The Turns Rule

- If you change the number of turns in the coils you change the induced emf. This allows you to change (transform) the voltage from primary to the secondary coil.

  The turns rule is:

$$\frac{N_s}{N_p} = \frac{V_s}{V_p} \qquad \text{———— (1)}$$

where

N_s = the number of turns on the secondary coil

N_p = the number of turns on the primary coil

V_s = the voltage across the secondary coil

V_p = the voltage across the primary coil

So if number of turns in secondary is greater than in primary, the voltage will be greater in secondary than in the primary. This is called a **step up transformer**.

- Thus, by a suitable choice of the turns ratio (N_S / N_p), we can transform an alternating p.d. to a supply of the same frequency at any other p.d. values.

- For an actual transformer, the above expression would be roughly true if
  - (i) the primary coil resistance and current were small
  - (ii) very little flux escaped from the soft iron core
  - (iii) the secondary current was small.

Power Transfer in a Transformer

Of course you can't create energy by stepping up voltage.

The energy put into a transformer by the primary each second = energy removed by the secondary each second.

For an ideal transformer, the power supply in the primary coil will be fully transferred to the secondary output. (i.e. no energy losses)

Hence, *power input* = *power output*

$$I_p V_p = I_S V_S$$

$$\frac{V_S}{V_P} = \frac{I_P}{I_S} \qquad \text{———— (2)}$$

Combining (1) & (2),

$$\boxed{\frac{V_s}{V_p} = \frac{I_P}{I_s} = \frac{N_s}{N_p}}$$

Thus, in a step-up transformer,

$$V_S > V_p$$

$$I_S < I_p$$

Energy losses in transformers $I_pV_p = I_sV_s$ + power loss

In practice, $I_S V_S < I_p V_p$ due to power losses in the :

(a) <u>Resistance of windings</u>

- joule heating (I^2R) is inevitable.
- for transformer handling very high electrical power, the windings are made of very thick wires so as to reduce the power lost as heat.

(b) <u>Eddy currents</u>

- alternating flux induces eddy currents in the iron core and causes heating.
- This effect is reduced by a laminated core.

(c) <u>Hysteresis</u>

- continual reversal of magnetism gives rise to the hysteresis loop.
- This is because each time the direction of magnetization of the core is reversed, some energy is wasted in overcoming internal friction.
- can be reduced by proper choice of metal core (mumetal most common).

(d) <u>Flux leakage</u>

- flux due to the primary may not be 100% linked to the secondary if the core is badly designed or has air gaps in it.
- can be reduced by having two coils wound round a common core.

Example 10
A transformer operates at V_p = 8.5 kV on the primary side and supplies electrical energy to a number of nearby houses at V_s = 120 V. Assume an ideal transformer.
(a) What is the turns ratio N_p/N_s of this transformer?
(b) Is this a step-up or a step down transformer?
(c) The rate of average energy consumption in the houses served by the transformer at a given time is 78 kW. What are the rms current in the primary and secondary windings of the transformer?

a) $\frac{N_p}{N_s} = \frac{V_p}{V_s} = \frac{8500}{120} = 71$

b) Step - down transformer.

c) $P_{ave} = I_s V_s$

$I_s = \frac{78 \times 10^3}{120}$

$= 650A$

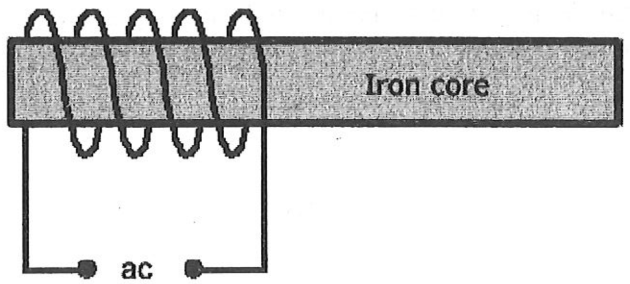
$\frac{I_p}{I_s} = \frac{N_s}{N_p} = \frac{120}{8500}$

$I_p = 9.18A$

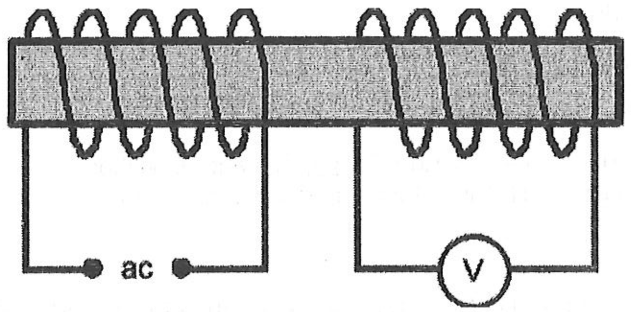
Principles of Operation

Transformers work on the principles of electromagnetism and electromagnetic induction.

Here's how they work



- A.C. in a coil will set up a **changing magnetic field** in the coil, which will mean that the core becomes a constantly changing magnet.



- Put a second coil around this changing magnet (the core) and you **induce an alternating emf** in the coil.
- We name the first coil the **primary** and the second coil the **secondary**.

That's how transformers work!

The transformer

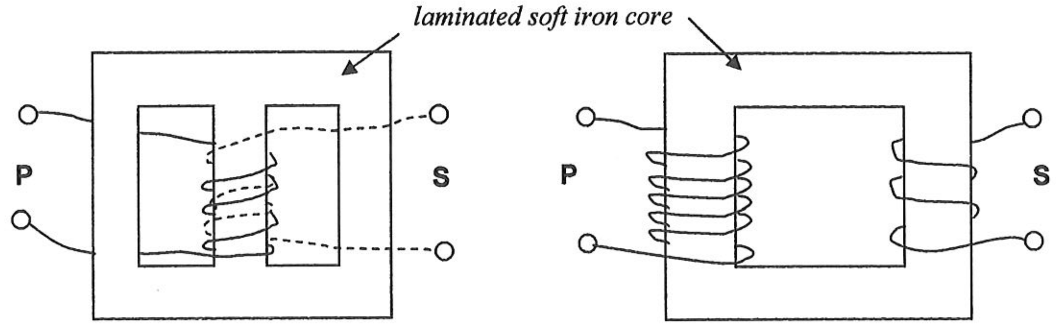
A transformer is a device used for stepping up or stepping down a given supply voltage using the mutual induction principle. It is essential for

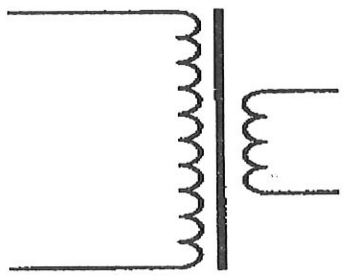
(a) electrical power transmission and

(b) regulating voltage for proper operations of electrical appliance.

Structure

- It consists of two wires, a primary coil and a secondary coil wound on the same soft iron core either one on top of the other or on separate limbs of the core as shown below.





Symbol of transformer

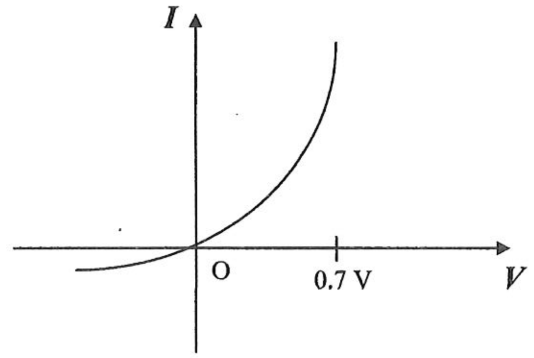
- There is no electrical connection between the coils, but they are linked magnetically – the presence of the soft iron core ensures that all the flux associated with one coil also passes through the other.
- These coils are wound on a laminated soft-iron core for better permeability of the magnetic field or flux linkage of the two coils.

Rectification

A d.c. can be obtained from an a.c. supply by means of a rectifier. It is a device that will allow current to pass in one direction only. A semiconductor diode is an example of a rectifier.

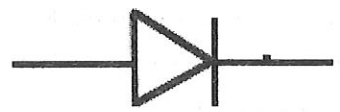
The Rectifier

- Rectifiers are non-ohmic devices that have the property which their resistance depends on the polarity of the applied p.d.
- They have **a low resistance** to current flow in one direction, and a **high resistance** in the opposite or reverse direction. This is shown by the characteristic curve of a semi-conductor junction diode :

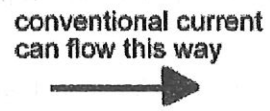


Diodes only allow current to flow in one direction

Low R to current flow in one direction
High R to other direction



Symbol of Rectifier

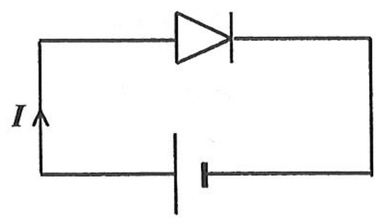


Forward Bias

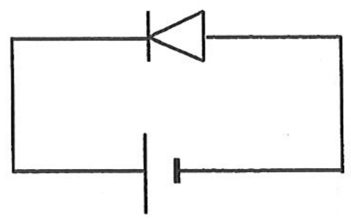
When connection is made to a supply such that the rectifier conducts.

Reverse Bias

When connection is in the non-conducting state - negligible current flow.



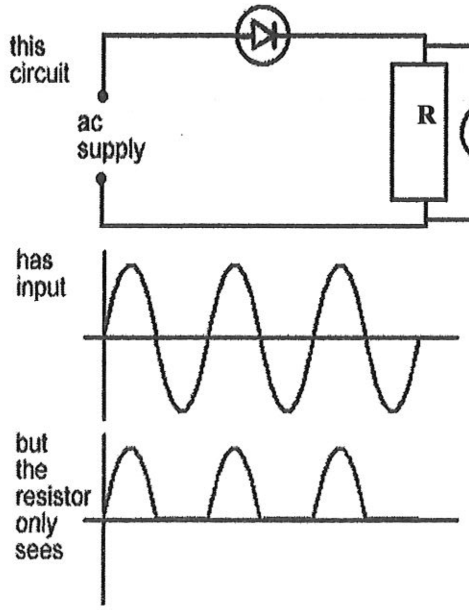
Forward bias



Reverse bias

Half-wave rectification

The half-wave rectifier can be constructed by just connecting a diode in series with the a.c. input to be rectified and the load requiring the d.c. output. For simplicity, we let the load be a simple resistor, ***R***.



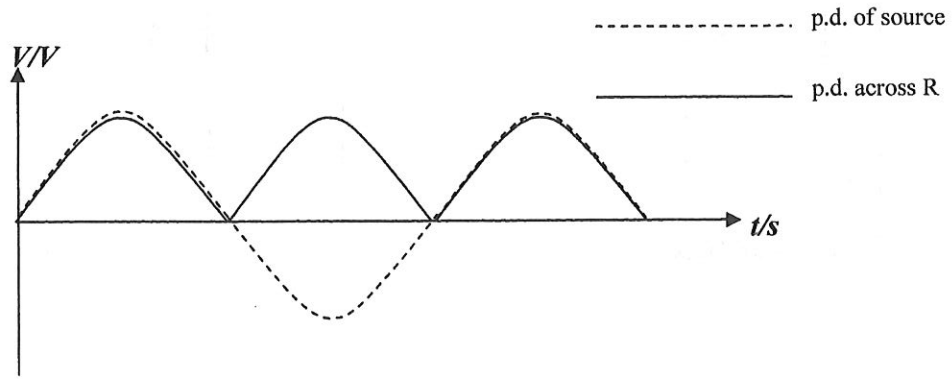
This is called half wave rectification.

