Reducing Energy and Life Cycle Costs using Sinusoidal Motor Controllers

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Ever increasing electricity prices, concern for the environment and CO2 emission, and business demands for increased profitability, lead companies to seek energy saving solutions and reduce the total cost of ownership (TCO). This paper explains how energy saving, increasing motor life expectancy and smooth motor startups can be achieved to reduce the overall Life Cycle Cost (LCC) from initial costs to operation and maintenance costs.

The paper starts out explaining the different costs of using electrical motors, and goes on to address ways to increase investment value for money, smooth and linear motor start up and reducing the energy consumption. Starting from theory, exploring the history of energy saving devices, introducing modern solutions and presenting case studies of different applications provide comprehensive information on how to reduce the overall life cycle cost of induction motors.

***Index Terms*—Energy conservation, Harmonic distortion, Induction motors, Life Cycle Costing, Motor economics, Motor protection, Reactive power.**

I. Motor Costs

The cost of an electrical motor, over its lifetime, is a combination of its initial cost, its operation and maintenance costs, and the cost of disposal. Fig. 1 illustrates the relationships between the different costs, according to the United States Department of Energy.

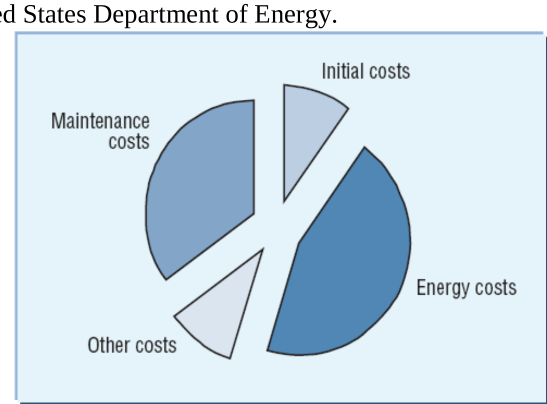

Fig. 1. Life Cycle Cost of Electrical Motor (source: US DoE)

The overall costs are calculated according to:

$LCC = C_{IC} + C_{IN} + C_E + C_O + C_M + C_S + C_{ENV} + C_D$

LCC = life cycle cost

C_{IC} = initial costs, purchase price (motor, system, auxiliary services)

C_{IN} = installation and commissioning cost (including training)

C_E = energy costs (predicted cost for system operation, including drive, controls, and any auxiliary services)

C_O = operation costs (labor cost of normal system supervision)

C_M = maintenance and repair costs (routine and predicted repairs)

C_S = down time costs (loss of production)

C_{ENV} = environmental costs (contamination from pumped liquid and auxiliary equipment)

C_D = decommissioning/disposal costs (including restoration of the local environment and disposal of auxiliary services).

II. Initial Costs

The initial costs consist of equipment purchase, installation and commissioning costs.

Initial costs can be reduced in two ways, which can be implemented simultaneously:

- Reducing the purchase, installation and commissioning costs
- Increasing the life expectancy of the equipment

While every purchasing manager makes every effort to reduce the initial costs, increasing the life expectancy is usually not considered. The life expectancy of the equipment can be increased both by selecting durable equipment and by improving the machinery's operating conditions, thus enabling it to work longer.

There are three parameters that affect the life expectancy of an electrical motor:

- Mechanical stress – vibrations, friction, balance, etc.
- Voltage stress – voltage levels, waveform cutouts, transients and partial discharge
- Working temperature – every 10 degrees Celsius causes 50% reduction in insulation materials (Arrhenius law)

This means that reducing the motor stress and temperature will increase the life expectancy and reduce the net present value (NPV) of the initial costs of the motor.

Like motors, the electrical infrastructure is also affected by the voltage stress and temperature.

III. Operation Costs

A. Energy Efficiency

The operation costs include the energy costs and the labor cost of normal system supervision. Responsibility for reducing the labor costs lies with the process engineers; reducing the energy costs is the responsibility of the electrical engineers.
To reduce the energy consumption it is necessary first to understand that only energy that is being wasted can be saved. In a typical electrical network with motors, three major components that waste energy can be found: motors, conductors (cables) and transformers.

