Alternators

In order to supply the power required for the starter motor, for ignition and fuel-injection systems, for the ECUs to control the electronic equipment, for lighting, and for safety and convenience electronics, motor vehicies need an alternator to act as their own efficient and highly reliable source of energy. Energy which must always be available, at any time of day or night.

Generation of electrical energy in the motor vehicle

Onboard electrical energy

Assignments and operating conditions

Whereas, with the engine stopped, the battery is the vehicle's energy store, the alternator becomes the on-board "electricity generating plant" when the engine is running. Its task is to supply energy to all the vehicle's current-consuming loads and systems (Fig. 1). In order that the entire system is reliable and trouble-free in operation, it is necessary that the alternator output, battery capacity, and starter power requirements, together with all other electrical loads, are matched to each other as optimally as possible.

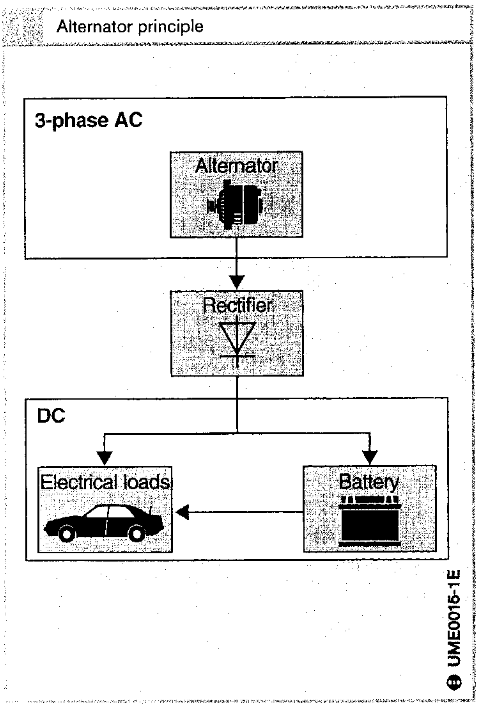

Alternator principle

Fig. 1
The 3-phase AC is rectified in the alternator to provide the DC for the vehicle's electrical loads and for charging the battery.

For instance, following a normal driving cycle (e.g. town driving in winter), the battery must always still have sufficient charge so that the vehicle can be started again without any trouble no matter what the temperature. And the ECUs, sensors and actuators for the vehicle's electronic systems (e.g. for fuel management, ignition, Motronic, electronic engine-power control, antilock braking system (ABS), traction control (TCS), etc.) must always be ready for operation.

Apart from this, the vehicle's safety and security systems as well as its signaling systems must operate immediately, the same as the lighting system at night or in fog. Furthermore, the driver-information and convenience systems must always function correctly, and with the vehicle parked, a number of electrical loads should continue to operate for a reasonable period without discharging the battery so far that the vehicle cannot be started again.

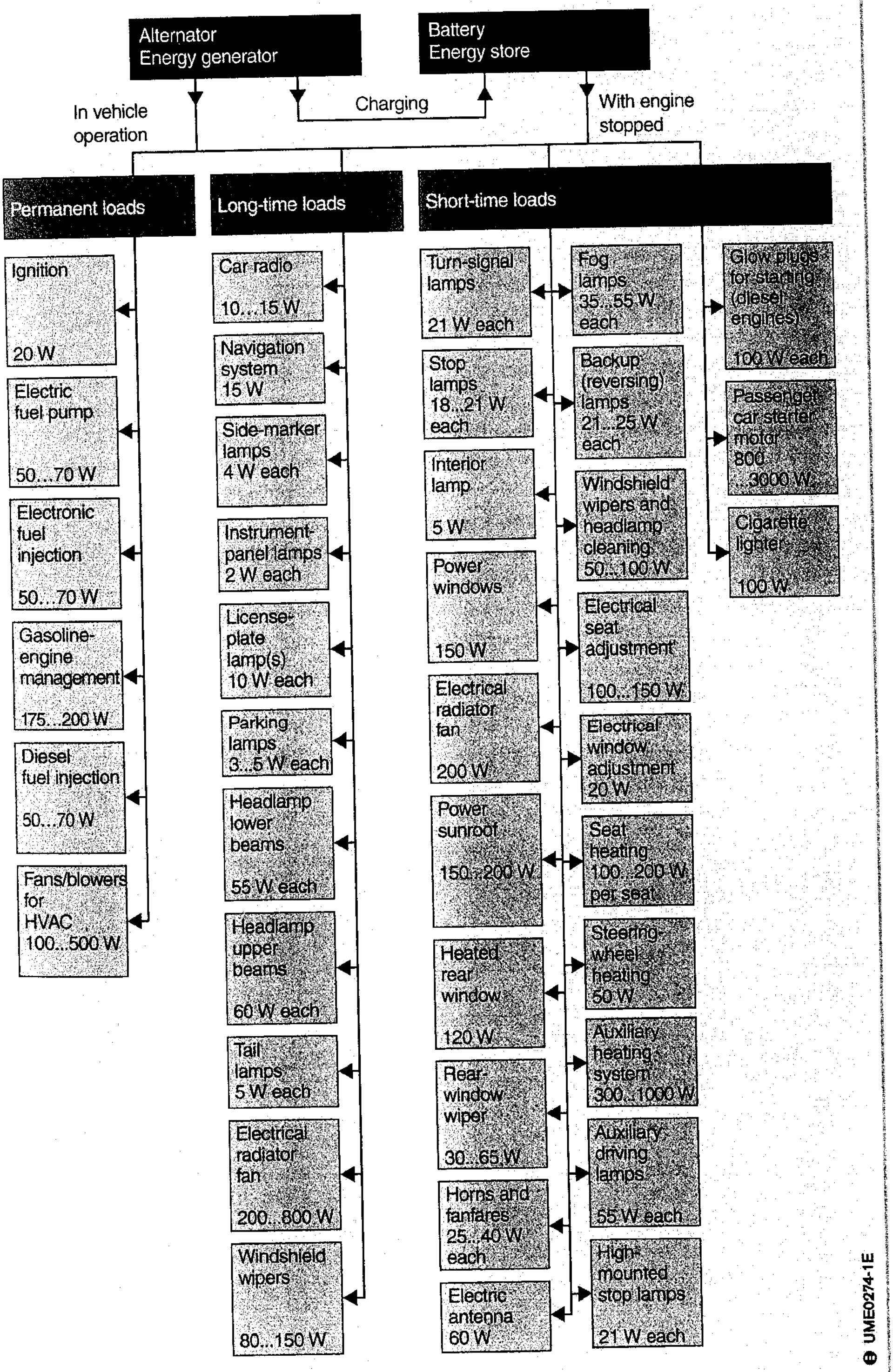
As a matter of course, millions of motorists expect their vehicle to always be fully functional, and demand a high level of operational reliability from its electrical system. For many thousands of miles – in both summer and winter.

