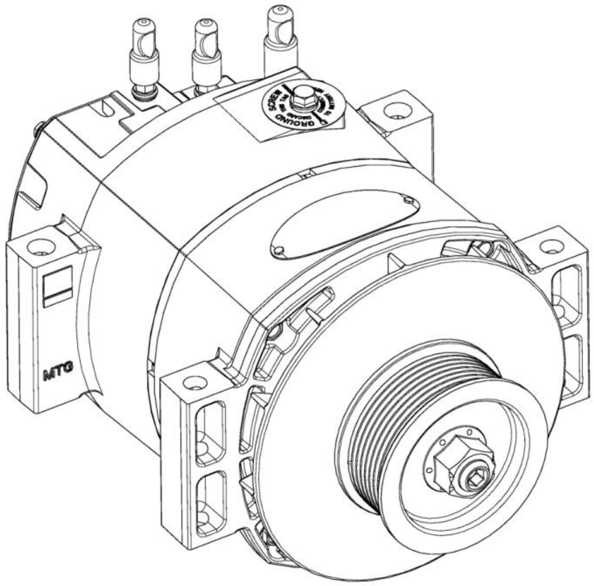
Improving Alternator Efficiency Measurably Reduces Fuel Costs



BY

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Executive Summary

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%, a belt efficiency of 98% and an alternator efficiency of 55%, this leads to an overall energy conversion efficiency of only 21%. Assuming a fuel cost of $4.00/gal, this leads to an on-board electrical power cost of $0.51/kWh, or roughly 4 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.

The following paper 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 3 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 3 studies. The following chart shows the fuel cost savings possibly over a typical life cycle by increasing the alternator efficiency 20% 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 1 year. Over the life of the vehicle, these savings can reach in the thousands of dollars.

A wide range of efficiencies exists between current production manufacturers and even from within a given manufacturers portfolio of products. Peak efficiencies at full output vary from 55% to almost 80%. 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.

Alternator losses result in more fuel being consumed
to produce a given amount of electrical power.

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

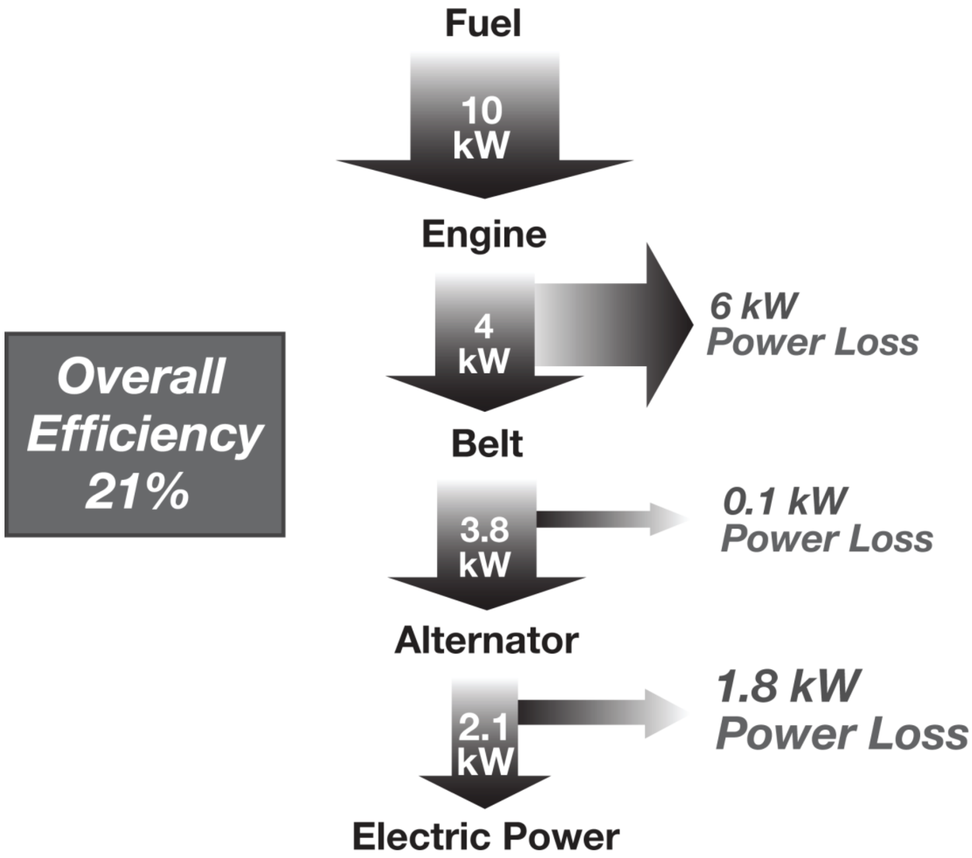

Figure 1. Energy conversion chain

Engine Efficiency

To understand how improving alternator efficiency reduces fuel usage, we will examine each element of the energy conversion chain above 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:

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

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

η = engine efficiency

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

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

P_{losses} = engine power losses

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

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 the map, engine efficiency ranges from 34-42% depending on the operating conditions.

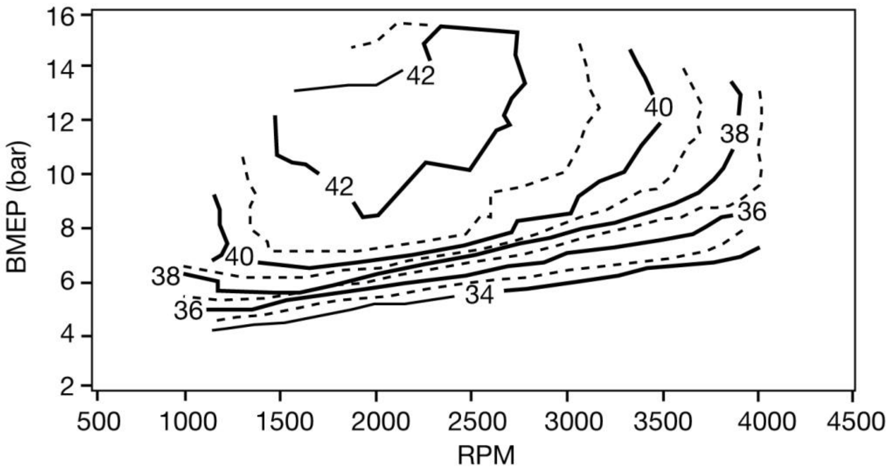

Figure 2. Brake thermal efficiency as a function of engine load and speed

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 impacts 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.

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%.

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%.

