7

Electric Machines and their Controllers

Electric motors are a key component of an electric vehicle, and in this chapter we consider the main types of motors used. The more advanced modern electric machines need fairly complex controllers, so these are also described in this chapter.

We start, in Section 7.1, with an explanation of the simplest types of DC motors that can run with hardly any electronic control. In Section 7.2 we cover the basics of the power electronics that are needed to operate the more advanced motors frequently used nowadays. Then, in Section 7.3 we consider the different types of these more sophisticated motors, such as the 'switched reluctance motor' (SRM), the 'brushless' motor and the tried and tested induction motor. There are issues that apply to all motors when it comes to their selection and use, and these aspects, such as cooling, efficiency, size and mass, are considered in Section 7.4. Finally, in Section 7.5, we consider the special factors that apply to electric machines in hybrid electric vehicles (HEVs).

7.1 The 'Brushed' DC Electric Motor

7.1.1 Operation of the Basic DC Motor

Electric vehicles use what can seem a bewildering range of different types of electric motors. However, the simplest form of electric motor, at least to understand, is the 'brushed' DC motor. This type of motor is very widely used in applications such as portable tools, toys, electrically operated windows in cars, and small domestic appliances such as hair dryers, even if they are AC mains powered.[1] However, it is also still used as a traction motor, although the other types of motors considered later in this chapter are becoming more common for this application. The brushed DC motor is a good starting point because, as well as being widely used, most of the important issues in electric motor control can be more easily explained with reference to this type of motor.

The classical DC electric motor is shown in Figure 7.1. It is a DC motor, equipped with permanent magnets and brushes. This simplified motor has one coil, and the current

[1] In this case the appliance will also have a small rectifier.

Electric Vehicle Technology Explained, Second Edition. James Larminie and John Lowry.

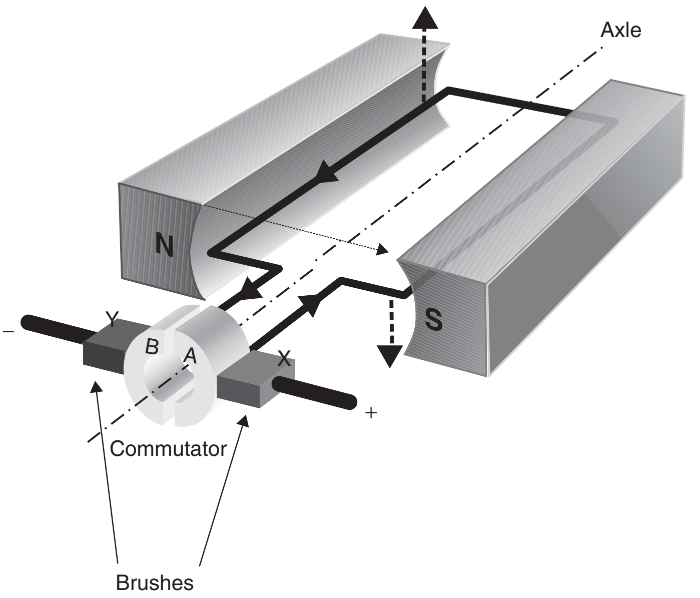


Figure 7.1 Diagram to explain the operation of the simple permanent magnet DC motor

passing through the wire near the magnet causes a force to be generated in the coil. The current flows through brush X, commutator half ring A, round the coil, and out through the other commutator half ring B and brush Y (XABY). On one side (as shown in the diagram) the force is upwards, and on the other it is downwards, because the current is flowing back towards the brushes and commutator. The two forces cause the coil to turn. The coil turns with the commutator, and once the wires are clear of the magnet the momentum carries it on round until the half rings of the commutator connect with the brushes again. When this happens the current is flowing in the same direction relative to the magnets, and hence the forces are in the same direction, continuing to turn the motor as before. However, the current will now be flowing through brush X, half ring B, round the coil to A and out through Y, so the current will be flowing in the opposite direction through the coil (XBAY).

The commutator action ensures that the current in the coil keeps changing direction, so that the force is in the same direction, even though the coil has moved.

Clearly, in a real DC motor there are many refinements over the arrangement of Figure 7.1. The most important of these are as follows:

- The rotating wire coil, often called the armature, is wound round a piece of iron, so that the magnetic field of the magnets does not have to cross a large air gap, which would weaken the magnetic field.
- More than one coil will be used, so that a current-carrying wire is near the magnets for a higher proportion of the time. This means that the commutator does not consist of two half rings (as in Figure 7.1) but several segments, two segments for each coil.

- Each coil will consist of several wires, so that the torque is increased (more wires, more force).
- More than one pair of magnets may be used, to increase the turning force further.

Figure 7.2a is the cross-section diagram of a DC motor several steps nearer reality than that of Figure 7.1. Since we are in cross-section, the electric current is flowing in the wires either up out of the page, or down into the page. Figure 7.2b shows the convention used when using such diagrams. It can be seen that most of the wires are both carrying a current and in a magnetic field. Furthermore, all the wires are turning the motor in the same direction.

7.1.2 Torque Speed Characteristics

If a wire in an electric motor has a length l metres, carries a current I amperes and is in a magnetic field of strength B webers per square metre, then the force on the wire is

$$F = BIl \tag{7.1}$$

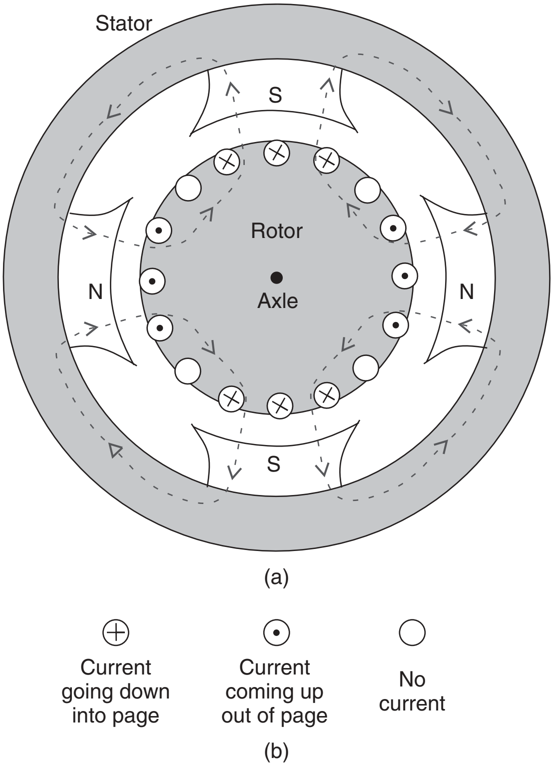


Figure 7.2 (a) Cross-section through a four-pole DC motor. The dashed lines show the magnetic flux. The motor torque is clockwise. (b) Shows the convention used to indicate the direction of current flow in wires drawn in cross-section

If the radius of the coil is r and the armature consists of n turns, then the motor torque T is given by the equation

$$T = 2nrBIl \tag{7.2}$$

The term $2Blr = B \times$ area can be replaced by Φ, the total flux passing through the coil. This gives

$$T = n\Phi I \tag{7.3}$$

However, this is the peak torque, when the coil is fully in the flux, which is perfectly radial. In practice this will not always be so. Also, it does not take into account the fact that there may be more than one pair of magnetic poles, as in Figure 7.2. So, we use a constant K_m, known as the motor constant, to connect the average torque with the current and the magnetic flux. The value of K_m clearly depends on the number of turns in each coil, but also on the number of pole pairs and other aspects of motor design. Thus we have

$$T = K_m\Phi I \tag{7.4}$$

We thus see that the motor torque is directly proportional to the rotor (also called armature) current I. However, what controls this current? Clearly it depends on the supply voltage to the motor, E_s. It will also depend on the electrical resistance of the armature coil R_a. But that is not all. As the motor turns, the armature will be moving in a magnetic field. This means it will be working as a generator or dynamo. If we consider the basic machine of Figure 7.1, and consider one side of the coil, the voltage generated is expressed by the basic equation

$$E_b = Blv \tag{7.5}$$

This equation is the generator form of Equation (7.1). The voltage generated is usually called the 'back EMF', hence the symbol E_b. It depends on the velocity v of the wire moving through the magnetic field. To develop this further, the velocity of the wire moving in the magnetic field depends on ω, the angular velocity, and r, the radius according to the simple equation $v = r\omega$. Also, the armature has two sides, so Equation (7.5) becomes

$$E_b = 2Blr\omega$$

But as there are n turns, we have

$$E_b = 2nrBl\omega$$

This equation should be compared with Equation (7.2). By similar reasoning we simplify it to an equation like Equation (7.4). Since it is the same motor, the constant K_m can be used again, and it obviously has the same value. The equation gives the voltage or 'back EMF' generated by the dynamo effect of the motor as it turns:

$$E_b = K_m\Phi\omega \tag{7.6}$$

This voltage opposes the supply voltage E_s and acts to reduce the current in the motor. The net voltage across the armature is the difference between the supply voltage E_s and the back EMF E_b. The armature current is thus

$$I = \frac{V}{R_a} = \frac{E_s - E_b}{R_a} = \frac{E_s}{R_a} - \frac{K_m \Phi}{R_a}\omega$$

This equation shows that the current falls with increasing angular speed. We can substitute it into Equation (7.4) to get the equation connecting the torque and the rotational speed:

$$T = \frac{K_m \Phi E_s}{R_a} - \frac{\left(K_m \Phi\right)^2}{R_a}\omega \tag{7.7}$$

This important equation shows that the torque from this type of motor has a maximum value at zero speed, when stalled, and it then falls steadily with increasing speed. In this analysis we have ignored the losses in the form of torque needed to overcome friction in bearings, and at the commutator, and windage losses. This torque is generally assumed to be constant, which means the general form of Equation (7.9) still holds true, and gives the characteristic graph of Figure 7.3.

The simple linear relationship between speed and torque, implied by Equation (7.9), is replicated in practice for this type of constant magnetic flux DC motor. However, except in the case of very small motors, the low-speed torque is reduced, either by the electronic controller, or by the internal resistance of the battery supplying the motor. Otherwise, the currents would be extremely high and would damage the motor. Let us take an example. A popular motor used on small electric vehicles is the 'Lynch'-type machine, an example of which is shown in Figure 7.4. A typical motor of this type[2] might have the following data given in its specification:

- Motor speed $= 70\,\text{rpm}\,\text{V}^{-1}$
- Armature resistance $= 0.016\,\Omega$.

The motor speed information connects with Equation (7.6), and refers to the no-load speed. Equation (7.6) can be rearranged to

$$\omega = \frac{E}{K_m \Phi}\,\text{rad}\,\text{s}^{-1} = \frac{60}{2\pi K_m \Phi} E\,\text{rpm}$$

So in this case we can say that

$$\frac{60}{2\pi K_m \Phi} = 70 \Rightarrow K_m \Phi = \frac{60}{2\pi \times 70} = 0.136$$

If this motor were to be run off a fixed 24 V supply, Equation (7.7) for this motor would be

$$T = 205 - 1.16\omega \tag{7.8}$$

since R_a is given as $0.016\,\Omega$. However, this would mean an initial zero-speed torque of 205 N m. This is a huge figure, but may not seem impossibly large till the current is

[2] The data given is for a 1998 model of a Lynch disc armature 'type 200' DC motor.

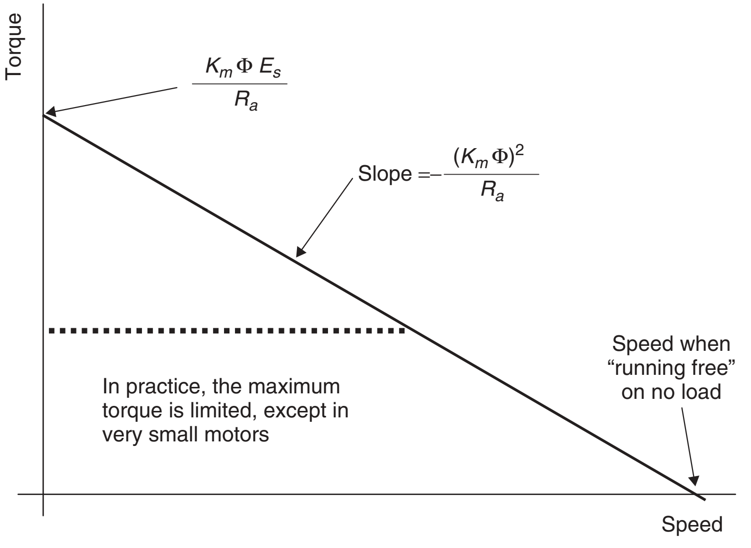


Figure 7.3 Torque/speed graph for a brushed DC motor

Figure 7.4 Small (10 kW) DC 'Lynch'-type DC motor, which is labelled **M**. This go-kart is fuel cell powered. The unit in front of the motor is the air pump, which is driven by its own motor – a smaller version of the traction motor

calculated. At zero speed there is no back EMF, and thus only this armature resistance R_a opposes the 24 V supply, so the current would be

$$I \frac{V}{R} = \frac{E_s}{R_a} = \frac{24}{0.016} = 1500\,\text{A}$$

This is clearly far too large a current. The stated limit on current is 250 or 350 A for up to 5 s. We can use this information, and Equation (7.4), to establish the maximum torque as

$$T = K_m \Phi I = 0.136 \times 250 = 34\,\text{N m} \tag{7.9}$$

Equation (7.8), modified by Equation (7.9) giving a maximum torque, is typical of the characteristic equations of this type of motor. The maximum power is about 5 kW.

