{25,985 \angle -54,7^\circ} \checkmark$$

$$= 3,848 \angle 54,7^\circ \checkmark$$

$$= 2,224 + j3,14$$

$$I_A = I_T - I_B$$

$$= (3 + j0) - (2,224 + j3,14) \checkmark$$

$$= 0,776 - j3,14$$

$$= 3,234 \angle -76,1^\circ \checkmark$$

(8)

$$2.2 \quad Z_A = \frac{V_T}{I_A} = \frac{100 \angle 0^\circ}{3,234 \angle -76,1^\circ} \checkmark$$

$$= 30,921 \angle 76,1^\circ \, \Omega \checkmark$$

(2)  
[10]

## QUESTION 3

3.1 3.1.1 Zener diode ✓

3.1.2 PN-junction diode ✓

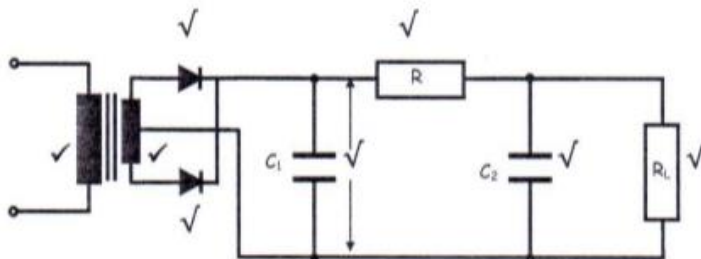
3.1.3 Varactor diode ✓

3.1.4 Tunnel diode ✓

3.1.5 Varactor ✓

(5 x 1) (5)

3.2



(5)

3.3 3.3.1  $V_m = \sqrt{2} V_{rms}$   
 $= 1,414 \times 200$  ✓  
 $= 282,8 \text{ V}$  ✓

(2)

3.3.2  $V_{dc} = \frac{V_m}{\pi} = \frac{282,8}{\pi}$  ✓  
 $= 90,006 \text{ V}$  ✓

(2)

3.3.3  $PIV = V_m$   
 $= 282,8 \text{ V}$  ✓

(1)  
[15]

## QUESTION 4

- 4.1
- Less noisy than the bipolar transistors
  - Very high input resistance
  - Relatively unaffected by radiation
  - Considerable thermal stability
  - No offset voltage when used as a switch
- (5 x 1) (5)

4.2 4.2.1

$$h_{ie} = \frac{\Delta V_{bc}}{\Delta I_b} = \frac{3}{3 \times 10^{-6}} \checkmark$$

$$= 1 \text{ M}\Omega \checkmark$$

4.2 4.2.2

$$h_{re} = \frac{\Delta V_{be}}{\Delta V_{ce}} = \frac{3}{5} \checkmark$$

$$= 0,6 \checkmark$$

4.2.3

$$h_{fe} = \frac{\Delta I_c}{\Delta I_b} = \frac{5 \times 10^{-3}}{3 \times 10^{-6}} \checkmark$$

$$= 1\,666,667 \checkmark$$

4.2.4

$$h_{oe} = \frac{\Delta I_c}{\Delta V_{ce}} = \frac{5 \times 10^{-3}}{5} \checkmark$$

$$= 0,001 \checkmark$$

(4 x 2) (8)

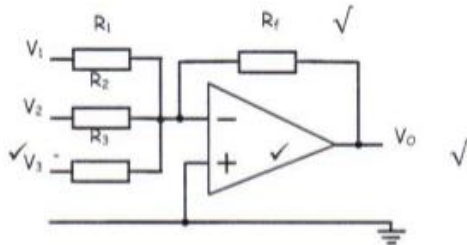
- 4.3 It occurs during the period when one transistor starts to switch off and the other one starts to switch on. ✓
- (2)  
[15]

**QUESTION 5**

- 5.1
- Cheap
  - Small size
  - Highly stable
  - Low power consumption
  - Highly reliable

(5 x 1) (5)

5.2



(3)

5.3

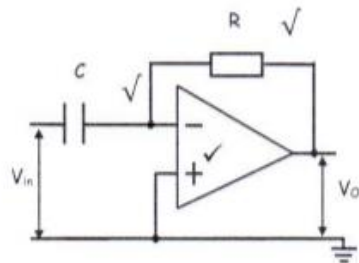
$$\text{Rate of change} = \frac{V_{in}}{CR_{in}}$$

$$50 = \frac{5}{10 \times 10^{-6} \times R_{in}} \quad \checkmark \checkmark$$

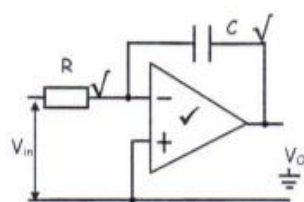
$$R_{in} = 10 \text{ k}\Omega \quad \checkmark$$

(3)

5.4 5.4.1



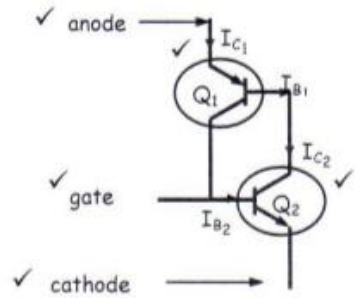
5.4.2



(2 x 2) (4)  
[15]

**QUESTION 6**

6.1



(5)

6.2

- 6.2.1 A
- 6.2.2 C
- 6.2.3 C
- 6.2.4 B
- 6.2.5 C

(5 x 1) (5)

6.3

- 6.3.1 The desired value is set at the reference input.
- 6.2.2 Compares the output with the actual condition.
- 6.2.3 Triggers the SCR.
- 6.2.4 Detects the process variable.
- 6.2.5 Displays the output.

(5 x 1) (5)  
[15]

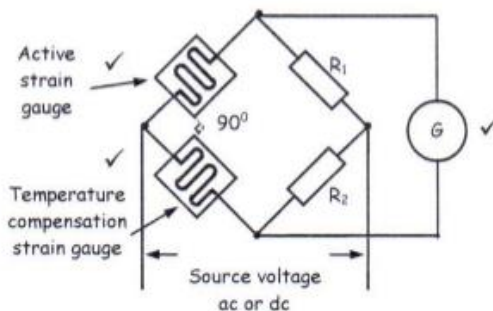
**QUESTION 7**

7.1

- Accuracy required ✓
- The environment in which the transducer will be used ✓
- The physical quantity to be measured ✓
- The type of supply that is available (AC or DC) ✓
- The converting principle which is most suitable

(Any 3 x 1) (3)

7.2



(3)

- If there is no pressure applied to the active gauge, the bridge will be balanced and the output in the galvanometer will be zero.
- If pressure is applied in the active gauge, the bridge will be out of balance due to the change in length and thus in the area and resistance.
- The compensation gauge will prevent false observation due to temperature variations.
- The change that has taken place can now be read in a galvanometer.