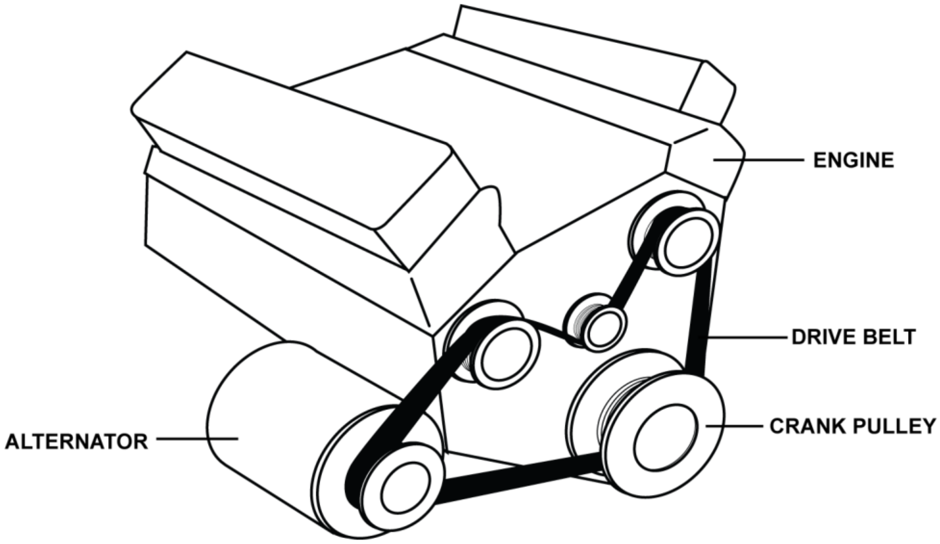

Figure 3. Accessory drive belt diagram

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, let’s back up a bit and first examine how an alternator works.

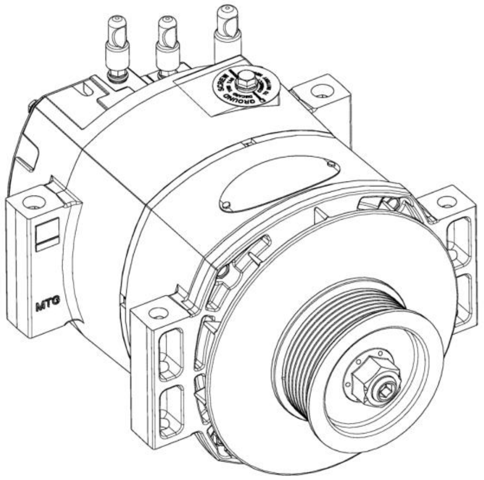

Figure 4. Alternator front view

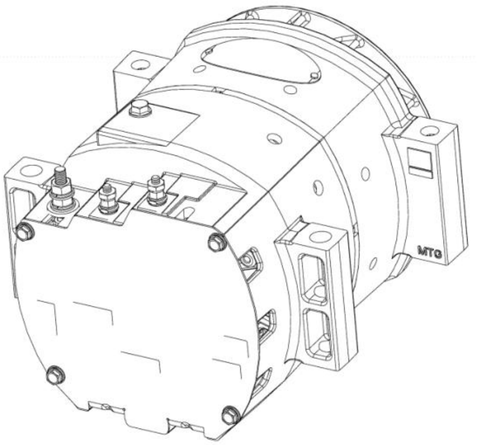

Figure 5. Alternator rear view

Simply stated, an alternator is a synchronous AC electric generator with DC diode rectification and pulse width modulation voltage control. Unless you are an electrical machine designer, however, 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.

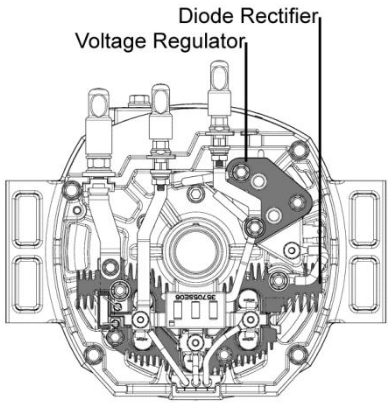

Figure 6. Regulator and Rectifier

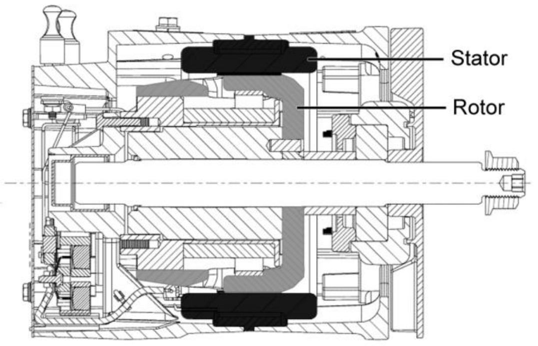

Figure 7. Rotor and Stator

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

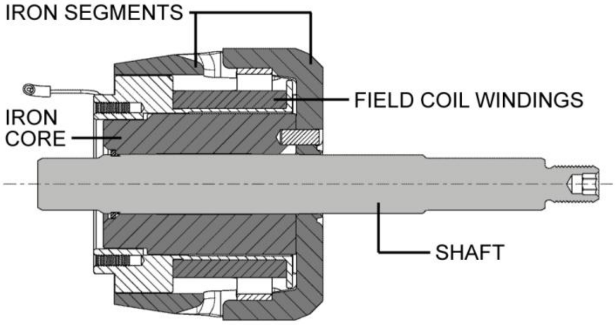

Figure 8. Rotor

The field coil winding typically consists of 300-500 tightly wrapped coils of round, insulated copper wire wound over an iron core. A DC current, typically 2-5 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. Still further, 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.

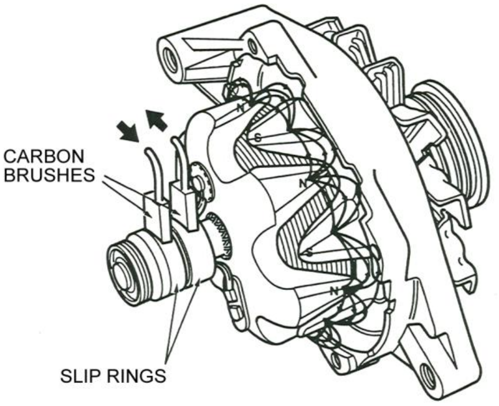

Figure 9. Brushes

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 iron magnetic path that connects the N and S poles of the rotor via the stator.

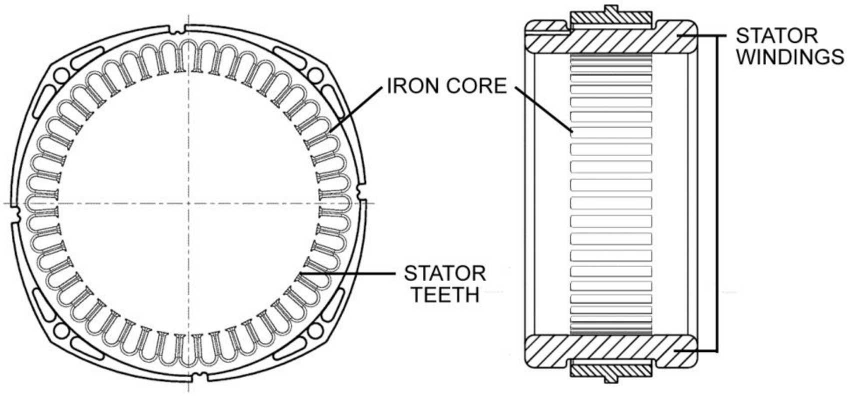

Figure 10. Stator (illustration on left shows stator without windings)

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.