7.1.3 Controlling the Brushed DC Motor

Figure 7.5 and Equation (7.7) show us that the brushed DC motor can be very easily controlled. If the supply voltage E_s is reduced, then the maximum torque falls in proportion, and the slope of the torque/speed graph is unchanged. In other words, any torque and speed can be achieved below the maximum values. We will see in Section 7.2 that the supply voltage can be controlled simply and efficiently, so this is a good way of controlling this type of motor.

However, reducing the supply voltage is not the only way of controlling this type of motor. In some cases we can also achieve control by changing the magnetic flux Φ. This is possible if coils rather than permanent magnets provide the magnetic field. If the magnetic flux is reduced then the maximum torque falls, but the slope of the torque/speed graph becomes flatter. Figure 7.5 illustrates this. Thus the motor can be made to work

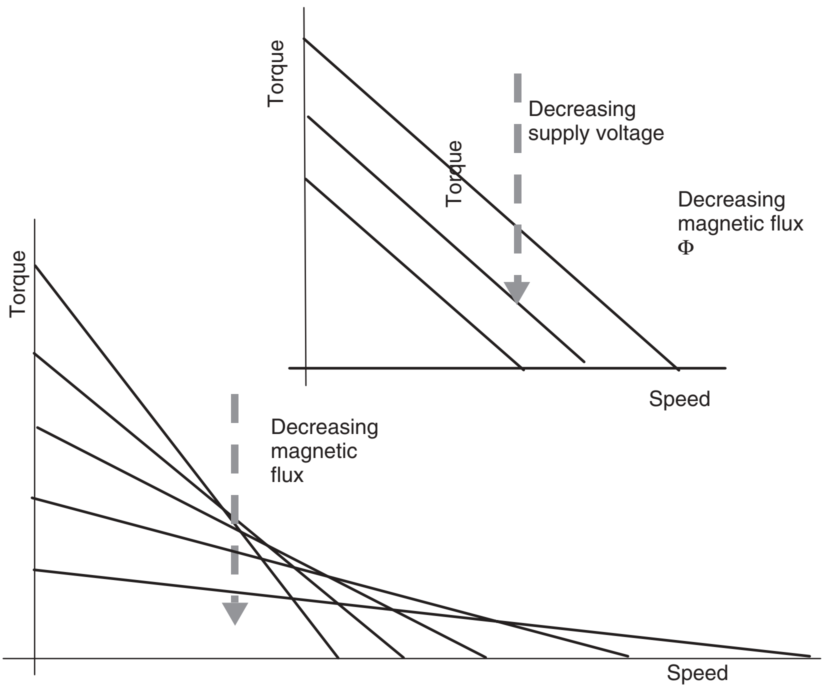


Figure 7.5 How changing the supply voltage and the magnetic field strength affects the torque/speed characteristic of the DC motor

at a wide range of torque and speed. This method is sometimes better than simply using voltage control, especially at high-speed/low-torque operation, which is quite common in electric vehicles cruising near their maximum speed. The reason for this is that the iron losses to be discussed in Section 7.1.5 below, and which are associated with high speeds and strong magnetic fields, can be substantially reduced.

So, the brushed DC motor is very flexible as to control method, especially if the magnetic flux Φ can be varied. This leads us to the next section, where the provision of the magnetic flux is described.

7.1.4 Providing the Magnetic Field for DC Motors

In Figures 7.1 and 7.2 the magnetic field needed to make the motor turn is provided by permanent magnets. However, this is not the only way this can be done. It is possible to use coils, through which a current is passed, to produce the magnetic field. These *field windings* are placed in the stator of the electric motor.

An advantage of using electromagnets to provide the magnetic field is that the magnetic field strength Φ can be changed, by changing the current. A further advantage is that it is a cheaper way of producing a strong magnetic field – though this is becoming less and less of a factor as the production of permanent magnets improves. The main disadvantage is that the field windings consume electric current and generate heat – thus it seems that the motor is almost bound to be less efficient. In practice the extra control of magnetic field can often result in *more* efficient operation of the motor, as the iron losses to be discussed in the next section can be reduced. The result is that brushed DC motors with field windings are still often used in electric vehicles.

There are three classical types of brushed DC motor with field windings, as shown in Figure 7.6. However, only one need concern us here. The behaviour of the 'series' and 'shunt' motors is considered in books on basic electrical engineering. However, they do allow the control of speed and torque that is required in an electric vehicle; the only serious contender is the 'separately excited' motor, as in Figure 7.6c.

The shunt (or parallel) wound motor of Figure 7.6a is particularly difficult to control, as reducing the supply voltage also results in a weakened magnetic field, thus reducing the back EMF and tending to increase the speed. A reduction in supply voltage can in some circumstances have very little effect on the speed. The particular advantage of the series motor of Figure 7.6b is that the torque is very high at low speeds and falls off

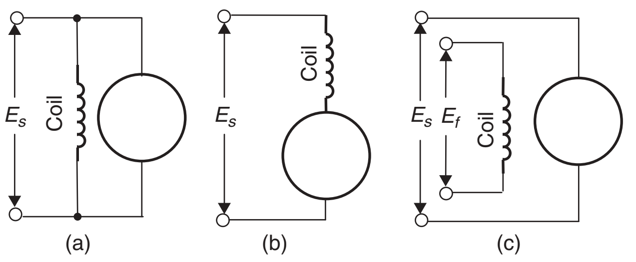


Figure 7.6 (a–c) Three standard methods of supplying current to a coil providing the magnetic field for brushed DC motors

rapidly as the speed rises. This is useful in certain applications, for example the starter motor of IC engines, but it is not what is usually required in traction applications.

The separately excited motor of Figure 7.6c allows us to have independent control of both the magnetic flux Φ (by controlling the voltage on the field winding E_f) and also the supply voltage E_s. This allows the required torque at any required angular speed to be set with great flexibility. It allows both the control methods of Figure 7.5 to be used – reducing armature supply voltage E_s *or* reducing the magnetic flux Φ.

For these reasons the separately excited brushed DC motor is quite widely used as the traction motor in electric vehicles. In the case of the many smaller motors that are found on any vehicle, the magnetic field is nearly always provided by permanent magnets. This makes for a motor that is simpler and cheaper to manufacture. Such permanent magnet (PM) motors are also sometimes used as traction motors.

7.1.5 DC Motor Efficiency

The major sources of loss in the brushed DC electric motor are the same as for all types of electric motor, and can be divided into four main types.

Firstly, there are the **copper losses**. These are caused by the electrical resistance of the wires (and brushes) of the motor. This causes heating, and some of the electrical energy supplied is turned into heat energy rather than electrical work. The heating effect of an electric current is proportional to the square of the current:

$$P = I^2 R$$

However, we know from Equations (7.3) and (7.4) that the current is proportional to the torque T provided by the motor, so we can say that

$$\text{Copper losses} = k_c T^2 \tag{7.10}$$

where k_c is a constant depending on the resistance of the brushes and the coil, and also the magnetic flux Φ. These copper losses are probably the most straightforward to understand and, especially in smaller motors, they are the largest cause of inefficiency.

The second major source of losses is the **iron losses**, because they are caused by magnetic effects in the iron of the motor, particularly in the rotor. There are two main causes of these iron losses, but to understand both it must be understood that the magnetic field in the rotor is continually changing. Imagine a small ant clinging to the edge of the rotor of Figure 7.2. If the rotor turns round one turn then this ant will pass a north pole, then a south pole, and then a north pole, and so on. As the rotor rotates, the magnetic field supplied by the magnets may be unchanged, but that seen by the turning rotor (or the ant clinging to it) is always changing. Any one piece of iron on the rotor is thus effectively in an ever-changing magnetic field. This causes two types of loss. The first is called 'hysteresis' loss, and is the energy required to magnetise and demagnetise the iron continually, aligning and realigning the magnetic dipoles of the iron. In a good magnetically soft iron this should be very small, but will not be zero. The second iron loss results from the fact that the changing magnetic field will generate a current in the iron, by the normal methods of electromagnetic induction. This current will result in heating of the iron. Because these currents just flow around and within the iron rotor they are called 'eddy currents'. These eddy currents are minimised by making the iron rotor not out of one piece, but using thin sheets all bolted or glued together. Each sheet is separated from its neighbour by a layer of paint. This greatly reduces the eddy currents by effectively increasing the electrical resistance of the iron.

It should be clear that these iron losses are proportional to the *frequency* with which that magnetic field changes – a higher frequency results in more magnetising and demagnetising, and hence more hysteresis losses. Higher frequency also results in a greater rate of change of flux, and hence greater induced eddy currents. However, the rate of change of magnetic flux is directly proportional to the speed of the rotor – to how quickly it is turning. We can thus say that

$$\text{Iron losses} = k_i \omega \tag{7.11}$$

where k_i is a constant. In fact, it will not really be constant, as its value will be affected by the magnetic field strength, among other non-constant factors. However, a single value can usually be found which gives a good indication of iron losses. The degree to which we can say k_i is constant depends on the way the magnetic field is provided – it is more constant in the case of the permanent magnet motor than the separately excited one.

The third category of loss is that due to **friction and windage**. There will of course be a friction torque in the bearings and brushes of the motor. The rotor will also have a wind resistance, which might be quite large if a fan is fitted to the rotor for cooling. The friction force will normally be more or less constant. However, the wind resistance force will increase with the square of the speed. To get at the power associated with these forces, we must multiply by the speed, as

$$\text{Power} = \text{torque} \times \text{angular speed}$$

The power involved in these forces will then be

$$\text{Friction power} = T_f \omega \quad \text{and} \quad \text{windage power} = k_w \omega^3 \tag{7.12}$$

where T_f is the friction torque and k_w is a constant depending mainly on the size and shape of the rotor, and whether or not a cooling fan is fitted.

Finally, we address those losses that occur even if the motor is totally stationary, and that vary neither with speed nor torque. In the case of the separately excited motor these are definitely not negligible, as current (and hence power) must be supplied to the coil providing the magnetic field. In the other types of motor to be described in the sections that follow, power is needed for the electronic control circuits that operate at all times. The only type of motor for which this type of loss could be zero is the permanent magnet motor with brushes. The letter C is used to designate these losses.

It is useful to bring together all these different losses into a single equation that allows us to model and predict the losses in a motor. When we do this it helps to combine the terms for the iron losses and the friction losses, as both are proportional to motor speed. Although we have done this for the brushed DC motor, it is important to note that *this equation is true, to a good approximation, for all types of motor*, including the more sophisticated types to be described in later sections.

If we combine Equations (7.10)–(7.12), we have

$$\text{Total losses} = k_c T^2 + k_i \omega + k_w \omega^3 + C \tag{7.13}$$

However, it is usually the motor efficiency η_m that we want. This is found as follows:

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

$$\eta_m = \frac{\text{output power}}{\text{output power} + \text{losses}} = \frac{T\omega}{T\omega + k_c T^2 + k_i\omega + k_w\omega^3 + C} \tag{7.14}$$

This equation will be very useful when we come to model the performance of electric vehicles in Chapter 8. Suitable values for the constants in this equation can usually be found by experimentation, or by regression using measured values of efficiency. For example, typical values for a permanent magnet motor of the 'Lynch' type that we were considering in Section 7.1.2, that might be fitted to an electric scooter, are as follows:

$$k_c = 0.8 \qquad k_i = 0.1 \qquad k_w = 10^{-5} \qquad C = 20$$

It is useful to plot the values of efficiency on a torque/speed graph, giving what is sometimes known as an 'efficiency map' for the motor, which gives an idea of the efficiency at any possible operating condition. Such a chart is shown in Figure 7.7. MATLAB is an excellent program for producing plots of this type, and in Appendix 1 we have included the script file used to produce this graph.

