Electrical Machinery – Part 4
Some Ideal Machines

Transformers

Let us now add a second winding to an inductor to make a transformer (fig 4.1) – the primary winding has $N_p$ turns and the secondary winding has $N_s$ turns. The battery voltage is $V_p$ and when it is connected to the primary winding, it produces a magnetic flux $\Phi$ in the core:

$$\Phi = \left( \frac{V_p \cdot t}{N_p} \right)$$

The flux rises at a rate that induces a voltage $\mathcal{E}$ in every turn of both windings such that the total voltage induced in the primary winding is equal to the battery voltage $V_p$ and opposing it:

$$V_p = \mathcal{E} \cdot N_p$$

Similarly, the total voltage $V_s$ induced in the secondary winding is:

$$V_s = \mathcal{E} \cdot N_s = V_p \left( \frac{N_s}{N_p} \right)$$

If we now connect a load resistor $R$ to the secondary – a current $I_s$ flows in accordance with Ohm’s Law:

$$I_s = \frac{V_s}{R}$$

Energy is now flowing from the transformer to the load – but where is it coming from?

When the load $R$ is connected, the flux $\Phi$ must continue to rise at its original rate to maintain the induced voltage that balances the supply voltage $V_p$ – thus the total current encircling the flux in the core must also continue to rise at its original rate.

Before the load is connected, the only current flowing is that in the primary winding – so the total current encircling the flux is: $I_p \cdot N_p$

After the load is connected, there is also a current flowing in the secondary – the total current encircling the flux due to this is: $I_s \cdot N_s$

The primary current automatically adjusts itself to leave the total current encircling the flux in the core unaffected by the current in the secondary winding.

The primary and secondary currents encircle the core in opposite directions – thus the primary current $I_p$ has to increase by an amount:

$$I_s \left( \frac{N_s}{N_p} \right)$$

Fig 4.2 shows graphically how the primary current increases.

We can therefore say:

The primary voltage controls the secondary voltage.
The secondary current controls the primary current.
Are we saying that it is possible to connect an unchanging voltage source to the primary winding and obtain an unchanging voltage from the secondary winding?

The important thing to note is that the action of transferring voltage, current, and energy from the primary circuit to the secondary circuit does not depend on the input voltage changing – yet alone be ‘alternating’. But as illustrated in fig 4.2 – the primary current and flux in the core will eventually rise to an impractical level. Actual limitations will be considered in Part 5 but for now we will just acknowledge that there will be some limit. There are various methods that can be used to cause the current and flux to return to zero but the simplest, and most relevant to the present discussion, is to reverse the supply voltage. This is illustrated in fig 4.3 for the primary winding of a transformer with no load.

As before, the current $I_p$ starts to rise when the voltage $V_p$ is applied. When the current reaches the desired maximum value, the voltage is inverted and the current falls to zero; it then continues in a negative direction until the voltage is again inverted.

The dashed line $P_p$ shows the product of $I_p$ and $V_p$. The area under this line represents the energy $E_p$ stored in the inductor. When the polarity of $V_p$ changes, $P_p$ becomes negative, that is, power starts to flow out of the inductor, thus reducing the stored energy.

When the stored energy is released, it is returned to the source and becomes available for reuse. Thus, on average, no energy is taken.

The current $I_p$ is called the magnetising current and examination of the waveforms show that this current lags the voltage by a quarter cycle and thus the current is flowing in the reverse direction to the applied voltage half the time.

Any attempt to calculate power using separate voltage and current meters or of attempting to apply Ohm’s Law to the circuit, is doomed to failure. Measurements need to be made with a proper watt meter or joule meter.

In Part 3 we saw that, by increasing the number of turns on an inductor by a factor of $N$, the flux $\Phi$ is decreased by a factor of $N$ while the current is decreased by a factor of $N^2$. In reality, there will be a minimum number of primary turns that are required to prevent the flux, and the magnetising current, rising too quickly for a given maximum supply voltage and minimum supply frequency.

Thus the number of turns on the primary winding of a transformer is by no means arbitrary.

Thus, even for a perfectly lossless transformer, we are only justified in saying:

$$\frac{\text{primary turns}}{\text{secondary turns}} = \frac{\text{primary voltage}}{\text{secondary voltage}} = \frac{\text{secondary current}}{\text{primary current}}$$

if we ignore the magnetising current.