As discussed above, when the rotor rotates with DC current flowing in the field winding, it will produce an AC magnetic flux in the stationary stator. This time varying flux that links the rotor and stator serves to induce a voltage in the stator wire according to Faraday’s law:

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

where e = voltage induced in conductor

N_c = number of conductors in series

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

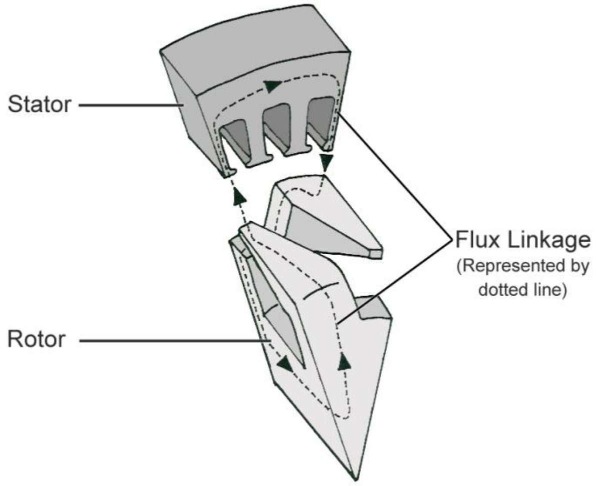

Figure 11. Flux linkage

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 this is beyond the scope of this paper.

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 3 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.

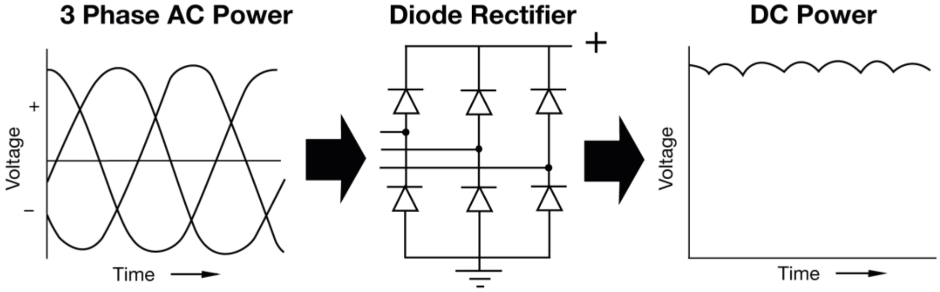

Figure 12. AC power converted to DC power

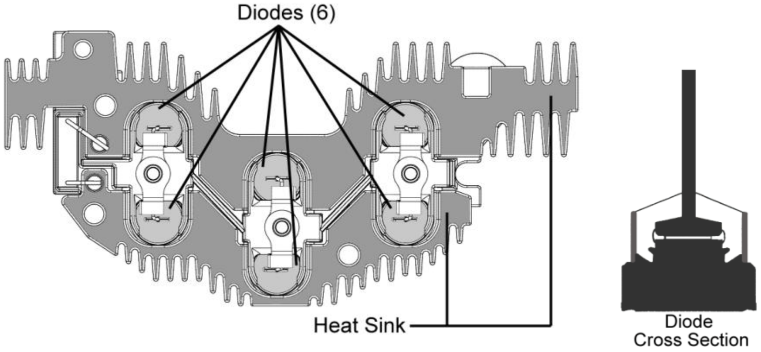

Figure 13. Rectifier

How does it do that? To accomplish this task, the rectifier employs 6 diodes. The diode behaves like a check valve that allow 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.

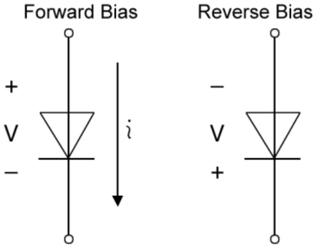

Figure 14. Diode bias

Using two diodes per stator phase, the diode rectifier converts, or rectifies, the AC power into DC power with a corresponding voltage ripple.

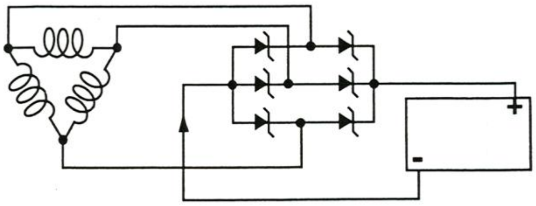

Figure 15. Rectifier circuit

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 regulators 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.

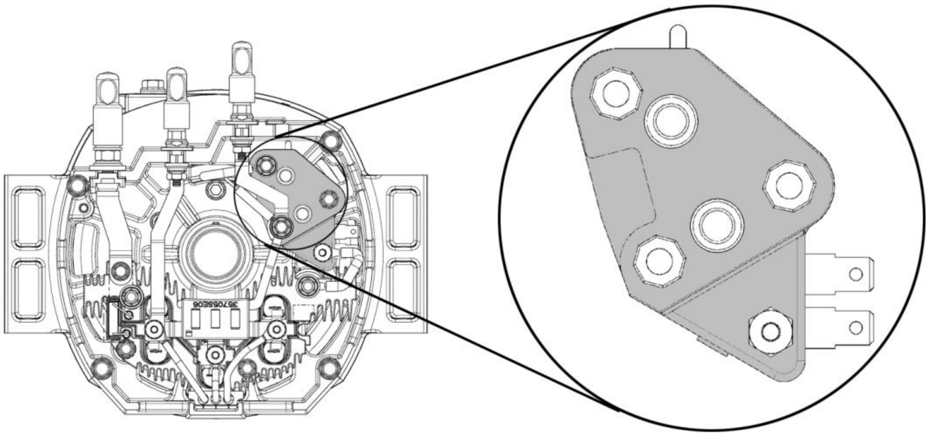

Figure 16. Voltage regulator

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

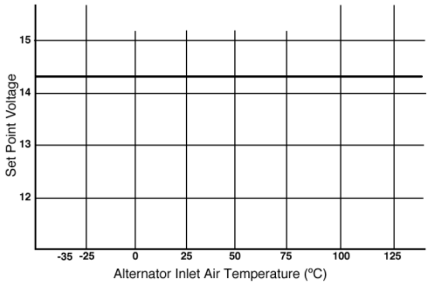

Figure 17. Fixed regulator voltage

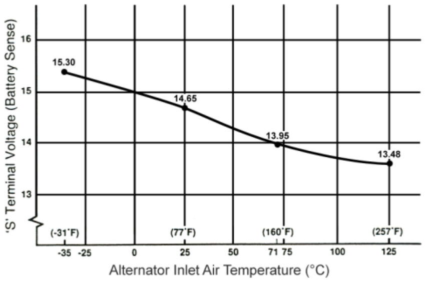

Figure 18. Variable regulator voltage

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 and thus 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. 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.

