E-save TECHNOLOGY

White Paper

Motor Efficiency Controllers

THE SCIENCE BEHIND MOTOR EFFICIENCY CONTROLLERS

What is Motor Efficiency?

- If AC induction motors would operate at 100% efficiency, every kilowatt of power delivered to the motor would be converted to useful work at the motor shaft. However, this is not the case. In many cases only a percentage of the delivered power is converted to useful work.

- The **Efficiency-of-a-Motor** is defined as the ratio of power delivered by the motor at the shaft to the power delivered to the motor at the terminals.

Efficiency (of Motor) = Motor Power Out (at Shaft) / Electrical Power In (at Terminals)

Electrical Motor Efficiency

- The efficiency curve for typical standard efficiency AC motors is shown in Figure 1.

- AC motors operate most efficiently at around 75% of full rated load, with the efficiency falling off only slightly until somewhere below 50% of full load, where the efficiency begins to drop significantly.

- Larger motors are generally more efficient so the load percentage has to drop more before the efficiency starts to drop.

- NEMA Premium Efficiency motors are designed to have full load motor efficiency above 80% for all size motors and over 93% for motors above 100Hp, but the efficiency will still drop below 60% at low loads.

- Therefore, even large NEMA Premium Efficiency motors will run very inefficiently at loads under 30%.

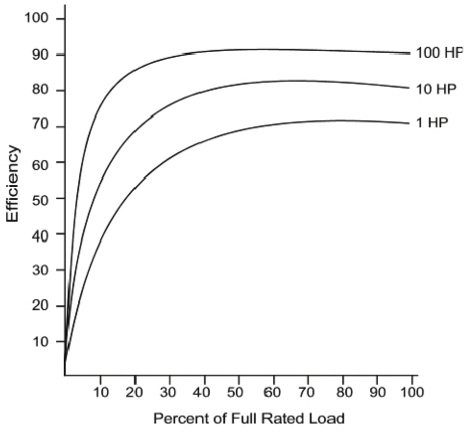

Figure 1

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.
- When reactive elements, such as capacitors or inductors, are present the energy stored in these elements result in a time difference between the Current and Voltage waveforms.
- With an inductive load, the current lags behind the voltage as shown in Figure 2.

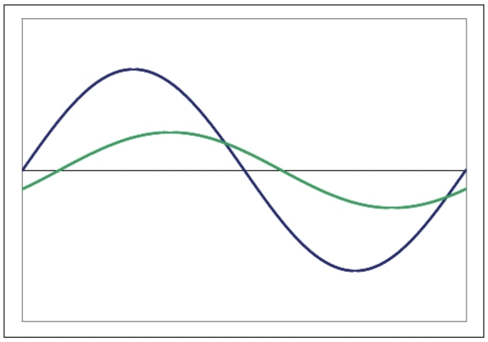

Figure 2

- 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, all 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.

- A motor with a **low-Power-factor** more has more energy return to the source which makes it unavailable to do work at the load.

- Therefore, 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**.

AC Power Flow

- AC power flow has three components:
    - **Real power** (P), measured in watts (W), which can be thought of as the work performed by the motor;
    - **Reactive power** (Q), measured in reactive volt-amps (VAr), which can be thought of as the current that doesn't perform work and is stored in the circuit and generally given off as heat or returned to the source;
    - **Apparent power** (S), measured in volt-amps (VA), which can be thought of as the power you pay for, to perform the work of the motor.

- **Real power** (P) is the capacity of the motor for performing work in a particular time.

- Due to reactive elements of the load, the **Apparent power** (S), 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** (Q) is a measure of the stored energy that is reflected to the sources during each alternating current cycle.

- The **Power factor** can be expressed as **P/S,** or **Real power** divided by **Apparent power**.

- 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).

Power Factor and Motor Efficiency

- While **Power factor** and **Motor efficiency** are not directly related, there is a physical correlation between the two, which will be explained in the following discussion of **Slip** and **Torque**.

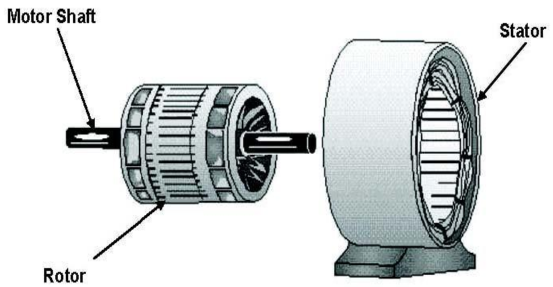

Figure 3

- In an AC motor, the input power is used to magnetize the stator core. (See Figure 3)

- As the **stator's-magnetic-field** rotates, it induces a current flow and a magnetic field in the rotor core.

- The stator's-magnetic-field interacts with the rotor's magnetic field.

- The rotor attempts to align its field with the stator's-magnetic-field's rotation, and the rotor begins to rotate to follow the stator field.

- However, since the rotor has mass, and there are other losses within the motor, this creates a **load-on-the-rotor-shaft** which will always causes it to rotate at a slightly lower speed than the stator's-magnetic-field.