Electrical loads

The various electrical loads have differing duty cycles (Fig. 2). A distinction is made between permanent loads (ignition, fuel injection, etc.), long-time loads (lighting, car radio, vehicle heater, etc.), and short-time loads (turn signals, stop lamps, etc.).

Some electrical loads are only switched on according to season (air-conditioner in summer, seat heater in winter). And the operation of electrical radiator fans depends on temperaure and driving conditions.

Power requirements of the loads in the vehicle (average values)



Charge-balance calculation

Here, a computer program is used to determine the state of battery charge at the end of a typical driving cycle, whereby such influences as battery size, alternator size, and load input powers must be taken into account.

Rush-hour driving (low engine speeds) combined with winter operation (low charging-current input to the battery) is regarded as a normal passenger-car driving cycle.

In the case of vehicles equipped with an air conditioner, summer operation can be even more unfavorable than winter.

Vehicle electrical system

The nature of the wiring between alternator, battery, and electrical equipment also influences the voltage level and, as a result, the state of battery charge.

If all electrical loads are connected at the battery, the total current (sum of battery charging current and load current) flows through the charging line, and the resulting high voltage drop causes a reduction in the charging voltage.

Conversely, if all electrical devices are connected at the alternator side, the voltage drop is less and the charging voltage is higher. This though may have a negative effect upon devices which are sensitive to voltage peaks or high voltage ripple (electronic circuitry).

For this reason, it is advisable to connect voltage-insensitive equipment with high power inputs to the alternator, and voltage-sensitive equipment with low power inputs to the battery.

Appropriate line cross-sections, and good connections whose contact resistances do not increase even after long periods of operation, contribute to keeping the voltage drop to a minimum.

Electrical power generation using alternators

The availability of reasonably priced power diodes as from around 1963, paved the way for Bosch to start with the series production of alternators. Thanks to its design principle, the alternator has far higher electromagnetic efficiency than the DC generator. This fact, together with the alternator's much wider rotational-speed range, enables it to deliver power, and cover the vehicle's increased power requirements, even at engine idle. Since the alternator speed can be matched to that of the engine by means of a suitable transmission, this means that the battery remains at a high charge level even in winter during frequent town driving.

The increased power requirements mentioned above, result from the following factors: The increase in the amount of electrical equipment fitted in the vehicle, the number of ECUs required for the electronic systems (e.g. for engine management and for chassis control), and the safety, security and convenience electronics. The expected power requirements up to the year 2010 are shown in Fig. 3.

3 Alternator output power

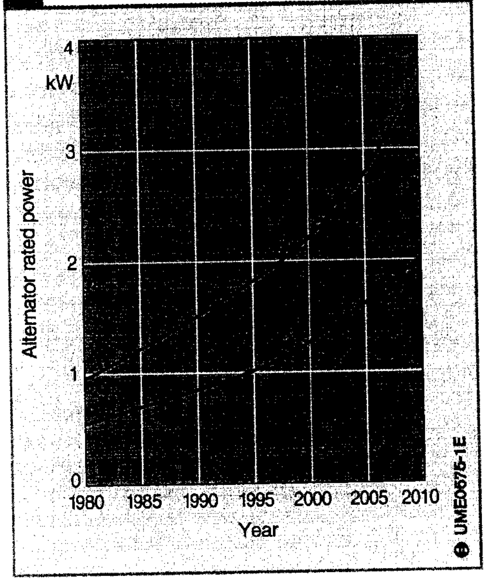


Fig. 3
Expected developments for passenger cars up to the year 2010.

1 Luxury car
2 Intermediate-size car

Apart from these factors, typical driving cycles have also changed, whereby the proportion of town driving with extended stops at idle has increased (Fig. 4).

The rise in traffic density leads to frequent traffic jams, and together with long stops at traffic lights this means that the alternator also operates for much of the time at low speeds which correspond to engine idle. Together with the fact that longer journeys at higher speeds have become less common, this has a negative effect on the battery's charge balance. And it is imperative that the battery continues to be charged even when the engine is idling.

At engine idle, an alternator already delivers at least a third of its rated power (Fig. 5).

Alternators are designed to generate charging voltages of 14 V (28 V for commercial vehicles), and 42 V (undergoing development). The three-phase winding is incorporated in the stator, and the excitation winding in the rotor.

The three-phase AC generated by the alternator must be rectified, the rectifiers also preventing battery discharge when the vehicle is stationary.

The additional relay as required for the DC generator can be dispensed with.

Design factors

Rotational speed

An alternator's efficiency (energy generated per kg mass) increases with rotational speed. This factor dictates as high a conversion ratio as possible between engine crankshaft and alternator. For passenger cars, typical values are between 1:2.2 and 1:3, and for commercial vehicles up to 1:5.

Temperature

The losses in the alternator lead to heating up of its components. The input of fresh air to the alternator, or the use of liquid cooling, are suitable measures for reducing component temperature and increasing alternator service life.

Vibration

Depending on installation conditions and the engine's vibration patterns, vibration accelerations of between 500...800 m/s^2 can occur at the alternator. Critical resonances must be avoided.

Further influences

The alternator is also subjected to such detrimental influences as spray water, dirt, oil, fuel mist, and road salt.

