

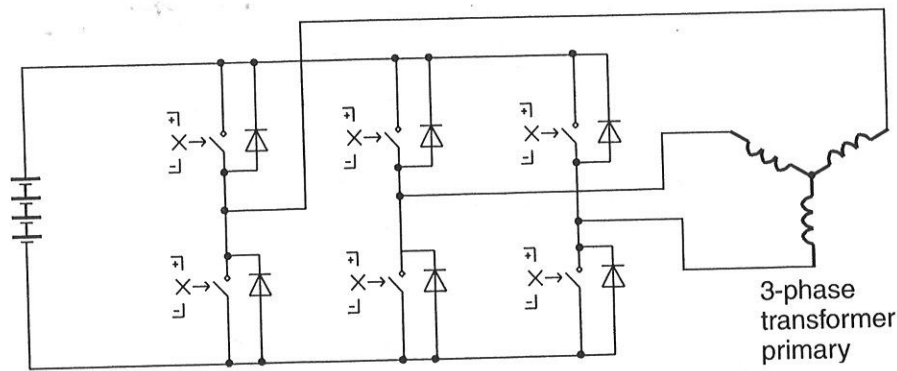


Figure 7.21 Three-phase inverter circuit

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 losses 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

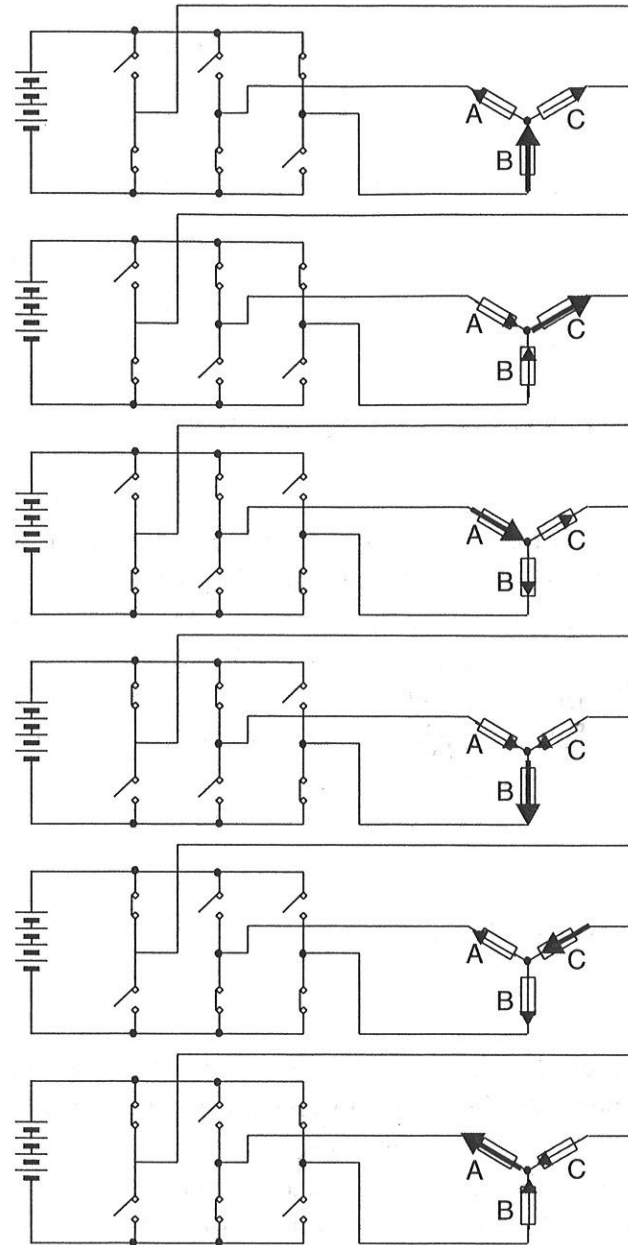


Figure 7.22 Switching pattern to generate three-phase alternating current

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.