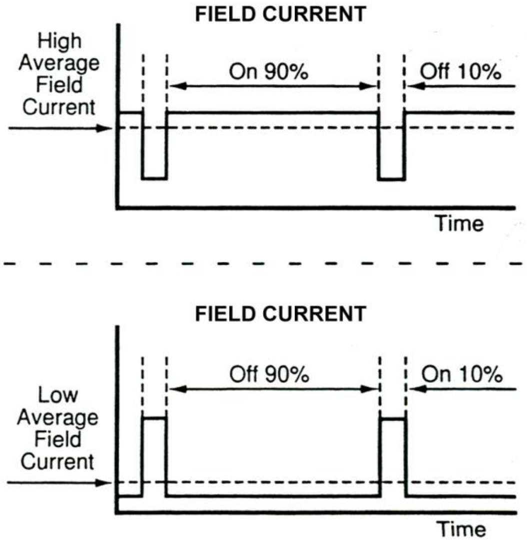

Figure 19. Alternator field current

Putting all the pieces together, the following schematic shows how the four major elements of the alternator are electrically connected:

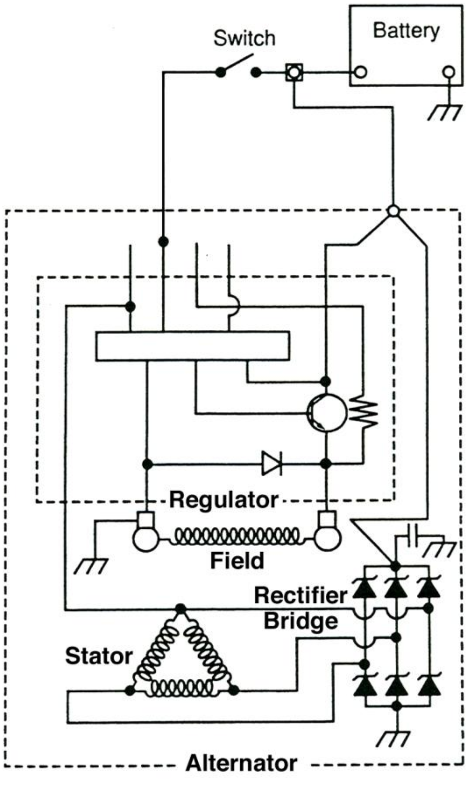

Figure 20. Alternator circuit

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, as stated above, an alternator is a synchronous AC electric generator with DC diode rectification and pulse width modulation voltage control.

Losses in an Alternator

Now that we have a cursory understanding of how an alternator actually works, let's next examine where and how power losses occur within the alternator. This will lead us up to quantify how alternator efficiency plays a role in vehicle fuel consumption.

Power losses occur in the alternator due to a number of different mechanisms. These can be lumped into 3 categories: electrical, magnetic, and mechanical.

Electrical Losses

Turning first to electrical, the largest source of loss within an alternator is the ohmic loss occurring within the stator windings. This is the familiar i^2R loss that occurs when current flows through a resistance.

$$P_{stator} = (i_{stator})^2 (R_{stator})$$

where P_{stator} = stator winding power loss

i_{stator} = stator winding current

R_{stator} = stator phase resistance

Another source of ohmic loss, but considerably smaller, occurs in the rotor field winding.

$$P_{field} = (i_{field})^2 (R_{field})$$

where P_{field} = field winding power loss

i_{field} = field winding current

R_{field} = field coil resistance

Still smaller, on brushed alternators, there is an ohmic type loss that occurs within the brushes and a resistive contact drop between the brushes and slip rings:

$$P_{brushes} = (i_{field})^2 (R_{brush})$$

where $P_{brushes}$ = brush power loss

i_{field} = field (brush) current

R_{brush} = effective brush resistance

Also electrical in nature, is the power loss that occurs due to the forward voltage drop in the rectifier diodes. This is characterized as follows:

$$P_{diode} = (V_d)\,(i_{diode})$$

where P_{diode} = diode power loss

V_d = forward voltage drop of the diode

i_{diode} = diode current

Similarly, there is a small power loss that occurs in the regulator output device:

$$P_{regulator} = (V_d)\,(i_{field})$$

where $P_{regulator}$ = regulator power loss

V_d = forward voltage drop of the output device

i_{field} = field current

Magnetic Losses

Next, are the magnetic losses that are often referred to as iron losses or core losses. These occur within the iron components that are part of the magnetically active circuit. There are two types of iron magnetic losses: hysteresis and eddy currents.

Hysteresis loss occurs in areas of the iron where there is an AC flux. Hysteresis comes about from the microscopic action of the magnetic domains within the iron itself trying to align with the external magnetic field. In a section of iron that is not in the influence of a magnetic field, the magnetic alignment of these individual domains is random. This magnetic alignment can be thought of as tiny compasses with a needle pointing toward the N pole in each individual domain.

No magnetic field present

Magnetic field present

Figure 21. Domain alignment in a magnetic field

As an external magnetic field is applied to the iron, these domains try to align themselves with the polarity of the external field. As the strength of the external field increases, so does the overall alignment of these individual domains. Then as the external magnetic field switches direction, the domains also switch their direction of magnetic orientation. It is this switching of magnetic direction by the individual domains within the iron that give rise to the hysteresis power loss. Areas such as the stator teeth that experience an AC flux have hysteresis loss. Conversely, the rotor core that has DC flux has little or no hysteresis loss.

On a flux density versus magnetizing intensity plot, or so-called BH curve, the area contained within the loop as the material sweeps out a complete magnetic cycle is a measure of hysteresis. The ‘fatter’ this loop is for a given material, the higher the hysteresis loss. This loss is can be described by the following relation:

$$P_{\text{hysteresis}} = (k)\,(\text{RPM})\,(B)^2$$

where $P_{\text{hysteresis}}$ = hysteresis power loss

k = constant

RPM = alternator rotational speed

B = flux density of the iron cross section

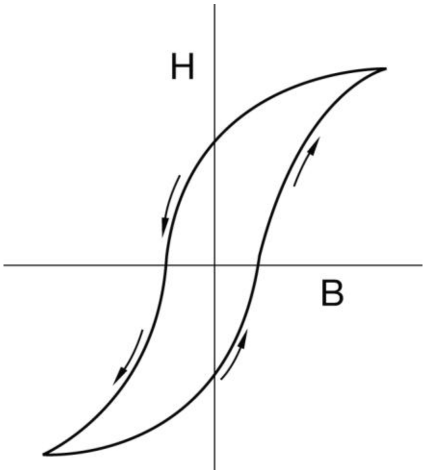

Figure 22. Magnetic BH curve

The next magnetic loss is eddy currents. Eddy currents come about in the iron sections where there is a time varying flux. Just as a voltage is induced in the copper stator wires as they experience a time varying flux, voltage is also induced in the iron components. Since the iron is electrically conductive, electrical currents flow within the iron itself. These currents flowing in the iron establish themselves in such a manner to magnetically oppose the original induced voltage that created them. Because eddy currents vary with the square of frequency, and hence rotational speed, they are particularly troublesome at high speeds. Eddy current loss is modeled as:

$$P_{\text{eddy}} = (k)\,(t)^2\,(\text{RPM})^2\,(B)^2$$

where P_{eddy} = eddy current power loss
k = constant
t = thickness or length of iron path
RPM = alternator rotational speed
B = flux density of the iron cross section

