Charging systems

6.1 Requirements of the charging system

6.1.1 Introduction

The 'current' demands made by modern vehicles are considerable. The charging system must be able to meet these demands under all operating conditions and still 'fast charge' the battery.

The main component of the charging system is the alternator and on most modern vehicles – with the exception of its associated wiring – this is the only component in the charging system. Figure 6.1 shows an alternator in common use. The alternator generates AC but must produce DC at its output terminal as only DC can be used to charge the battery and run electronic circuits. The output of the alternator must be a constant voltage regardless of engine speed and current load.

To summarize, the charging system must meet the following criteria (when the engine is running).

- Supply the current demands made by all loads.
- Supply whatever charge current the battery demands.

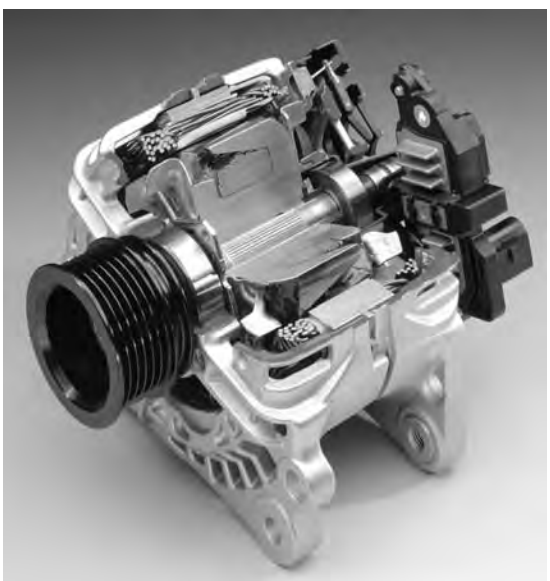

Figure 6.1 Alternator

- Operate at idle speed.
- Supply constant voltage under all conditions.
- Have an efficient power-to-weight ratio.
- Be reliable, quiet, and have resistance to contamination.
- Require low maintenance.
- Provide an indication of correct operation.

6.1.2 Vehicle electrical loads

The loads placed on an alternator can be considered as falling under three separate headings: continuous, prolonged and intermittent. The charging system of a modern vehicle has to cope with high demands under many varied conditions. To give some indication as to the output that may be required, consider the power used by each individual component and add this total to the power required to charge the battery. Table 6.1 lists the typical power requirements of various vehicle systems. The current draw (to the nearest 0.5 A) at 14 and 28 V (nominal; alternator output voltages for 12 and 24 V systems) is also given for comparison.

Figure 6.2 shows how the demands on the alternator have increased over the years, together with a prediction of the future.

Not shown in Table 6.1 are consumers, such as electrically pre-heated catalytic converters, electrical power assisted steering and heated windscreens, to list just three. Changes will therefore continue to take place in the vehicle electrical system and the charging system will have to keep up!

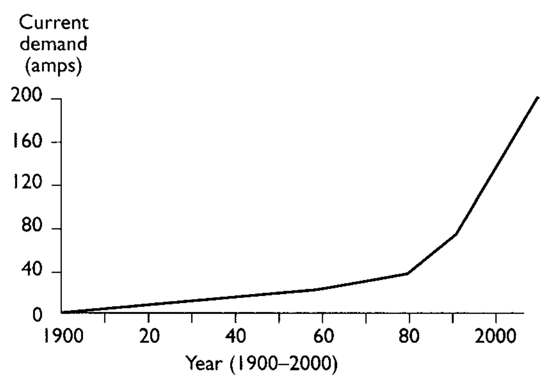

Figure 6.2 How the demands on the alternator have changed

The intermittent loads are used infrequently and power consumers such as heated rear windows and seat heaters are generally fitted with a timer relay. The factor of 0.1 is therefore applied to the total intermittent power requirement, for the purpose of further calculations. This assumes the vehicle will be used under *normal* driving conditions.

The consumer demand on the alternator is the sum of the constant loads, the prolonged loads and the intermittent loads (with the factor applied). In this example:

$$180 + 260 + 170 = 610\,\text{W}\ (43\,\text{A at}\ 14\,\text{V})$$

Table 6.1 Typical power requirements of some common vehicle electrical components

Continuous loads	Power (W)	Current at 14 V	28 V
Ignition	30	2.0	1.0
Fuel injection	70	5.0	2.5
Fuel pump	70	5.0	2.5
Instruments	10	1.0	0.5
Total	180	13.0	6.5
Prolonged loads	**Power (W)**	**Current at 14 V**	**28 V**
Side and tail lights	30	2.0	1.0
Number plate lights	10	1.0	0.5
Headlights main beam	200	15.0	7.0
Headlights dip beam	160	12.0	6.0
Dashboard lights	25	2.0	1.0
Radio/Cassette/CD	15	1.0	0.5
Total (Av. main & dip)	260	19.5	9.5
Intermittent loads	**Power (W)**	**Current at 14 V**	**28 V**
Heater	50	3.5	2.0
Indicators	50	3.5	2.0
Brake lights	40	3.0	1.5
Front wipers	80	6.0	3.0
Rear wipers	50	3.5	2.0
Electric windows	150	11.0	5.5
Radiator cooling fan	150	11.0	5.5
Heater blower motor	80	6.0	3.0
Heated rear window	120	9.0	4.5
Interior lights	10	1.0	0.5
Horns	40	3.0	1.5
Rear fog lights	40	3.0	1.5
Reverse lights	40	3.0	1.5
Auxiliary lamps	110	8.0	4.0
Cigarette lighter	100	7.0	3.5
Headlight wash wipe	100	7.0	3.5
Seat movement	150	11.0	5.5
Seat heater	200	14.0	7.0
Sun-roof motor	150	11.0	5.5
Electric mirrors	10	1.0	0.5
Total	1.7 kW	125.5	63.5

The average consumption of the intermittent loads is estimated using a factor of 0.1 ($0.1 \times 1.7\,\text{kW} = 170\,\text{W}$).

The demands placed on the charging system therefore are extensive. This load is in addition to the current required to recharge the battery. Further sections in this chapter discuss how these demands are met.

6.2 Charging system principles

6.2.1 Basic principles

Figure 6.3 shows a representation of the vehicle charging system as three blocks, the alternator, battery and vehicle loads. When the alternator voltage is less than the battery (engine slow or not running for example), the direction of current flow is from the battery to the vehicle loads. The alternator diodes prevent current flowing into the alternator. When the alternator output is greater than the battery voltage, current will flow from the alternator to the vehicle loads and the battery.

From this simple example it is clear that the alternator output voltage must be greater than the battery voltage at all times when the engine is running. The actual voltage used is critical and depends on a number of factors.

6.2.2 Charging voltages

The main consideration for the charging voltage is the battery terminal voltage when fully charged. If the charging system voltage is set to this value then there can be no risk of overcharging the battery. This is known as the constant voltage charging technique. The chapter on batteries discusses this issue in greater detail. The figure of $14.2 \pm 0.2\,\text{V}$ is the accepted charging voltage for a 12 V system. Commercial vehicles generally employ two batteries in series at

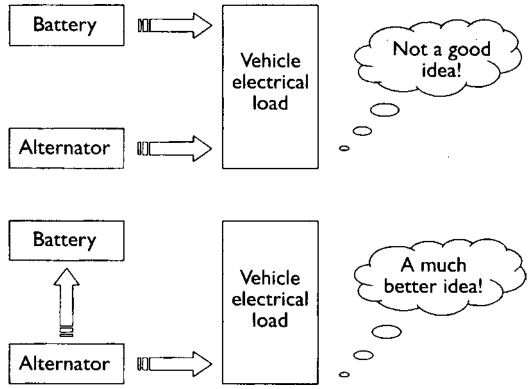

Figure 6.3 Vehicle charging system

a nominal voltage of 24 V, the accepted charge voltage would therefore be doubled. These voltages are used as the standard input for all vehicle loads. For the purpose of clarity the text will just consider a 12 V system.

The other areas for consideration when determining the charging voltage are any expected voltage drops in the charging circuit wiring and the operating temperature of the system and battery. The voltage drops must be kept to a minimum, but it is important to note that the terminal voltage of the alternator may be slightly above that supplied to the battery.

6.3 Alternators and charging circuits

6.3.1 Generation of electricity

Figure 6.4 shows the basic principle of a three-phase alternator together with a representation of its output. Electromagnetic induction is caused by a rotating magnet inside a stationary loop or loops of wire. In a practical alternator, the rotating magnet is an electromagnet that is supplied via two slip rings.

Figure 6.5 shows the most common design, which is known as a claw pole rotor. Each end of the rotor will become a north or a south pole and hence each claw will be alternately north and south. It is common practice, due to reasons of efficiency, to use claw pole rotors with 12 or 16 poles.

The stationary loops of wire are known as the stator and consist of three separate phases, each with a number of windings. The windings are mechanically spaced on a laminated core (to reduce eddy currents), and must be matched to the number of poles on the rotor. Figure 6.6 shows a typical example.

The three-phase windings of the stator can be connected in two ways, known as star or delta windings – as shown in Figure 6.7. The current and

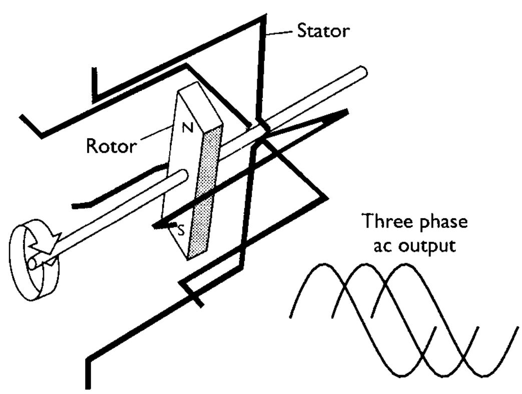

Figure 6.4 Principle of a three-phase alternator

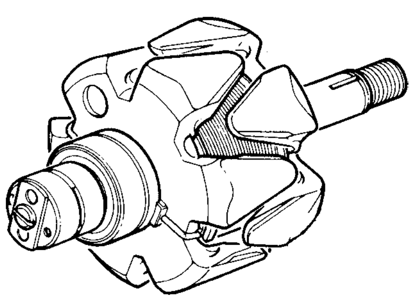

Figure 6.5 Rotor

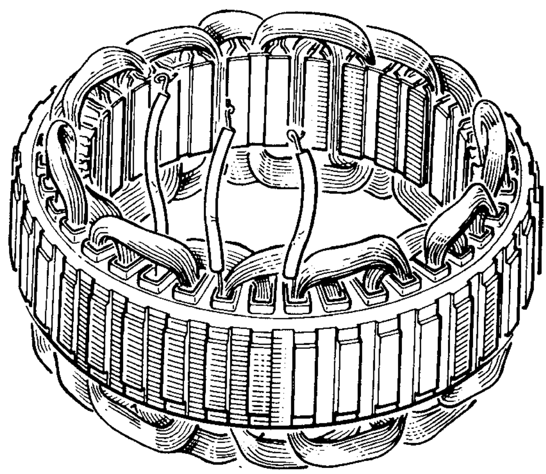

Figure 6.6 Stator

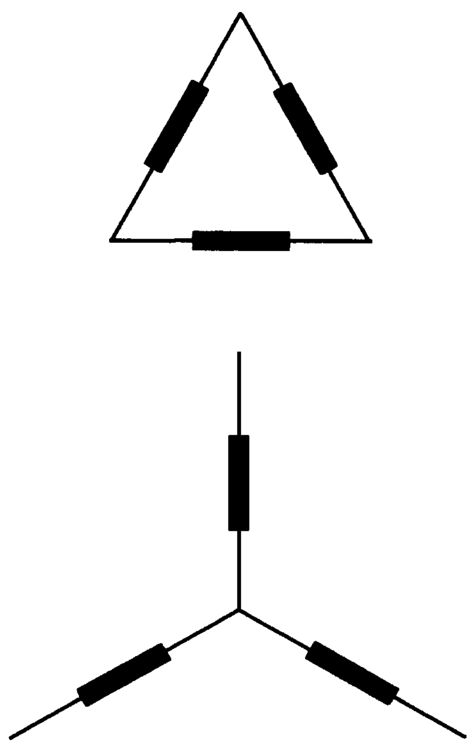

Figure 6.7 Delta and star stator windings

voltage output characteristics are different for star- and delta-wound stators.

Star connection can be thought of as a type of series connection of the phases and, to this end, the output voltage across any two phases will be the vector sum of the phase voltages. Current output will be the same as the phase current. Star-wound stators therefore produce a higher voltage, whereas delta-wound stators produce a higher current.

The voltage and current in three-phase stators can be calculated as follows.

Star-wound stators can be thought of as a type of series circuit.

$$V = V_p\sqrt{3}$$
$$I = I_p$$

A delta connection can similarly be thought of as a type of parallel circuit. This means that the output voltage is the same as the phase voltage but the output current is the vector sum of the phase currents.

$$V = V_p$$
$$I = I_p\sqrt{3}$$

where V = output voltage; V_p = phase voltage; I = output current; and I_p = phase current.

Most vehicle alternators use the star windings but some heavy-duty machines have taken advantage of the higher current output of the delta windings. The majority of modern alternators using star windings incorporate an eight-diode rectifier so as to maximize output. This is discussed in a later section.

The frequency of an alternator output can be calculated. This is particularly important if an AC tapping from the stator is used to run a vehicle rev-counter:

$$f = \frac{pn}{60}$$

where f = frequency in Hz; n = alternator speed in rev/min; and p = number of pole pairs (a 12 claw rotor has 6 pole pairs).

An alternator when the engine is at idle, will have a speed of about 2000 rev/min, which, with a 12 claw rotor will produce a frequency of $6 \times 2000/60 = 200$ Hz.

A terminal provided on many alternators for this output is often marked W. The output is half-wave rectified and is used, in particular, on diesel engines to drive a rev-counter. It is also used on some petrol engine applications to drive an electric choke.

6.3.2 Rectification of AC to DC

In order for the output of the alternator to charge the battery and run other vehicle components it must be converted from alternating current (AC) to direct current (DC). The component most suitable for this task is the silicon diode. If single-phase AC is passed through a diode, its output is half-wave rectified as shown in Figure 6.8. In this example, the diode will only allow the positive half cycles to be conducted towards the positive of the battery. The negative cycles are blocked.

Figure 6.9 shows a four-diode bridge rectifier to full-wave rectify single phase AC. A diode is often considered to be a one-way valve for electricity. While this is a good analogy it is important to remember that while a good quality diode will block reverse flow up to a pressure of about 400 V, it will still require a small voltage pressure of about 0.6 V to conduct in the forward direction.

In order to full-wave rectify the output of a three-phase machine, six diodes are required. These are connected in the form of a bridge, as shown in Figure 6.10. The 'bridge' consists of three positive diodes and three negative diodes. The output produced by this configuration is shown compared with the three-phase signals.

A further three positive diodes are often included in a rectifier pack. These are usually smaller than the main diodes and are only used to supply a small current back to the field windings in the rotor. The extra diodes are known as the auxiliary, field or excitation

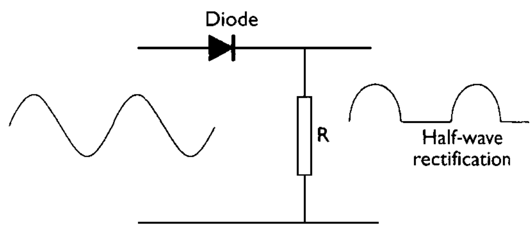

Figure 6.8 Half-wave rectification

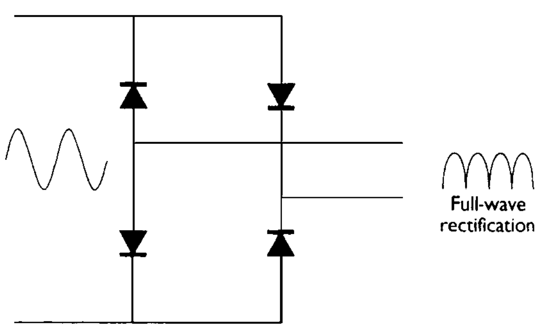

Figure 6.9 Full-wave bridge rectifier (single phase)

diodes. Figure 6.11 shows the layout of a nine-diode rectifier.

Owing to the considerable currents flowing through the main diodes, some form of heat sink is required to prevent thermal damage. In some cases diodes are connected in parallel to carry higher currents without damage. Diodes in the rectifier pack also serve to prevent reverse current flow from the battery to the alternator. This also allows alternators to be run in parallel without balancing, as equalizing current cannot flow from one to the other. Figure 6.12 shows examples of some common rectifier packs.

When a star-wound stator is used, the addition of the voltages at the neutral point of the star is, in theory, 0 V. In practice, however, due to slight inaccuracies in the construction of the stator and rotor, a potential develops at this point. This potential (voltage) is known as the third harmonic and is shown in Figure 6.13. Its frequency is three times the fundamental frequency of the phase windings. By employing two extra diodes, one positive and one negative connected to the star point, the energy can be collected. This can increase the power output of an alternator by up to 15%.

Figure 6.14 shows the full circuit of an alternator using an eight-diode main rectifier and three field diodes. The voltage regulator, which forms the starting point for the next section, is also shown in this diagram. The warning light in an alternator circuit, in addition to its function of warning of charging faults, also acts to supply the initial excitation to the field windings. An alternator will not always self-excite as the residual magnetism in the fields is not usually enough to produce a voltage that will

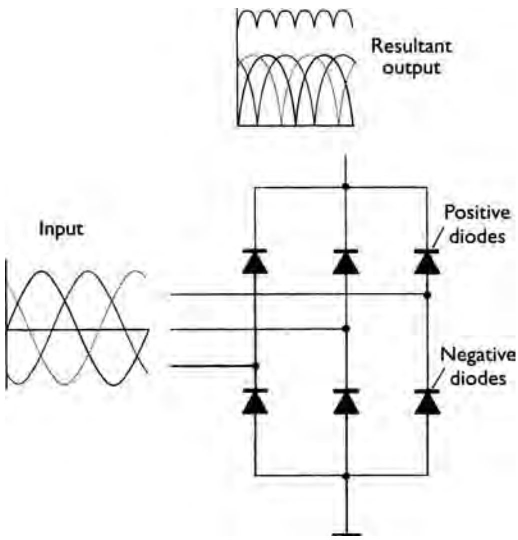

Figure 6.10 Three-phase bridge rectifier

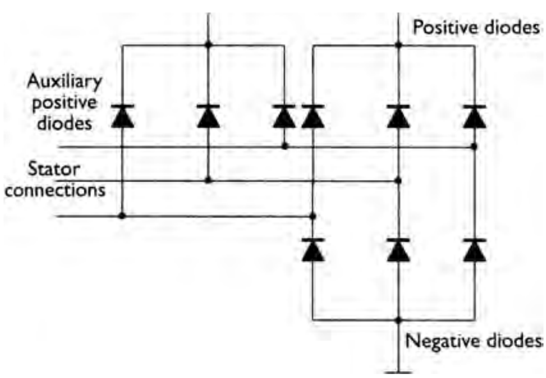

Figure 6.11 Nine-diode rectifier

Figure 6.12 Rectifier packs in common use

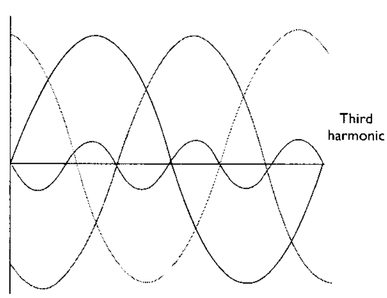

Figure 6.13 The third harmonic

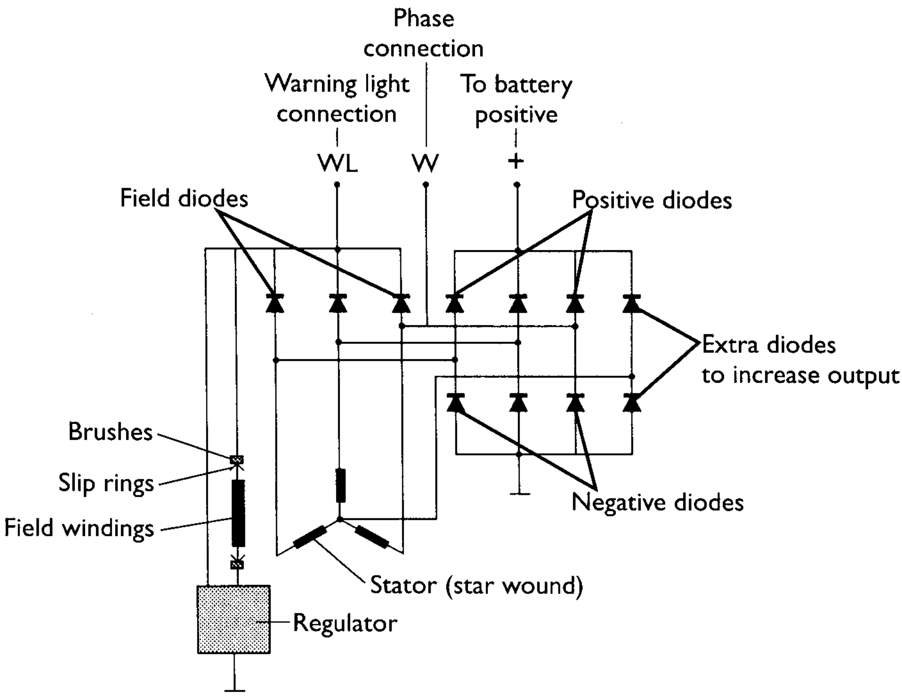

Figure 6.14 Complete internal alternator circuit

overcome the 0.6 or 0.7 V needed to forward bias the rectifier diodes. A typical wattage for the warning light bulb is 2 W. Many manufacturers also connect a resistor in parallel with the bulb to assist in excitation and allow operation if the bulb blows. The charge warning light bulb is extinguished when the alternator produces an output from the field diodes as this causes both sides of the bulb to take on the same voltage (a potential difference across the bulb of 0 V).