Referring to the diagram above, and consider a complete cycle over one period.

- If the first half cycle acts in the forward direction of the rectifier, a pulse of current, flows round the circuit, creating a pd across R which will have almost the same value as the applied pd if the forward resistance of the rectifier is small compared to R.
- The second half cycle reverse biases the rectifier, little or no current flows and the pd across the R is zero.
- This is repeated for each cycle of a.c. input. The current pulses are unidirectional and so the pd across R is direct. Although its magnitude changes, its direction remains constant.

Full wave rectification

In this process, both halves of every cycle of input p.d produce current pulses and the p.d developed across the load is shown below.



Example 9

A power station feeds 1.0 x 10^8 W of electrical power at 760 kV into a transmission line. 10 % of this power is lost heating the resistance of the transmission line itself. What percentage of the power would be lost if the power station were to feed 340 kV into the transmission line instead of 760 kV ?

$P_{gen} = V_{in} I$ At 760 kV, current flowing along the line, $I = \frac{P}{V}$

$= 132 A$

$P_{loss} = \left[\frac{P_{gen}}{V_{in}}\right]^2 R = 1.0 \times 10^7 W$

$R = \frac{P_{lost}}{I^2}$

$= 577.6 \Omega$

When $V_{in} = 340000 V$, New current flow, $I' = \frac{P}{V'}$

$= \frac{1 \times 10^8}{340 \times 10^3}$

$= 294 A$

New power lost $= (I')^2 R$

$= 5.0 \times 10^7 W$

% power lost $= \frac{5.0 \times 10^7}{1.0 \times 10^8} = 50\%$

1.0 x 10^8 W of Electrical Power transmitted at	Line resistance, R	I/A	Power loss/W
760 kV	578 Ω	132	1×10^7
340kV	578 Ω	294	5×10^7

Summary

- For more efficient **transmission** we need very high voltages.
- High pd are extremely dangerous and has to be stepped down with high efficiency, reliability and safety.
- For safe **distribution** we need low voltages.
- **Transformers** meets these requirements.
- It is only able to function on a.c. This is one reason why a.c. is used for the transmission of electrical power.

Advantages of AC

Alternating currents (instead of d.c.) are widely used for the transmission of electrical energy because:

a) a.c. voltages are easier to step up/down with little loss using transformers. Electric power is transmitted most efficiently at high voltage and low current. These conditions result in a minimum loss of energy as heat.

On the other hand, low voltages are desirable in factories and at homes for reasons of safety and insulation.

For alternating currents, the job of changing voltage from one value to another can be done easily and cheaply by a transformer.

large electrical generators happen to generate a.c naturally

b) a.c. are easier to generate than d.c. conversion to DC will involve an extra step

c) a.c. are just as suitable for heating as for d.c. (refer to definition of rms values)

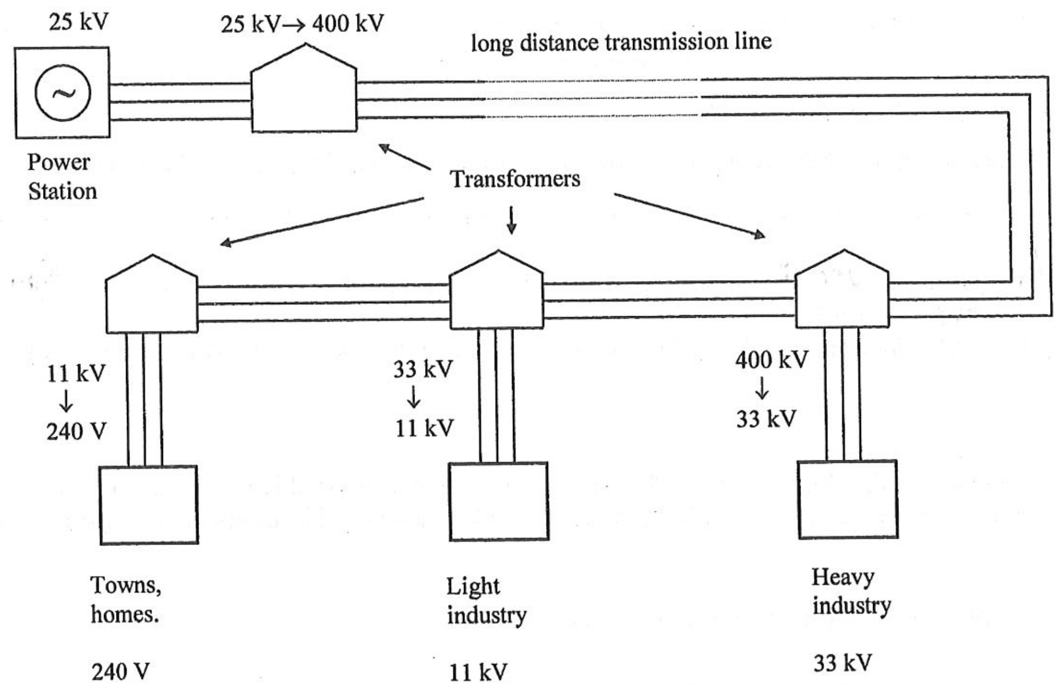
d) where d.c. are required, it is easy to convert or rectify a.c. into d.c. (refer to rectification of a.c.)

e) a.c. voltage is easier to switch on and off as it passes through zero many times per second.

transformer only operates with a.c

The distribution of electrical energy in a country is called the national grid *system*. It consists of a network of cables, which connects all the power stations and carries electrical energy from them to consumers

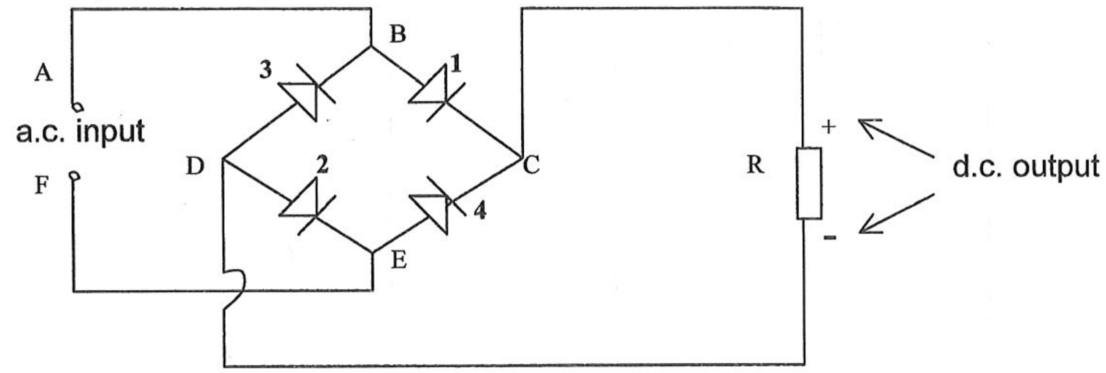
A grid system may work as shown below.



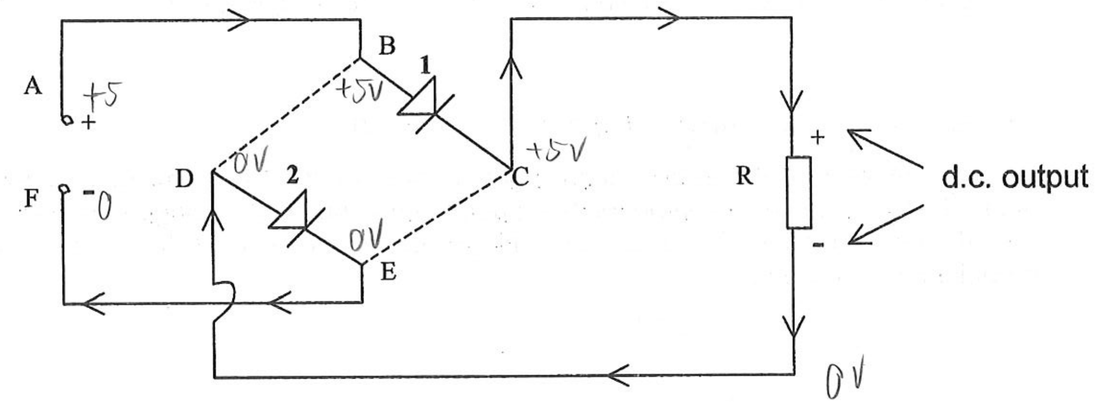
Disadvantage of AC: Transmission lines radiate EM waves because of the oscillating electrons in the current → waste of electricity

Bridge full-wave rectifier

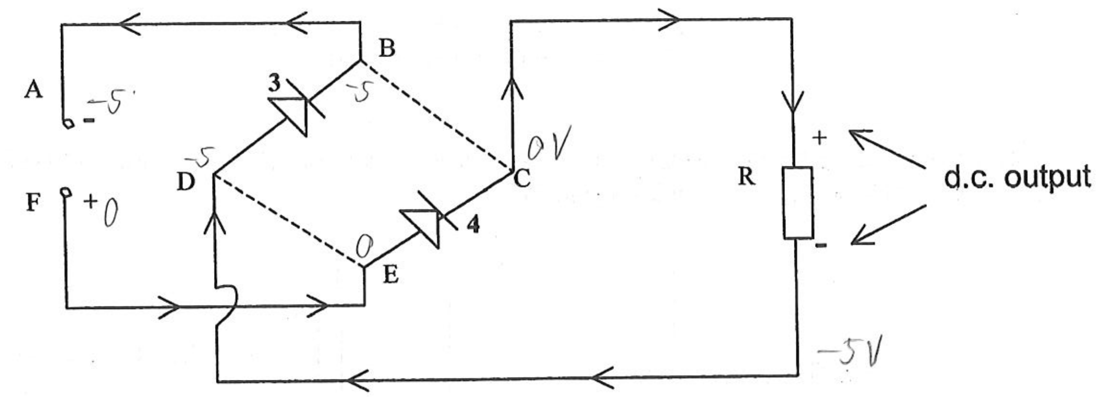
It is an electrical device that can convert an alternating voltage to the above form. Four rectifiers are arranged in a bridge network as shown below.



If A is positive during the first half-cycle, diodes 1 and 2 conduct and current takes the path ABC, R, DEF.



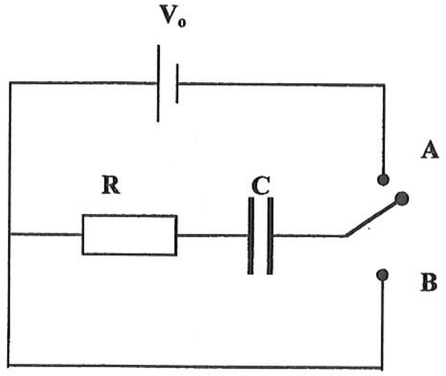
On the next half-cycle, when F is positive, diodes 3 and 4 are forward bias and current follows the path FEC, R, DBA.