Finally, stray loss is a ‘catch-all’ term that is lumped under magnetic loss. Stray loss literally is a ‘catch-all’ term that is used by electrical machine designs to account for the generally small, secondary loss mechanisms that occur within the machine but generally are difficult to accurately model. Different approaches are used to account for stray but one approach is to model it as a function of the total power loss:

$$P_{\text{stray}} = 0.01\ (P_{\text{total loss}})$$

where P_{stray} = stray loss

$P_{\text{total loss}}$ = total power loss

Mechanical Losses

This leads us to the third and final group of losses, the mechanical losses. The first of these is bearing friction. Frictional losses occur between the stationary lip of the seals of the bearing and the rotating inner race. Frictional losses also occur between the rolling elements of the bearing and the cage that contains them and the rolling/sliding of these elements across the inner race. On brushed alternators, frictional loss also occurs between the slip ring and brush.

Frictional losses are modeled as:

$$P_{\text{friction}} = k\ (\text{RPM})$$

where P_{friction} = frictional loss

k = constant

RPM = alternator rotational speed

The other mechanical loss is windage. For an air-cooled alternator, windage represents the shearing of air from the rotational surfaces, most notably the fans. Since windage increases with the cube of speed, it can be quite large at high speeds.

Windage varies as the follows:

$$P_{\text{windage}} = k\ (\text{RPM})^3$$

where P_{windage} = windage power loss

k = constant

RPM = alternator rotational speed

The following table summarizes the various power losses:

Electrical	
Stator winding loss	$P_{stator} = (i)^2 (R_{stator})$
Rotor winding loss	$P_{field} = (i)^2 (R_{field})$
Rectifier diode voltage drop loss	$P_{diode} = (V_d) (i_{diode})$
Regulator output device drop loss	$P_{regulator} = (V_d) (i_{regulator})$
Brush drop	$P_{brushes} = (i_{field})^2 (R_{brush})$
Magnetic	
Eddy current	$P_{eddy} = (k) (T)^2 (RPM)^2 (B)^2$
Hysteresis	$P_{hysteresis} = (k) (RPM) (B)^2$
Stray	$P_{stray} = (0.01) (P_{total\ loss})$
Mechanical	
Bearing friction	$P_{bearing} = (k) (RPM)$
Windage	$P_{windage} = (k) (RPM)^3$

Now that we qualitatively looked at how an alternator works and the mechanisms that cause power loss, let's look at it quantitatively. Figure 23 below shows the losses of a typical alternator at full output conditions. As can be seen, the two largest sources of loss within the alternator are typically the stator ohmic and diode rectification. The losses of all mechanisms are dependent upon actual output current and speed as shown above.

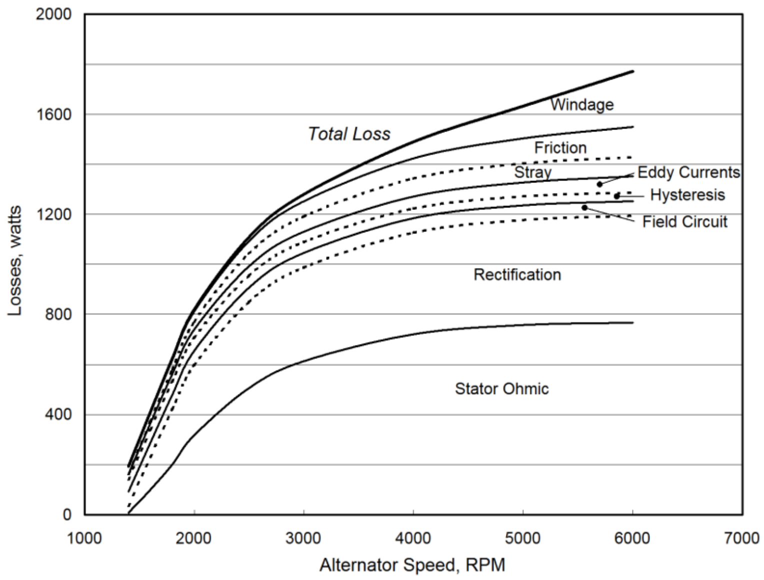

Figure 23. Full output power loss

Losses are also secondarily dependent upon temperature and voltage as shown below in figures 24 and 25.

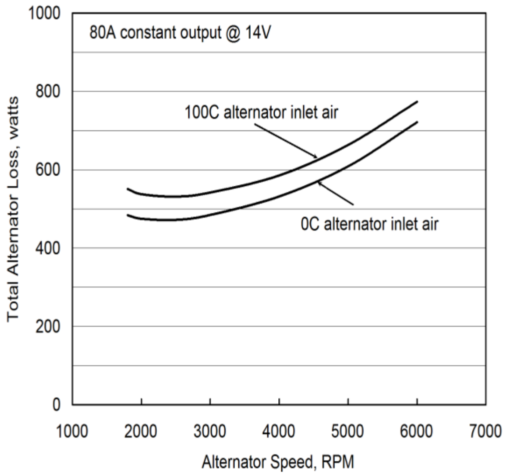

Figure 24. Impact of temperature on loss

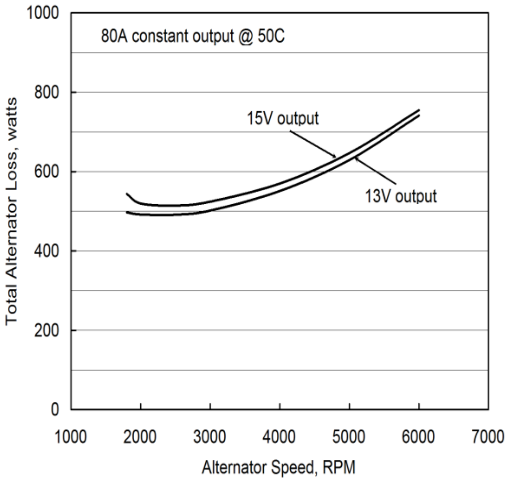

Figure 25. Impact of voltage on loss

Although it appears that voltage doesn’t play a large role in alternator losses, a word of caution is in order here. In the graph shown the output current is held constant. But the output voltage is increased from 13 to 15 volts. Therefore the power out of the alternator is actually much higher since power is voltage times current. For a given current level, efficiency increases, not decreases, with increasing voltage. Also, the example shown is for a fixed voltage system, 14V, and a fixed alternator design. Increasing the overall system voltage to say 28V, can and does have a very profound impact on overall efficiencies. The alternator efficiency can improve significantly with such a change.

