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Alternators

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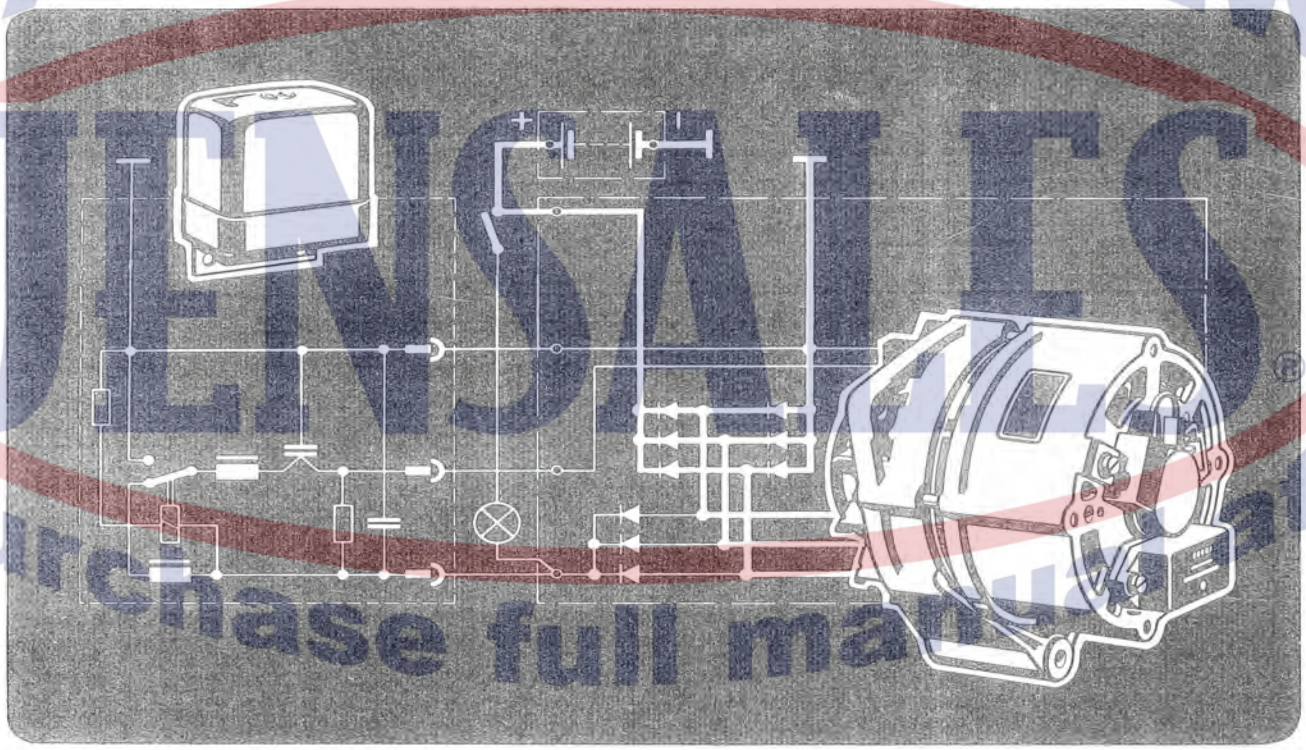

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Editor in chief: Ulrich Adler
Editor: Helmut Scheuerle
Translation: Blöks, Girling
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Introduction

Background

Driven by the vehicle's engine, the alternator has the task of supplying current to the electrical accessories used in the vehicle while the engine is running. Additionally, the alternator must keep the battery properly charged. This requires direct current. The alternator, by design, generates a three-phase alternating current but this is ultimately converted into direct current. Logically, since the end product of an alternator is direct current, it might well be called a ,,direct current generator''. The specific nomenclature, ,,alternator'', serves to distinguish the internal construction differences between these units and their counterpart, direct current generators having commutators.

Why Alternators?

Constantly increasing traffic density, especially in metropolitan areas, means that vehicles are spending ever longer periods of their total driving time merely standing in traffic (up to 40 % for city buses). During these periods the DC generator often does not produce any power at all while the engine is idling. Further demands have been placed on the electrical power source through the addition of many new electrical accessories, several of which require relatively large amounts of current (e.g. halogen driving lamps, foglamps, air conditioner, power windows, etc.).

Under these circumstances the generator must have sufficient output, even during engine idle, to keep the battery properly charged – particularly in winter. This requires a considerable broadening of the speed range within which the generator must supply power. One eventually reaches the point where conventional DC generators (with commutators) are no longer practical, since broadening the speed range makes it progressively more difficult to control the commutation, or conversion, of the induced alternating current into the direct current necessary for battery charging.

The advent of the semi-conductor diode has solved this problem by making it possible to obtain direct current without the use of commutators. Their small physical size allows them to be easily mounted inside alternators where, in place of the commutator, they assume the task of rectifying the alternating current. The term ,,dynamo without slip-rings'' originates from here. Due to the extended speed range, resulting from the elimination of the commutator, the alternator can satisfy power demands even while the engine is idling. Fig. 1 shows a comparison curve of the current output vs. rev/min for both a DC generator and an alternator of about the same maximum output. It can readily be seen that the alternator starts to supply current at considerably lower speeds, that means battery charging begins at lower engine speeds. The curves also indicate that a DC generator cannot maintain constant output at variable speeds.