Figure 6.15 Voltage regulators

6.3.3 Regulation of output voltage

To prevent the vehicle battery from being overcharged the regulated system voltage should be kept below the gassing voltage of the lead-acid battery. A figure of 14.2 $\pm$ 0.2 V is used for all 12 V charging systems. Accurate voltage control is vital with the ever-increasing use of electronic systems. It has also enabled the wider use of sealed batteries, as the possibility of over-charging is minimal. Figure 6.15 shows two common voltage regulators. Voltage regulation is a difficult task on a vehicle alternator because of the constantly changing engine speed and loads on the alternator. The output of an alternator without regulation would rise linearly in proportion with engine speed. Alternator output is also proportional to magnetic field strength and this, in turn, is proportional to the field current. It is the task of the regulator to control this field current in response to alternator output voltage. Figure 6.16 shows a flow chart which represents the action of the regulator, showing how the field current is switched off as output voltage increases and then back on again as output voltage falls. The abrupt switching of the field current does not cause abrupt changes in output voltage due to the very high inductance of the field (rotor) windings. In addition, the whole switching process only takes a few milliseconds. Many regulators also incorporate some temperature compensation to allow a higher charge rate in colder conditions and to reduce the rate in hot conditions.

When working with regulator circuits, care must be taken to note 'where' the field circuit is interrupted. For example, some alternator circuits supply a constant feed to the field windings from the excitation diodes and the regulator switches the earth side. In other systems, one side of the field windings is

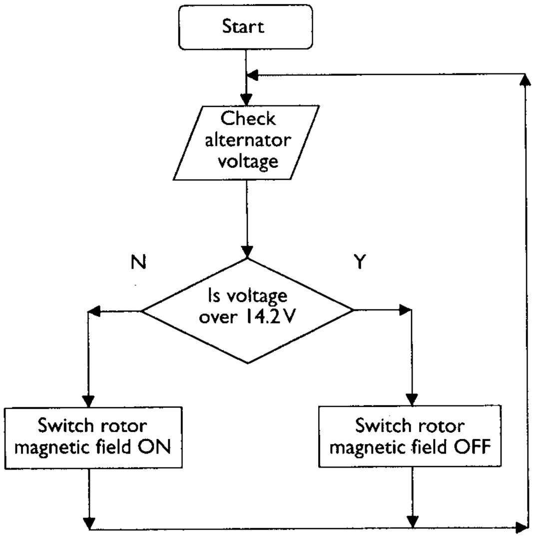

Figure 6.16 Action of the voltage regulator

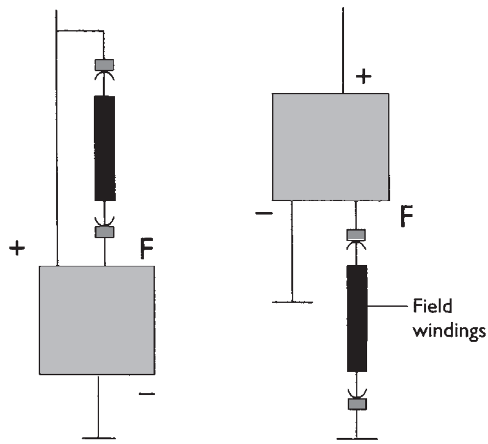

Figure 6.17 How the voltage regulator is incorporated in the field circuit

constantly earthed and the regulator switches the supply side. Figure 6.17 shows these two methods.

Alternators do not require any extra form of current regulation. This is because if the output voltage is regulated the voltage supplied to the field windings cannot exceed the pre-set level. This in turn will only allow a certain current to flow due to the resistance of the windings and hence a limit is set for the field strength. This will then limit the maximum current the alternator can produce.

Regulators can be mechanical or electronic, and the latter are now almost universal on modern cars. The mechanical type uses a winding connected across the output of the alternator. The magnetism produced in this winding is proportional to the output voltage. A set of normally closed contacts is attached to an armature, which is held in position by a spring.

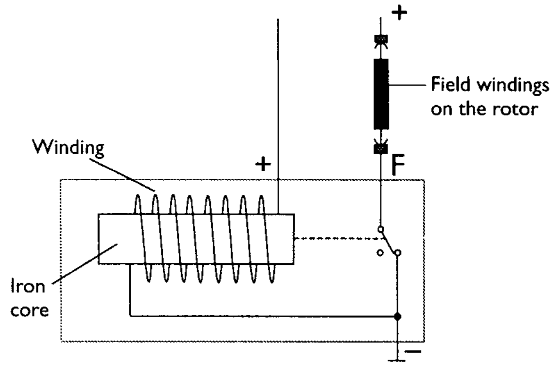

Figure 6.18 Mechanical regulator principle

The supply to the field windings is via these contacts. When the output voltage rises beyond a pre-set level, say 14 V, the magnetism in the regulator winding will overcome spring tension and open the contacts. This switches off the field current and causes the alternator output to fall. As the output falls below a pre-set level, the spring will close the regulator contacts again and so the process continues. Figure 6.18 shows a simplified circuit of a mechanical regulator. This principle has not changed from the very early voltage control of dynamo output.

The problem with mechanical regulators is the wear on the contacts and other moving parts. This has been overcome with the use of electronic regulators which, due to more accurate tolerances and much faster switching, are far superior, producing a more stable output. Due to the compactness and vibration resistance of electronic regulators they are now fitted almost universally on the alternator, reducing the number of connecting cables required.

The key to electronic voltage regulation is the Zener diode. As discussed in Chapter 3, this diode can be constructed to break down and conduct in the reverse direction at a precise level. This is used as the sensing element in an electronic regulator. Figure 6.19 shows a simplified electronic voltage regulator.

This regulator operates as follows. When the alternator first increases in speed the output will be below the pre-set level. Under these circumstances transistor T_2 will be switched on by a feed to its base via resistor R_3. This allows full field current to flow, thus increasing voltage output. When the pre-set voltage is reached, the Zener diode will conduct. Resistors R_1 and R_2 are a simple series circuit to set the voltage appropriate to the value of the diode when the supply is, say, 14.2 V. Once Z_D conducts, transistor T_1 will switch on and pull the base of T_2 down to ground. This switches T_2 off and so the field current is interrupted, causing output voltage

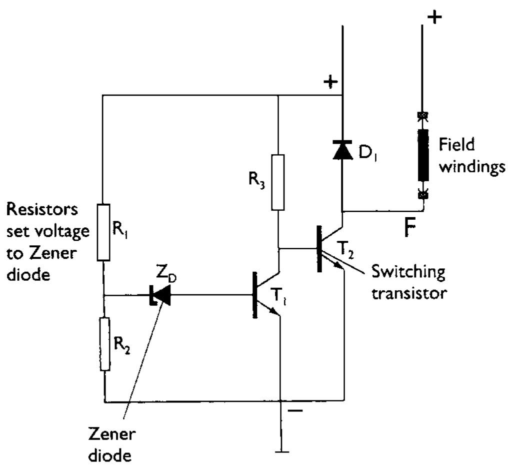

Figure 6.19 Electronic voltage regulator

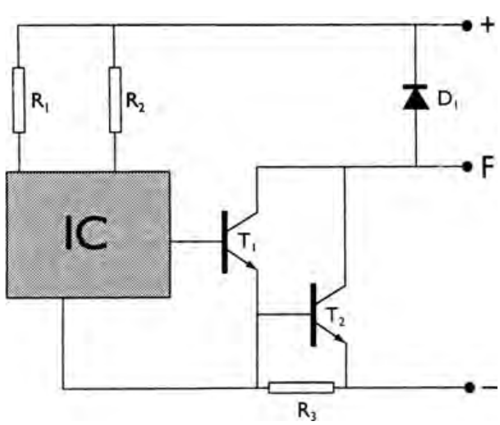

Figure 6.20 Hybrid IC regulator circuit

to fall. This will cause Z_D to stop conducting, T_1 will switch off, allowing T_2 to switch back on and so the cycle will continue. The conventional diode, D_1, absorbs the back EMF from the field windings and so prevents damage to the other components.

Electronic regulators can be made to sense either the battery voltage, the machine voltage (alternator), or a combination of the two. Most systems in use at present tend to be machine sensed as this offers some protection against over-voltage in the event of the alternator being driven with the battery disconnected.

Figure 6.20 shows the circuit of a hybrid integrated circuit (IC) voltage regulator. The hybrid system involves the connection of discrete components on a ceramic plate using film techniques. The main part of the regulator is an integrated circuit containing the sensing elements and temperature compensation components. The IC controls an output stage such as a Darlington pair. This technique produces a very compact device and, because of the low number of components and connections, is very reliable.

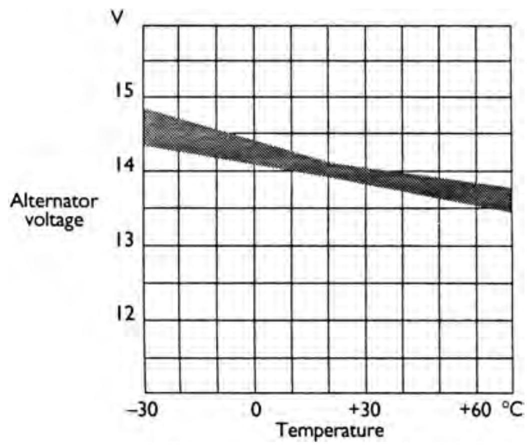

Figure 6.21 How the regulator response changes with temperature

Figure 6.21 is a graph showing how the IC regulator response changes with temperature. This change is important to ensure correct charging under 'summer' and 'winter' conditions. When a battery is cold, the electrolyte resistance increases. This means a higher voltage is necessary to cause the correct recharging current.

Over-voltage protection is required in some applications in order to prevent damage to electronic components. When an alternator is connected to a vehicle battery system, the voltage, even in the event of regulator failure, will not often exceed about 20 V due to the low resistance and swamping effect of the battery. If an alternator is run with the battery disconnected (which is not recommended), a heavy duty Zener diode connected across the output of the WL/field diodes will offer some protection as, if the system voltage exceeds its breakdown figure, it will conduct and cause the system voltage to be kept within reasonable limits.

6.3.4 Charging circuits

For many applications, the charging circuit is one of the simplest on the vehicle. The main output is connected to the battery via a suitably sized cable (or in some cases two cables to increase reliability and flexibility), and the warning light is connected to an ignition supply on one side and to the alternator terminal at the other. A wire may also be connected to the phase terminal if it is utilized. Figure 6.22 shows two typical wiring circuits. Note that the output of the alternator is often connected to the starter main supply simply for convenience of wiring. If the wires are kept as short as possible this will reduce voltage drop in the circuit. The voltage drop across the main supply wire when the alternator is producing full output current, should be less than 0.5 V.

Some systems have an extra wire from the alternator to 'sense' battery voltage directly. An ignition feed may also be found and this is often used to ensure instant excitement of the field windings. A number of vehicles link a wire from the engine management ECU to the alternator. This is used to send a signal to increase engine idle speed if the battery is low on charge.

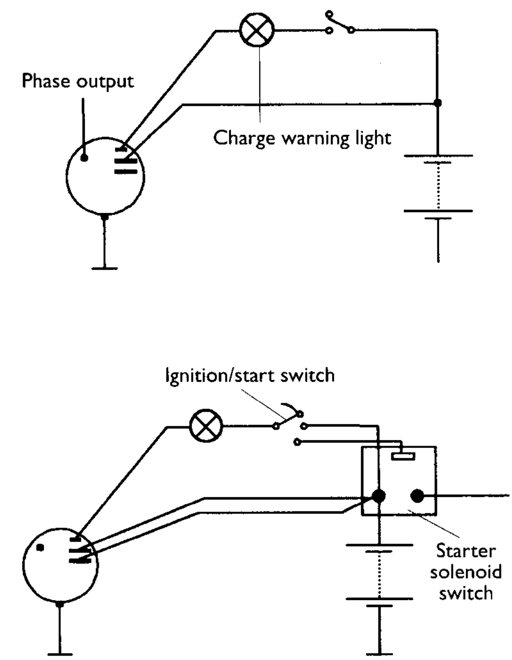

Figure 6.22 Example charging circuits

6.4 Case studies

6.4.1 An alternator in common use

Figure 6.23 shows the Lucas model A127 alternator used in large numbers by several vehicle manufacturers. The basic data relating to this machine are listed below.

- 12 V negative earth.
- Regulated voltage 14.0–14.4 V.
- Machine sensed.
- Maximum output when hot, 65 A (earth-return).
- Maximum speed 16 500 rev/min.
- Temperature range −40 to +105 °C.
- European plug and stud termination (7 mm).

This alternator has a frame diameter of 127 mm, a 15 mm drive shaft and weighs about 4 kg. It is a star-wound machine.

6.4.2 Bosch compact alternator

The Bosch compact alternator is becoming very popular with a number of European manufacturers

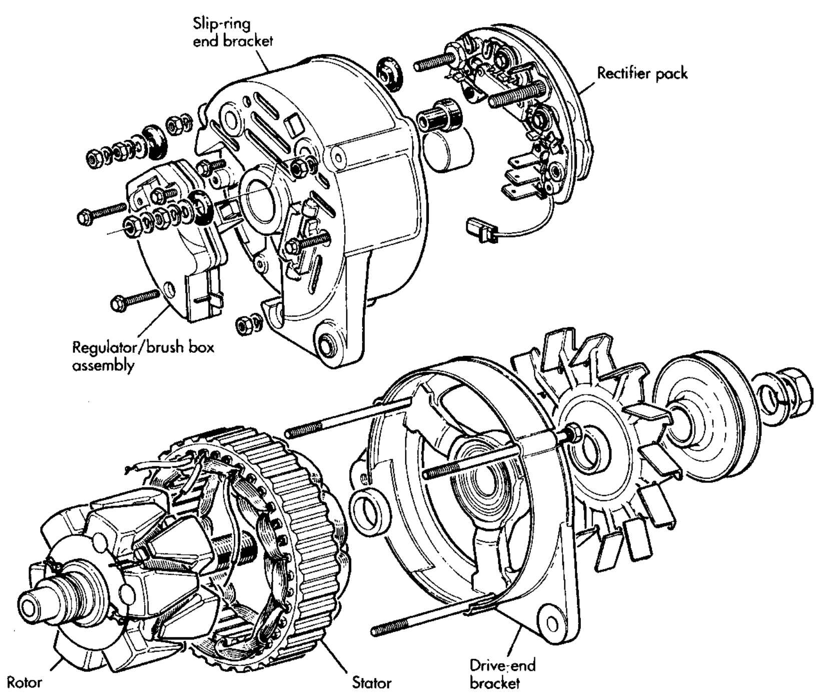

Figure 6.23 Lucas A127 alternator

and others. Figure 6.24 shows a cut-away picture of this machine. The key points are as follows:

- 20–70% more power than conventional units.
- 15–35% better power-to-weight ratio.
- Maximum speed up to 20 000 rev/min.
- Twin interior cooling fans.
- Precision construction for reduced noise.
- Versions available: 70, 90 and up to 170 A.

The compact alternator follows the well-known claw pole design. Particular enhancements have been made to the magnetic circuit of the rotor and stator. This was achieved by means of modern 'field calculation' programmes. The optimization reduces the iron losses and hence increases efficiency.

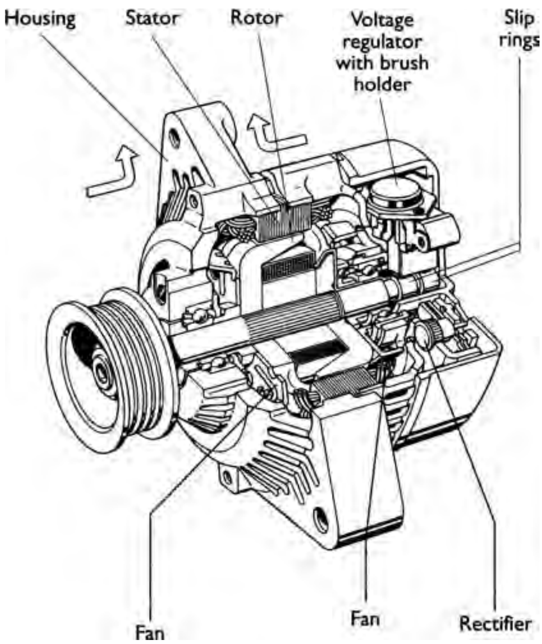

Figure 6.24 Bosch compact alternator

A new monolithic circuit regulator is used that reduces the voltage drop across the main power transistor from 1.2 V to 0.6 V. This allows a greater field current to flow, which again will improve efficiency.

The top speed of an alternator is critical as it determines the pulley ratio between the engine and alternator. The main components affected by increased speed are the ball bearings and the slip rings. The bearings have been replaced with a type that uses a plastic cage instead of the conventional metal type. Higher melting point grease is also used. The slip rings are now mounted outside the two bearings and therefore the diameter is not restricted by the shaft size. Smaller diameter slip rings give a much lower peripheral velocity, and thus greater shaft speed can be tolerated.

Increased output results in increased temperature so a better cooling system was needed. The machine uses twin internal asymmetric fans, which pull air through central slots front and rear, and push it out radially through the drive and slip ring end brackets over the stator winding heads.

High vibration is a problem with alternators as with all engine mounted components. Cars with four-valve engines can produce very high levels of vibration. The alternator is designed to withstand up to 80 g. New designs are thus required for the mounting brackets.

6.4.3 Japanese alternator

Figure 6.25 shows the internal and external circuit of a typical alternator used on a number of Japanese vehicles. It is an eight-diode machine and uses an integrated circuit regulator. Four electrical

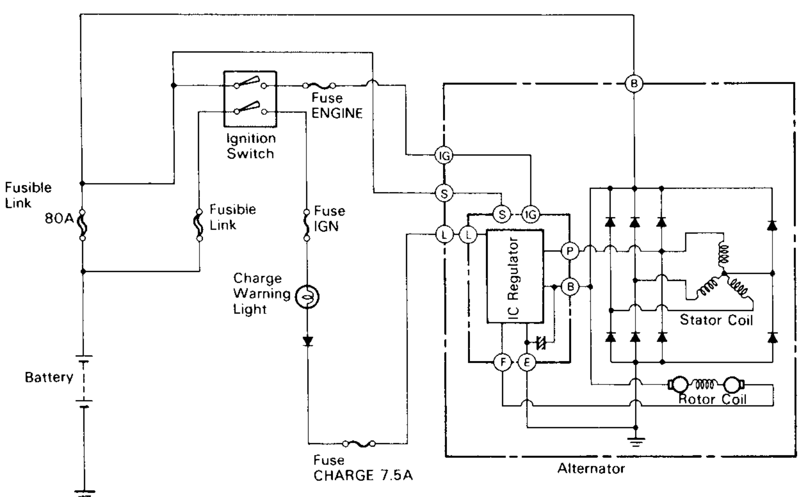

Figure 6.25 Japanese alternator circuit

connections are made to the alternator; the main output wire (B), an ignition feed (IG), a battery sensing wire (S) and the warning light (L).