(4)  
[10]



# Past Examination Papers



**higher education  
& training**

Department:  
Higher Education and Training  
**REPUBLIC OF SOUTH AFRICA**

**AUGUST 2015**

NATIONAL CERTIFICATE

**INDUSTRIAL ELECTRONICS N4**

(8080164)

**28 July 2015 (Y-Paper)  
13:00 – 16:00**

**This question paper consists of 6 pages and a formula sheet of 2 pages.**

**DEPARTMENT OF HIGHER EDUCATION AND TRAINING  
REPUBLIC OF SOUTH AFRICA  
NATIONAL CERTIFICATE  
INDUSTRIAL ELECTRONICS N4  
TIME: 3 HOURS  
MARKS: 100**

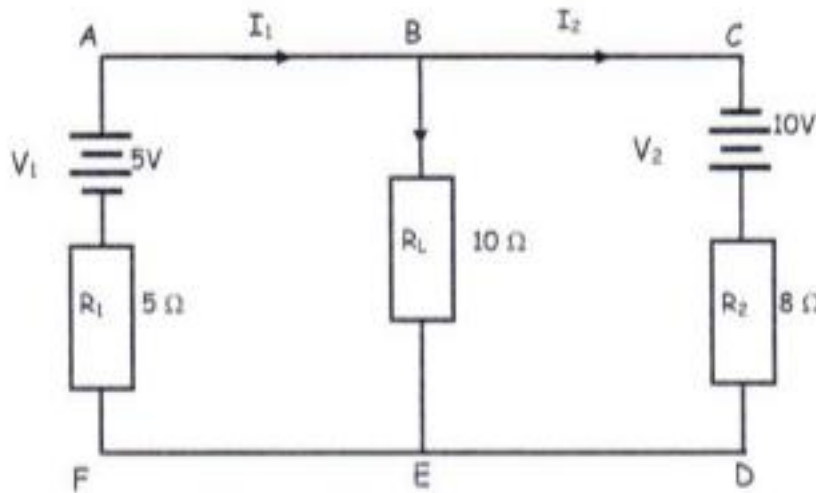
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**INSTRUCTIONS AND INFORMATION**

5. Answer ALL the questions.
  6. Read ALL the questions carefully.
  7. Number the answers according to the numbering system used in this question paper.
  8. Write neatly and legibly.
-

**QUESTION 1:**

- 1.1 Use Kirchhoff's law to calculate the current flowing through  $R_L$  in FIGURE 1 below. ( )

**FIGURE 1****[10]****QUESTION 2:**

- 2.1 The following values were calculated from an RLC circuit. (4)

Draw a neat, labelled phasor diagram of the following circuit.

- $I_1 = 20,85 \angle -30^\circ A$
- $I_2 = 15 \angle 110^\circ A$
- $I_T = 12,64 \angle 16^\circ A$

- 2.2 Various options are given as possible answers to the following questions. Choose the answer and write only the letter (A—C) next to the question number (2.2.1-2.2.3) in the ANSWER BOOK.

2.2.1 How much current will flow in a 50 Hz series RLC circuit if  $V_s = 10$  V,  $R_T = 60 \Omega$  and  $X_T = 50 \Omega$ ?

- A 0,5 A
- B 0,128 A
- C 0,345 A

2.2.2 What is the current-phase angle for a parallel-RLC circuit when  $I_L = 2,162$  A,  $I_C = 5$  A and  $I_R = 3$  A?

- A 2°
- B 1°
- C 3°

2.2.3 The Q-factor of a circuit will be ... if  $X_L = X_C = 1\ 500\ \Omega$  and the resistor value is  $15\ \Omega$ .

- A 120
- B 200
- C 100

(2 x 3) (6)  
[10]

### QUESTION 3:

3.1 Draw a neat symbol and a characteristic curve of a tunnel diode. Name also ONE of its applications. (5)

3.2 The output voltage across the second capacitor of a half-wave LC- $\pi$ -filter is 60 V DC.

The ripple voltage across the first capacitor is 10 V at a frequency of 100 Hz. When  $L = 3\ \text{H}$ ,  $R = 200\ \Omega$ ,  $C_2 = 5\ \mu\text{F}$  and  $R_L = 5\ \text{k}\Omega$ , calculate the following:

3.2.1 The output voltage across the first capacitor (2)

3.2.2 The ripple voltage across the second capacitor (3)

3.3 State FIVE differences between a bridge-rectifier circuit and two diodes with a centre-tap transformer circuit. (5)

[15]

### QUESTION 4:

4.1 Draw a circuit diagram to illustrate how a UJT can be used to trigger an SCR. (5)

4.2 The following information is given for an amplifier:

- Input power = 500 mW
- Input voltage = 15 V
- Output power = 450 W
- Output impedance = 150

Calculate the following:

4.2.1 Power gain in dB (2)

4.2.2 Voltage gain in dB (4)

4.2.3 Current gain in dB (4)

**[15]****QUESTION 5:**

5.1 Draw a neat, labelled pin layout for a 741 DIL 8-pin operational amplifier. (5)

5.2 The input voltage of a non-inverting amplifier is 0,5 V and the output voltage is 4 V. (5)

Calculate the value of the feedback resistance needed to be connected if the input resistance is 2 k $\Omega$ .

5.3 Indicate whether the following statements are TRUE or FALSE. Choose the correct answer and write only 'true' or 'false' next to the question number (5.3.1-5.3.4) in the ANSWER BOOK.

5.3.1 The basic operational amplifier is noted by the input terminals + and — signs. These are polarity signs. (1)

5.3.2 The output voltage of an inverting amplifier will be 3 V if the feedback resistor is 10 k $\Omega$ ,  $R_{in}$ , is 1 k $\Omega$  and the input voltage is 0,3 V. (2)

5.3.3 A comparator amplifier uses a negative feedback (1)

5.3.4 Operational amplifier is insensitive to temperature. (1)

**[15]****QUESTION 6:**

6.1 Illustrate, with the aid of a labelled characteristic curve, the principle of operation of the following thyristors:

6.1.1 LASCR

6.1.2 Quadrac

(3 x 2) (6)

6.2 Choose a description from COLUMN B that matches an item in COLUMN A. Write only the letter (A—E) next to the question number (6.2.1-6.2.5) in the ANSWER BOOK.

COLUMN A	COLUMN B
6.2.1 LASCR	A it is a four-layer p-n-p-n device
6.2.2 Diac	B it a multilayer three-terminal bi-directional semi-conductor device
6.2.3 Triac	C it is a bi-directional trigger diode

6.2.4 SCR	D it is basically a triac and a diac combined together in a single package
6.2.5 Quadrac	E it is basically a conventional SCR that turns on by Incident light

(5 x 1) (5)

6.3 Explain the following terms:

6.3.1 Open-loop system

6.3.2 Closed-loop system

(2 x 2) (4)

**[15]****QUESTION 7:**7.1 Define the term *transducer*. (2)

7.2 Name TWO quantities that can be measured with the aid of a LVDT. (2)

7.3 Show by means of a neat, labelled diagram of a transducer how you would measure temperature with a thermistor. Also state the purpose of the compensation gauge used in a circuit. (6)

**[10]****QUESTION 8:**

8.1 Draw a neat, labelled block diagram of a cathode-ray-tube. (5)

8.2 An oscilloscope displays a sine wave over 2 vertical divisions and 4 horizontal divisions. The vertical amplifier setting is 0,3 V/div and the time-base is at 2  $\mu\text{sec/div}$ .