Advantages of the Alternator

The alternator has proved its superiority due to the following inherent advantages:

Output at engine idle permitting early start of charging;
High maximum speed;
Requires little maintenance;
Less wear, resulting in longer life;
High operating reliability;
Lighter weight in relation to output;
The regulator does not need a reverse current switch;
Not dependant upon direction of rotation with regard to electrical components (rotational direction only of importance when certain types of cooling fan are used);
Battery size may be reduced since rapid recharging is guaranteed.

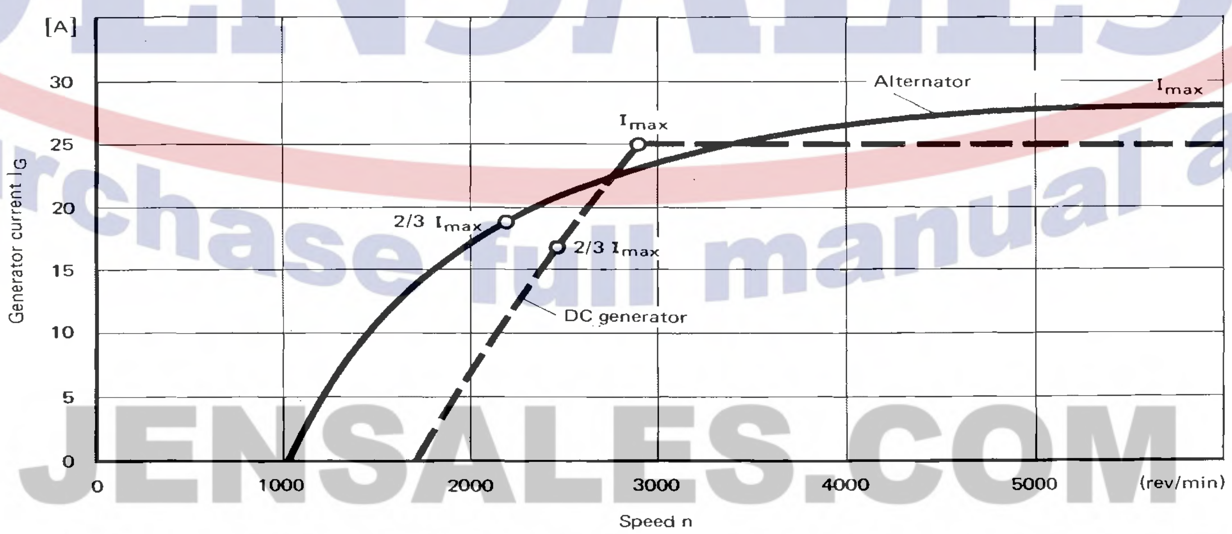

Fig. 1 Current as function of rev/min
Comparison between DC generator and alternator of similar maximum output

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Construction and Operating Principles

Alternators

Electromagnetic Induction Principle

This principle is based on the fact that, when an electrical conductor cuts through the lines of force of a magnetic field, an electrical potential (electromotive force – EMF) is ,,induced" in the conductor.
It is immaterial whether the magnetic field remains stationary while the conductor moves or vice versa (i.e. the conductor is stationary while the magnetic field moves). In the Bosch alternator the conductor (stator or stator winding) is stationary and the magnetic field moves (rotates, hence the term rotor). The induction effect can be multiplied by subjecting not only one, but a large number of conductor loops to the alternating magnetic field. These ,,loops" together form the stator winding.
As the rotor turns the poles of the magnetic field move in the direction of rotation and an ,,alternating" voltage, alternating in direction as well as in magnitude, is induced in the conductor.
The pointer deflections of the voltmeter (Figs. 2 and 3) indicate the respective maximum values after each half revolution.
Between the maximum values the voltage follows a sine wave curve if the rotor is turned at a uniform rate (Fig. 4).
The induced EMF becomes greater when the magnetic field is strengthened (i.e. the lines of force become more dense) and when the speed with which the lines of force are cut is increased. Bosch alternators have electromagnets for generation of the magnetic field. The field is only present when current flows through the field (rotor) winding (excitation winding).