Figure 6.26 shows all the main components of the alternator. Internal cooling fans are used to draw air through the slots in the end brackets. The diameter of the slip rings is only about 14 mm. This keeps the surface speed (m/s) to a minimum, allowing greater rotor speeds (rev/min).

The IC regulator ensures consistent output voltage with built-in temperature compensation. The ignition-controlled feed is used to ensure that the machine charges fully at low engine speed. Because of this ignition voltage supply to the fields, the cut-in speed is low.

6.4.4 LI-X series of alternators from Bosch

There is still plenty of room for improvements in belt-driven alternators for motor vehicles. A combination of longtime experience, modern development methods and innovative production processes has enabled development engineers at Bosch to achieve dramatic gains in alternator performance compared to conventional models – a 35% increase in power density to 1.43 watt per cubic centimetre, a rise in maximum operating temperature from 105 ° C to 120 ° C, and an increase in the maximum degree of efficiency to 76% (VDA average 72%). The developers also succeeded in lowering operating noise by a clearly perceptible 5 dB(A). The result is the new Bosch LI-X range of alternators. (Figure 6.27)

The improved performance parameters offer automobile manufacturers a reduction in fuel consumption of up to 0.2 litre per hundred kilometres, a saving in space of up to 400 cubic centimetres, and finally an increase in power output of as much as 1 kilowatt. The improvements are largely due to the so-called ‘Flat Pack’ technique, which achieves a very high density of the copper wires in the stator windings.

Bosch supply its 14 V LI-X alternators in three different sizes: ‘Compact’, ‘Medium’ and ‘High Line’, with outputs ranging from 1.9 to 3.8 kilowatts. The model range is designed to be extremely flexible and the power outputs can easily be adjusted for use in both diesel and gasoline engines. Bosch is also planning a 42 volt version with a peak power output of 4 kilowatts.

The alternator regulator is multifunctional and can be operated through a variety of interfaces (for

Figure 6.26 Alternator components

Figure 6.27 LI-X alternator (Source: Bosch Press)

smart charging, etc.), such as BSS, LIN or RVC, in line with the manufacturer's preference.

6.5 Diagnosing charging system faults

6.5.1 Introduction

As with all systems, the six stages of fault-finding should be followed.

1. Verify the fault.
2. Collect further information.
3. Evaluate the evidence.
4. Carry out further tests in a logical sequence.
5. Rectify the problem.
6. Check all systems.

The procedure outlined in the next section is related primarily to stage 4 of the process. Table 6.2 lists some common symptoms of a charging system malfunction together with suggestions for the possible fault.

6.5.2 Testing procedure

After connecting a voltmeter across the battery and an ammeter in series with the alternator output wire(s), as shown in Figure 6.28, the process of checking the charging system operation is as follows.

1. Hand and eye checks (drive belt and other obvious faults) – belt at correct tension, all connections clean and tight.
2. Check battery (see Chapter 5) – must be 70% charged.
3. Measure supply voltages to alternator – battery volts.
4. Maximum output current (discharge battery slightly by leaving lights on for a few minutes, leave lights on and start engine) – ammeter should read within about 10% of rated maximum output.
5. Regulated voltage (ammeter reading 10 A or less) – 14.2 ± 0.2 V.
6. Circuit volt drop – 0.5 V maximum.

If the alternator is found to be defective then a quality replacement unit is the normal recommendation. Figure 6.29 explains the procedure used by Bosch to ensure quality exchange units. Repairs are possible but only if the general state of the alternator is good.

6.6 Advanced charging system technology

6.6.1 Charging system – problems and solutions

The charging system of a vehicle has to cope under many varied conditions. An earlier section gave some indication as to the power output that may be required. Looking at two of the operating conditions that may

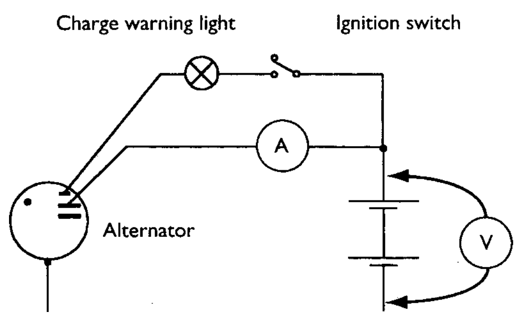

Figure 6.28 Alternator testing

Table 6.2 Common symptoms and faults of a charging system malfunction

Symptom	Possible fault
Battery loses charge	• Defective battery. • Slipping alternator drive belt. • Battery terminals loose or corroded. • Alternator internal fault (diode open circuit, brushes worn or regulator fault etc.). • Open circuit in alternator wiring, either main supply, ignition or sensing wires if fitted. • Short circuit component causing battery drain even when all switches are off. • High resistance in the main charging circuit.
Charge warning light stays on when engine is running	• Slipping or broken alternator drive belt. • Alternator internal fault (diode open circuit, brushes worn or regulator fault etc.). • Loose or broken wiring/connections.
Charge warning light does not come on at any time	• Alternator internal fault (brushes worn open circuit or regulator fault etc.). • Blown warning light bulb. • Open circuit in warning light circuit.

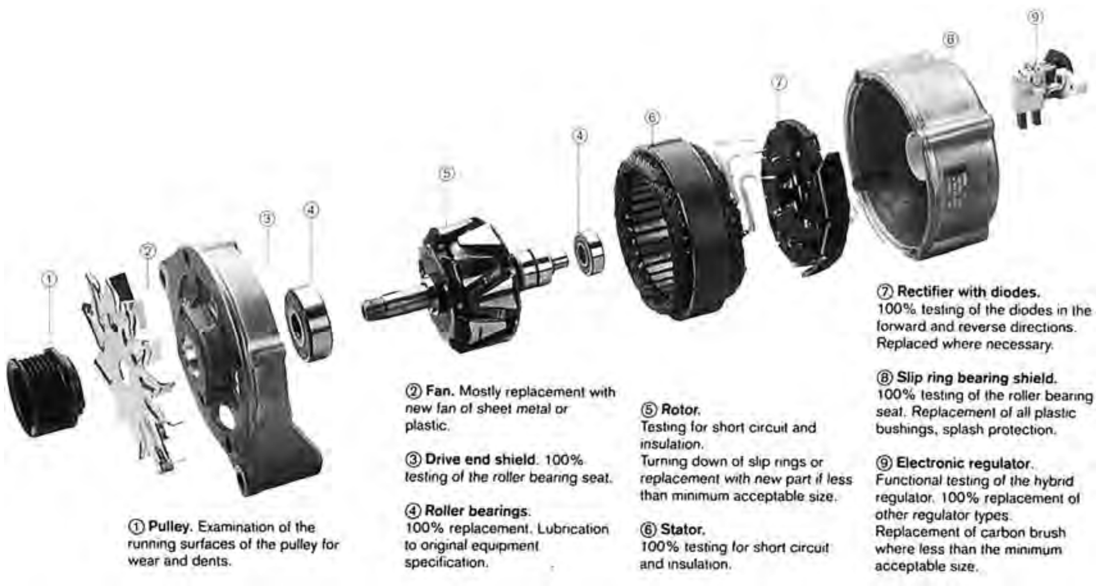

Figure 6.29 Alternator overhaul procedure (Bosch)

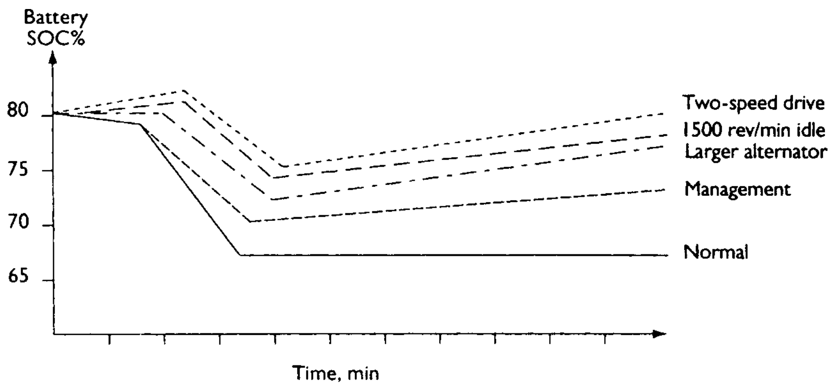

Figure 6.30 Graphical representation comparing various charging techniques when applied to a vehicle used for winter commuting

be encountered makes the task of producing the required output even more difficult.

The first scenario is the traffic jam, on a cold night, in the rain! This can involve long periods when the engine is just idling, but use of nearly all electrical devices is still required. The second scenario is that the car has been parked in the open on a frosty night. The engine is started, seat heaters, heated rear window and blower fan are switched on whilst a few minutes are spent scraping the screen and windows. All the lights and wipers are now switched on and a journey of half an hour through busy traffic follows. The seat heaters and heated rear window can generally be assumed to switch off automatically after about 15 minutes.

Tests and simulations have been carried out using the above examples as well as many others. At the end of the first scenario the battery state of charge will be about 35% less than its original level; in the second case the state of charge will be about 10% less. These situations are worst case scenarios, but nonetheless possible. If the situations were repeated without other journeys in between, then the battery would soon be incapable of starting the engine. Combining this with the ever-increasing power demands on the vehicle alternator makes this problem difficult to solve. It is also becoming even more important to ensure the battery remains fully charged, as ECUs with volatile memories and alarm systems make a small but significant drain on the battery when the vehicle is parked.

A number of solutions are available to try and ensure the battery will remain in a state near to full charge at all times. A larger capacity battery could be used to 'swamp' variations in electrical use and operating conditions. Some limit, however, has to be set due to the physical size of the battery. Five options for changes to the power supply system are represented graphically in Figure 6.30 and are listed below.

- Fitting a more powerful alternator.
- Power management system.
- Two-stage alternator drive mechanism or increased alternator speed.
- Increased engine idle speed.
- Dual voltage systems.

The five possible options listed above have some things in their favour and some against, not least of which are the technical and economic factors. For the manufacturers, I would predict that a combination of a more powerful alternator, which can be run at a higher speed, together with a higher or dual voltage system, would be the way forward. This is likely to be the most cost effective and technically feasible solution. Each of the suggestions is now discussed in more detail.

The easiest solution to the demand for more power is a larger alternator, and this is, in reality, the only method available as an after-market improvement. It must be remembered, however, that power supplied by an alternator is not 'free'. For each watt of electrical power produced by the alternator, between 1.5 and 2 W are taken from the engine due to the inefficiency of the energy conversion process. An increase in alternator capacity will also have implications relating to the size of the drive belt, associated pulleys and tensioners.

An intelligent power management system, however, may become more financially attractive as electronic components continue to become cheaper. This technique works by switching off headlights and fog lights when the vehicle is not moving. The cost of this system may be less than increasing the size of the alternator. Figure 6.31 shows the operating principle of this system. A speed sensor signal is used via an electronic processing circuit to trigger a number of relays. The relays can be used to interrupt the chosen lighting circuits. An override switch is provided, for use in exceptional conditions.

A two-speed drive technique which uses a ratio of 5 : 1 for engine speeds under 1200 rev/min and usually about 2.5 : 1 at higher speeds shows some promise but adds more complications to the drive system. Due to improvements in design, however, modern alternators are now being produced that are capable of running at speeds up to 20 000 rev/min. If the maximum engine speed is considered to be about 6000 rev/min, a pulley ratio of about 3.3 : 1 can be used. This will allow the alternator to run as fast as 2300 rev/min, even with a low engine idle speed of 700 rev/min. The two-speed drive is only at the prototype stage at present.

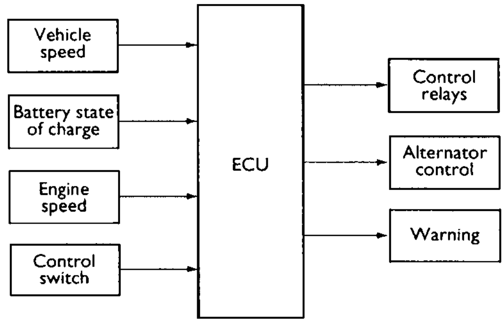

Figure 6.31 Operating principles of a power management system

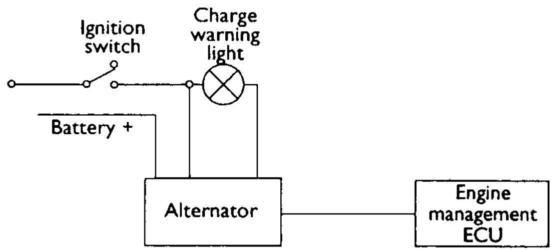

Figure 6.32 Alternator wiring to allow engine management system to sense current demand and control engine idle speed to prevent stalling

Increased idle speed may not be practical in view of the potential increase in fuel consumption and emissions. It is nonetheless an option, but may be more suitable for diesel-engined vehicles. Some existing engine management systems, however, are provided with a signal from the alternator when power demand is high. The engine management system can then increase engine idle speed both to prevent stalling and ensure a better alternator output. Figure 6.32 shows the wiring associated with this technique.

Much research is being carried out on dual voltage electrical systems. It has long been known that a 24 V system is better for larger vehicles. This, in the main, is due to the longer lengths of wire used. Double the voltage and the same power can be transmitted at half the current (watts = volts × amps). This causes less volt drop due to the higher resistance in longer lengths of cable. Wiring harnesses used on passenger cars are becoming increasingly heavy and unmanageable. If a higher supply voltage was used, the cross-section of individual cables could be halved with little or no effect. Because heavy vehicle electrics have been 24 V for a long time, most components (bulbs etc.) are already available if a change in strategy by the vehicle manufacturers takes place. Under discussion is a −12, 0, +12 V technique using three bus bars or rails. High power loads can be connected between −12 and +12 (24 V), and

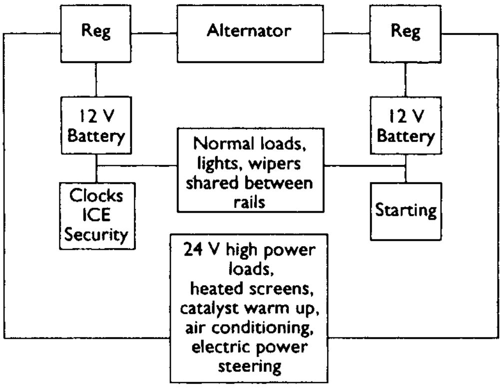

Figure 6.33 Dual rail power supply technique

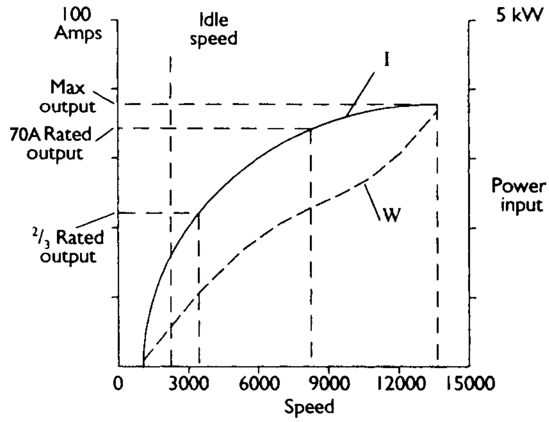

Figure 6.34 Typical alternator characteristic curve

loads which must be supplied by 12 V can be balanced between the −12, 0 and 0, +12 voltage supply rails. A representation of this is shown in Figure 6.33. Note, however, that running some bulbs (such as for high power headlights) can be a problem because the filament has to be very thin. Some commercial (24 V) vehicles actually use a 12 V supply to the headlights for this reason.

6.6.2 Charge balance calculation

The charge balance or energy balance of a charging system is used to ensure that the alternator can cope with all the demands placed on it and still charge the battery. The following steps help to indicate the size of alternator required or to check if the one fitted to a vehicle is suitable.

As a worked example, the figures from Table 6.1 will be used. The calculations relate to a passenger car with a 12 V electrical system. A number of steps are involved.

1. Add the power used by all the continuous and prolonged loads.
2. Total continuous and prolonged power (P_1) = 440 W.
3. Calculate the current at 14 V ($I = W/V$) = 31.5 A.
4. Determine the intermittent power (factored by 0.1) (P_2) = 170 W.
5. Total power ($P_1 + P_2$) = 610 W.
6. Total current = 610/14 = 44 A.

Electrical component manufacturers provide tables to recommend the required alternator, calculated from the total power demand and the battery size. However, as a guide for 12 V passenger cars, the rated output should be about 1.5 times the total current demand (in this example $44 \times 1.5 = 66$ A). Manufacturers produce machines of standard sizes, which in this case would probably mean an alternator rated at 70 A. In the case of vehicles with larger batteries and starters, such as for diesel-powered engines and commercial vehicles, a larger output alternator may be required.

The final check is to ensure that the alternator output at idle is large enough to supply all continuous and prolonged loads (P_1) and still charge the battery. Again the factor of 1.5 can be applied. In this example the alternator should be able to supply (31.5×1.5) = 47 A, at engine idle. On normal systems this relates to an alternator speed of about 2000 rev/min (or less). This can be checked against the characteristic curve of the alternator.

6.6.3 Alternator characteristics

Alternator manufacturers supply ‘characteristic curves’ for their alternators. These show the properties of the alternator under different conditions. The curves are plotted as output current (at stabilized voltage), against alternator rev/min and input power against input rev/min. Figure 6.34 shows a typical alternator characteristic curve.

It is common to mark the following points on the graph.

- Cut in speed.
- Idle speed range.
- Speed at which 2/3 of rated output is reached.
- Rated output speed.
- Maximum speed.
- Idle current output range.
- Current 2/3 of rated output.
- Rated output.
- Maximum output.

The graphs are plotted under specific conditions such as regulated output voltage and constant temperature (27 °C is often used). The graph is often used when working out what size alternator will be required for a specific application.

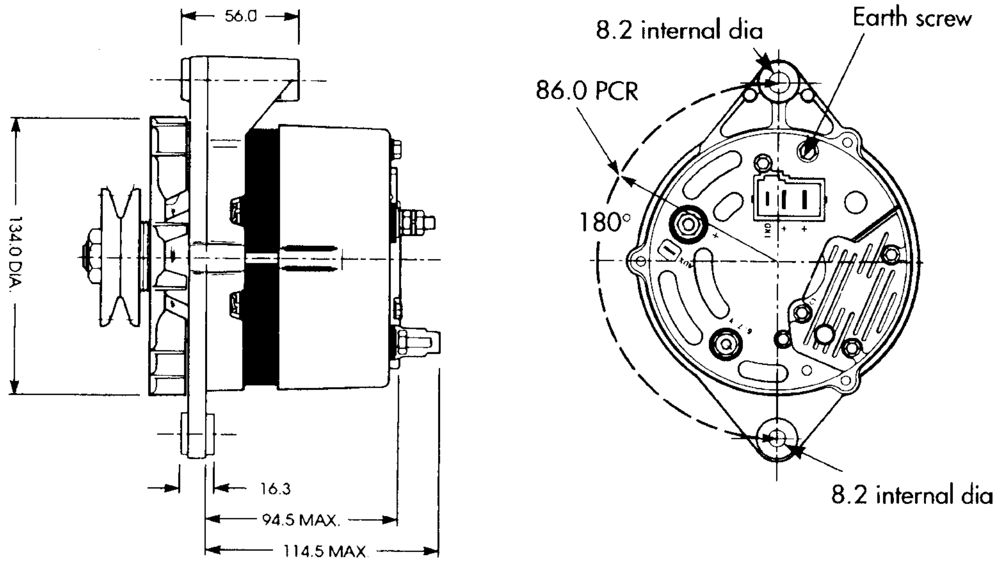

Figure 6.35 Extract from information supplied by Lucas Automotive Ltd. relating to the Plus Pac alternator

The power curve is used to calculate the type of drive belt needed to transmit the power or torque to the alternator. As an aside, the power curve and the current curve can be used together to calculate the efficiency of the alternator. At any particular speed when producing maximum output for that speed, the efficiency of any machine is calculated from:

Efficiency = Power out/Power in

In this case, the efficiency at 8000 rev/min is

(Power out = 14 V × 70 A = 980 W

980 W/2300 W = 0.43 or about 43%

Efficiency at 2/3 rated output

(Power out = 14 V × 47 A = 653 W)

653/1100 = 0.59 or about 59%

These figures help to illustrate how much power is lost in the generation process. The inefficiency is mainly due to iron losses, copper losses, windage (air friction) and mechanical friction. The energy is lost as heat.

