Motor Efficiency Controllers

The Science Behind the Power Genius™

What is Motor Efficiency?

In a perfect world, AC induction motors would operate at 100% efficiency – in other words, every kilowatt of power delivered to the motor terminals would be converted to useful work at the motor shaft. However, in the real world (the world in which most of us live), this is not the case. Only a percentage of the delivered power is converted to useful work, and that percentage will vary. The efficiency is the ratio of power delivered by the motor at the shaft to the power delivered to the motor at the terminals.

$$Efficiency = \frac{useful\ power\ out}{total\ power\ input}$$

In general, AC motors operate most efficiently at around 75% of full rated load, with the efficiency falling off only slightly until somewhere between 25% and 50% of full load, where the efficiency begins to drop significantly. As a rule of thumb, the larger the motor, the flatter this curve is, and the lower the load percentage has to drop before the efficiency starts to drop. The efficiency curve for typical AC motors is shown below:

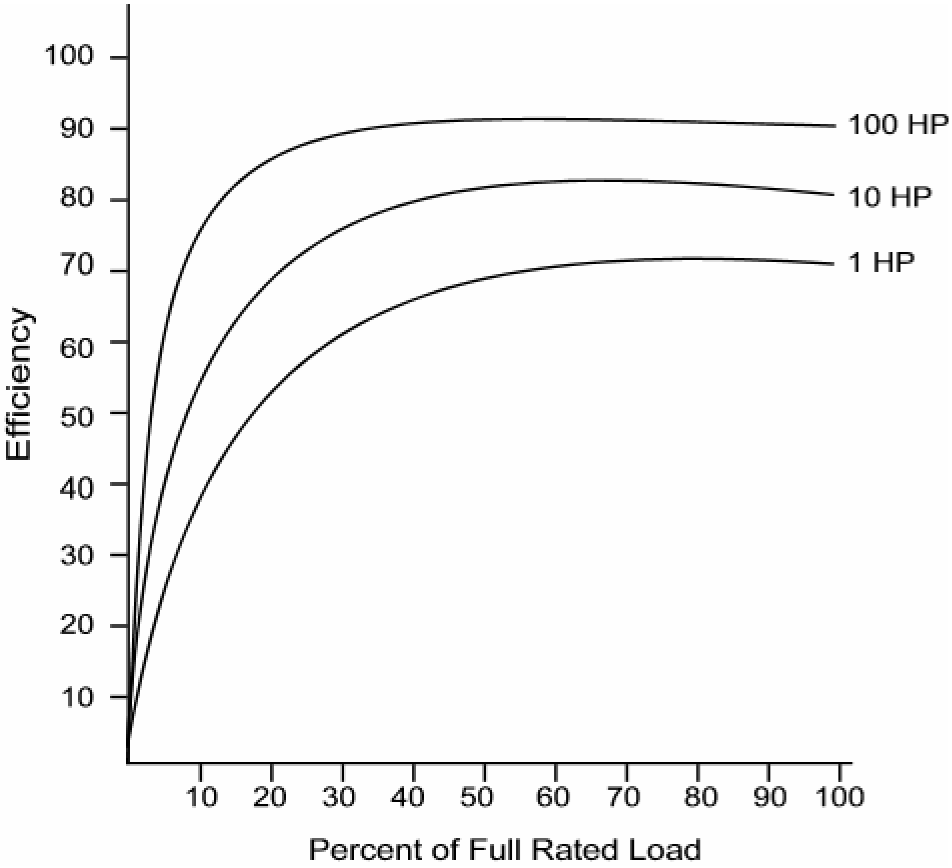

Figure 1

What is Power Factor?

In a purely resistive AC circuit, voltage and current waveforms are in phase, changing polarity at the same instant in each cycle.