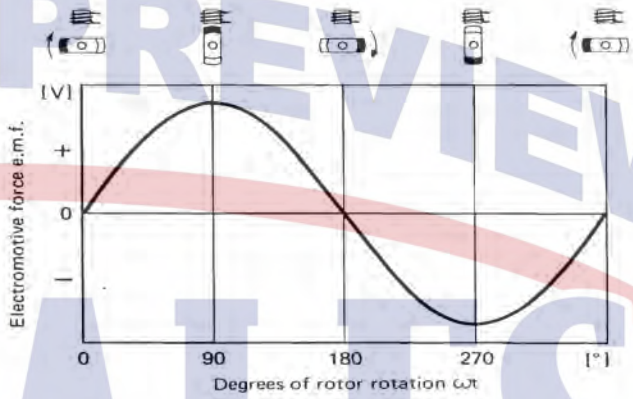

Fig. 4 Curve of induced alternating current during one turn of the rotor

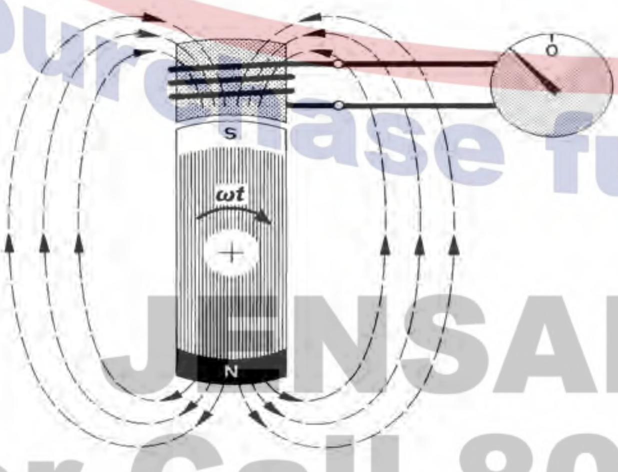

Fig. 2 Magnetic flux in the stator winding, the lines of force flow from North pole to South pole

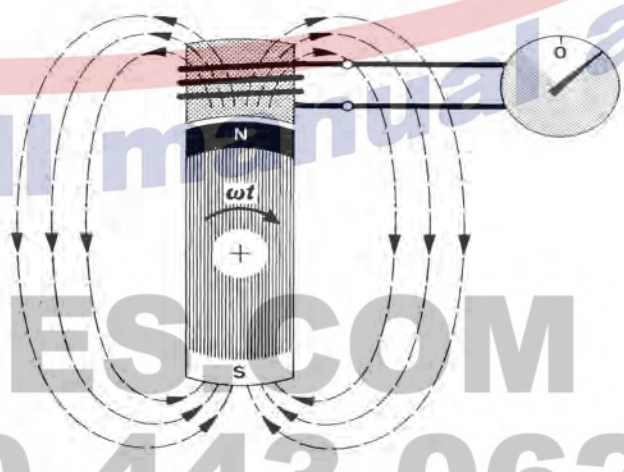

Fig. 3 When the magnetic field is reversed, the polarity of the induced voltage changes

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What is Three-Phase Current?

In an alternator, the stator consists of three windings which are spaced apart fron one another (Fig. 5). In each winding an alternating voltage is induced and an alternating current, termed ,,phase" (u, v w), flows. These windings are arranged so that the phases are equally spaced in time, which results in a phase shift of 120° (Figs. 5 and 6). The resulting three-phase alternating current is termed simply three-phase current. Three-phase current results in better utilization of the alternator than a single-phase alternating current.

The three phases are connected in a circuit using either the ,,wye" or ,,delta" configuration. Fig. 7 shows the symbols for the two methods of connection.

The two types of connection result in changes in generated current and voltage. The following relationships apply:

"Wye" connection	"Delta" connection
$I = I_p;\ U = U_p\sqrt{3}$	$U = U_p;\ I = I_p\sqrt{3}$

In the above equations p stands for u, v, w.

I = Alternator current
I_p = Phase current
U = Alternator voltage
U_p = Phase voltage
($\sqrt{3} = 1.73$)

Most Bosch alternators are manufactured with the ,,wye" configuration.

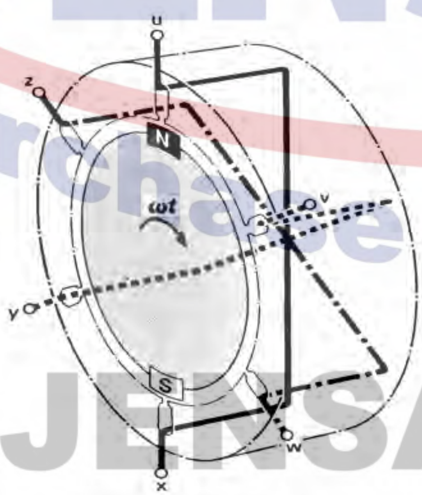

Fig. 5 Generation of three-phase current by three windings spaced 120° apart from each other