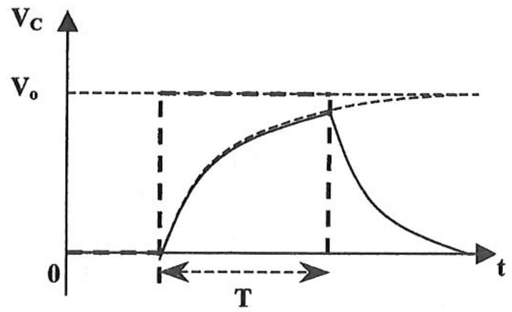


Note that during both half-cycles of input pd, the current flowing through R is unidirectional. Hence, a **d.c. output** is obtained.

Charging and discharging of a capacitor *(not included in the syllabus)*

Consider what happens when the switch is brought into contact with A, and is then flipped to B after a time T before the capacitor can be discharged.



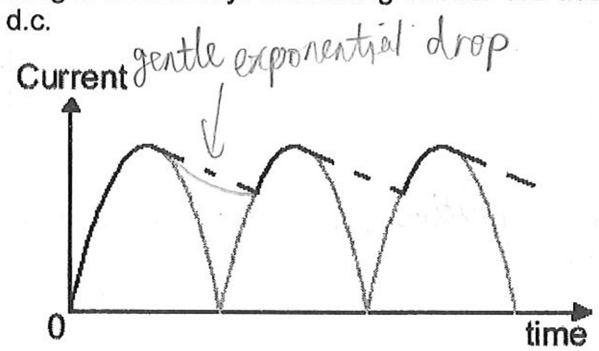


Current flows in and out of C continuously. C is constantly undergoing charging and discharging.

- Time constant, $\tau = RC$ is the time taken for the current I, the capacitor charge, Q and the capacitor voltage, V to decrease to 1/e = 0.368 of their original value.

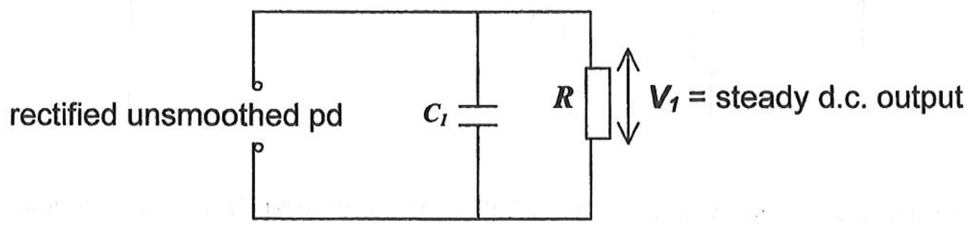
Smoothing of an a.c. *(this is included in syllabus!)*

The d.c derived from the above circuits fluctuates from zero to a maximum value and back again. Most d.c. electrical components cannot function on such changing current. To produce a steady d.c., smoothing is necessary. Smoothing circuits are used to convert a varying d.c. output into a steady d.c.



shows current before smoothing
— — shows current after smoothing

The simplest smoothing circuit consists of a large capacitor, 16 μF or more, called a **reservoir capacitor**, placed in parallel with the load R.

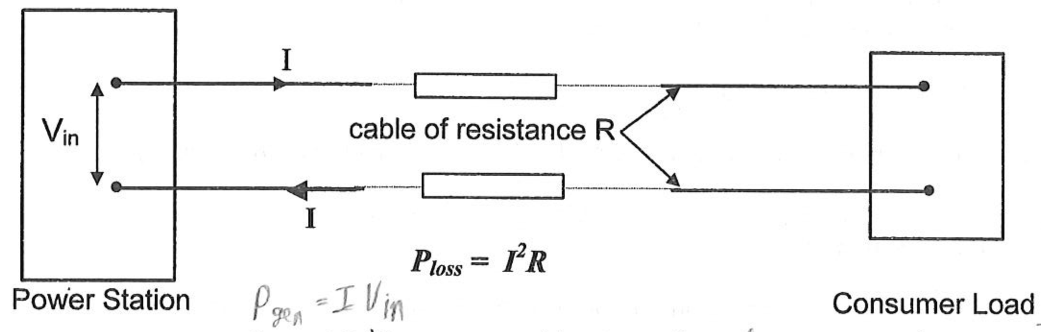


Transmission of electrical energy

The transmission and distribution of electrical power from the power station to the consumer loads (households and industries) should be done with due consideration for costs and efficiency.

Principal Losses in Transmission Systems

a) **Line losses**
Due to ohmic resistance of the lines.
Line losses are a major factor in transmission losses (about 10 % or more)



$P_{loss} = I^2R$

$P_{gen} = I V_{in}$
$P_{loss} \neq I V_{in}$ cause Vin is not p.d across transmission line
$= I V_{R\text{-}line}$

$P_{loss} = I^2 R_{line}$

$= \left[\dfrac{P_{gen}}{V_{in}}\right]^2 R$ where P_{gen} is the power generated and

V_{in} is the input voltage at the power station

Pause and Ponder

To minimise P_{loss}, we can reduce R or I.

How can these be achieved and what are the advantages or disadvantages of each method?

When V_{in} is high, current would be low ⇒ more economical to transmit power at high voltage and low current.
However, there is a limitation to the value of V_{in}. A higher value of V_{in} would raise the cost of insulation.

b) **Leakage losses**
Electrons may leak off the wire - to the air, ground, trees and buildings, and from wire to wire. This factor is significant at high voltages. Weather conditions appreciably affect this loss.

c) **Transformer losses** (refer to transformer).

Therefore factors to consider for most economical transmission of electrical power are :

1. **cable resistance**
2. **voltage of transfer**
3. **insulation costs**

Ways to reduce power loss
1) Reduce current of power transmitted
-step up voltage transmitted
-thicker insulation
2) Reduce cable resistance by using thicker cables
→ more costly

Example 8
An electric kettle, designed for travellers, can be used with different supply voltages. It is rated at 700 W for a 240 V rms alternating supply. What will be its power output if used on
(i) a 120 V rms alternating supply,
(ii) a 120 V direct supply?

$P_{mean} = 700\,W \quad V_{rms} = 240\,V$

i) $P_{mean} = \frac{V_{mean}^2}{R}$

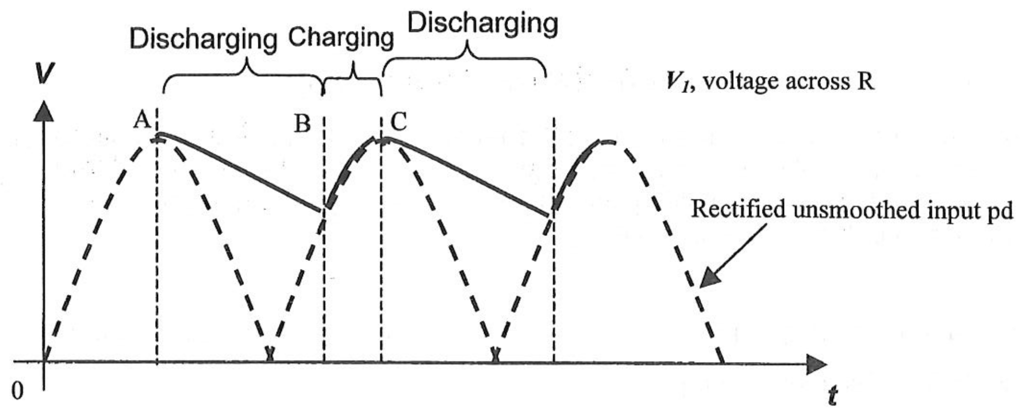
$R = \frac{240^2}{700} = 82.3\,\Omega$

$\therefore P_{mean(120V)} = \frac{120^2}{82.3} = 175\,W$

ii) $P_{d.c} = 175\,W$

Pause and Ponder
The Edison story and AC vs DC story.
Most electrical appliances make use of d.c. So why is it that a.c. is used in our power transmission?

Appendix I



C_1 is the reservoir capacitor and it is connected in parallel to the lead as shown. Its action can be followed from the above diagram where V_1 represents the pd across C_1.
same as p.d across R as they are parallel

Charging of reservoir capacitor

- Initially, the rectifier input pd causes the current to flow through R and at the same time C_1 becomes charged almost to the peak value of the input as shown by OA.

Discharging of reservoir capacitor

- At A, the input pd falls below V_1 and C_1 starts to discharge. But it cannot discharge through the diode since the polarity is wrong. So it discharges through the load, R and thus maintains current flow by its charge storing or reservoir action.

Recharging of reservoir capacitor

- Along AB, V_1 falls. At B, when the input pd equals the value to which V_1 has fallen, rectifier current I again flows to quickly recharge C_1 to the peak pd as shown by BC.

- The charge-discharging process takes place continuously and so the voltage across the ***CR***-combination is a **ripple voltage** as shown in the figure. In another words, the amplitude of the fluctuations is much less than when C_1 is absent.

- The smoothing action of C_1 arises from its large capacitance making the time constant C_1R large so that the pd across it cannot follow the variation of input pd. A very large value of C_1 would give a better smoothing but initially the uncharged reservoir capacitor would act almost as a short circuit and the resulting surge of current might damage the rectifier.

- The value of C_1 required will depend on the value of R and the frequency of the a.c. that is rectified. Generally, we choose C_1 such that the time constant C_1R is larger than the period of the a.c. source by about 5 times or more.

Speed of discharge of capacitor depends on R and C
↑ RC, longer it takes to discharge, gentle recified graph

Appendix II

Principles of Operation (Quantitative Understanding)

A transformer tranforms an alternating p.d. from one value to another of greater or smaller value using the mutual induction principle. (refer to EMI lecture) When an alternating p.d. is applied to the primary, the resulting current produces a large magnetic flux which links the secondary and induces an e.m.f. in it.

Let

N_p = no. of turns in the primary

N_s = no. of turns in the secondary

V_p = applied a.c. voltage in the primary

I_p = current induced in the primary

I_s = current induced in the secondary

E_p = back emf induced in the primary

E_s = back emf induced in the secondary

Φ = the flux in the iron core linking the coils

At the primary coil

- The a.c. voltage V_p sets up a fluctuating magnetic field that in turn self-induces a back emf, E_p in the primary to oppose the applied V_p. (Lenz's law)

$$\mathbf{E_p = - d/dt\ (N_p\ \Phi)}$$
$$\mathbf{= - N_p\ d\Phi/dt}$$

where $\frac{d\Phi}{dt}$ is the rate of change of flux through the core due to the current change in the primary.

- Therefore, $\mathbf{V_p + E_p = I_p\ r_p}$ **(r_p : primary coil resistance)**

The above equation is the result of applying Kirchhoff's second rule to the primary circuit.

$$\mathbf{V_p - N_p\ d\Phi/dt = I_p\ r_p}$$

For an ideal transformer, $r_p \cong 0$

Thus, $V_p = N_p \dfrac{d\Phi}{dt}$ ——————(1)

- P_o or P_{max} is the **peak** instantaneous power.
- $P_o = I_o V_o$.