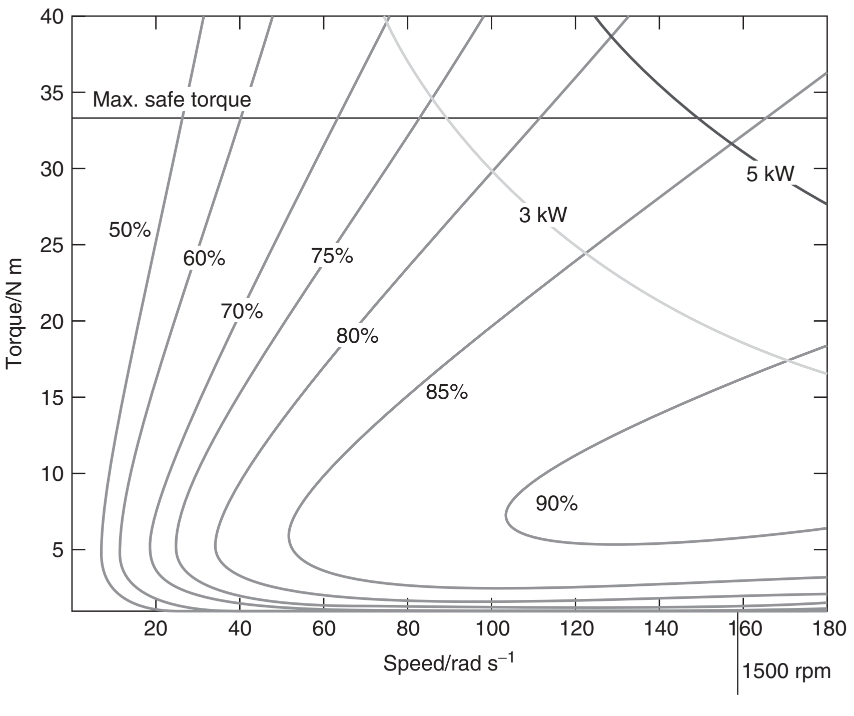


Figure 7.7 Efficiency map for a typical permanent magnet DC motor, with brushes

7.1.6 Motor Losses and Motor Size

While it is obvious that the losses in a motor affect its efficiency, it is not so obvious that the losses also have a crucial impact on the maximum power that can be obtained from a motor of any given size.

Consider a brushed motor of the type we have described in this section. The power produced could be increased by increasing the supply voltage, and thus the torque, as per Figure 7.6. Clearly, there must be a limit to this, as the power cannot be increased to infinity. One might suppose the limiting factor is the voltage at which the insulation around the copper wire breaks down, or some such point. However, that is not the case. The limit is in fact temperature related. Above a certain power the heat generated as a result of the losses, as given by Equation (7.13), becomes too large to be conducted, convected and radiated away, and the motor overheats.

An important result of this is that the key electric motor parameters of *power density* and *specific power*, being the power per unit volume and the power per kilogram mass, are not controlled by electrical factors so much as how effectively the waste heat can be removed from the motor.[3]

This leads to a very important disadvantage of the classical brushed DC motor. In this type of motor virtually all the losses occur in the *rotor* at the centre of the motor. This means that the heat generated is much more difficult to remove. In the motors to be considered in later sections the great majority of the losses occur on the *stator*, the stationary outer part of the motor. Here they can much more easily be removed. Even if we stick with air cooling it can be done more effectively, but in larger motors liquid cooing can by used to achieve even higher power density.

This issue of motor power being limited by the problem of heat removal also explains another important feature of electric motors. This is that they can safely be driven well in excess of their rated power for short periods. For example, if we take a motor that has a rated power of 5 kW, this means that if it is run at this power for about 30 min, it will settle down to a temperature of about 80 °C, which is safe and will do it no harm. However, being fairly large and heavy, a motor will take some time to heat up. If it is at, say, 50 °C, we can run it in excess of 5 kW, and its temperature will begin to increase quite rapidly. However, if we do not do this for more than about 1 min, then the temperature will not have time to rise to a dangerous value. Clearly this must not be overdone, otherwise local heating could cause damage, nor can it be done for too long, as a dangerous temperature will be reached. Nevertheless, in electric vehicles this is particularly useful, as the higher powers are often only required for short time intervals, such as when accelerating.

7.1.7 Electric Motors as Brakes

The fact that an electric motor can be used to convert kinetic energy back into electrical energy is an important feature of electric vehicles. How this works is easiest to understand in the case of the classical DC motor with brushes, but the broad principles apply to all motor types.

[3] Though obviously the losses are affected by electrical factors, such as coil resistance.

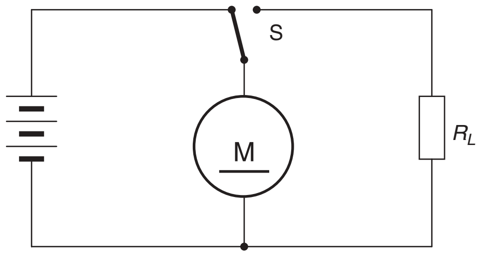


Figure 7.8 Motor circuit with resistor to be used for dynamic braking

Consider Figure 7.8. A DC motor is connected to a battery of negligible internal resistance, and voltage E_s. It reaches a steady state, providing a torque T at a speed ω. These variables will be connected by Equation (7.7). Suppose the switch S is now moved over to the right. The motor will continue to move at the same angular speed. This will cause a voltage to be generated, as given by Equation (7.6). This voltage will be applied to the resistor R_L, as in Figure 7.8, with the current further limited by the resistance of the rotor coil (armature). The result is that the current will be given by the formula

$$I = \frac{K_m \Phi \omega}{R_a + R_L} \tag{7.15}$$

This current will be flowing *out* of the motor, and will result in a negative torque. The value of this torque will still be given by the torque equation produced earlier as Equation (7.4). So, the negative torque, which will slow the motor down, will be given by the equation

$$T = -\frac{\left(K_m \Phi\right)^2 \omega}{R_a + R_L} \tag{7.16}$$

We thus have a negative torque, whose value can be controlled by changing the resistance R_L. The value of this torque declines as the speed ω decreases. So, if R_L is constant we might expect the speed to decline in an exponential way to zero.

This way of slowing down an electric motor, using a resistor, is known as 'dynamic braking'. Note that all the kinetic energy of the motor (and the vehicle connected to it) is ultimately converted into heat, just like normal friction brakes. However, we do have control of where the heat is produced, which can be useful. We also have the potential of an elegant method of controlling the braking torque. Nevertheless, the advance over normal friction brakes is not very great, and it would be much better if the electrical energy produced by the motor could be stored in a battery or capacitor.

If the resistor of Figure 7.8 were replaced by a battery, then we would have a system known as 'regenerative braking'. However, the simple connection of a battery to the motor is not practical. Suppose the voltage of the battery is V_b, and the motor is turning at speed ω; then the current that will flow out of the motor will be given by the equation

$$I = \frac{V}{R} = \frac{K_m \Phi \omega - V_b}{R_a} \tag{7.17}$$

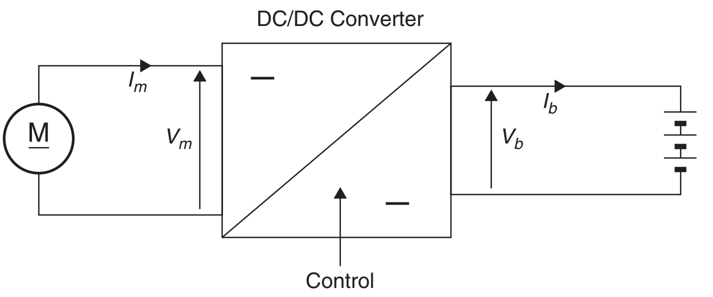


Figure 7.9 Regenerative braking of a DC motor

The slowing down torque will be proportional to this current. Once the value of ω reaches the value where the voltage generated by the motor ($=K_m\Phi\omega$) reaches the battery voltage, then there will be no more braking effect. Unless the battery voltage is very low, then this will happen quite soon. If the battery voltage is low, then it will be difficult to use the energy stored in it, and the braking effect might well be far too strong at high speeds, with the current given by Equation (7.16) being impracticably large.

A solution lies in a voltage converter circuit as in Figure 7.9. The converter unit, know as a 'DC/DC converter', draws a current from the motor I_m, which will occur at a voltage V_m. This voltage V_m will change with motor (and hence vehicle) speed. The current I_m will change with the desired braking torque. The DC/DC converter will take this electrical power ($= V_m \times I_m$) and put it out at an increased voltage (and reduced current) so that it matches the rechargeable battery or capacitor that is storing the energy. The battery might well be the same battery that provided the electricity to make the motor go in the first place. The key point is that the motor voltage might be considerably *lower* than the battery voltage, but it can still be providing charge to the battery.

Such a converter circuit sounds as if it is a little 'too good to be true' and the possibility of it remote. It seems to be like getting water to flow up hill. However, such circuits are quite possible with modern power electronics. We are not producing power, we are exchanging a low voltage and high current for a higher voltage and lower current. It is like a transformer in AC circuits, with the added facility of being able to vary continuously the ratio of the input and output voltages.

Although voltage converter circuits doing what is described above can be made, they are not 100% efficient. Some of the electrical power from the braking motor will be lost. We can say that

$$V_b \times I_b = \eta_c \times V_m \times I_m \tag{7.18}$$

where η_c is the efficiency of the converter circuit.

We have thus seen that a motor can be used to provide a controllable torque over a range of speeds. The motor can also be used as a brake, with the energy stored in a battery or capacitor. To have this range of control we need power electronics circuits that can control the voltages produced. The operation of these circuits is considered in the section that follows.

7.2 DC Regulation and Voltage Conversion

7.2.1 Switching Devices

The voltage from all sources of electrical power varies with time, temperature and many other factors, especially current. Fuel cells, for example, are particularly badly regulated, and it will always be necessary to control the output voltage so that it only varies between set boundaries. Battery voltage is actually quite well regulated, but frequently we will want to change the voltage, to a lower or higher value, usually to control the speed of a motor. We saw in the previous section that if an electric motor is to be used in regenerative braking we need to be able to boost the voltage (and reduce the current) in a continuously variable way.

A good example to illustrate the variable voltage from a fuel cell system is given in Figure 7.10. It summarises some data from a real 250 kW fuel cell used to drive a bus (Spiegel, Gilchrist and House, 1999). The voltage varies from about 400 to over 750 V, and we also see that the voltage can have different values at the same current. This is because, as well as current, the voltage also depends on temperature, air pressure, and on whether or not the compressor has got up to speed, among other factors.

Most electronic and electrical equipment requires a fairly constant voltage. This can be achieved by dropping the voltage down to a fixed value below the operating range of the fuel cell or battery, or boosting it up to a fixed value. In other cases we want to produce a variable voltage (e.g. for a motor) from the more or less fixed voltage of a battery. Whatever change is required, it is done using 'switching' or 'chopping' circuits, which are described below. These circuits, as well as the inverters and motor controllers to be described in later sections, use *electronic switches*.

As far as the user is concerned, the particular type of electronic switch used does not matter greatly, but we should briefly describe the main types used, so that the reader

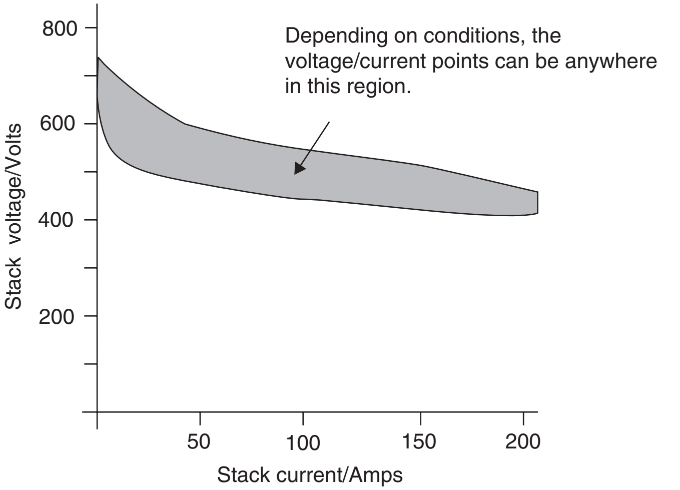
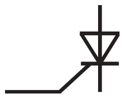
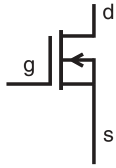
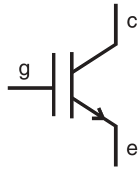


Figure 7.10 Graph summarising some data from a real 250 kW fuel cell used to power a bus. (Derived from data in Spiegel, Gilchrist and House (1999).)

Table 7.1 Key data for the main types of electronic switches used in modern power electronics equipment

Type	Thyristor	MOSFET	IGBT
Symbol			
Maximum voltage (V)	4500	1000	1700
Maximum current (A)	4000	50	600
Switching time (μs)	10–25	0.3–0.5	1–4

has some understanding of their advantages and disadvantages. Table 7.1 gives the main characteristics of the most commonly used types.

The metal oxide semiconductor field effect transistor (MOSFET) is turned on by applying a voltage, usually between 5 and 10 V, to the gate. When 'on' the resistance between the drain (d) and source (s) is very low. The power required to ensure a very low resistance is small, as the current into the gate is low. However, the gate does have a considerable capacitance, so special drive circuits are usually used. The current path behaves like a resistor, whose ON value is $R_{DS_{ON}}$. The value of $R_{DS_{ON}}$ for a MOSFET used in voltage regulation circuits can be as low as about 0.01 Ω. However, such low values are only possible with devices that can switch low voltages, in the region of 50 V. Devices which can switch higher voltages have values of $R_{DS_{ON}}$ of about 0.1 Ω, which causes higher losses. MOSFETs are widely used in low-voltage systems of power less than about 1 kW.