Phase voltages U_u, U_v, U_w
Degrees of rotor rotation ωt

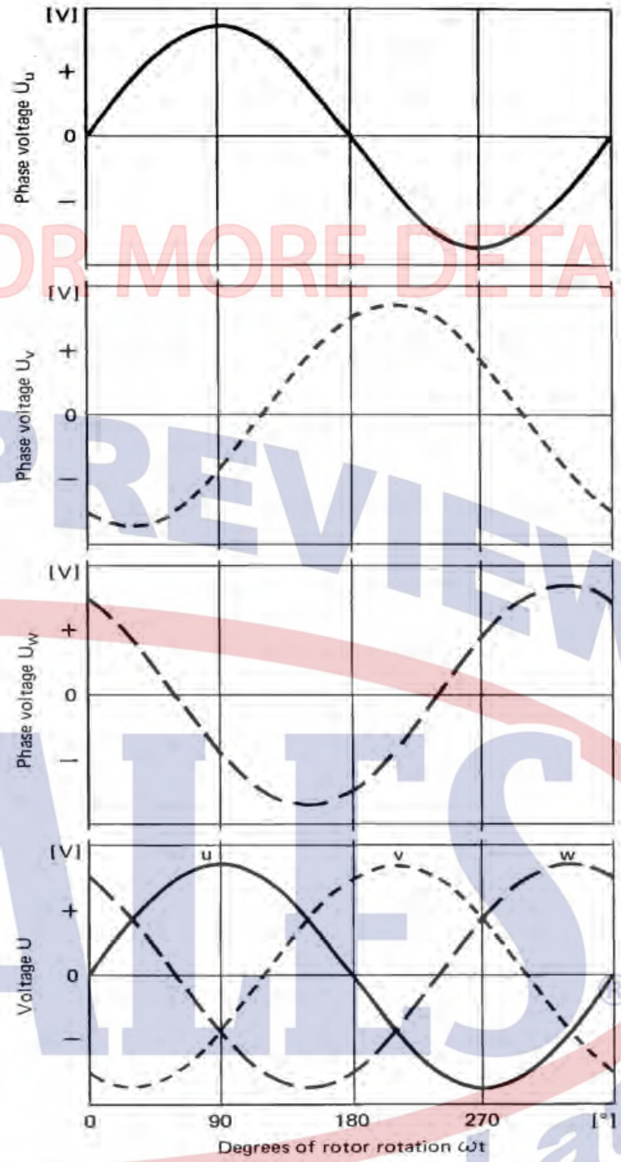

Fig. 6 The combination of the phase voltages induced in the three windings results in three-phase current

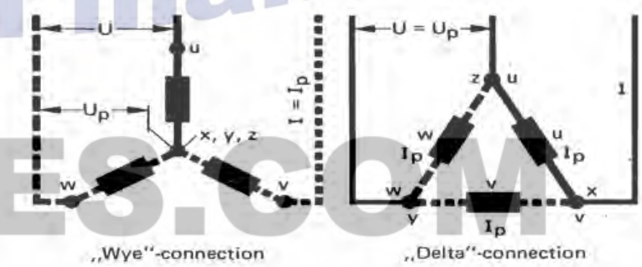

Fig. 7 Three-phase connection of the three stator windings
left: ,,Wye"-connection
right: ,,Delta"-connection

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Rectification by Semiconductor Diodes

The three-phase current generated in the stator windings must be rectified in order to charge the vehicle battery. This is done with the aid of semiconductor diodes, in this case silicon diodes. Diodes of this type (Figs. 8 and 9 show the front view, the construction and the symbol of such a diode) permit current flow in only one direction (forward direction, in the direction of the arrow) and block current in the opposite direction (inverse direction), thus acting as a rectifier and making it possible to take off direct current at the alternator terminals.

It must be realized, however, that the effective range of semiconductor diodes does have certain limits (Fig. 10). In order for silicon diodes to begin conducting, a voltage of about 0.6 V must be applied in the forward direction; the peak inverse voltage (maximum voltage that can be effectively blocked) for these diodes is approximately 100 V. This voltage range, however, is particularly suitable for the standard low-voltage systems of motor vehicles.

In automotive electrics two types of diode are used. The two diode types differ from one another internally only in that the silicon wafer (rectifying material) is mounted in the case the opposite way around. This type of construction is necessary since the diodes have only one connecting lead (Fig. 11) and their cases are secured in metal supports (see Cooling, page 23). These supports (heat sinks) are connected electrically to either the positive or negative terminal of the battery.

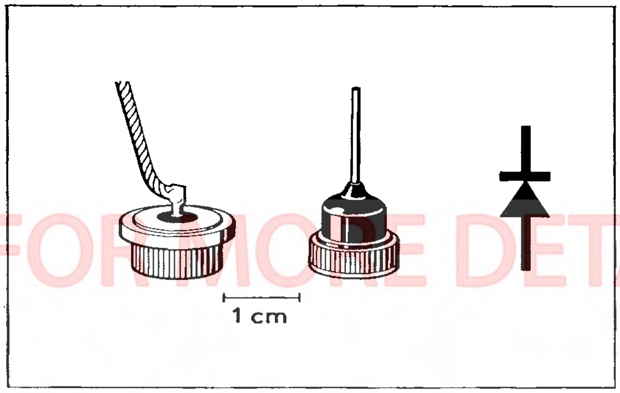

Fig. 8 Front view and symbol of silicon diodes. Glass-enclosed diode at left and cast resin diode at right

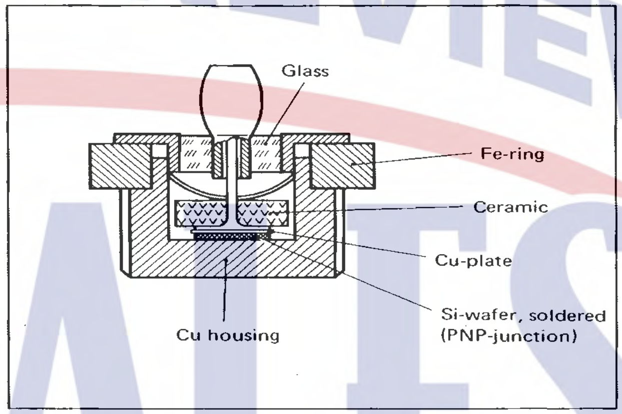

Fig. 9 Cross-sectional view of a glass-enclosed diode

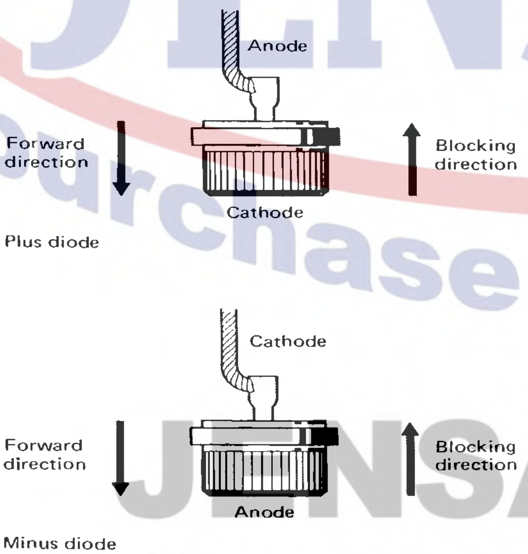

Fig. 11 Diode type
above: PN (positive) diode with cathode on case
below: NP (negative) diode with anode on case