Calculate the following:

8.2.1 The amplitude (2)

8.2.2 The peak-to-peak value (1)

8.2.3 The average value (2)

**[10]****TOTAL: 100**

## INDUSTRIAL ELECTRONICS N4

## FORMULA SHEET

$$\frac{1}{R_T} = \left( \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n} \right) \quad R_T = \frac{R_1 R_2}{R_1 + R_2} \quad V_2 = \frac{R_2}{R_1 + R_2} \times \frac{V_T}{1}$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad \cos \theta^\circ = \frac{R}{Z} \quad P = I^2 R \quad P = \frac{V^2}{R} \quad P = VI \cos \theta$$

$$P = V \cdot I \quad F_r = \frac{1}{2\pi\sqrt{LC}} \quad Q = \frac{X_L}{R} \quad \text{OF} \quad \frac{1}{R} \sqrt{\frac{L}{C}}$$

$$I_t = \sqrt{I_R^2 + (I_C - I_L)^2} \quad Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_C} - \frac{1}{X_L}\right)^2}} \quad \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

$$V_{rms} = 0,707 V_m \quad i = I_s \left( e^{\frac{qv}{kT}} - 1 \right) \quad R = \frac{kT}{qi} \quad V \cdot R = \frac{V_{SI} - V_{FL}}{V_{FL}}$$

$$V_{av} = 0,637 V_m$$

$$f = \frac{1}{t} \quad \text{Rate of change} = - \frac{V_m}{CR_{in}}$$

$$V_{dc} / V_{gs} = 0,318 V_m$$

$$V_{dc} / V_{gs} = 0,637 V_m$$

$$V_{rms} / V_{r_{wgk}} = 0,385 V_m$$

$$PIV = V_m \quad \text{or/of} \quad 2 V_m$$

$$V_{rms} / V_{r_{wgk}} = \frac{V_r (p - p)}{2\sqrt{3}}$$

$$V_{dc} / V_{gs} = V_m - \frac{V_r (p - p)}{2}$$

$$r = \frac{V_{rms} / V_{r_{wgk}}}{V_{dc} / V_{gs}}$$

$$V_{rms} / V_{r_{wgk}} = \frac{V_{dc} / V_{gs}}{R_L 2\sqrt{3} FC}$$

$$V_{dc} / V_{gs} = V_m \frac{I_{dc} / I_{gs}}{2FC}$$

$$r = \frac{I_{dc} / I_{gs}}{V_{dc} / V_{gs} 2\sqrt{3} FC}$$

$$V_{r_{rms}} / V_{r'_{wgk}} = \frac{X_C}{\sqrt{R^2 + X_C^2}} \times \frac{V_{rms} / V_{r_{wgk}}}{1}$$

$$V'_{dc} / V'_{gs} = \frac{R_L}{R_L + R_S} \times \frac{V_{dc} / V_{gs}}{1}$$

$$V'_{r_{rms}} / V'_{r'_{wgk}} = \frac{V_{rms} / V_{r_{wgk}}}{(2\pi f)^2 LC}$$

$$R_{in} = \frac{V_{be}}{I_b} \quad R_{out} = \frac{V_{ce}}{I_c} \quad R_c = \frac{V_{cc}}{I_c} \quad V_{out} = R_c C \frac{dv_i}{dt}$$

$$\text{Static current gain} = \frac{I_{out}}{I_{in}}$$

$$\text{Dynamic current gain} = \frac{\Delta I_{out}}{\Delta I_{in}}$$

$$V_{cc} = V_{RC} + V_{ce} \quad V_{ce} = V_{ce} - V_{RC} \quad R = \frac{\rho \ell}{a}$$

$$A_p = 10 \log \frac{P_{out}}{P_{in}} \quad A_v = 20 \log \frac{V_{out}}{V_{in}} \quad A_i = 20 \log \frac{I_{out}}{I_{in}}$$

$$\text{Static voltage gain} = \frac{V_{out}}{V_{in}}$$

$$\text{Dynamic voltage gain} = \frac{\Delta V_{out}}{\Delta V_{in}}$$

$$h_{ie} = \frac{\Delta V_{in}}{\Delta I_{in}} = \frac{\Delta V_{be}}{\Delta I_b} \quad V_{ce} = \text{constant}$$

$$h_{re} = \frac{\Delta V_{in}}{\Delta V_{out}} = \frac{\Delta V_{be}}{\Delta V_{ce}} \quad I_b = \text{constant}$$

$$h_{fe} = \frac{\Delta I_{out}}{\Delta I_{in}} = \frac{\Delta I_c}{\Delta I_b} \quad V_{ce} = \text{constant}$$

$$h_{oe} = \frac{\Delta I_{out}}{\Delta V_{out}} = \frac{\Delta I_c}{\Delta V_{ce}} \quad I_b = \text{constant}$$

$$V_{out} = \frac{R_f}{R_{in}} \times V_{in} \quad V_{out} = - \left( \frac{R_f V_1}{R_1} + \frac{R_f V_2}{R_2} + \dots + \frac{V_n R_f}{R_n} \right)$$

$$V_{out} = \left( 1 + \frac{R_f}{R_{in}} \right) V_{in} \quad V_{out} = - \frac{1}{CR_{in}} \int V_{in}(t) dt$$

Boltzmann's constant =  $1,38 \times 10^{-23} \text{ J/k}$

Electron charge =  $1,6 \times 10^{-19} \text{ C}$

NB: Any applicable formula may be used.

# Marking Guidelines



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**AUGUST 2015**

NATIONAL CERTIFICATE

**INDUSTRIAL ELECTRONICS N4**

(8080164)

**28 July 2015 (Y-Paper)  
13:00 – 16:00**

**QUESTION 1**

1.1 Consider loop ABEFA

$$V_1 = I_1 R_1 + (I_1 - I_2)$$

$$5 = 5I_1 + 10I_1 - 10I_2 \checkmark$$

$$= 15I_1 - 10I_2 \checkmark$$

(2)

Consider loop CDEBC

$$V_2 = I_2 R_2 - (I_1 - I_2) R_L$$

$$10 = 8I_2 - 10I_1 + 10I_2 \checkmark$$

$$= -10I_1 + 18I_2 \checkmark$$

(2)

$$(1) \times 10: 50 = 150I_1 - 100I_2 \checkmark$$

(2)

$$(2) \times 15: 150 = 150I_1 + 270I_2 \checkmark$$

$$(3) + (4): 200 = 170I_2$$

$$I_2 = 1,176 \text{ A} \checkmark$$

(1)

Substitute  $I_2$  in (1)

$$5 = 15I_1 - 10(1,176)$$

$$16,76 = 15I_1 \checkmark$$

$$I_1 = 1,117 \text{ A} \checkmark$$

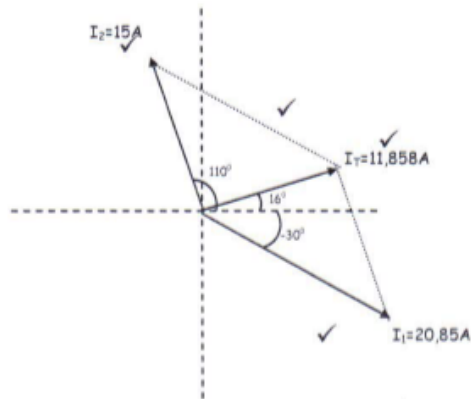
$$I_1 - I_2 = 1,117 - 1,176$$

$$= -0,059 \text{ A} \checkmark$$

(3)  
[10]

**QUESTION 2**

2.1



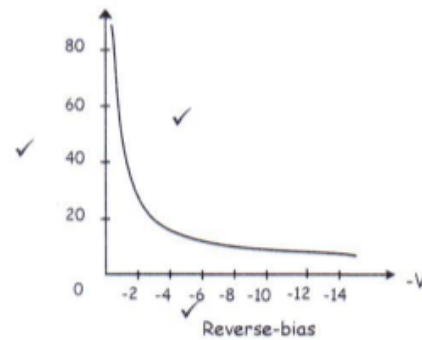
(4)