6.6.4 Mechanical and external considerations

Most light vehicle alternators are mounted in similar ways. This usually involves a pivoted mounting on the side of the engine with an adjuster on the top or bottom to set drive belt tension. It is now common practice to use 'multi-V' belts driving directly from the engine crankshaft pulley. This type of belt will transmit greater torque and can be worked on smaller diameter pulleys or with tighter corners than the more traditional 'V' belt. Figure 6.35 is an extract from information regarding the mounting and drive belt fitting for a typical alternator.

The drive ratio between the crank pulley and alternator pulley is very important. A typical ratio is about 2.5 : 1. In simple terms, the alternator should be driven as fast as possible at idle speed, but must not exceed the maximum rated speed of the alternator at maximum engine speed. The ideal ratio can therefore be calculated as follows:

Maximum ratio 5 max alternator speed/
max engine speed.

For example:

15 000 rev/min / 6000 rev/min = 2.5 : 1.

During the design stage the alternator will often have to be placed in a position determined by the space available in the engine compartment. However, where possible the following points should be considered:

- Adequate cooling.
- Suitable protection from contamination.
- Access for adjustment and servicing.
- Minimal vibration if possible.
- Recommended belt tension.

6.7 New developments in charging systems

6.7.1 General developments

Alternators are being produced capable of ever greater outputs in order to supply the constantly increasing demands placed on them by manufacturers. The main problem to solve is that of producing high output at lower engine speeds. A solution to this is a variable drive ratio, but this is fraught with mechanical problems. The current solution is tending towards alternators capable of much higher maximum speeds, which allows a greater drive ratio and hence greater speed at lower engine rev/min.

The main design of alternators does not appear to be changing radically; however, the incremental improvements have allowed far more efficient machines to be produced.

6.7.2 Water-cooled alternators

Valeo have an interesting technique involving running the engine coolant through the alternator. A 120–190 A output range is available. Compared with conventional air-cooled alternators the performance of these new machines has been enhanced more particularly in the following areas:

- Improved efficiency (10–25%).
- Increased output at engine idle speed.
- Noise reduction (10–12 dB due to fan elimination).
- Resistance to corrosion (machine is enclosed).
- Resistance to high ambient temperature (>130 °C).

Additional heating elements can be integrated into the alternator to form a system that donates an additional 2–3 kW to the coolant, enabling faster engine warm up after a cold start. This contributes to reduced pollution and increased driver comfort.

Valeo have also developed an alternator with a 'self-start' regulator. This can be thought of as an independent power centre because the warning light and other wires (not the main feed!) can be eliminated. This saves manufacturing costs and also ensures that output is maintained at idle speed.

6.7.3 Smart charging

Introduction

The 'current' demands made by modern vehicles on the charging system are considerable – and increasing. The charging system must be able to meet these demands under all operating conditions and still fast charge the battery.

The main component of the charging system is the alternator and on most modern vehicles, with the exception of its associated wiring, it is the only component in the charging system. The alternator generates AC but must produce DC at its output terminal, as only DC can be used to charge the battery and run electronic circuits.

Traditionally the output of the alternator was regulated to a constant voltage regardless of engine speed and electrical load – but this is changing (Figure 6.36).

Basic operating principles

A generator, or alternator, is a machine that converts mechanical energy from the engine into electrical energy. The basic principle of an alternator is a magnet (the rotor) rotating inside stationary loops of wire (the stator). Electromagnetic induction caused by

Figure 6.36 Alternator on a vehicle (Source: DigitalUP)

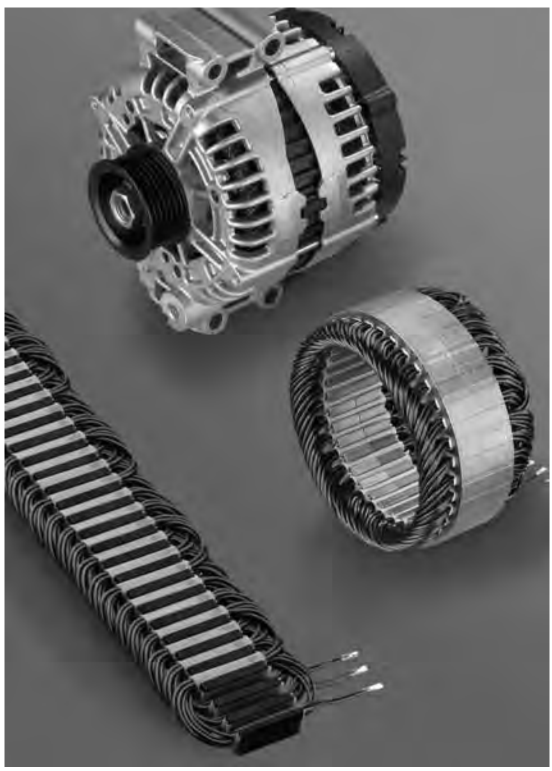

Figure 6.37 Alternator and stator construction (Source: Bosch Press)

the rotating magnet produces an electromotive force in the stator windings.

In order for the output of the alternator to charge the battery and run other vehicle components, it must be converted from alternating current to direct current. The component most suitable for this task is the silicon diode. In order to full-wave rectify the output of a three-phase machine six diodes are needed. These are connected in the form of a bridge in a rectifier pack. Many rectifiers now include two extra diodes that pick up extra power from a centre connection to the stator.

A regulator, which controls rotor magnetic field strength, is used to control the output voltage of an alternator as engine speed and current demand change.

Manufacturers strive to produce ever more efficient machines. A modern alternator's high performance and efficiency are achieved primarily by a very dense winding of the copper wire in the stator grooves. To do so, the wires are first wound onto a flat stator core, which is easier to access, after which it is then bent into the usual rounded form (Figure 6.37).

As another response to the constantly growing demands vehicle electrical systems place on their power supply, Bosch has developed the liquid-cooled alternator. It works extremely quietly due to the absence of a fan and its complete encapsulation; moreover, its lower operating temperature leads to a longer service life. This machine even has the advantage of reducing engine warm up times as initially it passes heat to the coolant (Figure 6.38).

Figure 6.38 Water-cooled alternator (Source: Bosch Press)

Closed loop regulation of output voltage

To prevent the vehicle battery from being overcharged the regulated system voltage should be kept below the gassing voltage of the lead-acid battery. A figure of 14.2 ± 0.2 V was traditionally used for all 12 V (nominal) charging systems. Accurate voltage control is vital with the ever-increasing use of electronic systems. It has also enabled the widespread use of sealed batteries, as the possibility of overcharging is minimal.

Traditionally the regulator base plate or heat sink temperature was used as a reference to estimate battery temperature. This is because the ideal maximum charge rate for a battery varies with its temperature. Further, if the regulator senses a significant change in voltage, a function is employed to quickly recover this to the normal set regulation point. In normal regulators this function is integrated into the regulator itself.

This method of closed loop control (regulator senses the output voltage and increases rotor field strength if the output is low, or decreases it if the output is too high) has worked well – up until now! (Figure 6.39).

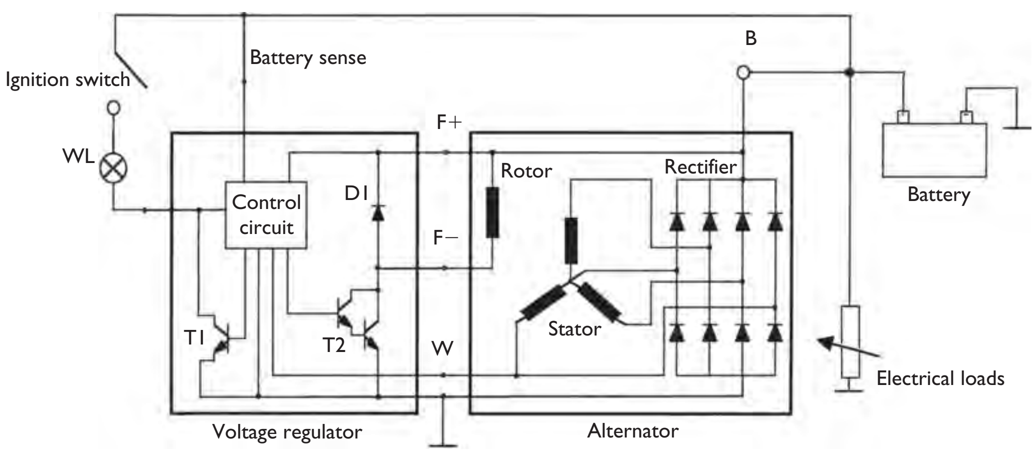

Figure 6.39 Modern closed loop alternator and regulator circuit

Open loop control

Some manufacturers are now bringing together alternator output control, electrical power distribution and mechanical power distribution. This is known as intelligent or smart charging.[1]

The principle of open loop control charging is that the alternator regulator and the powertrain control module (PCM) communicate. In simple terms the alternator can talk to the PCM and the PCM can talk to the alternator (Figure 6.40). This allows new features to be developed that benefit the battery and offer other improvements such as:

- Reduced charge times.
- Better idle stability.
- Improved engine performance.
- Increased alternator reliability.

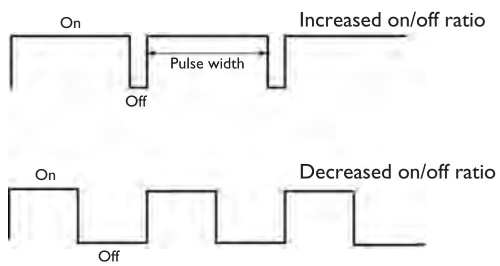

Figure 6.40 Two signals with different pulse width modulation (PCM)

- Better control of electrical load.
- Improved diagnostic functions.

Communication between regulator and PCM is by signals that are pulse width modulated (PCM). This signal is used in both directions. It is a constant frequency square wave with a variable on/off ratio or duty cycle.

The PCM determines the set voltage point (regulated voltage) and transmits this to the regulator using a specific duty cycle signal. The regulator responds by transmitting back the field transistor duty cycle (T2 in Figure 6.39, for example). In this way a variety of features can be implemented.

Battery lifetime

Closed loop regulators estimate the battery temperature based on their own temperature. This does not always result in an accurate figure and hence battery charge rates may not be ideal. With an open loop 'smart charge' system the PCM can calculate a more accurate figure for battery temperature because it has sensors measuring, for example, coolant temperature, intake air temperature and ambient air temperature. This means a more appropriate charge rate can be set (Figure 6.41).

Battery recharge times are not only reduced but a significant increase in battery lifetime can be achieved because of this accurate control.

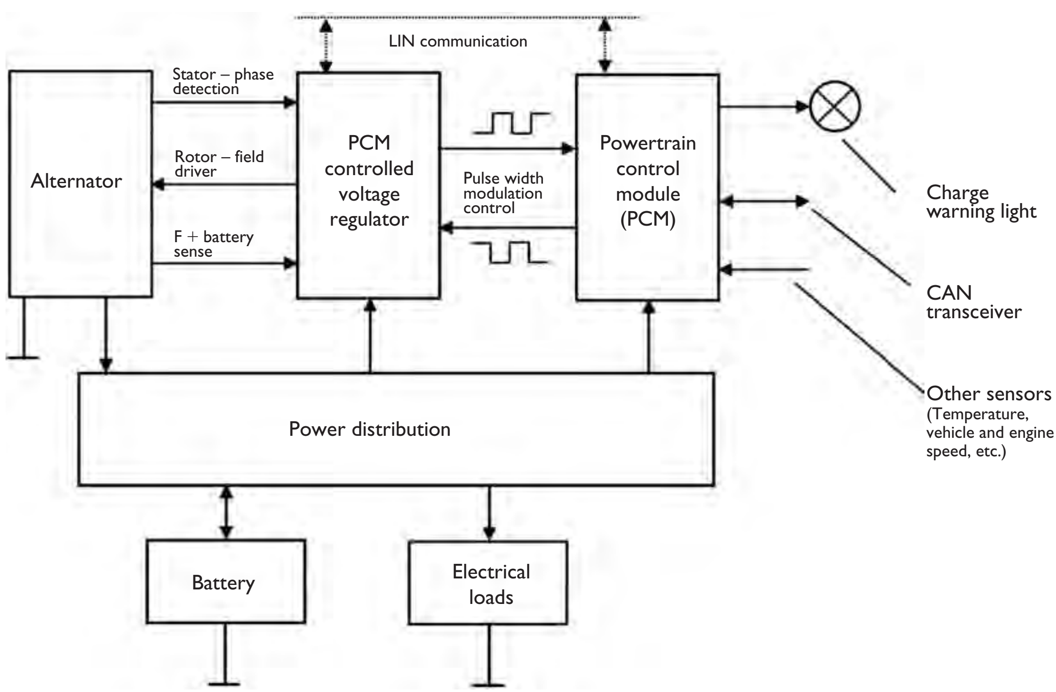

Figure 6.41 Block diagram showing 'smart charge' system

[1]John Reneham et al, International Rectifier Automotive Systems, Pub., AutoTechnology 6/2002

Engine performance

The powertrain control modules (PCMs) usually control engine idle speed in two ways. The main method is throttle control, using either a stepper motor or an air bypass valve. This is a good method but can be relatively slow to react. Changes in ignition timing are also used and this results in a good level of control. However, there may be emission implications.

One of the main causes of idle instability is the torque load that the alternator places on the engine. Because a PCM control system is 'aware' of the alternator load, it calculates the corresponding torque load and sets the idle speed accordingly. Overall the idle can be set at a lower value thus reducing fuel consumption and emissions. Equally, when required, the PCM can increase idle speed to increase alternator output and prevent battery drain. This would be likely to occur after a cold start, in the dark, when the screen is frosted over. In these conditions it is likely that, because the driver would switch on lights, interior heaters and screen heaters, there would be an increased electrical load. In addition to the normal electrical load (fuel, ignition, etc.), the battery would also create a high demand after a cold start. The PCM can ensure that it sets an idle speed which results in sufficient alternator output to prevent battery drain.

A dynamic adjustment to the set voltage point is also possible. This may be used during starting to reduce load on the battery. It can also be used during transient engine loads or, in other words, during acceleration. An alternator producing 70 A at 14 V is putting out about 1 kW of power ($P = VI$). Taking into account the mechanical to electrical energy conversion efficiency of the alternator, the result is a significant torque load on the engine. If the set point (regulated voltage) is reduced during hard acceleration, the 0 to 60 time can be increased by as much as 0.4 s (Figure 6.42).

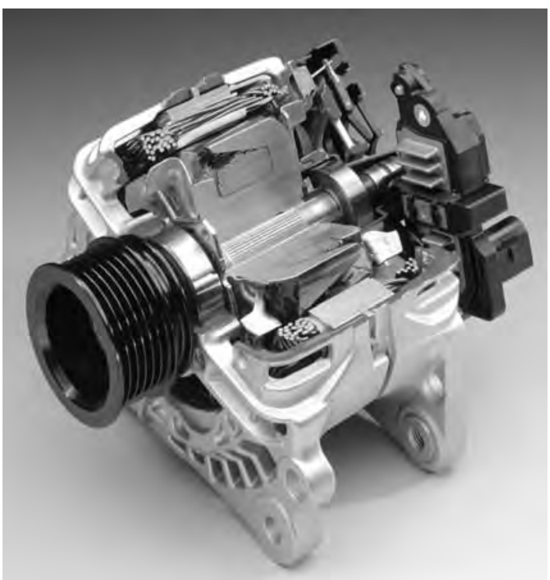

Figure 6.42 Cutaway view of a modern alternator (Source: Bosch Press)

Fault conditions

As well as communicating the load status of the alternator to the PCM, the regulator can also provide diagnostic information. In general the following fault situations can be communicated:

- No communication between regulator and PCM.
- No alternator output due to mechanical fault (drive belt for example).
- Loss of electrical connection to the alternator.
- System over or under voltage due to short or open circuit field driver.
- Failure of rotor or stator windings.
- Failure of a diode.

The PCM can initiate appropriate action in response to these failure conditions, for example, to allow fail-safe operation or at least illuminate the warning light! Suitable test equipment can be used to aid diagnostic work.

Network protocols – CAN and LIN

The PWM communication system is proving to be very effective. However, a second system is already establishing itself as an industry standard. The system is known as local interconnect network (LIN). This is a protocol that allows communication between intelligent actuators and sensors. It is, in effect, a cut down version of the controller area network (CAN) protocol and is used where large bandwidth is not necessary. LIN enabled regulators are not yet in production but the protocol is starting to be used for body systems such as door locks and seat movement.

Summary

Smart or intelligent charging systems are here now, and are here to stay. The ability of the alternator regulator and engine control systems to communicate means new possibilities, increased efficiency and improved performance.

New diagnostic equipment may be necessary but new diagnostic techniques certainly are required. However, remember that PWM signals can be examined on a scope or even a duty cycle meter. And, if the voltage you measure across the battery is less than 13 V, it is probably not recharging – unless of course you are measuring it during a 0 to 60 acceleration test!

6.8 Self-assessment

6.8.1 Questions

1. State the ideal charging voltage for a 12 V (nominal) battery.
2. Describe the operation of an alternator with reference to a rotating 'permanent magnet'.
3. Make a clearly labelled sketch to show a typical external alternator circuit.
4. Explain how and why the output voltage of an alternator is regulated.
5. Describe the differences between a star-wound and a delta-wound stator.
6. Explain why connecting two extra diodes to the centre of a star-wound stator can increase the output of an alternator.
7. Draw a typical characteristic curve for an alternator. Label each part with an explanation of its purpose.
8. Describe briefly how a rectifier works.
9. Explain the difference between a battery-sensed and a machine-sensed alternator.
10. List five charging system faults and the associated symptoms.

6.8.2 Assignment

Investigate and test the operation of a charging system on a vehicle. Produce a report in the standard format (as set out in *Advanced Automotive Fault Diagnosis*, Tom Denton (2000), Arnold).

Make recommendations on how the system could be improved.

6.8.3 Multiple choice questions

The purpose of a rectifier in an alternator is to:
1. change AC to DC voltage
2. control alternator output current
3. change DC to AC voltage
4. control alternator output voltage

'Star' and 'Delta' are types of:
1. rotor winding
2. stator winding
3. field winding
4. regulator winding

Technician A says an alternator rotor uses semi conductor components to rectify the direct current to alternating current. Technician B says a stator winding for a light vehicle alternator will usually be connected in a 'star' formation. Who is right?
1. A only
2. B only
3. Both A and B
4. Neither A nor B

The three auxiliary diodes in a nine-diode alternator provide direct current for the:
1. vehicle auxiliary circuits
2. initial excitation of the rotor
3. rotor field during charging
4. warning light simulator

The purpose of the regulator in the charging system of a vehicle is to control:
1. engine speed
2. fuel consumption
3. generator input
4. generator output

The function of the zener diode in the electronic control unit of an alternator is to act as a:
1. current amplifier
2. voltage amplifier
3. voltage switch
4. current switch

The charging voltage of an engine running at approximately 3000 rev/min should be:
1. 12.6 volts
2. 14.2 volts
3. 3 volts above battery voltage
4. the same as battery voltage

Rotor windings are connected and supplied by:
1. soldered connections
2. crimped connections
3. adhesive bonding
4. brushes and slip rings

An alternator has been dismantled and the rotor slip rings are blackened with carbon deposits. Technician A says clean them with a soft cloth and alcohol. Technician B says the rotor must be replaced. Who is right?
1. A only
2. B only
3. Both A and B
4. Neither A nor B

When fitting a new rectifier pack it is usual to:
1. remove the stator winding
2. replace the regulator
3. connect the battery lead
4. unsolder the connections

7
Starting systems

7.1 Requirements of the starting system

7.1.1 Engine starting requirements

An internal combustion engine requires the following criteria in order to start and continue running.