Since $P_{mean} =$ **1/2** P_o, we have

$$P_{mean} = \sqrt{1/2}\ I_o \times \sqrt{1/2}\ V_o$$
$$= I_{rms} \times V_{rms}$$
$$= I_{rms}\ (I_{rms}\ R)$$
$$= I_{rms}^2 R$$

Summary of voltage and power in a resistive circuit.

	Voltage	Power
Instantaneous values	$V = V_0 \sin \omega t$	$P = IV = I^2R = P_0 \sin^2 \omega t$
Peak values	V_0	$P_0 = I_0V_0 = I_0^2R = \frac{V_0^2}{R}$
rms values	$V_{rms} = \frac{V_0}{\sqrt{2}}$	$P_{mean} = I_{rms}V_{rms} = I_{rms}^2R = \frac{V_{rms}^2}{R} = \frac{1}{2}P_0$

***Note**: Power and voltage values marked on most electrical appliances are usually mean power and rms voltage values respectively.*

Example 7
An electric kettle is marked 240 V and 1440 W. Find
(a) the rms current, I_{rms} (b) the peak current, I_o
(c) the peak voltage, V_o (d) the peak power, P_o

$V_{rms} = 240\,V$ $P_{mean} = 1440\,W$

a) $I_{rms} = \frac{1440}{240}$
$= 6.0\,A$

b) $I_0 = \sqrt{2}\, I_{rms}$
$= \sqrt{2}(6.0)$
$= 8.5\,A$

c) $V_0 = \sqrt{2}\, V_{rms}$
$= \sqrt{2}(240)$
$= 339\,V$

d) $P_0 = 2P_{mean}$
$= 2880\,W$

$P_{mean} = \frac{1}{2}P_0$

Example 6
Voltage of Singapore household mains is rated as 230V. What is the max voltage, and the peak-to-peak voltage? What about that of Taiwan's household mains (rated 110V)?

$230 = \frac{V_0}{\sqrt{2}}$ $V_{max} = \sqrt{2}\, V_{rms}$

$V_{max} = 230\sqrt{2} = 325\ V$ $V_{p-p} = 2V_{max} = 651\ V$

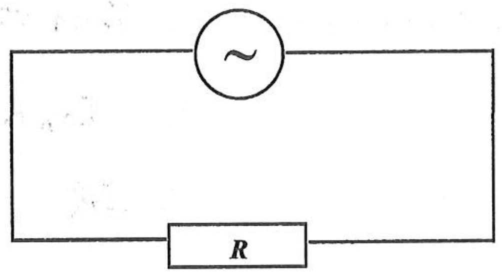
$110 = \frac{V_0}{\sqrt{2}}$

$V_{max} = 110\sqrt{2} = 156\ V$

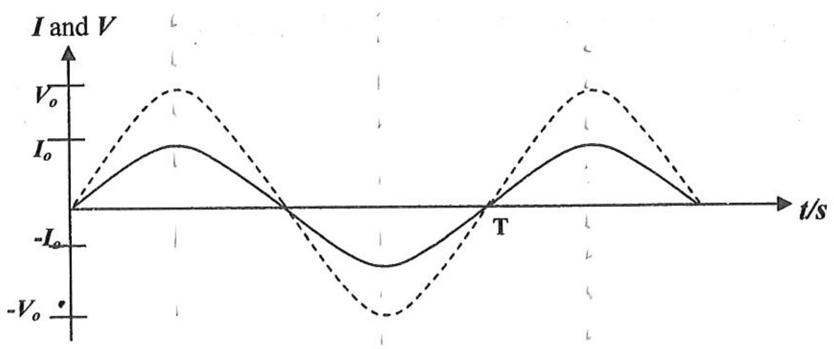
$V_{p-p} = 2V_{max} = 311\ V$

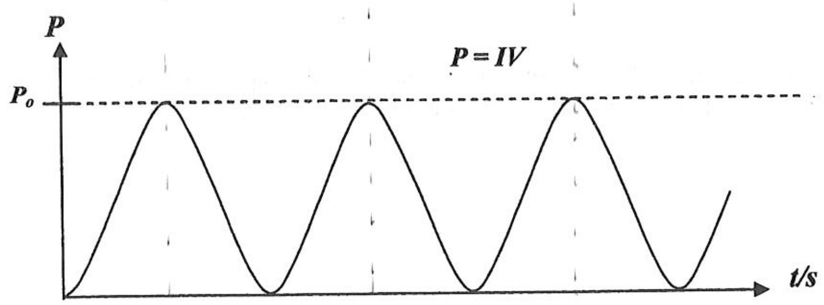
Power in a resistive circuit

To get an a.c. through a resistor we connect the resistor to an alternating *emf* which will provide an alternating *voltage* across the resistor.



Current and voltage across resistor will then be $I = I_o \sin \omega t$ and $V = V_o \sin \omega t$ respectively.





- Instantaneous power fluctuates from zero to a maximum and back to zero.

At the secondary coil

- The same alternating flux in the core also induces an emf in the secondary coil of N_S turns. The emf E_S induced in the secondary is

$$E_s = -\,d/dt\,(N_s\,\Phi)$$
$$= -\,N_s\, d\Phi/dt$$

- If the secondary is an open circuit or the current taken from it is small, then to a good approximation,

$$E_S \approx V_S$$

where V_S is the p.d. across the secondary.

Thus, $$V_S = -N_S \frac{d\Phi}{dt} \qquad (2)$$

- From (1) and (2),

$$\frac{V_S}{V_P} = -\frac{N_S}{N_P} \qquad (3)$$

- Thus, by a suitable choice of the turns ratio (N_S / N_p), we can transform an alternating p.d. to a supply of the same frequency at any other p.d. values.
- The minus sign in equation 3 indicates that the voltage in the secondary is completely out of phase with the applied voltage in the primary.

- For an actual transformer, the above expression would be roughly true if
  - (iv) the primary coil resistance and current were small
  - (v) very little flux escaped from the soft iron core
  - (vi) the secondary current was small.

Alternating Current Tutorial

Characteristics of A.C.

Self-Attempt Questions

1 An alternating current I in amperes varies with time t in seconds as $I = 4 \sin 200 \pi t$. Find the r.m.s. value of the current and the frequency. [4 / √2 A, 100 Hz]

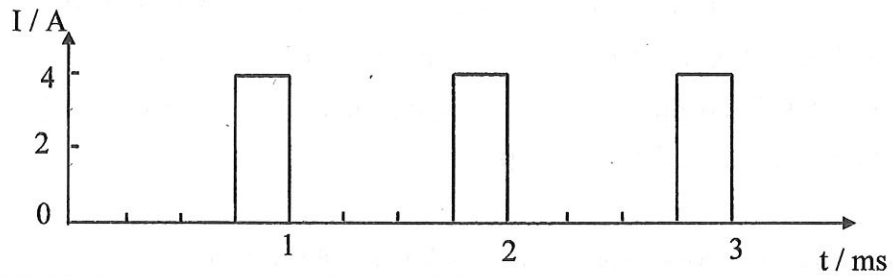
2 Calculate the peak current in a 60 W lamp working from a 240 V_{rms} supply. [0.35 A]

3 The output of an alternating supply is given by the expression: $V = 20 \sin 628t$. What is:
(i) the maximum voltage of the supply?
(ii) the r.m.s. value of the voltage?
(iii) the frequency of the supply? [20V, 14V, 100Hz]

4 When a domestic electric heater is operated from a 240 V a.c. supply, a rms current of 8.0 A flows. Assuming that the heater is purely resistive, calculate
(a) its resistance
(b) the mean power
(c) the maximum instantaneous power. [30Ω, 1920W, 3840W]

Discussion Questions

5 The diagram shows (in part) the variation with time of a periodic current.



(a) What is the average value of the current ?
(b) Find the root-mean-square current.
(c) The periodic current passes through a resistor, producing heat at a certain rate. What steady current, passing through the same resistor, would have an identical heating effect ? [1.0A, 2.0A, 2.0A]

6 State and explain the physical significance of root mean square current in an a.c. circuit.

7 An electric heater bears a plate marked " 240 V a.c., 2000 W ".
(a) What is the rms current in the heater when it is connected to the 240 V supply ?
(b) What is the peak current in the heater ?
(c) Fuses labelled 6 A, 10 A, and 13 A are available. Which should be used in the heater circuit? Explain your choice.
(d) What will be its power output if used on (i) 120 V_{rms} alternating supply
(ii) 120 V direct supply?
[8.33A, 11.8A, 500W]

8 A steady current I dissipates a certain power in a variable resistor. The resistance has to be halved to obtain the same power when a sinusoidal alternating current is used. What is the r.m.s. of the alternating current? [√2 I]

Example 3
A steady current I dissipates a certain power in a variable resistor. The resistance has to be halved to obtain the same power when a sinusoidal alternating current is used. What is the rms value of the alternating current?

$I_{DC} R^2 = I_{rms}\left(\frac{R}{2}\right)^2$

$I_{rms} = \sqrt{2I^2}$

$= \sqrt{2}\, I$

Rms and peak value for Voltage in a resistive circuit

- For a sinusoidal a.c., the instantaneous current $I = I_0 \sin \omega t$

  the instantaneous voltage $V = V_0 \sin \omega t$

- rms value of the voltage is $V_{rms} = I_{rms} R$

- And the peak value of the voltage is $V_o = I_o R$

Example 4
An alternating voltage of 10 V_{rms} and frequency 50 Hz is applied to a resistor of 5.0 Ω. Determine the peak current.

$V_{rms} = I_{rms} R$

$10 = I_{rms}(5)$

$= \frac{I_0}{\sqrt{2}}(5)$

$I_0 = 2.83A$

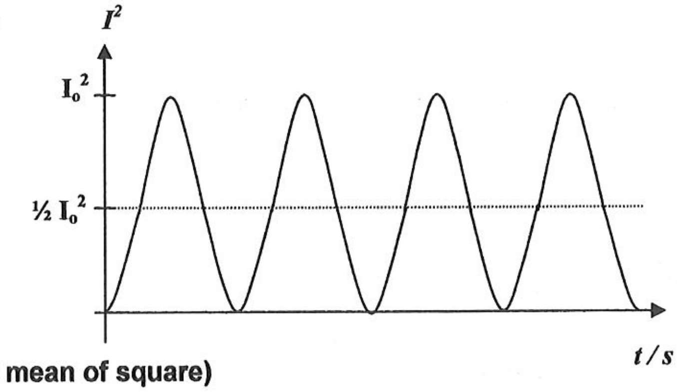
Example 5
A certain lamp requires a current of 0.50 A to give the specified illumination Calculate the resistance of the bulb if the peak voltage across it is 340 V.

$340 = \sqrt{2}(0.5)R$

$R = \frac{680}{\sqrt{2}}$

$= 481\,\Omega$

- Graphically,



Step 3 (Root of mean of square)

Take square root of the value from Step 2 to get I_{rms}.