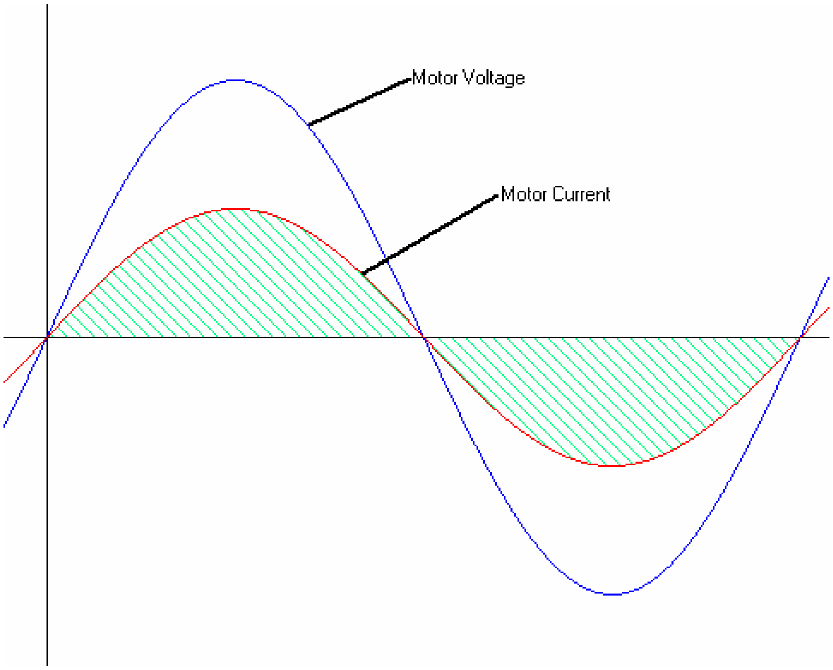

Figure 2

When reactive elements are present, such as capacitors or inductors (such as an AC induction motor), energy storage in these reactive elements results in a time difference between the current and voltage waveforms. With an inductive load, the current lags behind the voltage:

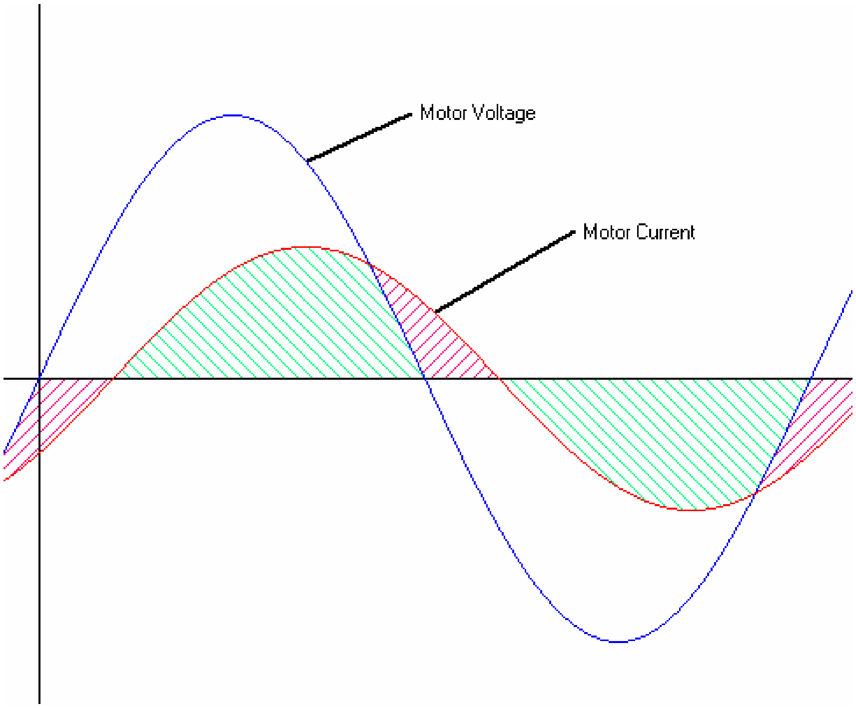

Figure 3

Since this stored energy returns to the source (in other words, the power company) and is not available to do work at the load, a motor with a low power factor will require more current draw to do a given amount of work than a motor with a high power factor. In the graphs above, the Green shaded region represents the period of time during which the current is doing useful work, and the Pink shaded region represents the time when the current is merely being stored in the reactive elements and returned to the source.

AC power flow has three components:

- Real power (***P***), measured in watts (W), which can be thought of as the green shaded area in Figure 2 and Figure 3;
- Reactive power (***Q***), measured in reactive volt-amps (VAr), which can be thought of as the pink shaded area in Figure 3;
- and Apparent power (***S***), measured in volt-amps (VA), which can be thought of as the combination of the pink and the green areas.

