Physics Factsheet

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Transformers

A transformer changes (or transforms) voltages which are alternating. Fig 1 shows the elements of a transformer; two separate coils wound on a soft iron core. One coil, the **input** or **primary**, is fed with an alternating potential difference. The other coil, the **output** or **secondary**, supplies an alternating potential difference of greater or smaller value. There is no direct electrical connection between the two coils, so how does electricity get from one coil to the other? The answer lies in the magnetic field that both coils share.

Fig 1. Transformer

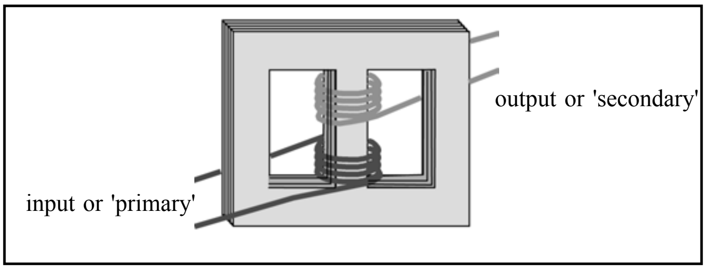
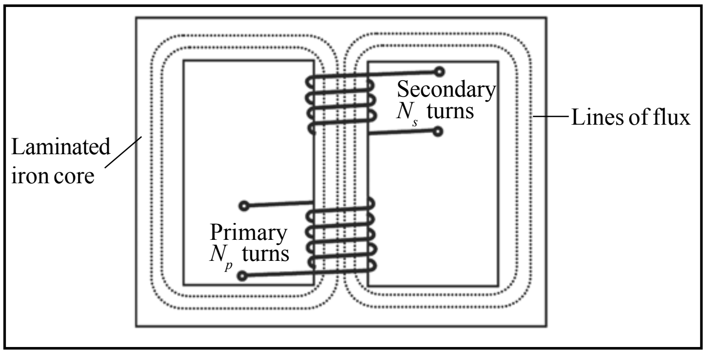


Fig 2 shows a simplified transformer diagram with lines of flux passing through both coils. When there is an alternating current in the primary coil, the flux produced is also alternating and this changing flux also passes through the secondary coil. Recall what you have learnt about induced emfs and the rate of change of flux; apply this to the secondary coil:- 'Because there is always flux changing in the secondary, there is always an (alternating) emf induced in it.'

Fig 2 Simplified transformer



Turns and turns ratio

The number of turns on each coil is important; this information enables us to calculate the output or secondary voltage.
If the number of turns on the primary and secondary are denoted by N_p and N_s then three cases arise. (i) $N_s = N_p$ (ii) $N_s > N_p$ and (iii) $N_s < N_p$.

(i) If $N_s = N_p$ then the alternating voltage induced in the secondary equals the alternating voltage applied to the primary. ie $V_s = V_p$.(this is a rare use of transformers)

(ii) If $N_s > N_p$ then the alternating voltage induced in the secondary is greater than the alternating voltage applied to the primary. ie $V_s > V_p$. In this case where the pd is increased, the transformer is described as being 'step up'

(iii) If $N_s < N_p$ then the alternating voltage induced in the secondary is less than the alternating voltage applied to the primary. ie $V_s < V_p$. Here the voltage is reduced and the transformer is described as 'step down'.

We shall show later that the ratio of the turns is the same as the ratio of the voltages.

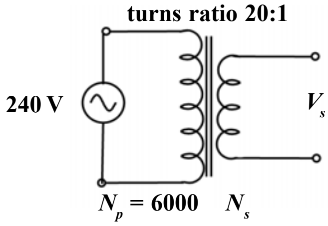
$$\frac{N_s}{N_p} = \frac{V_s}{V_p}$$

where: N_s = *number of turns on secondary*
N_p = *number of turns on primary*
V_s = *voltage on secondary*
V_p = *voltage on primary*

The ratio $\frac{N_s}{N_p}$ *is called the turns ratio.*

When the turns ratio is **greater** than one we have a **step up** transformer; if **less** than one it is a **step down** transformer.