Hence, we have

$$I_{rms} = \sqrt{\tfrac{1}{2} I_o^2} = I_o\sqrt{\tfrac{1}{2}} = \frac{I_o}{\sqrt{2}}$$

In exactly the same way, the rms voltage of a sinusoidal voltage is given by

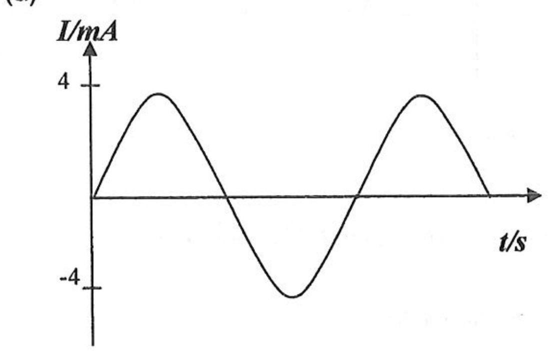
$$V_{rms} = \frac{V_o}{\sqrt{2}}$$

***Important:** These equations are applicable only for **sinusoidal waveforms,** but the general steps can be applied to other waveforms to find out their rms values.

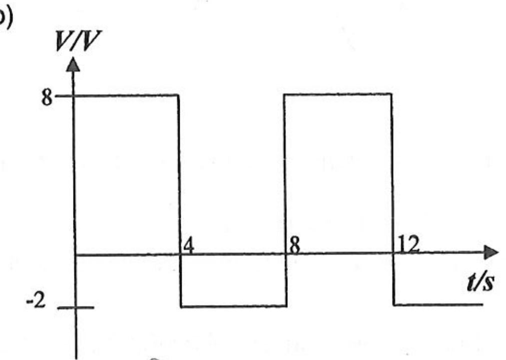
Example 2

Find the peak, average and rms value of the following :

(a)



(b)



$I_o = 4 mA$

$I_{ave} = 0$

$I_{rms} = \frac{I_o}{\sqrt{2}}$

$= 2.82 mA$

$T = 8 s$

$V_o = 8$ in +ve direction

$= 2$ in -ve direction

$V_{ave} = \frac{4\times 8 + 4\times(-2)}{8}$

$= 3 V$

Area under V^2 graph $= (64\times 4) + (4\times 4)$

$= 272$

$\langle V^2 \rangle = \frac{272}{8} = 34$

$V_{rms} = \sqrt{34} = 5.83 V$

The Transformer

$\frac{50}{500} = \frac{V}{230}$

Self-Attempt Questions

1 Complete the following table of an ideal transformers:

Primary p.d.	Secondary p.d.	Primary turns	Secondary turns	Step up or down
230 V_{rms}	23 V_{rms}	500	50	step down
230 V_{rms}	1 150 V_{rms}	400	2000	step up
11 000 V_{rms}	132 000 V_{rms}	1000	12000	step up

[23V, down, 400, up, 12 000, up]

2 An output of 20 V r.m.s. from a coil is connected to the primary of an ideal transformer. The transformer has 50 turns on its primary winding and 1800 turns on its secondary. The output current from the transformer is 0.042 A r.m.s. Calculate, for the transformer,

(i) the r.m.s. output voltage,
(ii) the mean output power
(iii) the maximum output power
(iv) the r.m.s. input current [720V, 30.2W, 60.5W, 1.5 A]

Discussion Questions

3 You are given a transformer enclosed in a wooden box, its primary and secondary terminals being available at two opposite faces of the box. How could you find the turns ratio without opening the box?

4 The output voltage of a 40 W transformer is 25 V and the input current is16 A.

(a) Is this a step-up or a step-down transformer?
(b) By what factor is the voltage multiplied? [10]

5 An ideal transformer has 500 primary turns and 10 secondary turns.
(i) If V_p for the primary is 120 V, what is V_s for the secondary, assumed an open circuit ?
(ii) If the secondary now has a resistive load R of 15 Ω, what are I_p and I_s? [2.4V, 3.2mA, 0.16A]

6 Explain why transformers can only operate successfully if the input voltage is an alternating voltage.

(ii) The secondary coil of a transformer is made of thicker wire than the primary. State and explain your conclusions about the nature of the transformer.

(iii) The iron cores of transformers are normally laminated.

1. State what is meant by a laminated core.

2. Explain the advantage of using a laminated core.

Transmission of Electrical Energy

Self-Attempt question

1 An a.c. transmission line transfers energy at the rate P_{av} = 5.0 MW from a generating plant to a factory.
(a) What current I_{rms} is present in the line if the transmission voltage V_{rms} is 120 V ?
(b) If V_{rms} = 80 kV ?
(c) What is the ratio of the thermal energy losses in the line for these two cases? [4.2 kA, 62.5A, 4.5x10^5]

$V = E - Ir$

Discussion Questions

2 A small power station generates 2 MW of electricity. How much power is lost in cables of resistance 2 Ω if the electricity is transmitted at (a) 40 kV (b) 4 kV [5kW,500kW]

3(a) A power station generates a current of 100 A at 25 kV. The electricity is transferred along 100 km of power lines to a chemical factory. The power line has a total resistance of 50 Ω. Calculate the power lost in the power line and the percentage efficiency.

(b) The above system is improved by adding two transformers, one to step up the voltages to 125 kV and a second to step it back down at the factory. The first transformer has a turns ratio of 1 : 5; the second has a turns ratio of 5 : 1. By how much does this reduce the power losses? What is the percentage efficiency? (Assume both transformers are 100 % efficient).

[$5.0\text{x } 10^5$ W, 80%, 0.48 MW, 99.2%]

4 A transmission line that has a resistance per unit length of $4.50 \text{ x } 10^{-4}\ \Omega m^{-1}$ is to be used to transmit 5.00 MW over $6.44 \text{ x } 10^5$ m. The output voltage of the generator is 4.50 kV.

(a) What is the line loss if a transformer is used to step up the voltage to 500 kV?
(b) What fraction of the input power is lost to the line under these circumstances?
(c) What difficulties would be encountered on attempting to transmit the 5.00 MW at the generator voltage of 4.50 kV? [2.9 x 104 W, 0.58%]

6) The changing magnetic field is not only found in the primary and secondary coils, but also in the soft iron core itself.
An emf will be induced in the transformer core and drives induced current (Eddy current) in the core. This brings about heating effect.
To reduce this energy loss, the core is made of iron sheets which are built up like plywood. Each of these "iron plywood" is then insulated from one another which limits the induced current flow and hence reduced power loss.

Calculation of rms values

If Power = V I

then, obviously, peak power occurs at time of peak voltage and current.

Peak power = $V_o I_o$
So, as we've said,

Average power = ½ x peak power = ½ $V_o I_o$

$$\frac{1}{2}V_0I_0 = \frac{V_0I_0}{2} = \frac{V_0}{\sqrt{2}}\cdot\frac{I_0}{\sqrt{2}}$$

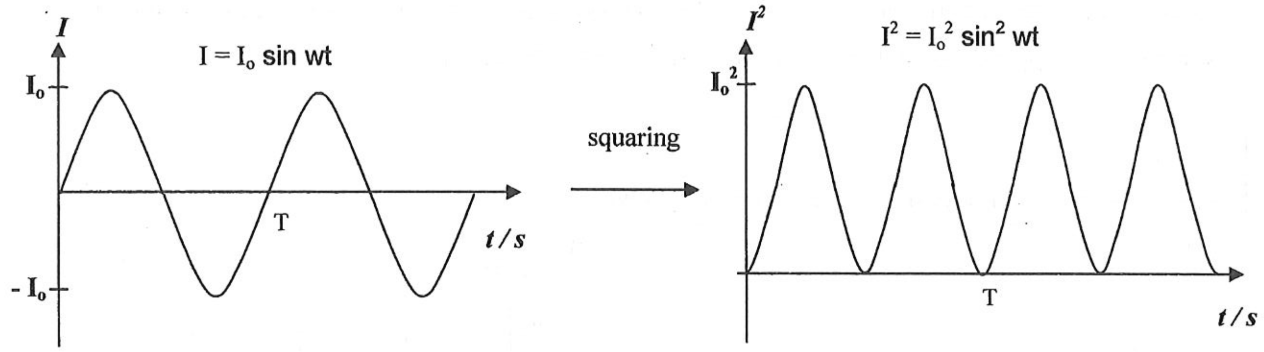
$$\text{Average power} = \frac{V_0}{\sqrt{2}}\cdot\frac{I_0}{\sqrt{2}}$$ only true for sinusoidal A.C

$$V_{rms} = \frac{V_0}{\sqrt{2}} \quad \text{and} \quad I_{rms} = \frac{I_0}{\sqrt{2}}$$

Graphical Method

Step 1 (Square)

Using the original plot, square every value to get I^2 and sketch out the squared graph.



Note: The maximum value for the $\sin^2 \omega t$ function is unity.

Step 2 (Mean of square)

Find the mean or average of the squared graph over **one period** to get $< I_o^2 \sin^2 wt >$

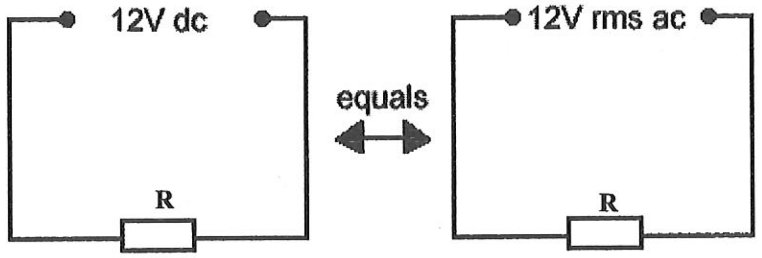
- Find the area enclosed by the squared graph within one cycle.
- Divide the area by its period, T.
- Average value of a function y(t) is

$$\langle y(t)\rangle = \frac{\int_0^T y(t)dt}{T}$$

Hence, $< I_o^2 \sin^2 wt > = \frac{1}{2} I_o^2$

RMS Values

They are the d.c. equivalent of an a.c. value. In other words, if you had two circuits, one d.c. and one a.c., and you wanted them to use exactly the same amount of power (energy each second) then you would choose the d.c. values of current and voltage to be the same as the rms values of current and voltage in the a.c. circuit:



The energy used each second in both of these circuits is the same.

- I_{rms} is defined as ***the direct current*** **that produces the** same heating effect **as the *alternating current*, assuming a pure resistance.** (ie $P_{ave} = I_{rms}^2 R = I_{DC}^2 R$)
- It is the <u>**square root**</u> of the <u>**average value**</u> of the <u>**square**</u> of the current taken over one cycle.
- This principle can also be used for an alternating voltage.

