Improving alternator efficiency measurably reduces fuel costs

By Mike Bradfield

Electrical power on a vehicle is not free. It comes as a direct result of consuming fuel within the engine to drive the alternator. With a typical engine efficiency of 40 percent, a belt efficiency of 98 percent and an alternator efficiency of 55 percent, this leads to an overall energy conversion efficiency of only 21 percent. Assuming a fuel cost of $4/gal., this leads to an on-board electrical power cost of $0.51/kWh, or roughly four times a typical household utility rate. Consequently, the fuel costs associated with providing electric power can be quite significant and should no longer be ignored.

This article addresses the topic of how improving alternator efficiency can combat this problem by measurably reducing fuel cost. First, a fundamental overview of how an alternator works is given. Each of the major power related elements of the alternator are reviewed: rotor, stator, rectifier and voltage regulator. Next, an inside look at where the actual power losses occur within the alternator is examined. This includes electrical losses, magnetic losses and mechanical losses. This is followed with a discussion on the topic of alternator efficiency from an overall machine standpoint.

Prepped with the preceding information, case studies of three different real-world applications are completed for a line haul tractor, city tractor and school bus. Real-time operating data was collected on each of these applications for the overall vehicle and electrical system. This measured data serves as the baseline for each of these three studies. The following chart shows the fuel cost savings possibly over a typical life cycle by increasing the alternator efficiency 20 percent over the baseline condition.

Application	Average Current	Fuel Cost with Base Efficiency	Fuel Cost with a 20% Improvement in Efficiency	Fuel Savings with Higher Efficiency
Line Haul Tractor	84 amps	$4534 / 500k mi	$3778 / 500k mi	$756 / 500k mi
City Tractor	40 amps	$2235 / 350k mi	$1863 / 350k mi	$372 / 350k mi
School Bus	102 amps	$9040 / 250k mi	$7533 / 250k mi	$1507 / 250k mi

What may not be obvious from this chart is the fact that an efficient alternator on a commercial application can more than pay for itself in less than one year. Over the life of the vehicle, these savings can reach thousands of dollars.

A wide range of efficiencies exists between current production manufacturers and even from within a given manufacturer's portfolio of products. Peak efficiencies at full output vary from 55 percent to almost 80 percent. With the high price of fuel, fleet and vehicle owners should no longer ignore this important parameter. Increasing alternator efficiency can, and will, measurably reduce fuel costs.

The energy conversion chain

Electrical power on a vehicle is not free. This power comes as a direct result of fuel being consumed within the engine to feed an energy conversion chain.

This chain, as depicted below, starts with chemical energy stored in the fuel and ends with electrical energy from the alternator. Along the way there are power losses associated with every energy conversion process, including the alternator.

These losses result in *more fuel being consumed to produce a given amount of electrical power*. Clearly, as the alternator becomes more efficient in the process of converting mechanical power into electrical power, less fuel is consumed. And even though the power demands of the alternator are generally small in comparison to the overall vehicle, the impact on fuel cost is not trivial.

In fact, with today's high fuel prices, changes in alternator efficiency can measurably impact fuel operating cost as we shall see later. (See Figure 1).

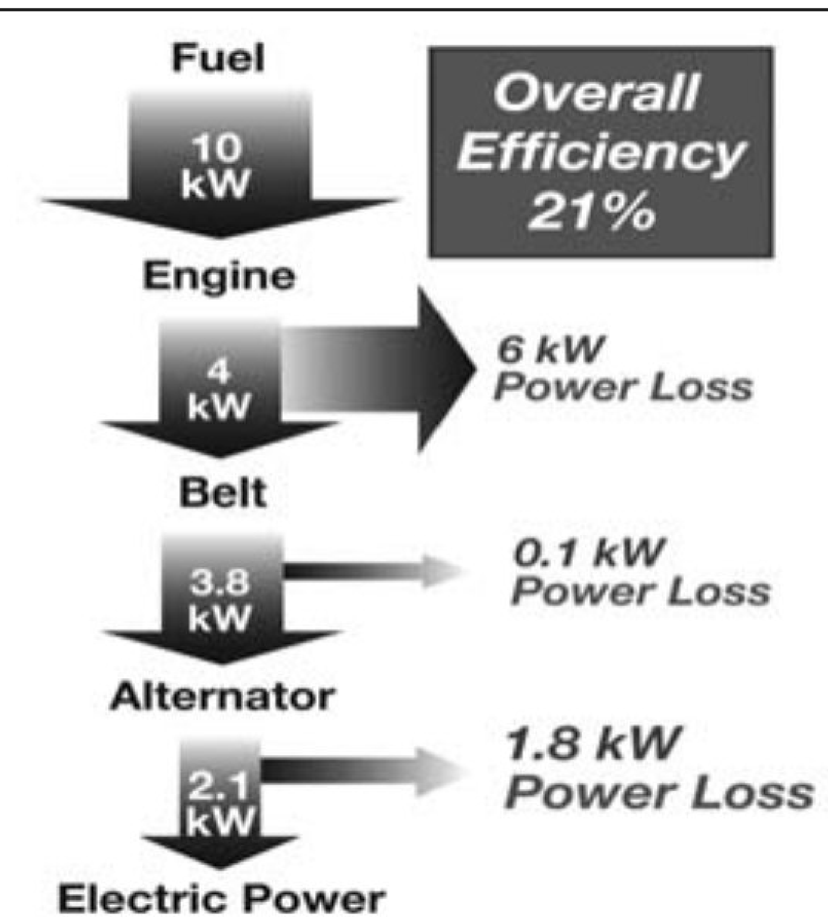

Figure 1 — Energy conversion chain.

Engine efficiency

To understand how improving alternator efficiency reduces fuel usage, we will examine each element of the energy conversion chain starting with the engine and ending with the alternator.

The engine combusts fuel to convert the stored chemical energy of the fuel into thermodynamic pressure. This pressure does expansion work within the cylinder of the engine creating linear power. It is converted into rotational power by the connecting rods and crankshaft.

The conversion of fuel chemical energy into rotating mechanical power by the engine is accompanied with power losses. These losses, and therefore the efficiency, are dependent upon a number of factors including engine speed and mechanical load.

Often engine efficiency is reported as brake thermal efficiency. This is simply engine efficiency as measured on an engine dynamometer (brake). The efficiency of the engine may be expressed as:

Where

$$\eta = \frac{P_{engine\ out}}{P_{engine\ in}}$$

$P_{engine\ out} = P_{engine\ in} - P_{losses}$

η = engine efficiency

$P_{engine\ out}$ = mechanical power output

$P_{engine\ in}$ = fuel energy input

P_{losses} = engine power losses

The following efficiency map depicts the engine efficiency as a function of engine speed and brake mean effective pressure (BMEP). BMEP is a theoretical number expressing the average pressure inside the engine cylinder over a complete cycle. BMEP is an indication of the mechanical torque of the engine.

As shown in Figure 2, engine efficiency ranges from 34 to 42 percent depending on the operating conditions.

Only a portion of the total engine output power is needed for input power to the alternator. An even smaller portion of this power is needed to account for alternator losses.

Consequently, changes in losses in the alternator do not significantly alter the overall efficiency operating point of the engine. Therefore, from an analysis standpoint, engine efficiency can be assumed to be unaffected by changes in alternator losses.

At this point it's worth expanding upon a few finer points relating to the correlation between the fuel consumption of the engine to the electrical power delivered by the alternator. In the truest sense of the word, the operating condition of the engine and alternator is not steady-state.

Dynamic changes in speed, load and operating conditions are constantly occurring that impact the correlation between fuel usage and electrical power. For instance, during deceleration periods for the engine, such as when the vehicle is slowing down, an incremental power load of the alternator on the engine does not equate to an increase in fuel usage. Essentially this power is "free." Conversely, during engine accelerations, the rotational inertia effects of the alternator will increase the power demand, and therefore fuel demand on the engine.