The insulated gate bipolar transistor (IGBT) is essentially an integrated circuit combining a conventional bipolar transistor and a MOSFET, and has the advantages of both. The IGBT requires a fairly low voltage, with negligible current at the gate to turn on. The main current flow is from the collector to the emitter, and this path has the characteristics of a p–n junction. This means that the voltage does not rise much above 0.6 V at all currents within the rating of the device. This makes it the preferred choice for systems where the current is greater than about 50 A. IGBTs can also be made to withstand higher voltages. The longer switching times compared with the MOSFET, as given in Table 7.1, are a disadvantage in lower power systems. However, the IGBT is now almost universally the electronic switch of choice in systems from 1 kW up to several hundred kilowatts, with the 'upper' limit rising each year.

The thyristor has been the electronic switch most commonly used in power electronics. Unlike the MOSFET and IGBT, the thyristor can only be used as an electronic switch – it has no other applications. The transition from the blocking to the conducting state is triggered by a pulse of current into the gate. The device then remains in the conducting state until the current flowing through it falls to zero. This feature makes it particularly useful in circuits for rectifying AC, where it is still widely used. However, various variants of the thyristor, particularly the gate turn-off (GTO) thyristor, can be switched off, even while a current is flowing, by the application of a negative current pulse to the gate.

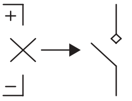


Figure 7.11 Circuit symbol for a voltage-operated electronic switch of any type

Despite the fact that the switching is achieved by just a pulse of current, the energy needed to effect the switching is much greater than for the MOSFET or the IGBT. Furthermore, the switching times are markedly longer. The only advantage of the thyristor (in its various forms) for DC switching is that higher currents and voltages can be switched. However, the maximum power of IGBTs is now so high that this is very unlikely to be an issue in electric vehicle systems, which are usually below 1 MW in power.[4]

Ultimately the component used for the electronic switch is not of great importance. As a result the circuit symbol used is often the 'device-independent' symbol shown in Figure 7.11. In use, it is essential that the switch moves as quickly as possible from the conducting to the blocking state, or vice versa. No energy is dissipated in the switch while it is open circuit, and only very little when it is fully on; it is while the transition takes place that the product of voltage and current is non-zero, and that power is lost.

7.2.2 Step-Down or 'Buck' Regulators

The 'step-down' or 'buck' switching regulator (or chopper) is shown in Figure 7.12. The essential components are an electronic switch with an associated drive circuit, a diode and an inductor. In Figure 7.12a the switch is on, and the current flows through the inductor and the load. The inductor produces a back EMF, making the current gradually rise. The switch is then turned off. The stored energy in the inductor keeps the current flowing through the load, using the diode, as in Figure 7.12b. The different currents flowing during each part of this on–off cycle are shown in Figure 7.13. The voltage across the load can be further smoothed using capacitors if needed.

If V_1 is the supply voltage, and the 'on' and 'off' times for the electronic switch are t_{ON} and t_{OFF}, then it can be shown that the output voltage V_2 is given by

$$V_2 = \frac{t_{ON}}{t_{ON} + t_{OFF}} V_1 \tag{7.19}$$

It is also clear that the ripple depends on the frequency – higher frequency, less ripple. However, each turn-on and turn-off involves the loss of some energy, so the frequency should not be too high. A control circuit is needed to adjust t_{ON} to achieve the desired output voltage; such circuits are readily available from many manufacturers.

The main energy losses in the step-down chopper circuit are:

- Switching losses in the electronic switch.
- Power lost in the switch while on ($0.6 \times I$ for an IGBT or $R_{DS_{ON}} \times I^2$ for a MOSFET).
- Power lost due to the resistance of the inductor.
- Losses in the diode, $0.6 \times I$.

[4] Electric railway locomotives would be an exception to this.

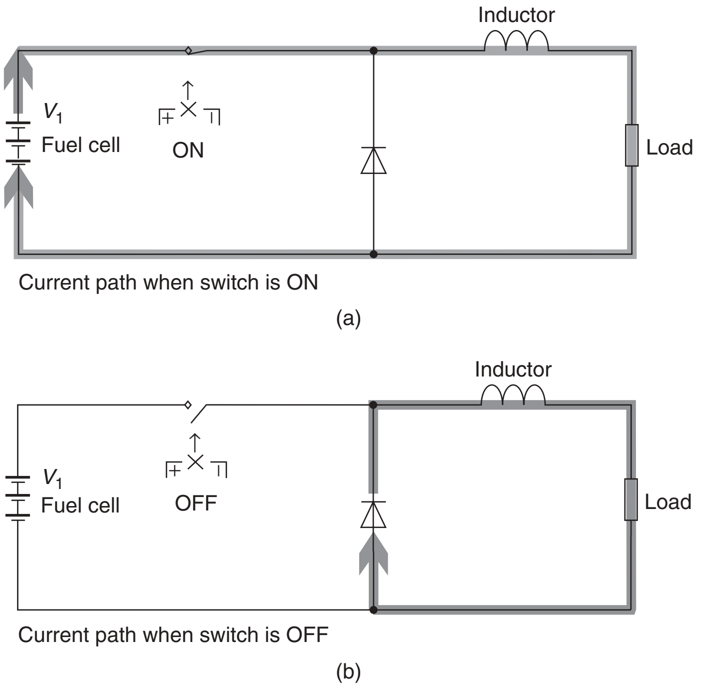


Figure 7.12 Circuit diagram showing the operation of a switch-mode step-down regulator

In practice all these can be made very low. The efficiency of such a step-down chopper circuit should be over 90%. In higher voltage systems, about 100 V or more, efficiencies as high as 98% are possible.

We should at this point briefly mention the 'linear' regulator circuit. The principle is shown in Figure 7.14. A transistor is used again, but this time it is not switched fully on or fully off. Rather, the gate voltage is adjusted so that its resistance is at the correct value to drop the voltage to the desired value. This resistance will vary continuously, depending on the load current and the supply voltage. This type of circuit is widely used in small electronic systems, but should *never* be used with traction motors. The voltage is dropped by simply converting the surplus voltage into heat. Linear regulators have no place in systems where efficiency is paramount, such as an electric vehicle.

7.2.3 Step-Up or 'Boost' Switching Regulator

It is often desirable to step-up or boost a DC voltage, regenerative braking being just one example. This can also be done quite simply and efficiently using switching circuits. Voltage boost circuits are also needed for regenerative braking.

The circuit of Figure 7.15 is the basis usually used. We start our explanation by assuming some charge is in the capacitor. In Figure 7.15a the switch is on, and an electric current is building up in the inductor. The load is supplied by the capacitor discharging. The diode

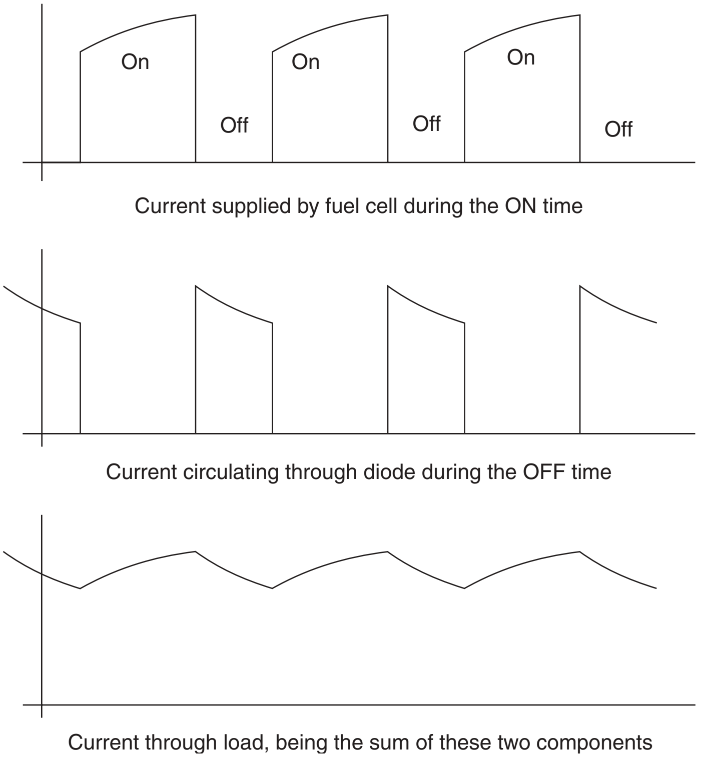


Figure 7.13 Currents in the switch-mode step-down regulator circuit

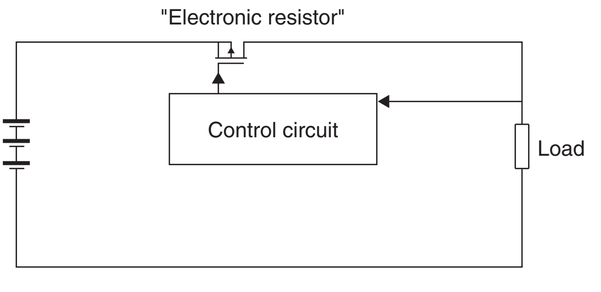


Figure 7.14 Linear regulator circuit

prevents the charge from the capacitor flowing back through the switch. In Figure 7.15b the switch is off. The inductor voltage rises sharply, because the current is falling. As soon as the voltage rises above that of the capacitor (plus about 0.6 V for the diode) the current will flow through the diode, and charge up the capacitor and flow through the load. This will continue as long as there is still energy in the inductor. The switch is then closed again, as in Figure 7.15a, and the inductor re-energised while the capacitor supplies the load.

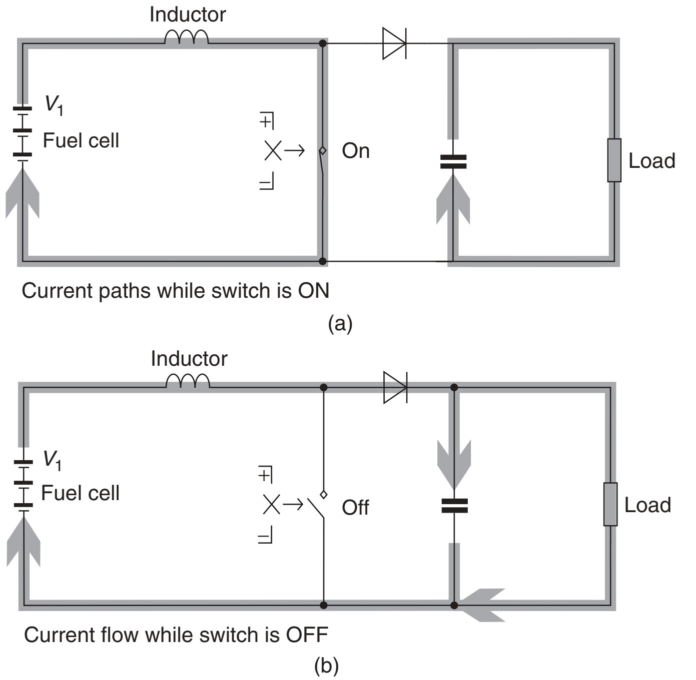


Figure 7.15 Circuit diagram to show the operation of a switch-mode boost regulator

Higher voltages are achieved by having the switch off for a short time. It can be shown that for an ideal convertor with no losses

$$V_2 = \frac{t_{ON} + t_{OFF}}{t_{OFF}} V_1 \tag{7.20}$$

In practice the output voltage is somewhat less than this. As with the step-down (buck) switcher, control circuits for such boost or step-up switching regulators are readily available from many manufacturers.

The losses in this circuit come from the same sources as for the step-down regulator. However, because the currents through the inductor and switch are higher than the output current, the losses are higher. Also, *all* the charge passes through the diode this time, and so is subject to the 0.6 V drop and hence energy loss. The result is that the efficiency of these boost regulators is somewhat less than for the buck. Nevertheless, over 80% should normally be obtained, and in systems where the initial voltage is higher (over 100 V), efficiencies of 95% or more are possible.

For the regulation of fuel cell voltages, in cases where a small variation in output voltage can be tolerated, an up-chopper circuit is used at *higher currents only*. This is illustrated in Figure 7.16. At lower currents the voltage is not regulated. The circuit of Figure 7.15 is used, with the switch permanently off. However, the converter starts operating when the fuel cell voltage falls below a set value. Since the voltage shift is quite small, the efficiency would be higher.