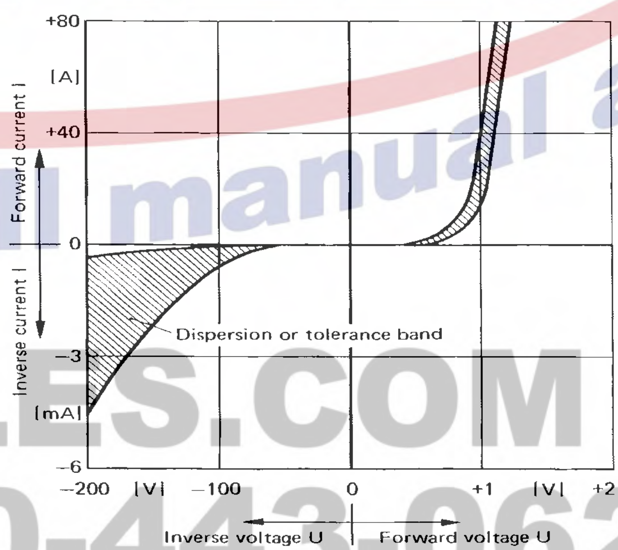

Fig. 10 Characteristics of silicon diodes

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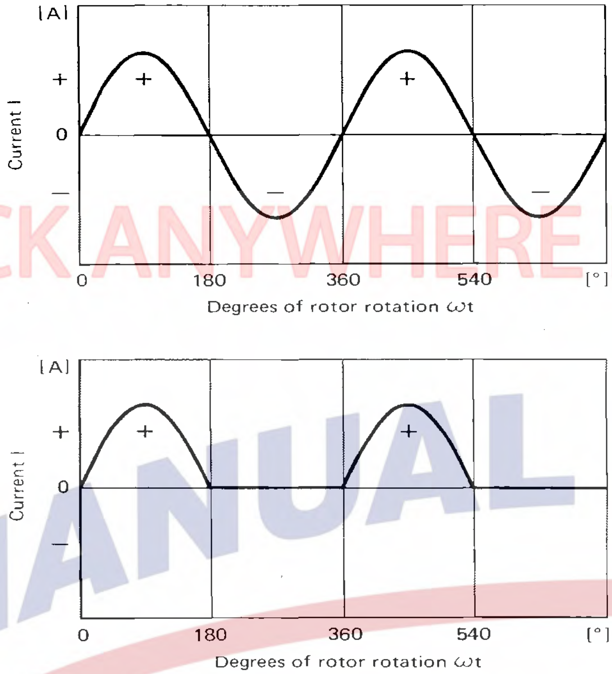

Fig. 12 Diode rectification of single-phase
in front of the diode, single-phase alternating current
after the diode, pulsating direct current

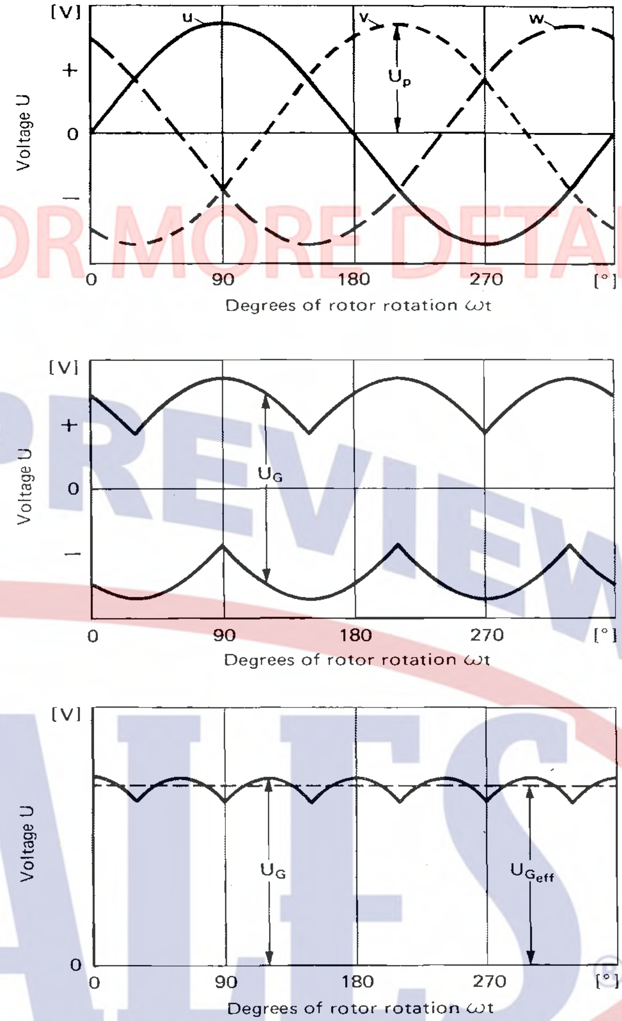

Fig. 13 Full-wave rectification

above: three-phase current
center: generation of alternator voltage
below: rectified alternator voltage (terminal voltage)

Diode rectification of one of the three alternating current phases is shown in Fig. 12. The diode blocks the negative half waves, and yields pulsating direct current.

