Total System Efficiency

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Total cost of ownership is not just a buzz phrase; it's a philosophy for creating a sustainable business model in today's environment of shrinking resources and increasing energy costs. Based on worldwide energy usage figures (Ref. 1), humans will double their current energy consumption by the year 2035 (a mere 25 years), as shown in Figure 1. Much of the industrial energy being consumed by systems is wasted through inefficiency. For this article, a system will be defined as the following components working together: electrical input power, variable frequency drives, induction motors, gearboxes and transmission elements (chains, belts, etc.).

No single component within a system is 100 percent efficient. Converting some of the intended work output to heat is a necessary evil of any process. However, the amount of heat (wasted energy) created by a process can be minimized through thoughtful and careful selection of individual components.

Each component introduces its own inefficiency to the entire system. Each efficiency is multiplied together to obtain an overall efficiency for the system, as shown in Figure 2. One individual component with a poor efficiency rating has a multiplicative effect on the rest of the system. Look at Equation 1 for a theoretical example of an ideal system where each individual component is 99 percent efficient (η is the symbol used for efficiency).

Even using ideal values, a system with six different components results in 94.15 percent efficiency. Another way to look at this is 5.85 percent of the energy put into this system is merely converted to heat and wasted, and this is with an ideal system. Now let's examine a more realistic system using good, efficient components, as shown in Equation 2.

These good components result in a total system efficiency of 79.76 percent. A staggering 20.24 percent of the input energy is simply converted to heat and wasted. Remember, these are good components. How can we prevent this loss of energy, and where do we have the greatest potential for energy savings (Ref. 2)? The greatest potential gains in efficiency lie in the mechanical components, followed by electronic speed control and increased efficiency motors (Table 1).

Let's break this system down into its individual components and analyze where and how we can recover some of this lost energy.

Electrical Input Power

The first part of our theoretical system is the electrical input power. The majority of industrial electrical loads are inductive as opposed to being resistive or capacitive in nature. This inductive loading causes a shift in the phase relationship between voltage and current as shown in Figure 3. This phase shift results in reactive power. Reactive power is not used by the load to accomplish useful work like real power (kilowatts); it is inefficiency. The reactive power is actually the negative power shown in Figure 4. The phase shift caused by inductive loads can be corrected by introducing capacitance into the

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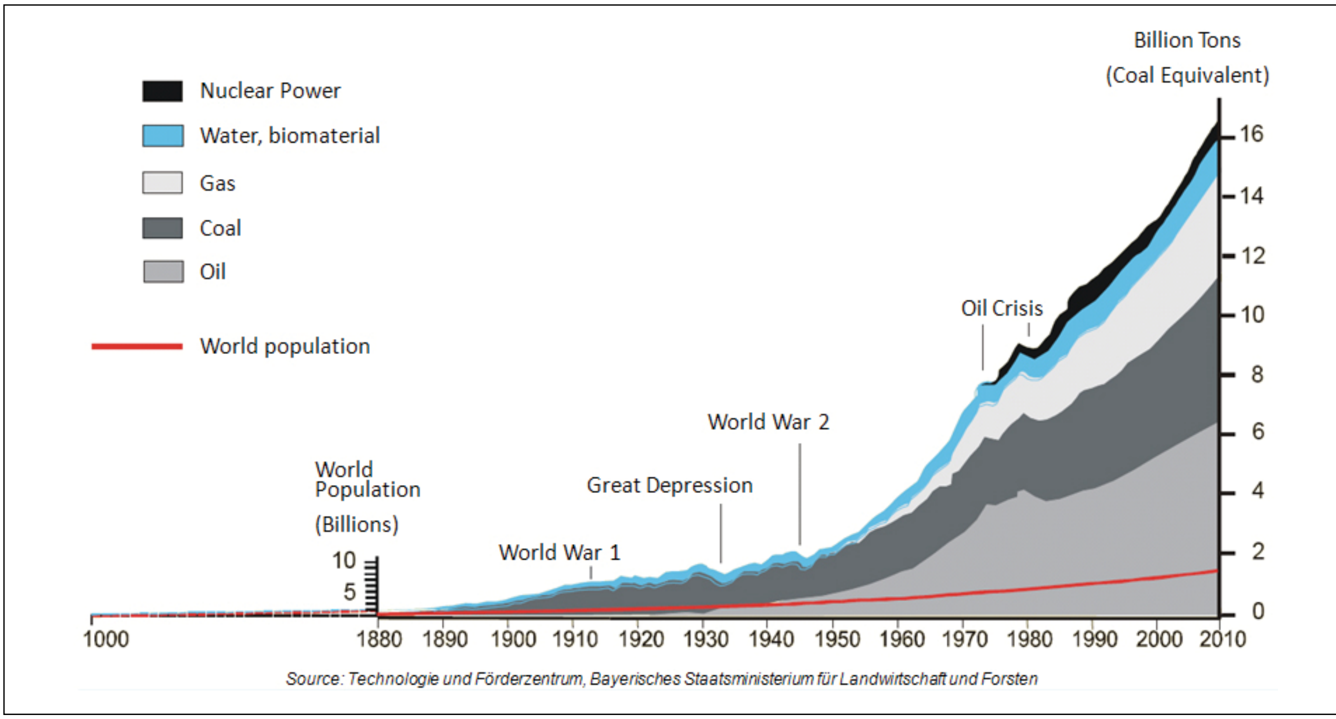