4 Proportion of time at standstill

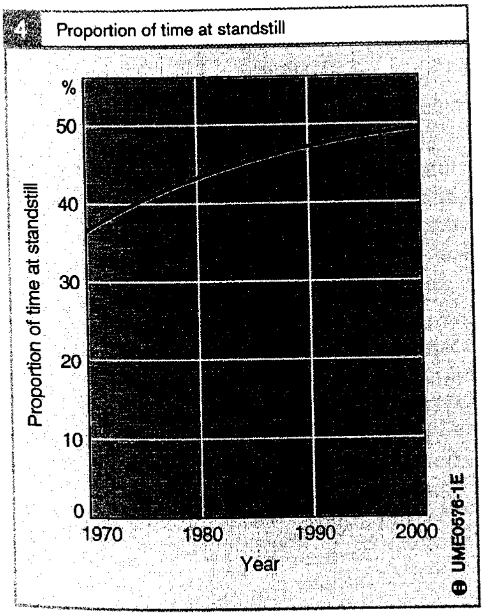


Fig. 4
Developments for urban traffic (large cities) up to the year 2000.

5 Alternator current characteristic

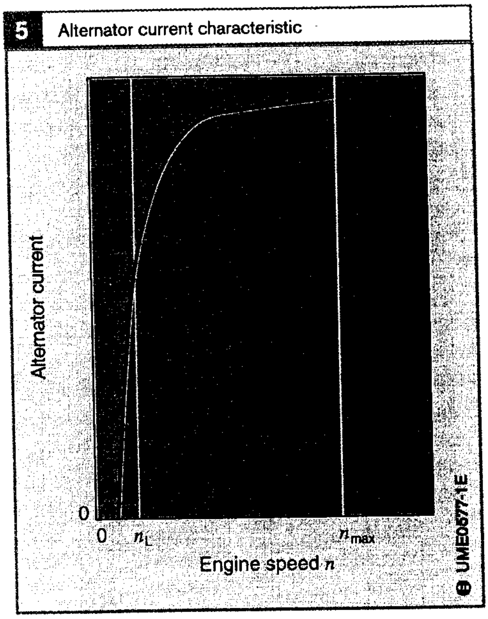


Fig. 5
At constant voltage
n_L Idle speed
n_{max} Maximum speed

Electrical power generation using DC generators

Originally, the conventional lead-acid battery customarily fitted in motor vehicles led to the development of the DC generator, and for a long time this generator system was able to meet the majority of the demands made upon it.

Consequently, until the middle of the seventies, most vehicles were equipped with such DC generators. Today though, these have become virtually insignificant in the automotive sector and will not be dealt with in detail here.

With the DC generator, it proved to be more practical to rotate the magnetic lines of force, while locating the electrically excited magnetic system in the stationary housing. The alternating current generated by the machine is then rectified relatively simply by mechanical means using a commutator, and the resulting direct current supplied to the vehicle electrical system or the battery.

Requirements to be met by automotive generators

The type and construction of an automotive electrical generator are determined by the necessity of providing electrical energy for powering the vehicle's electrical equipment, and for charging its battery.

Initially, the alternator generates alternating current (AC). The vehicle's electrical equipment though requires direct current (DC) for keeping the battery charged and for powering the electronic subassemblies. The electrical system must therefore be supplied with DC.

The demands made upon an automotive generator are highly complex and varied:

- Supplying all connected loads with DC.
- Providing power reserves for rapidly charging the battery and keeping it charged, even when permanent loads are swiched on.
- Maintaining the voltage output as constant as possible across the complete engine speed range independent of the generator's loading.
- Rugged construction to withstand the under-hood stresses (e.g. vibration, high ambient temperatures, temperature changes, dirt, dampness, etc.).
- Low weight.
- Compact dimensions for ease of installation.
- Long service life.
- Low noise level.
- A high level of efficiency.

Characteristics (summary)

The alternator's most important characteristics are:

- It generates power even at engine idle.
- Rectification of the AC uses power diodes in a three-phase bridge circuit.
- The diodes separate alternator and battery from the vehicle electrical system when the alternator voltage drops below the battery voltage.
- The alternator's higher level of electrical efficiency means that for the same power output, they are far lighter than DC generators.
- Alternators feature a long service life. The passenger-car alternator's service life corresponds roughly to that of the engine. It can last for as much as 200,000 km, which means that no servicing is necessary during this period.
- On vehicles designed for high mileages (trucks and commercial vehicles in general), brushless alternator versions are used which permit regreasing. Or bearings with grease-reserve chambers are fitted.
- Alternators are able to withstand such external influences as vibration, high temperatures, dirt, and dampness.
- Normally, operation is possible in either direction of rotation without special measures being necessary, when the fan shape is adapted to the direction of rotation.

Basic physical principles

Electrodynamic principle

Induction

Electromagnetic induction is the basis for the generation of electricity. The principle is as follows:

When an electric conductor (wire or wire loop) cuts through the lines of force of a DC magnetic field, a voltage is generated (induced) in the conductor. It is immaterial whether the magnetic field remains stationary and the conductor rotates, or vice versa.

A wire loop is rotated between the North and South poles of a permanent magnet, and its ends are connected through collector rings and carbon brushes to a voltmeter. The continuously varying relationship of the wire loop to the poles is reflected in the varying voltage shown by the voltmeter. If the wire loop rotates uniformly, a sinusoidal voltage curve is generated whose maximum values occur at intervals of 180°. Alternating current (AC) flows as soon as the circuit is closed (Fig. 1).

How is the magnetic field generated?

The magnetic field can be generated by permanent magnets. Due to their simplicity, these have the advantage of requiring only a minimum of technical outlay. They are used for small generators (e.g. bicycle dynamos).

On the other hand, electromagnets through which DC current flows permit considerably higher voltages and are controllable. This is why they are applied for generation of the (exciter) magnetic field.

Electromagnetism is based on the fact that, when an electric current flows through wires or windings, it generates a magnetic field around them.

The number of turns in the winding and the magnitude of the current flowing through it determine the magnetic field's strength. This excitation field can be further increased by using a magnetizable iron core, which, when it rotates, induces an alternating voltage in the armature coil. In practical generator applications, in order to increase the effects of induction, instead of a single wire loop, a number of wire loops are used to form the "winding" which rotates in the magnetic field.