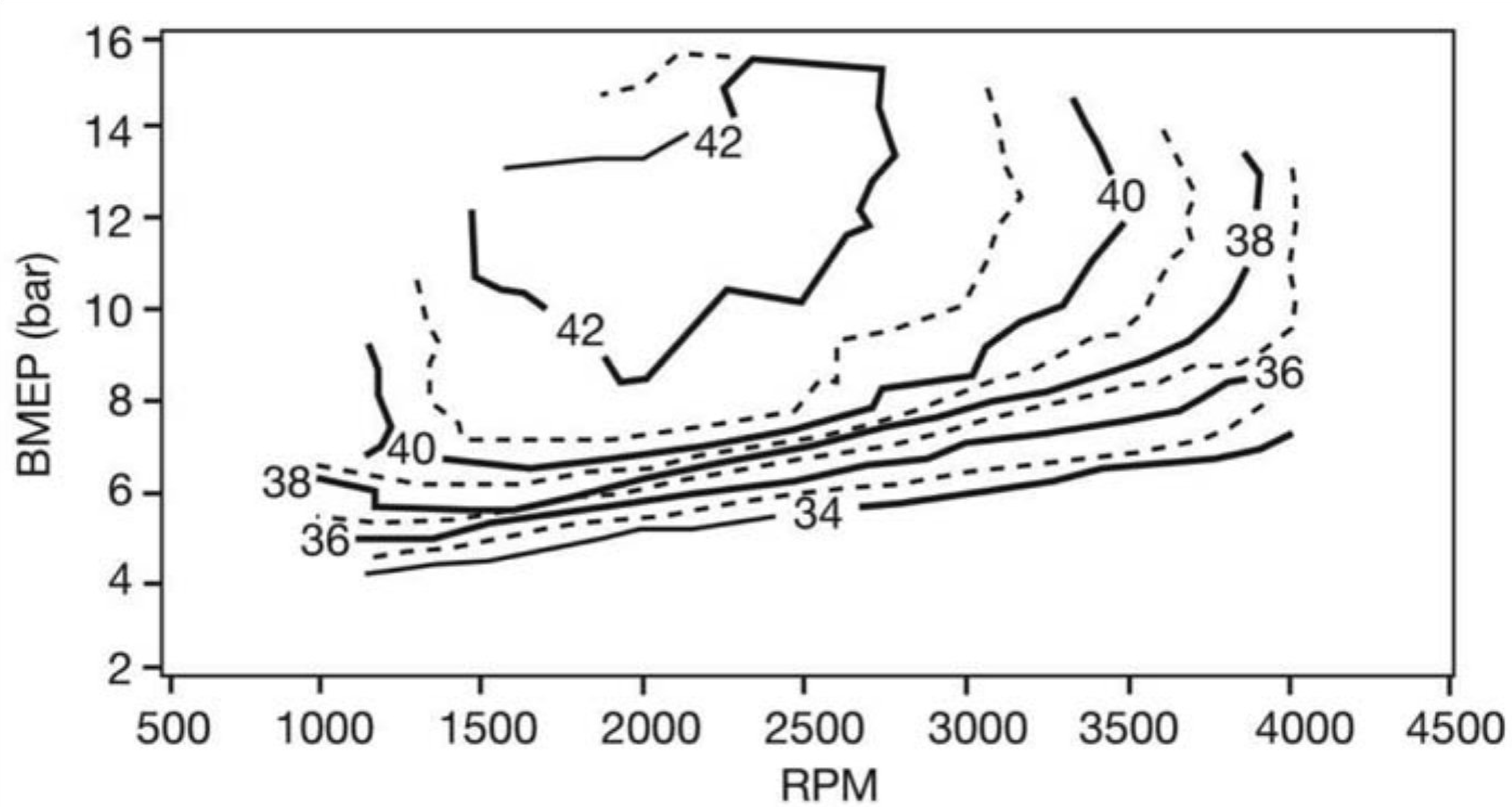

Figure 2— Brake thermal efficiency as a function of engine load an speed.

Having said that, however, as a first order approximation, it is useful to think of the engine-alternator interaction as steady-state operation where an incremental increase in alternator loading will cause an incremental increase in fuel usage according to the engine efficiency map. For a diesel engine, typical engine efficiency is 40 percent.

Belt efficiency

The next element in the power conversion chain is the flexible drive belt. Even the belt has losses associated with it as it transfers the rotational energy from the engine crank pulley to the alternator drive pulley.

Frictional losses occur both within the belt itself and at the belt-pulley interface. Generally speaking, these losses are small in comparison to the overall energy transferred, but nonetheless they do occur and cause additional fuel usage.

Belt efficiency is defined by the ratio of power delivered to the alternator to the power input by the engine and is typically 98 percent. (See Figure 3).

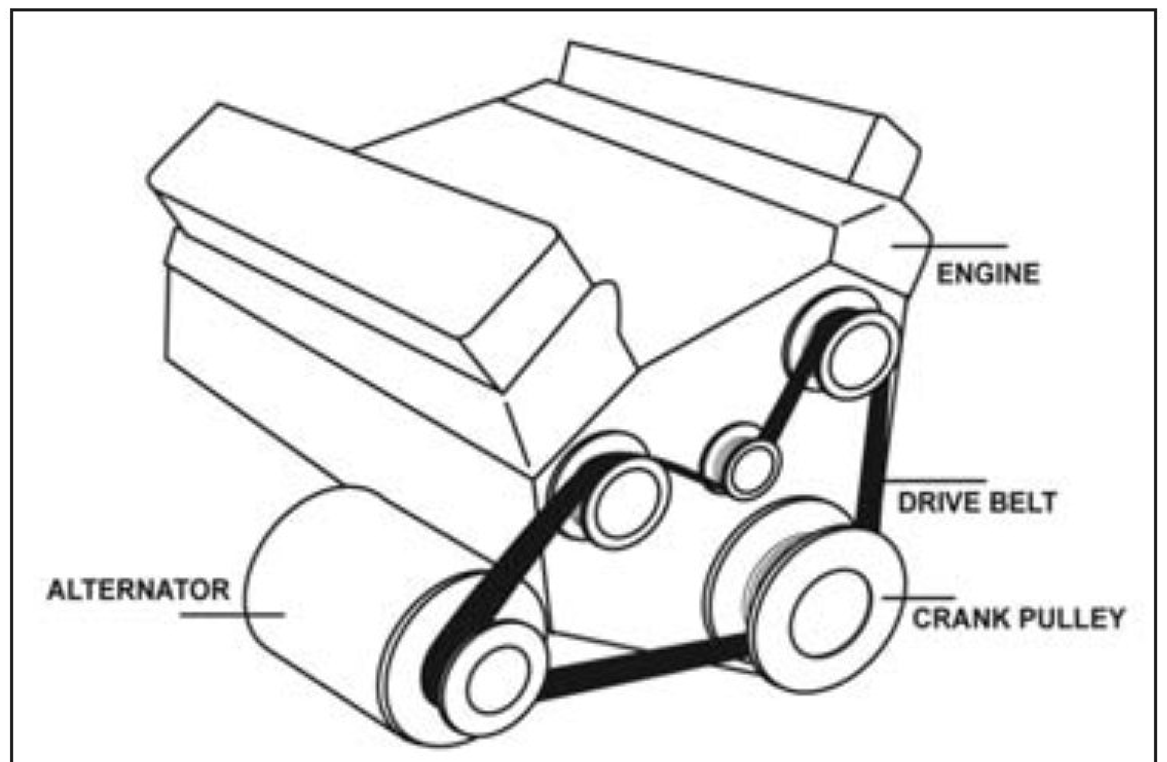

Figure 3— Accessory drive belt diagram.

How an alternator works

Now we are ready to undertake the alternator in this power conversion chain. Rather than simply jump straight into alternator efficiency, first examine how an alternator works. (See Figures 4 and 5).

Simply stated, an alternator is a synchronous AC electric generator with DC diode rectification and pulse width modulation voltage control. However, unless you are an electrical machine designer, that probably means nothing to you. So let's break an alternator down into its essential power producing elements. These are the rotor, stator, diode rectifier and voltage regulator. (See Figures 6 and 7).

Rotor

The heart of an alternator is the rotor. It provides the rotating magnetic field that makes electrical power production possible. The essential elements of the rotor are the field coil winding, an iron core, two

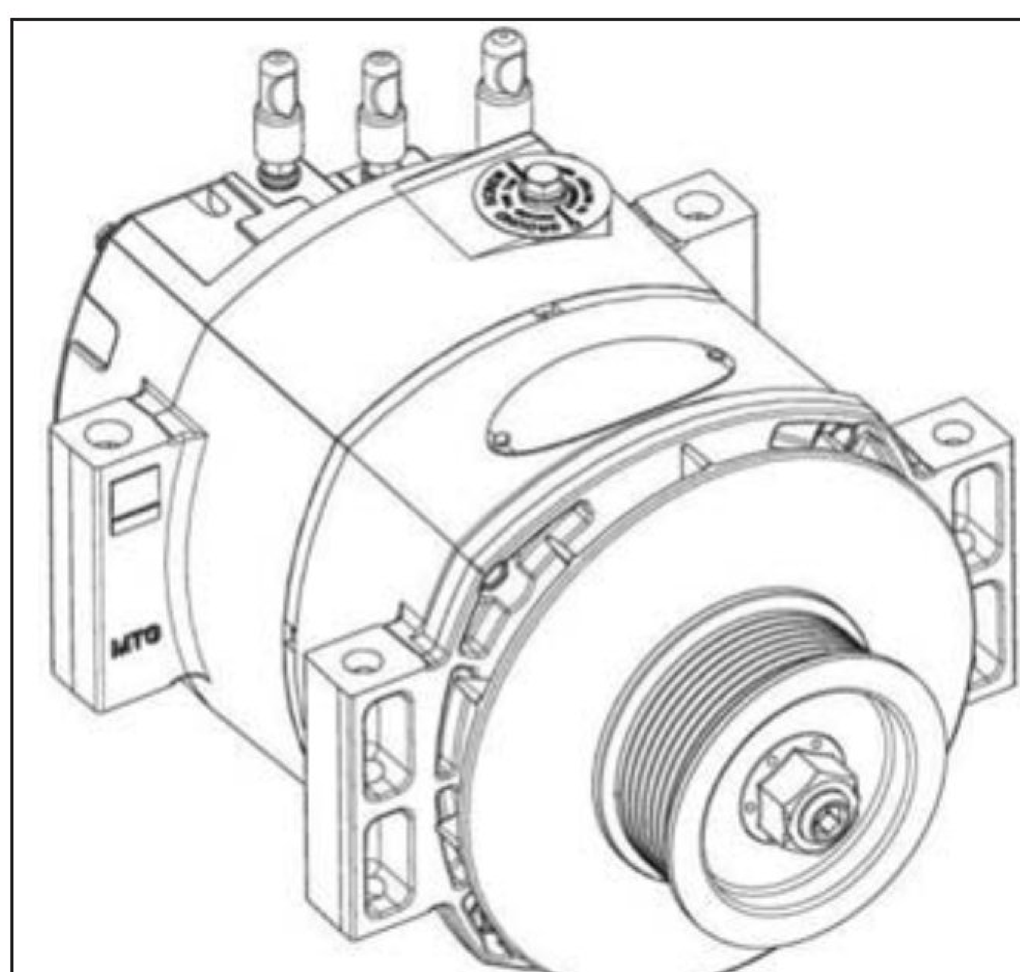
Figure 4— Alternator front view.