- Combustible mixture.
- Compression stroke.
- A form of ignition.
- The minimum starting speed (about 100 rev/min).

In order to produce the first three of these, the minimum starting speed must be achieved. This is where the electric starter comes in. The ability to reach this minimum speed is again dependent on a number of factors.

- Rated voltage of the starting system.
- Lowest possible temperature at which it must still be possible to start the engine. This is known as the starting limit temperature.
- Engine cranking resistance. In other words the torque required to crank the engine at its starting limit temperature (including the initial stalled torque).
- Battery characteristics.
- Voltage drop between the battery and the starter.
- Starter-to-ring gear ratio.
- Characteristics of the starter.
- Minimum cranking speed of the engine at the starting limit temperature.

It is not possible to view the starter as an isolated component within the vehicle electrical system, as Figure 7.1 shows. The battery in particular is of prime importance.

Another particularly important consideration in relation to engine starting requirements is the starting limit temperature. Figure 7.2 shows how, as temperature decreases, starter torque also decreases and the torque required to crank the engine to its minimum speed increases.

Typical starting limit temperatures are −18 °C to −25 °C for passenger cars and −15 °C to −20 °C for trucks and buses. Figures from starter manufacturers are normally quoted at both +20 °C and −20 °C.

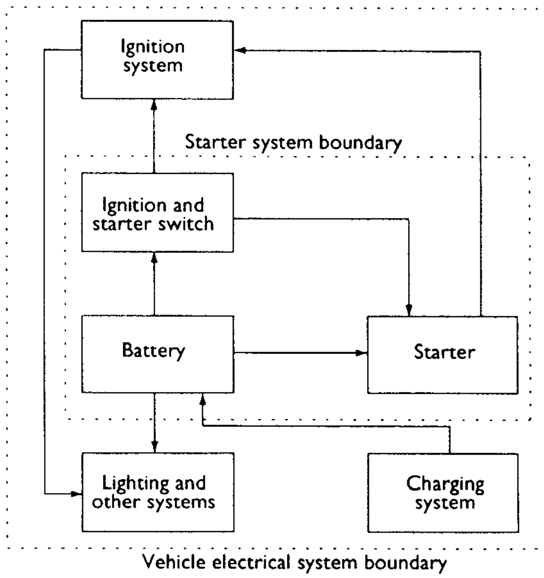

Figure 7.1 Starting system as part of the complete electrical system

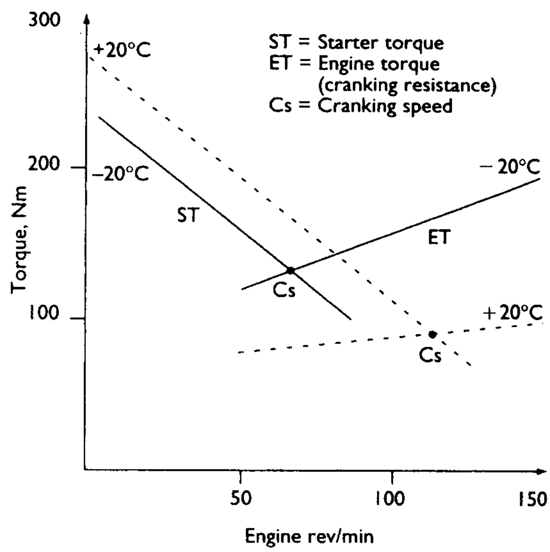

Figure 7.2 Starter torque and engine cranking torque

7.1.2 Starting system design

The starting system of any vehicle must meet a number of criteria in excess of the eight listed above.

- Long service life and maintenance free.
- Continuous readiness to operate.
- Robust, such as to withstand starting forces, vibration, corrosion and temperature cycles.
- Lowest possible size and weight.

Figure 7.3 shows the starting system general layout. It is important to determine the minimum cranking speed for the particular engine. This varies considerably with the design and type of engine. Some typical values are given in Table 7.1 for a temperature of −20 °C.

The rated voltage of the system for passenger cars is, almost without exception, 12 V. Trucks and buses are generally 24 V as this allows the use of half the current that would be required with a 12 V system to produce the same power. It will also considerably reduce the voltage drop in the wiring, as the length of wires used on commercial vehicles is often greater than passenger cars.

The rated output of a starter motor can be determined on a test bench. A battery of maximum capacity for the starter, which has a 20% drop in capacity at −20 °C, is connected to the starter by a cable with a resistance of 1 mΩ. These criteria will ensure the starter is able to operate even under the most adverse conditions. The actual output of the starter can now be measured under typical operating conditions. The rated power of the motor corresponds to the power drawn from the battery less copper losses (due to the resistance of the circuit), iron losses (due to eddy currents being induced in the iron parts of the motor) and friction losses.

Figure 7.4 shows an equivalent circuit for a starter and battery. This indicates how the starter output is very much determined by line resistance and battery internal resistance. The lower the total resistance, the higher the output from the starter.

There are two other considerations when designing a starting system. The location of the starter on the engine is usually pre-determined, but the position of the battery must be considered. Other constraints may determine this, but if the battery is closer to the starter the cables will be shorter. A longer run will mean cables with a greater cross-section are needed to ensure a low resistance. Depending on the intended use of the vehicle, special sealing arrangements on the starter may be necessary to prevent the ingress of contaminants. Starters are available designed with this in mind. This may be appropriate for off-road vehicles.

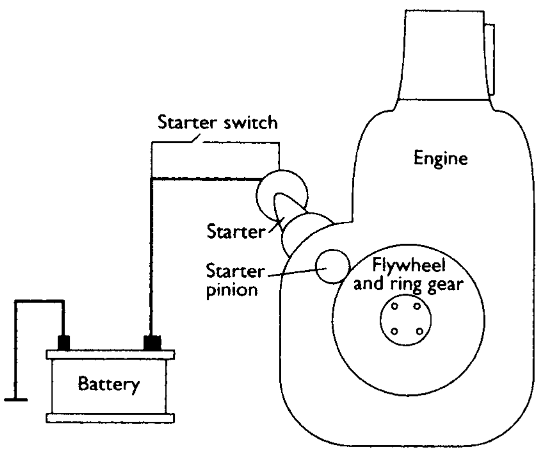

Figure 7.3 Starter system general layout

Table 7.1 Typical minimum cranking speeds

Engine	Minimum cranking speed (rev/min)
Reciprocating spark ignition	60–90
Rotary spark ignition	150–180
Diesel with glow plugs	60–140
Diesel without glow plugs	100–200

7.1.3 Choosing a starter motor

As a guide, the starter motor must meet all the criteria previously discussed. Referring back to Figure 7.2 (the data showing engine cranking torque compared with minimum cranking speed) will determine the torque required from the starter.

Manufacturers of starter motors provide data in the form of characteristic curves. These are discussed in more detail in the next section. The data will

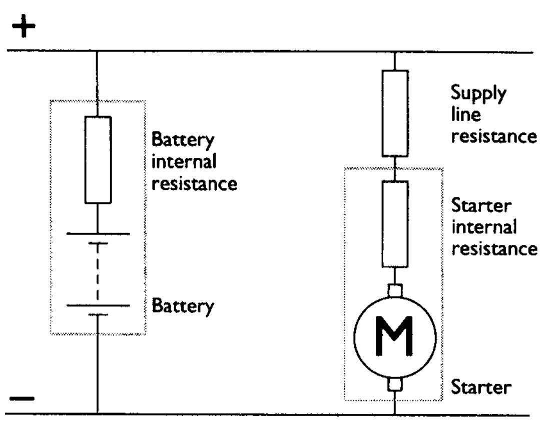

Figure 7.4 Equivalent circuit for a starter system

show the torque, speed, power and current consumption of the starter at +20 °C and −20 °C. The power rating of the motor is quoted as the maximum output at −20 °C using the recommended battery.

Figure 7.5 shows how the required power output of the starter relates to the engine size.

As a very general guide the stalled (locked) starter torque required per litre of engine capacity at the starting limit temperature is as shown in Table 7.2.

A greater torque is required for engines with a lower number of cylinders due to the greater piston displacement per cylinder. This will determine the peak torque values. The other main factor is compression ratio.

To illustrate the link between torque and power, we can assume that, under the worst conditions (−20 °C), a four-cylinder 2-litre engine requires 480 Nm to overcome static friction and 160 Nm to maintain the minimum cranking speed of 100 rev/min. With a starter pinion-to-ring gear ratio of 10 : 1, the motor must therefore, be able to produce a maximum stalled torque of 48 Nm and a driving torque of 16 Nm. This is working on the assumption that stalled torque is generally three to four times the cranking torque.

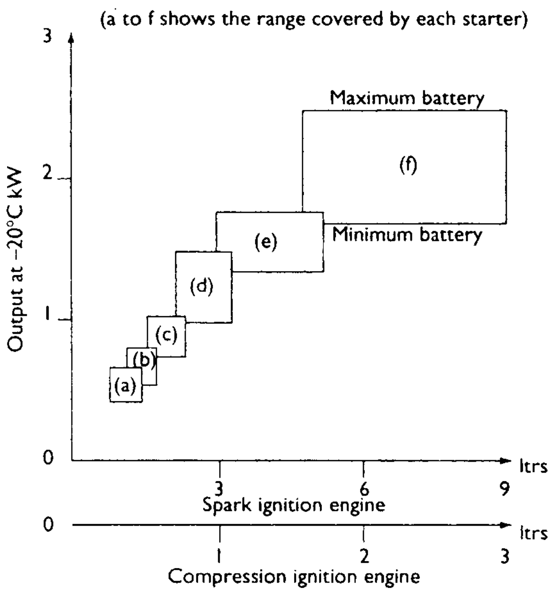

Figure 7.5 Power output of the starter compared with engine size

Table 7.2 Torque required for various engine sizes

Engine cylinders	Torque per litre [Nm]
2	12.5
4	8.0
6	6.5
8	6.0
12	5.5

Torque is converted to power as follows:

$$P = T\omega$$

where P = power, T = torque and ω = angular velocity.

$$\omega = \frac{2\pi n}{60}$$

where n = rev/min.

In this example, the power developed at 1000 rev/min with a torque of 16 Nm (at the starter) is about 1680 W. Referring back to Figure 7.5, the ideal choice would appear to be the starter marked (e).

The recommended battery would be 55 Ah and 255 A cold start performance.

7.2 Starter motors and circuits

7.2.1 Starting system circuits

In comparison with most other circuits on the modern vehicle, the starter circuit is very simple. The problem to be overcome, however, is that of volt drop in the main supply wires. The starter is usually operated by a spring-loaded key switch, and the same switch also controls the ignition and accessories. The supply from the key switch, via a relay in many cases, causes the starter solenoid to operate, and this in turn, by a set of contacts, controls the heavy current. In some cases an extra terminal on the starter solenoid provides an output when cranking, which is usually used to bypass a dropping resistor on the ignition or fuel pump circuits. The basic circuit for the starting system is shown in Figure 7.6.

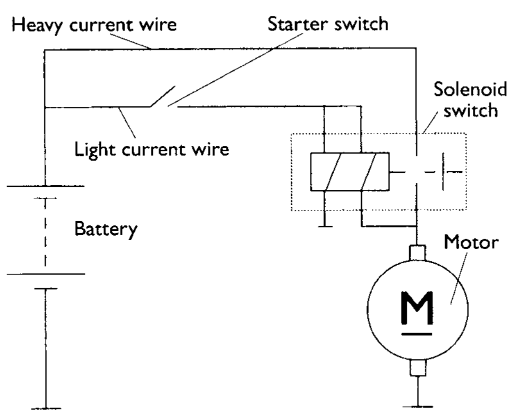

Figure 7.6 Basic starting circuit

The problem of volt drop in the main supply circuit is due to the high current required by the starter, particularly under adverse starting conditions such as very low temperatures.

A typical cranking current for a light vehicle engine is of the order of 150 A, but this may peak in excess of 500 A to provide the initial stalled torque. It is generally accepted that a maximum volt drop of only 0.5 V should be allowed between the battery and the starter when operating. An Ohm's law calculation indicates that the maximum allowed circuit resistance is 2.5 mΩ when using a 12 V supply. This is a worst case situation and lower resistance values are used in most applications. The choice of suitable conductors is therefore very important.

7.2.2 Principle of operation

The simple definition of any motor is a machine to convert electrical energy into mechanical energy. The starter motor is no exception. When current flows through a conductor placed in a magnetic field, a force is created acting on the conductor relative to the field. The magnitude of this force is proportional to the field strength, the length of the conductor in the field and the current flowing in the conductor.

In any DC motor, the single conductor is of no practical use and so the conductor is shaped into a loop or many loops to form the armature. A many-segment commutator allows contact via brushes to the supply current.

The force on the conductor is created due to the interaction of the main magnetic field and the field created around the conductor. In a light vehicle starter motor, the main field was traditionally created by heavy duty series windings wound around soft iron pole shoes. Due to improvements in magnet technology, permanent magnet fields allowing a smaller and lighter construction are replacing wire-wound fields. The strength of the magnetic field created around the conductors in the armature is determined by the value of the current flowing. The principle of a DC motor is shown in Figure 7.7.

Most starter designs use a four-pole four-brush system. Using four field poles concentrates the magnetic field in four areas as shown in Figure 7.8. The magnetism is created in one of three ways, permanent magnets, series field windings or series–parallel field windings.

Figure 7.9 shows the circuits of the two methods where field windings are used. The series–parallel fields can be constructed with a lower resistance, thereby increasing the current and hence torque of

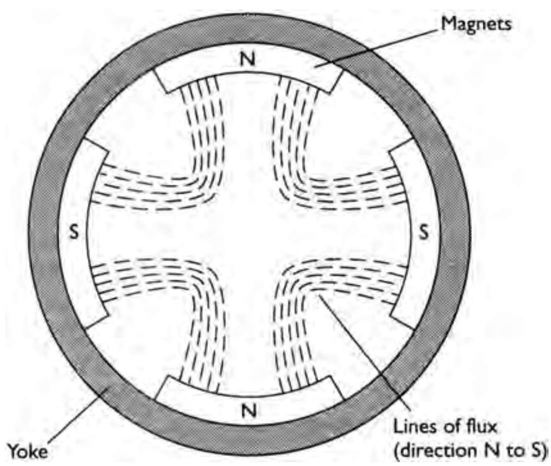

Figure 7.8 Four-pole magnetic field

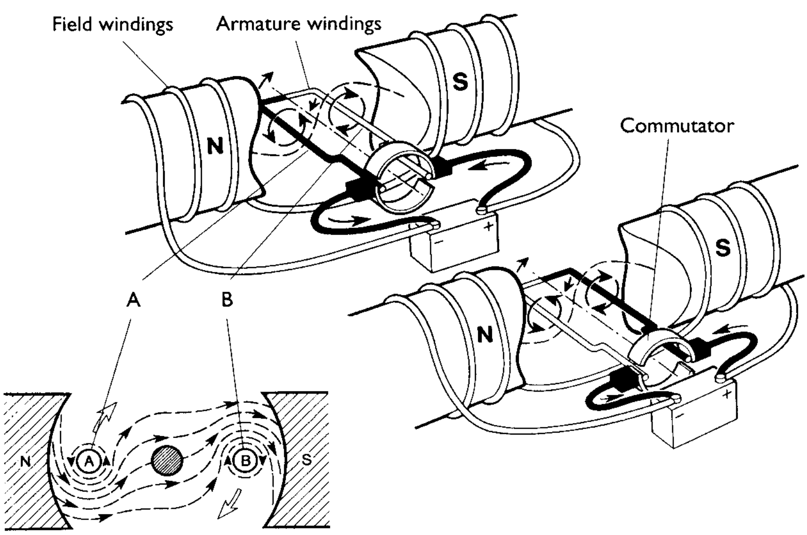

Figure 7.7 Interaction of two magnetic fields results in rotation when a commutator is used to reverse the supply each half turn

the motor. Four brushes are used to carry the heavy current. The brushes are made of a mixture of copper and carbon, as is the case for most motor or generator brushes. Starter brushes have a higher copper content to minimize electrical losses. Figure 7.10 shows some typical field coils with brushes attached. The field windings on the right are known as wave wound.

The armature consists of a segmented copper commutator and heavy duty copper windings. The windings on a motor armature can, broadly speaking, be wound in two ways. These are known as lap winding and wave winding. Figure 7.11 shows the difference between these two methods. Starter motors tend to use wave winding as this technique gives the most appropriate torque and speed characteristic for a four-pole system.

A starter must also have some method of engaging with, and release from, the vehicle's flywheel ring gear. In the case of light vehicle starters, this is achieved either by an inertia-type engagement or a pre-engagement method. These are both discussed further in subsequent sections.

7.2.3 DC motor characteristics

It is possible to design a motor with characteristics that are most suitable for a particular task. For a comparison between the main types of DC motor, the speed–torque characteristics are shown in

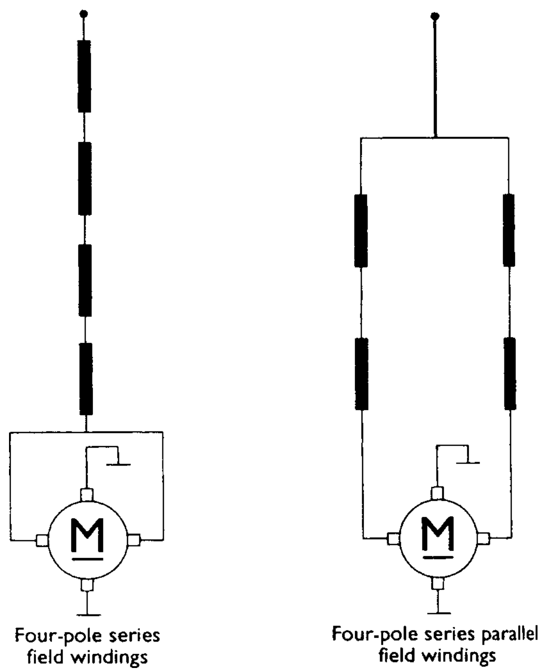

Figure 7.9 Starter internal circuits

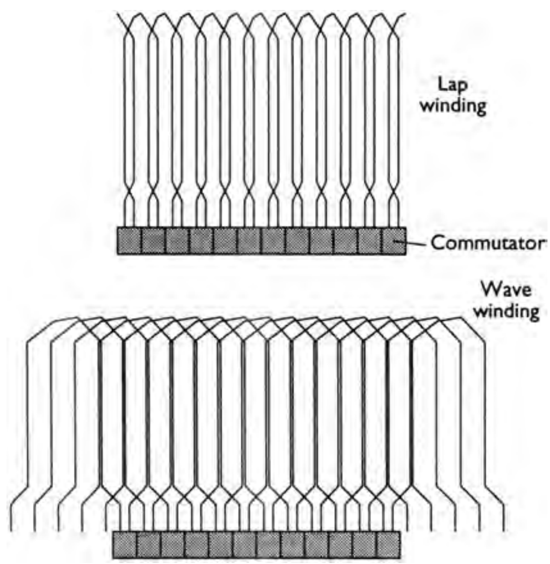

Figure 7.11 Typical lap and wave wound armature circuits

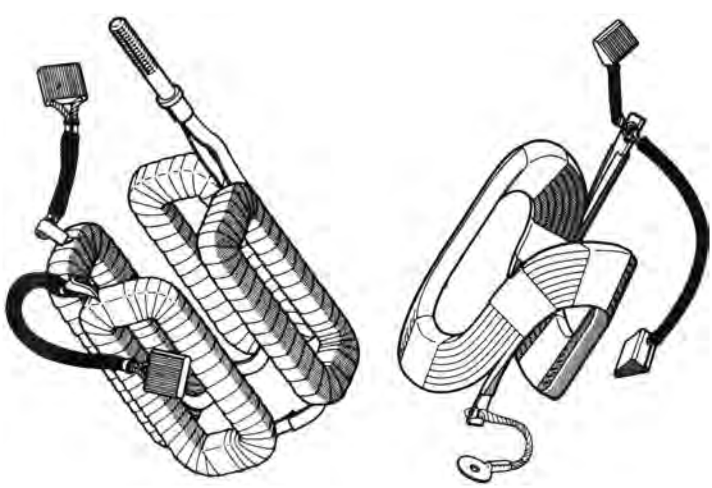

Figure 7.10 Typical field coils and brushes

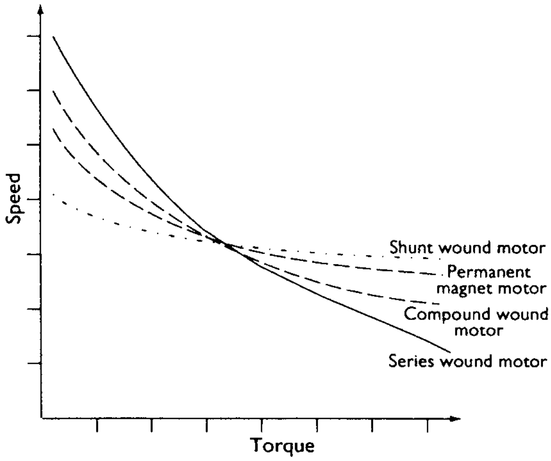

Figure 7.12 Speed and torque characteristics of DC motors

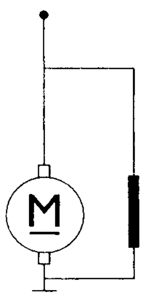

Figure 7.13 Shunt wound motor (parallel wound)

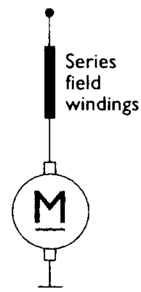

Figure 7.14 Series wound motor

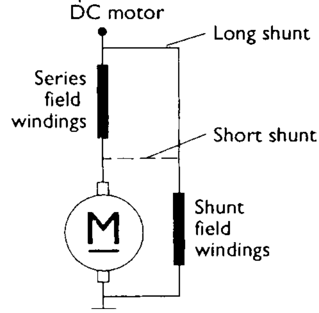

Figure 7.15 Compound wound motor

Figure 7.12. The four main types of motor are referred to as shunt wound, series wound, compound wound and permanent magnet excitation.