But, as implied above, the factors that determine the magnetising current play an essential part in the design of the whole transformer.
Consider a transformer as in fig 4.1 having a secondary with \( n \) times the number of primary turns – thus making a 1:\( n \) step-up transformer. The waveforms in fig 4.4 are for a transformer with \( n=2 \).

A) A voltage \( V_p \) is applied to the primary winding

B) A magnetising current \( I_{mag} \) flows in the primary circuit

C) A voltage \( V_s = n \cdot V_p \) is induced in the secondary winding

D) A current \( I_s = V_s / R \) flows in the secondary circuit

E) The resultant total primary current \( I_p = n \cdot I_s + I_{mag} \)
Let us now apply what we know in order to build a lossless but otherwise realistic transformer.

First let us consider the primary winding of the transformer:

Let the supply frequency be 50 Hz and the supply voltage be ±200 V.

A maximum flux density of 1 T would be reasonable and will occur when 200 V has been applied for 5 ms. This will also be the time when the magnetising current is a maximum.

We will assume that the cross-sectional area of the core is 10 square centimetres.

We will also need to leave a gap in the core. With our ideal magnetic material, if we did not leave a gap, the reluctance of the magnetic circuit would be zero, which would make the equations in Part 3 moot. A gap of 0.1 mm will do.

When we get to Part 5 – Losses it will be apparent why we have chosen these particular values. For now they just need to be accepted as convenient round numbers.

Let us now plug these values into our existing equations:

\[ V = 200 \text{ V} \quad t = 0.005 \text{ s} \quad B = 1 \text{ T} \quad A = 0.001 \text{ m}^2 \quad d = 0.0001 \text{ m} \]

Flux:
\[ \Phi = BA = 1 \times 0.001 = 0.001 \text{ Wb} \]

Turns:
\[ N = \frac{Vt}{\Phi} = \frac{200 \times 0.005}{0.001} = 1000 \]

Reluctance:
\[ R = \frac{d}{\mu A} = \frac{0.0001 \times 1000000}{1.2566 \times 0.001} = \frac{100000}{1.2566} \text{ A/Wb} \]

Inductance:
\[ L = \frac{N^2}{R} = \frac{1000 \times 1000 \times 1.2566}{100000} = 12.566 \text{ H} \]

Current:
\[ I = \frac{Vt}{L} = \frac{200 \times 0.005}{12.566} = 0.0816 \text{ A} \]

Energy:
\[ E = \frac{(Vt)^2}{2L} = 0.0408 \text{ J} \]

Note that none of the above quantities depend on the energy actually being transferred from the input to the output of the transformer; all these quantities remain constant regardless of the load. Although a (magnetising) current flows and associated energy is stored in the transformer, this does not, of itself, constitute any form of loss from the transformer, as we have seen (fig 4.3) above.

When we consider losses in Part 5, we will find that any losses associated with magnetising the core tend to be independent of load and thus remain reasonably constant – thus the term ‘fixed losses’.

In the absence of losses we are able to draw unlimited power from the transformer. Again, when we get to Part 5, we will see that when we chose the cross-sectional area of the core we were making a major step towards determining the maximum power that can actually be transferred to the load. This is basically limited by losses due to the resistance of the windings. These losses will vary with the current drawn – thus the term ‘variable losses’.

We will make this a step-down transformer and put in some appropriate figures:

Secondary voltage = 10 V → Primary turns : Secondary turns = 20 : 1 → Secondary turns = 50
Secondary current = 5 A → Primary current = 0.25 A + magnetising current.
Generators & Motors

If we start with a current-carrying conductor moving in a magnetic field as described in Part 3, we need to consider how to convert this unidirectional linear motion into continuous circular motion.

Fig 4.5 shows a simple motor as found in school textbooks and on examination papers.

As the single-turn coil rotates, the flux $\Phi$ passing through it varies cyclically as does the rate of change of $\Phi$ which equals the voltage induced in the coil $\mathcal{E}$ – which swings positive and negative each revolution.

The split-ring commutator not only makes electrical connection to the rotating coil but also automatically reverses the connections to the coil just as the induced voltage passes through zero.

Although we can make a motor based on it and watch it whiz round merrily, it makes a very poor example. While it does illustrate the essential parts of a motor it is ultimately a practical and pedagogical dead end. We will deal with it later.