Example 1. A mains transformer accepts 240 volts and has a turns ratio of $\frac{1}{20}$***. There are 6000 turns on the primary.***



Calculate (i) the number of turns on the secondary
(ii) the secondary voltage.

(i) *turns ratio* $= \frac{N_s}{N_p}$

$$\frac{1}{20} = \frac{N_s}{6000}$$

$$N_s = \frac{6000}{20} = 300$$

(ii) $\frac{N_s}{N_p} = \frac{V_s}{V_p}$

$$\frac{300}{6000} = \frac{V_s}{240}$$

$$V_s = 240 \times \frac{300}{6000}$$

$$V_s = 12\ V$$

This is an example of a step down transformer. The secondary voltage has been reduced because there are fewer turns on the secondary coil.

Both the primary and secondary voltages are always alternating. In studying ac voltages a distinction is drawn between root mean square (r.m.s) values and peak values. In almost all transformer questions we use r.m.s values and this should be assumed unless otherwise stated. In this question the 240V and 12V are both r.m.s.

Power and Energy

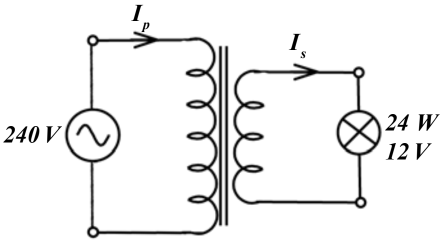
The main reason for using r.m.s values is to enable us to do power calculations. Your early studies of electricity were using direct current (dc) where you used three equations for power:-

$$P = V \times I \qquad P = I^2 \times R \qquad P = \frac{V^2}{R}$$

The same equations can be used with ac providing we use r.m.s values for current I and voltage V.

Now think of a transformer as a sort of machine. Energy is fed in at the primary and taken out at the secondary. The question is 'how efficient is a transformer?' The good news is that they almost 100% efficient and this makes calculations easy.

Example 2. A transformer is connected to a lamp rated at 12V and 24 W. Calculate (i) the secondary current I_s and (ii) the primary current I_p.



(i) at the secondary,

$P = V_s \times I_s$

$24 = 12 \times I_s$

$I_s = 2A$

(ii) We now take the transformer to be 100% efficient. That is, if 24 watts are taken from the secondary, 24 watts are supplied to the primary. N.B. the 24 watts at the primary are supplied at a high voltage of 240V.

At the primary,

$P = V_p \times I_p$

$24 = 240 \times I_p$

$I_p = \frac{24}{240}$

$I_p = 0.1\ A$

Notice what has happened here, the secondary voltage has gone down but the secondary current has gone up. So, at 100% efficiency, there are no power losses,the primary power equals the secondary power.

At 100% efficiency $V_p \times I_p = V_s \times I_s$ *where:*
V_p *= voltage on primary*
I_p *= current on primary*
V_s *= voltage on secondary*
I_s *= current on secondary*

In this example, the value of primary current is only one twentieth that of the secondary.

Of the two coils, which do you think will have the thinnest wire, the primary or the secondary?

Exam Hint: *In transformer calculations, remember that the currents are determined by the load in the* ***secondary****.*
It is a good idea to look first at the secondary ***and then*** *the primary.*

Transmission of electrical energy

One of the most important uses of transformers is to distribute energy from power stations to the consumer. To illustrate how this works we will compare two cases: (i) without a transformer and (ii) with a transformer. Suppose the generator develops 100 000 W at 5000 V.

(i) Without a transformer:

$P = V \times I$

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

$I = \frac{100{,}000}{5000}$

$I = 20\ A$

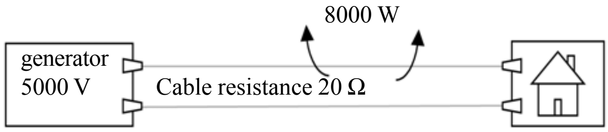
Suppose further that the total cable resistance is 20 Ω. This resistance will dissipate the usual Joule heating (I^2R).