In shunt wound motors, the field winding is connected in parallel with the armature as shown in Figure 7.13. Due to the constant excitation of the fields, the speed of this motor remains constant, virtually independent of torque.

Series wound motors have the field and armature connected in series. Because of this method of connection, the armature current passes through the fields making it necessary for the field windings to consist usually of only a few turns of heavy wire. When this motor starts under load the high initial current, due to low resistance and no back EMF, generates a very strong magnetic field and therefore high initial torque. This characteristic makes the series wound motor ideal as a starter motor. Figure 7.14 shows the circuit of a series wound motor.

The compound wound motor, as shown in Figure 7.15, is a combination of shunt and series wound motors. Depending on how the field windings are connected, the characteristics can vary. The usual variation is where the shunt winding is connected, which is either across the armature or across the armature and series winding. Large starter motors are often compound wound and can be operated in two stages. The first stage involves the shunt winding being connected in series with the armature. This unusual connection allows for low meshing torque due to the resistance of the shunt winding. When the pinion of the starter is fully in mesh with the ring gear, a set of contacts causes the main supply to be passed through the series winding and armature giving full torque. The shunt winding will now be connected in parallel and will act in such a way as to limit the maximum speed of the motor.

Permanent magnet motors are smaller and simpler compared with the other three discussed. Field excitation, as the name suggests, is by permanent magnet. This excitation will remain constant under all operating conditions. Figure 7.16 shows the accepted representation for this type of motor.

The characteristics of this type of motor are broadly similar to the shunt wound motors. However, when one of these types is used as a starter motor, the drop in battery voltage tends to cause the motor to behave in a similar way to a series wound machine. In some cases though, the higher speed and lower torque characteristic are enhanced by using an intermediate transmission gearbox inside the starter motor.

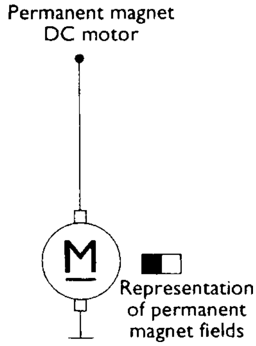

Figure 7.16 Permanent magnet motor

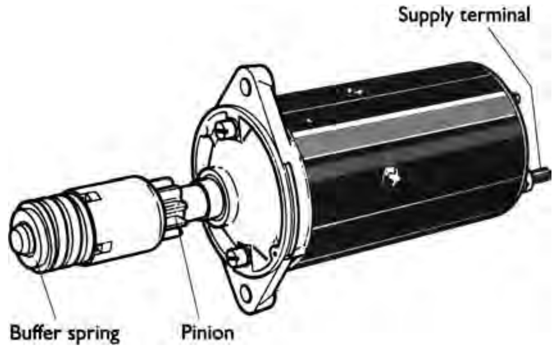

Figure 7.18 Inertia type starter

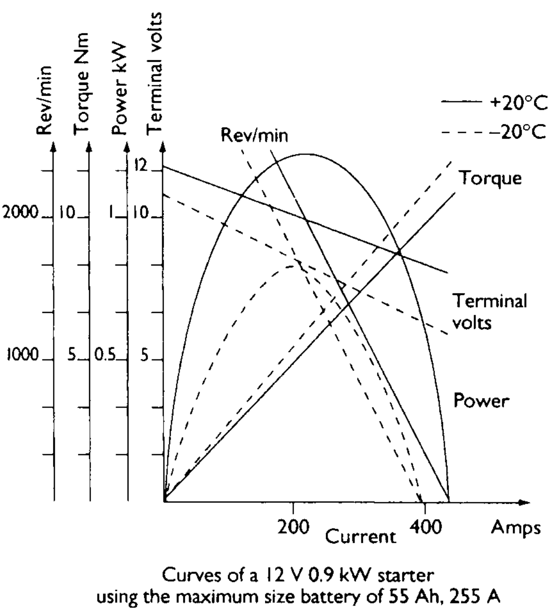

Figure 7.17 Starter motor characteristic curves

Information on particular starters is provided in the form of characteristic curves. Figure 7.17 shows the details for a typical light vehicle starter motor.

This graph shows how the speed of the motor varies with load. Owing to the very high speeds developed under no load conditions, it is possible to damage this type of motor. Running off load due to the high centrifugal forces on the armature may cause the windings to be destroyed. Note that the maximum power of this motor is developed at mid-range speed but maximum torque is at zero speed.

7.3 Types of starter motor

7.3.1 Inertia starters

In all standard motor vehicle applications it is necessary to connect the starter to the engine ring gear only during the starting phase. If the connection remained permanent, the excessive speed at which the starter would be driven by the engine would destroy the motor almost immediately.

The inertia type of starter motor has been the technique used for over 80 years, but is now becoming redundant. The starter shown in Figure 7.18 is the Lucas M35J type. It is a four-pole, four-brush machine and was used on small to medium-sized petrol engined vehicles. It is capable of producing 9.6 Nm with a current draw of 350 A. The M35J uses a face-type commutator and axially aligned brush gear. The fields are wave wound and are earthed to the starter yoke.

The starter engages with the flywheel ring gear by means of a small pinion. The toothed pinion and a sleeve splined on to the armature shaft are threaded such that when the starter is operated, via a remote relay, the armature will cause the sleeve to rotate inside the pinion. The pinion remains still due to its inertia and, because of the screwed sleeve rotating inside it, the pinion is moved to mesh with the ring gear.

When the engine fires and runs under its own power, the pinion is driven faster than the armature shaft. This causes the pinion to be screwed back along the sleeve and out of engagement with the flywheel. The main spring acts as a buffer when the pinion first takes up the driving torque and also acts as a buffer when the engine throws the pinion back out of mesh.

One of the main problems with this type of starter was the aggressive nature of the engagement. This tended to cause the pinion and ring gear to wear prematurely. In some applications the pinion tended to fall out of mesh when cranking due to the engine almost, but not quite, running. The pinion was also prone to seizure often due to contamination by dust from the clutch. This was often compounded by application of oil to the pinion mechanism, which tended to attract even more dust and thus prevent engagement.

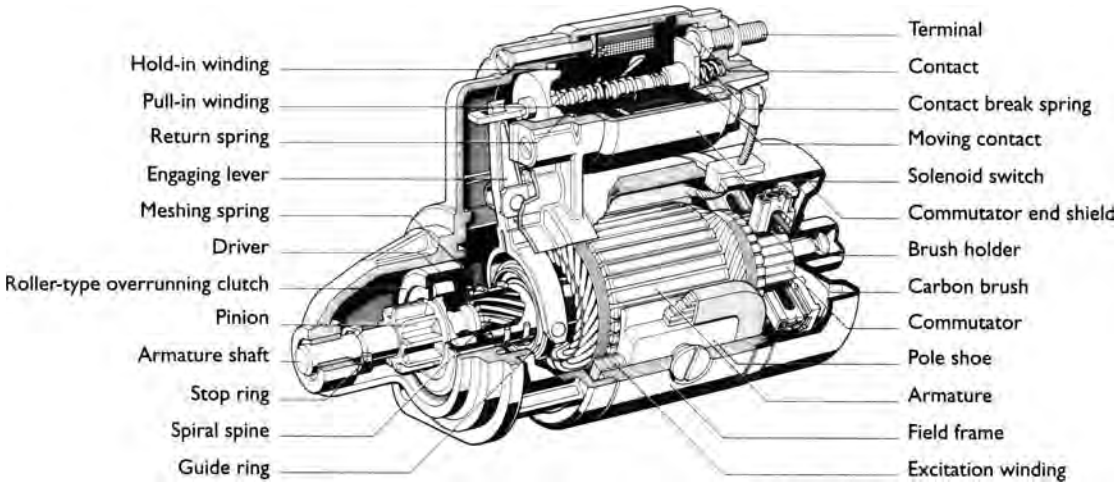

Figure 7.19 Pre-engaged starter

The pre-engaged starter motor has largely overcome these problems.

7.3.2 Pre-engaged starters

Pre-engaged starters are fitted to the majority of vehicles in use today. They provide a positive engagement with the ring gear, as full power is not applied until the pinion is fully in mesh. They prevent premature ejection as the pinion is held into mesh by the action of a solenoid. A one-way clutch is incorporated into the pinion to prevent the starter motor being driven by the engine. One example of a pre-engaged starter in common use is shown in Figure 7.19, the Bosch EF starter.

Figure 7.20 shows the circuit associated with operating this type of pre-engaged starter. The basic operation of the pre-engaged starter is as follows. When the key switch is operated, a supply is made to terminal 50 on the solenoid. This causes two windings to be energized, the hold-on winding and the pull-in winding. Note that the pull-in winding is of very low resistance and hence a high current flows. This winding is connected in series with the motor circuit and the current flowing will allow the motor to rotate slowly to facilitate engagement. At the same time, the magnetism created in the solenoid attracts the plunger and, via an operating lever, pushes the pinion into mesh with the flywheel ring gear. When the pinion is fully in mesh the plunger, at the end of its travel, causes a heavy-duty set of copper contacts to close. These contacts now supply full battery power to the main circuit of the starter motor. When the main contacts are closed, the pull-in winding is effectively switched off due to equal voltage supply on both ends. The hold-on winding holds the plunger in position as long as the solenoid is supplied from the key switch.

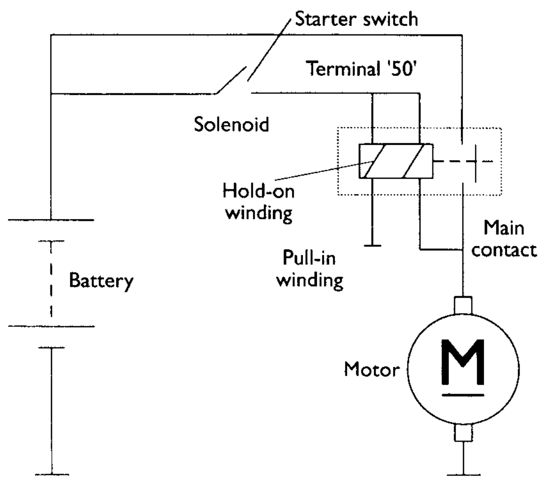

Figure 7.20 Starter circuit

When the engine starts and the key is released, the main supply is removed and the plunger and pinion return to their rest positions under spring tension. A lost motion spring located on the plunger ensures that the main contacts open before the pinion is retracted from mesh.

During engagement, if the teeth of the pinion hit the teeth of the flywheel (tooth to tooth abutment), the main contacts are allowed to close due to the engagement spring being compressed. This allows the motor to rotate under power and the pinion will slip into mesh.

Figure 7.21 shows a sectioned view of a one-way clutch assembly. The torque developed by the starter is passed through the clutch to the ring gear. The purpose of this free-wheeling device is to prevent

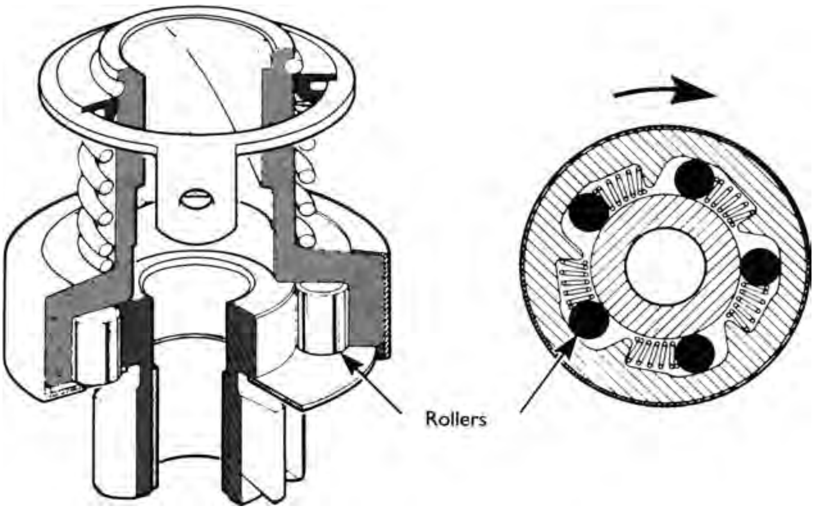

Figure 7.21 One-way roller clutch drive pinion

the starter being driven at an excessively high speed if the pinion is held in mesh after the engine has started. The clutch consists of a driving and driven member with several rollers between the two. The rollers are spring loaded and either wedge-lock the two members together by being compressed against the springs, or free-wheel in the opposite direction.

Many variations of the pre-engaged starter are in common use, but all work on similar lines to the above description. The wound field type of motor has now largely been replaced by the permanent magnet version.

7.3.3 Permanent magnet starters

Permanent magnet starters began to appear on production vehicles in the late 1980s. The two main advantages of these motors, compared with conventional types, are less weight and smaller size. This makes the permanent magnet starter a popular choice by vehicle manufacturers as, due to the lower lines of today's cars, less space is now available for engine electrical systems. The reduction in weight provides a contribution towards reducing fuel consumption.

The standard permanent magnet starters currently available are suitable for use on spark ignition engines up to about 2 litre capacity. They are rated in the region of 1 kW. A typical example is the Lucas Model M78R/M80R shown in Figure 7.22.

The principle of operation is similar in most respects to the conventional pre-engaged starter motor. The main difference being the replacement of field windings and pole shoes with high quality permanent magnets. The reduction in weight is in the region of 15% and the diameter of the yoke can be reduced by a similar factor.

Permanent magnets provide constant excitation and it would be reasonable to expect the speed and torque characteristic to be constant.

However, due to the fall in battery voltage under load and the low resistance of the armature windings, the characteristic is comparable to series wound motors. In some cases, flux concentrating pieces or interpoles are used between the main magnets. Due to the warping effect of the magnetic field, this tends to make the characteristic curve very similar to that of the series motor.

Development by some manufacturers has also taken place in the construction of the brushes. A copper and graphite mix is used but the brushes are made in two parts allowing a higher copper content in the power zone and a higher graphite content in the commutation zone. This results in increased service life and a reduction in voltage drop, giving improved starter power. Figure 7.23 shows a modern permanent magnet (PM) starter.

For applications with a higher power requirement, permanent magnet motors with intermediate transmission have been developed. These allow the armature to rotate at a higher and more efficient speed whilst still providing the torque, due to the gear reduction. Permanent magnet starters with intermediate transmission are available with power outputs of about 1.7 kW and are suitable for spark ignition engines up to about 3 litres, or compression ignition engines up to about 1.6 litres. This form of permanent magnet motor can give a weight saving of up to 40%. The principle of operation is again similar to the conventional pre-engaged starter. The intermediate transmission, as shown in Figure 7.24, is of the epicyclic type.

The sun gear is on the armature shaft and the planet carrier drives the pinion. The ring gear or annulus remains stationary and also acts as an intermediate bearing. This arrangement of gears gives a reduction ratio of about 5 : 1. This can be calculated by the formula:

$$\text{Ratio} = \frac{AS}{S}$$

where A = number of teeth on the annulus, and S = number of teeth on the sun gear.

The annulus gear in some types is constructed from a high grade polyamide compound with mineral additives to improve strength and wear resistance. The sun and planet gears are conventional steel. This combination of materials gives a quieter

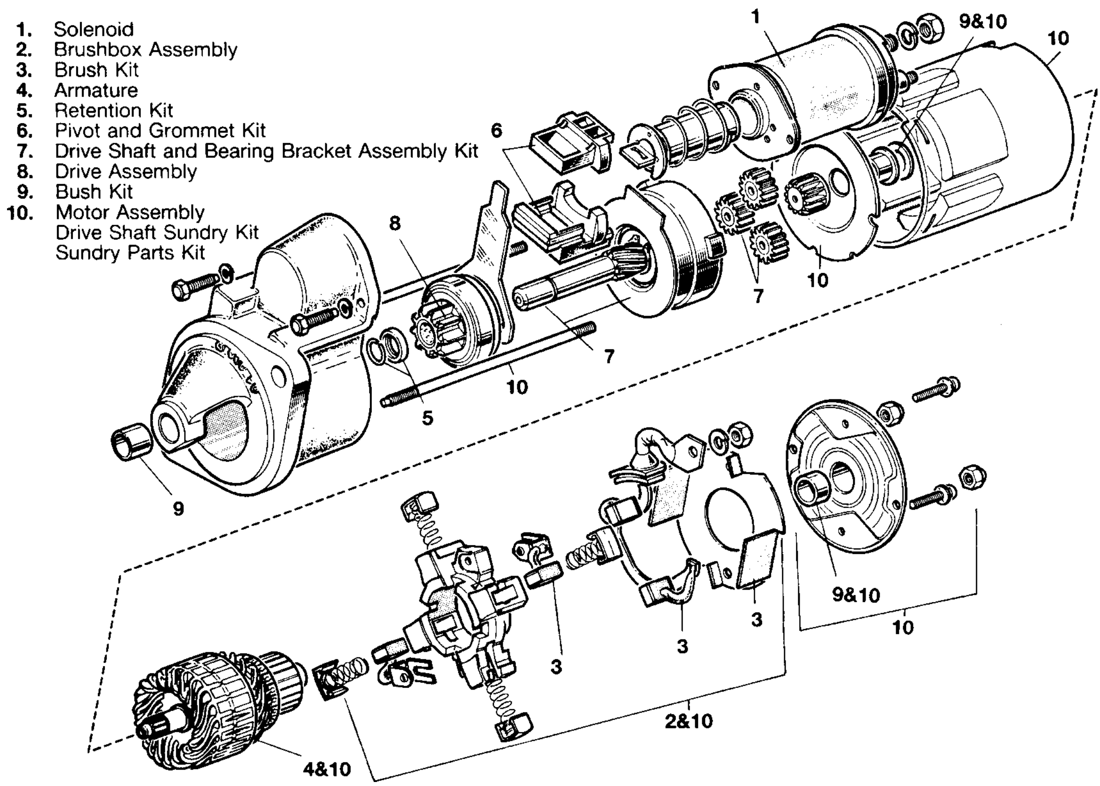

Figure 7.22 Lucas M78R/M80R starter

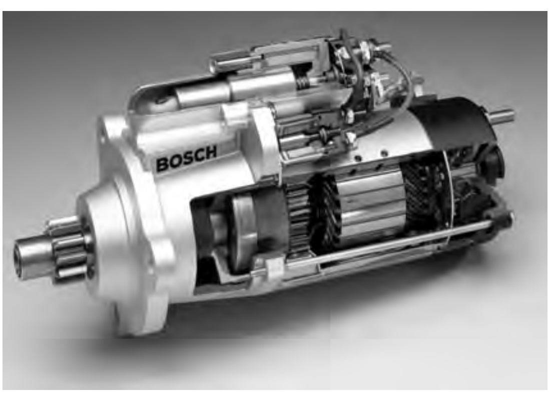

Figure 7.23 Modern permanent magnet starter (Source: Bosch Press)

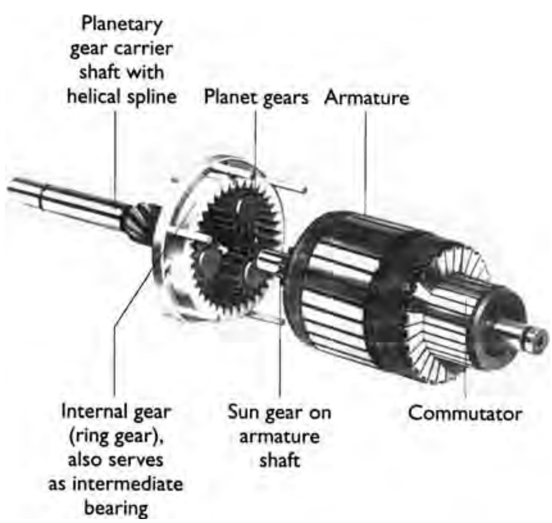

Figure 7.24 Starter motor intermediate transmission

and more efficient operation. Figure 7.25 shows a PM starter with intermediate transmission, together with its circuit and operating mechanism.