Induced single-phase alternating current

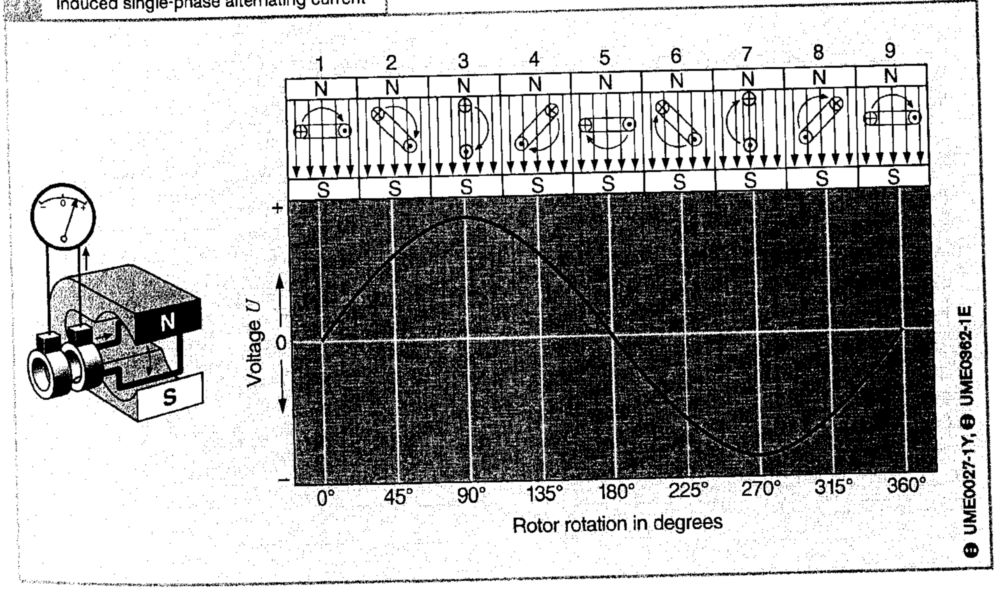


Fig. 1
Voltage curve generated during one full revolution of a winding rotating in a magnetic field.
The position of the rotor on the left corresponds to position 3.

When this principle is applied to the generator or alternator, a decisive advantage lies in the fact that the magnetic field, and with it the induced voltage, can be strengthened or weakened by increasing or decreasing the (excitation) current flowing in the (excitation) winding.

Except for slight residual or residual magnetism, the electromagnet in the form of the excitation winding loses its magnetism when the excitation current is switched off. If an external source of energy (e.g. battery) provides the excitation current, this is termed "external excitation". If the excitation current is taken from the machine's own electric circuit this is termed "self-excitation". In electric machines, the complete rotating system comprising winding and iron core is referred to as the rotor.

Principle of operation of the alternator

3-phase current (3-phase AC, Fig. 2) is also generated by rotating the rotor in a magnetic field, the same as with single-phase AC as described above. One of the advantages of 3-phase AC lies in the fact that it makes more efficient use of the electrical generator's potential. The generator for 3-phase AC is designated an "alternator" and its armature comprises three identical windings which are offset from each other by 120°. The start points of the three windings are usually designated u, v, w, and the end points x, y, z. In accordance with the laws of induction, when the rotor rotates in the magnetic field, sinusoidal voltages are generated in each of its three windings. These voltages are of identical magnitude and frequency, the only difference being that their 120° offset results in the induced voltages also being 120° out-of-phase with each other, as well as being out-of-phase by 120° with respect to time.

Therefore, with the rotor turning, the alternator generates a constantly recurring 3-phase alternating voltage.

Normally, with the windings not connected, an alternator would require 6 wires to output the electrical energy that it has generated (Fig. 3a). However, by interconnecting the 3 circuits the number of wires can be reduced from 6 to 3. This joint use of the conductors is achieved by the "star" connection (Fig. 3b) or "delta" connection (Fig. 3c).

Induced three-phase AC

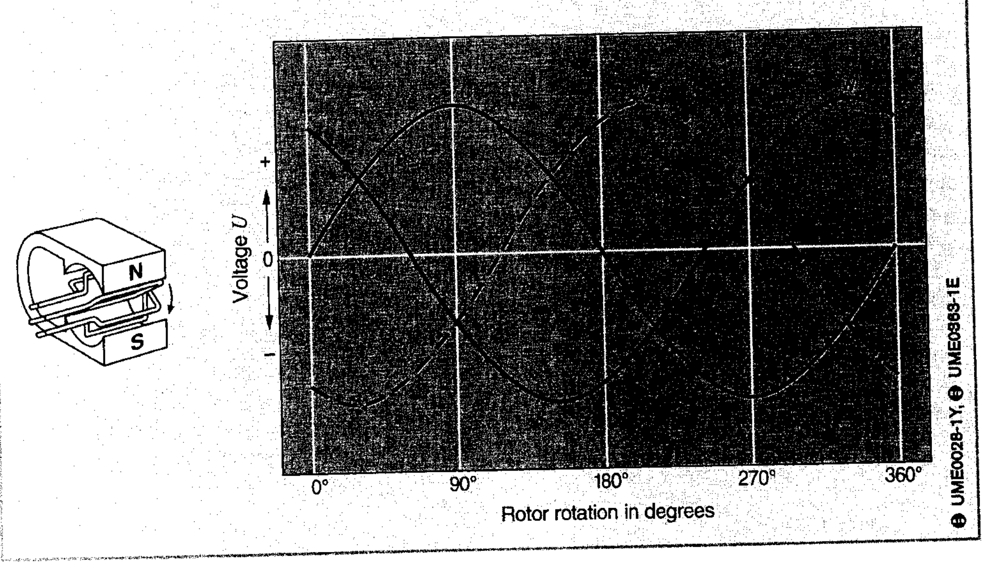


Fig. 2
Voltage curves generated during one revolution of three windings (phases) rotating in a magnetic field. The windings are offset from each other by 120°. The connection of the individual phase voltages results in a 3-phase alternating voltage.

In the case of the "star" connection, the ends of the 3 winding phases are joined to form a "star" point. Without a neutral conductor, the sum of the 3 currents at any instant time is always 0.