In order to make it into a useful motor we need to go back to that current-carrying conductor moving in a magnetic field as described in Part 3. If instead of a single conductor moving in a gap in the core, we cut a pair of gaps, we can mount a coil with its commutator attached so that it is free to turn in the magnetic field – as shown in fig 4.6

We now have a properly defined, low reluctance, magnetic circuit. The purpose of the core inside the coil is simply to reduce the reluctance of the magnetic circuit. The core may rotate with the coil or the coil may rotate independently.

We can further reduce the reluctance of the magnetic circuit by winding the coil in slots in the core and thus make the gap even smaller – as shown in fig 4.7

Fig 4.8 shows the alternating voltage induced in the coil.

Fig 4.9 shows the voltage as seen at the motor terminals after the commutator – the significant point is that the voltage is not constant but dips to zero, twice per revolution as the induced voltage changes polarity.

In Part 3 we found that the velocity, battery voltage, induced voltage, force, and current all played nicely together to give an induced voltage equal to the battery voltage and constant velocity, force, and current.

In this case, the induced voltage, as seen at the terminals, does not balance the battery voltage – the coil short-circuits the battery twice per revolution and the whole argument collapses in ruins.
We can solve this problem by having multiple coils arranged in slots around the rotor core and a multi-segment commutator.

*Fig 4.10* shows an actual rotor from a small motor. There are numerous ways of arranging these coils in the slots and arranging their connections to the commutator. We will choose a simple example with 12 slots, 12 coils, and 12 commutator segments.

Let us use the generic terms: *rotor* for the part that rotates, and *stator* for the part that remains stationary. *Fig 4.11* shows the rotor and stator of such a motor rolled out flat. The coils and commutator move in the direction shown while the brushes and magnetic poles remain fixed.

Starting at commutator segment 1, there is a single turn coil, shown in red, which passes through a slot in the rotor and returns through a diametrically opposite slot and finishes on segment 2. Then, from this segment there is another coil which finishes at segment 3. Note that the coils that start on segments 2 to 6, go away from the commutator (shown by a solid line) over a south pole and return to the commutator (shown by a dashed line) over a north pole; as the rotor turns, the voltages induced in each of these coils add up. We therefore place a brush in contact with each end of these five coils as shown. The fact that these brushes are also each shorting out a coil (the red one and the blue one) is of no consequence because there is no voltage being induced in either of these coils.

As we go on, the coils starting on segments 7 to 12, go out over a north pole and return over a south pole; as the rotor turns, the voltages induced in each of these coils add up but the voltages are acting in the opposite direction to those induced in the first set. When the end of the last coil is finally connected to segment 1, thus making a complete circuit, the voltages around the rotor have cancelled out and the short circuit is of no consequence. Also, the two existing brushes are in just the right place to make contact with the correct commutator segments connected to these coils.

*Fig 4.12* is the equivalent circuit of the rotor with the voltage induced in each coil shown by a cell.
Fig 4.13 shows the ubiquitous Westminster Motor Kit assembled. It would be useful to investigate why it works so badly and indeed why it works at all.

This represents a practical realisation of fig 4.1 but with two significant differences:

- The impossible pair of magnetic monopoles floating in space are replaced by a pair of slab magnets adhering to a mild steel yoke.
- The split-ring commutator has been reduced to a pair of bare wire ends that only make contact with the brushes momentarily twice per revolution.

Without the yoke the flux from each slab magnet naturally flows from the north to the south pole of the *same* magnet. Having a facing pair only slightly modifies that. Adding the steel yoke provides a low reluctance path joining the magnets and thus making them into a single magnet. There is now a small, but reasonably well defined, flux passing across the gap in which the rotor turns. The field is weak because the gap is wide but at least it is where it is needed.

The original commutator allowed the brushes to short the commutator segments and hence the battery; the modified design avoids this. It also has the effect of confining the region where current can flow to a small angle either side of the horizontal position of the rotor. The force acting on the rotor and the induced voltage in the rotor are both a maximum in this position; both fall to zero when the rotor is vertical.

Fig 4.14 shows the rotor current (A) v time (ms). The battery only supplies current when the rotor is in its most favourable position. The motor progresses at about 1600 revolutions/minute in a series of kicks – two per revolution.