Real power is the capacity of the motor for performing work in a particular time. Due to reactive elements of the load, the apparent power, which is the product of the voltage and current in the circuit, will be equal to or greater than the real power. The reactive power is a measure of the stored energy that is reflected to the source during each alternating current cycle.

The power factor can be expressed as:

$$\frac{P}{S}$$

In the case of a sinusoidal waveform (as in Figure 2 and Figure 3), P, Q and S can be expressed as vectors that form a triangle such that:

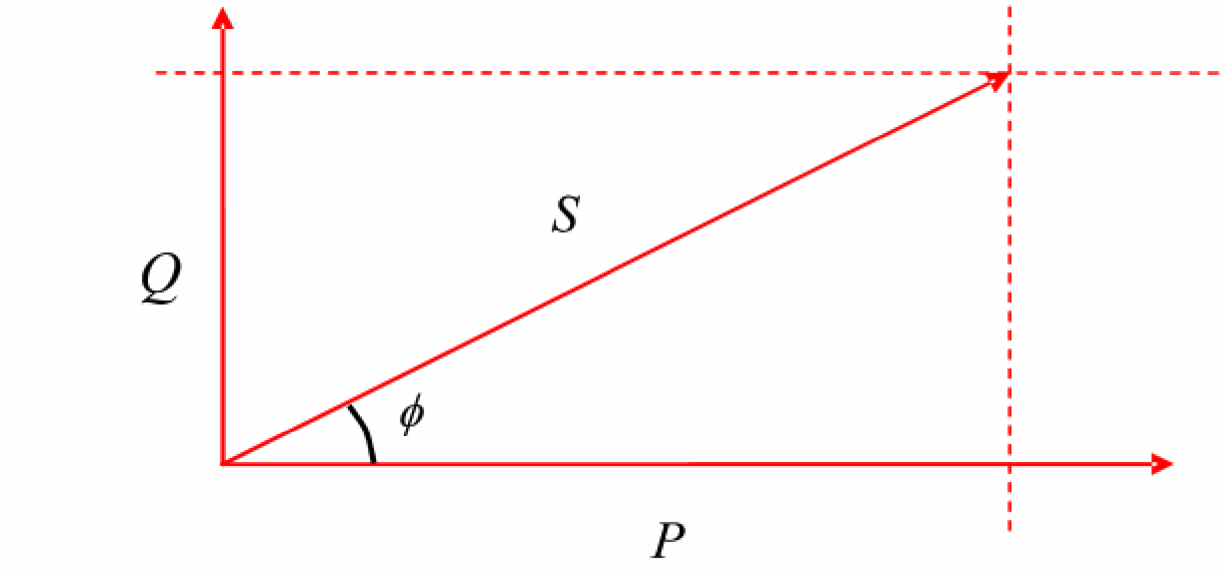

Figure 4

and: $$S^2 = P^2 + Q^2$$

If φ is the phase angle between the current and voltage, then the power factor is equal to

$|\cos\phi|$, and: $$P = S * |\cos\phi|$$

By definition, the power factor is a dimensionless number between 0 and 1. When power factor is equal to 0, the energy flow is entirely reactive, and stored energy in the load returns to the source on each cycle. When the power factor is 1, all the energy supplied by the source is consumed by the load. Power factors are usually stated as "leading" or "lagging" to show the sign of the phase angle.

For example, to get 1 kW of real power if the power factor is unity, 1 kVA of apparent power needs to be transferred (1 kVA = 1 kW × 1). At low values of power factor, more apparent power needs to be transferred to get the same real power. To get 1 kW of real power at 0.2 power factor 5 kVA of apparent power needs to be transferred (1 kW = 5 kVA × 0.2).

How are Power Factor and Efficiency related?

While power factor and efficiency are not directly related (i.e., there is no equation that will solve for efficiency given power factor or vice versa), there is a physical correlation between the two, and will be explained in the following discussion of slip and torque. In an AC motor, the input power is used to magnetize the stator core.