- If the rotor's rotational speed was to achieve the same speed as the stator's-magnetic-field rotation, the latter would have no relative motion to the rotor.

- The stator's-magnetic-field has to have relative motion (speed difference) to the **conductor-windings** on the rotor in order for the force lines of the stator's-magnetic-field to exert on the conductor windings to produce **Torque** on the rotor.

- This speed differential is referred to as “**Slip**”, and is simply the ratio of; the speed of the rotor relative to the strator’s-magnetic-field speed; to the strator’s-magnetic-field speed.

- When the rotor **Slips** relative to the rotational speed of stator’s-magnetic-field, this causes the lines of force of the stator’s-magnetic-field flux to operate on the rotor’s conductor windings to produce **Torque**.

- It is the magnetic flux cutting the rotor conductors during **Slip** which produces **Torque** which allows the motor to do useful work and produce **Real power.**

- 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, **Real power-is-minimized,** and motor operation **is** at **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. Thus **Real Power-is- maximized** and motor operation is at **high-efficiency**.

- As for **Power factor**;
  - An **unloaded-motor** is similar to a transformer with no resistive load on the secondary. Little resistance (little work on load) is reflected from the secondary (rotor) to the primary (stator). Thus the power line sees a reactive load (most power returned to source), as low as 0.1 (10%) **Power Factor**.
  - As the **rotor-is-loaded**, an increasing resistive component (work done on load) 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 the **Motor efficiency**.

E-Save Technology®

- 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 which is generally above 75% of the motor’s full rated load.

- However, in many applications, when the driven load can vary over a large range, the motor must be sized for the peak load. Since the engineer designing the equipment has no control over the load profile, the motor must be sized to match the peak load in the application.

- As a result, it is common to see a motor operating at less than 40% of the rated load for significant periods of time.

AC Motor Power Loss Sources

- 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 loss, Windage, loss, and Sound loss, 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.

Voltage-Based AC Motor Low-load Power Saving

- 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 consumed by the load has not changed (during low load), the **Motor efficiency** (Power Out/Power In) is increased.
    - Also, by reducing the **Magnetizing-current**, we reduce the inductive component to the total current, as well as, the total power (in the circuit), and therefore increase the **Power factor**.

- Since the **Power factor** and **Motor efficiency** tend to rise and fall together, it is possible to indirectly monitor the **Motor Efficiency** by measuring the **Power factor**.

- When the voltage at the motor terminals decreases, The **Power factor** and the **Motor efficiency** is increased. Therefore, an increase in **Power factor** is also an increase in **Motor efficiency**.

Nola Technology versus E-SaveTechnology®

- In 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 or lag 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.

- While E-Save Technology is based on the Nola technology, it is much improved. The basic functionality of improving Power factor and efficiency by reducing the voltage remains the same.

- E-Save Technology has a number of proprietary and patented improvements that resolve many of the issues that have been encountered with product using the Nola patents.

- It is because of these improvements that E-Save Technology works on a broader range of motors, applications and can save more energy.

E-Save Technology on Voltage and Current

- In the context of this paper Voltage is equivalent to the RMS voltage (Vrms), which is a measure of the effective voltage.

- Since AC voltage is a sinusoidal function, the voltage varies between the positive and negative peak values (Figure 4).

- The RMS voltage is approximately equal to 70% of the peak voltage when the voltage is a true sine wave.

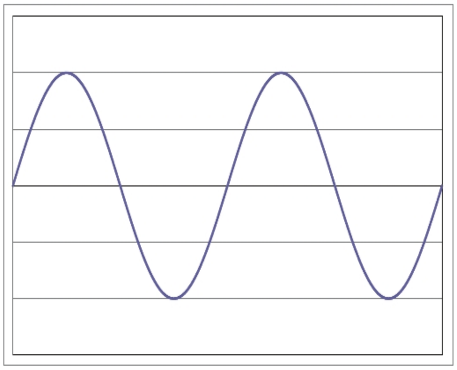

Figure 4

- 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 will be reduced.
    - Therefore, the longer the time that voltage is removed, the lower the Voltage goes (Figure 5).

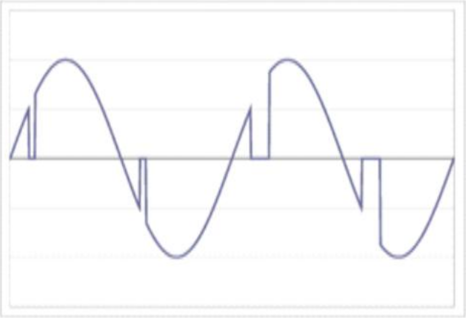

Figure 5

- Just like Voltage, Current is equivalent to the RMS Current (Arms) and is shown in Figure 6.