B. Motor Efficiency

1) What is motor efficiency?
Efficiency is the ratio between the amount of mechanical work the motor performs and the electrical power consumed it consumes to do this. Motor efficiency is usually represented by a percentage from 0% to 100%. In practice, 100% efficiency is not possible due to the motor losses. According to the principle of energy conservation, the total input and output energy must be equal. This means that the losses are wasted energy expressed as motor heat.
The motor efficiency depends on two major parameters:

- Motor design – the materials, construction, rated power etc.
- Operating conditions – the motor load, power quality and temperature

The effect of motor load on motor efficiency is shown in Fig. 2 below:

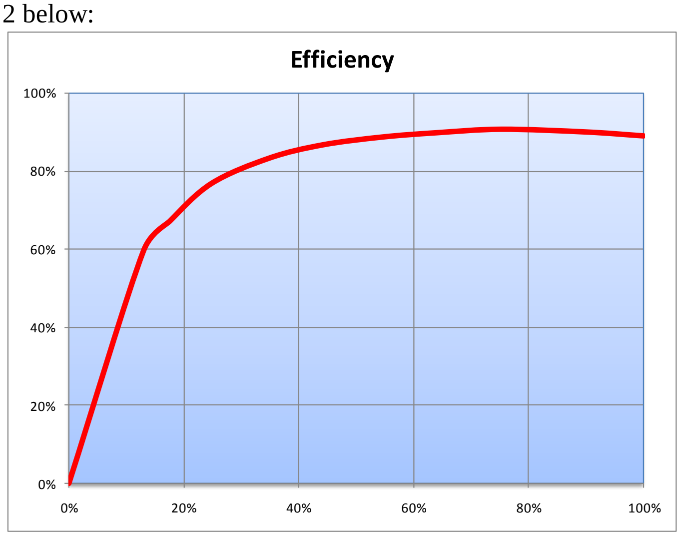

Fig. 2. Motor Efficiency vs. Motor Load

2) What is Power Factor and how is it related to Efficiency?
There are three types of power definitions in an AC electrical network:

- Active power, or real power – the power that is capable of working and is measured in kW (kilo-watts) and represented by the letter P.
- Reactive power – power that flows to the motor and returns to the network without performing any work, however still requires "transportation", meaning sufficient cable cross-sections and associated heat. Reactive power is measured in kVAr (kilo Volt-Ampere Reactive) and is represented by the letter Q.
- Total power, or apparent power – a combination of the active and reactive power, measured in kVA (kilo Volt-Ampere) and represented by the letter S.

The three types of powers are related to each other as shown in Fig. 3 below:

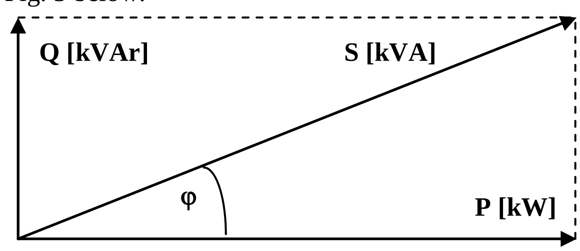

Fig. 3. Power Triangles

The phase between the S vector and the P vector is called φ (phi) and the ratio between P and S is equivalent to Cos (φ) or Power Factor (PF). The Power Factor also represents the ratio between the active and the total Power. Since reactive power does not perform any work, the PF indicates the percentage of useful energy from the total energy, and it is best to have it as close to unity as possible. Low PF means low efficiency and high losses.
Fig. 4 shows the PF vs. motor load. The PF, which is related to the motor's internal efficiency, as well as to the efficiency of the entire network, is reduced when the motor load is less than 70%.