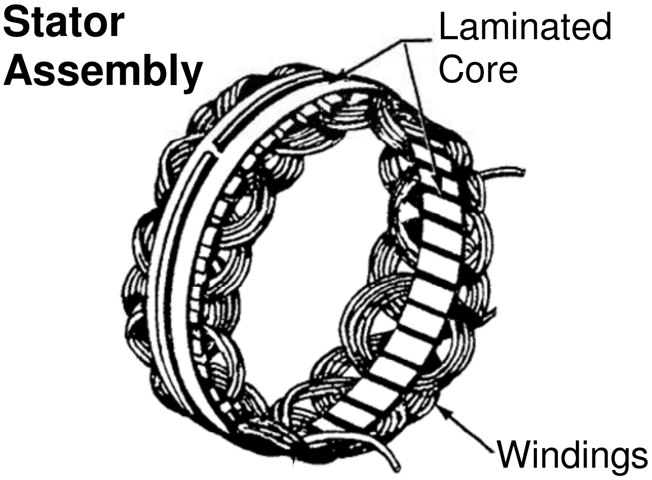

Figure 5

As the stator magnetic field rotates, it induces a current flow and in turn a magnetic field in the rotor core. The stator's magnetic field interacts with the rotor's magnetic field.

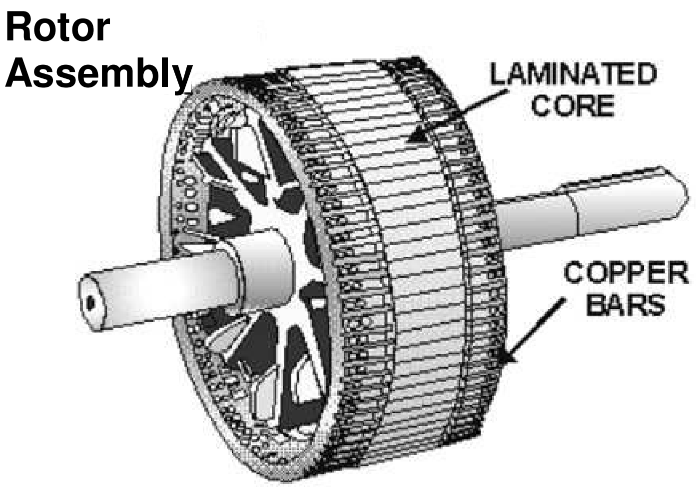

Figure 6

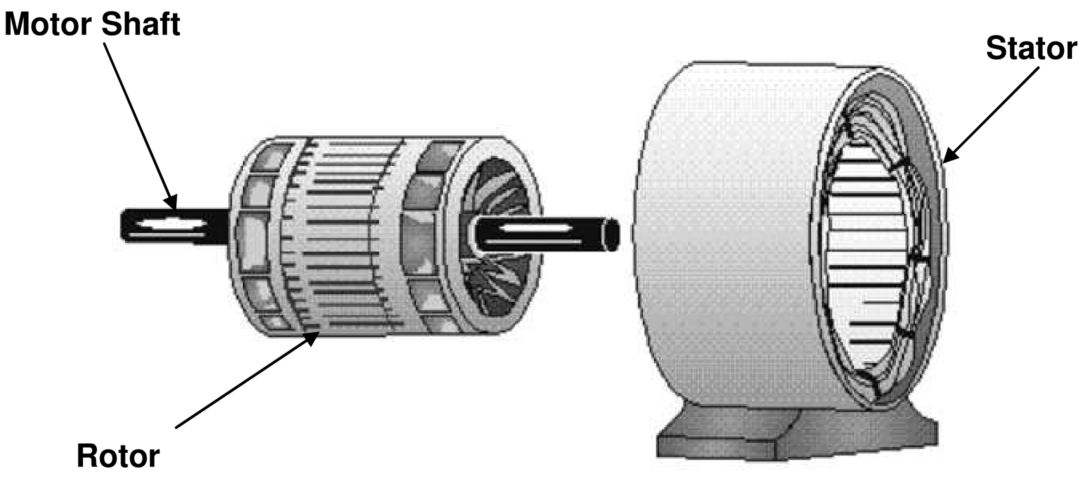

Figure 7

The rotor attempts to align its field with the rotating stator field, and the rotor begins to rotate to follow the stator field. If there were no load on the rotor, the rotor would eventually "catch up" to the stator field and rotate at a synchronous speed. However, since the rotor has mass, and there are other losses within the motor (bearing friction, windage losses, etc.), the rotor will always rotate at a slightly lower frequency than the stator field. The differential in speeds is referred to as "slip", and is simply the ratio of the difference between the synchronous (stator field) speed and the rotor speed to the synchronous speed:

$$Slip = \frac{(f_s - f_r)}{f_s}$$

where f_s is the synchronous speed and f_r is the rotor speed. It is the magnetic flux cutting the rotor conductors as it slips which produces torque. The greater the load on the rotor shaft, the larger the slip and therefore the greater the torque produced.

In an unloaded motor, there is very little slip and very little torque produced. The motor is performing only a very small amount of useful work. Thus, the motor is operating at a very low efficiency. In a heavily-loaded motor, the slip is high (typically about 5%) and most of the input energy total is used to move the load, and the motor is operating very efficiently.

As for power factor, an unloaded motor is similar to a transformer with no resistive load on the secondary. Little resistance is reflected from the secondary (rotor) to the primary (stator). Thus the power line sees a reactive load, as low as 0.1 (10%) power factor. As the rotor is loaded an increasing resistive component is reflected from rotor to stator, increasing the power factor. We can, therefore, use the power factor as an indicator of how large the load is (as a percentage of rated load) and how efficiently the motor is operating.

The Technology (Implementation of the Science)

How can the efficiency be controlled?

As can be seen from the above discussions, the only way to increase the efficiency is to better match the amount of energy delivered to the motor with the amount of energy required to drive the load at the output. The best way to do this is to match the motor size to the load being driven, so that the motor is driving a load that is at the top end of the efficiency curve (i.e., ~75% of the full rated load). In many applications, however, this is not feasible. In many cases, when the driven load can vary over a large range, the motor must be sized for the peak load. In some cases, it is quite likely to see a motor operating at less than 20% of the rated load for significant periods of time (in some cases, such as large escalators, for well over 99% of the time). Since the engineer designing the equipment has no control over the load profile, and the motor must be sized to match the peak load in the application, the only way to improve the efficiency is to reduce the amount of power delivered to the motor.

In an AC motor, there are five components to the power that is lost: Friction loss, Windage loss, Sound loss, Copper loss, and Iron loss. The first three, friction, windage, and sound, are mechanical losses, are fairly constant, and generally represent a very small fraction of the total wasted or lost power. The copper loss is basically the energy lost to heat in the windings and is a function of the load. The iron loss is the energy lost due to eddy currents and hysteresis effects in the magnetic iron cores of the stator and rotor, and is a function of the voltage at the motor terminals – it is independent of the load. A motor is operating most efficiently when the iron loss and the copper loss are equal, which occurs when the motor is driving ~75% to 90% of the full rated load. As the load increases, the copper loss dominates. When the load is very low, the iron loss dominates, representing most of the energy loss. By lowering the voltage, we can reduce the magnetizing current and thus reduce the iron loss. This reduces the total power delivered to the motor, and since the power delivered to the load has not changed, the efficiency is increased. Also, by reducing the magnetizing current, we reduce the inductive component to the total power as well as the total current, and therefore increase the power factor.

Since it is very difficult to measure the actual efficiency of an AC motor directly, and since the power factor and efficiency tend to rise and fall together, it is possible to indirectly monitor the efficiency by measuring the power factor. When the voltage at the motor terminals is decreased, we increase the power factor and the efficiency of the motor. The more we increase the power factor, the more we increase the efficiency. Thus by controlling the power factor, we can indirectly control the efficiency of the motor.

What is the “Nola Energy Savings Technology”?

About 30 years ago (1977), a NASA engineer by the name of Frank Nola patented a method for improving the efficiency of lightly loaded single phase induction motors by measuring and reducing the phase angle (“lag” in Figure 3 above) between the voltage and current waveforms. In the next few years, Nola patented several improvements to the technique, along with a version for improving the efficiency of lightly loaded three phase induction motors.