In order to make use of both half waves of each phase (full-wave rectification), one diode per phase is secured in the positive metal support and one diode per phase is secured in the negative metal support. In all, six power diodes are required for rectification of the total alternator output (Fig. 14). This type of circuit is known as a three-phase bridge.

Fig. 13 shows the result of full-wave rectification: The three-phase AC (U_u, U_v, U_w) becomes DC with a slight ripple (U_G).

To increase the number of pole reversals per revolution, different types of rotors are used. This will be more thoroughly described in the section on alternator design.

The full-wave rectifier circuit is not only used for the output current of the alternator, but is also used for the exciter current which magnetizes the poles of the exciter field.

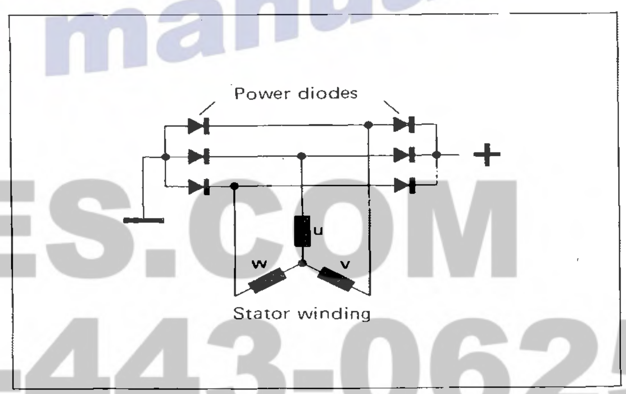

Fig. 14 Three-phase bridge circuit

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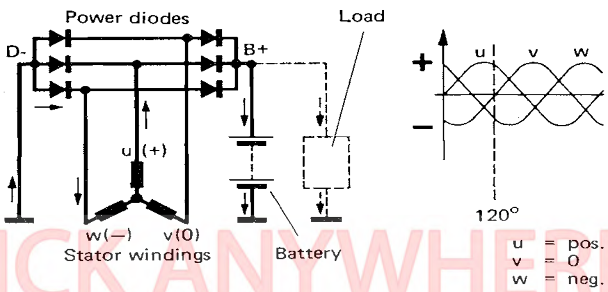

Fig. 15 Charging circuit with phase angle of phase u = 120°

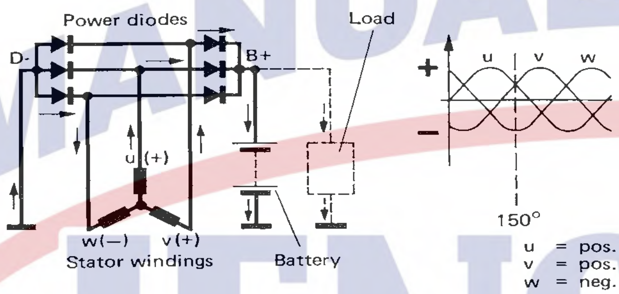

Fig. 16 Charging circuit with phase angle of phase u = 150°

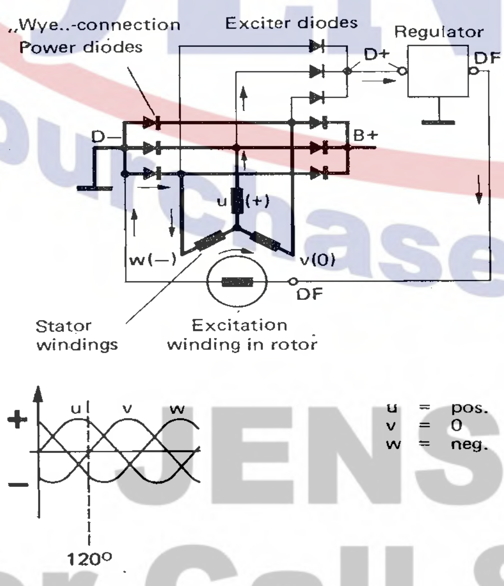

Fig. 17 Exciter circuit with phase angle of phase u = 120° (refer to Fig. 15)

In an alternator these are three separate circuits:

The charging circuit (power circuit)

The exciter circuit

The pre-excitation circuit

Charging Circuit

Current for battery charging and for the electrical accessories in the system is taken from the B+ terminal of the alternator. The flow of current for battery charging and electrical accessories is depicted in Fig. 15. The instant of time for this example is at the 120° phase angle of phase u, as shown by the dotted line on the graph to right of the wiring diagram (both half waves together are 360°). From the diagram we can see that the voltage at the winding u is positive at this instant, while it is negative at w and zero at v (no voltage). The current flows from winding u through the PN diode to alternator terminal B+.