Finally, figure 26 depicts the total losses of a typical alternator as a function of speed and output current. As shown, as either load or speed increases, so do the total losses. These losses are the source of fuel waste during the conversion of mechanical to electrical power within the alternator.

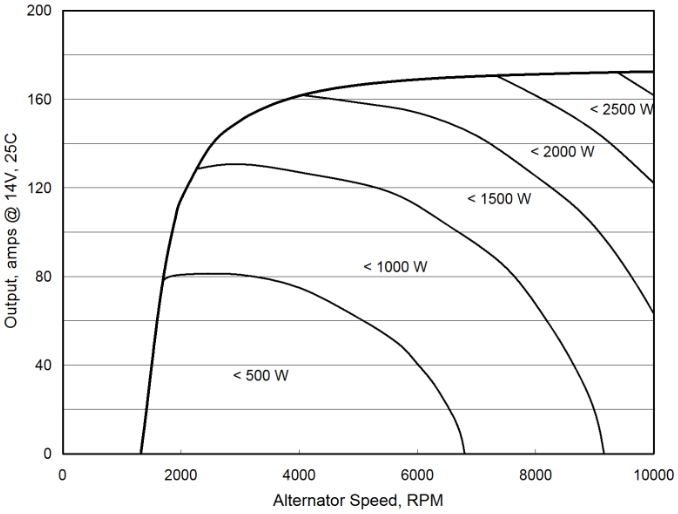

Figure 26. Loss as a function of speed and output current

Alternator Efficiency

Now we are ready to turn our attention directly to alternator efficiency. In words, alternator efficiency is simply the ratio of electrical output power by the alternator to the mechanical input power. As an equation:

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

where η = alternator efficiency

P_{out} = electrical input power

P_{in} = mechanical output power

Further, by the law of conservation of energy (please note that energy is simply the product of power multiplied by time), the mechanical input power is equal to the electrical output power plus the losses:

$$\mathrm{P_{in} = P_{out} + P_{losses}}$$

where P_{in} = mechanical input power

P_{out} = electrical output power

P_{losses} = alternator power losses

so that:

$$\eta = \frac{P_{out}}{(P_{out} + P_{losses})}$$

where η = alternator efficiency

P_{out} = electrical output power

P_{losses} = alternator power losses

If we study this simple relationship a bit we will see that for a given amount of electrical output power, if the losses go down, the efficiency goes up. And since the mechanical power input is equal to the electrical power output plus the losses, it must go down. So as losses go down, efficiency goes up and mechanical input power from the engine goes down.

Figure 27 shows the full output efficiency for an alternator. This is the type of curve that is typically published by manufacturers. Efficiencies for production alternators can vary widely from one manufacturer to another. Differences greater than 20% exist on similarly sized alternators manufactured by different companies.

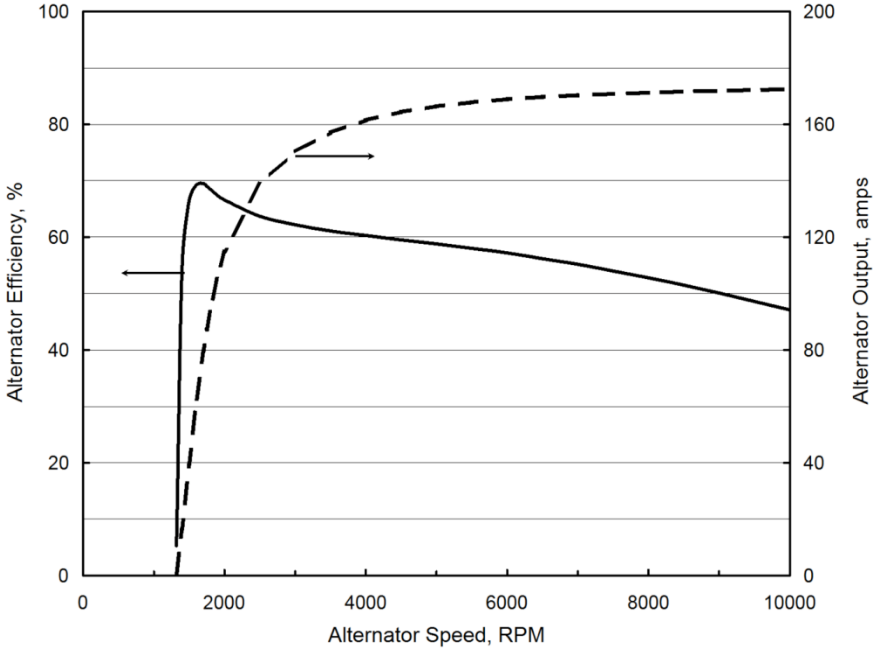

Figure 27. Alternator efficiency

However, the information shown above is only part of the story since most of the time an alternator in actual use is not at full output. Figure 28 gives a more descriptive image of alternator efficiency by showing the efficiency as a function of output current.

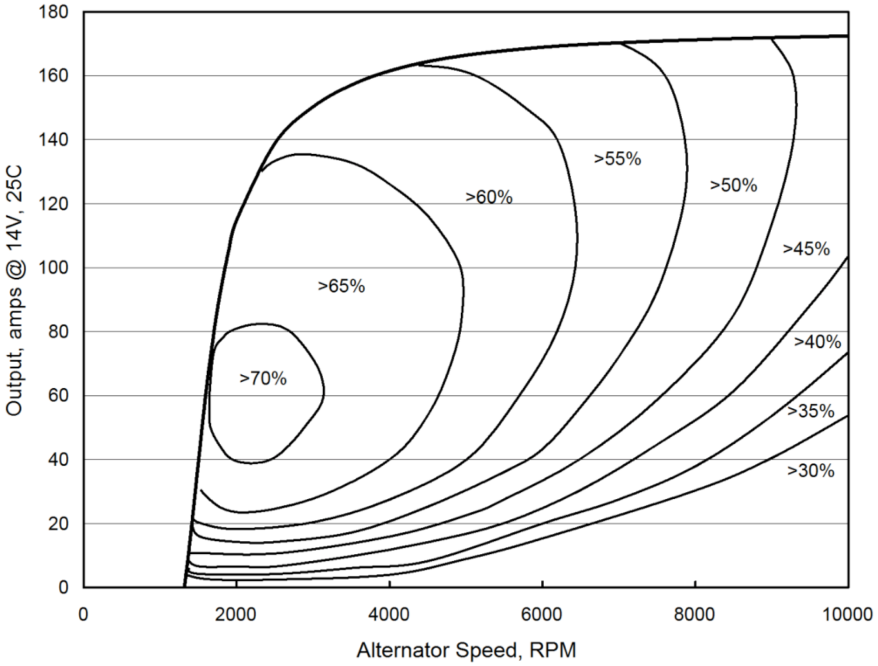

Figure 28. Alternator efficiency map

As shown above, efficiency increases when output is reduced from full output. This is due primarily to the nonlinear reduction in stator ohmic losses, i^2R, as current is reduced. This continues up to a maximum that is speed dependent, and then the efficiency degrades with decreasing output. At this point the fixed losses, such as friction and windage, begin to dominate and the reduction in output is not accompanied by an equal or greater reduction in losses.