When we refer to the Voltage in an AC circuit, we are really referring to the RMS Voltage (V_{rms}) which is a measure of the effective voltage, and can be thought of as the equivalent DC voltage required to deliver the same amount of power into a load. Mathematically, the RMS (Root Mean Square) is the square root of the mean value of the squares of the instantaneous voltage. Since AC voltage is a sinusoidal function, the voltage varies between the positive and negative peak values (Figure 8). The RMS voltage is approximately equal to 70% of the peak voltage when the voltage is a true sine wave (there is a lot of math and physics behind this which we won’t go into at this time).

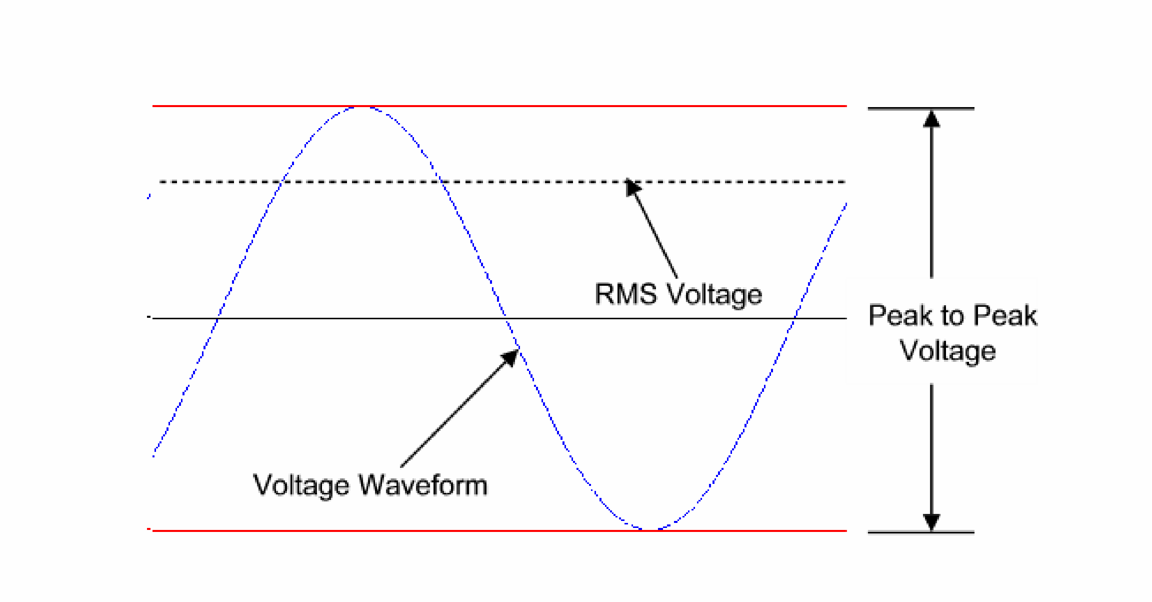

Figure 8

However, if we were to remove a portion of each cycle, so that the voltage is equal to zero for some portion of each cycle, then the RMS value, which can be thought of as being based on the area under the curve (blue shaded area in Figure 9), will be reduced. The more of each cycle we remove, the lower the voltage goes.