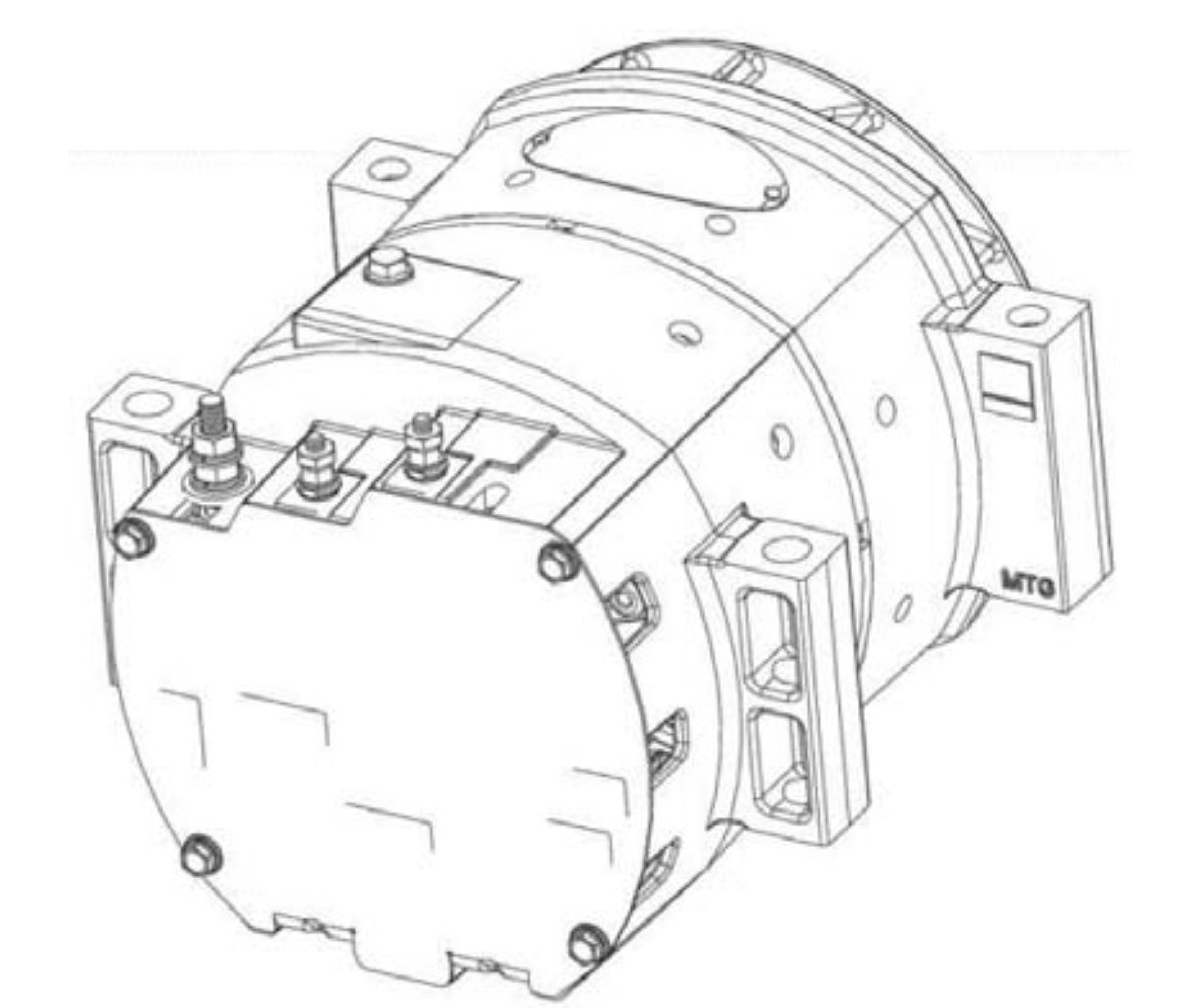

Figure 5— Alternator rear view.

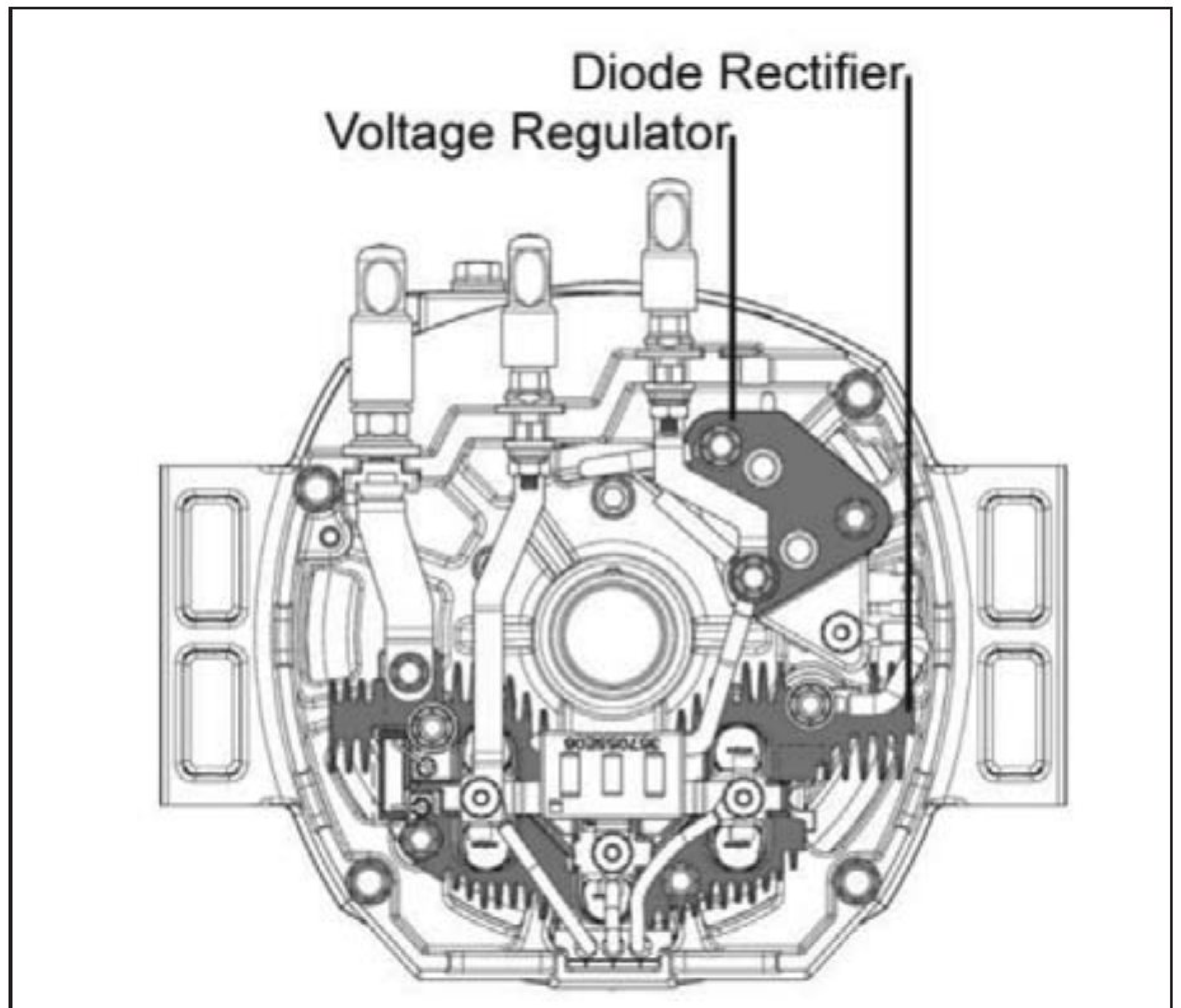

Figure 6—Regulator and rectifier.

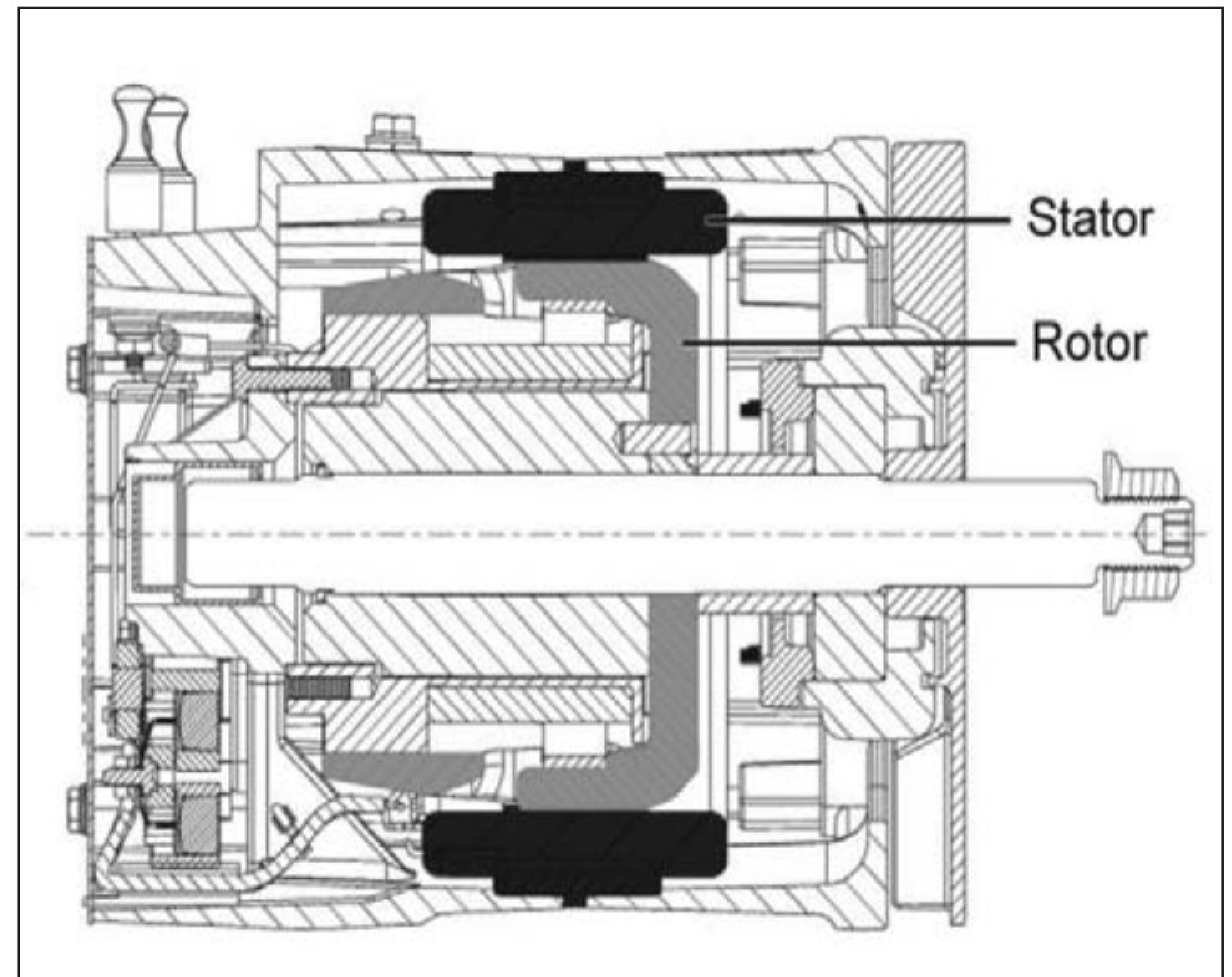

Figure 7— Rotor and stator.

iron segments that are claw-shaped in appearance (hence the term claw pole alternator), and a shaft. (See Figure 8).