Although the figures shown are for a specific alternator, they qualitatively represent efficiency for claw pole alternators. As shown, the peak efficiency for an alternator tends to occur at 30-40% of its maximum output and from 2000-2500 RPM.

The actual effective efficiency for an alternator depends on the actual application and its usage. Speed, output current, voltage, and temperature all play a role in determining the effective, or average, alternator efficiency. To demonstrate the relationship between output current and effective efficiency on an application, the same alternator was applied to three different actual applications. (We will look at these applications in more detail in the next section.) The average output current from the alternator was varied from 20 to 140 amps on each of these applications. Based on the actual usage profiles of these schedules, the effective alternator efficiency was calculated. Here are the results:

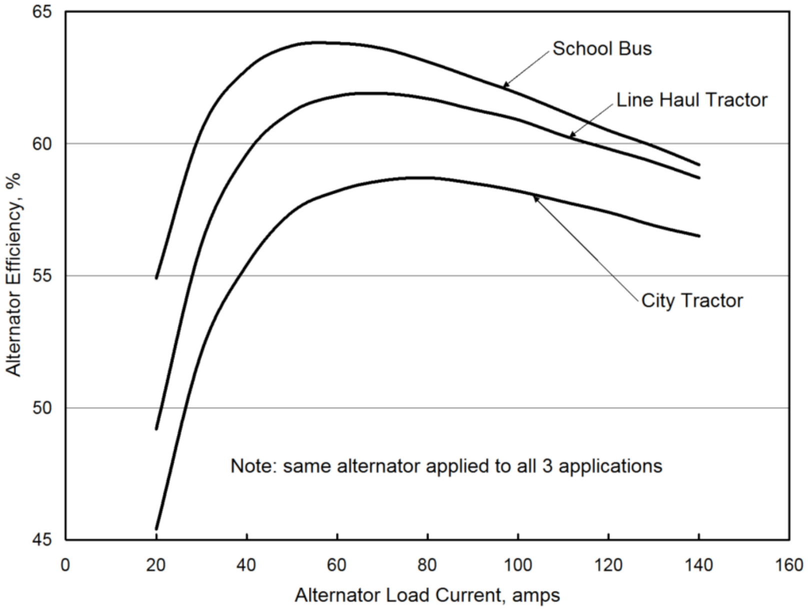

Figure 29. Efficiency as a function of application and output current

As can be seen, the effective alternator efficiency in use depends on the speed and load profile of the actual application. The exact same alternator on different applications and load conditions can yield widely varying efficiencies. However, an alternator that yields a high efficiency at full output conditions will also yield higher efficiency when compared to other alternators on actual applications.

Improving Alternator Efficiency Reduces Fuel Cost

Now we are ready to put it all together, from the fuel tank to the alternator electrical output, to see how alternator efficiency relates to fuel costs in a monetary sense. Figure 1 above depicts the overall energy flow for this system. As shown, a typical overall efficiency is only 21% for on-board electrical power.

With an assumed fuel cost of $4.00/gal, this equates to an electrical power cost of $0.51/kWh. On a comparison basis, the electricity that you use in your home from a utility company is typically $0.13/kWh. In other words, the electrical power on your vehicle cost roughly 4 times that of your home!

To demonstrate the impact of alternator efficiency on fuel usage, three different types of applications were examined: a line haul tractor, a city tractor, and a school bus. For each of these applications, actual measured real-time data was collected and used to determine the various input profiles. This real-time information was converted into the speed and electrical load histograms shown below.