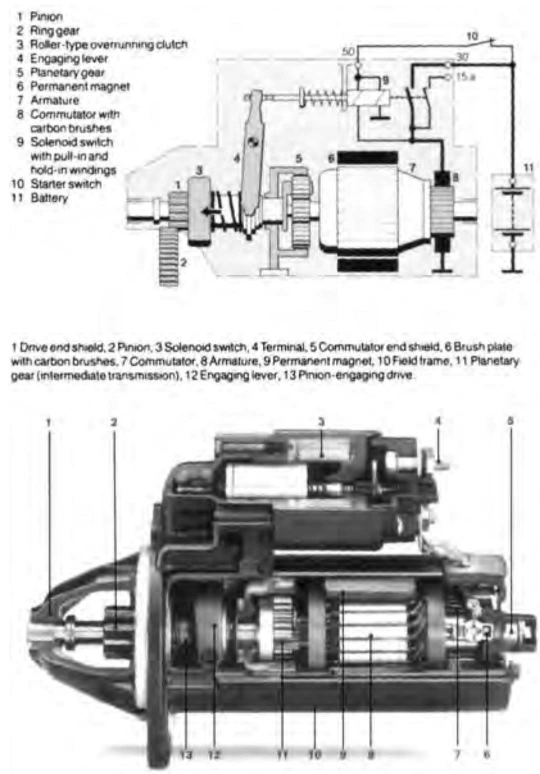

Figure 7.25 Pre-engaged starter and details (Bosch)

7.3.4 Heavy vehicle starters

The subject area of this book is primarily the electrical equipment on cars. This short section is included for interest, hence further reference should be made to other sources for greater detail about heavy vehicle starters.

The types of starter that are available for heavy duty applications are as many and varied as the applications they serve. In general, higher voltages are used, which may be up to 110 V in specialist cases, and two starters may even be running in parallel for very high power and torque requirements.

Large road vehicles are normally 24 V and employ a wide range of starters. In some cases the design is simply a large and heavy duty version of the pre-engaged type discussed earlier. The Delco-Remy 42-MT starter shown in Figure 7.26 is a good example of this type. This starter may also be fitted with a thermal cut-out to prevent overheating damage due to excessive cranking. Rated at 8.5 kW, it is capable of producing over 80 Nm torque at 1000 rev/min.

Other methods of engaging the pinion include sliding the whole armature or pushing the pinion with a rod through a hollow armature. This type uses a solenoid to push the pinion into mesh via a rod through the centre of the armature.

Sliding-armature-type starters work by positioning the field windings forwards from the main armature body, such that the armature is attracted

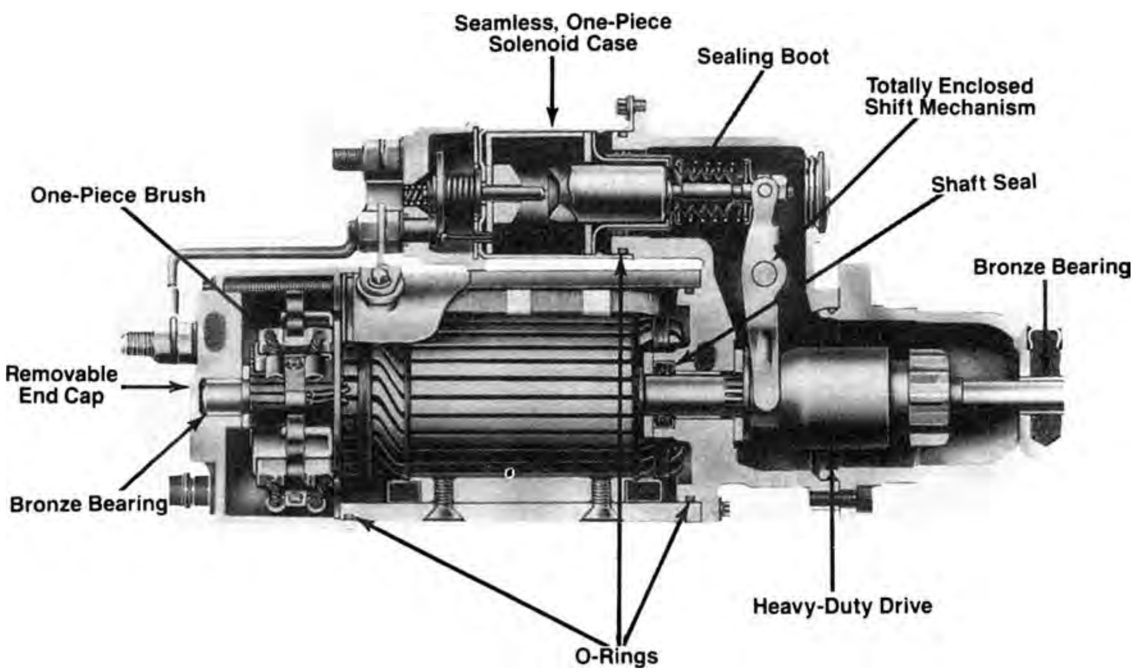

Figure 7.26 Delco-Remy 42-MT starter

forwards when power is applied. A trip lever mechanism will then only allow full power when the armature has caused the pinion to mesh.

7.3.5 Integrated starters

A device called a 'dynastart' was used on a number of vehicles from the 1930s through to the 1960s. This device was a combination of the starter and a dynamo. The device, directly mounted on the crankshaft, was a compromise and hence not very efficient.

The method is now known as an Integrated Starter Alternator Damper (ISAD). It consists of an electric motor, which functions as a control element between the engine and the transmission, and can also be used to start the engine and deliver electrical power to the batteries and the rest of the vehicle systems. The electric motor replaces the mass of the flywheel.

The motor transfers the drive from the engine and is also able to act as a damper/vibration absorber unit. The damping effect is achieved by a rotation capacitor. A change in relative speed between the rotor and the engine due to the vibration, causes one pole of the capacitor to be charged. The effect of this is to take the energy from the vibration.

Using ISAD to start the engine is virtually noiseless, and cranking speeds of 700 rev/min are possible. Even at −25 °C it is still possible to crank at about 400 rev/min. A good feature of this is that a stop/start function is possible as an economy and emissions improvement technique. Because of the high speed cranking, the engine will fire up in about 0.1–0.5 seconds.

The motor can also be used to aid with acceleration of the vehicle. This feature could be used to allow a smaller engine to be used or to enhance the performance of a standard engine.

When used in alternator mode, the ISAD can produce up to 2 kW at idle speed. It can supply power at different voltages as both AC and DC. Through the application of intelligent control electronics, the ISAD can be up to 80% efficient.

Citroën have used the ISAD system in a Xsara model prototype. The car can produce 150 Nm for up to 30 seconds, which is significantly more than the 135 Nm peak torque of the 1580 cc, 65 kW fuel injected version. Citroën call the system 'Dynalto'. A 220 V outlet is even provided inside the car to power domestic electrical appliances!

7.3.6 Electronic starter control

'Valeo' have developed an electronic switch that can be fitted to its entire range of starters. Starter control will be supported by an ECU. The electronic starter incorporates a static relay on a circuit board integrated into the solenoid switch. This will prevent cranking when the engine is running.

Figure 7.27 Integrated starter alternator damper (Source: Bosch Press)

'Smart' features can be added to improve comfort, safety and service life.

- Starter torque can be evaluated in real time to tell the precise instant of engine start. The starter can be simultaneously shut off to reduce wear and noise generated by the free-wheel phase.
- Thermal protection of the starter components allows optimization of the components to save weight and to give short circuit protection.
- Electrical protection also reduces damage from misuse or system failure.
- Modulating the solenoid current allows redesign of the mechanical parts allowing a softer operation and weight reduction.

It will even be possible to retrofit this system to existing systems.

7.3.7 Starter installation

Starters are generally mounted in a horizontal position next to the engine crankcase with the drive pinion in a position for meshing with the flywheel or drive plate ring gear.

The starter can be secured in two ways: either by flange or cradle mounting. Flange mounting is the most popular technique used on small and medium-sized vehicles and, in some cases, it will incorporate a further support bracket at the rear of the starter to reduce the effect of vibration. Larger vehicle

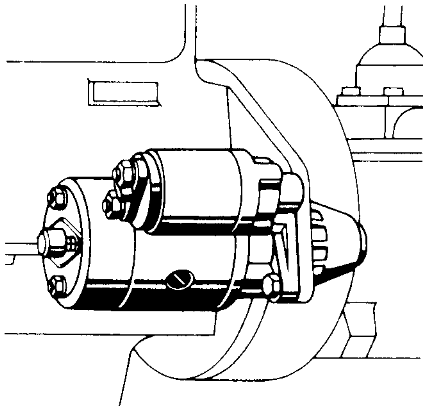

Figure 7.28 Flange mounting is used for most light vehicle starter motors

starters are often cradle mounted but again also use the flange mounting method, usually fixed with at least three large bolts. In both cases the starters must have some kind of pilot, often a ring machined on the drive end bracket, to ensure correct positioning with respect to the ring gear. This will ensure correct gear backlash and a suitable out of mesh clearance. Figure 7.28 shows the flange mountings method used for most light vehicle starter motors.

Clearly the main load on the vehicle battery is the starter and this is reflected in the size of supply cable required. Any cable carrying a current will experience power loss known as I^2R loss. In order to reduce this power loss, the current or the resistance must be reduced. In the case of the starter the high current is the only way of delivering the high torque. This is the reason for using heavy conductors to the starter to ensure low resistance, thus reducing the volt drop and power loss. The maximum allowed volt drop is 0.5 V on a 12 V system and 1 V on a 24 V system. The short circuit (initial) current for a typical car starter is 500 A and for very heavy applications can be 3000 A.

Control of the starter system is normally by a spring-loaded key switch. This switch will control the current to the starter solenoid, in many cases via a relay. On vehicles with automatic transmission, an inhibitor switch to prevent the engine being started in gear will also interrupt this circuit.

Diesel engined vehicles may have a connection between the starter circuit and a circuit to control the glow plugs. This may also incorporate a timer relay. On some vehicles the glow plugs are activated by a switch position just before the start position.

7.3.8 Summary

The overall principle of starting a vehicle engine with an electric motor has changed little in over 80 years. Of course, the motors have become far more reliable and longer lasting. It is interesting to note that, assuming average mileage, the modern starter is used about 2000 times a year in city traffic! This level of reliability has been achieved by many years of research and development.

7.4 Case studies

7.4.1 Ford

The circuit shown in Figure 7.29 is from a vehicle fitted with manual or automatic transmission. The inhibitor circuits will only allow the starter to operate when the automatic transmission is in ‘park’ or ‘neutral’. Similarly for the manual version, the starter will only operate if the clutch pedal is depressed.

The starter relay coil is supplied with the positive connection by the key switch. The earth path is connected through the appropriate inhibitor switch. To prevent starter operation when the engine is running the power control module (EEC V) controls the final earth path of the relay.

A resistor fitted across the relay coil reduces back EMF. The starter in current use is a standard pre-engaged, permanent magnet motor.

7.4.2 Toyota

The starter shown in Figure 7.30 has been in use for several years but is included because of its unusual design. The drive pinion incorporates the normal clutch assembly but is offset from the armature. Drive to the pinion is via a gear set with a ratio of about 3 : 1. The idle gear means the pinion rotates in the same direction as the armature.

Ball bearings are used on each end of the armature and pinion. The idler gear incorporates a roller bearing. The solenoid acts on the spring and steel ball to move the pinion into mesh. The electrical operation of the machine is standard. It has four brushes and four field poles.

7.4.3 Ford integrated starter-generator (ISG)

Ford has produced a new integrated starter-generator and 42-volt electric system that will be used by an Explorer over the next few years. The vehicle will achieve breakthrough levels of fuel economy and offer more high-tech comfort and convenience features. It will use the new higher voltage electrical system that enables several fuel saving functions, including the ability to shut off the engine when the vehicle is stopped and to start it instantly on demand.

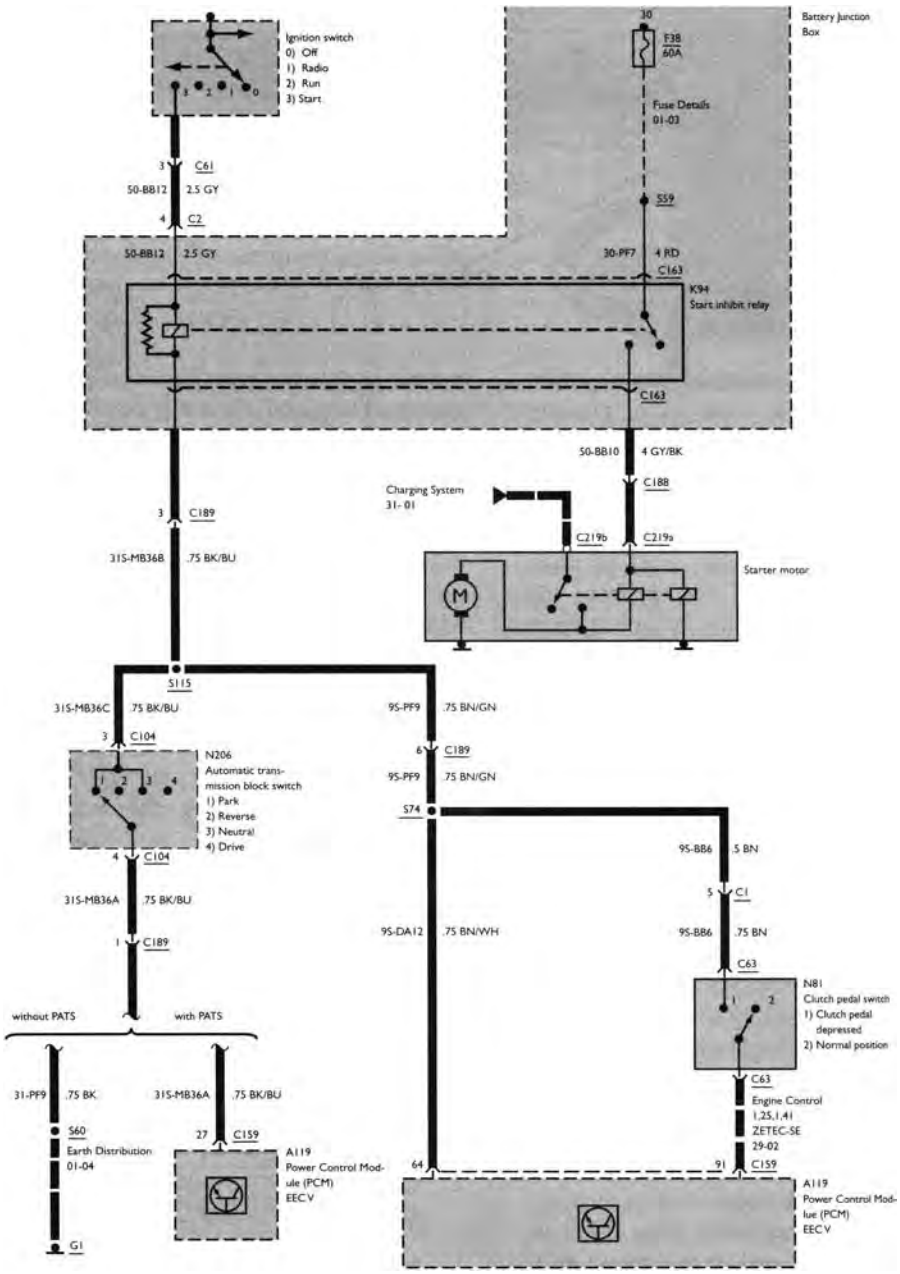

Figure 7.29 Starter circuit as used by Ford

The integrated starter-generator, as its name implies, replaces both the conventional starter and alternator in a single electric device. A vehicle equipped with the ISG system could be considered a mild hybrid because it is capable of most of the functions of a hybrid electric vehicle.

There are three functions common to both a full hybrid electric vehicle and ISG, or mild hybrid, and a fourth function unique to a full HEV:

- Start/Stop: When the engine is not needed, such as at a stoplight, it automatically turns off. It restarts smoothly and instantly when any demand for power is detected. This ‘stop/start’ function provides fuel savings and reduced emissions.
- Regenerative Braking: This feature collects energy created from braking and uses it to recharge the vehicle’s batteries. This allows items such as the headlights, stereo and climate control system to continue to operate when the engine shuts off. By greatly reducing the amount of electric power that must be generated by the engine, regenerative braking significantly reduces fuel consumption.