Discussions up to this point have centered on the alternator version with stationary excitation field and rotating armature winding in which the load current is induced.

For automotive alternators though, the 3-phase (star or delta connected) winding system is in the stator (the stationary part of the alternator housing) so that the winding is often referred to as the stator winding.

The poles of the magnet together with the excitation winding are situated on the rotor. The rotor's magnetic field builds up as soon as current flows through the excitation winding.

When the rotor rotates, its magnetic field induces a 3-phase alternating voltage in the stator windings which provides the 3-phase current when the alternator is loaded.

Rectification of the AC voltage

The 3-phase AC generated by the alternator cannot be stored in the vehicle's battery nor can it be used to power the electronic components and ECUs. To do so, it must first of all be rectified. One of the essential prerequisites for this rectification is the availability of high-performance power diodes which can operate efficiently throughout a wide temperature range.

Rectifier diodes have a reverse and a forward direction, the latter being indicated by the arrow in the symbol. A diode can be compared to a non-return valve which permits passage of a fluid or a gas in only one direction and stops it in the other.

The rectifier diode suppresses the negative half waves and allows only positive half-waves to pass. The result is a pulsating direct current. So-called full-wave rectification is applied in order to make full use of all the half-waves, including those that have been suppressed.

Bridge circuit for the rectification of the 3-phase AC

The operating principle of the diode in the rectification of an alternating current is shown in Fig. 4 (following page). Half-wave rectification is shown in Fig. 4a, and full-wave rectification in Fig. 4b.

The AC generated in the 3 windings of the alternator is rectified in an AC bridge circuit using 6 diodes (Fig. 5).

Fig. 3
- a Windings not connected
- b Star connection. Alternator voltage and phase voltage (partial voltage) differ by the factor $\sqrt{3} = 1.73$

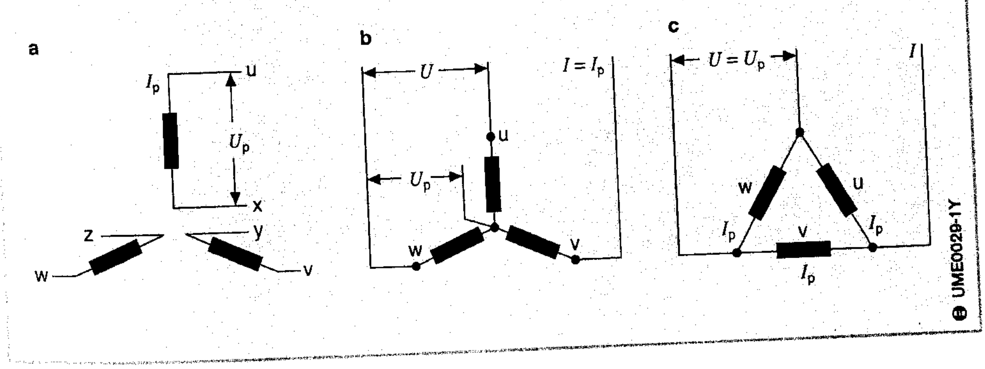
Alternator current I equals phase current

$U = U_p \cdot \sqrt{3}$; $I = I_p$

- c Delta connection. Alternator voltage equals phase voltage U_p. The alternator current and phase curren differ by the fact $\sqrt{3} = 1.73$

$U = U_p$; $I = I_p \cdot$

Connection of the three windings



Two power diodes are connected into each phase, one diode to the positive side (Term. B+) and one to the negative side (Term. B–). The six power diodes are connected to form a full-wave rectification circuit. The positive half-waves pass through the positive-side diodes, and the negative half-waves through the negative-side diodes. Rectification takes place.

With full-wave rectification using a bridge circuit, the positive and negative half-wave envelopes are added to form a rectified alternator voltage with a slight ripple (Fig. 5).

This means that the direct current (DC) which is taken from the alternator at Terminals B+ and B– to supply the vehicle electrical system is not ideally "smooth" but has a slight ripple. This ripple is further smoothed by the battery, which is connected in parallel to the alternator, and by any capacitors in the vehicle electrical system. The excitation current which magnetizes the poles of the excitation field is tapped off from the stator winding and rectified by a full-wave bridge rectifier. Older-version alternators have three "exciter diodes". The three "exciter diodes" at Term. D+, and the three power diodes at Term. B– (negative side) form the bridge circuit for the excitation current. With the aim of increasing power output at high speeds (above 3,000 rpm), "auxiliary diodes" can be used with star-connected versions to make full use of the alternator voltage's harmonic component.

Reverse-current block
The rectifier diodes in the alternator not only rectify the alternator and excitation voltage, but also prevent the battery discharging through the 3-phase winding in the stator.