The field coil winding typically consists of 300 to 500 tightly wrapped coils of round, insulated copper wire wound over an iron core. A DC current, typically 2 to 5 amps, flows through this coil and is controlled by the voltage regulator. Current flowing through a coil of wire that is wound over an iron core in this fashion produces a strong electromagnet with a North (N) and South (S) magnetic pole.

Channeling the magnetic flux produced from this electromagnet to the appropriate surface on the stator are the two claw pole iron segments. Since the current in the field winding is DC, one segment is always magnetic N and the other magnetic S. Further, since the claw poles of the two segments are interlaced, this results in an alternating N pole, S pole arrangement. Further still, since the segments are attached to the alternator shaft, as the shaft is rotated, the magnetic field that the stator experiences at any fixed point alternates between N and S in a cyclical or AC fashion. Therefore, although the magnetic field in the rotor is always DC, it produces an AC magnetic field in the stator. (See Figure 9).

Stator

Now we are ready for the stator. The stator is stationary and is where the mechanical-to-electrical energy conversion takes place within the alternator. The stator consists of an iron core and copper windings. The iron core completes the magnetic circuit created by the rotor. Tooth-like structures, hence the name teeth, extend radially inward from the outer diameter of the stator core. These teeth face the rotor poles and provide an

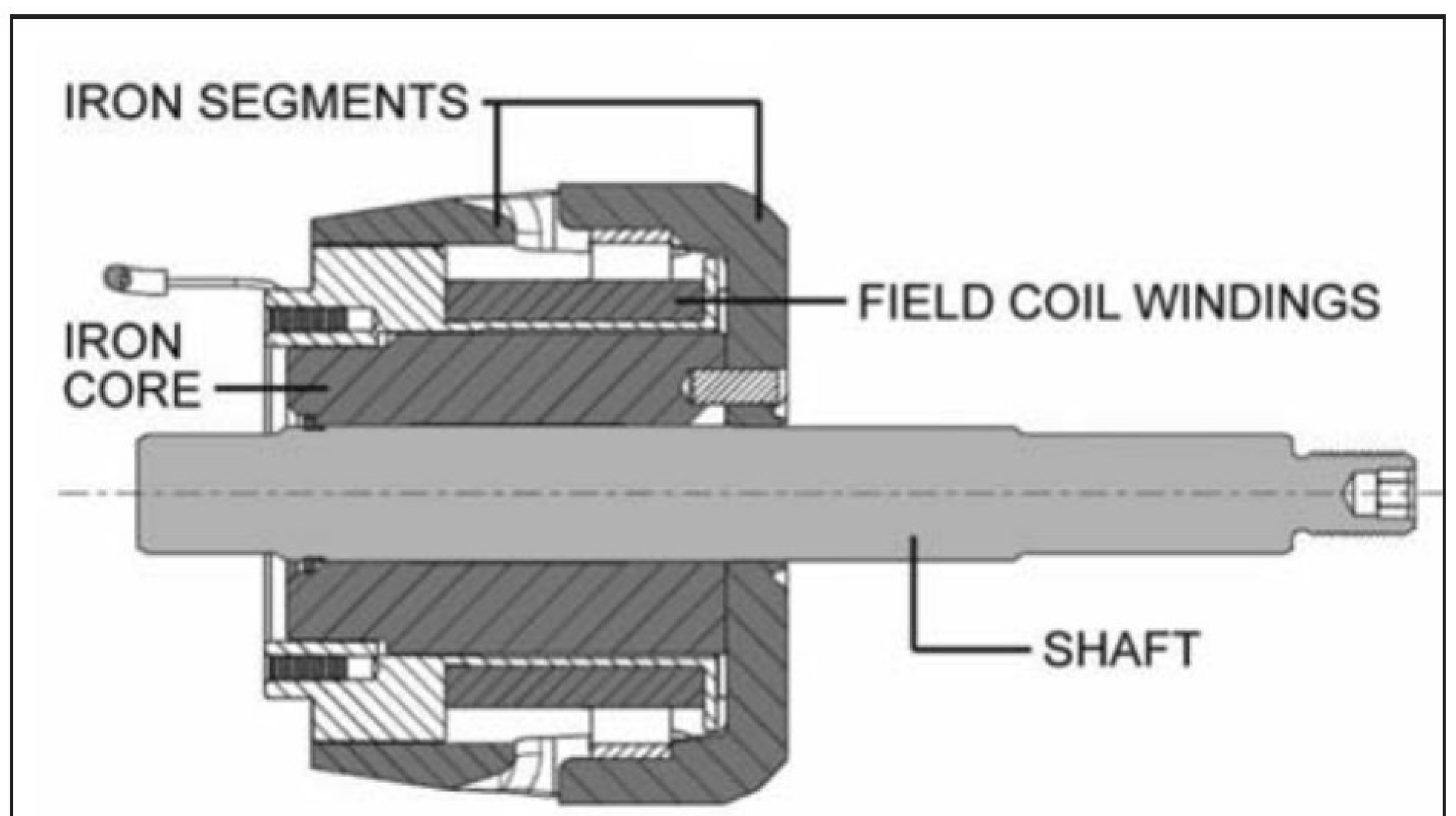

Figure 8— Rotor.

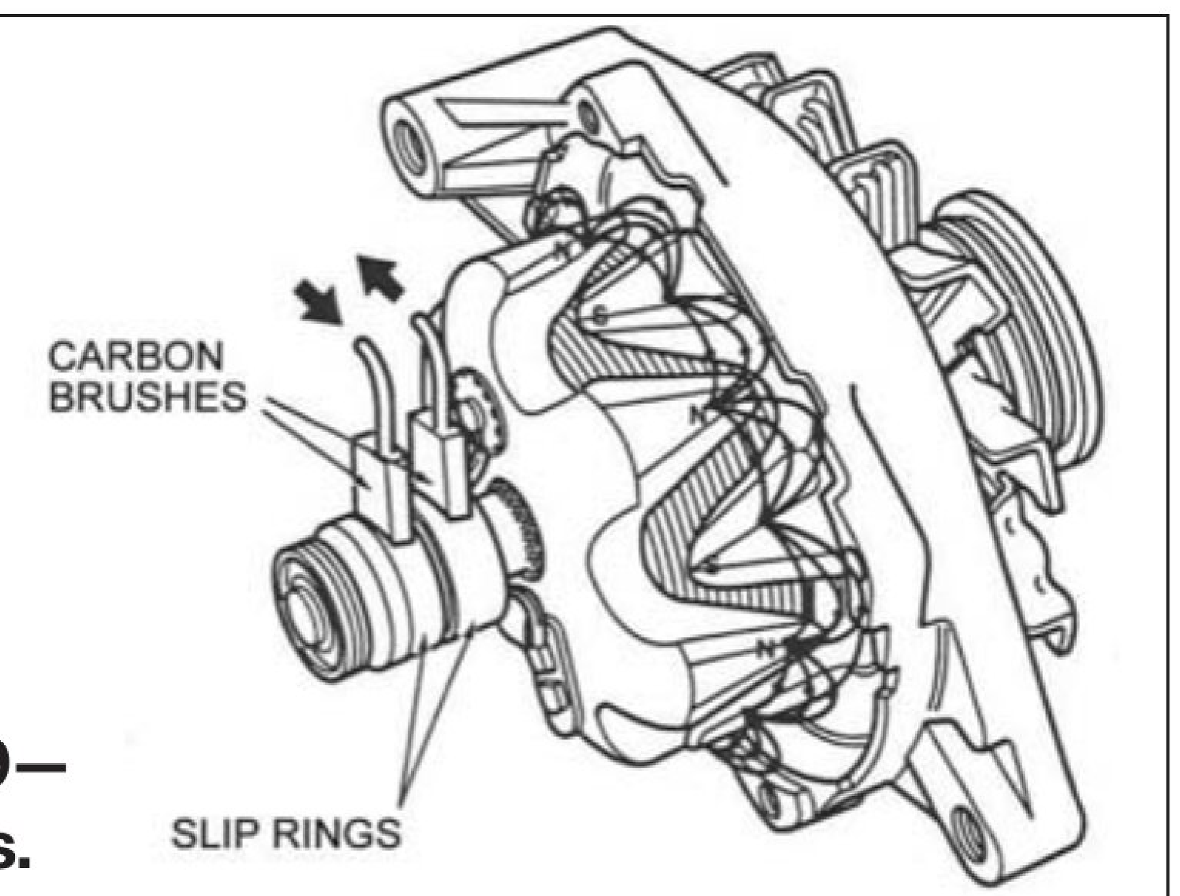

Figure 9— Brushes.