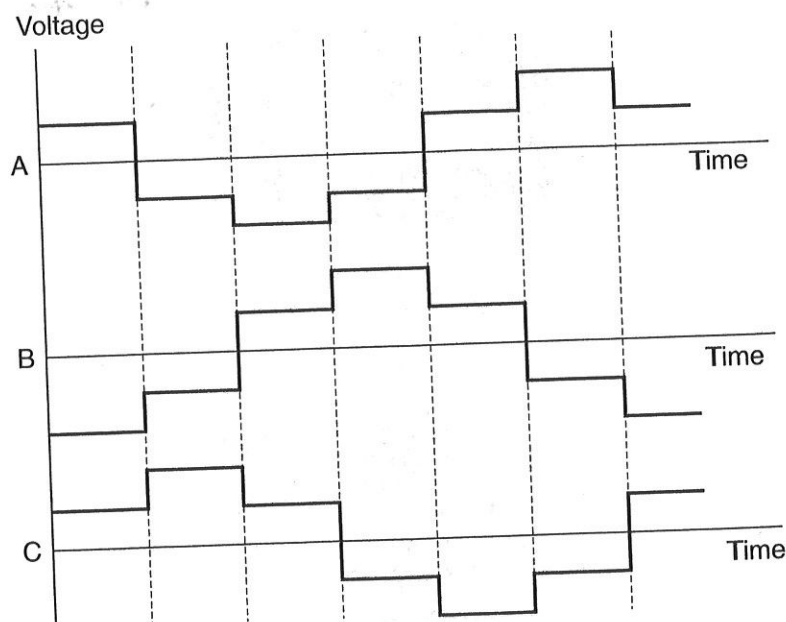


Figure 7.23 Current/time graphs for the simple three-phase AC generation system shown in this figure, assuming a resistive load. One complete cycle for each phase is shown. Current flowing *out* from the common point is taken as *positive*

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.

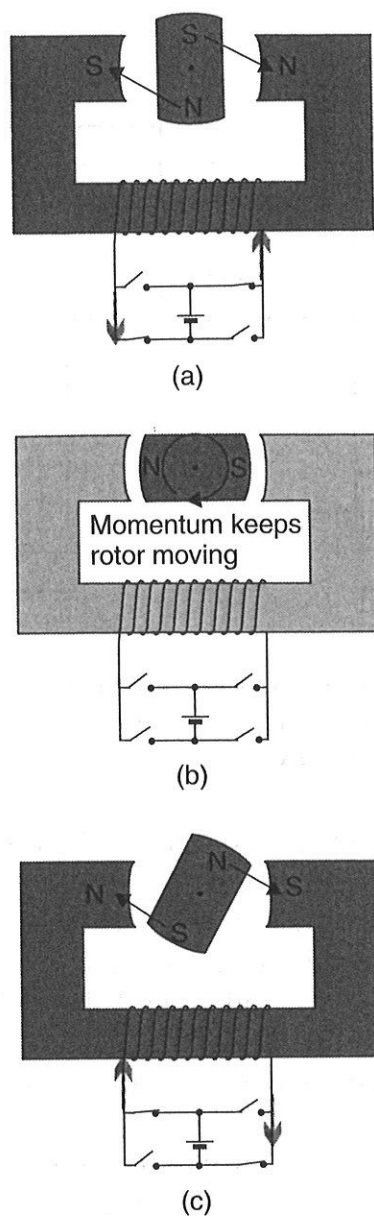


Figure 7.24 (a–c) Diagram showing the basis of operation of the brushless DC motor

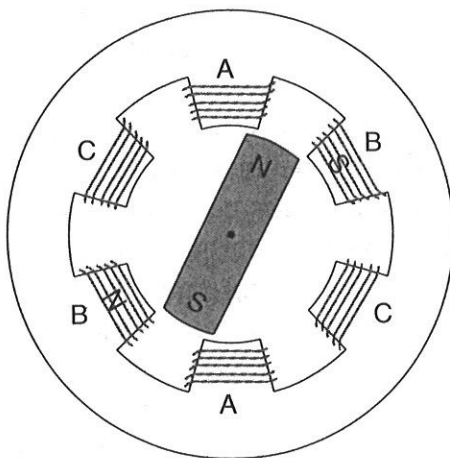


Figure 7.25 Diagram showing an arrangement of three coils on the stator of a BLDC motor

