Copper and Electricity: Transformers and the Grid

Transformers

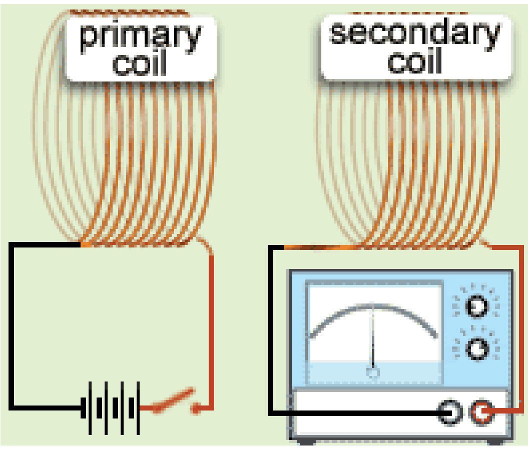
Using transformers

We use transformers to change the size of a voltage. We can step the voltage down from a high voltage to a smaller one, for example in a mobile phone charger, or we can step it up, for example at a power station, to produce the very high voltages needed to transmit electricity through the National Grid power lines. The principles are the same. A transformer has two coils - a primary coil and a secondary coil. An alternating current flows in the primary coil and this induces a voltage in the secondary coil.

Let's see why.

Principles of a transformer

Imagine two coils next to each other. The primary coil is part of a circuit with a battery. The secondary coil is connected to an ammeter.



When we close the switch in the primary circuit, the ammeter flicks to the right.
When we open the switch, the ammeter flicks to the left.

There is no induced current once the switch is left either open or closed. That is, for a steady current in the primary coil, there is no current in the secondary coil.

Step-up transformers increase the voltage from the generators at a power station for transmission over high-voltage cables in the Grid.

Mobile phone chargers contain a step-down transformer to convert the input of 220 V to a working output voltage of around 5 V.

Copper windings in a transformer.

This is because the primary coil behaves like an electromagnet when we close the switch. It is as if we have pushed a bar magnet towards the secondary coil. And this induces a voltage in the secondary coil, but only while the 'magnet' is moving i.e. whilst the current is changing. Once the magnetic field is steady, there is no induced electromotive force (EMF) in the secondary coil.

When we open the switch, the electromagnet is switched off. This is like pulling a bar magnet away from the secondary coil. Again, this induces an EMF (in the opposite direction).

The primary coil produces a magnetic field in the secondary coil. It is only while this magnetic field is changing that we get an EMF induced in the secondary coil.

Transformers

We can make the magnetic field carry on changing by using an alternating current in the primary coil.

This produces a magnetic field in the secondary coil. Since the current is alternating, the magnetic field also alternates back and forth. This changing magnetic field induces an alternating EMF in the secondary coil.

It is important to get as strong a magnetic field as possible in the secondary coil. To achieve this, we can put a soft iron core through the coils. The soft iron core increases the magnetic flux density and guides the magnetic field from the primary coil to the secondary coil. This increases the induced EMF. Iron is a 'soft' magnetic material so it takes very little energy to change the magnetic field within it. Modern transformers often use silicon steel which is also magnetically soft as an alternative to iron.

We get the best effect by mounting the coils on a closed loop of soft iron. This is how we build transformers.

Transformers and turns ratio

From Faraday's Law, we can deduce that the greater the rate at which the magnetic field changes, the greater the EMF induced. Also, the more turns there are on the secondary coil, the bigger the induced EMF. If we increase the turns on the secondary coil, the output voltage increases in proportion.

We find that the ratio of the induced EMF to the input voltage is the same as the ratio of the turns on the secondary coil to the turns on the primary coil.
Induced EMF / Input voltage = Turns on the secondary coil / Turns on the primary coil

$$V_{out} / V_{in} = N_s / N_p$$

Step-down transformers

If the number of turns on the secondary coil is less than the number on the primary coil, then the output voltage will be smaller than the input voltage. We call this type of transformer a step-down transformer. We use a step-down transformer to step the voltage down from a high voltage to a low voltage.
Pieces of electronic equipment (like TVs and radios) use a step-down transformer to reduce the mains voltage from 230 V to the operating voltage of the electronics.

Step-up transformers

If the secondary coil has more turns than the primary coil then the output voltage is bigger than the input voltage. We call this a step-up transformer.

At first it may seem that we are getting something for nothing. However, this is not the case when we consider the amount of energy going into and out of the transformer. We never get more energy out than we put in. The voltage may be bigger on the output, but the current will be bigger on the input. The power is voltage x current. Therefore, in an ideal transformer, the power in and the power out will be the same.

The Grid

Using transformers

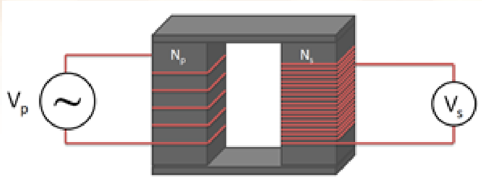
In the UK, the National Grid relies on transformers. There are at least five transformers between a power station and a domestic user.