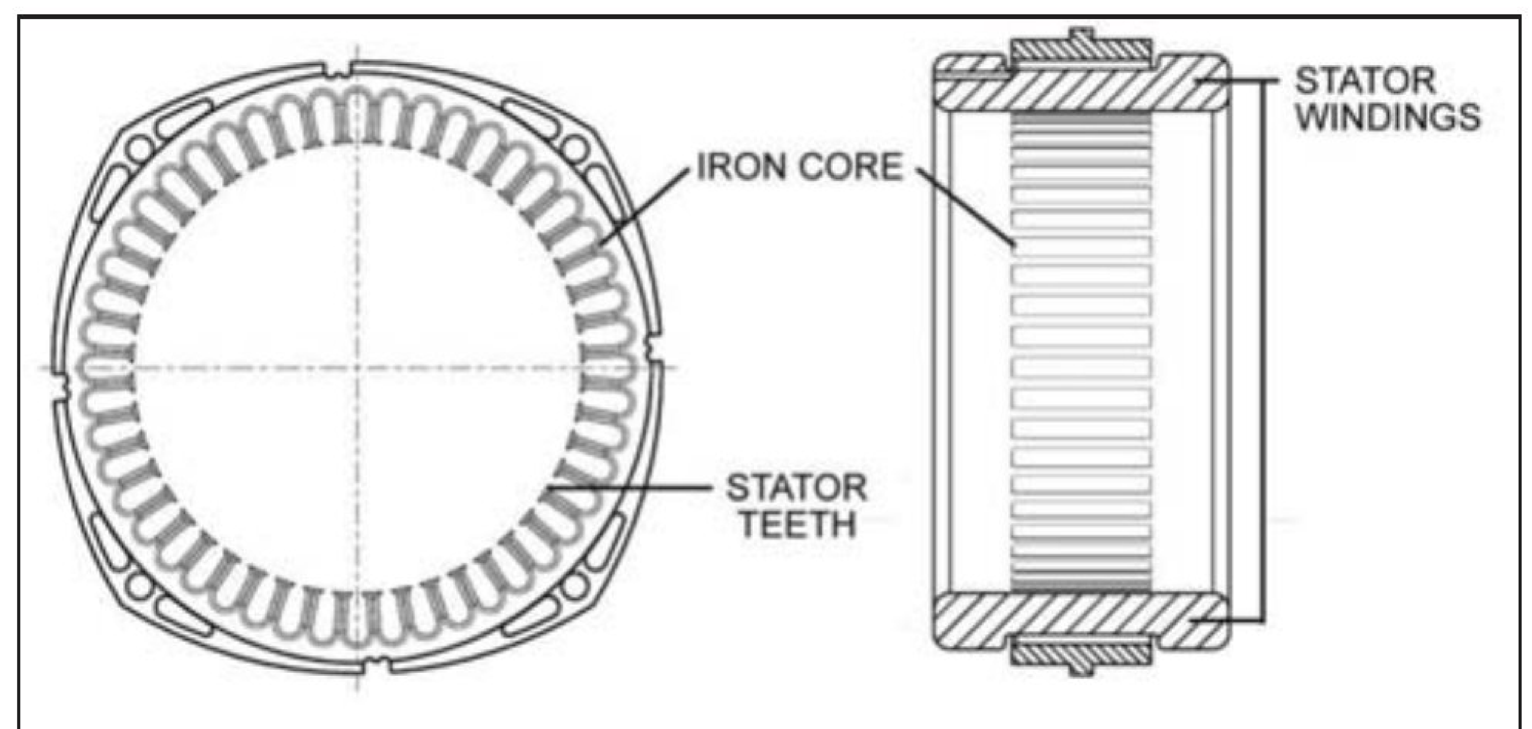

Figure 10 — Stator (illustration on left shows stator without windings).

iron magnetic path that connects the N and S poles of the rotor via the stator. (See Figure 10, page 23).

Besides funneling and channeling the flux through the stator, these teeth house the stator windings. The stator windings are insulated copper wires that are formed into coils and inserted into the empty slots between adjacent teeth.

When the rotor rotates with DC current flowing in the field winding, it will produce an AC magnetic flux in the stationary stator. (See Figure 11). This time varying flux that links the rotor and stator serves to induce a voltage in the stator wire according to Faraday's law:

Where

$$e = -N_C\left(\frac{d\Phi}{dt}\right)$$

e = voltage induced in conductor

N_C = number of conductors in series

$\frac{d\Phi}{dt}$ = time rate of change of flux

This relationship describes the voltage induced in each length of the stator wire located in the slots. Since the voltage induced in the stator wire is directly proportional to the number of conductors in series, typically the stator wire will be coiled multiple times through each slot to increase N_C and thereby increase the voltage induced in the total length of wire. There are design reasons limiting the optimum number of conductors per slot, but is beyond the scope of this article.

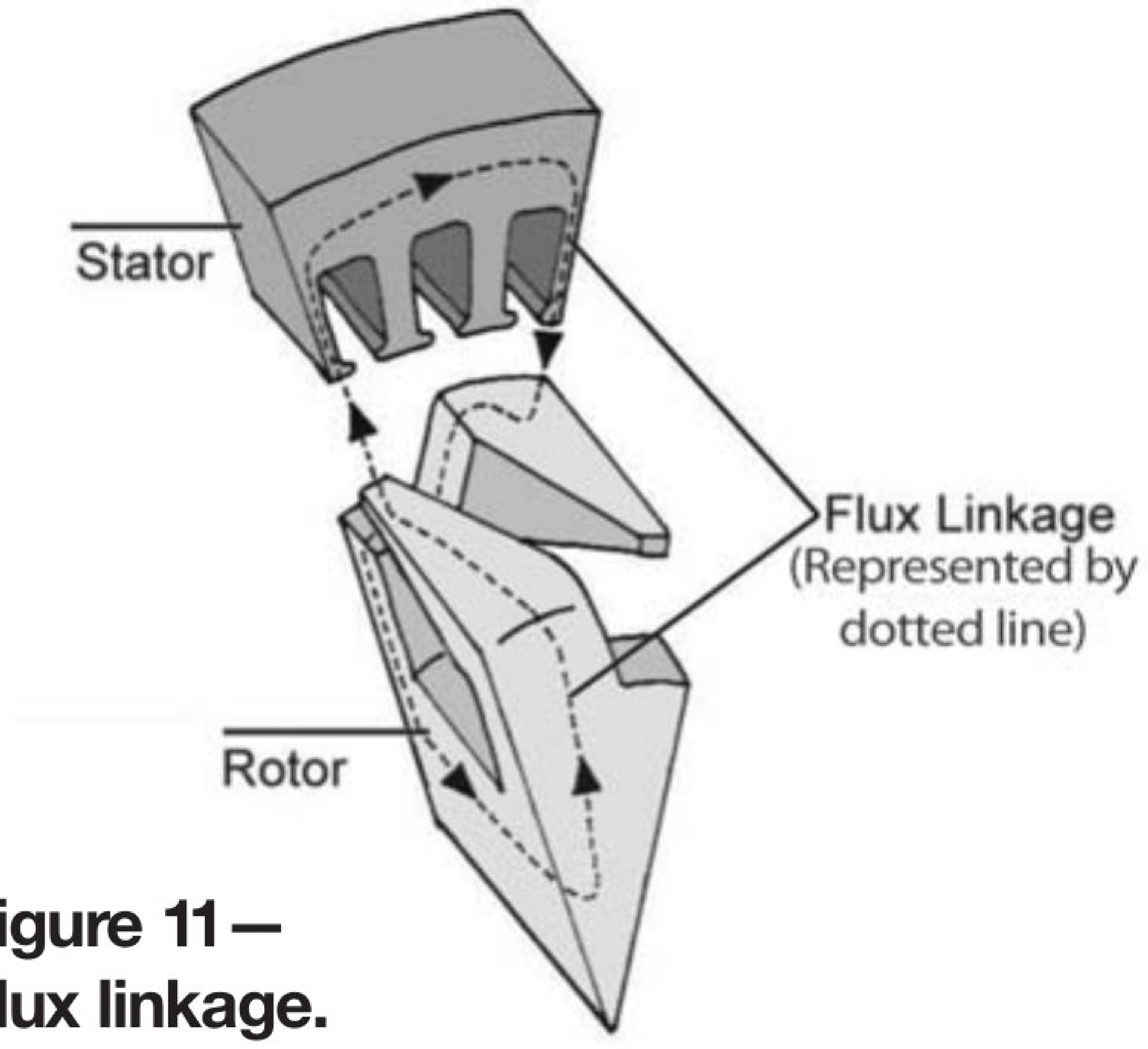

Figure 11— Flux linkage.

If only one stator wire or winding were used in this manner we would end up with a single phase machine. However, this is not an efficient use of the machine space and iron circuit. Consequently, almost all alternators employ three stator windings to create a 3-phase machine.

Rectifier

Since the electrical power produced by the stator and rotor is AC, it is necessary to convert it to DC to be compatible with the electrical system of the vehicle, most notably the batteries. This brings us to the diode rectifier. The diode rectifier takes the AC electrical power coming from the stator and converts it to DC electrical power. (See Figure 12).

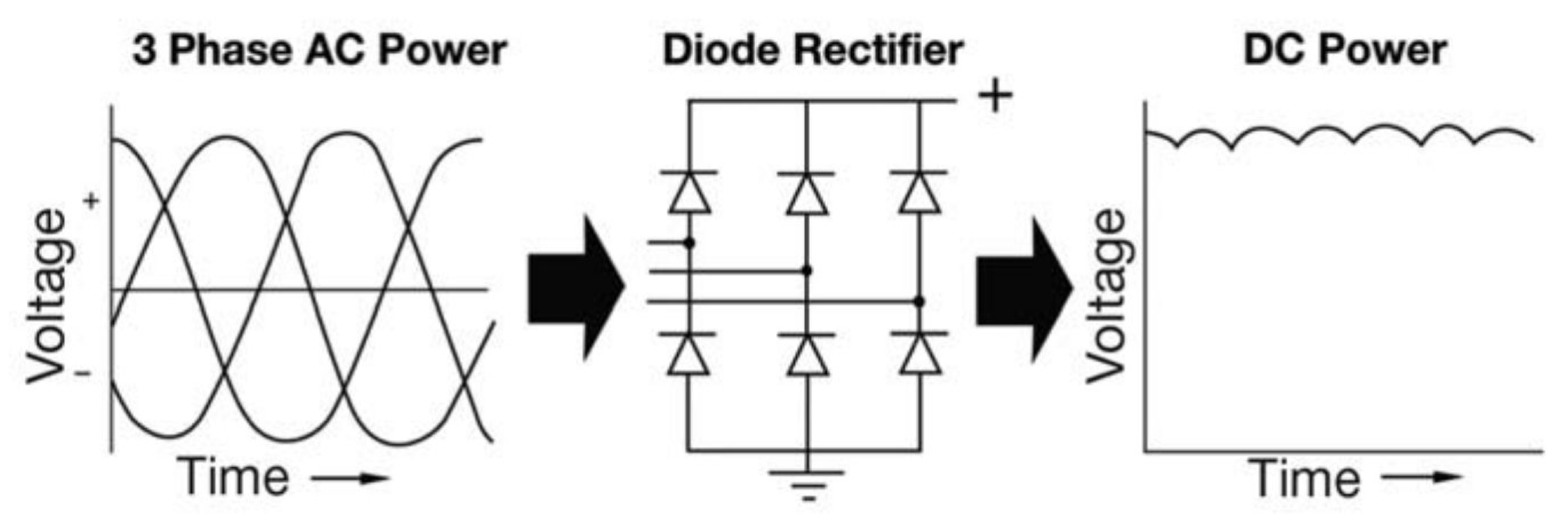

Figure 12— AC power converted to DC power.