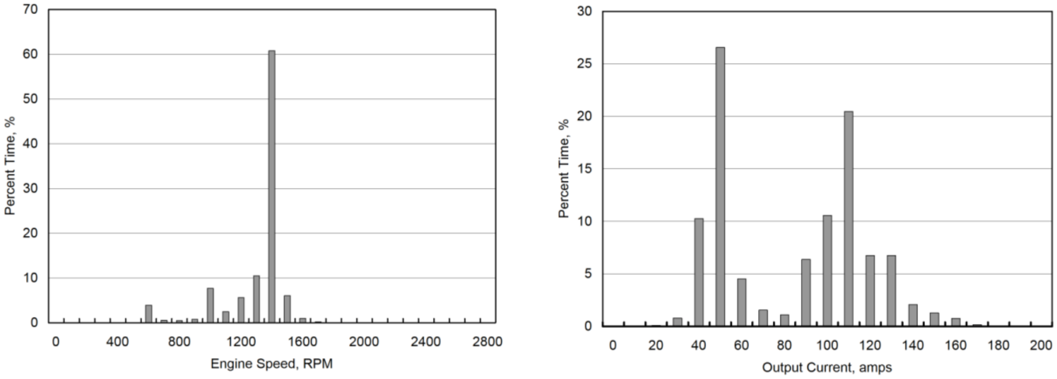

Figure 30. Line haul tractor

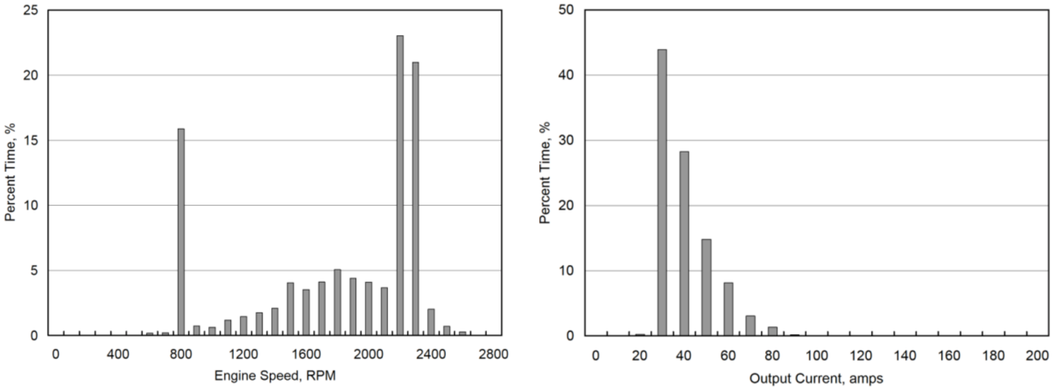

Figure 31. City tractor

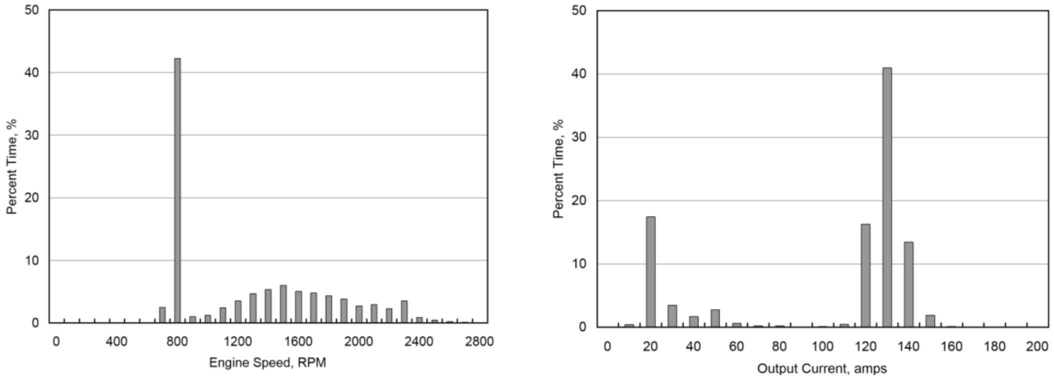

Figure 32. School bus

Assuming $4.00/gal for fuel, and using the same alternator applied to each application, the following results were obtained for typical life cycle costs:

Application	Average Current	Average Efficiency	Fuel Cost
Line Haul Tractor	84 amps	60.5%	$4534 / 500k mi
City Tractor	40 amps	54.1%	$2235 / 350k mi
School Bus	102 amps	59.1%	$9040 / 250k mi

To show the impact of increasing efficiency, the efficiency of the alternator was increased by 20% at each operating point. The following results were obtained:

Application	Average Current	Average Efficiency	Fuel Cost	Fuel Savings
Line Haul Tractor	84 amps	72.6%	$3778 / 500k mi	$756 / 500k mi
City Tractor	40 amps	64.9%	$1863 / 350k mi	$372 / 350k mi
School Bus	102 amps	70.9%	$7533 / 250k mi	$1507 / 250k mi

These results are for the actual current levels measured on the vehicle shown in the table. As the current demand and operating time increases, so does the important of efficiency. To further illustrate this significance, the following two charts were generated.

The first chart reveals the yearly fuel costs to generate 100 amps of current at 14V as a function of alternator efficiency assuming 2000 hours per year of vehicle use. First note the yearly fuel costs are over $1000 per year for these conditions. Then note the impact of alternator efficiency on fuel cost. The yearly fuel cost difference between 50% and 60% efficiency is over $250.

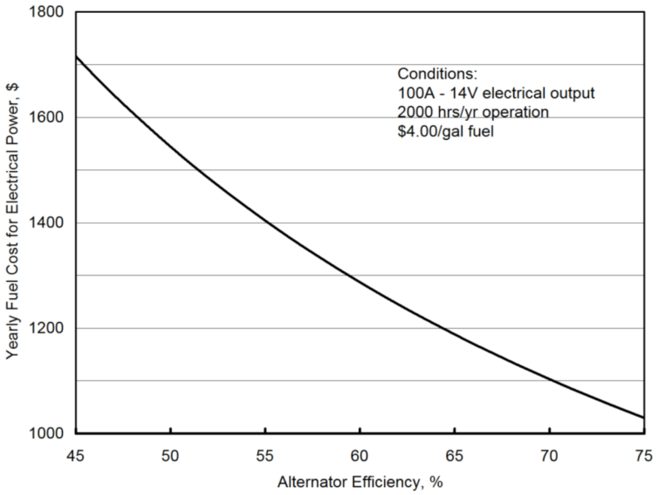

Figure 33. Cost to generate 100 amps at 14V over 2,000 hours of operation

Since the chart above is based on a fixed 2000 hours per year of operation, the following chart was created to demonstrate the impact of varying operating time. As the operating time per year increases, so do the costs associated with electrical power generation and the significance of alternator efficiency. At 5000 hours per year, representative of line haul tractors with team driving, the yearly fuel cost for electrical power is over $3000. Under this scenario the savings in improving alternator efficiency 20% by going from 50% to 60%, is over $600 per year. Quite significant.

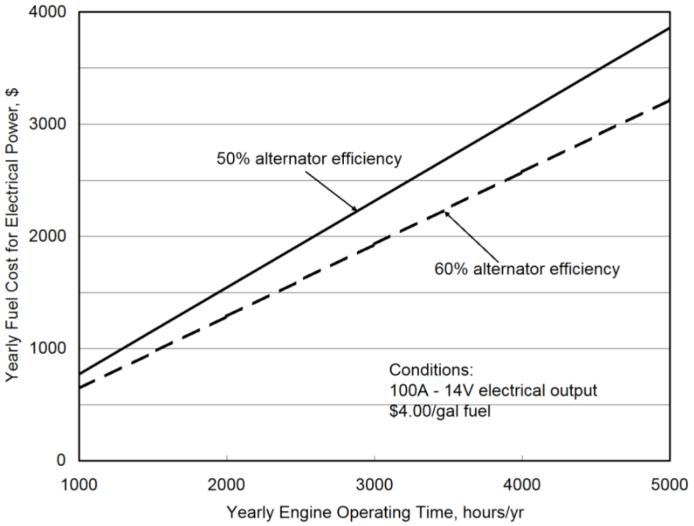

Figure 34. The impact of varying operating time

By now, the results should be clear. Generating on-board electrical power for a vehicle is not free. The fuel cost associated with creating this electrical power can be quite significant. But increasing alternator efficiency can combat this problem in a real and measurable way.

Summary

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 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 this paper calculation results are presented for a truck operating under the following scenario:

2,000 hours / year operation

100 amps average electrical current (14V system)

$4/gallon fuel cost

In this case it will cost over $1,000/year to generate on-board electricity. The fuel cost difference between a 50% and 60% efficient alternator under this scenario is over $250/year.

If a truck operates for 2,000 hours and fuel costs $4/gallon, it costs over $1,000 just to generate 100 amps of electricity.

Further, if the assumed annual operating time is increased to 5,000 hours /year, representative of line haul tractors with team driving, everything else remaining the same, the annual cost of generating electricity is over $3,000. In this case, the difference between an alternator that’s 50% efficient and one that’s 60% efficient is over $600/year.

If a truck operates for 5,000 hours, the difference between a 50% and 60% efficient alternator is over $600 in fuel costs.

About the Author

Mike Bradfield is currently an Engineer at Remy, Inc. He began his career in 1984 with Delco Remy Division of General Motors that later became Delphi Automotive Systems.

His areas of responsibilities and specialty includes electromagnetic machine design, mechanical product design, analysis of vehicle electrical systems, heat transfer and cooling design. His engineering experience also includes program management, design of laboratory tests and field correlations, expert witness and product failure analysis.

Over the course of his career he has been responsible for the initial product engineering design that has led to over 3 billion dollars in sales and the receipt of 24 patents. He received a BSME and MSME from Iowa State University in 1984 and 1987 respectively where he was selected as a General Motors Scholar.

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