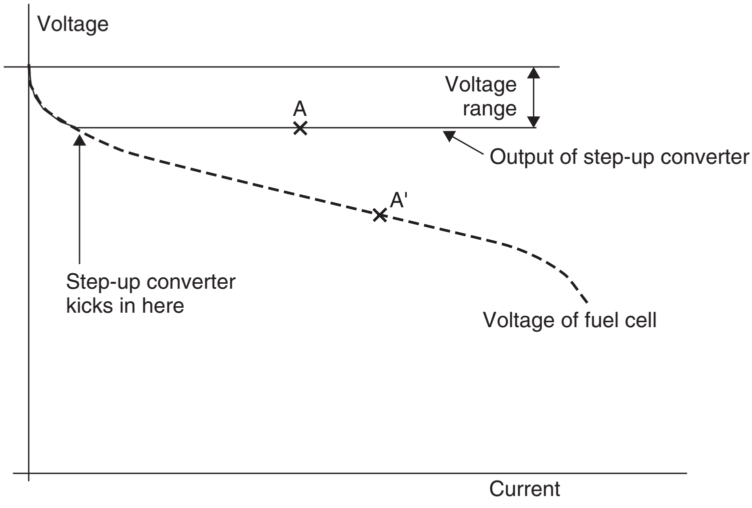


Figure 7.16 Graph of voltage against current for a fuel cell with a step-up chopper circuit that regulates to a voltage a little less than the maximum stack voltage

It should be pointed out that, of course, the current out from a step-up converter is less than the current in. In Figure 7.16, if the fuel cell is operating at point A, the output will be at point A′ – a higher voltage but a lower current. Also, the system is not entirely ‘loss-free’ while the converter is not working. The current would all flow through the inductor and the diode, resulting in some loss of energy.

These step-up and step-down switcher or chopper circuits are called DC/DC converters. Complete units, ready made and ruggedly packaged, are available as ‘off-the-shelf’ units in a wide range of powers and input and output voltages. However, when they are used as motor controller circuits, as in the case of electric vehicles, the requirements of having to produce a variable voltage, or a fixed output voltage for a variable input voltage (as in the case when braking a motor using regenerative braking), then such off-the-shelf units will not often be suitable. In such cases special circuits must be designed, and most motors can be supplied with suitable controllers. As we have seen, the circuits required are, in principle, quite simple. The key is to control properly the switching of an electronic switch. This control is usually provided by a microprocessor.

7.2.4 Single-Phase Inverters

The circuits of the previous two sections are the basis of controlling the classical DC motor. However, the motors to be considered in the next section require alternating current. The circuit that produces AC from DC sources such as batteries and fuel cells is known as an inverter. We will begin with the single-phase inverter.

The arrangement of the key components of a single-phase inverter is shown in Figure 7.17. There are four electronic switches, labelled A, B, C and D, connected in what is called an ‘H-bridge’. Across each switch is a diode, whose purpose will become

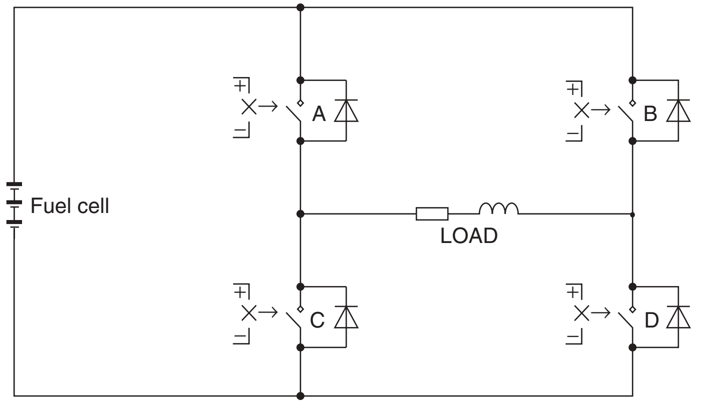


Figure 7.17 H-bridge inverter circuit for producing single-phase alternating current

clear later. The load through which the alternating current is to be driven is represented by a resistor and an inductor.

The basic operation of the inverter is quite simple. First switches A and D are turned on, and a current flows to the right through the load. These two switches are then turned off – at this point we see the need for the diodes. The load will probably have some inductance, and so the current will not be able to stop immediately, but will continue to flow in the same direction, through the diodes across switches B and C, back into the supply. The switches B and C are then turned on, and a current flows in the opposite direction, to the left. When these switches turn off, the current 'freewheels' through the diodes in parallel with switches A and D.

The resulting current waveform is shown in Figure 7.18. The fact that it is very far from a sine wave may be a problem in some cases, which we will consider here.

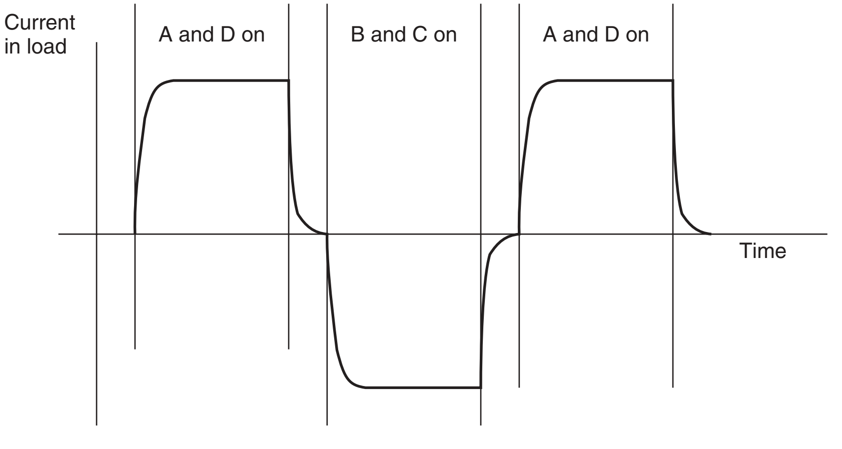


Figure 7.18 Current/time graph for a square wave switched single-phase inverter

The difference between a pure sine wave and any other waveform is expressed using the idea of 'harmonics'. These are sinusoidal oscillations of voltage or current whose frequency, f_v, is a whole-number multiple of the fundamental oscillation frequency. It can be shown that *any* periodic waveform of *any* shape can be represented by the addition of harmonics to a fundamental sine wave. The process of finding these harmonics is known as Fourier analysis. For example, it can be shown that a square wave of frequency f can be expressed by the equation

$$v = \sin(\omega t) - \frac{1}{3}\sin(3\omega t) + \frac{1}{5}\sin(5\omega t) - \frac{1}{7}\sin(7\omega t) + \frac{1}{9}\sin(9\omega t)\ldots$$

where $\omega = 2\pi ft$. So, the difference between a voltage or current waveform and a pure sine wave may be expressed in terms of higher frequency harmonics imposed on the fundamental frequency.

In mains-connected equipment these harmonics can cause a wide range of problems, but that is not our concern here. With motors the main problem is that the harmonics can increase the iron losses mentioned back in Section 7.1.5. We saw that these iron losses are proportional to the *frequency* of the change of the magnetic field. If our alternating current is being used to produce a changing magnetic field (which it nearly always will be) then the real rate of change, and hence the losses, will be noticeably increased by these higher harmonic frequencies. For this reason the simple switching pattern just described is often not used in favour of a more complex system that produces a more smoothly changing current pattern. This method is known as 'pulse width modulation'.

The principle of pulse width modulation is shown in Figure 7.19. The same circuit as shown in Figure 7.17 is used. In the positive cycle only switch D is on all the time, and switch A is on intermittently. When A is on, current builds up in the load. When A is off, the current continues to flow, because of the load inductance, through switch D and the 'freewheeling' diode in parallel with switch C, around the bottom right loop of the circuit.

In the negative cycle a similar process occurs, except that switch B is on all the time, and switch C is 'pulsed'. When C is on current builds in the load; when off it continues to flow – though declining – through the upper loop in the circuit, and through the diode in parallel with switch A.

The precise shape of the waveform will depend on the nature (resistance, inductance, capacitance) of the load, but a typical half cycle is shown in Figure 7.20. The waveform is still not a sine wave, but is a lot closer than that of Figure 7.18. Clearly, the more pulses there are in each cycle, the closer will be the wave to a pure sine wave, and the weaker will be the harmonics. Twelve pulses per cycle is a commonly used standard, and generally this gives satisfactory results. In modern circuits the switching pulses are generated by microprocessor circuits.

7.2.5 Three Phase

Most large motors, of the type used in electric vehicles, have three sets of coils rather than just one. For these systems – as well as for regular mains systems – a 'three-phase' AC supply is needed.

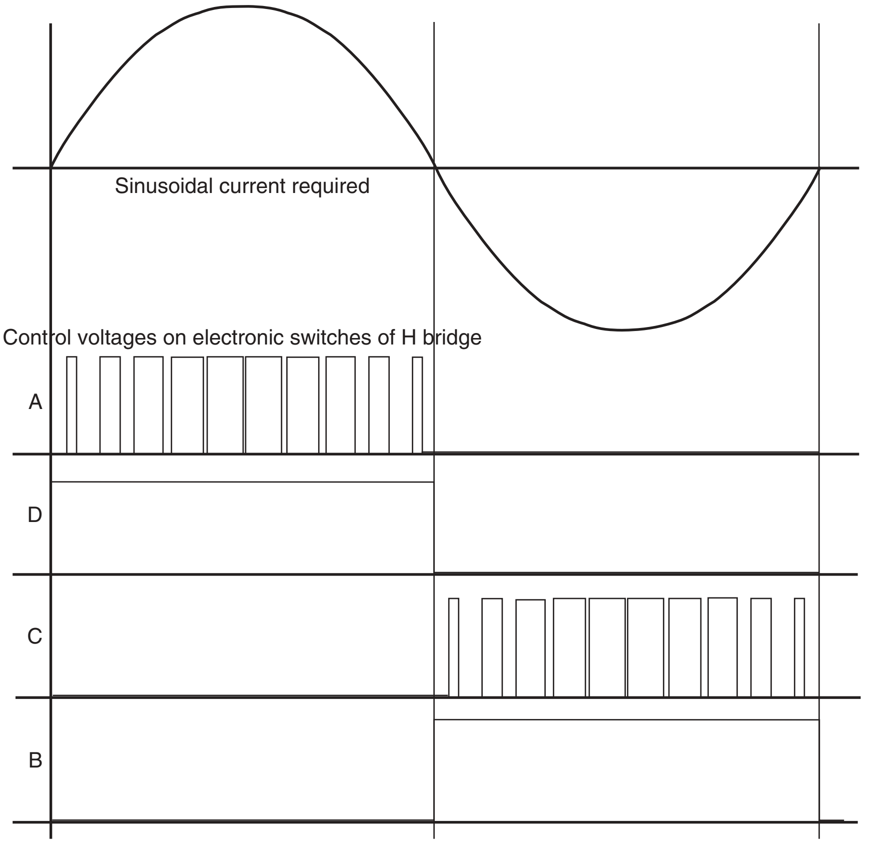


Figure 7.19 Pulse width modulation switching sequence for producing an approximately sinusoidal alternating current from the circuit of Figure 7.17

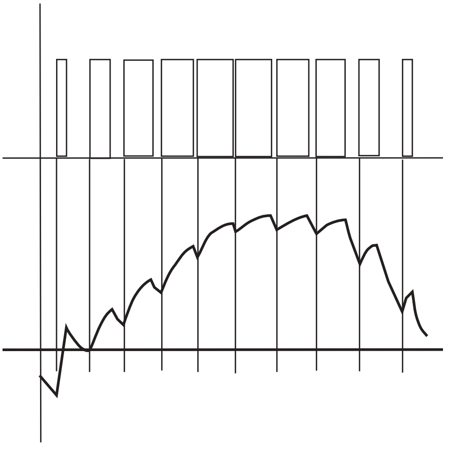


Figure 7.20 Typical voltage/time graph for a pulse modulated inverter

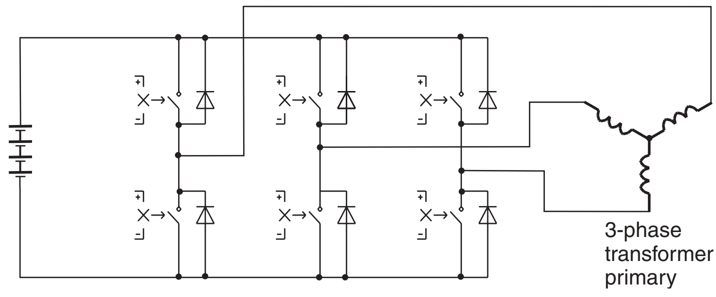


Figure 7.21 Three-phase inverter circuit

Such a supply is only a little more complicated than single phase. The basic circuit is shown in Figure 7.21. Six switches, with freewheeling diodes, are connected to the three-phase transformer on the right. The way in which these switches are used to generate three similar but out-of-phase voltages is shown in Figure 7.22. Each cycle can be divided into six steps. The graphs of Figure 7.23 show how the current in each of the three phases changes with time using this simple arrangement. These curves are obviously far from sine waves. In practice the very simple switching sequence of Figure 7.22 is modified using pulse width modulation, in the same way as for the single-phase inverters described above.