$I_{rms} = \sqrt{}$ **(mean value of I^2)**

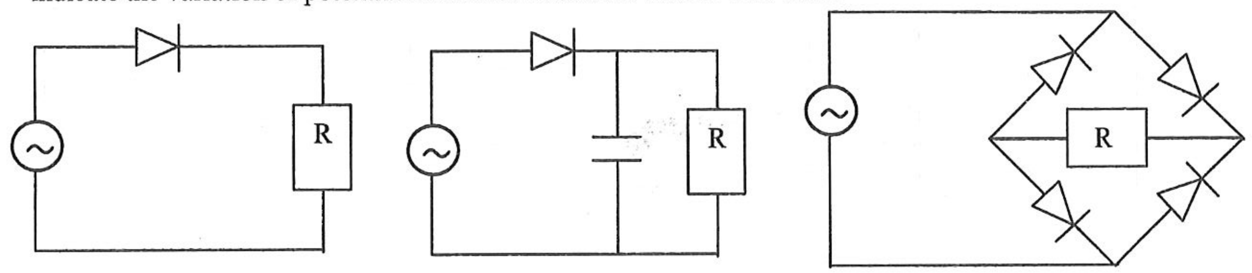
$= \sqrt{\langle I^2 \rangle}$

$V_{rms} = \sqrt{}$ **(mean value of V^2)**

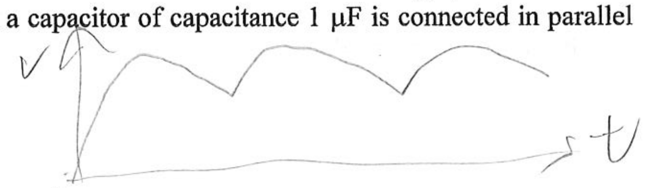
$= \sqrt{\langle V^2 \rangle}$

Rectification Conversion of a.c to d.c
Self-attempt questions

1 Three circuits used to rectify an alternating current are shown below. Sketch graphs in each diagram to indicate the variation of potential difference across the load R with time.



2 The output from a 50 Hz full-wave rectifier is fed into resistive load of 5 kΩ. Sketch a graph to show how the current through the load varies with time when a capacitor of capacitance 1 μF is connected in parallel with the load.



Discussion questions

3 A transformer and rectifier are to be used to convert the a.c. mains supply into a much lower d.c. output voltage. The r.m.s. value of the mains voltage is 230 V and its frequency is 50 Hz. The desired d.c. output is 15 V.

(i) Calculate the peak value of the mains voltage. [325 V]

(ii) Determine the number of turns in the secondary coil given that the number of turns in the primary coil is 3000. [138]

(iii) Copy Fig. 3 and complete it by drawing

1. a circuit which could be connected between the secondary coil of the transformer and the load to provide a full-wave rectified current through the load of 5 kW.

2. another separate circuit to show the path followed by the current when terminal P is positive with respect to Q.

3. a third circuit to show the current when terminal P is positive with respect to Q.

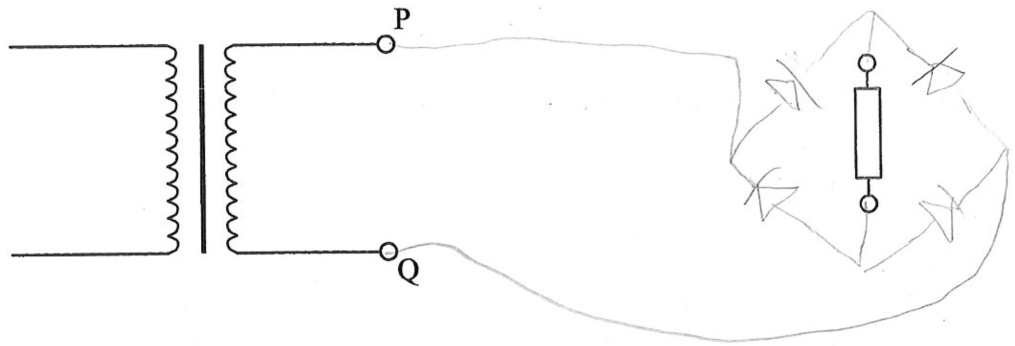
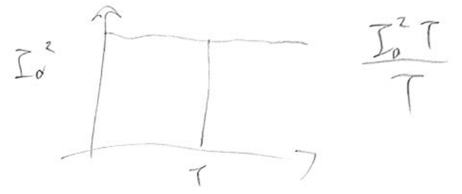


Fig.3

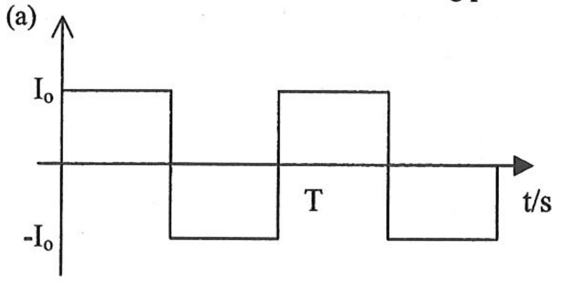
(iv) With reference to the figure you have copied, state and explain how the rectified current could be smoothed to give a steady voltage across the load.



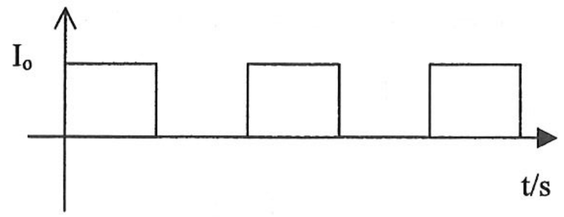
Assignment Questions

1 Calculate the rms values of the following periodic currents:

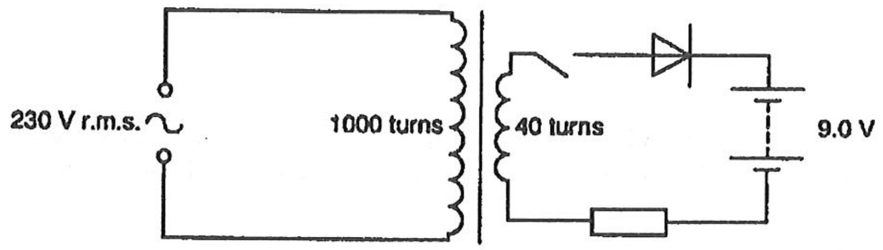
(a)



(b)



2 The primary coil of a transformer has 1000 turns and is connected to a 230 V $_{rms}$ supply. The secondary coil has 40 turns and may be connected, through a switch and a diode, to a 9.0 V rechargeable battery, as illustrated in figure below



(a) Initialy the switch is open. Considering both the transformer and the diode to be ideal, calculate

(i) the r.m.s. potential difference across the secondary,

(ii) the peak potential difference across the secondary.

(b) The switch is now closed so that the battery is being recharged.

(i) Suggest why the diode is necessary in the secondary circuit.

(ii) Suggest why the resistor is necessary in the circuit.

3. Figure 3.1 shows the circuit of a full-wave rectifier using four diodes.

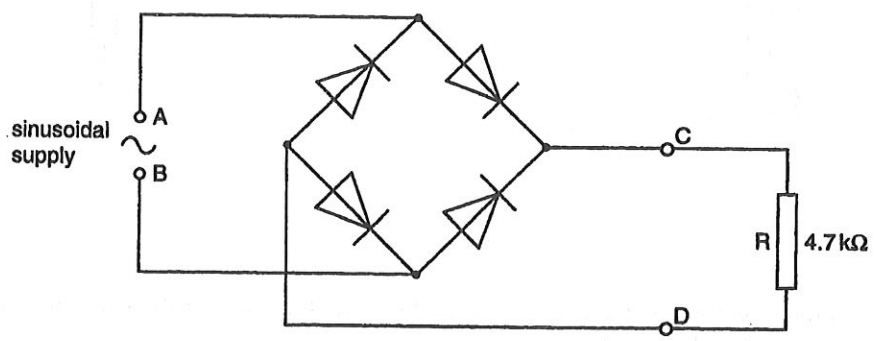
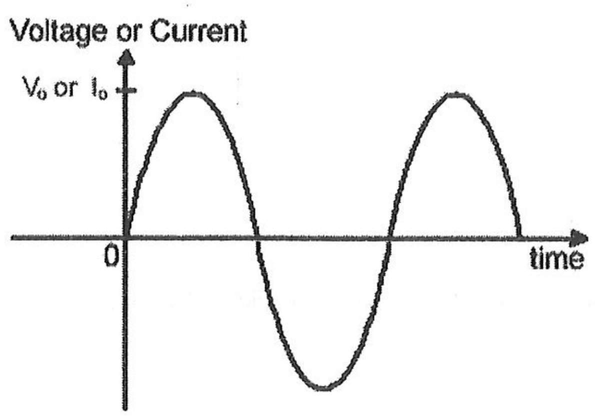


Figure 3.1

Root-mean-square value

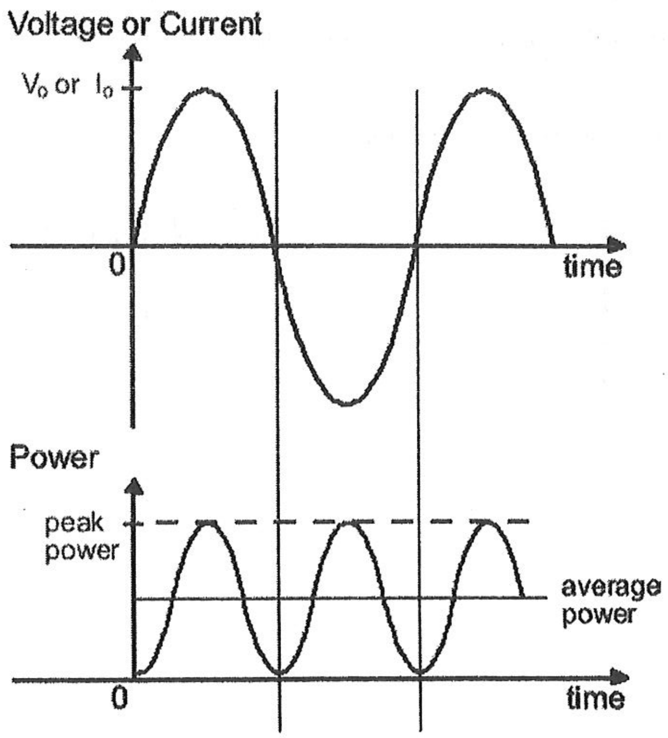
Alternating current electricity is easy to make and easy to transform so it is the most common form of electrical supply. The problem with it is that it isn't quite as easy to do calculations with as it is always changing! So what value do you put in your calculations?

Your first guess would be to use an average. But look:



- The current in an AC circuit changes periodically which means I_{ave} is ___0___,
- As such, it is meaningless to use I_{ave} in the calculation of average power dissipated.

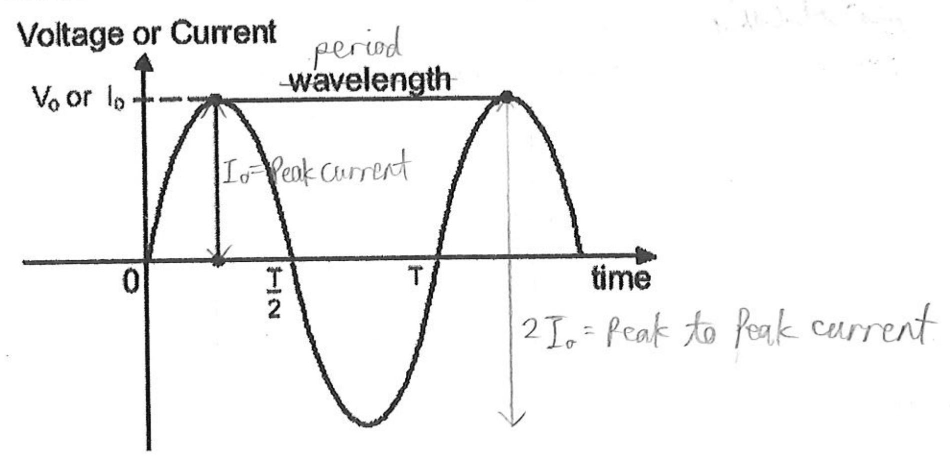
What else can we consider?