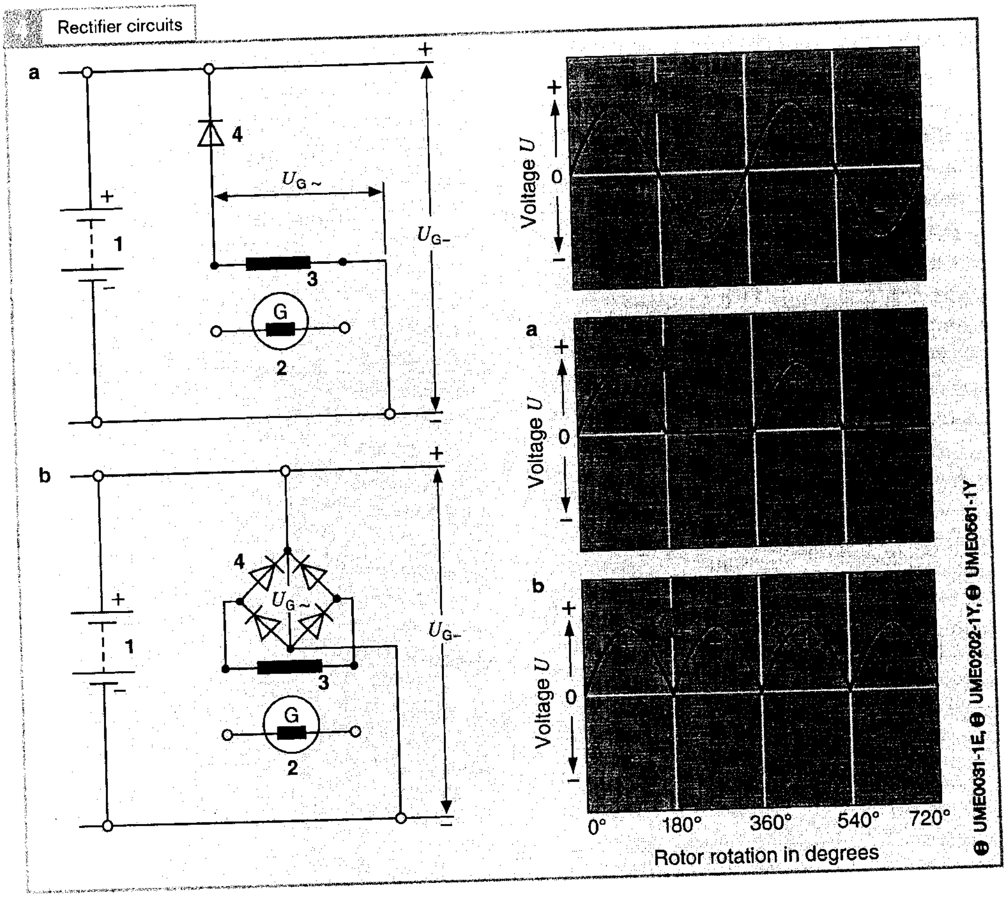

Rectifier circuits

Fig. 4
- a Half-wave rectification
- b Full-wave rectification.

U_G~ AC voltage upstream of the diodes
U_G– Pulsating DC downstream of the diodes

1 Battery
2 Excitation winding (G)
3 Stator winding
4 Rectifier diodes

With the engine stopped, or with it turning too slowly for self-excitation to take place (e.g. during cranking), without the diodes battery current would flow through the stator winding. With respect to the battery current, the diodes are polarized in the reverse direction so that it is impossible for battery-discharge current to flow. Current flow can only take place from the alternator to the battery.

Rectifier diodes

Regarding their operation, the power diodes on the plus and negative sides are identical. The only difference between them lies in their special design for use as rectifiers in the alternator. They are termed positive and negative diodes, and in one case the diode's knurled metal casing acts as a cathode and in the other as an anode. The metal casing of the positive diode is pressed into the positive plate and functions as a cathode. It is connected to the battery's positive pole and conducts towards B+ (battery positive). The metal casing of the negative diode is pressed into the negative plate and functions as an anode. It is connected to ground (B-). The diode wire terminations are connected to the ends of the stator winding (Fig. 6, overleaf). The positive and negative plates also function as heat sinks for cooling the diodes. The power diodes can be in the form of Zener diodes which also serve to limit the voltage peaks which occur in the alternator due to extreme load changes (load-dump protection).

3-phase bridge circuit

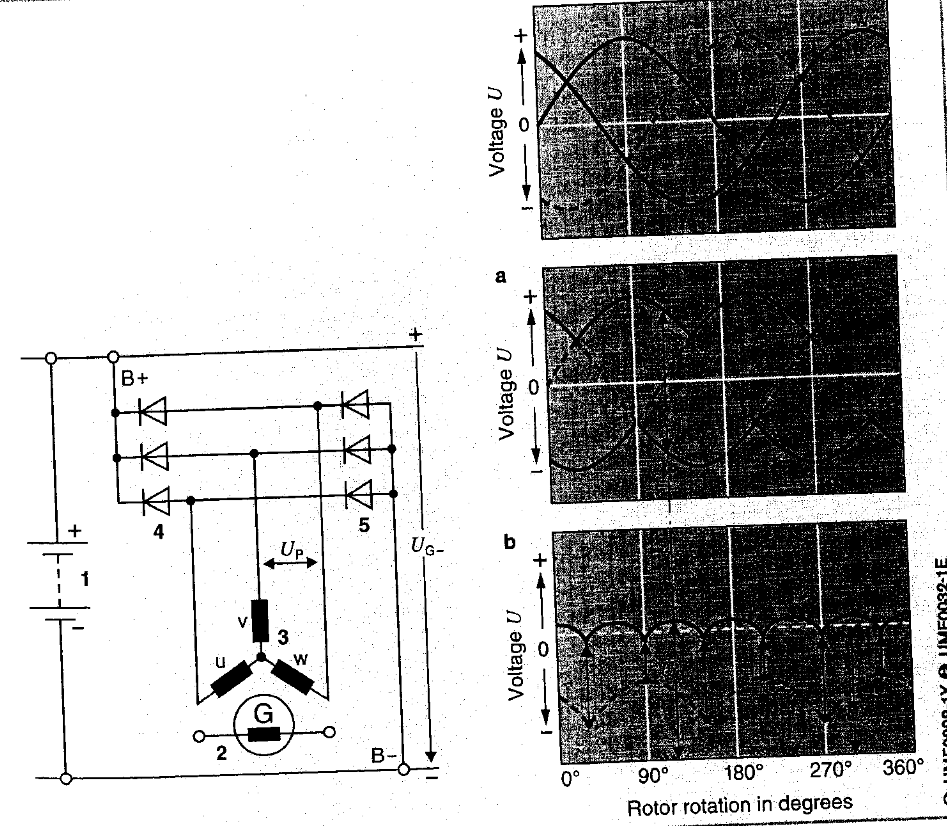


Fig. 5
- a 3-phase AC voltage
- b Formation of the alternator voltage by the envelope curves of the positive and negative half-waves
- c Rectified alternator voltage.

U_P Phase voltage,
U_G Voltage at the rectifier (negative not to ground),
U_{G^-} Alternator DC voltage output (negative to ground),
U_{Gms} r.m.s. value of the alternator DC output.

1	Battery
2	Excitation winding
3	Stator winding
4	Positive diodes
5	Negative diodes

The alternator's circuits

Standard-version alternators have the following three circuits:

- Pre-excitation circuit (separate excitation using battery current)
- Excitation circuit (self-excitation)
- Generator or main circuit

Pre-excitation circuit

When the ignition or driving switch (Fig. 7, Item 4) is operated, the battery current IB first of all flows through the charge-indicator lamp (3), through the excitation winding (1d) in the stator, and through the voltage regulator (2) to ground. In the rotor, this battery current serves to pre-excite the alternator.