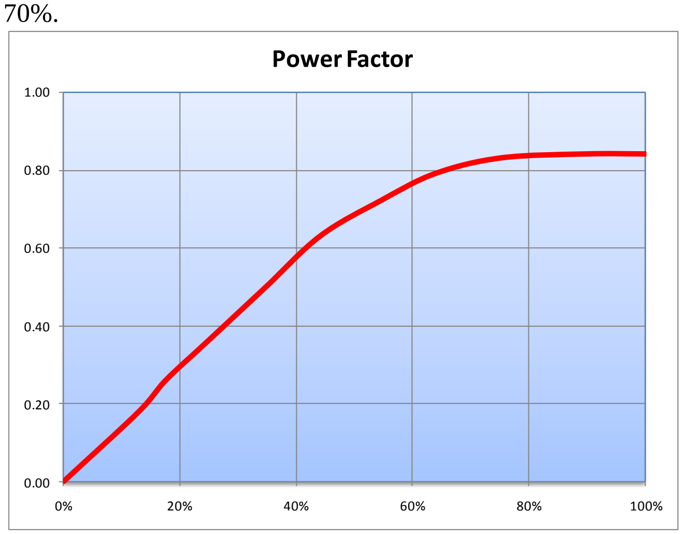

Fig. 4. Power Factor vs. Motor Load

3) *Frank Nola Patent*

As can be seen from Fig. 2 and Fig. 4, when the load on the motor is partial, both motor efficiency and network efficiency are reduced. In 1977 Frank Nola, a NASA engineer, patented a system to take advantage of this fact to improve the motor efficiency and its power factor. Nola's idea was to reduce the motor voltage to a single phase motor, thereby reducing its full rated power, increasing its power factor and reducing its wasted power. Following the first patent, Nola registered subsequent patents to his original idea with regard to three phase motors and improved performance. In 2000 Nola received the NASA Marshall Center Patent Award.

4) *Harmonics and Harmonics Effects*

Nola's patent is to reduce the voltage by chopping part of the voltage waveform, which reduces the average voltage (RMS). The main disadvantage of this method, as well as other electronic switching technologies, is the generation of harmonics.

Harmonics are waveforms at higher frequencies that are integer multiplications of the fundamental. Fig. 5 shows a pure sinusoidal waveform with 5^{th} order harmonic current and the distorted waveform.

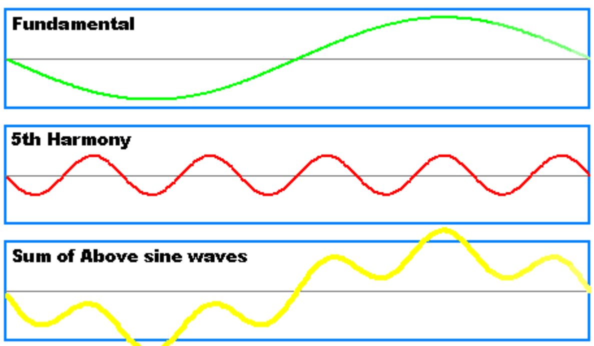

Fig. 5. Harmonic Distorted Waveform

Harmonics issues are among the most difficult to solve in the electrical field. Some of the implications of harmonics are:

- Increased losses throughout the network – conductors, loads, transformers and more.
- Overheating that reduces equipment and infrastructure lifetime and may even cause fire.
- Negative force in motors from counterclockwise (CCW) harmonics (the 5^{th} harmonic order is the most dominant in the industry and works CCW to the fundamental, thus creating a negative force that breaks the motor).
- Unexplained breaker tripping due to extreme overheating.
- Controller malfunction and other unexplained phenomena due to distorted waveforms.

Thomas Mark Empson explains, in his publication, that in some cases the waste due to non-sinusoidal currents will be greater than the saving.

C. *Network Losses*

The network losses are conduction losses derived from the resistance of the electrical conductors. The major parameters that affect the conducted losses are the wire cross section, wire length, ambient temperature and harmonics (which cause skin and proximity effects).

If the conductor length and resistance are known, losses can be calculated according to:

$P_{losses}=I^2R$, $R=r_m$*Length, r_m is the resistance per centimeter.

The resistance can be measured using a high current loop tester, which is not commonly available. A good alternative is to use the voltage drop analysis as follows:

Where:

V_S=Voltage at the transformer secondary

V_L=Voltage at the load

$V_{\%}$=Voltage drop in % = $100\%-V_L/V_S$

$$P_{LOSSES}=(V_S-V_L)\times I=V_{\%}\times V_S*I=V_{\%}\times S\ (kVA)=V_{\%}\times P/PF$$

Different standards provide different limits on voltage drops and state different values from 2% to 5%. This means that for a power factor of 0.5 and voltage drop of 4%, the losses are 8% of the active power.

D. *Transformer Losses*

Transformers are one of the most dominant contributors to energy losses in the electrical network. The transformer losses include the winding resistance, Hysteresis losses, Eddy currents, magnetostriction and mechanical losses. In addition, in the presence of harmonics, the skin and proximity effects create additional winding losses.

Transformer losses depend on transformer design (e.g., copper vs. aluminum), transformer load (no-load losses are fixed), transformer size (larger transformers are more efficient than smaller ones), ambient temperature and harmonics (harmonics dramatically increase transformer losses and requires the use of special K-Transformers).