- 2.2    2.2.1    B
- 2.2.2    B
- 2.2.3    C

(2 x 3)    (6)  
[10]

**QUESTION 3**

3.1



Characteristic curve

Computers ✓

(5)

3.2    3.2.1     $V'_{dc} = \frac{R_L}{R_L + R} \times V_{dc}$

$$60 = \frac{5\,000}{5\,000 + 200} \times V_{dc} \checkmark$$

$$V_{dc} = 62,4 \text{ V } \checkmark$$

(2)

3.2.2

$$V_r (rms) = \frac{V_{r(rms)}}{4\pi^2 f^2 LC}$$

$$= \frac{10}{4\pi^2 \times 100^2 \times 3 \times 5 \times 10^{-6}} \checkmark \checkmark$$

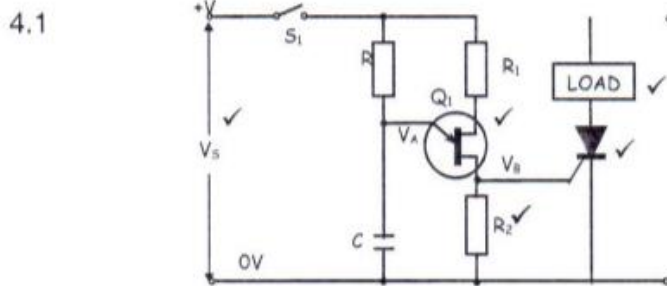
$$= 1,689 \text{ V } \checkmark \quad (3)$$

3.3

Bridge rectifier circuit	Centre-tap circuit
Four diodes	Two diodes
Forward voltage drop is double that of centre-tap.	Forward voltage drop is half that of a bridge.
PIV is equals maximum voltage	PIV is twice the maximum voltage
Full wave is achieved without a centre-tap	Need a centre-tap to achieve full wave
Can be directly supplied from the ac	The supply is always via the centre-tap transformer

(5 x 1) (5)  
[15]

QUESTION 4



(5)

4.2 4.2.1

$$A_p = 10 \log \frac{P_o}{P_{in}}$$

$$= 10 \log \frac{450}{500 \times 10^{-3}} \checkmark$$

$$= 29,542 \text{ dB } \checkmark \quad (2)$$

$$4.2.2 \quad P_o = I_o^2 \times Z_o$$

$$450 = I_o^2 \times 15$$

$$I_o = 5,477 \text{ A } \checkmark$$

$$V_o = I_o \times Z_o$$

$$= 5,477 \times 15$$

$$= 82,158 \text{ V } \checkmark$$

$$A_V = 20 \log \frac{V_o}{V_{in}}$$

$$= 20 \log \frac{82,158}{15} \checkmark$$

$$= 14,771 \checkmark$$

(4)

4.2.3

$$I_{in} = \frac{P_{in}}{V_{in}} = \frac{500 \times 10^{-3}}{15} \checkmark$$

$$= 0,033 \text{ A } \checkmark$$

$$A_i = 20 \log \frac{I_o}{I_{in}}$$

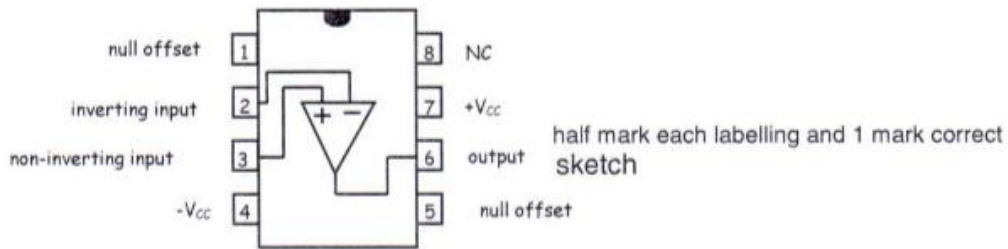
$$= 20 \log \frac{5,477}{0,033} \checkmark$$

$$= 44,401 \text{ dB } \checkmark$$

(4)  
[15]

**QUESTION 5**

5.1



(5)

5.2

$$V_o = \text{gain} \times V_{in}$$

$$4 = \text{gain} \times 0,5 \checkmark$$

$$\text{gain} = 8 \text{ V} \checkmark$$

$$\text{gain} = 1 + \frac{R_f}{R_{in}}$$

$$8 = 1 + \frac{R_f}{2\ 000} \checkmark$$

$$7 = \frac{R_f}{2000} \checkmark$$

$$R_f = 14 \text{ k}\Omega \checkmark$$

(5)

5.3

- 5.3.1 False ✓
- 5.3.2 True ✓✓
- 5.3.3 False ✓
- 5.3.4 True ✓

(1)

(2)

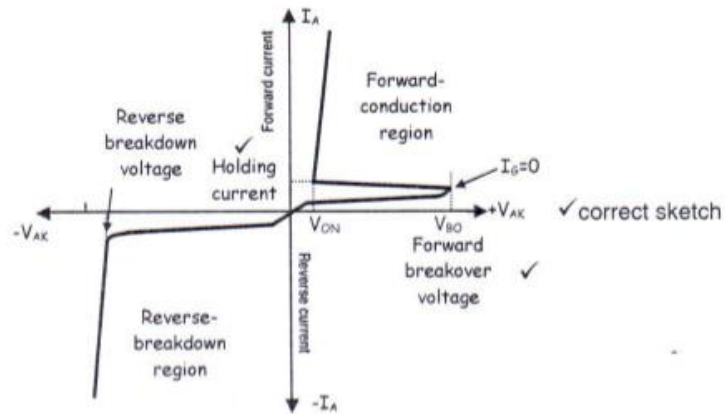
(1)

(1)

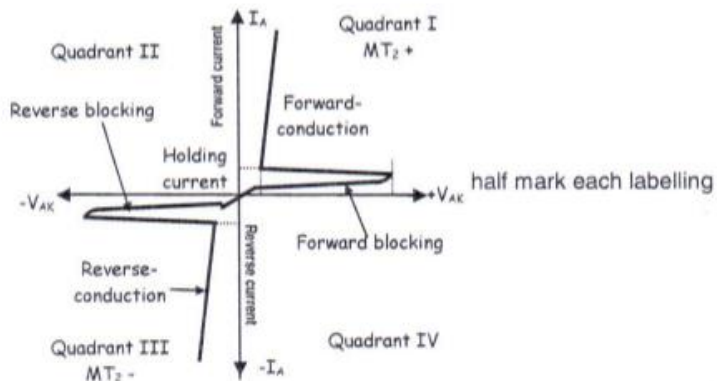
[15]

QUESTION 6

6.1 6.1.1



6.1.2 6.1.2



(3 x 2) (6)

- 6.2 6.2.1 E
- 6.2.2 C
- 6.2.3 B
- 6.2.4 A
- 6.2.5 D

(5 x 1) (5)

6.3 6.3.1 It is an amplifier without feedback and it doesn't have a comparator. ✓✓