$P = I^2 \times R$

$P = 20^2 \times 20$

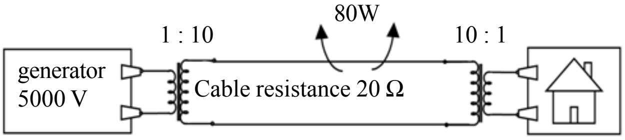
$P = 8000\ W$

This energy is lost into the atmosphere



(ii) With a transformer:

A better way is to use a step up transformer at the generator and a (similar) step down transformer at the consumer.



If the transformer at the generator has a turns ratio of 1:10, the secondary voltage will be 50 000V. From equation 2, the secondary current is now 20 ÷ 10 = 2.0 A. This much smaller current is in the same cables of resistance 20 Ω. The power dissipated is calculated as before.

$P = I^2 \times R$

$P = 2^2 \times 20$

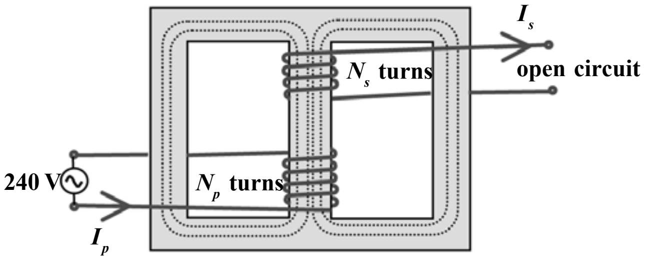
$P = 80\ W$

This is only 1% of the former value! To complete the process, a step down transformer close to the consumer brings the voltage down to the original 5000 V.

Heat losses in a resistor depend on (current)^2.
So if the current is reduced by a factor of 10, then the losses are reduced by a factor of $(10)^2$ - the heat loss is small when the current is small.
In transformers a ***small*** *current appears with a* ***high*** *voltage.*
This is the reason for using pylons carrying cables at 132000 volts or more.

Transformer theory

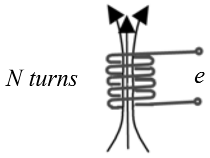
The transformer below has the primary connected to an ac supply of 240 volts, the secondary is not connected.



(i) What is the secondary current I_s?
and , remembering that it is connected to 240 V,
(ii) what is the current in the primary I_p?

The answer to part (i) is simple;
even if there is an induced emf, there isn't a complete circuit and so the current I_s is zero.

In part (ii) we see 240 volts connected to some turns of copper wire the resistance of which is a few ohms. A low resistance should lead to a large current. The amazing thing is that the current I_p is very small and in many cases is neglected altogether. To understand why this is so we must use Faraday's law of electro-magnetic induction.

> ***Faraday's law of electro-magnetic induction***
> *If there is a changing flux threading a coil of N turns, the induced emf is given by* $e = -N\times\frac{d\phi}{dt}$
>
> 
>
>
> $e = -N\times\frac{d\phi}{dt}$

In what follows, the minus sign is not important and is omitted for simplicity.

The secondary with N_s turns is threaded by an alternating flux ϕ and this gives us the useful secondary voltage V_s.

In this case, $V_s = N_s\times\frac{d\phi}{dt}$ *equation 3*

Do not forget that the same flux threads the primary of N_p turns.

The induced emf is $N_p\times\frac{d\phi}{dt}$

There are now two sources of p.d. in the primary, the applied p.d. V_p and the induced emf, $N_P\times\frac{d\phi}{dt}$

Because the primary current is practically zero, this emf is balanced by the applied voltage V_p,

ie $V_p = N_p\times\frac{d\phi}{dt}$ *equation 4*

Dividing equation 3 by equation 4 gives:

$$\frac{V_s}{V_p}=\frac{N_s\times\cancel{\frac{d\phi}{dt}}}{N_p\times\cancel{\frac{d\phi}{dt}}}$$