From this terminal the current is either directed to the battery for charging, or to the electrical accessories, and is grounded. From ground the current is led back to the alternator by terminal D–, and passes through the respective NP diode to winding w, the current completes its circuit at the neutral point („wye'' center).

If a time instant is chosen where the phase angle of u is 150° the current would flow as in Fig. 16. In this case none of the phases are at zero and currents of equal magnitude flow from the windings u and v to the corresponding PN diodes and return to the neutral point („wye'' center) through the respective NP diode and winding w. Note that not all the diodes belonging to the various phases are used at the instant of time examined in this example. This remains true for all the other innummerable instants of time which could be examined. Individual phase currents change in magnitude and polarity, while the output current to the battery or electrical accessories maintains its uniform direction.

Exciter Circuit

The exciter current for generation of the magnetic field is tapped from the stator winding and is rectified by three special exciter diodes and the three NP power diodes. The exciter current follows the path shown in Fig. 17. From winding u (positive at this instant of time), through its corresponding exciter diode and the alternator terminal D+ to the voltage regulator terminal D+. The current is led from the regulator terminal DF to the excitation winding via terminal „DF'' of the alternator, and goes by way of the alternator terminal D– and the NP power diode to winding w (negative at this instant of time) completing its circuit at the neutral point („wye'' center).

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Pre-excitation Circuit

Bosch alternators are usually self-exciting, that is, the exciter current is obtained from the alternator itself by tapping from the main current. But how is excitation, or rather the build-up of a magnetic field, possible when the alternator is started from a standstill and no exciter current is flowing? This question can be answered by the principle of „residual magnetism" or „remanence". When the current of an electromagnet is disconnected, the magnetic field does not disappear completely, the iron core remains slightly magnetic (Fig. 18). If the alternator is driven by the vehicle engine, the residual magnetism in the core is sufficient to induce a small EMF in the stator windings. This small EMF causes a weak current to flow through the closed circuit of the excitation winding. This current produces a weak magnetic field of its own which is added to the residual magnetism of the core and slightly boosts the intensity of the exciter field. A boosted exciter field results in a higher EMF, the effect is cumulative and the process repeats itself until the desired EMF, corresponding to the alternator speed is reached.

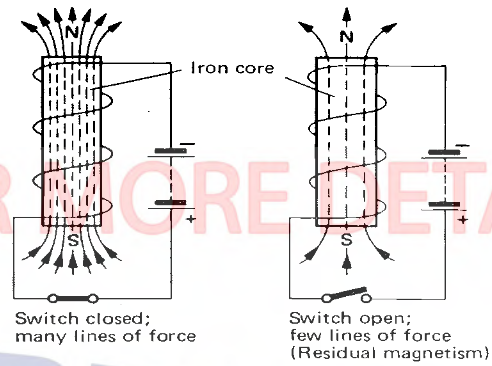

Fig. 18 Residual magnetism (remanence)

The exciter circuit in an alternator contains two diodes. Therefore, self-excitation cannot start until the induced EMF is 2 x 0.6 V = 1.2 V (i.e. the total voltage required by the two diodes to pass current in their forward direction (Fig. 10).
The existing residual magnetic field of the rotor generates this voltage only at high speed. Therefore, it is advantageous to pre-excite the alternator during start-up. This is done by drawing current from the battery via the charge indicator lamp. When the ignition switch is turned on, the pre-exciter current flows (Fig. 19) from the positive terminal of the battery through the ignition switch and charge indicator lamp to terminal D+ of the regulator. The current then goes from the regulator to the excitation winding where it is grounded and returned to the negative side of the battery.

By using a charge indicator lamp with a sufficiently high current draw, the current, which also passes through the excitation winding produces a magnetic field strong enough to start self-excitation of the generator.

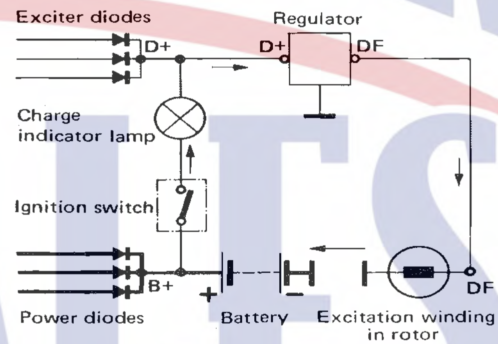

Fig. 19 Pre-excitation circuit

Alternator Designs

Basic Construction

The basic construction of an alternator consists of a three-phase stator winding (stationary conductor); a rotor (armature) with a shaft that carries the magnet poles and excitation winding as well as (in the majority of designs) two slip-rings. The rotor shaft is supported at both ends by bearings which are built into the ends of the alternator housing. Six power diodes, three exciter diodes, and finally two carbon brushes complete the basic unit. (The carbon brushes press against the slip-rings. Exciter current flows from the stator winding to the revolving excitation winding by means of the brushes and slip-rings). Terminals are provided on the alternator for connection to the vehicle electrical system.
Alternators can be rotated in either direction because current reversal, as required by a DC generator when rotated backwards, is not necessary. The direction of rotation for an alternator is pre-determined only by the type of fan disc used for cooling.