Why is pre-excitation necessary?

On most alternators, the residual magnetism in the excitation winding's iron core is very weak at the instant of starting and at low speeds, and does not suffice to provide the self-excitation needed for building up the magnetic field.

Self-excitation can only take place when the alternator voltage exceeds the voltage drop across the two diodes (2 x 0.7 = 1.4 V). This serves to support the pre-excitation current which flows through the charge-indicator lamp from the battery. It generates a field in the rotor which in turn induces a voltage in the stator proportional to the rotor speed.

When the engine is started, in order that alternator self-excitation can "get going", the engine must turn at a speed which enables the induced voltage to exceed the voltage drop across the diodes in the excitation circuit. Since the charge-indicator lamp increases the pre-excitation circuit resistance compared to that of the excitation circuit, this speed is above the engine idle speed. It is therefore affected by the charge-indicator lamp's wattage rating.

Charge-indicator lamp

When the ignition or driving switch (Fig. 7, Item 3) is operated, the charge-indicator lamp (3) in the pre-excitation circuit functions as a resistor and determines the magnitude of the pre-excitation current. A suitably dimensioned lamp provides a current which is enough to generate a sufficiently strong magnetic field to initiate self-excitation. If the lamp is too weak, as is the case, for instance, with electronic dis-

Fig. 6

1 Battery
2 Excitation winding (G)
3 Stator winding
4 Positive-plate diodes
5 Negative-plate diodes
6 Auxiliary diodes
7 Excitation diodes

6 Excitation-current rectification

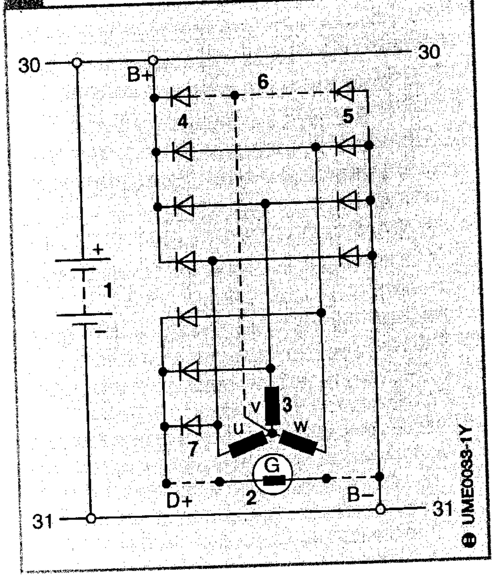
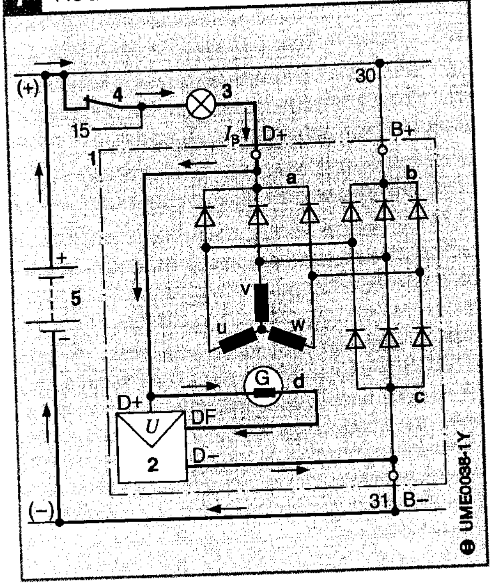


Fig. 7

1 Alternator
1a Excitation diodes
1b Positive-plate diodes
1c Negative-plate diodes
1d Excitation winding
2 Voltage regulator
3 Charge-indicator lamp
4 Ignition switch
5 Battery

7 Pre-excitation circuit



plays, a resistor must be connected in parallel to guarantee adequate alternator self-excitation. The lamp remains on as long as the alternator voltage is below battery voltage. The lamp goes out the first time the speed is reached at which maximum alternator voltage is generated and the alternator starts to feed power into the vehicle electrical system.
Typical ratings for charge-indicator lamps are:
2 W for 12 V systems,
3 W for 24 V systems.

Pre-excitation on alternators with multifunctional voltage regulator
Alternators with multifunctional regulators draw their excitation current directly from Term. B+. This means that excitation diodes can be dispensed with (Fig. 8). As from the Series B "Compact" alternator range, the multifunctional regulator has been fitted as standard. When it receives the information "Ignition on" from the L connection, the multifunctional regulator switches on the pre-excitation current. When the rotor starts to turn, the regulator registers a voltage at the phase connection V, whose frequency it uses to calculate the alternator speed. A switch-on speed is set in the regulator, and as soon as this is reached, the regulator switches through the final stage so that the alternator starts to deliver current to the vehicle's electrical system.

Excitation circuit
During alternator operation, it is the task of the excitation current I_{err} to generate a magnetic field in the rotor so that the required alternator voltage can be induced in the stator windings.