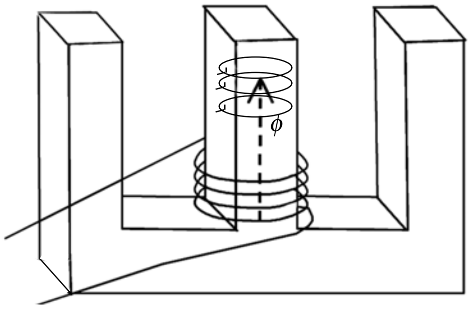
$$\frac{V_s}{V_p}=\frac{N_s}{N_p}= \text{turns ratio}$$

Losses in a transformer

The small losses that occur in a transformer arise from several causes:

- **Flux losses** - This happens when some lines of flux from the primary do not thread the secondary. From the shape of the core in fig 1 and 2 you can see that this loss is very small.
- **Copper losses -** This is the usual Joule heating (I^2R) that occurs in the copper coils having resistance R. To reduce this energy loss the resistance has to be reduced by using thicker wire. There is an economic choice here, the cost of thicker wire or heat loss.
- **Iron losses** - There are two types.
  (a) **Hysteresis losses** - This is because energy is constantly being used to magnetise and demagnetise the iron core as the current alternates. It is reduced by using 'soft' iron in the core. 'Soft' means magnetically soft, easy to magnetise and demagnetise.

  (b) **Eddy current losses** - The diagram below shows a solid iron core without a secondary.



The alternating flux will induce currents in the iron core itself. These are called 'eddy currents.' If the core is in the form of a solid chunk of iron, the resistance offered will be very small and large currents will flow. To prevent this large loss of energy, the core is made from many thin sheets (laminae) each insulated from each other. You will see 'soft iron laminations' in other components where a.c. is used

Efficiency

Although transformers are close to 100% efficient, we may have to use the equation for **efficiency** to get a realistic value for current in the secondary.

As a rule, when calculating efficiency we always use energy or power. The efficiency of any device is given by:

$$\text{efficiency}=\frac{\text{power output}}{\text{power input}}$$

For a transformer, the equation becomes:

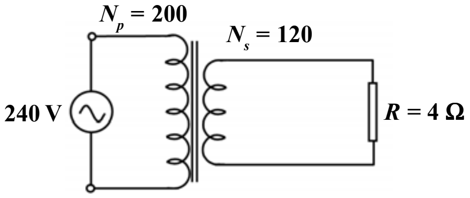
$$\text{efficiency}=\frac{V_s\times I_s}{V_p\times I_p}\times 100\%$$

Exam Hint:
1. *Remember effciency cannot be greater than 100% - if you find a value that seems to be, go back and check*
2. *You must use **power** (or energy) in the efficiency equation, not voltage or current.*

Exam Workshop

This is a typical poor student's answer to an exam question. The comments explain what is wrong with the answers and how they can be improved. The examiner's mark scheme is given below.

A transformer has a primary of 2400 turns and a secondary of 120 turns. The secondary has a load of 4 Ω and the primary is connected to 240 volts a.c.



For the first part of this question you may assume the transformer to be 100% efficient. Calculate:

(i) the turns ratio

$\text{turns ratio} = \frac{2400}{120}$ ×

> The candidate is almost right.
>
> The turns ratio $= \frac{N_s}{N_p} = \frac{120}{240} = \frac{1}{20}$

(ii) the secondary voltage

$\frac{120}{2400} = \frac{V_s}{240}$ ✓ $\frac{120}{2400} \times 240 = V_s$ $V_s = 12\ V$ ✓

> Full marks. The candidate has correctly recognised that the ratio of the turns is the corresponding ratio of the voltages. The calculation is correct.