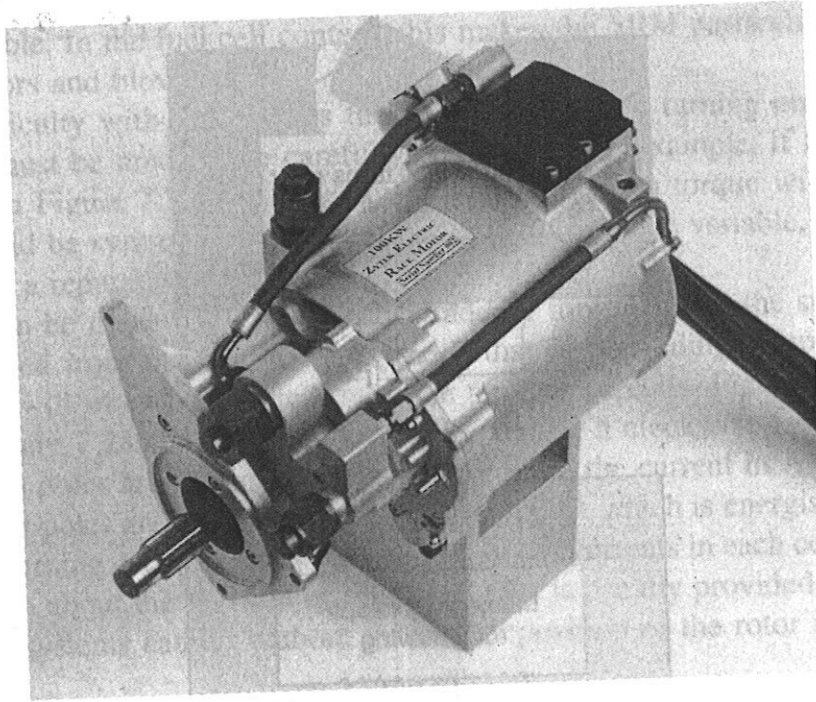


Figure 7.26 A 100 kW, oil-cooled BLDC motor for automotive application. This unit weighs just 21 kg. (Photograph reproduced by kind permission of Zytec Ltd.)

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

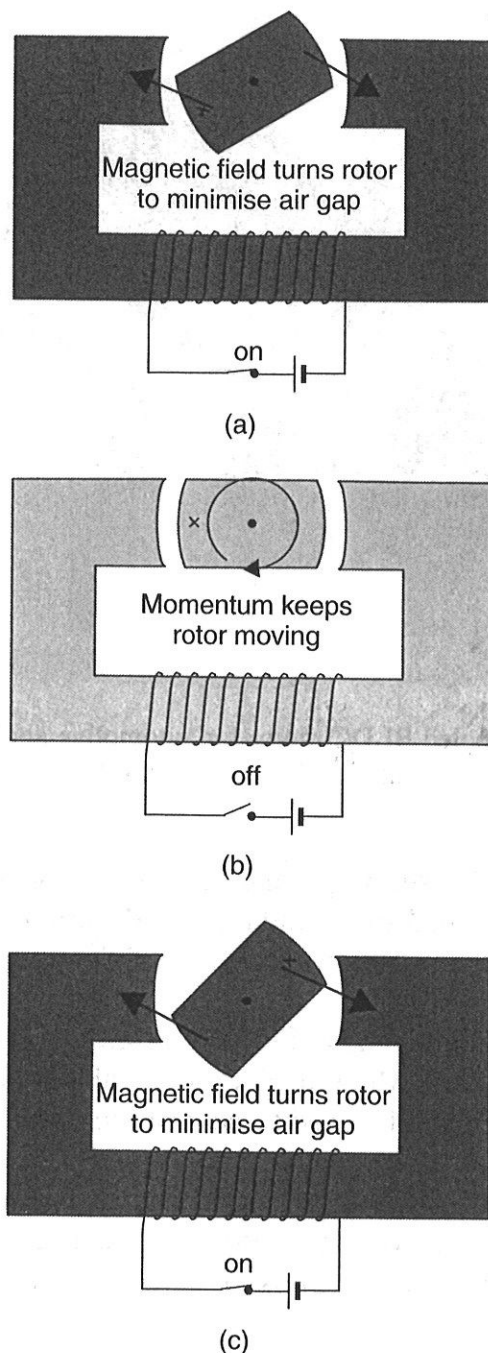


Figure 7.27 (a–c) Diagram showing the principle of operation of the switched reluctance motor