Figure 1—World energy consumption.

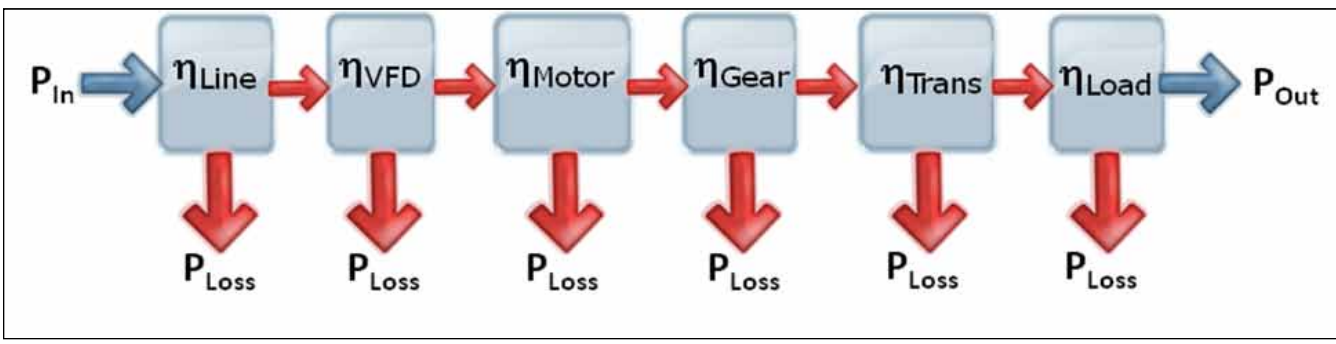

Figure 2—Total system efficiency.

$$\eta_{System} = \eta_{Line} \times \eta_{VFD} \times \eta_{Motor} \times \eta_{Gear} \times \eta_{Trans} \times \eta_{Load}$$

$$\eta_{System\ (Ideal)} = 99\% * 99\% * 99\% * 99\% * 99\% * 99\% = \mathbf{94.15\%}$$

Equation 1—Ideal system efficiency.

$$\eta_{System\ (Good)} = 98\% * 96\% * 92\% * 95\% * 99\% * 98\% = \mathbf{79.76\%}$$

Equation 2—Realistic system efficiency.