Average power = $\frac{1}{2}$ Peak Power = $\frac{1}{2} P_o$

The Sinusoidal A.C.

A sinusoidal a.c. varies with time in the following way.



It is represented by the equation

$$I = I_o \sin \omega t$$

$$\text{or } I = I_o \sin 2\pi f t \text{ where } \omega = 2\pi f.$$

I is the instantaneous current,
I_o is the peak or maximum current,
ω is the angular frequency of the supply,
f, the frequency of the supply, is the number of cycles per second.

For an alternating voltage, $V = V_o \sin \omega t$ or $V = V_o \sin 2\pi f t$ where $\omega = 2\pi f$.
V_o is the peak or maximum voltage.

Pause and Ponder
For a DC, the drift speed of electrons in a copper wire is in the order of 10^{-5} ms^{-1} in a particular direction.
How do electrons move in an AC?

- Typical drift speed of electrons in a D.C is 4×10^{-5} ms^{-1}
- Magnitude of drift speed in AC should be of the same order.
- If their direction is reversed every $\frac{1}{100}$ s, such electrons could move only about 4.0×10^{-7} ms^{-1} in one half-cycle
- So the electrons will oscillate with that amplitude.

Example 1
The peak voltage supplied by the power station in Singapore is 339 V at 50 Hz. Write down the sinusoidal expression for the voltage supply in terms of t.

$V = 339 \sin 2\pi(50)t$
$= 339 \sin (100\pi)t$

The terminals A and B are connected to a sinusoidal supply. A resistor R of resistance 4.7 kΩ is connected across the output CD of the rectifier.

(a) On Fig. 3.1,

i. Draw a tick (√) on those diodes that are conducting when terminal B is positive with respect to terminal A,

ii. Mark the positive (+) and negative (-) terminals of the output of the rectifier.

(b) Fig. 3.2 shows the variation with time t of the potential difference V across the load resistor R.

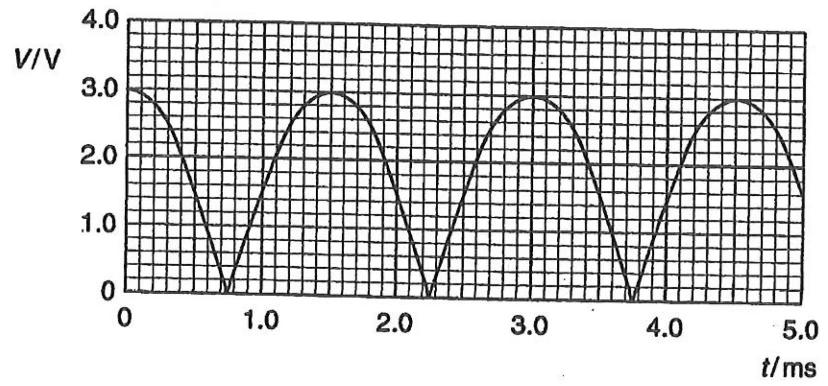


Fig. 3.2

i. Determine the mean power dissipated in the resistor R.

ii. Suggest the effect, if any, on the mean power dissipated in the resistor R when a smoothing capacitor is connected in parallel with the resistor.

(c) Figure 3.3 shows the variation with time t of the potential difference V across the resistor R when a capacitor of capacitance 1.15 μF is connected in parallel with R.

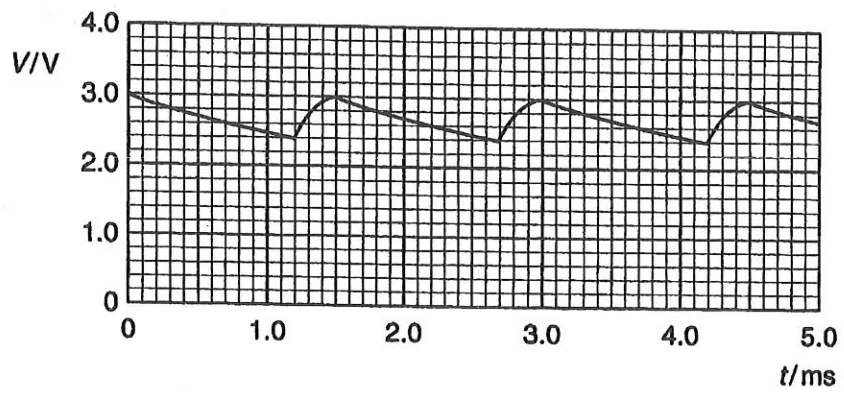


Fig. 3.3

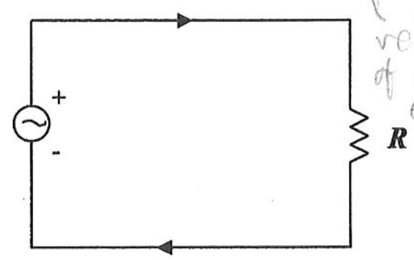
Determine, for the time from $t = 0$ to $t = 1.2$ ms,

i. the change in the charge stored on the capacitor,
ii. the mean current in the resistor R.

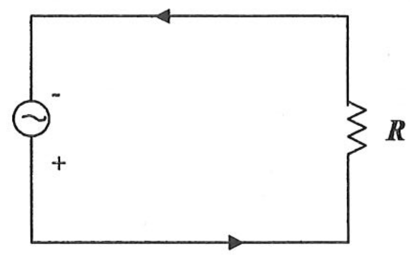
A.C. Circuit

- We can define an a.c. circuit as one in which the direction of its current or polarity of voltage vary periodically with time.
- The direction of the drift velocity reverses, usually many times per second.

velocity of mobile electrons



One Instant

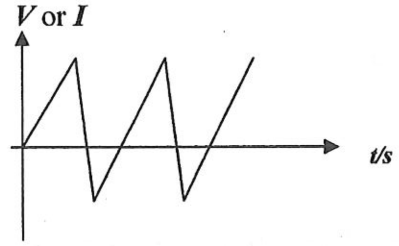


Next Instant

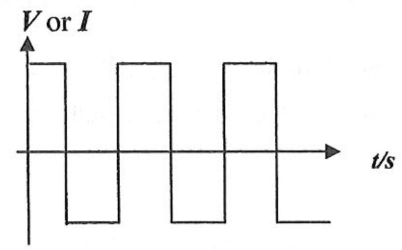
The **polarity** of the EMF changes with time, and is known as an alternating EMF. The current that such an EMF causes to flow, repeatedly changes its direction and is known as alternating current (AC).

The following are examples of some types of alternating voltages that can be generated by a signal generator in the lab.

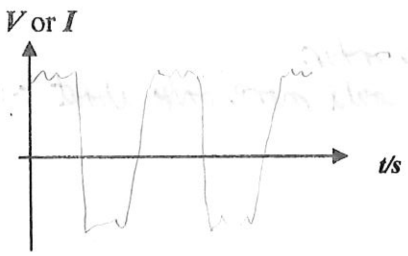
1) Saw tooth
(across deflecting coils on a TV set)



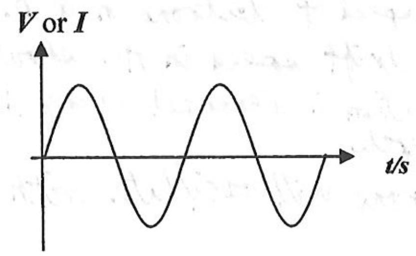
2) Rectangular
(computer information)



3) Irregular
(audio current)



4) Sinusoidal
(mains supply)

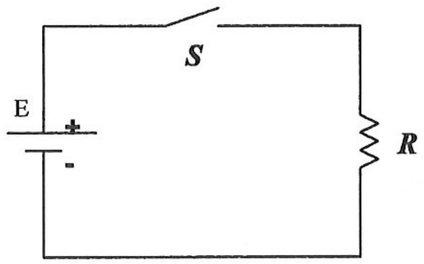


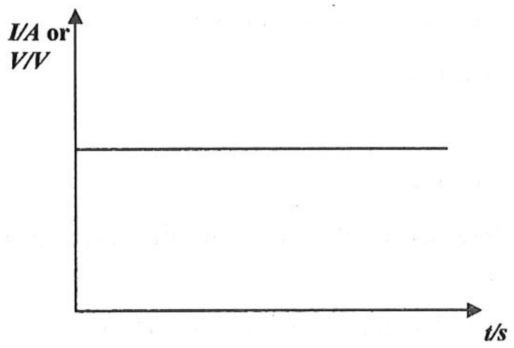
Introduction

Steady D. C.

A steady direct current or voltage flows in the circuit shown below.

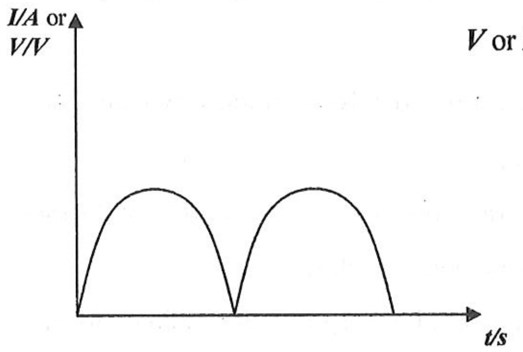
- The magnitude of the current remains constant through time.
- The drift velocity superimposed on the random motion of the charge carriers (e.g. electrons), is in one direction.

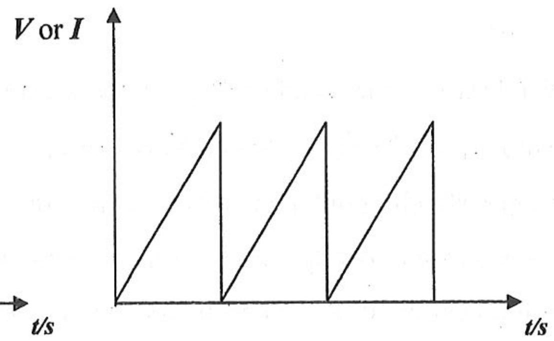




Varying D. C.

In other complicated circuits, the magnitude of the direct current or voltage may vary but the direction of flow remains constant.





- Hence a d.c. circuit can be defined as one whose direction of flow of its current or polarity of voltage remains constant.

Alternating Current

Content

(i) Characteristics of alternating currents

(ii) The transformer

(iii) Transmission of electrical energy

(iv) Rectification

Assessment Objectives

When you have completed work in this unit, you should be able to:

(a) show an understanding of and use, the terms period, frequency, peak value and root mean square value as applied to an alternating current or voltage.

(b) deduce that the mean power in a resistive load is half the maximum power for a sinusoidal alternating current.