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

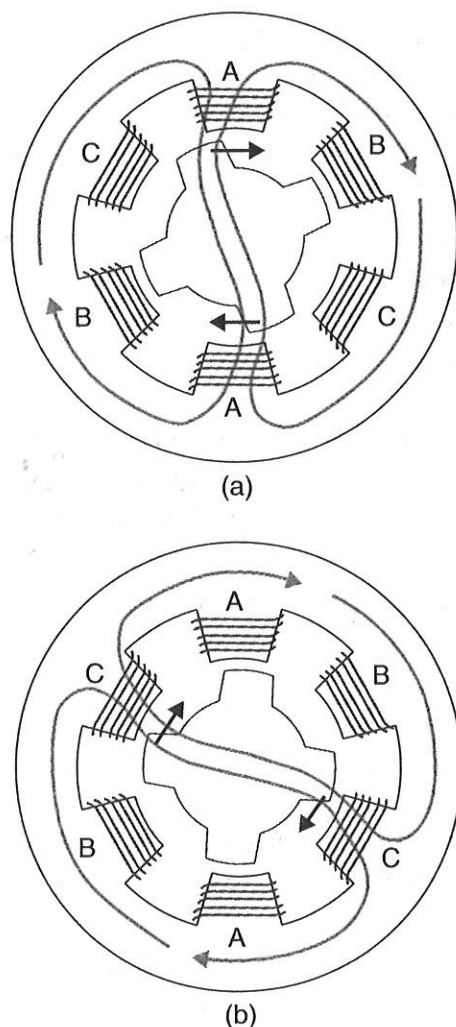


Figure 7.28 Diagram showing the operation of an SRM with a four salient pole rotor

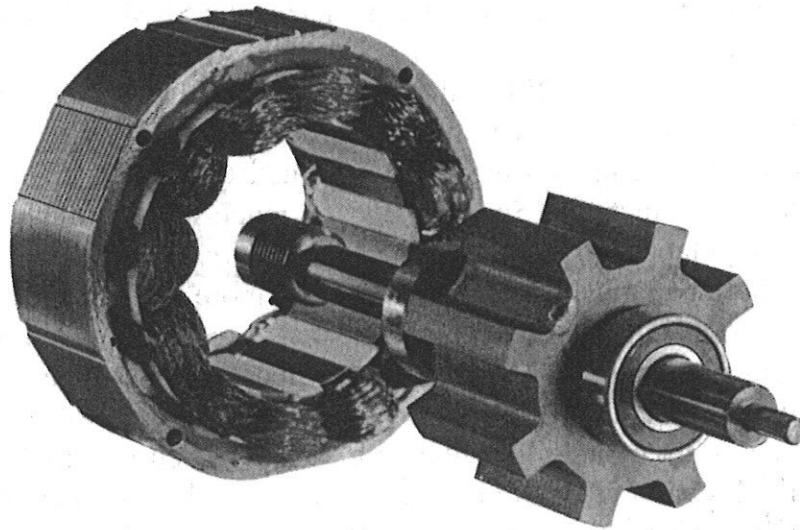


Figure 7.29 The rotor and stator from an SRM. (Photograph reproduced by kind permission of SR Drives Ltd.)

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.