7.3 Brushless Electric Motors

7.3.1 Introduction

In Section 7.1 we described the classical DC electric motor. The brushes of this motor are an obvious problem – there will be friction between the brushes and the commutator, and both will gradually wear away. However, a more serious problem with this type of motor was raised in Section 7.1.5. This is that the heat associated with the loses is generated in the middle of the motor, in the rotor. If the motor could be so arranged that the heat was generated in the outer stator, that would allow the heat to be removed much more easily, and allow smaller motors. If the brushes could be disposed of as well, then that would be a bonus. In this section we describe three types of motors that are used as traction motors in vehicles that fulfil these requirements.

One of the interesting features of electric motor technology is that there is no clear winner. *All three types of motors described here, as well as the brushed DC motor of Section 7.1, are used in current vehicle designs*.

7.3.2 The Brushless DC Motor

The brushless DC (BLDC) motor is really an AC motor! The current through it alternates, as we will see. It is called a 'brushless DC motor' because the alternating current *must* be variable frequency and so derived from a DC supply, and because its speed/torque characteristics are very similar to the ordinary 'with brushes' DC motor. As a result of 'BLDC' being not an entirely satisfactory name, it is also known as a 'self-synchronous

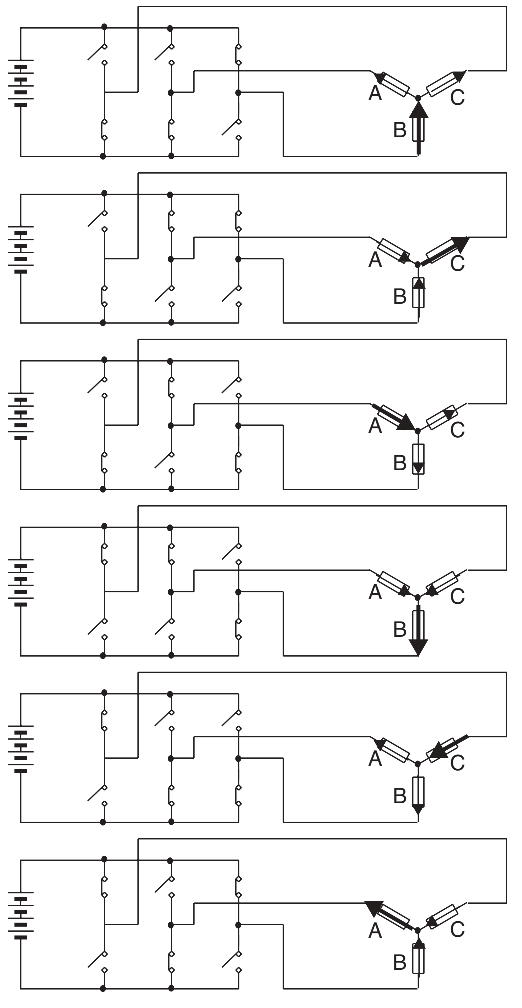


Figure 7.22 Switching pattern to generate three-phase alternating current

AC motor', a 'variable frequency synchronous motor', a 'permanent magnet synchronous motor' and an 'electronically commutated motor' (ECM).

The basis of operation of the BLDC motor is shown in Figure 7.24. The rotor consists of a permanent magnet. In Figure 7.24a the current flows in the direction that magnetises the stator so that the rotor is turned clockwise, as shown. In Figure 7.24b the rotor passes between the poles of the stator, and the stator current is switched off. Momentum carries the rotor on, and in Figure 7.24c the stator coil is re-energised, but the current and hence the magnetic field are reversed. So the rotor is pulled on round in a clockwise direction. The process continues, with the current in the stator coil alternating.

Obviously, the switching of the current must be synchronised with the position of the rotor. This is done using sensors. These are often Hall effect sensors that use the magnetism of the rotor to sense its position, but optical sensors are also used.

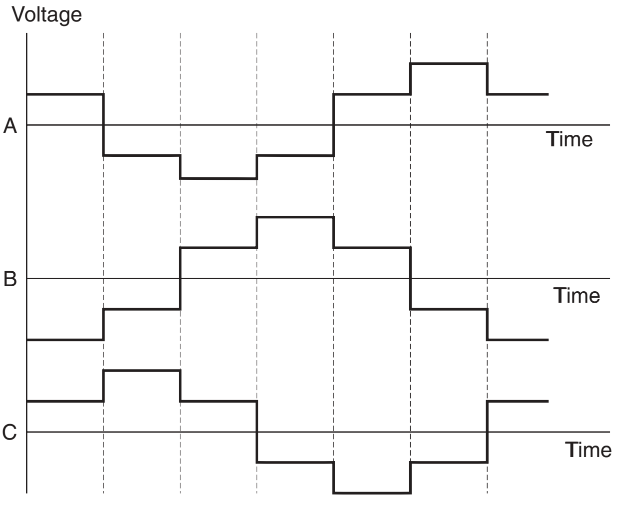


Figure 7.23 Current/time graphs for the simple three-phase AC generation system shown in this figure, assuming a resistive load. One complete cycle for each phase is shown. Current flowing *out* from the common point is taken as *positive*

A problem with the simple single-coil system of Figure 7.24 is that the torque is very unsteady. This is improved by having three (or more) coils, as in Figure 7.25. In this diagram coil B is energised to turn the motor clockwise. Once the rotor is between the poles of coil B, coil C will be energised, and so on.

The electronic circuit used to drive and control the coil currents is usually called an inverter – and it will be the same as, or very similar to, our 'universal inverter' circuit of Figure 7.21. The main control inputs to the microprocessor will be the position sense signals.

A feature of these BLDC motors is that the torque will reduce as the speed increases. The rotating magnet will generate a back EMF in the coil which it is approaching. This back EMF will be proportional to the speed of rotation and will reduce the current flowing in the coil. The reduced current will reduce the magnetic field strength, and hence the torque. Eventually the size of the induced back EMF will equal the supply voltage, and at this point the maximum speed has been reached. This behaviour is exactly the same as with the brushed DC motor of Section 7.1.

We should also notice that this type of motor can very simply be used as a generator of electricity, and for regenerative or dynamic braking.

Although the current through the motor coils alternates, there must be a DC supply, which is why these motors are generally classified as 'DC'. They are very widely used in computer equipment to drive the moving parts of disc storage systems and fans. In these small motors the switching circuit is incorporated into the motor with the sensor switches. However, they are also used in higher power applications, with more sophisticated controllers (as of Figure 7.21), which can vary the coil current (and hence torque) and thus produce a very flexible drive system. Some of the most sophisticated electric vehicle drive motors are of this type, and one is shown in Figure 7.26. This is a 100 kW, oil-cooled motor, weighing just 21 kg.

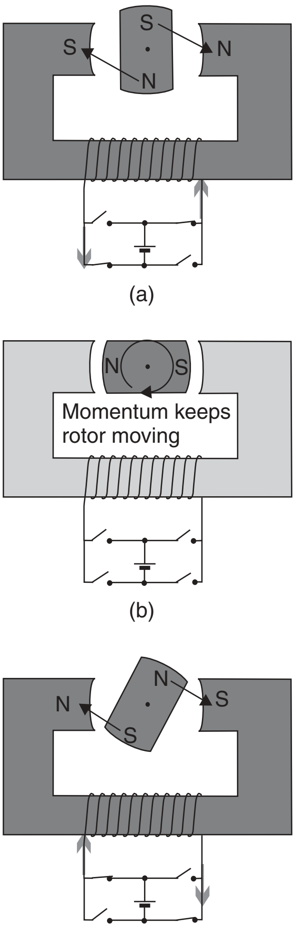


Figure 7.24 (a–c) Diagram showing the basis of operation of the brushless DC motor

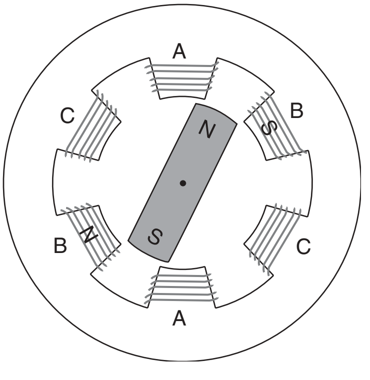


Figure 7.25 Diagram showing an arrangement of three coils on the stator of a BLDC motor

Figure 7.26 A 100 kW, oil-cooled BLDC motor for automotive application. This unit weighs just 21 kg. (Photograph reproduced by kind permission of Zytek Ltd.)

These BLDC motors need a strong permanent magnet for the rotor. The advantage of this is that currents do not need to be induced in the rotor (as with, for example, the induction motor), making them somewhat more efficient and giving a slightly greater specific power.

Permanent magnet synchronous motors which are a type of BLDC motors are increasingly used in electric vehicles. Modern electronics allow the supply frequency to be continuously varied so that it can be used to control the motor speed and hence the vehicle speed. Permanent magnet synchronous motors are highly efficient and tend to replace induction motors in many applications. This is due to the fact that permanent magnet motors have a higher torque-to-volume ratio as compared with the induction motors. Also, the decrease in the manufacturing cost of permanent magnets makes the permanent magnet motors appealing.

7.3.3 Switched Reluctance Motors

Although only recently coming into widespread use, the switched reluctance motor (SRM) is, in principle, quite simple. The basic operation is shown in Figure 7.27. In Figure 7.27a the iron stator and rotor are magnetised by a current through the coil on the stator. Because the rotor is out of line with the magnetic field a torque will be produced to minimise the air gap and make the magnetic field symmetrical. We could lapse into rather ‘medieval’ science and say that the magnetic field is ‘reluctant’ to cross the air gap, and seeks to minimise it. Medieval or not, this is why this type of motor is called a reluctance motor.

At the point shown in Figure 7.27b the rotor is aligned with the stator, and the current is switched off. Its momentum then carries the rotor on round over a quarter of a turn, to the position of Figure 7.27c. Here the magnetic field is reapplied, in the same direction

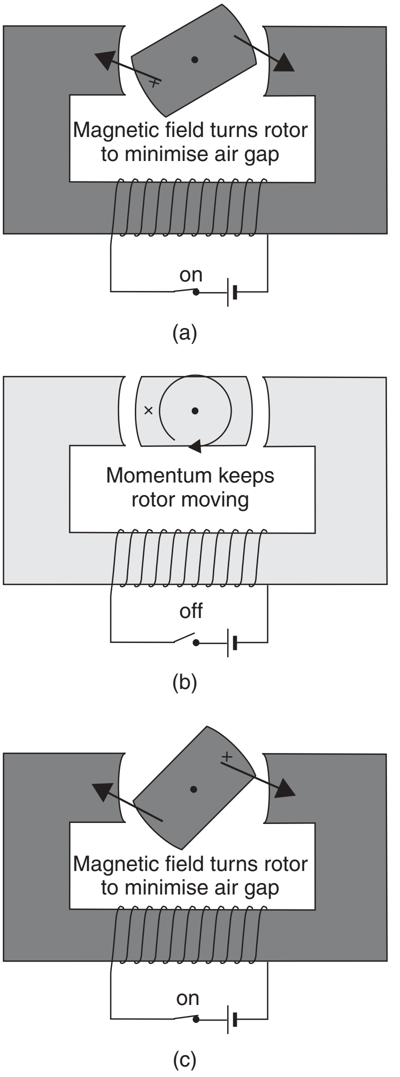


Figure 7.27 (a–c) Diagram showing the principle of operation of the switched reluctance motor

as before. Again, the field exerts a torque to reduce the air gap and make the field symmetrical, which pulls the rotor on round. When the rotor lines up with the stator again, the current is switched off.

In the SRM, the rotor is simply a piece of magnetically soft iron. Also, the current in the coil does not need to alternate. Essentially then, this is a very simple and potentially low-cost motor. The speed can be controlled by altering the length of time that the current is on for each 'power pulse'. Also, since the rotor is not a permanent magnet, there is no back EMF generated in the way it is with the BLDC motor, which means that higher speeds are possible. In the fuel cell context, this makes the SRM particularly suitable for radial compressors and blowers.

The main difficulty with the SRM is that the timing of the turning on and off of the stator currents must be much more carefully controlled. For example, if the rotor is 90° out of line, as in Figure 7.24a, and the coil is magnetised, no torque will be produced, as the field would be symmetrical. So, the torque is much more variable, and as a result early SRMs had a reputation for being noisy.