We have already established that, for a single conductor of length $l$ carrying current $I$ moving at velocity $v$ in a field of flux density $B$, the induced voltage $\mathcal{E}$ and force $F$ are:

$$\mathcal{E} = Blv \text{ V and } F = BIl \text{ N}$$

For a rectangular coil 5 cm x 3 cm having 5 turns, rotating at 1600 rpm, and a 1.5 V battery:

$$B = 1.2 \text{ T and } F = 2.5 \text{ N}$$

These results are absurd. A flux density of 1.2 T over such a large volume would require a very large, very heavy, and very expensive magnet. A force of 2.5 N requires that there must be an equal mechanical load for it to act against – but there is no such load, just windage and friction.

Fig 4.15 shows the current drawn by the same motor when the rotor is forcibly held stationary. This is not much higher than with the motor turning and indicates that the vast majority of the battery voltage is lost in the resistance of the rotor and other conductors. All this energy is wasted as heat while the rotor is just left beating the air and doing no useful work.
Let us now analyse the machine represented by fig 4.11

As the rotor turns, the flux $\Phi_{\text{INSIDE}}$ passing through any single-turn coil varies cyclically as does the rate of change of $\Phi_{\text{INSIDE}}$, which equals the voltage induced in the coil $\mathcal{E}$.

If we consider the BLUE coil that is connected to commutator segments 7 & 8 which are currently under the NEGATIVE brush: the flux $\Phi_{\text{INSIDE}}$ is equal to the total flux $\Phi$.

As the rotor turns, $\Phi_{\text{INSIDE}}$ decreases to zero and, after half a revolution, the BLUE coil will be in the position originally occupied by the coil shown in RED and its commutator segments 7 & 8 are under the POSITIVE brush: the flux $\Phi_{\text{INSIDE}}$ is now equal to $-\Phi$ because it is passing through the coil in the opposite direction.

Therefore the total change of the flux $\Phi_{\text{INSIDE}}$ is equal to $2\Phi$ in half a revolution. If the rotor is turning at a speed of $f$ complete revolutions per second, the average voltage $\mathcal{E}$ induced in this single-turn coil is equal to $4\Phi f$ volts.

Let us now consider the rest of the coils currently between the POSITIVE brush and the NEGATIVE brush. These are all connected in series with each other and with the BLUE coil that we were originally considering. If there are $n$ coils on the rotor there will $\frac{1}{2}n$ coils between the brushes. These coils will have the same average voltage $\mathcal{E}$ induced in each. Thus there will be an induced voltage between the brushes of $2\Phi fn$ volts.

As there are likely to be more than a single turn on each coil, we can multiply this voltage by the number of turns on each coil. Thus if there are $N$ turns on the rotor in total we can say that the induced voltage between the brushes $V = 2\Phi fN$ volts.

The remaining $\frac{1}{2}n$ coils on the rotor are also connected in series between the brushes and also generate $2\Phi fN$ volts but, as shown in fig 4.12 above, these form a parallel path and have no effect on the overall induced voltage, though it does result in the wire forming the coils only having to carry half the current.

Why have we gone to so much trouble to examine a motor that is both complicated and which will never appear on an examination paper?

We must start from what we have – in this case it is the motor found in GCSE textbooks where we are presented with a number of fallacious statements about a motor that barely resembles a real motor and which barely works at all. We are also asked to accept that these statements apply equally to a real motor in practical use.

By a series of rational steps, from the original crude design, we have derived a motor, which could equally well be a generator, of a type in common use and which is reasonably efficient. If we disregard the losses, which we will deal with in Part 5, we can use it as the basis of an ideal machine.

In Part 3 we derived an equation for the voltage induced in a conductor moving in a uniform magnetic field at constant velocity:

$$\mathcal{E} = Blv$$ volts

In the case of any of the rotary machines discussed, both $B$ and $v$ are vectors having values which vary in magnitude and direction and therefore the above assumptions do not apply. However the analysis of fig 4.11 shows that the multiple coils effectively average out the variations in $B$ and by considering the angular velocity we avoid the variations in $v$ and the commutator deals with the polarity changes. Then, by applying exactly the same principles that we used in Part 3, we have obtained the equivalent equation for our ideal, but realistic, machine:

$$V = 2\Phi fN$$ volts

We will have to put up with the complexity of the machine for the simplicity of this result.
Note that the induced voltage depends only on the flux $\Phi$, the total number of turns on the rotor $N$, and its speed of rotation $f$.

Note that it does not depend on:

- whether the machine is a motor or a generator,
- the number of commutator segments, coils, or slots,
- whether the rotor windings are fixed to the core or whether they rotate independently,
- whether the coils are wound on the surface of the rotor or in slots,
- the length or diameter of the rotor,
- the current in the rotor windings,
- the mechanical or electrical load on the machine.