(iii)the secondary current

$I = \frac{V}{R}$ $I = \frac{12}{4}$ ✓ $I = 3\ A$

> Correct calculation and unit for current

(iv) the secondary power

$\text{power} = \text{volts} \times \text{amps} = 12 \times 3 = 36\ W$ ✓

> Correct calculation and unit for power

(v) the primary current

$\text{primary current} = \frac{V_p}{R} = \frac{240}{4} = 60\ A$ ×

> This is incorrect, the candidate has used the primary voltage (240V) with resistance R = 4 Ω in the secondary

Examiner's Answers

(i) $\text{turns ratio} = \frac{N_s}{N_p} = \frac{120}{2400} = \frac{1}{20}$

(ii) $\text{voltage ratio} = \frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{1}{20}$

$\frac{V_s}{200} = \frac{1}{20}$

$V_s = 240 \times \frac{1}{20}$ $V_s = 12\ V$

(iii) $\text{secondary current} = \frac{V_s}{R} = \frac{12}{4} = 3\ A$

(iv) $\text{secondary power} = V_s \times I_s = 12 \times 3 = 36\ W$

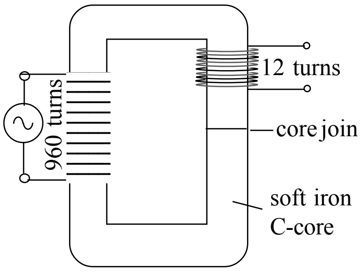
(v) *to find the primary current, assume 100% efficiency*

$\text{efficiency} = \frac{V_s \times I_s}{V_p \times I_p} \times 100\%$ $\frac{96}{100} = \frac{36\text{ W}}{\text{primary power}}$

$\text{primary power} = \frac{36 \times 100}{96} = 37.5\text{ W}$

Typical Exam Question

The figure below shows a demonstration transformer made from two joined soft iron C-cores.



The primary coil is commercially made and consists of 960 turns. A student winds a 'loose' coil of 12 turns on the other limb of the transformer. An alternating supply of 240 volts is connected to the primary.

(i) What voltage would you expect at the secondary ?

(ii) If a 3V bulb is connected to the secondary would the bulb light normally?

(iii) Will the brightness of the bulb be affected by the fact that the secondary coil is not closely wound on the core? Explain your answer.

(iv) The secondary is now moved up and down on the core. How, if at all, will the brightness change now? Explain your answer.

(v) The bulb is rated at 1.2W and is at normal brightness. Calculate the secondary and primary currents in the transformer.

(vi) The place where the two C- cores join is now opened up slightly so that there is a small air gap between the cores. How, if at all, will the brightness change now?
Explain your answer.

Answers

(i) $\frac{V_s}{V_p} = \frac{N_s}{N_p}$

$\frac{12}{960} = \frac{V_s}{240} \Rightarrow V_s = 3\ V$

(*ii) The bulb is supplied with the correct voltage and will light normally.*

(iii) If the turns of the secondary aren't close fitting to themselves or the core the brightness is not affected. This is because the same amount of (changing) flux links the coil giving the same induced emf.

(iv) No change in brightness. Same reason as (iii).

(v) Starting at the secondary,

$\text{power} = \text{volts} \times \text{amps}$
$1.2 = 3 \times I_s$
$I_s = 0.4\ A$

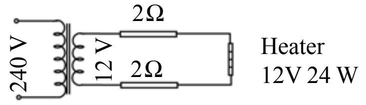
At the primary, we assume 100% efficiency so the same power is delivered at 240V.

$\text{power} = \text{volts} \times \text{amps}$
$1.2 = 240 \times I_p$
$I_p = 0.4\ A$

(vi) When there is a small air gap between the two iron cores, the flux linking the coils will be reduced .This reduction leads to a reduced emf in the secondary and the bulb's brightness will be much reduced.

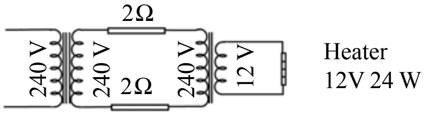
Practice Questions

1. The diagram below show a heater that is supplied by long leads having a total resistance of 4Ω.



The heater is to work off 12volts and consumes 24 watts. Calculate:
(i) the current the heater is designed to take,
(ii) the resistance of the heater,
(iii) the current when the heater is fed by the leads with resistance 4Ω as in Fig A
(iv) the power wasted in the leads.

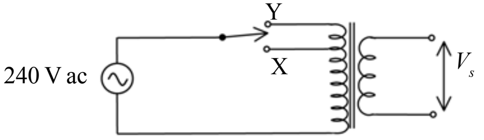
An alternative situation is shown below where a second transformer is used.