Table1—Energy Savings Potential

	Energy Savings Potential
Mechanical System Optimization	60%
Electronics Speed Control	30%
Use of Higher Efficiency Motors	10%

system. Ideally, if the capacitive properties equal the inductive properties of a circuit, then all of the electrical power is used by the load with no reactive power being created. When there is no phase shift and all of the power is being used by the load, all of the power is positive and can be measured in kilowatts as shown in Figure 5.

Electronic Speed Control Devices

Next, we have an electronic speed control device. There is an urban legend out there that adding an electronic speed control device automatically makes a system more efficient. This is not true. Think of it this way: We know that no single component is 100 percent efficient. If we change nothing in a system other than introducing an extra component, what happens to the efficiency? It goes down. While an electronic speed control device can't make a system more efficient, the proper application of such a device can. An electronic speed control device can save energy during the starting of a motor.

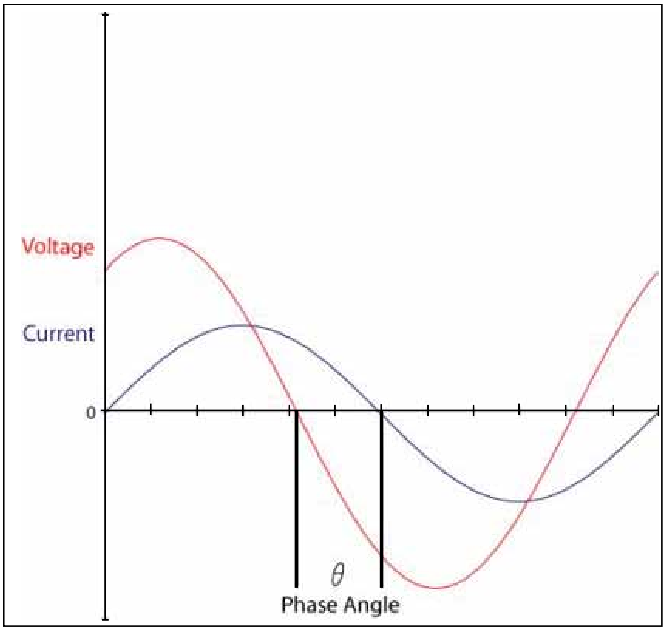

Figure 3—Electrical phase shift.

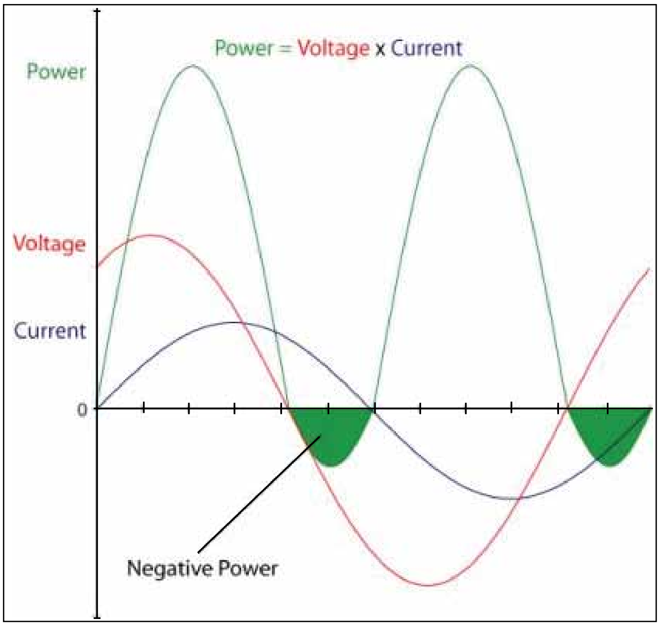

Figure 4—Reactive power.