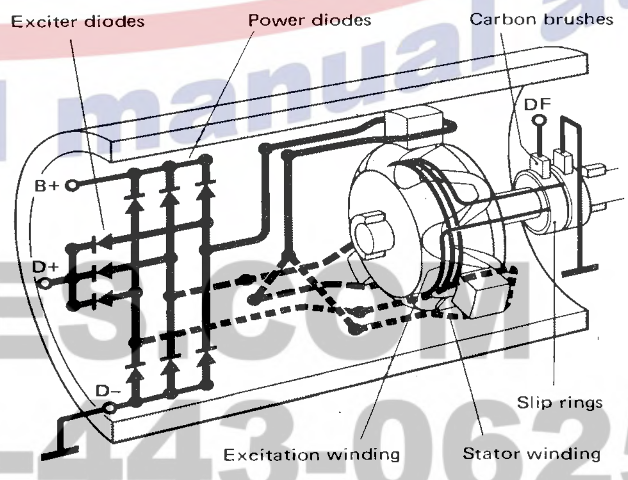

Fig. 20 Basic construction of an alternator

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The development (taking into particular consideration economy, low maintenance requirements and production costs) from theoretical principles into a product suitable for practical application resulted in a series of basic designs. These designs differ in performance and overall dimensions but above all in rotor shape.

Four basic Bosch designs are currently available:

Claw-pole alternator with slip-rings

Single-pole alternator with slip-rings

Claw-pole alternator with exciter (without slip-rings)

Alternator with permeable rotor (without slip-rings)

Claw-pole Alternator with Slip-rings

The name of this type of alternator is derived from the shape of the rotor. It consists of two claw-pole halves, whose claws interlace (Fig. 23), and which envelop the toroid-shaped excitation winding. Each half has six claw-shaped poles, this results in a total of 12 poles (6 north poles and 6 south poles (Fig. 22). A magnetic field exists between the poles (Fig. 21). The lines of force cut each of the three stator windings as the rotor turns. Twelve pole passes occur during one full rotor revolution (360°). Each pole passage induces a voltage halv-wave which is either positive or negative depending on the polarity of the pole. Therefore in one revolution of the rotor a total of 12 x 3 = 36 half waves are induced in the three windings of the stator. By comparison a two-pole rotor would only induce six half waves (Fig. 24).

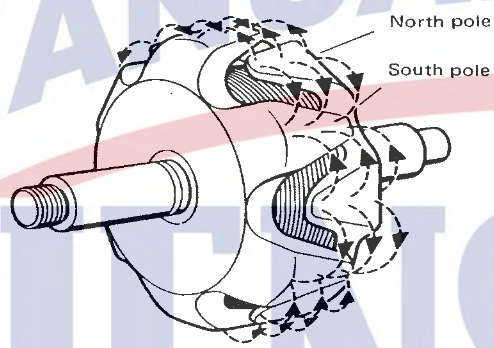

Fig. 21 Lines of force of a claw-pole rotor with 12 poles

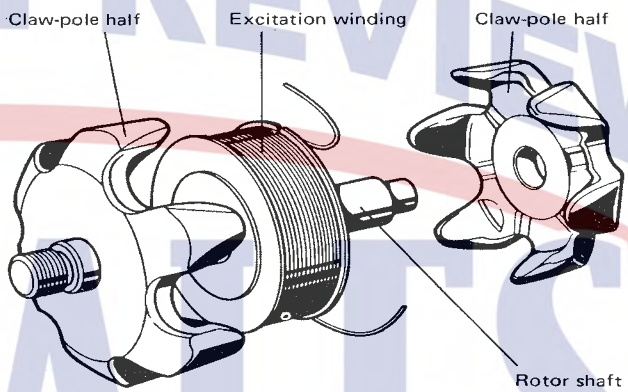

Fig. 23 Parts of a claw-pole rotor

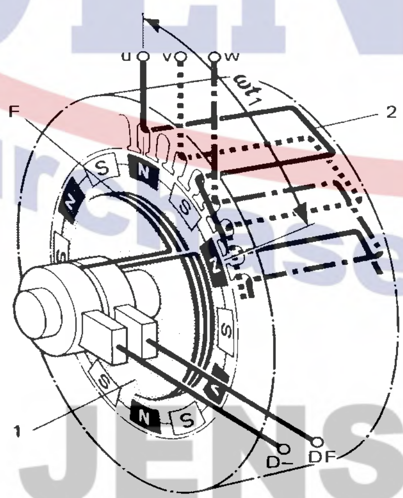

Fig. 22 Principle of the claw-pole alternator

Stator windings u, v, w
F = Excitation winding
ωt_1 = 1 phase
1 = Rotor
2 = Stator winding

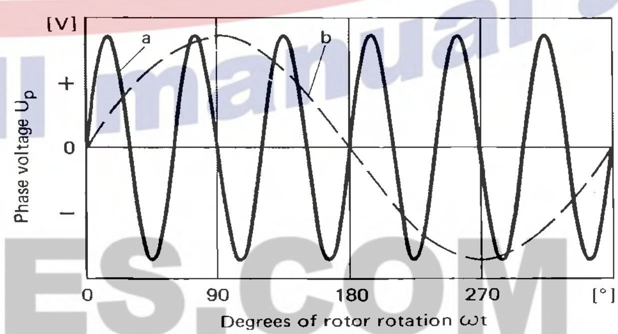

Fig. 24 Induced voltage in one phase during one revolution of the rotor

a) 12-pole rotor
b) 2-pole rotor

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