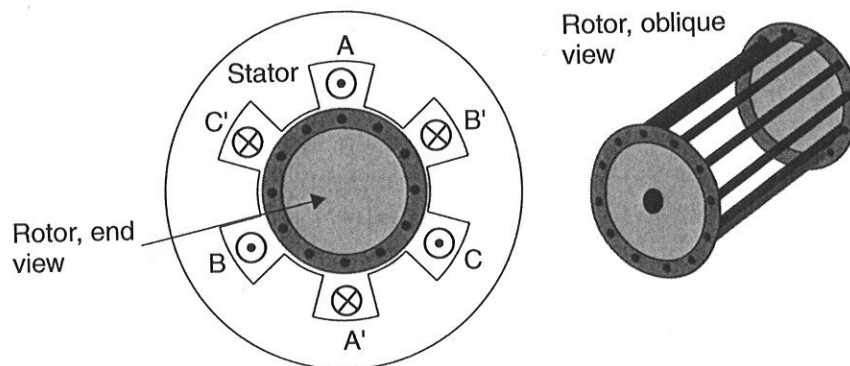


Figure 7.30 Diagram showing the stator and rotor of an induction motor

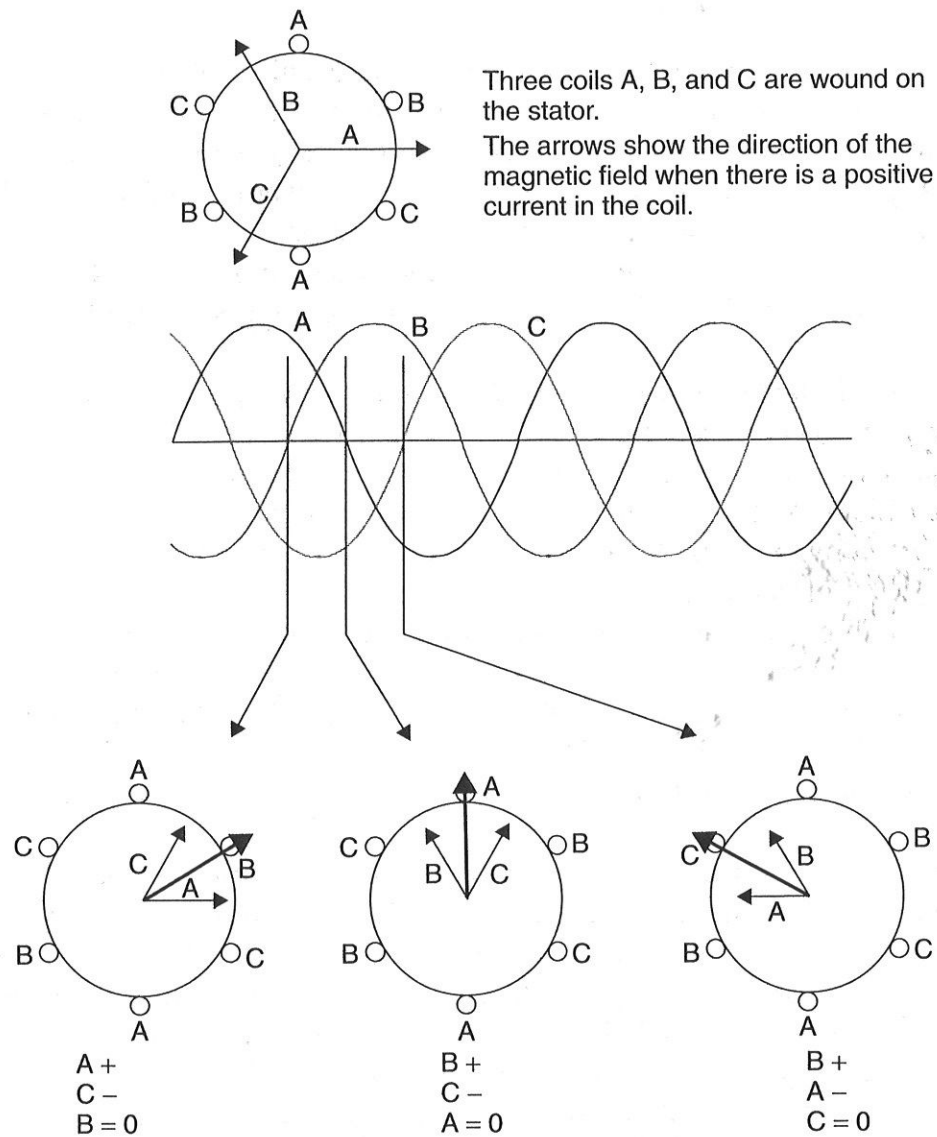


Figure 7.31 Diagrams to show how a rotating magnetic field is produced within an induction motor