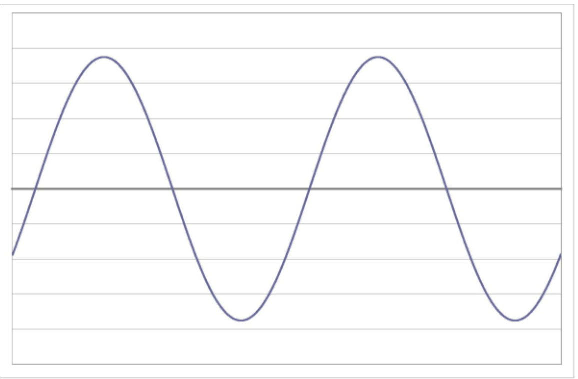

Figure 6

- The longer this flat portion, or no current being sent to the motor, the lower the peak of the sine wave.
    - Therefore, just like Voltage, the longer the time that current is removed, the lower the Current goes.

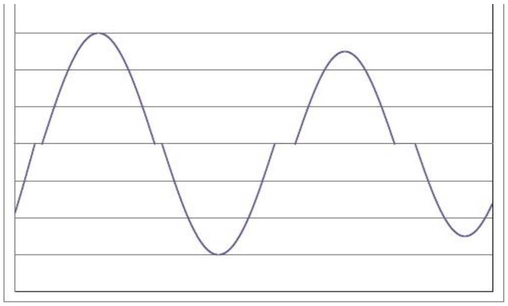

Figure 7

- This reduction in Voltage and Current to the motor will result in reduced motor magnetic flux;
    - Which will result in small changes in Slip.

- Since Slip, Speed and Torque have linear relationships;
    - The Slip change will provide a corresponding change in Speed and Torque.
    - However, these changes are very small and in real applications the resulting Speed and Torque changes will be under 0.5% when the Motor Efficiency Controller is saving the most amount of energy.

- Also, from above we know that Iron Losses and Copper losses are the major factors to motor efficiency.

- Since Iron losses are directly related to Voltage, and Copper losses are directly related to Current,
    - Both of the major losses of a motor are directly impacted by the reduction of Voltage and Current by E-Save Technology.
    - The Current reduction will result in significant energy savings when a motor is running lightly-loaded and therefore operating inefficiently.
- The power that is lost when a motor runs inefficiently is part of that which appears as consumption on your utility bill. By using E-Save Technology to increase the efficiency of the motor you are reducing the amount of your power consumption.

Applications

- The power measurements in Figures 8 and 9 below were made by a utility company during the installation of Power Efficiency's Motor Efficiency Controller with E- Save Technology.

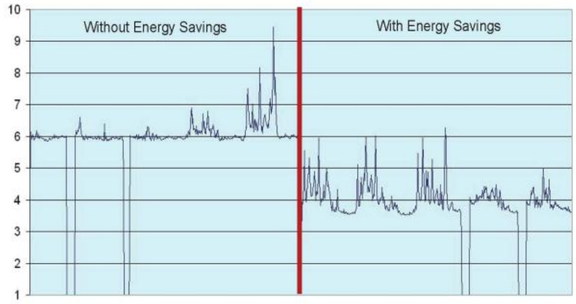

Figure 8

Hotel Escalator

- The application shown in Figure 8 is a 40 HP, 460V motor operating a hotel escalator.
- The motor nameplate info tells us that the FLA is 51 amps and the efficiency at full load is 92%. However, since the motor was sized to be able to drive a full load of 250lbs per step, the motor spends a considerable amount of time lightly loaded and the motor maybe operating at 30% efficiency during these times.
- The actual power consumption by the escalator under normal operating conditions averages 6.1kW.
- Since the escalator runs 24 hours a day, 7 days a week it is estimated that the escalator will operate 8760 hours per year.
- Therefore, this escalator then consumes 53,436 kWh each year and at $.12/kWh a yearly power cost of $6412.
- In this case the savings was 34% of the consumed power by improving the efficiency of the motor with E-Save Technology and the customer saves over $2100 every year in power costs.

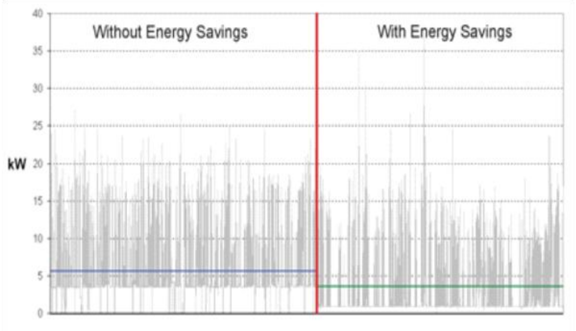

Figure 9

Industrial Plastic Granulator

- The application shown in Figure 9 is a 50 HP, 460V motor operating an industrial plastic granulator.
- In this application the motor was sized to grind up plastic waste and bottles into small granules that can be reused or resold.
- Since this was a batch process the motor spends a considerable amount of time lightly loaded with no plastic waste or bottle in the equipment and the motor is just spinning small blades through air.
- The actual power consumption by the granulator under normal operating conditions averages 5.69kW and with E-Save Technology it was reduced to 3.54kW.
- This savings of over 30%, resulted in $1597/year of energy savings at the current price of $.09/kWh.
- In addition, an annual reduction of 15 tons of CO2 resulted from the use of a Motor Efficiency Controller with E-Save Technology in this application.