(c) represent an alternating current or an alternating voltage by an equation of the form $x = x_o \sin \omega t$.

(d) distinguish between r.m.s and peak values and recall and solve problems by using the relationship $I_{r.m.s} = I_o/\sqrt{2}$ for the sinusoidal case.

(e) show an understanding of the principle of operation of a simple iron-cored transformer and solve problems using $N_s/N_p = V_s/V_p = I_p/I_s$ for an ideal transformer.

(f) show an appreciation of the scientific and economic advantages of alternating current and of high voltages for the transmission of electrical energy.

(g) distinguish graphically between half-wave and full-wave rectification.

(h) explain the use of a single diode for the half-wave rectification of an alternating current.

(i) explain the use of 4 diodes (bridge rectifier) for the full-wave rectification of an alternating current.

(j) analyse the effect of a single capacitor for smoothing, including the effect of the value of capacitance in relation to the load resistance.

Tan Zhi Yang 0356H Alternating Current Ass

Seen

Subject:

Date: 7/7/04

1a) $I_{rms} = \sqrt{\frac{I_0^2 T}{T}}$

$= I_0$

1b) $I_{rms} = \sqrt{\frac{I_0^2 \frac{1}{2} T}{T}}$

$= I_0 \sqrt{\frac{1}{2}}$

$= \frac{I_0}{\sqrt{2}}$

2ai) $\frac{V_s}{V_p} = \frac{N_s}{N_p}$

$V_{rms(s)} = \frac{40}{1000} \times 230$

$= 9.2V$

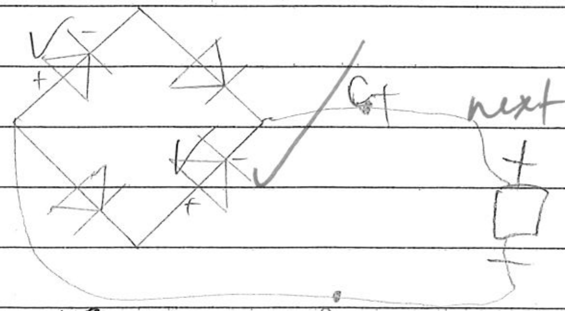
2aii) $\cancel{V_{rms}}\ V_{0(s)} = 9.2(\sqrt{2})$

$= 13.0V$ (3 s.f)

2bi) This prevents current from flowing through the battery in the wrong direction and damaging the battery. X

2bii) The resistor reduces the secondary peak potential difference to below 9.0V so the battery is not damaged by an abnormally high potential difference across it. X

3ai)



next part?

3bi) $P_{mean} = \frac{V_{rms}^2}{R}$

$= \frac{(\frac{3.0}{\sqrt{2}})^2}{4.7 \times 10^3}$

$= 9.57 \times 10^{-4}$ W (3s.f)

Subject: Date:

3bii) The mean power increases as capacitor will release charges when the potential difference across the circuit falls below 3.0V. increase in mean P dissipated

3ci) Change in charge ΔQ = ~~[illegible]~~ $C\Delta V$ final − initial

$= 1.15 \times 10^{-6} \times (3.0 - 2.4)$

$= 6.90 \times 10^{-7}$ C (3s.f)

decrease in charge

3cii) $\langle I \rangle = \frac{6.90 \times 10^{-7}}{1.2 \times 10^{-3}}$ $\frac{\Delta Q}{t}$

$= 5.75 \times 10^{-4}$ A (3s.f)

2bi) Prevents discharging of battery when p.d across battery is lower than p.d of a.c.

2bii) Prevent short circuit → I large → overheating

Name: ______________________ Reg: __________ Date: __________

2. Properties of Op-amp

Figure 2 shows an operational amplifier (op-amp) in a circuit. The op-amp in this question may be considered to be ideal. The input voltage, V_1, is set at – 2.0 V. The split power supply is not shown.

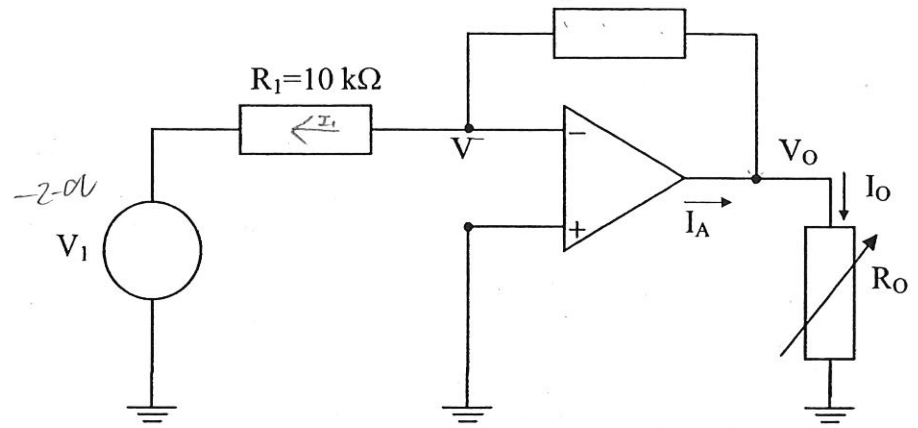


Fig. 2

(a) Assuming the amplifier is not saturated, condition state the property of the op-amp that requires the voltage at the inverting input V^- to be virtually earth. [1]

Infinite open-loop gain

(b) Calculate the current flowing through R_1. Draw an arrow **inside R_1** showing the direction of flow. Label the arrow I_1. [2]

$\frac{2}{10} = 0.2\,mA$, left

$I_1 = \frac{V_1}{R_1} = -\frac{2.0}{10000} = -2.0\times10^{-4}\,A$

(c) Hence, or otherwise, show that the V_O = + 8.0 V. [1]

$V_o = -\frac{R_2}{R_1} \times V_1 = \frac{40}{10} \times -2$ or $V_o - 0 = R_2 \times \cancel{R_1} I_1 = 40 \times 0.2 = 8$

(d) A variable resistor R_O is connected at the output of the amplifier. Its resistance is initially set to 20 kΩ.

(i) Determine I_O, the current flowing through R_O.

$I_o = \frac{8.0}{20\times10^3} = 4.0\times10^{-4}\,A$

$I_o = \frac{8}{20} = 0.4\,mA$

(ii) Write down an equation relating I_1, I_O and I_A (the current flowing at the output of the amplifier).

$\cancel{I_A = I_o + I_1}$ $I_A = I_o + I_1$

(iii)Hence, calculate the value of I_A.

$\cancel{I_A = 0.4 + 0.2}$ $I_A = 0.4 + 0.2$

$\cancel{= 0.6\,mA}$ $= 0.6\,mA$

(iv)If the resistance of R_O is changed to 2 kΩ, determine new value of I_A.

$I_o = \frac{8}{2} = 4\,mA$

$I_A = 4 + 0.2 = 4.2\,mA$

(v) Briefly explain how your answers in (iii) and (iv) show that an ideal op-amp has zero output impedance. [7]

Ideal op-amp is able to provide any current required by the load, while remaining constant output voltage.

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National Junior College – 2004 JC2 Physics

Date: ___________

Group Discussions on Analogue Electronics

1. Frequency Response

Figure 1.1 shows the frequency response of a typical operational amplifier.
The amplifier is used to amplify the input singal shown in Fig 2.2.

$A = \frac{V_o}{V_{in}}$

$10^4 = \frac{V_o}{1.0 \times 10^{-3}}$

$V_o = 10 V$

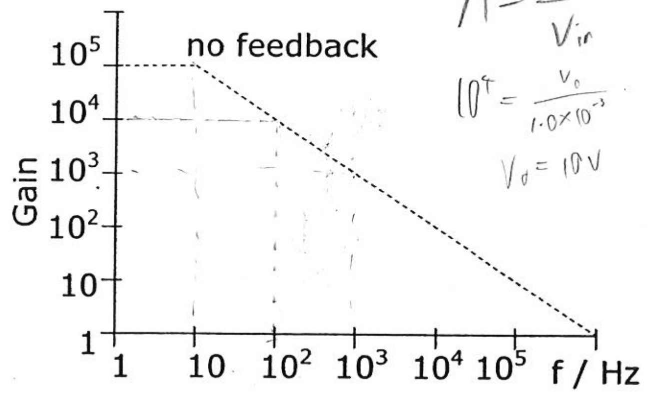


Fig 1.1

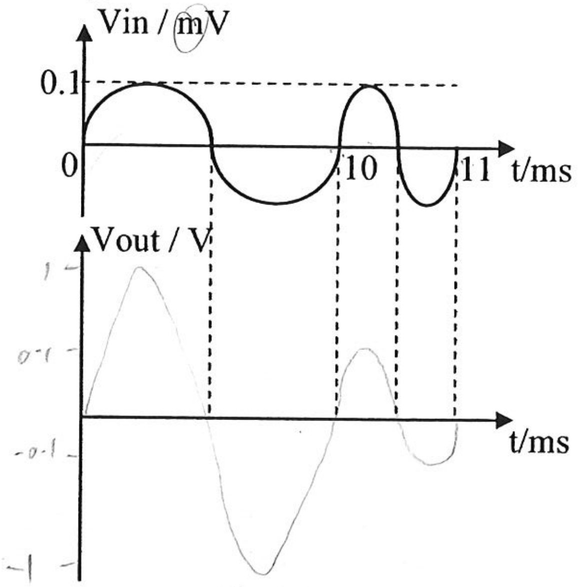
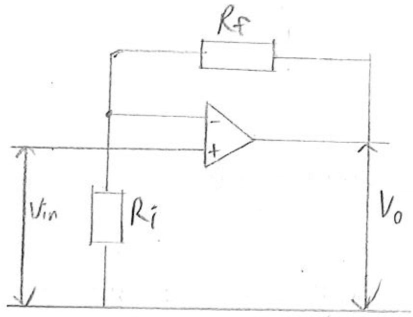
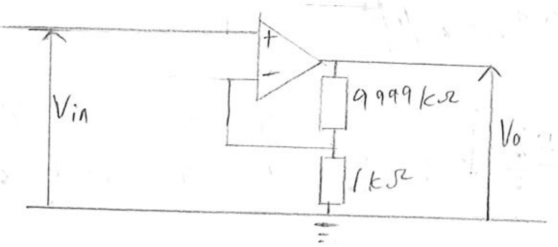


Fig 1.2

(a) Draw a circuit diagram for a *non-inverting amplifier* with a gain of 10^4. Label clearly the values of the resistors you use. $A = 1 + \frac{R_f}{R_1}$ [3]





(b) Determine the bandwidth of the amplifier you have drawn. 100 Hz [1]

(c) Sketch the output of the amplifier when connected to the above input signal. Indicate significant values on the axes. [Hint: Take into account the frequency response of the op-amp.] [2]

(d) Explain how your graph shows that the output signal is distorted. [2]

Different frequency signals amplified by different gain
The output does not resemble the input

(e) Discuss how the circuit in (a) can be modified to prevent this distortion. [1]

Reduce gain to 10^3

(f) State the effect of increasing the level of feedback on (reducing Rf)
(i) gain decrease
(ii) bandwidth. increase [2]