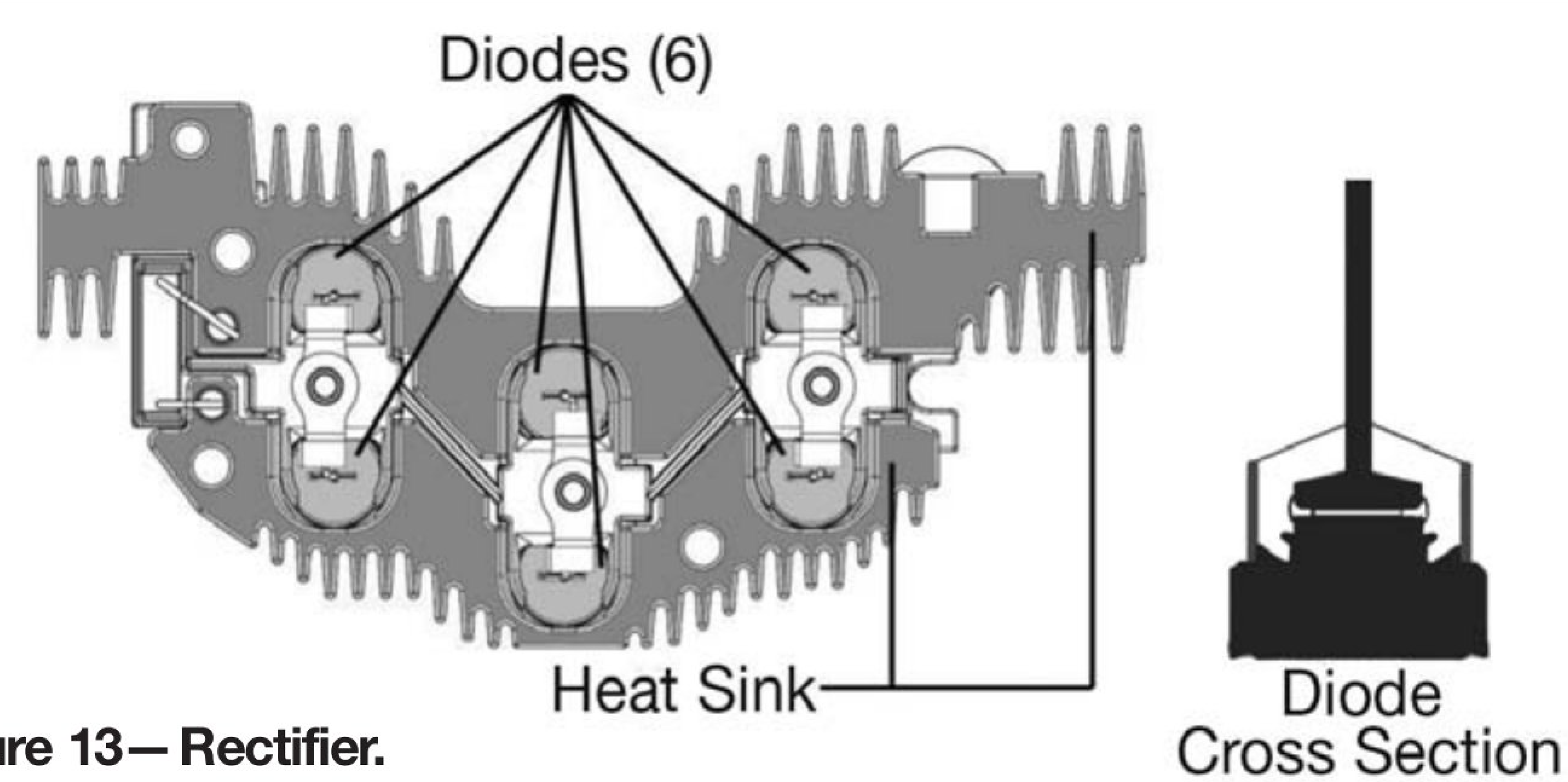

Figure 13— Rectifier.

To accomplish this task, the rectifier employs six diodes. (See Figure 13). The diode behaves like a check valve that allows current to flow in only one direction. When the voltage on the anode side of the diode is larger than the voltage on the cathode side, the diode becomes forward biased and allows current to flow through it. When this condition doesn't exist, no current flows through the diode and it behaves like an open circuit. (See Figure 14).

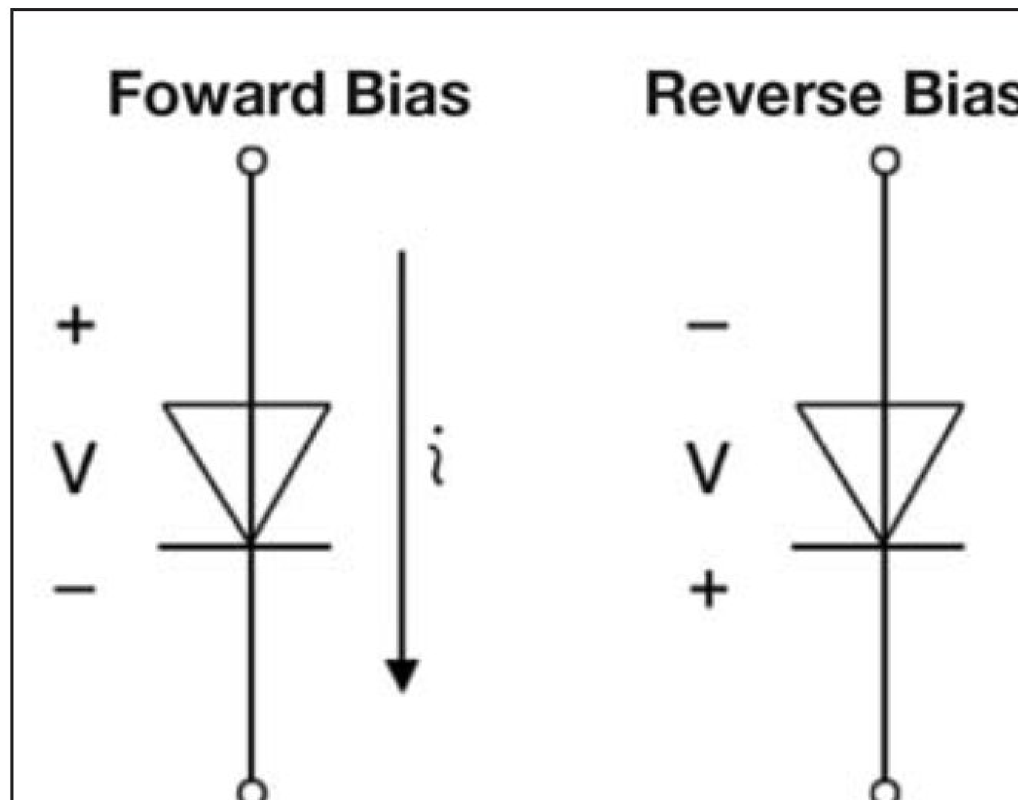

Figure 14— Diode bias.

Using two diodes per stator phase, the diode rectifier converts, or rectifies, the AC power into DC power with a corresponding voltage ripple. (See Figure 15, page 26).

Voltage regulator

So far we have built up a machine that can produce DC electrical power, but is uncontrolled. Enter the voltage regulator. The voltage regulator's role is to sense the operating voltage, either at the output of the alternator itself, or remotely such as at the battery pack, and adjust the output of the alternator accordingly. (See Figure 16).

Built into the regulator electronic circuitry is a voltage set point that can be either constant or variable with respect to temperature as shown in Figures 17 and 18.

The regulator compares the external voltage signal with that of its internal set point. If the voltage is too high, it responds to reduce the output of the alternator. If the voltage is too low, it responds to increase the output. It accomplishes this by controlling the DC field current. Inside the regulator is a silicon output device (DMOS) that when turned on allows DC voltage to be applied across the field winding producing DC field current. When the device is turned off, full voltage is removed across the field. It turns on and off in a pulse width fashion, typically at a 400 Hz frequency level, hence the term "pulse width modulation." If the regulator determines the system voltage is too low and more output is needed, the DC voltage applied across the field winding is on for a larger percentage of time.

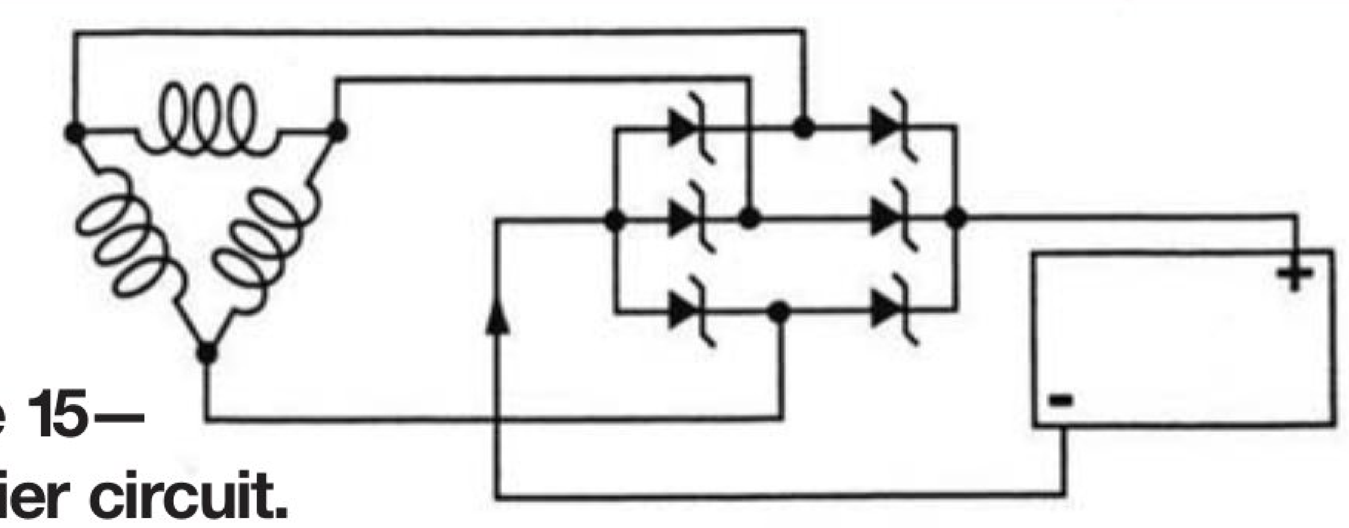

Figure 15— Rectifier circuit.