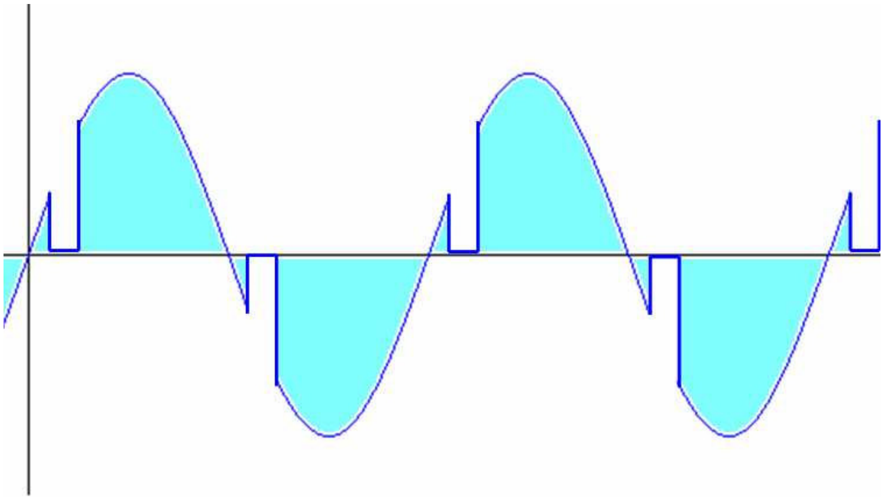

Figure 9

Essentially, the Nola power factor controller reduces the voltage delivered to the motor by damping the voltage signal for a portion of every half cycle, reducing the RMS voltage delivered to the motor.

How is the Power Genius™ different?

The Power Genius™, while it is based on the Nola technology, is much improved. While the basic functionality (improving power factor and efficiency by reducing the voltage) remains, Power Efficiency Corporation has made a number of proprietary (most of them patented) improvements on the basic design, which resolve a host of problems that have been encountered. **It is because of these improvements that the Power Genius™ works on a broader range of motors than other Nola-based devices on the market.**

Phase balancing: While the Nola device was more than adequate for the motors that were around 30 years ago, modern (more efficient) motors tend to go into an unstable vibration mode under certain conditions. PEC solved this problem with a phase-balancing circuit which smoothes out the motor voltage signal at the comparator that is the heart of the Nola device. Since this patented circuit is found only on the Power Genius™, PEC's devices work on a much broader range of motors than any other Nola-based device on the market.

Fast response: Another problem with the Nola device was that it had difficulty responding to a rapid increase in the load on the motor such as what is encountered when a large mass is dropped onto a conveyor, or an elevator goes from idle to lifting a full car. With Nola's device, the motor would tend to stall out. The Power Genius™ incorporates a proprietary "fast response" algorithm that allows it to apply full power to the motor when required. Again, few competing devices on the market have anything remotely similar, and none have PEC's proprietary method which also incorporates a boost response that resolves a comparator signal problem during rapid load increase.

Power savings set-point control: The Nola device was essentially permanently set to maximum power savings as long as the device was in-circuit. The Power Genius™ incorporates an effective means of controlling the degree to which the device affects the power delivered to the motor. Because of this, a standard PEC controller can, in effect, be customized for every application without requiring a custom build process. Also, since the device also functions as a configurable soft-starter, the set-point can be configured to reduce or eliminate the power-savings functionality, allowing for troubleshooting motor problems with the device still in-circuit.

Application targeting: As noted above, there are certain applications where this technology is a perfect fit, and there are others where this device has no effect whatsoever. PEC concentrates its sales and marketing efforts only on those applications where the Power Genius™ will have the greatest effect, thereby ensuring a consistently satisfied customer base and a wide variety of application case studies that support the efficacy of our device.

Real World Application

How does improving efficiency reduce my power bill?

The bill most of us receive from the power company reflects the amount of real power (P from the equation above) that is delivered. The reactive component (Q from above) is returned to the source (the power company) and doesn't affect the billing (unless there is a power factor penalty, but this normally applies only to business customers, and is corrected in bulk at the facility entrance rather than at individual loads). The real power is normally charged in increments of the kilowatt-hour (kWh), which is one kilowatt of power delivered for one hour. The power that is lost (such as the iron and copper losses) is real power, which appears as a real charge on your power bill. By increasing the efficiency, and reducing the loss, you are reducing the amount of power consumed and that reduces your power bill.

What kind of reductions will I see?

That will depend on the load profile of your application. If the motor spends a significant time unloaded or lightly loaded, then the reduction from improved efficiency will be a significant percentage of the power consumed without improvement. Of course, since your bill reflects charges for kWh, if the application is a very small motor that consumes little power even fully loaded, a significant fraction of a small amount is still a small amount (although this is offset somewhat when we consider that smaller motors tend to be inherently less efficient). However, in applications with larger motors, that savings can translate to some decent money.