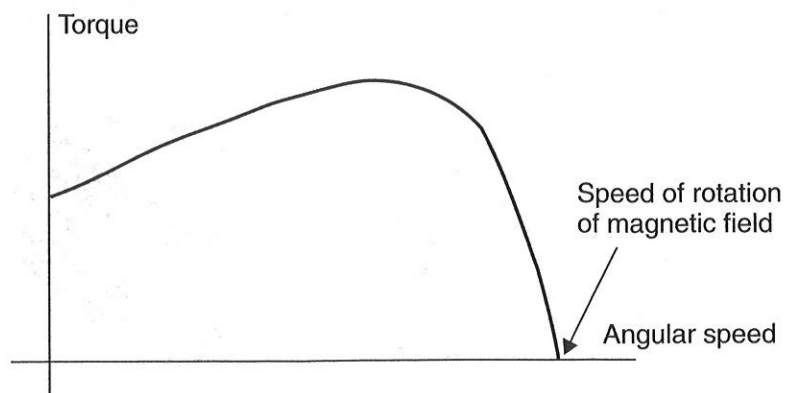


Figure 7.32 Typical torque/speed curve for an induction motor

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

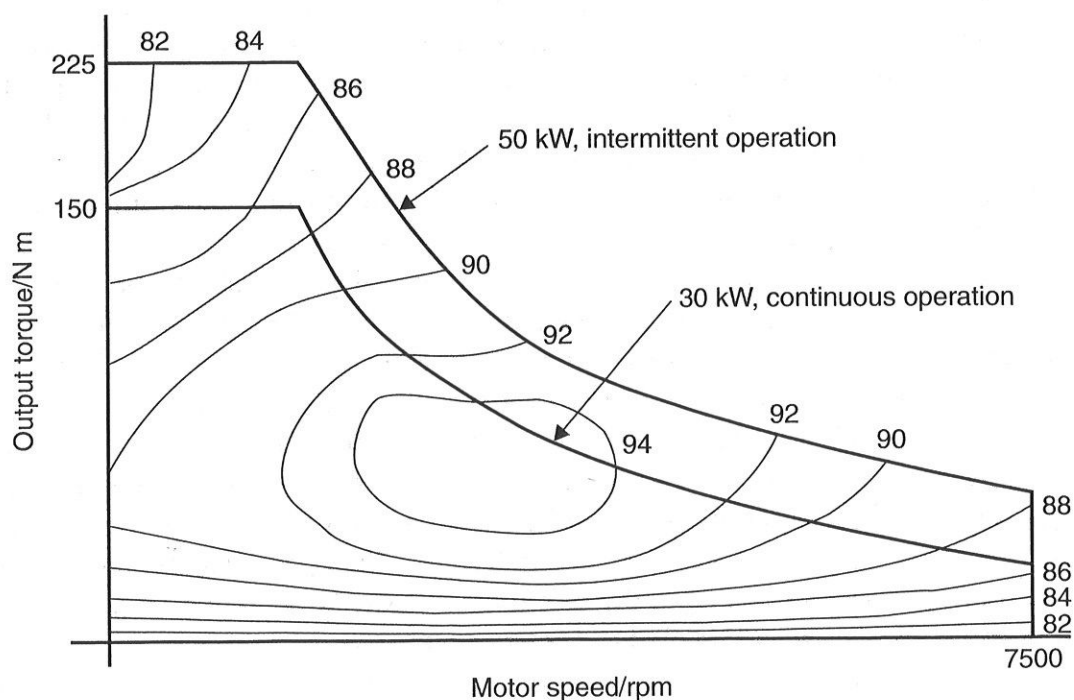


Figure 7.33 The efficiency map for a 30 kW BLDC motor. This is based on manufacturers' data, but note that in fact at zero speed the efficiency must be 0%

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 than 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