The two equations:

$$E = \frac{\Phi lv}{A} = Blv \text{ volts ..........}(i)$$

and:

$$V = 2\Phi fN \text{ volts ...................(ii)}$$

look very different – but we can show that both equations lead to the same result.

If we consider the hypothetical case of a rotor having just two coils (fig 4.16):

$N = 2$

For a rotor with radius $r$:

$$v = 2\pi fr$$

Hence:

$$f = \frac{v}{2\pi r}$$

Assume that we have a uniform radial flux $\Phi$ that is spread over an area $A$ equal to half of the circumference of the rotor times its length $l$:

$$\Phi = BA = B(\pi rl)$$

But:

$$V = 2\Phi fN \text{ .................}(ii)$$

Hence:

$$V = \frac{4B(\pi rl)v}{2\pi r} = 2Blv$$

We chose $N = 2$ because it is the smallest number of coils to which equation $(ii)$ applies. The two coils are effectively in parallel so we can disregard one of them. This leaves one coil having two conductors, each of length $l$ moving in the magnetic field so as to cause the voltages induced in each to add.

Therefore the induced voltage $E$ in one conductor is:

$$E = Blv \text{ ......................}(i)$$
**Let us now consider the effect of applying a mechanical load to the motor**

Fig 4.17 shows the motor circuit in schematic form – we will ignore any connections to the stator circuit and just assume that the magnetic field is supplied by a permanent magnet.

The motor is turning at constant speed and driving a constant mechanical load. As it is a rotary machine, it will be convenient to express these quantities as:

- speed \( f \) revolutions/second
- torque \( \tau \) newton \cdot metres [N\cdot m]

The motor is supplied with a voltage \( V \) and draws a current \( I \).

We have already established that: 
\[
V = 2 \Phi f N \text{ volts}
\]

Hence:
\[
f = \frac{V}{2 \Phi N} \text{ revolutions/second} \quad \text{........................................(1)}
\]

We can also say that:

\[
\text{Electrical Input Power} = \text{Mechanical Output Power}
\]

\[
VI = 2\pi \tau f \text{ watts}
\]

Hence:
\[
I = \frac{\pi \tau}{\Phi N} \text{ amperes} \quad \text{...........................................(2)}
\]

Note that the terms on the right hand side of equations (1) and (2) are things over which we generally have control, whereas those on the left are a consequence of these decisions.

**We can say:**

- The electrical input voltage \( V \) controls the mechanical output speed \( f \)
- The mechanical load on the output \( \tau \) controls the electrical input current \( I \)

When we consider loses in Part 5 it will be seen that it is desirable to keep the flux \( \Phi \) as high as possible. Then, once we have chosen the operating voltage \( V \), we can chose the number of turns \( N \) to give the required speed \( f \). If the voltage is low then only a small number of turns of thick wire will be required. Conversely, if the required operating voltage is higher, the same performance can to achieved by using more turns of thinner wire – this will take up the same space so the rotor size will be unchanged. The operating current will be reduced proportionately.

Trading increased torque for reduced speed *does* require a larger rotor for the same output power.

**What can we say about the direction of rotation?**

The terms clockwise and anti-clockwise can be ambiguous. A machine with a shaft that is turning clockwise, when viewed from one end; will be turning anti-clockwise, when viewed from the other.

It is clearer if the rotation is shown as a vector as in fig 4.18 where it is applied to a ‘can’ motor.

This motor has an improved version of the ‘Westminster’ stator comprising a pair of curved magnets on the inside of a steel tube which forms the body as shown in the cutaway illustration.
“Sweet exists by convention, bitter by convention, colour by convention; atoms and Void (alone) exist in reality . . .”

Democritus (lived about 460 – 370 BC) Ancilla to the Pre-Socratic Philosophers, by Kathleen Freeman, [1948]

There is a resemblance between the diagram showing mechanical rotation and that showing electric current and its associated magnetic flux (fig 3.1) – the essential difference is that the direction of mechanical rotation represents a real movement of atoms whereas the directions of current and flux are arbitrary conventions.

How then have we been able to establish a real direction of rotation starting with such arbitrary conventions? Traditionally, we would conceal the arbitrary nature of these conventions by applying apparently arbitrary rules that have actually been cunningly designed to cause the right answer to pop out at the end. This all provides an abundance of mark fodder for examiners. Instead, we have considered energy, which always has a real direction of flow, and the direction of motion just falls out naturally without any hand waving.