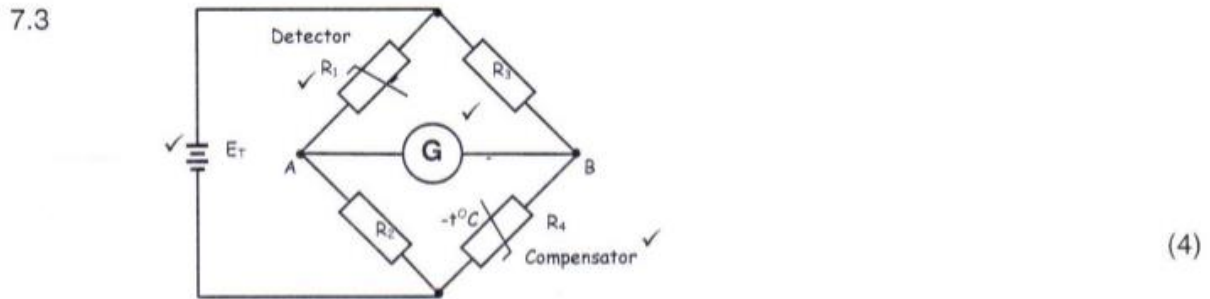
6.3.2 It is an amplifier with feedback and has a comparator. ✓✓

(2 x 2) (4)  
[15]

**QUESTION 7**

7.1 It is a device that converts non-electrical physical parameters into electrical signal ✓✓ (2)

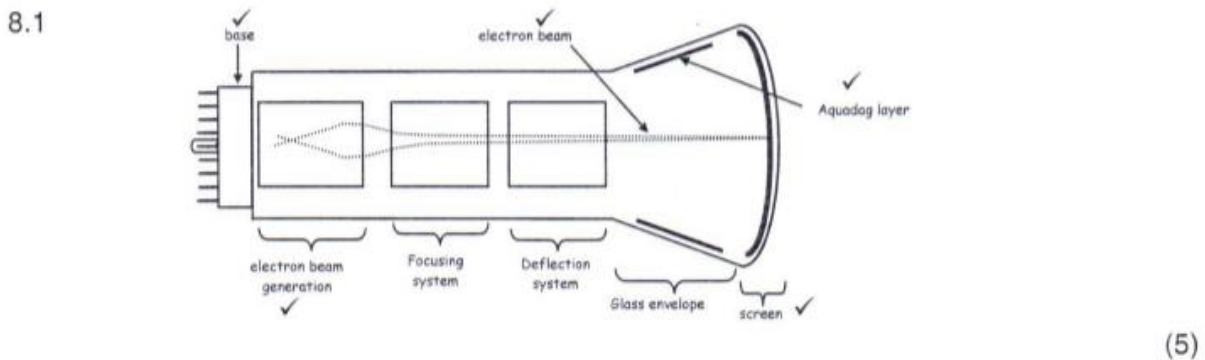
- 7.2
- Force ✓
  - Displacement ✓
- (2)



The compensation gauge prevents false observation due to temperature variations. ✓✓ (2)

**[10]**

**QUESTION 8**



8.2 8.2.1 Amplitude = no of divisions x V/div  
 = 2 x 0,3 ✓  
 = 0,6 V ✓ (2)

8.2.2  $V_{p-p} = \text{no.of divisions} \times V/\text{div}$

$$= 4 \times 0,3$$

$$= 1,2 \text{ V} \checkmark$$

(1)

8.2.3  $V_{ave} = 0,637 \times V_p$

$$= 0,637 \times 0,6 \checkmark$$

$$= 0,382 \text{ V} \checkmark$$

(2)

[10]

**TOTAL: 100**

# Past Examination Papers



**higher education  
& training**

Department:  
Higher Education and Training  
**REPUBLIC OF SOUTH AFRICA**

**APRIL 2015**

**NATIONAL CERTIFICATE**

**INDUSTRIAL ELECTRONICS N4**

(8080164)

**10 April 2015 (Y-Paper)  
13:00 – 16:00**

**This question paper consists of 6 pages and 1 formula sheet.**

**DEPARTMENT OF HIGHER EDUCATION AND TRAINING  
REPUBLIC OF SOUTH AFRICA  
NATIONAL CERTIFICATE  
INDUSTRIAL ELECTRONICS N4  
TIME: 3 HOURS  
MARKS: 100**

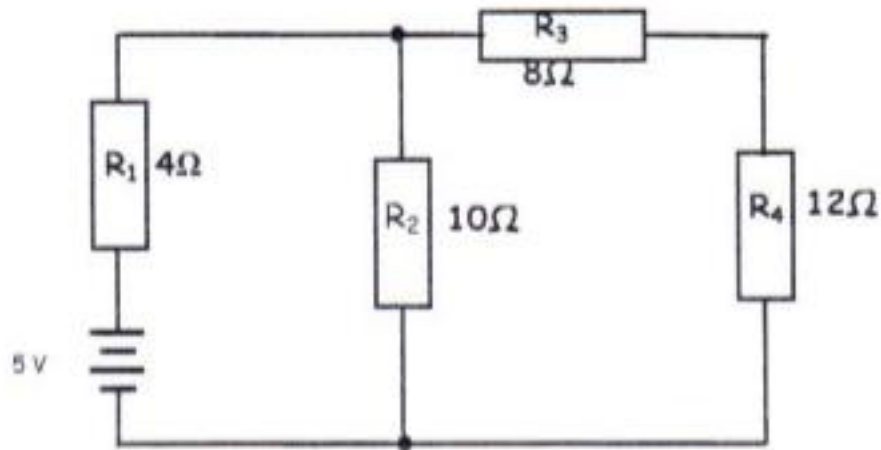
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**INSTRUCTIONS AND INFORMATION**

9. Answer ALL the questions.
  10. Read ALL the questions carefully.
  11. Number the answers according to the numbering system used in this question paper.
  12. Start each answer on a NEW page.
  13. ALL calculations must be shown.
  14. ALL final answers must be approximated accurately to THREE decimal places.
  15. Write neatly and legibly.
-

**QUESTION 1:**

- 1.1 Use Thevenin's method to determine the current flowing through  $R_4$  in FIGURE 1 below.

**FIGURE 1****[10]****QUESTION 2:**

A coil of  $200\ \Omega$  resistance and  $100\ \mu\text{H}$  inductance are connected in parallel with a variable capacitor across a  $5\ \text{V}$ ,  $1\ \text{MHz}$  AC supply.

Calculate the following:

- 2.1 The capacitance of the capacitor when the supply current is at minimum. (5)
- 2.2 The dynamic impedance. (3)
- 2.3 The supply current. (2)

**[10]****QUESTION 3:**

- 3.1 Draw a circuit diagram of a varactor diode used in tuning circuits and give THREE of its areas of application. (6)

3.2

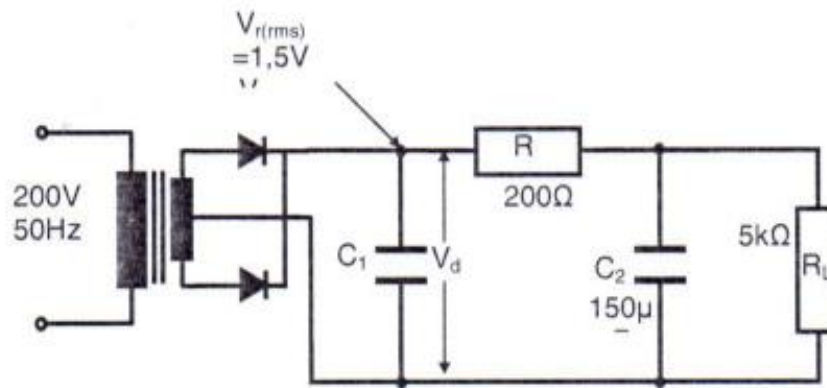


FIGURE 2

Consider the circuit diagram shown in FIGURE 2 above and calculate the following:

- 3.2.1 The output DC voltage (3)
- 3.2.2 The output ripple voltage (4)
- 3.2.3 The output ripple factor (2)