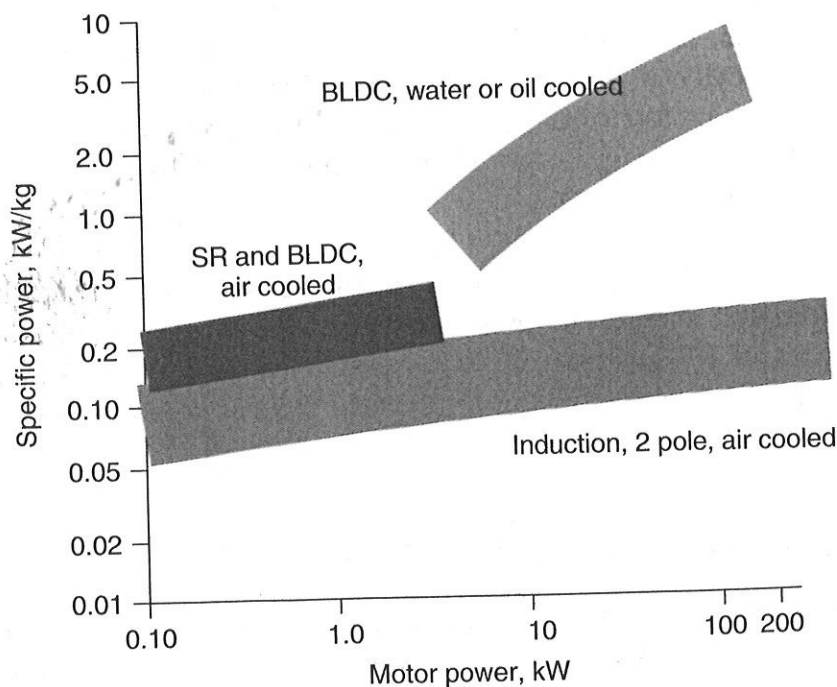


Figure 7.34 Chart to show the specific power of different types of electric motors at different powers. The power here is the continuous power. Peak specific powers will be about 50% higher. Note the logarithmic scales (This chart was compiled using data from several motor manufacturers)