Typical transformer losses in low harmonics conditions and 80% load are estimated to be between 2% to 5%. The losses are proportional to the kVA consumption but increase the kW charges, which means reducing the kVA consumption will subsequently reduce the kW consumption.

E. *Air Conditioning*

Due to the law of energy conservation, there is no such thing "lost" energy. The "lost" energy is converted into thermal energy (heat). If a facility is air-conditioned, every "lost" watt will be cooled. Air conditioners work on the concept of heat exchange, which allows them to work at efficiency higher than 100%. The Coefficient of Performance (COP) is the ratio between consumed energy to cooled energy. Modern air conditioners have a COP between 2 and 3, which means 0.5W to 0.33W of energy for each 1W lost energy. In other words, if the facility is fully air conditioned, all losses should be multiplied by 1.33 to 1.5.

F. Utility Charges

Utilities, like energy users, waste a lot of energy in their transmission and distribution network. In order to reduce their losses they encourage energy users to consume the energy efficiently. This is done by defining their charges based on efficiency parameters, depending on their needs. The most common charge is low power factory penalties. Other common charges are peak demand and capacity charges (kVA charges).

The SinuMEC can reduce utility charges by increasing the power factor and reducing the peak demand and kVA.

IV. Maintenance Costs

Maintenance costs are usually the least considered costs, even though these are very significant in the motor life cycle. In some applications these are more than 50% of the costs.

The maintenance costs include the repair costs (labor and parts) and the downtime costs (lost revenues, lost labor cost, other machines that cannot operate, etc.). It is estimated that unscheduled downtime is ten times more expensive than scheduled downtime.

Downtime can be reduced by increasing reliability. Smoother startup, using the SinuMEC reduced voltage starting technique, is one example of increasing reliability. Another example is reducing the total current and the harmonics to lower the working temperature. Reliability can be increased up to 10% using SinuMEC.

V. Sinusoidal Motor Efficiency Controller

The new generation of motor efficiency controllers provides the benefits of Nola's concept without introducing harmonics (and even mitigates some existing harmonics, if there are such).

Power Electronics Systems introduced the SinuMEC – Sinusoidal Motor Efficiency Controller, which utilizes patented transformation technology, using a specially designed power transformer, electro-mechanical contactors and a sophisticated controller. The unique architecture enables pure sinusoidal voltage control, while the use of simple components makes the apparatus very reliable.

In addition, due to the proprietary design, the overall size is several times smaller than conventional full transformation, providing a *cost effective solution* and *very low self losses*.

VI. Economical and Environmental Benefits

The use of the Sinusoidal Motor Efficiency Controller (SinuMEC) provides significant benefits:

- Reduces the electricity bill by reducing the kWh consumption, reactive energy charges and overall network losses
- Increases the motor life expectancy due to less downtime resulting from reduced voltage stress and reduced operating temperature
- The SinuMEC includes integral motor protection functionality to protect the motor from operating under severe conditions
- The sinusoidal voltage control function is used for motor startup
- Smoother startup allows more startup processes, which may provide additional operation benefits such as more frequent shutdown periods and longer overall shutdown time

VII. Case Studies

The SinuMEC is recommended for any AC inductive motor with partial or variable load. Some examples of installations are:

A quarry installed the SinuMEC on *conveyors.* The SinuMEC provided an 18% reduction in the kWh, reducing the current and total power by 48%, the conduction losses by 73% and the reactive power by 58%. The conveyor startup current was limited to 1.76 of nominal and the total return on investment (ROI) was 2.2 years.

The SinuMEC was installed in an escalator in public transportation, resulting in a 20% reduction in the kWh, 40% in the current, 64% in network losses and increased motor lifetime.

Plastic injection molding machines work in cycles with different load over time. A SinuMEC was installed in a 100HP plastic injection machine, achieving a 16% reduction in kWh, 42% in network losses, 38% in reactive power and an increase in the lifetime of the expensive machine, as well as increasing reliability and reducing costly downtime.

VIII. Summary

Installing sinusoidal motor efficiency controllers, which allow voltage control while maintaining the waveform undistorted, can provide significant benefits including energy saving, increased motor life expectancy and easier motor startup. The saving is achieved by reducing all types of energy - kW, kVA and kVAr. The motor life expectancy benefits from the reduced voltage and reduced motor operating temperature, while the easy startup utilizes the reduced voltage startup (RVS) startup method.

Installation of the SinuMEC in various applications, such as conveyors, escalators or plastic injection machines, provided significant benefits and ROI of two years.