The torque can be made much smoother by adding more coils to the stator. The rotor is again laminated iron, but has 'salient poles', that is protruding lumps. The number of salient poles will often be two less than the number of coils. Figure 7.28 shows the principle. In Figure 7.28a coil A is magnetised, exerting a clockwise force on the rotor. When the salient poles are coming into line with coil A, the current in A is switched off. Two other salient poles are now nearly in line with coil C, which is energised, keeping the rotor smoothly turning. Correct turning on and off of the currents in each coil clearly needs good information about the position of the rotor. This is usually provided by sensors, but modern control systems can do without these. The position of the rotor is inferred from

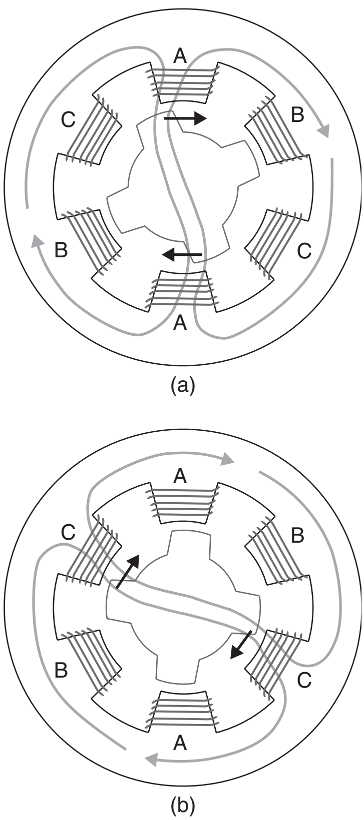


Figure 7.28 Diagram showing the operation of an SRM with a four salient pole rotor

Figure 7.29 The rotor and stator from an SRM. (Photograph reproduced by kind permission of SR Drives Ltd.)

the voltage and current patterns in the coils. This clearly requires some very rapid and complex analysis of the voltage and current waveforms, and is achieved using a special type of microprocessor called a digital signal processor.[5]

An example of a rotor and stator from an SRM is shown in Figure 7.29. In this example the rotor has eight salient poles.

The stator of an SRM is similar to that in both the induction and BLDC motor. The control electronics are also similar – a microprocessor and some electronic switches, along the lines of Figure 7.21. However, the rotor is significantly simpler, and so cheaper and more rugged. Also, when using a core of high magnetic permeability the torque that can be produced within a given volume exceeds that produced in induction motors (magnetic action on current) and BLDC motors (magnetic action on permanent magnets) (Kenjo, 1991, p. 161). Combining this with the possibilities of higher speed means that a higher power density is possible. The greater control precision needed for the currents in the coils makes these motors somewhat harder to apply on a 'few-of' basis, with the result that they are most widely used in cost-sensitive mass-produced goods such as washing machines and food processors. However, we can be sure that their use will become much more widespread.

Although the peak efficiency of the SRM may be slightly below that of the BLDC motor, SRMs maintain their efficiency over a wider range of speed and torque than any other motor type.

As mentioned above, permanent magnet motors have become popular for driving electric vehicles. This is because permanent magnet motors have higher torque-to-volume ratio compared with the induction motors. Also, the decrease in manufacturing cost of permanent magnets makes the permanent magnet motors appealing. They are used in a wide range of modern electric vehicles.

[5] Although digital signal processors were originally conceived as devices for processing audio and picture signals, their major application is now in the control of motors. BLDC motors can also operate without rotor position sensors in a similar way.

7.3.4 The Induction Motor

The induction motor is very widely used in industrial machines of all types. Its technology is very mature. Induction motors require an AC supply, which might make them seem unsuitable for a DC source such as batteries or fuel cells. However, as we have seen, alternating current can easily be generated using an inverter, and in fact the inverter needed to produce the alternating current for an induction motor is no more complicated or expensive than the circuits needed to drive the BLDC motors or SRMs we have just described. So, these widely available and very reliable motors are well suited to use in electric vehicles.

The principle of operation of the three-phase induction motor is shown in Figures 7.30 and 7.31. Three coils are wound right around the outer part of the motor, known as the stator, as shown in the top of Figure 7.30. The rotor usually consists of copper or aluminium rods, all electrically linked (short-circuited) at the end, forming a kind of cage, as also shown in Figure 7.30. Although shown hollow, the interior of this cage rotor will usually be filled with laminated iron.

The three windings are arranged so that a positive current produces a magnetic field in the direction shown in Figure 7.31. If these three coils are fed with a three-phase alternating current, as in Figure 7.23, the resultant magnetic field rotates anti-clockwise, as shown at the bottom of Figure 7.31.

This rotating field passes through the conductors on the rotor, generating an electric current.

A force is produced on these conductors carrying an electric current, which turns the rotor. It tends to ‘chase’ the rotating magnetic field. If the rotor were to go at the same speed as the magnetic field, there would be no relative velocity between the rotating field and the conductors, and so no induced current and no torque. The result is that the torque/speed graph for an induction motor has the characteristic shape shown in Figure 7.32. The torque rises as the angular speed ‘slips’ behind that of the magnetic field, up to an optimum slip, after which the torque declines somewhat.

The winding arrangement of Figures 7.30 and 7.31 is known as ‘two-pole’. It is possible to wind the coils so that the magnetic field has four, six, eight or any even number of poles. The speed of rotation of the magnetic field is the supply frequency divided by the number of pole pairs. So, a four-pole motor will turn at half the speed of a two-pole motor, given the same frequency AC supply, a six-pole motor a third the speed, and so on.

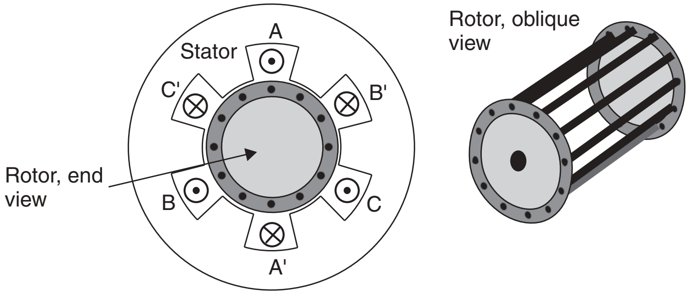


Figure 7.30 Diagram showing the stator and rotor of an induction motor

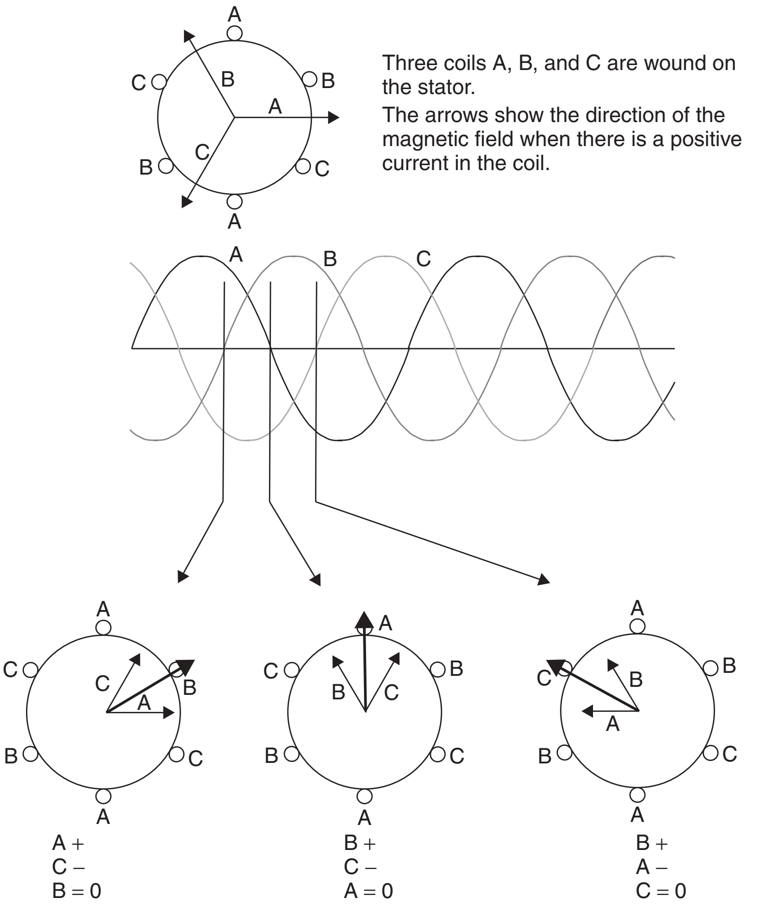


Figure 7.31 Diagrams to show how a rotating magnetic field is produced within an induction motor

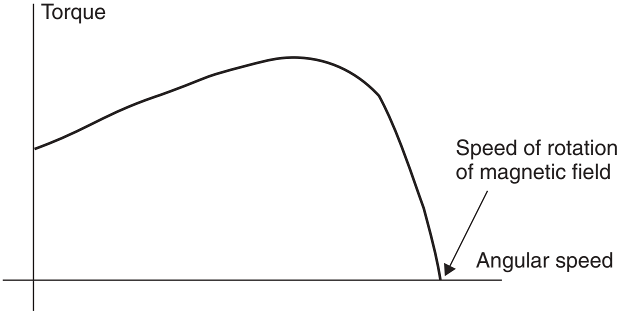


Figure 7.32 Typical torque/speed curve for an induction motor

This gives a rather inflexible way of controlling speed. A much better way is to control the frequency of the three-phase supply. Using a circuit such as that of Figure 7.21 this is easily done. The frequency does not precisely control the speed, as there is a 'slip' depending on the torque. However, if the angular speed is measured, and incorporated into a feedback loop, the frequency can be adjusted to attain the desired speed.

The maximum torque depends on the strength of the magnetic field in the gap between the rotor and the coils on the stator. This depends on the current in the coils. A problem is that as the frequency increases, the current reduces, if the voltage is constant, because of the inductance of the coils having an impedance that is proportional to the frequency. The result is that, if the inverter is fed from a fixed voltage, the maximum torque is inversely proportional to the speed. This is liable to be the case with a fuel cell or battery system.

Induction motors are very widely used. Very high volume of production makes for a very reasonably priced product. Much research has gone into developing the best possible materials. Induction motors are as reliable and well developed as any technology. However, the fact that a current has to be induced in the rotor adds to the losses, with the result that induction motors tend to be a little (1 or 2%) less efficient than the other brushless types, all other things being equal.

7.4 Motor Cooling, Efficiency, Size and Mass

7.4.1 Improving Motor Efficiency

It is clear that the motor chosen for any application should be as efficient as possible. How can we predict what the efficiency of a motor might be? It might be supposed that the *type* of motor chosen would be a major factor, but in fact it is not. Other factors are much more influential than whether the motor is BLDC, switched reluctance or induction.

An electric motor is, in energy terms, fairly simple. Electrical power is the input, and mechanical work is the desired output, with some of the energy being converted into heat. The input and output powers are straightforward to measure – the product of voltage and current for the input, and torque and angular speed at the output. However, the efficiency of an electric motor is not so simple to measure and describe as might be supposed. The problem is that it can change markedly with different conditions, and there is no single internationally agreed method of stating the efficiency of a motor (Auinger, 1999).[6] Nevertheless it is possible to state some general points about the efficiency of electric motors – the advantages and disadvantages of the different types, and the effect of motor size. *In Section 7.1.5 we also generated a general formula (Equation 7.14) for the efficiency of an electric motor that holds quite well for all motor types.*

The first general point is that motors become more efficient as their *size* increases. Table 7.2 gives the efficiency of a range of three-phase, four-pole induction motors. The efficiencies given are the minimum to be attained before the motor can be classified 'Class 1' efficiency under European Union regulations. The figures clearly show the effect of size. While these figures are for induction motors, exactly the same effect can be seen with other motor types, including BLDC motors and SRMs.

The second factor that has more control over efficiency than motor type is the *speed* of a motor. Higher speed motors are more efficient than lower ones. The reason for this

[6] The nearest to such a standard is IEC 34-2.

Table 7.2 The minimum efficiency of four-pole, three-phase induction motors to be classified as Class 1 efficiency under EU regulations. Efficiency measured according to IEC 36-2

Power (kW)	Minimum efficiency (%)
1.1	83.8
2.2	86.4
4	88.3
7.5	90.1
15	91.8
30	93.2
55	96.2
90	95.0

is that one of the most important losses in a motor is proportional to torque, rather than power, and a lower speed motor will have a higher torque, for the same power, and hence higher losses.

A third important factor is the cooling method. Motors that are liquid cooled run at lower temperatures, which reduces the resistance of the windings, and hence improves efficiency, though this will only affect things by about 1%.