**[15]****QUESTION 4:**

- 4.1 Draw a neat labelled symbol and characteristic curve of P-channel depletion MOSFET. (5)
- 4.2 The following dynamic values of a common emitter amplifier are given:
- $V_{be} = 0,67 \text{ V}$  and  $0,69 \text{ V}$
  - $I_c = 1 \text{ mA}$  and  $3 \text{ mA}$
  - $V_{ce} = 5 \text{ V}$  and  $15 \text{ V}$
  - $I_b = 10 \mu\text{A}$  and  $30 \mu\text{A}$

Calculate the following:

- 4.2.1 The dynamic forward current gain (2)
- 4.2.2 The dynamic input impedance (3)
- 4.2.3 The dynamic reverse voltage gain (2)
- 4.2.4 The dynamic output impedance (3)

**[15]****QUESTION 5:**

- 5.1 Draw a neat circuit symbol of an operational amplifier. (2)

- 5.2 How can the gain of an operational amplifier be changed? (2)
- 5.3 Name THREE operational amplifiers that use negative feedback. (3)
- 5.4 Consider FIGURE 3 below and answer the questions that follow:

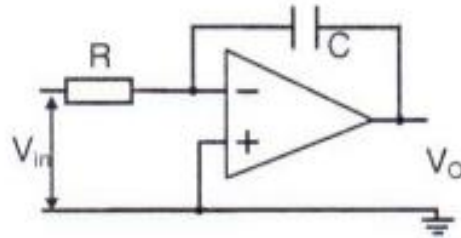


FIGURE 3

- 5.4.1 Identify the operational amplifier. (1)
- 5.4.2 Draw a 3600 input sine wave form and the expected output waveform. (3)
- 5.4.3 Calculate the resistance if  $C = 15 \text{ pF}$ ,  $V_{in} = 10 \text{ V}$  and the rate of change of the output voltage =  $0,6 \text{ V/sec}$ . (4)

**[15]****QUESTION 6:**

- 6.1 Draw neat, labelled symbols of the following Thyristors:
- 6.1.1 SCR
- 6.1.2 Triac
- 6.1.3 LASCR
- 6.1.4 Diac
- 6.1.5 QUADRAC (5 x 2) (10)
- 6.2 Give THREE differences between the open-loop and closed-loop control systems. (3)
- 6.3 What is the purpose of the diode in the gate of an SCR? (3)

**[15]****QUESTION 7:**

- 7.1 Use a circuit diagram to indicate how a photo-diode can be used in an emitter-coupled amplifier to secure a dangerous area. (4)
- 7.2 Name THREE convention methods by means of transducers. (3)
- 7.3 Explain the basic operating principle of a strain gauge. Also give the formula that describes the principle of its operation. (3)

**[10]****QUESTION 8:**

- 8.1 With reference to the oscilloscope, which circuit would you investigate if:
- 8.1.1 The oscilloscope is turned on and there is no horizontal trace but only a spot of light on the screen?
- 8.1.2 There is a horizontal trace on the screen but no vertical deflection when a sine wave is applied?
- 8.1.3 It is impossible to stabilize the signal display? (3 x 2) (6)
- 8.2 Calculate the width of one cycle of the sine wave if the frequency of the signal is 15 kHz in an oscilloscope at the scale setting of 60 psec/cm. (3)
- 8.3 Indicate whether the following statement is TRUE or FALSE. Choose the answer and write only 'true' or 'false' next to the question number (8.3) in the ANSWER BOOK. (1)

One application of a square wave is in timing circuits in digital electronics.

**[10]****TOTAL: 100**

## INDUSTRIAL ELECTRONICS N4

## FORMULA SHEET

$$\frac{1}{R_T} = \left( \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n} \right) \quad R_T = \frac{R_1 R_2}{R_1 + R_2} \quad V_2 = \frac{R_2}{R_1 + R_2} \times \frac{V_T}{1}$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad \cos \theta^\circ = \frac{R}{Z} \quad P = I^2 R \quad P = \frac{V^2}{R} \quad P = VI \cos \theta$$

$$P = V \cdot I \quad F_r = \frac{1}{2\pi\sqrt{LC}} \quad Q = \frac{X_L}{R} \quad \text{OF} \quad \frac{1}{R} \sqrt{\frac{L}{C}}$$

$$I_t = \sqrt{I_R^2 + (I_C - I_L)^2} \quad Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_C} - \frac{1}{X_L}\right)^2}} \quad \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

$$V_{rms} = 0,707 V_m \quad i = I_s \left( e^{\frac{qv}{kT}} - 1 \right) \quad R = \frac{kT}{qi} \quad V \cdot R = \frac{V_{SI} - V_{FL}}{V_{FL}}$$

$$V_{av} = 0,637 V_m$$

$$f = \frac{1}{t} \quad \text{Rate of change} = - \frac{V_m}{CR_{in}}$$

$$V_{dc} / V_{gs} = 0,318 V_m$$

$$V_{dc} / V_{gs} = 0,637 V_m$$

$$V_{rms} / V_{r_{wgk}} = 0,385 V_m$$

$$PIV = V_m \quad \text{or/of} \quad 2 V_m$$

$$V_{rms} / V_{r_{wgk}} = \frac{V_r (p - p)}{2\sqrt{3}}$$

$$V_{dc} / V_{gs} = V_m - \frac{V_r (p - p)}{2}$$

$$r = \frac{V_{rms} / V_{r_{wgk}}}{V_{dc} / V_{gs}}$$

$$V_{rms} / V_{r_{wgk}} = \frac{V_{dc} / V_{gs}}{R_L 2\sqrt{3} FC}$$

$$V_{dc} / V_{gs} = V_m \frac{I_{dc} / I_{gs}}{2FC}$$

$$r = \frac{I_{dc} / I_{gs}}{V_{dc} / V_{gs} 2\sqrt{3} FC}$$

$$V_{r_{rms}} / V_{r'_{wgk}} = \frac{X_C}{\sqrt{R^2 + X_C^2}} \times \frac{V_{rms} / V_{r_{wgk}}}{1}$$

$$V'_{dc} / V'_{gs} = \frac{R_L}{R_L + R_S} \times \frac{V_{dc} / V_{gs}}{1}$$

$$V_{r_{rms}} / V_{r'_{wgk}} = \frac{V_{rms} / V_{r_{wgk}}}{(2\pi f)^2 LC}$$

$$R_{in} = \frac{V_{be}}{I_b} \quad R_{out} = \frac{V_{ce}}{I_c} \quad R_c = \frac{V_{cc}}{I_c} \quad V_{out} = R_c C \frac{dv_i}{dt}$$

$$\text{Static current gain} = \frac{I_{out}}{I_{in}}$$

$$\text{Dynamic current gain} = \frac{\Delta I_{out}}{\Delta I_{in}}$$

$$V_{cc} = V_{RC} + V_{ce} \quad V_{ce} = V_{ce} - V_{RC} \quad R = \frac{\rho \ell}{a}$$

$$A_p = 10 \log \frac{P_{out}}{P_{in}} \quad A_v = 20 \log \frac{V_{out}}{V_{in}} \quad A_i = 20 \log \frac{I_{out}}{I_{in}}$$

$$\text{Static voltage gain} = \frac{V_{out}}{V_{in}}$$

$$\text{Dynamic voltage gain} = \frac{\Delta V_{out}}{\Delta V_{in}}$$

$$h_{ie} = \frac{\Delta V_{in}}{\Delta I_{in}} = \frac{\Delta V_{be}}{\Delta I_b} \quad V_{ce} = \text{constant}$$

$$h_{re} = \frac{\Delta V_{in}}{\Delta V_{out}} = \frac{\Delta V_{be}}{\Delta V_{ce}} \quad I_b = \text{constant}$$

$$h_{fe} = \frac{\Delta I_{out}}{\Delta I_{in}} = \frac{\Delta I_c}{\Delta I_b} \quad V_{ce} = \text{constant}$$

$$h_{oe} = \frac{\Delta I_{out}}{\Delta V_{out}} = \frac{\Delta I_c}{\Delta V_{ce}} \quad I_b = \text{constant}$$

$$V_{out} = \frac{R_f}{R_{in}} \times V_{in} \quad V_{out} = - \left( \frac{R_f V_1}{R_1} + \frac{R_f V_2}{R_2} + \dots + \frac{V_n R_f}{R_n} \right)$$

$$V_{out} = \left( 1 + \frac{R_f}{R_{in}} \right) V_{in} \quad V_{out} = - \frac{1}{CR_{in}} \int V_{in}(t) dt$$