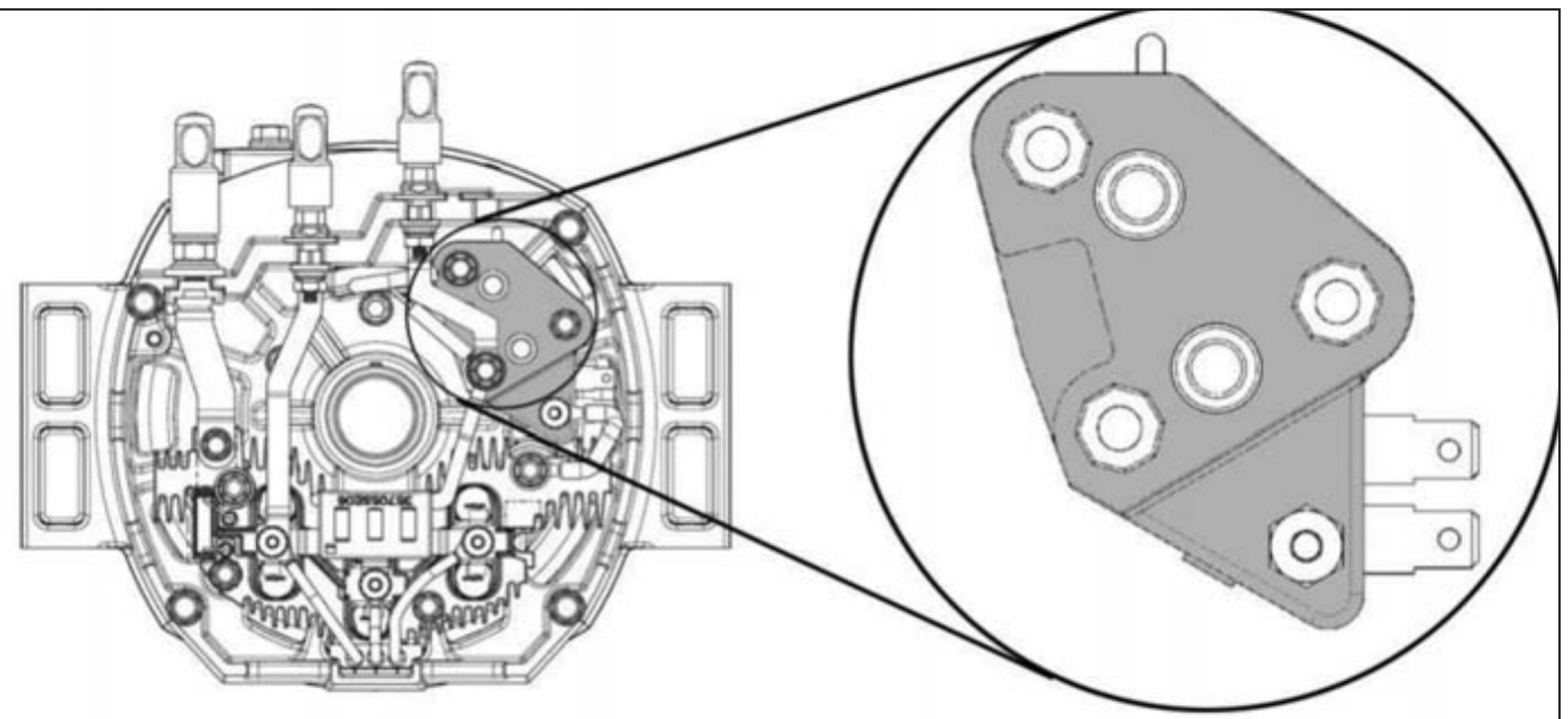

Figure 16— Voltage regulator.

If the regulator determines system voltage is too high and less output is needed, the DC voltage is turned off for a larger percentage of time. (See Figure 19, next page).

Putting the pieces together, Figure 20 on the next page shows how the four major elements of the alternator are electrically connected.

In summary, an alternator works like this:

1. The rotor provides a rotating magnetic field.
2. This rotating magnetic field induces a voltage in the stator windings.

The magnetic field in the stator rotates at the same speed, or synchronously, with the rotor field.

3. The stator windings are connected to a diode rectifier to convert the AC power into DC power.
4. A voltage regulator monitors system voltage and adjusts the output of the alternator accordingly by pulse width modulating the voltage applied to the field.

Hence, an alternator is a synchronous

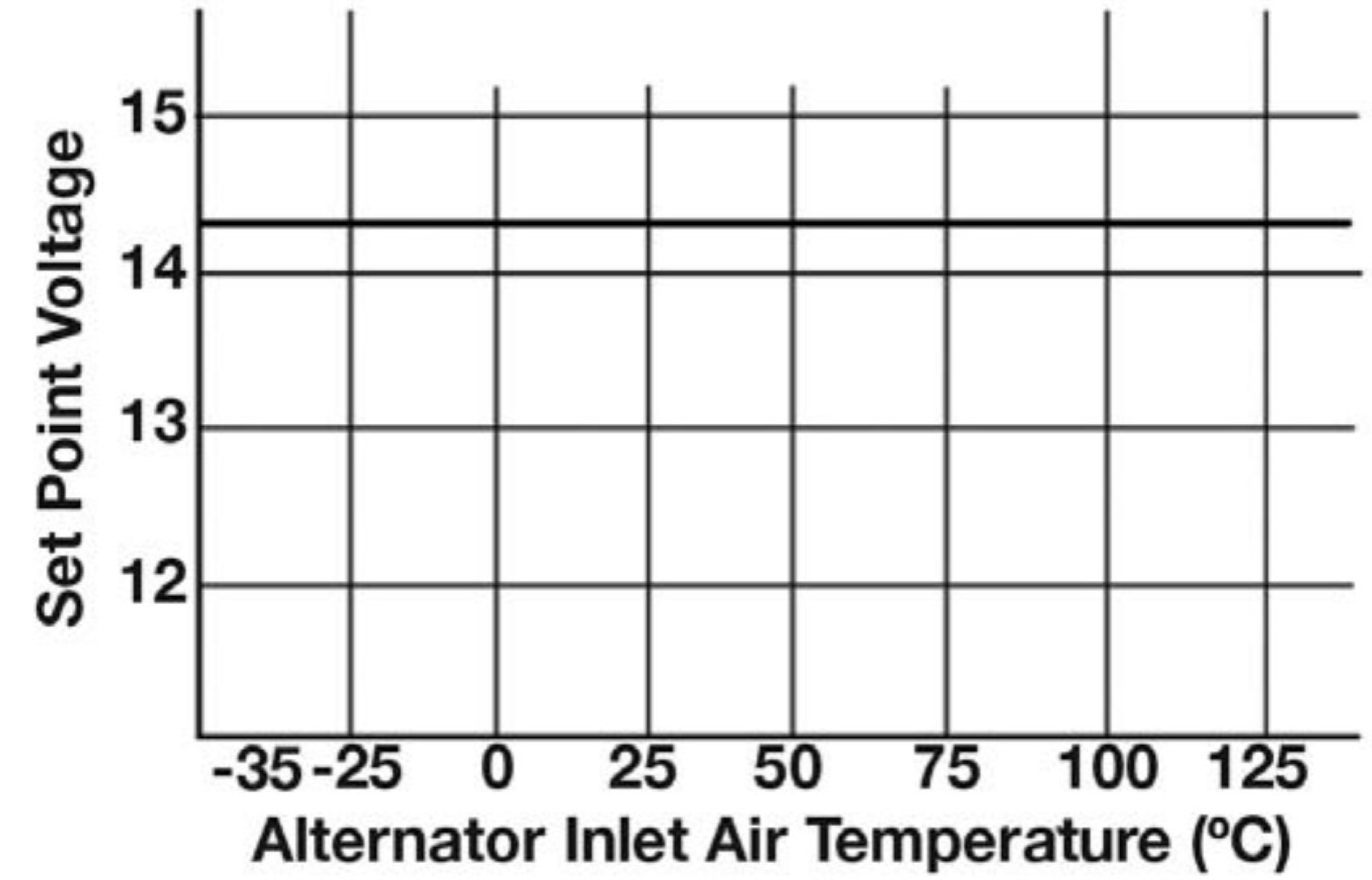

Figure 17— Fixed regulator voltage.