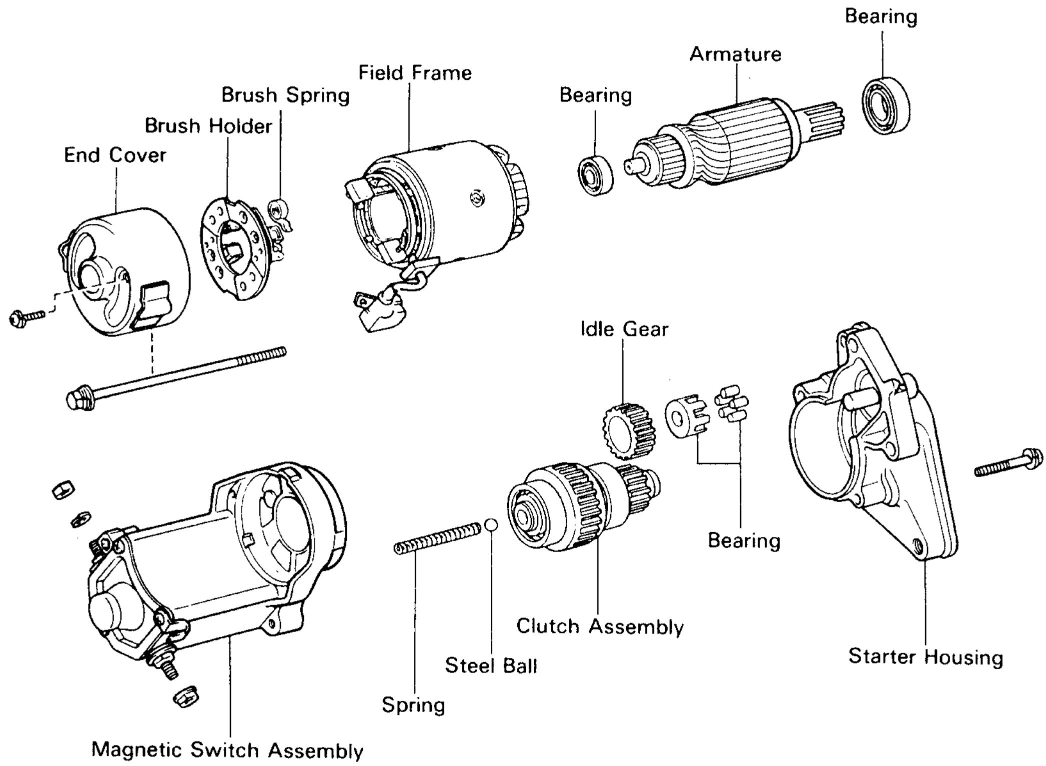

Figure 7.30 Toyota starter motor components

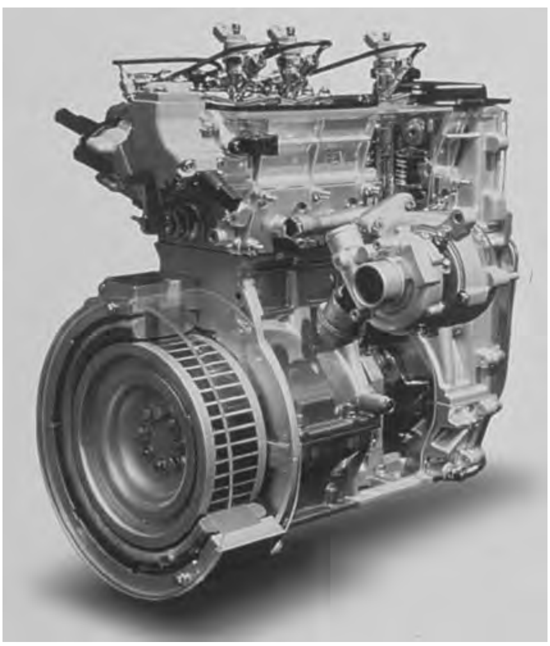

Figure 7.31 Engine fitted with an integrated starter generator (Source: Ford)

- Electrical Assist: Internal combustion engines on both types of systems receive assistance from an electric motor, but in vastly different ways. The electrical assist ISG system helps the engine at start-up and during hard acceleration, providing short bursts of added power. Because the ISG system uses a 42-volt battery and the hybrid electric vehicle uses a 300-volt battery with a much larger energy capacity, the HEV electrical assist is capable of providing much more power, more frequently and for a longer duration.
- Electric Drive: Only full hybrids have the ability to drive in electric-only mode. In the Escape HEV, this means the SUV's electric motor can drive the vehicle at low speeds (under 30 mph (km)) while the engine is off. The capacity for electric-only drive clearly separates a full hybrid electric vehicle from a mild hybrid vehicle using an ISG system.

In addition to the 42-volt battery and integrated starter generator the system is comprised of three major components: a slightly modified V-6 engine, new auto matic transmission and an inverter/motor controller.

When restarting, DC power from the battery is processed by the inverter/motor controller and supplied as adjustable frequency AC power to the ISG. The frequency of the AC power is controlled to bring the engine up to idle speed in a small fraction of a second.

Regenerative braking captures energy normally lost as heat energy during braking. The ISG absorbs power during vehicle deceleration, converts it to DC

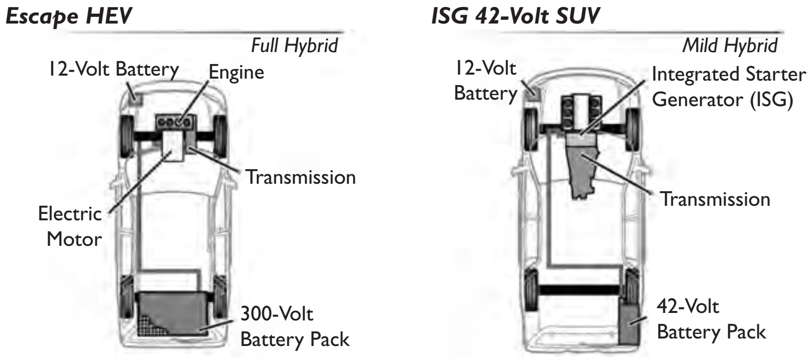

Figure 7.32 Hybrid electric vehicle (HEV) compared to an ISG (Source: Ford)

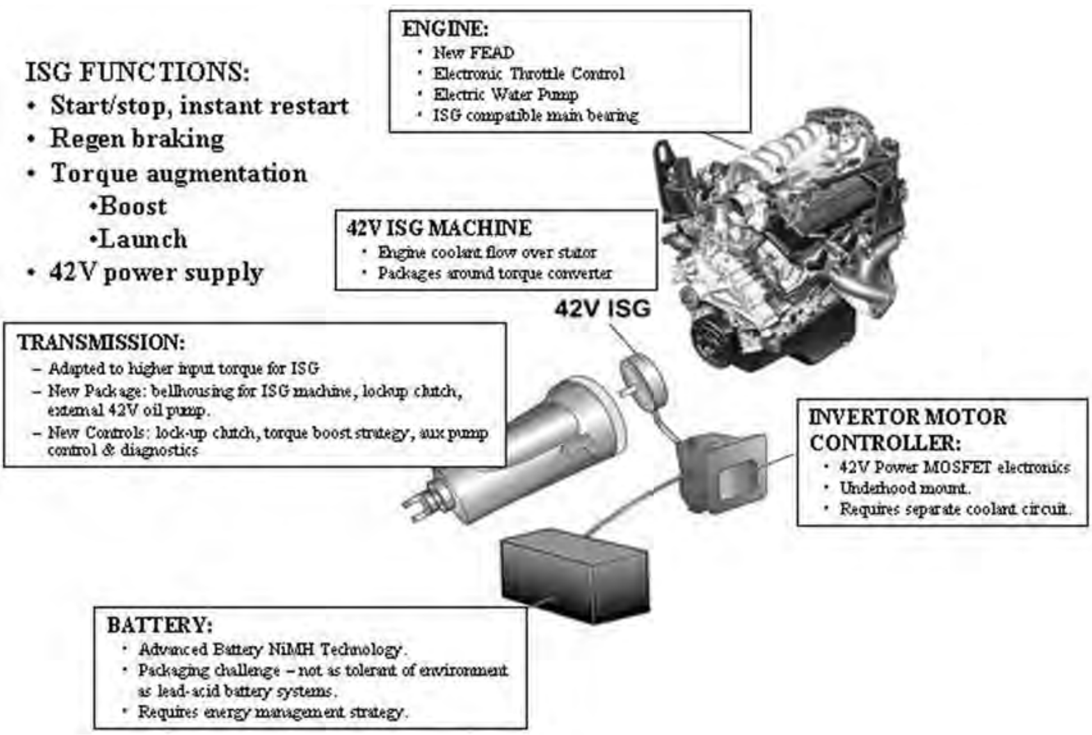

Figure 7.33 42 V Integrated starter generator (ISG) (Source: Ford)

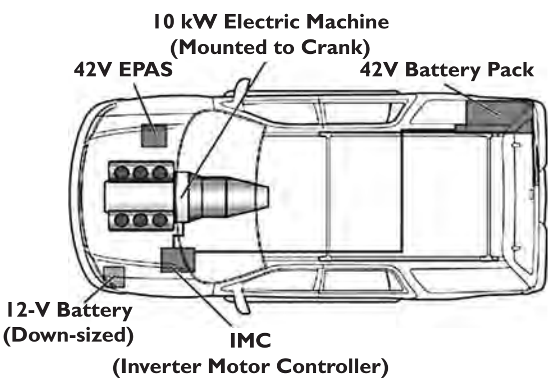

Figure 7.34 42 V ISG installation in the SUV (Source: Ford)

power and recharges the battery. Electro-hydraulic brakes replace the vacuum booster and microprocessors control the operation of front and rear brakes to maintain vehicle stability while braking. The vehicle's mechanical brakes are coordinated with the ISG, so the difference between mechanical and regenerative brakes is transparent to the driver.

The ISG also provides added power and performance. The ISG delivers battery power to the wheels to assist the engine during vehicle launch. The ISG is also referred to as an integrated starter alternator damper (ISAD) (Ford Motor Company, 2001).[1]

[1]Ford Press, 2001. Ford Explorer to Feature Hybrid Electric Technology, Ford Motor Company.

Table 7.3 Common symptoms of a charging system malfunction and possible faults

Symptom	Possible fault
Engine does not rotate when trying to start	● Battery connection loose or corroded. ● Battery discharged or faulty. ● Broken, loose or disconnected wiring in the starter or circuit. ● Defective starter switch or automatic gearbox inhibitor switch. ● Starter pinion or flywheel ring gear loose. ● Earth strap broken, loose or corroded.
Starter noisy	● Starter pinion or flywheel ring gear loose. ● Starter mounting bolts loose. ● Starter worn (bearings etc.). ● Discharged battery (starter may jump in and out).
Starter turns engine slowly	● Discharged battery (slow rotation). ● Battery terminals loose or corroded. ● Earth strap or starter supply loose or disconnected. ● High resistance in supply or earth circuit. ● Internal starter fault.

7.5 Diagnosing starting system faults

7.5.1 Introduction

As with all systems, the six stages of fault-finding should be followed.

1. Verify the fault.
2. Collect further information.
3. Evaluate the evidence.
4. Carry out further tests in a logical sequence.
5. Rectify the problem.
6. Check all systems.

The procedure outlined in the next section is related primarily to stage 4 of the process. Table 7.3 lists some common symptoms of a charging system malfunction together with suggestions for the possible fault.

7.5.2 Circuit testing procedure

The process of checking a 12 V starting system operation is as follows (tests 3 to 8 are all carried out while trying to crank the engine).

1. Battery (at least 70%).
2. Hand and eye checks.
3. Battery volts (minimum 10 V).
4. Solenoid lead (same as battery).
5. Starter voltage (no more than 0.5 V less than battery).
6. Insulated line volt drop (maximum 0.25 V).
7. Solenoid contacts volt drop (almost 0 V).
8. Earth line volt drop (maximum 0.25 V).

The idea of these tests is to see if the circuit is supplying all the available voltage to the starter. If it is, then the starter is at fault, if not then the circuit is at fault.

If the starter is found to be defective then a replacement unit is the normal recommendation. Figure 7.35 explains the procedure used by Bosch to ensure quality exchange units. Repairs are possible but only if the general state of the motor is good.

7.6 Advanced starting system technology

7.6.1 Speed, torque and power

To understand the forces acting on a starter motor let us first consider a single conducting wire in a magnetic field. The force on a single conductor in a magnetic field can be calculated by the formula:

$$F = BIl$$

where F = force in N, l = length of conductor in the field in m, B = magnetic field strength in Wb/m^2, I = current flowing in the conductor in amps.

Fleming's left-hand rule will serve to give the direction of the force (the conductor is at 90° to the field).

This formula may be further developed to calculate the stalled torque of a motor with a number of armature windings as follows:

$$T = BIlrZ$$

where T = torque in Nm, r = armature radius in m, and Z = number of active armature conductors.

Figure 7.35 Quality starter overhaul procedure

This will only produce a result for stalled or lock torque because, when a motor is running, a back EMF is produced in the armature windings. This opposes the applied voltage and hence reduces the current flowing in the armature winding. In the case of a series wound starter motor, this will also reduce the field strength B. The armature current in a motor is given by the equation:

$$I = \frac{V - e}{R}$$

where I = armature current in amps, V = applied voltage in volts, R = resistance of the armature in ohms, e = total back EMF in volts.

From the above it should be noted that, at the instant of applying a voltage to the terminals of a motor, the armature current will be at a maximum since the back EMF is zero. As soon as the speed increases so will the back EMF and hence the armature current will decrease. This is why a starter motor produces ‘maximum torque at zero rev/min’.

For any DC machine the back EMF is given by:

$$e = \frac{2p\phi nZ}{c}$$

where e = back EMF in volts, p = number of pairs of poles, ϕ = flux per pole in webers, n = speed in revs/second, Z = number of armature conductors, $c = 2p$ for lap-wound and 2 for a wave-wound machine.

The formula can be re-written for calculating motor speed:

$$n = \frac{ce}{2p\phi Z}$$

If the constants are removed from this formula it clearly shows the relationship between field flux, speed and back EMF,

$$n \propto \frac{e}{\phi}$$

To consider the magnetic flux (ϕ) it is necessary to differentiate between permanent magnet starters and those using excitation via windings. Permanent magnetism remains reasonably constant. The construction and design of the magnet determine its strength. Flux density can be calculated as follows:

$$B = \frac{\phi}{A} \quad \text{(units: T (tesla) or Wb/m}^2\text{)}$$

where A = area of the pole perpendicular to the flux.

Pole shoes with windings are more complicated as the flux density depends on the material of the pole shoe as well as the coil and the current flowing.

The magneto-motive force (MMF) of a coil is determined thus:

$$\text{MMF} = NI \text{ Ampere turns}$$

where N = the number of turns on the coil and I = the current flowing in the coil.

Magnetic field strength H requires the active length of the coil to be included:

$$H = \frac{NI}{l}$$

where l = active length of the coil, H = magnetic field strength.

In order to convert this to flux density B, the permeability of the pole shoe must be included:

$$B = H\mu_0\mu_r$$

where μ_0 = permeability of free space (4×10^{-7} Henry/metre), and μ_r = relative permeability of the core to free space.

To calculate power consumed is a simple task using the formula:

$$P = T\omega$$

where P = power in watts, T = torque in Nm, and ω = angular velocity in rad/s.

Here is a simple example of the use of this formula. An engine requires a minimum cranking speed of 100 rev/min and the required torque to achieve this is 9.6 Nm.

At a 10 : 1 ring gear to pinion ratio this will require a 1000 rev/min starter speed (n). To convert this to rad/s:

$$\omega = \frac{2\pi n}{60}$$

This works out to 105 rad/s.

$$P = T\omega$$

$$9.6 \times 105 = 1000\,\text{W or } 1\,\text{kW}$$

7.6.2 Efficiency

Efficiency = Power out/Power in ($\times$100%)

The efficiency of most starter motors is of the order of 60%.

1 kW/60% = 1.67 kW (the required input power)

The main losses, which cause this, are iron losses, copper losses and mechanical losses. Iron losses are due to hysteresis loss caused by changes in magnetic flux, and also due to induced eddy currents in the iron parts of the motor. Copper losses are caused by the resistance of the windings; sometimes called I^2R losses. Mechanical losses include friction and windage (air) losses.

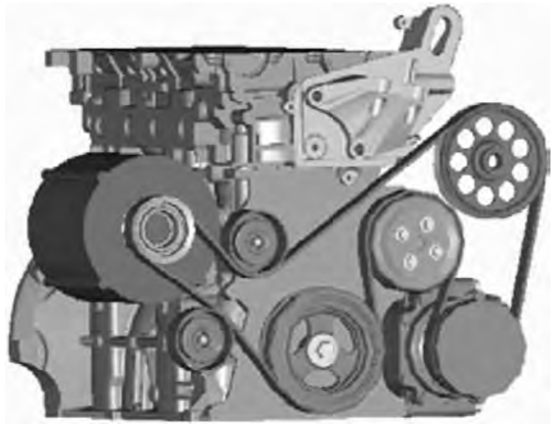

Figure 7.36 Belt-driven starter-generator concept (Source: Gates)

Using the previous example of a 1 kW starter it can be seen that, at an efficiency of 60%, this motor will require a supply of about 1.7 kW.

From a nominal 12 V supply and allowing for battery volt drop, a current of the order of 170 A will be required to achieve the necessary power.

7.7 New developments in starting systems

7.7.1 Belt-driven starter-generator

Gates, well known as manufacturers of drive belts, are working on a starter-generator concept that is belt driven. This work has been carried out in conjunction with Visteon. It is known as the Visteon/Gates E-M DRIVE System. It is an electromechanical system made up of a high efficiency induction motor, long-life belt-drive system and sophisticated electronic controls. The belt-driven starter-generator replaces the current alternator and has a similar space requirement.

One of the key components of this system, in addition to the starter-generator is a hydraulic tensioner. This must be able to prevent significant movement during starting but also control system dynamics during acceleration and deceleration of the engine. A dual pulley tensioner concept is shown below.

The combination of Visteon's motor design and Gates' belt technology has led to the development of a highly robust and economical power management system. The starter-generator is driven by a

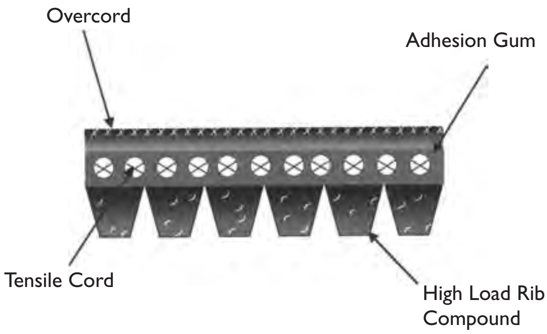

Figure 7.37 Micro-V belt in cross-section (Source: Gates)

multi-vee belt, which has been specially designed for the extra load.

The system allows implementation of intelligent fuel saving and emission reduction strategies. The main features are as follows:

- 42 V and 14 V capability with mechanical or electrically controlled tensioners.
- High load Micro-V® belt.
- Generating capability of 6 kW at 42 V and a brushless design for 10-year life.

The main benefits of this particular starting and generation method are as follows:

- Regenerative braking and electric torque assist.
- Power for increased feature content and silent cranking at a lower system cost than in-line starter-alternator systems.
- Can be added to existing engine/transmission designs with minimal changes.
- Allows implementation of fuel-saving strategies and emission reduction through hybrid electric strategies, increased cranking speed and start–stop systems.

Results of the current study show that the belt-drive system is capable of starting the engine with a 14 V starter-generator with a torque of 40 Nm. New machines working at 42 V and torque in the region of 70 Nm are under development. These will be used for larger petrol engines and the higher compression diesel engines (Dr-Ing. Manfred Arnold and Dipl.-Ing. Mohamad El-Mahmoud, 2003).[2]

The starter-generator concept is not new but until recently it could not meet the requirements of modern vehicles. These requirements relate to the starting torque and the power generation capabilities. The biggest advantage of the system under development is that it can be fitted to existing engine designs with only limited modifications. It may, therefore, become a 'stepping stone technology' that allows manufacturers to offer new features without the expense of development and extensive redesigning.

Figure 7.38 Starter-generator (Source: Gates)

7.8 Self-assessment

7.8.1 Questions

1. State four advantages of a pre-engaged starter when compared with an inertia type.
2. Describe the operation of the pull-in and hold-on windings in a pre-engaged starter solenoid.
3. Make a clearly labelled sketch of the engagement mechanism of a pre-engaged starter.
4. Explain what is meant by 'voltage drop' in a starter circuit and why it should be kept to a minimum.
5. Describe the engagement and disengagement of an inertia starter.
6. State two advantages and two disadvantages of a permanent magnet starter.
7. Calculate the gear ratio of an epicyclic gear set as used in a starter. The annulus has 40 teeth and the sun gear has 16 teeth.
8. Describe the operation of a roller-type one-way clutch.
9. Make a sketch to show the speed torque characteristics of a series, shunt and compound motor.
10. Describe the difference between a lap- and a wave-wound armature.

[2] Dr.-Ing. Manfred Arnold and Dipl.-Ing. Mohamad El-Mahmoud, 2003. A belt-driven starter-generator concept for a 4-cylinder gasoline engine, AutoTechnology, 3.