Boltzmann's constant =  $1,38 \times 10^{-23} \text{ J/k}$

Electron charge =  $1,6 \times 10^{-19} \text{ C}$

NB: Any applicable formula may be used.

# Marking Guidelines



**higher education  
& training**

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**REPUBLIC OF SOUTH AFRICA**

**APRIL 2015**

**NATIONAL CERTIFICATE**

**INDUSTRIAL ELECTRONICS N4**

(8080164)

**10 April 2015 (Y-Paper)  
13:00 – 16:00**

**QUESTION 1**

1.1 Consider loop ABEFA

$$V_1 = I_1 R_1 + (I_1 - I_2)$$

$$5 = 5I_1 + 10I_1 - 10I_2 \checkmark$$

$$= 15I_1 - 10I_2 \checkmark$$

(2)

Consider loop CDEBC

$$V_2 = I_2 R_2 - (I_1 - I_2) R_L$$

$$10 = 8I_2 - 10I_1 + 10I_2 \checkmark$$

$$= -10I_1 + 18I_2 \checkmark$$

(2)

$$(1) \times 10: 50 = 150I_1 - 100I_2 \checkmark$$

(2)

$$(2) \times 15: 150 = 150I_1 + 270I_2 \checkmark$$

$$(3) + (4): 200 = 170I_2$$

$$I_2 = 1,176 \text{ A} \checkmark$$

(1)

Substitute  $I_2$  in (1)

$$5 = 15I_1 - 10(1,176)$$

$$16,76 = 15I_1 \checkmark$$

$$I_1 = 1,117 \text{ A} \checkmark$$

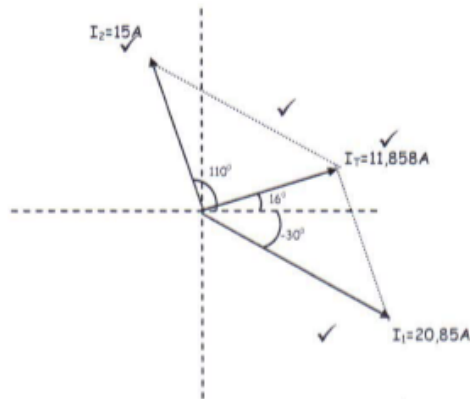
$$I_1 - I_2 = 1,117 - 1,176$$

$$= -0,059 \text{ A} \checkmark$$

(3)  
[10]

**QUESTION 2**

2.1



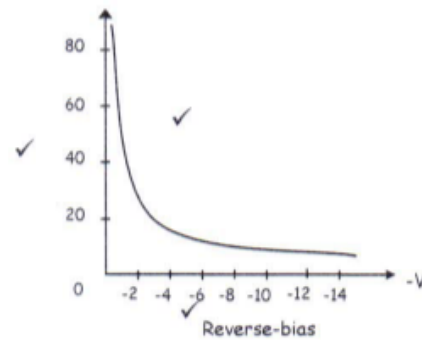
(4)

- 2.2    2.2.1    B
- 2.2.2    B
- 2.2.3    C

(2 x 3)    (6)  
[10]

**QUESTION 3**

3.1



Characteristic curve

Computers ✓

(5)

3.2    3.2.1     $V'_{dc} = \frac{5000}{R_L + R} \times V_{dc}$

$$60 = \frac{5000}{5000 + 200} \times V_{dc} \checkmark$$

$$V_{dc} = 62,4 \text{ V} \checkmark$$

(2)

3.2.2

$$V_r (rms) = \frac{V_{r(rms)}}{4\pi^2 f^2 LC}$$

$$= \frac{10}{4\pi^2 \times 100^2 \times 3 \times 5 \times 10^{-6}} \checkmark \checkmark$$

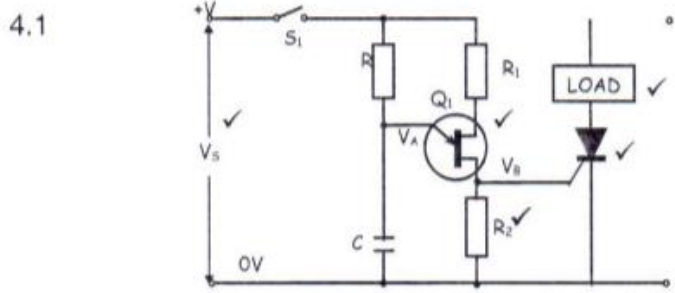
$$= 1,689 \text{ V } \checkmark \quad (3)$$

3.3

Bridge rectifier circuit	Centre-tap circuit
Four diodes	Two diodes
Forward voltage drop is double that of centre-tap.	Forward voltage drop is half that of a bridge.
PIV is equals maximum voltage	PIV is twice the maximum voltage
Full wave is achieved without a centre-tap	Need a centre-tap to achieve full wave
Can be directly supplied from the ac	The supply is always via the centre-tap transformer

(5 x 1) (5)  
[15]

QUESTION 4



(5)

4.2 4.2.1

$$A_p = 10 \log \frac{P_o}{P_{in}}$$

$$= 10 \log \frac{450}{500 \times 10^{-3}} \checkmark$$

$$= 29,542 \text{ dB } \checkmark \quad (2)$$

$$4.2.2 \quad P_o = I_o^2 \times Z_o$$

$$450 = I_o^2 \times 15$$

$$I_o = 5,477 \text{ A } \checkmark$$

$$V_o = I_o \times Z_o$$

$$= 5,477 \times 15$$

$$= 82,158 \text{ V } \checkmark$$

$$A_V = 20 \log \frac{V_o}{V_{in}}$$

$$= 20 \log \frac{82,158}{15} \checkmark$$

$$= 14,771 \checkmark$$

(4)

4.2.3

$$I_{in} = \frac{P_{in}}{V_{in}} = \frac{500 \times 10^{-3}}{15} \checkmark$$

$$= 0,033 \text{ A } \checkmark$$

$$A_i = 20 \log \frac{I_o}{I_{in}}$$

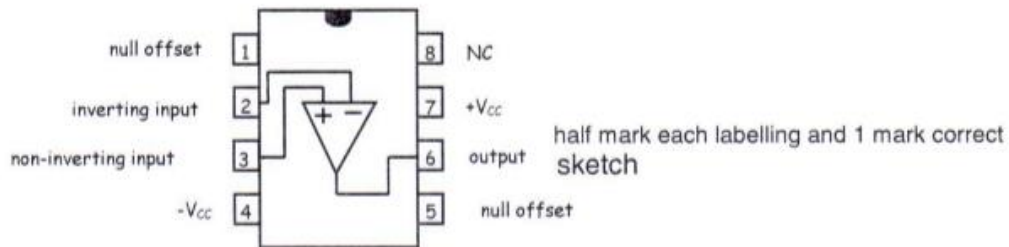
$$= 20 \log \frac{5,477}{0,033} \checkmark$$

$$= 44,401 \text{ dB } \checkmark$$

(4)  
[15]