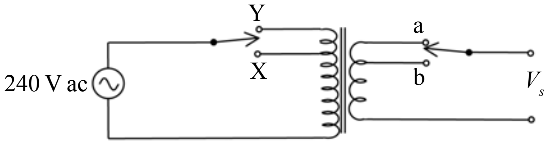
This transformer is assumed to be 100% efficient and supplies 12 volts to the heater. Calculate:

(v) the current in the heater
(vi) the current in the leads
(vii) the power wasted in the leads.

2. (a) The transformer shown has two terminals X and Y close together ('primary tappings').When will the secondary voltage V_s be greatest, using terminal X or Y ?
Give a reason for your answer.

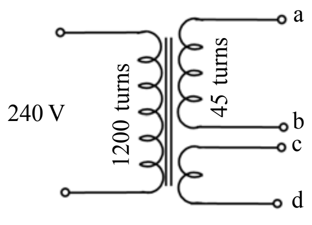


(b) The transformer now shows the secondary with tappings at terminals a and b.



Which pair of terminals gives:
(i) the greatest output voltage?
(ii) the least output voltage?

3. The transformer shown has a primary of 1200 turns connected to an alternating supply of 240V. There are two separate secondaries. The secondary between terminals a and b has 45 turns.



(i) What is the voltage between a and b ?
(ii) The secondary between c and d is to supply 3V, how many turns will be required?
(iii) How should the secondaries be connected to supply 12V?
(iv) How should the secondaries be connected to supply 6V?

4. A college building is to be supplied with 120 kW of power through cable having a total resistance of 0.1Ω. When the voltage at the college end is 240V calculate:

(i) the current in the cable
(ii) the heat loss in the cable.

An inspector suggests supplying the college with 10 000V. When this is done calculate:
(iii) the new current in the cable
(iv) the new heat loss in the cable.
(v) Give a sketch showing how this can be achieved using transformers. Will they be step up or step down? What will be the turns ratio?

5. A transformer with an efficiency of 90% is designed to operate from 20V and supply electrical energy at 240V.
(i) Is the transformer step up or step down?
(ii) What is the turns ratio?
(iii) A 240V lamp rated at 100W is connected to the secondary of the transformer. What will be the current in the primary ?

6. A step down transformer is used to operate a low voltage lamp in the usual way. Consider what would happen if the insulation between the soft iron laminations started to breakdown. What changes would occur in
(i) the transformer core ?
(ii) the secondary current?
(iii) the primary current?

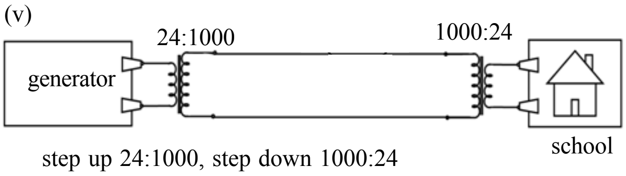
Answers

1. (i) I = 2A (ii) R = 6Ω (iii) I = 1.2 A (iv) P = 5.76W
(v) I = 2A (as part i) (vi) I_p = 0.1A (vii) P = 0.04W

2. In all cases $V_s = V_p \times \left(\dfrac{N_s}{N_p}\right)$
(a) terminal X to make N_p small.
(b) (i) terminals X and a to make N_p small and N_s large.
(ii) terminals Y and b to make N_p large and N_s small.

3. (i) V_s = 9V. (ii) N_s= 15 turns.
(iii) Add voltages, link b to c. 12V between a and d.
(iv) Subtract voltages, link b to d. 6V between a and c.

4. (i) I = 500A. (ii) 25kW (≈ 20%) (iii) I = 12A.
(iv) 14.4W (negligible).
(v)



step up 24:1000, step down 1000:24

5. (i) step up. (ii) Turns ratio = 12. (iii) 5.55A.

6. (i) Eddy currents in core which now gets hot.
(ii) secondary current unchanged.
(iii) primary current increases to supply extra energy now being dissipated in the core.

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