As an example, let's take a hypothetical 40 HP, 460V motor running a hotel escalator. Nameplate info tells us that the FLA is 52 amps, the efficiency at full load is 92%. However, since the motor was sized to be able to drive a full load (1-2 persons on every step), this motor spends almost all of its time very lightly loaded. Let's further assume that we measure the power consumption by this device under normal conditions, and it draws an average of 6kW. Since the escalator runs 24 hours a day, 7 days a week, a conservative estimate (allowing for downtimes for maintenance, etc.) would have the escalator running 8700 hours per year. This escalator then consumes 52,200 kWh each year, which at $.08/kWh (commercial power rates in southern Nevada) gives us $4176 in power costs per year. If we can save 30% of this power by improving the efficiency, that is <u>over $1,250 a year in savings</u>, a not insignificant dollar figure. If this same escalator were in the San Francisco Bay Area in California, where commercial power rates are in excess of $.12/kWh, the escalator would cost $6264 per year to operate, and the same <u>30% would save more than $1850</u> every year. As power rates continue to rise, the savings become ever more significant.

Obviously, different applications will have different savings percentages and different power consumption. However, if we only use this technology on applications that run lightly loaded most of the time, we can generally achieve 20% to 40% savings.

Why should I believe you?

The escalator in the above example is a real life application. The power measurements (Figure 10), including the power savings noted above, were made by Nevada Power Company, the electric utility serving southern Nevada (including Las Vegas). Since these measurements were made to determine whether or not this customer would be eligible for a rebate based on power savings (and based on these results, they are), the savings are certainly an accurate assessment of this application of the Power Genius™ controller.

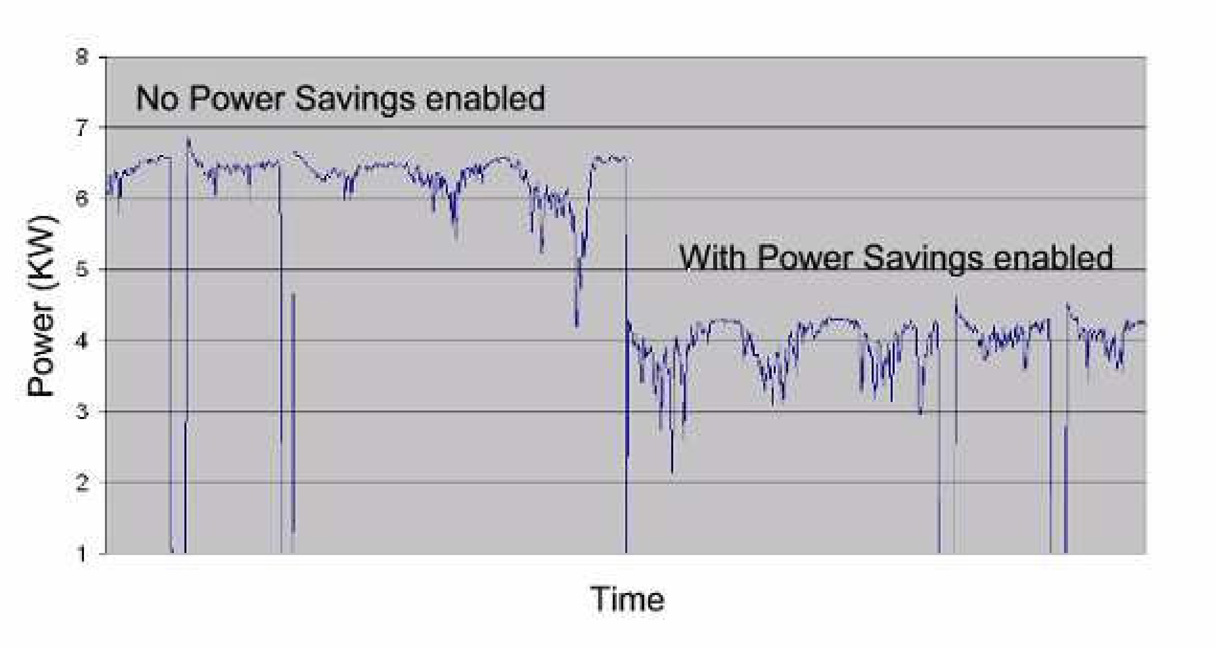

Figure 10

The two attached files include the above case study as well as the case study for another escalator application. These are representative of the savings that can be realized when the Power Genius™ is mated to appropriate applications.