This is because we use high voltage for carrying the electric current over large distances and we use small voltages in our homes. The high transmission voltages are to reduce large losses from joule heating in the transmission cables. And the low voltages in the home are for reasons of safety.

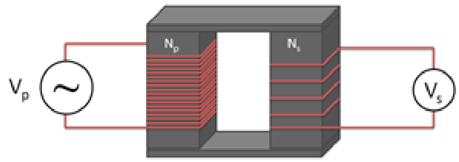
Transmission voltages

Imagine we want to supply a small town with electricity. The average power needed by the town is 100 MW. The National Grid has to supply this power. If we use a small transmission voltage (20 kV), there will need to be a large current in the transmission cables (5000 A). This will make the transmission lines very hot and waste energy. The wasted power increases with the square of current.

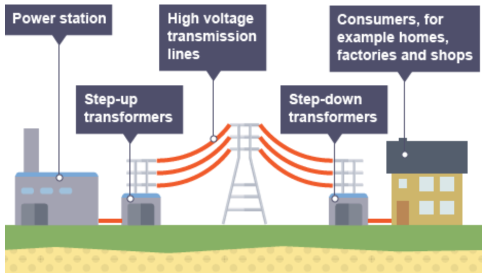
If we use a high transmission voltage (400 kV), then the current that needs to flow to the town will be less (and still deliver the same power). A smaller current causes less heating in the transmission cables. So there is less waste.



Increasing the number of turns in the secondary coil gives a step-up transformer. Vp = input voltage and Vs = output voltage. (Courtesy of physbot.co.uk.)



Decreasing the number of turns in the secondary coil gives a step-down transformer. Vp = input voltage and Vs = output voltage. (Courtesy of physbot.co.uk.)



The National Grid is used to distribute electricity around the country from power stations to consumers. (Courtesy of BBC Bitesize Transformers in the National Grid.)

The table below shows the calculations.

Quantity	Formula used	Low V	High V
Power requirement of town (W)	P_{out}	100,000,000	
Supply voltage at the town (V)	V_{out}	20,000	400,000
Current needed to provide the power (A)	$P_{out} = V_{out} x I$	5,000	250
Joule heating in power cables (W)	$P_{waste} = I^2R$	75,000,000	187,500
Power that the power station needs to supply (W)	$P_{in} = P_{waste} + P_{out}$	175,000,000	100,187,500
Efficiency of system (%)	$eff = (100 * P_{out}) \div P_{in}$	57.1	99.8

Table 1: Worked examples for a low transmission voltage (20 kV) and a high voltage (400 kV).
Resistance of cable is taken to be 3 W.

Notice that when the transmission voltage is 20 times bigger, the current needed is reduced by a factor of 20 as well. However, the wasted power is reduced by a factor of 400 (= 20^2). This is because the joule heating depends on the square of the current.

Better transformers

Transformers are highly efficient. The very best may achieve 99.5% efficiency but most are more likely to be about 98% efficient. Since the electricity has to pass through at least five transformers before it reaches the consumer, their combined efficiency is around 92%. In the UK, about 8.5% of all generated electricity is wasted in the grid and distribution system.

Most transformers in the system were installed during the 1960s when demand for electricity increased rapidly. The efficiency of many of these 40 year-old transformers is poor compared to the best practice of today. In fact, relatively poor transformers are still being installed so the system isn't necessarily improving with new transformers.

It is therefore desirable to manufacture and install more efficient transformers.

Losses occur:

- in the primary coil and secondary coil (because of their electrical resistance).
- in the core (because energy is lost as the magnetic field changes, and because small currents are induced in the core, and these waste energy).

The core losses are minimised by using high quality silicon steel for the core, and laminating the iron to reduce eddy currents.

The losses in the coils are known as load losses. They increase with the square of the current being taken from the transformer. Load losses are minimised by using copper windings for low resistance.

Questions

1. **Which of the following are true statements about a step-up transformer?**

   a) The voltage across the secondary coil is greater than the voltage across the primary.

   b) There are fewer turns on the secondary coil than the primary.

   c) The output power is greater than the input power.

   d) The current in the secondary coil is greater than the current in the primary coil.

   e) Attaching a 6 V battery to the primary coil will produce a bigger voltage on the secondary coil.

2. **Imagine you want to supply electricity to a remote house, which has a peak requirement of 11.5 kW. The 3 km cable to the house has a resistance of 50Ω. It is suggested that the transmission cables use the same voltage as the house - 230 V. Work through the parts to see if this is sensible (use the peak power for all the parts).**

   a) What will the current in the transmission cable be?

b) What will the joule heating in the cable be?

c) What is the total input power needed to provide 11.5 kW to the house?

d) How efficient is this system?

Imagine that we increase the supply voltage by a factor of 30.

e) How much smaller will the current in the cables be?

f) How much smaller will the joule heating be?

We will need a step-down transformer at the house to get the voltage back to 230 V.

g) What will be the turns ratio of the step-down transformer?

h) Why do we need to reduce the voltage?

Click here for answers

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