Fourthly, another important consideration is that the efficiency of an electric motor might well be very different from any figure given in the specification, if it operates well away from optimum speeds and torque. In some cases an efficiency map, like that of Figures 7.7 and 7.33 may be provided. That given in Figure 7.33 is based on a real

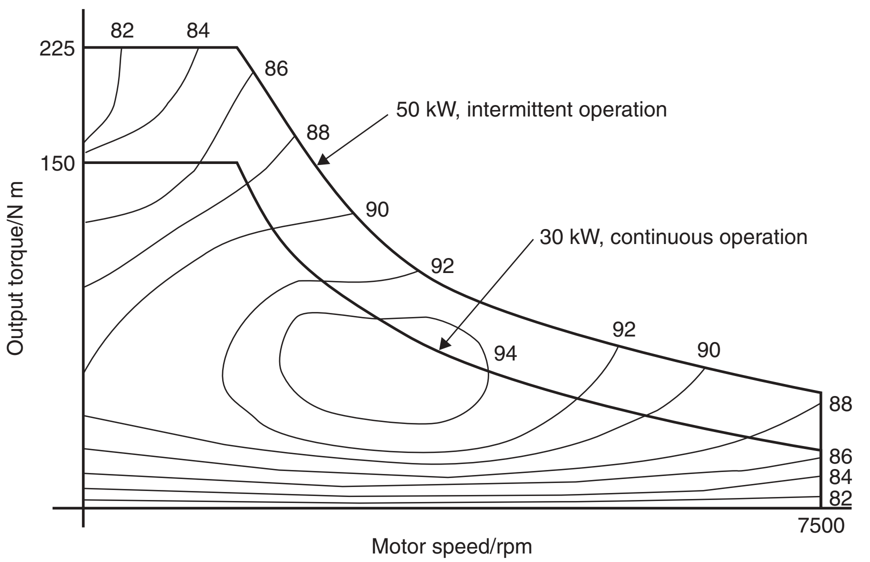


Figure 7.33 The efficiency map for a 30 kW BLDC motor. This is based on manufacturers' data, but note that in fact at zero speed the efficiency must be 0%

BLDC motor. The maximum efficiency is 94%, but this efficiency is only obtained for a fairly narrow range of conditions. It is quite possible for the motor to operate at well below 90% efficiency.

As a general guide, we can say that the maximum efficiency of a good-quality motor will be quite close to the figures given in Table 7.2 for all motor types, even if they are not induction motors. The efficiency of the BLDC motors and SRMs is likely to be 1 or 2% higher than for an induction motor, since there is less loss in the rotor. The SRM manufacturers also claim that their efficiency is maintained over a wider range of speed and torque conditions.

7.4.2 Motor Mass

A motor should generally be as small and light as possible while delivering the required power. As with the case of motor efficiency, the type of motor chosen is much less important than other factors (such as cooling method and speed) when it comes to the specific power and power density of an electric motor. The one exception to this is the brushed DC motor. We explained in Section 7.1.6 that the brushed DC motor is bound to be rather larger that other types, because such a high proportion of the losses are generated in the rotor, in the middle of the motor.

Figure 7.34 is a chart showing typical specific powers for different types of motors at different powers. Taking the example of the BLDC motor, it can be seen that the cooling method used is a very important factor. The difference between the air-cooled and liquid-cooled BLDC motor is most marked. The reason for this is that the size of the motor has

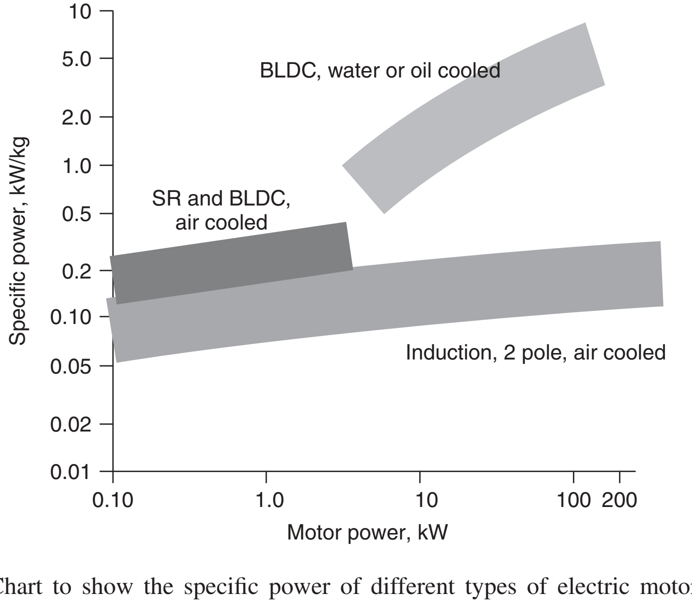


Figure 7.34 Chart to show the specific power of different types of electric motors at different powers. The power here is the continuous power. Peak specific powers will be about 50% higher. Note the logarithmic scales (This chart was compiled using data from several motor manufacturers)

Table 7.3 The mass of some 37 kW induction motors, from the same manufacturer, for different speeds. The speed is for a 50 Hz AC supply

Speed (rpm)	Mass (kg)
3000	270
1500	310
1000	415
750	570

to be large enough to dispose of the heat losses. If the motor is liquid cooled, then the same heat losses can be removed from a smaller motor.

We would then expect that efficiency should be an important factor. A more efficient motor could be smaller, since less heat disposal would be needed. This is indeed the case, and as a result all the factors that produce higher efficiency, and which were discussed in the previous section, also lead to greater specific power. The most important of these are:

- Higher *power* leads to higher efficiency, and hence higher specific power. This can be very clearly seen in Figure 7.34. (However, note that the logarithmic scale tends to make this effect appear less marked.)
- Higher *speed* leads to higher power density. The size of the motor is most strongly influenced by the motor *torque*, rather than *power*. The consequence is that a higher speed, lower torque motor will be smaller. So if a low-speed rotation is needed, a high-speed motor with a gearbox will be lighter and smaller than a low-speed motor. A good example is an electric vehicle where it would be possible to use a motor directly coupled to the axle. However, this is not often done, and a higher speed motor is connected by (typically) a 10:1 gearbox. Table 7.3 shows this, by giving the mass of a sample of induction motors of the same power but different speeds.
- The more efficient *motor types*, switched reluctance and BLDC, have higher power density than the induction motor.

The curves of Figure 7.34 give a good idea of the likely power density that can be expected from a motor, and can be used to estimate the mass. The lines are necessarily broad, as the mass of a motor will depend on many factors other than those we have already discussed. The material the frame is made from is of course very important, as is the frame structure.

7.5 Electric Machines for Hybrid Vehicles

The motors and alternators used in hybrid electric vehicles are in principle no different from those described above. Indeed in many cases there is no significant difference between the motors used in hybrid vehicles than any other type.

The basic principles of some types of hybrid vehicles were described in Chapter 2. In the series hybrid vehicle there is really nothing different about the electric machines from those used in a host of other applications. The traction motor, for example, will work in the same way as in the case of the classic battery-powered electric vehicle.

It is in the parallel hybrid that there is scope for some novelty in machine design. One example is the crankshaft-mounted electric machine that is used in a number of designs, including the groundbreaking Honda Insight. Here the electric machine, which can work as either a motor or generator, is mounted directly in line with the engine crankcase. Such machines are in most cases a type of BLDC (or synchronous AC) motor

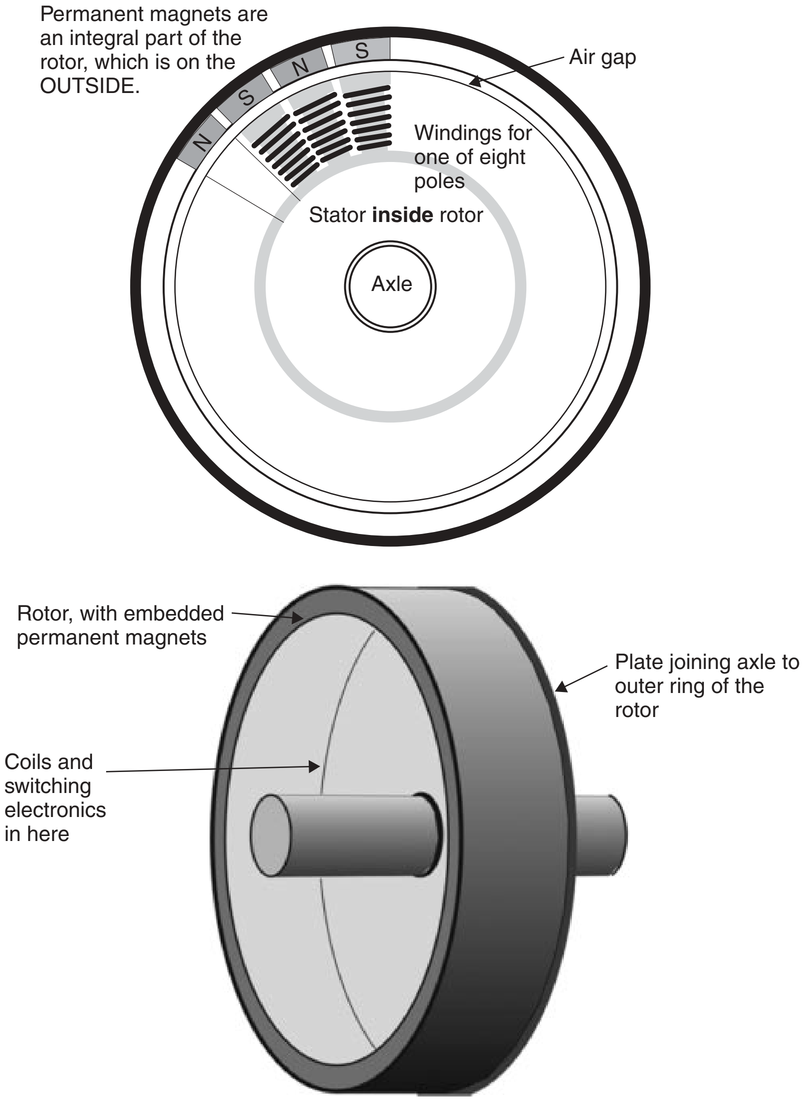


Figure 7.35 Diagram of 'inside-out' electric motor

as described in Section 7.3.2. They will be multiple-pole machines, since their location means their dimensions need to be short in length and wide in diameter. They nearly always are different from the machine of Figure 7.25 in one important respect: they are usually ‘turned inside out’, with the stationary coils being on the inside, and the rotor being a band of magnets moving outside the coil. The idea is shown in Figure 7.35. The larger diameter permits this construction, which has the advantage that the centrifugal force on the magnets tends to make them stay in place, rather than throw them out of their mounting.

It is worth pointing out that this same type of ‘inside-out’ motor is used in motors that are integral with wheels, such as the machine of Figure 9.9.

However, not all parallel hybrids use special multiple motors of this type. Some hybrid vehicles use a fairly conventional, single-pole, fairly high-speed machine, which is connected to the engine crankshaft much like the alternator in a conventional IC engine vehicle. The ‘fan belt’ type of connection is made rather more robust.

Another type of parallel hybrid where fairly conventional motors are used is the type where the front wheels are driven by an electric motor, and the rear ones are driven directly from the IC engine. The front wheels are electrically powered when more power is needed, or when driving very slowly in a queue, or when four-wheel drive is required for traction purposes. Similarly, braking is provided by the front axle, using the machine as a generator, regenerating some of the energy when slowing down. This type of parallel hybrid may well be suitable for some larger cars and vans. The machine driving, and being driven by, the front axle need not be any different from those described in Section 7.3.

Yet another parallel hybrid arrangement that has been tried with some success on the Smart car is shown in Figure 7.36. Here the main engine was left almost unaltered, but a motor was added near the base of the engine, so that it connects to the drive differential

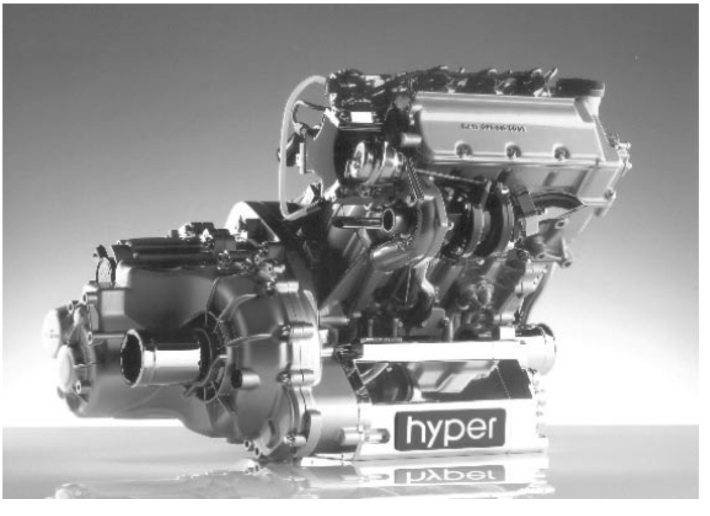


Figure 7.36 Demonstration hybrid diesel/electric power unit installed in a Smart car. The motor/generator is the unit marked ‘hyper’ at the base. (Photograph reproduced by kind permission of Micro Compact Car smart GmbH.)

via its own drive system. This allows it to drive the vehicle if the engine is not working, yet it does not have to be in line with the crankshaft. Minimal alterations are made to the rest of the engine, which reduces cost. The shape and working speeds of the electric motor mean that it does not need to be of a very special type.

7.6 Linear Motors

A linear motor is an electric motor that has had its stator 'unrolled' so that instead of producing a rotary torque it produces a linear force along its length. Linear permanent magnet synchronous motors are used on the maglev system. The permanent magnets are used on the train and the windings are a part of the track. The maglev train is discussed further in Chapter 15.

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