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

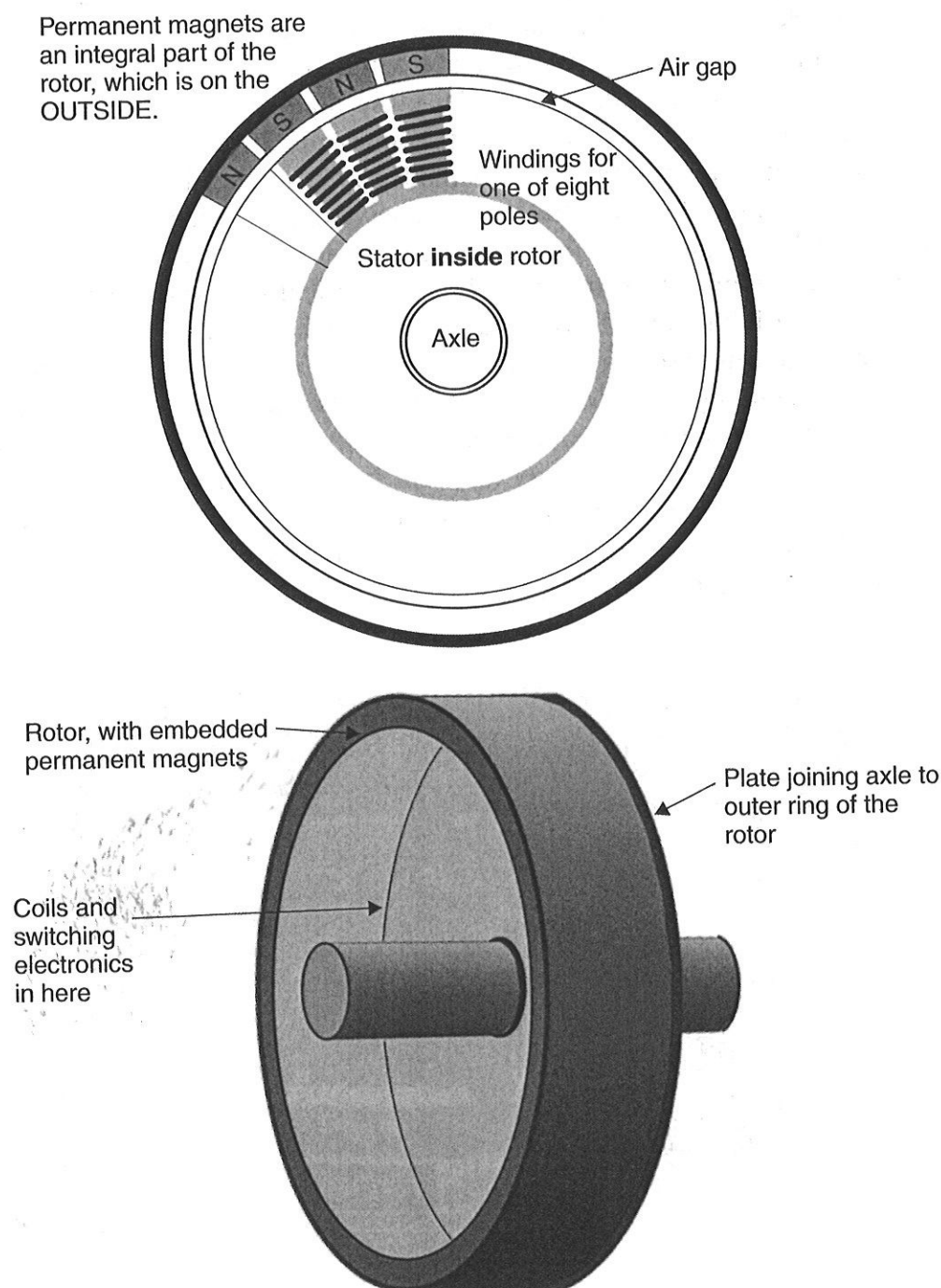


Figure 7.35 Diagram of 'inside-out' electric motor

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

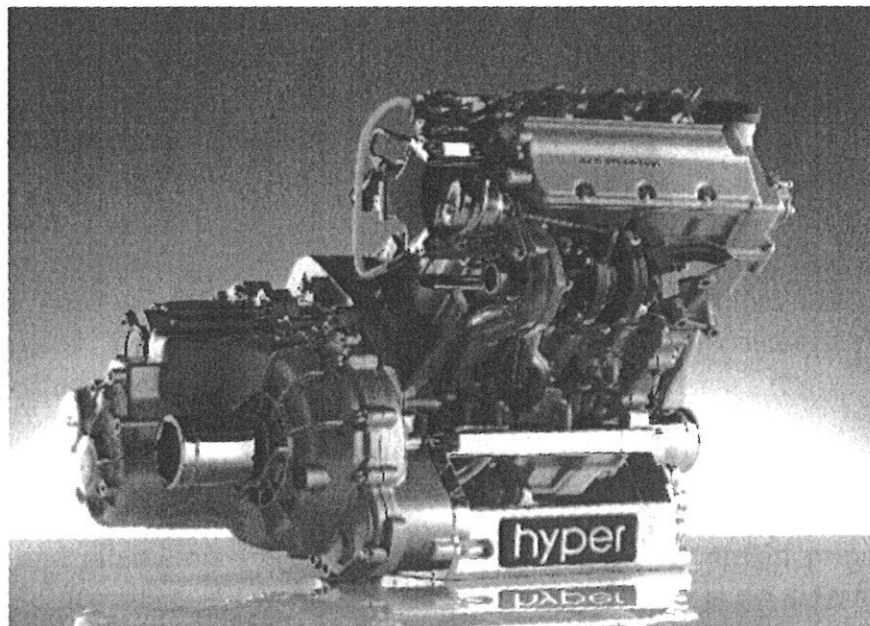


Figure 7.36 Demonstration hybrid diesel/electric power unit installed in a Smart car. The motor/generator is the unit marked 'hyper' at the base. (Photograph reproduced by kind permission of Micro Compact Car smart GmbH.)