**QUESTION 5**

5.1



(5)

5.2

$$V_o = \text{gain} \times V_{in}$$

$$4 = \text{gain} \times 0,5 \checkmark$$

$$\text{gain} = 8 \text{ V} \checkmark$$

$$\text{gain} = 1 + \frac{R_f}{R_{in}}$$

$$8 = 1 + \frac{R_f}{2\ 000} \checkmark$$

$$7 = \frac{R_f}{2000} \checkmark$$

$$R_f = 14 \text{ k}\Omega \checkmark$$

(5)

5.3

- 5.3.1 False  $\checkmark$
- 5.3.2 True  $\checkmark\checkmark$
- 5.3.3 False  $\checkmark$
- 5.3.4 True  $\checkmark$

(1)

(2)

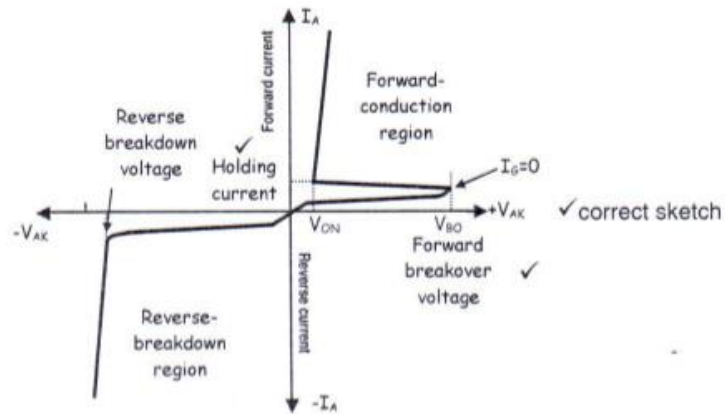
(1)

(1)

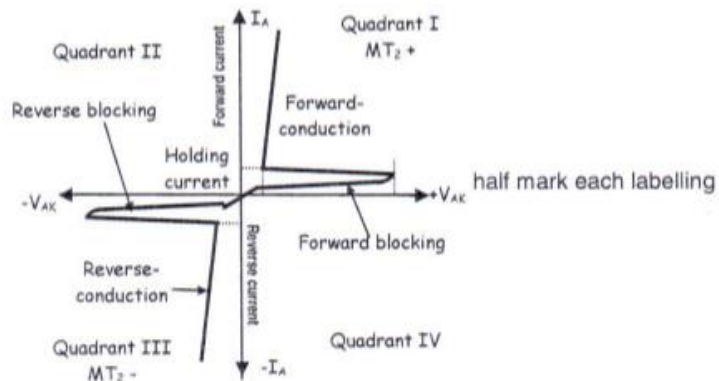
[15]

QUESTION 6

6.1 6.1.1



6.1.2 6.1.2



(3 x 2) (6)

- 6.2 6.2.1 E
- 6.2.2 C
- 6.2.3 B
- 6.2.4 A
- 6.2.5 D

(5 x 1) (5)

6.3 6.3.1 It is an amplifier without feedback and it doesn't have a comparator. ✓✓

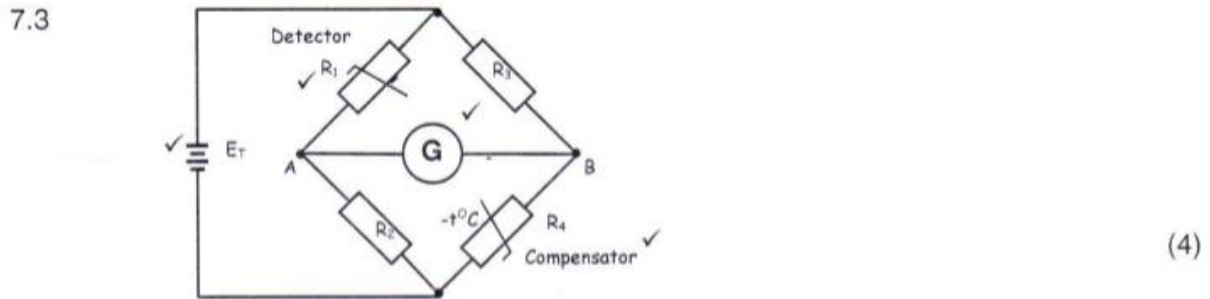
6.3.2 It is an amplifier with feedback and has a comparator. ✓✓

(2 x 2) (4)  
[15]

**QUESTION 7**

7.1 It is a device that converts non-electrical physical parameters into electrical signal ✓✓ (2)

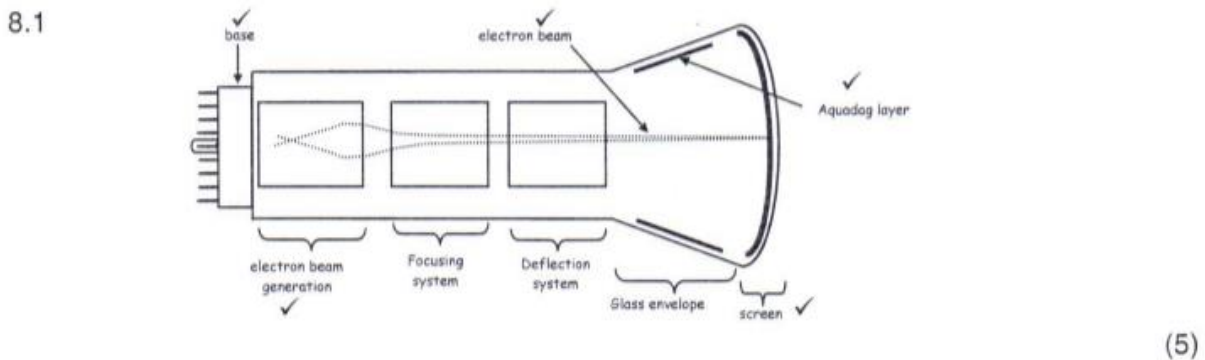
- 7.2
- Force ✓
  - Displacement ✓
- (2)



The compensation gauge prevents false observation due to temperature variations. ✓✓ (2)

**[10]**

**QUESTION 8**



8.2 8.2.1 Amplitude = no of divisions x V/div  
 = 2 x 0,3 ✓  
 = 0,6 V ✓ (2)

8.2.2  $V_{p-p} = \text{no.of divisions} \times V/\text{div}$

$$= 4 \times 0,3$$

$$= 1,2 \text{ V } \checkmark$$

(1)

8.2.3  $V_{ave} = 0,637 \times V_p$

$$= 0,637 \times 0,6 \checkmark$$

$$= 0,382 \text{ V } \checkmark$$

(2)

[10]

**TOTAL: 100**

**N4 Industrial Electronics is one of many publications introducing the gateways to Engineering Studies. This course is designed to develop the skills for learners that are studying toward an artisanship in the mechanical, engineering and related technology fields and to assist them to achieve their full potential in an engineering career.**

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**Practical activities are included throughout the book.**

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