9 Excitation circuit

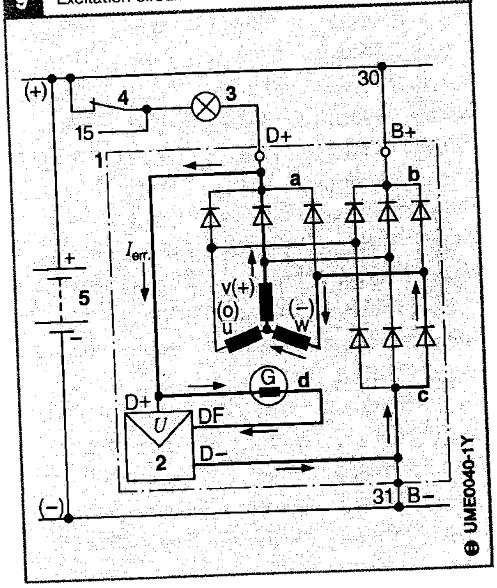
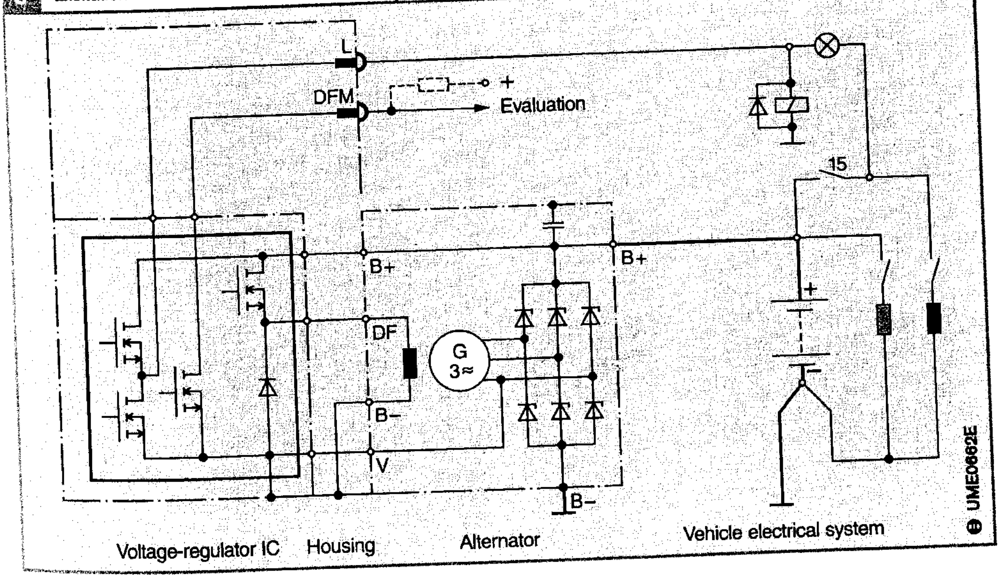


Fig. 9
1 Alternator
1a Excitation diodes
1b Positive-plate diodes
1c Negative-plate diodes
1d Excitation winding
2 Voltage regulator
3 Charge-indicator lamp
4 Ignition switch
5 Battery

8 Excitation circuit without excitation diodes



Since alternators are "self-excited", the excitation current must be tapped off from the current flowing in the 3-phase winding.

Depending on the type of regulator, the excitation current I_{err} takes the following path:

- Either through the excitation diodes (Fig. 9), carbon brushes, collector rings, and excitation winding to Term. DF of the monolithic or hybrid voltage regulator, and from Term. D– of the regulator to ground (B–) or
- Through the positive power diodes (Fig. 8), multifunctional regulator, carbon brushes, collector rings, and excitation winding to ground (B–)

In both cases, the excitation current flows from B– back to the stator winding through the negative power diodes.

Since the alternator provides its own excitation current, one refers to self-excitation.

Generator circuit

The alternating voltage induced in the three phases of the alternator must be rectified by the power diodes in the bridge circuit before it is passed on to the battery and to the loads.

The alternator current I_G, flows from the three windings and through the respective power diodes to the battery and to the loads in the vehicle electrical system. In other words, the alternator current is divided into battery-charging current and load current. In Fig. 11, the curves of the stator-winding voltages are shown as a function of the angle of rotation of the rotor.

Taking a rotor with six pole pairs, for instance, and an angle of rotation of 30°, the voltage referred to the star point at the end of winding v is positive, for winding w it is negative, and for winding u it is zero. The resulting current path is shown in Fig. 10.

Current flows from the end of winding v and through the positive diodes to alternator terminal B+ from where it flows through the battery, or the load, to ground (alternator terminal B–) and via the negative diodes (c) to winding end w. Taking a 45° angle of rotation, current from the v and w winding ends takes the same path to winding end u. In this case, there is voltage present across all of the phases.

Both examples though are momentary values. In reality, the phase voltages and currents continually change their magnitude and direction, whereas the DC supplied for battery charging and for the electrical loads always maintains the same direction.

Alternator circuit

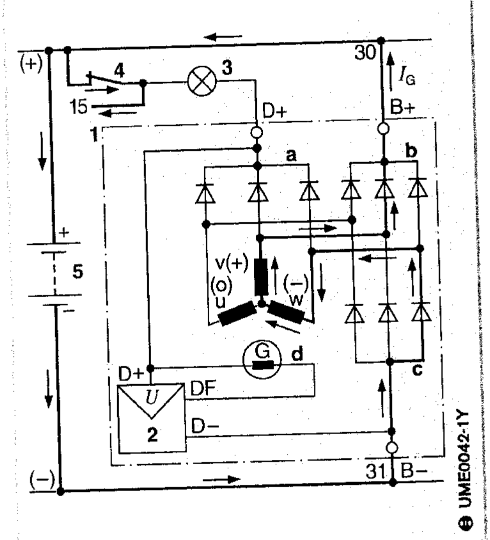


Fig. 10

1 Alternator
1a Excitation diodes
1b Positive-plate diodes
1c Negative-plate diodes
1d Excitation winding
2 Voltage regulator
3 Charge-indicator lamp
4 Ignition switch
5 Battery

Stator-winding voltages

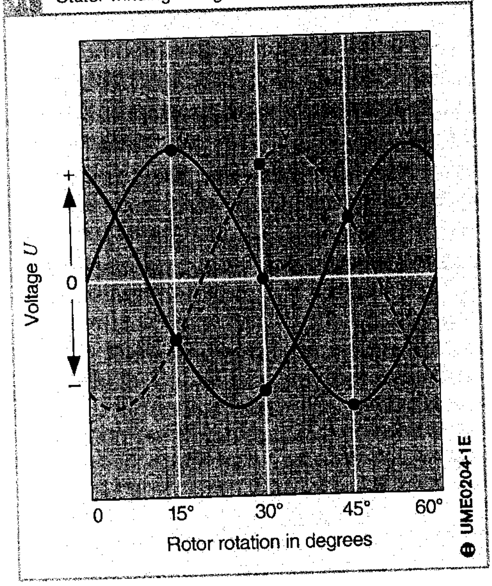


Fig. 11
Voltage curves as a function of the angle of rotation of a rotor with 6 pole pairs.