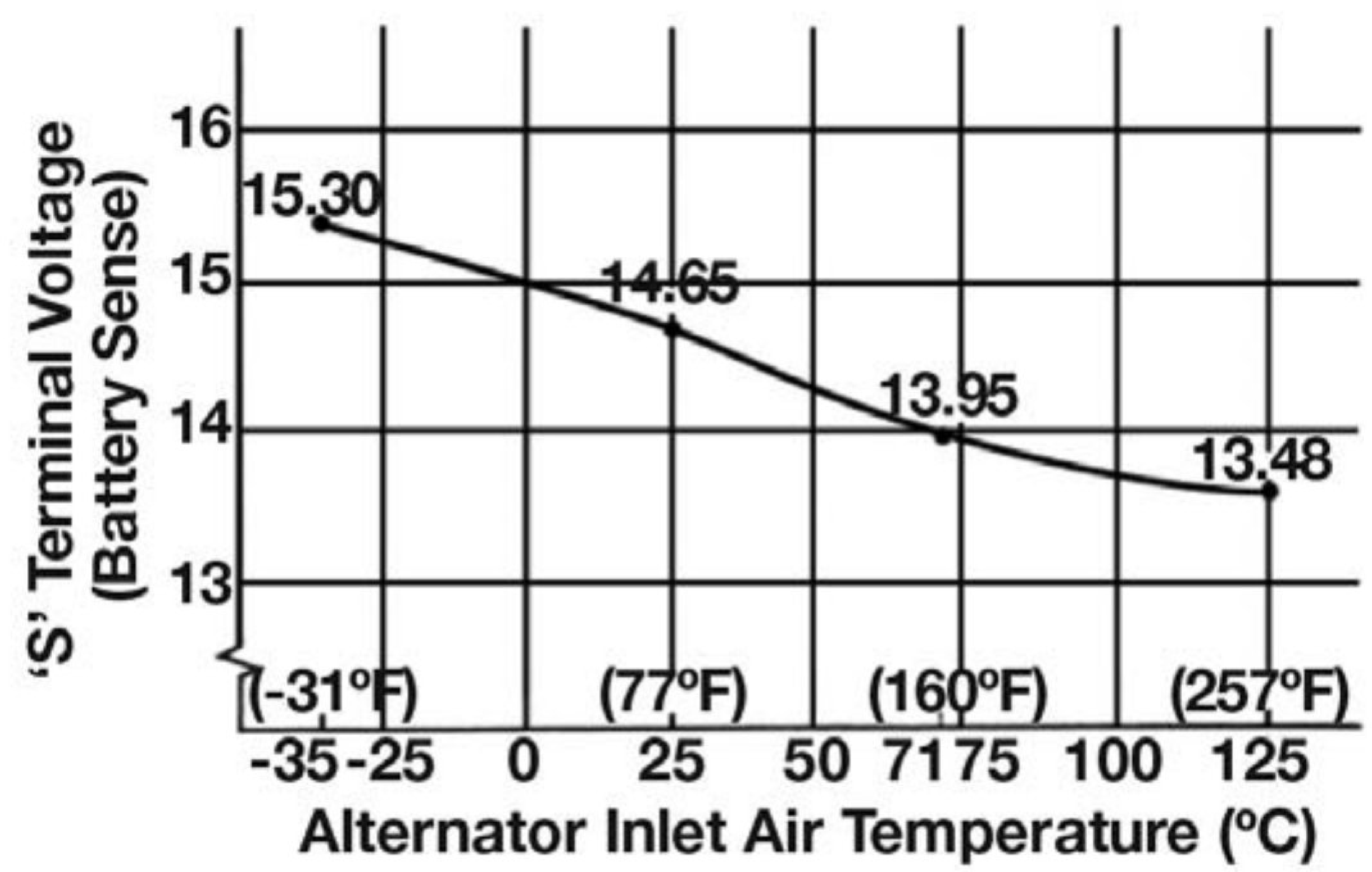

Figure 18— Variable regulator voltage.

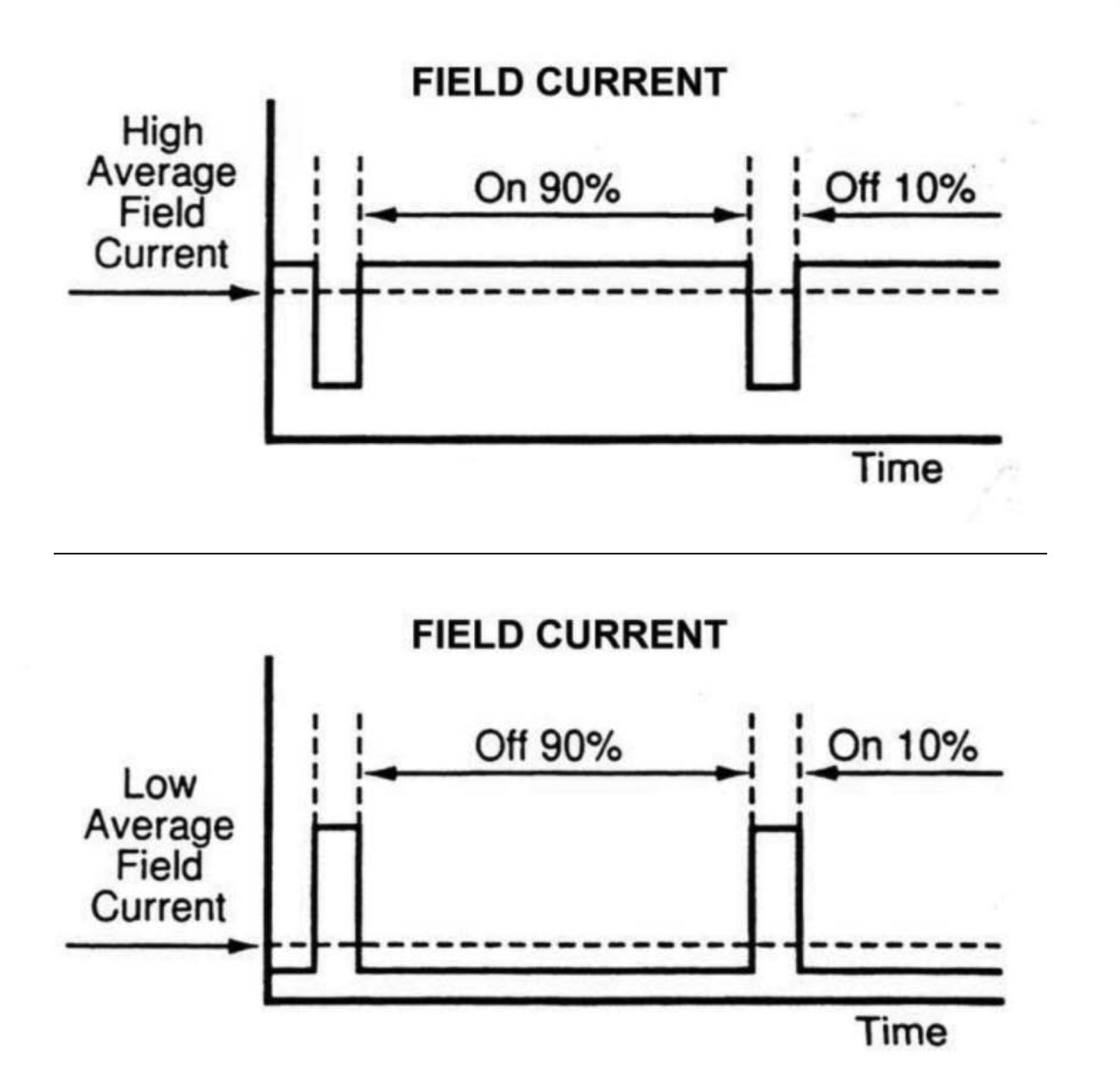

Figure 19— Alternator field current.

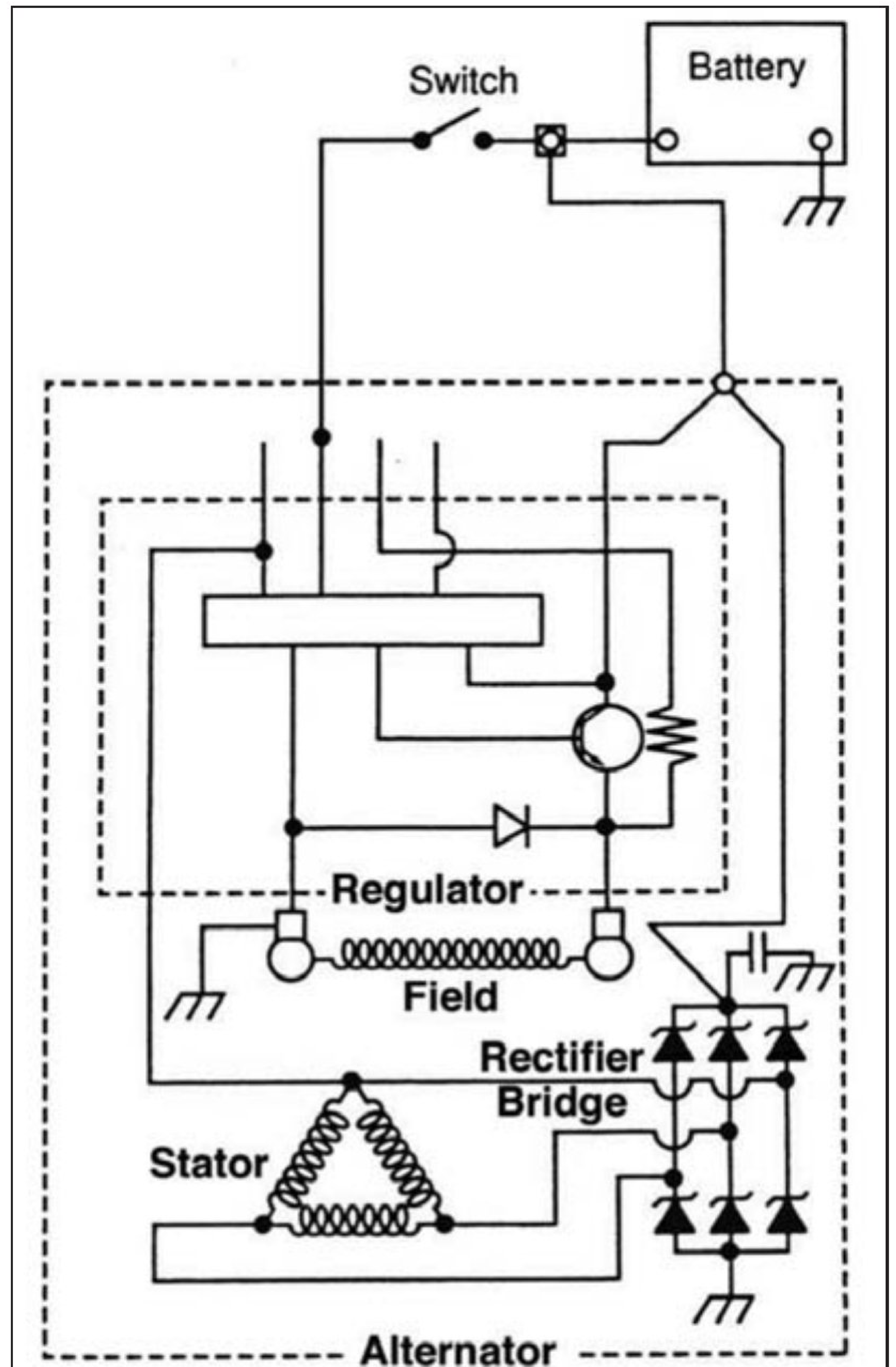

Figure 20— Alternator circuit.

AC electric generator with DC diode rectification and pulse width modulation voltage control.

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See Part II in the February issue.

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