Looking at fig 3.19 we can see that the direction of motion indicated by \( \mathbf{v} \) can be reversed simply by rotating or flipping over the drawing – these operations are exactly equivalent to reversing the battery connections or reversing the poles of the magnet. Exactly the same argument can be applied to the rotary version.

Fig 4.19 shows a stylised version of our can motor. The ends of the shaft are marked using the usual dot and cross convention to indicate the direction of the rotation vector shown in fig 4.18

Reversing the motor is equivalent to looking at it from the other end. We can illustrate this by taking the initial drawing (fig 4.19a) and turning it over.

A horizontal flip (fig 4.19b) turns the motor around and reverses the positive and negative terminals and hence the current.

A vertical flip (fig 4.19c) turns the motor around and reverses the direction of the magnetic field.

A horizontal and a vertical flip (fig 4.19d) reverses the current and reverses the direction of the magnetic field while the direction of rotation remains unchanged.

A real motor might not have the symmetry of our ideal motor and it may be necessary to physically rearrange the electric or magnetic polarity to reverse it – this could be by means of a simple change-over switch in the supply to the brushes or, if the permanent magnets are replaced by an electromagnet, in the supply to that.

We can use the machine as a generator – equations (1) & (2) still apply – so we can say:

- The mechanical input speed \( f \) controls the electrical output voltage \( V \)
- The electrical output current \( I \) controls the mechanical load on the input \( \tau \)
“And, has thou slain the Jabberwock?
Come to my arms, my beamish boy!
O frabjous day! Callooh! Callay!”
He chortled in his joy.

Lewis Carroll: *Jabberwocky* from *Through the Looking-Glass and What Alice Found There* (1872)

We have slain the Jabberwock, its many heads have turned out to be just reflections and shadows. Of the rules listed by Eric Laithwaite in *Part 2*, only *Lenz’s Law* remains and what a perfectly pointless ‘Law’ it is, it can be derived at any time from the *Law of Conservation of Energy*, it remains purely as a rule of thumb alongside those other rules that we have shown to be unnecessary but not necessarily un-useful.

In *Part 3* we finished with a list of three laws and two rules of arithmetic. We finish *Part 4* having added just a third rule of arithmetic: *Addition*. In *Part 5 – Losses* we will meet: *Subtraction*.

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**We are left with an uneasy feeling that, having described the operation of both transformers and rotary machines in terms of a very limited repertoire of physical laws, those two descriptions seem to be irreconcilably different – surely they should have more in common.**

*Fig 3.12* would seem to indicate that there should be some sort of connection – as indeed there is.

A rotary machine is required to have a constant flux in its magnetic circuit whereas a transformer is required to have an alternating flux in its magnetic circuit. The electrical input and output of a transformer are both AC whereas the electrical input of a motor and the electrical output of a generator are both DC. Finally, rotary machines rotate whereas transformers are static.

Let us take our motor (*fig 4.20a*) and hold the shaft stationary. The rest of the motor is now rotating in the reverse direction (*fig 4.20b*). We now have an ‘external rotor’ machine and the flux through the windings of our new ‘stator’ due to the rotating permanent magnets is now alternating.

The commutator provided a connection between the stationary and moving parts but also served to convert between AC and DC. The first function is now redundant, as the coils concerned do not move, and we can now envisage some form of switching arrangement between the motor terminals and the coils to perform the second function. Motors like this, not only exist but are made in huge quantities for use in computer fans.

Whereas the commutator in *fig 4.20a* allowed the rotating windings to produce a *stationary* magnetic field, the corresponding mechanism in *fig 4.20b* causes the stationary windings to produce a rotating magnetic field.

We can perhaps begin to see that there is no fundamental differences between the different types of machine and the same principles apply to them all.

There now opens up the possibility of building all sorts of motors and generators both DC and AC. The machine hinted at in *fig 3.12* which forms a transformer supplying its own rotor current from a rotating field in the stator is a very common one. Being able to use electronics to switch and control the various currents, allows all sorts of systems that were not practicable with a commutator. This even includes allowing a transformer to function with DC.

But we must heed *Feynman’s* warning in *Part 1* and stop here – we can leave the details to others. We have shown that even a GCSE knowledge of physics and mathematics provides a basis for understanding the operation of electrical machines – which was our aim.