As mentioned earlier, there is the potential for saving energy, but how? The most effective method is reducing the speed of the system. The majority of losses in any system are from mechanical components (various frictions). All friction losses are either directly proportional to or have a squared relationship to speed. Reducing the speed reduces the friction; reducing the friction reduces the losses; reducing the losses increases efficiency. Other areas of savings with electronic speed control devices are varying manners of recovering the regenerative energy created when an induction motor acts like a generator (during deceleration, overhauling load conditions and downward vertical movement, to name a few ways). One method of recovering regenerative energy is by using a regenerative power supply to recondition the regenerative energy and put it back on the main power supply. Another technique is to link the DC bus of several inverters together and share the regeneration of a decelerating drive to power a linked accelerating drive.

However, there are additional losses associated with electronic speed control devices. The easiest loss to point out is that of the electronic device itself. All of the components inside use energy-processors, resistors, inductors, capacitors, LEDs. All of these components create heat, and heat equals loss. These days, electronic speed control devices are essentially computers. Computers get hot and have losses, as do electronic speed control devices. Moreover, electronic heat loss is not the only inefficiency present in modern electronic speed control devices. Another concept that is often overlooked is that an electronic speed control device converts AC to DC and back to AC. This energy conversion process also yields losses.

A more abstract topic is that of harmonics. The pulse width modulated (PWM) output of the electronic speed control device is actually pulsed DC. The voltage signal does not look anything like the familiar sine wave to which an induction motor is accustomed. This square pulse signal creates harmonics. These harmonics induce a loss in the induction motor itself. The more pronounced the corners of the pulses, the more harmonics that are created, which in turn creates more losses. These harmonics can actually increase the motor losses up to 10 percent (Ref. 3). The increased frequency of a PWM signal also increases the losses of the supply cable running between the electronic speed control and the motor. These cable losses are typically on the magnitude of 1–4 percent. There is some good news on the cable between the source transformer and the electronic speed control device. Because the electronics contain capacitance, there is an improved power factor (compared to operating a motor directly from the mains without an electronic speed control device). This improved power factor can reduce the losses on this cable by about 20 percent.

Induction Motors

The induction motor is the next piece of the puzzle. Great strides have been taken by both standards organizations such as NEMA (*Ed's note: See sidebar page 22*) and the federal government to increase the minimum allowed efficiency of induction motors in the United States (Refs. 4–5). There are basically two ways to increase the efficiency of an induction motor: use better materials during the construction or oversize the active parts (windings, rotor cage and laminates). Both methods are equally effective. Motors may use either or both methods to increase efficiency.

Using better materials during the construction is simple enough to understand. Most rotor cages in standard-efficiency induction motors are aluminum. Aluminum (Ref. 6) is a fairly good conductor and lends itself to inexpensive manufacturing costs, but copper (Ref. 6) is an excellent conductor (approximately 35 percent better than aluminum). A better conductor creates less heat, and therefore reduces the losses (Fig. 6).

Another method to increase the efficiency of induction motors is through over-sizing the active parts of the motor. Imagine an induction motor with a nominal rated current of 1 ampere. Suppose this motor is operated with exactly 1 ampere of load and under these conditions the motor gets warm to the touch, not uncommon in typical induction motor applications. Now imagine that we replace that motor with one that has a nominal current rating of 2 amperes. Keeping the load constant at 1 ampere of current, how would one expect the temperature of the second motor to behave? You would be correct in assuming that the temperature will go down. If the motor is not creating as much heat, the losses are reduced. This is the basic concept behind over-sizing a motor to achieve an increased efficiency rating (Fig. 7).

Bear in mind that both of these situations (using copper for the rotor and over-sizing the motor) result in a few important changes to the operating characteristics. First and foremost, either method will increase the inertia of the motor. Copper is more dense than aluminum, and the shape of an object affects its inertia more than the mass. Additionally, energy-efficient motors are designed for situations where the motor is continuously energized for long periods of time, not applications with high cycling rates.

The Gearbox

Now we get to heart of the matter—the greatest potential for energy savings—mechanics. The gearbox being driven by

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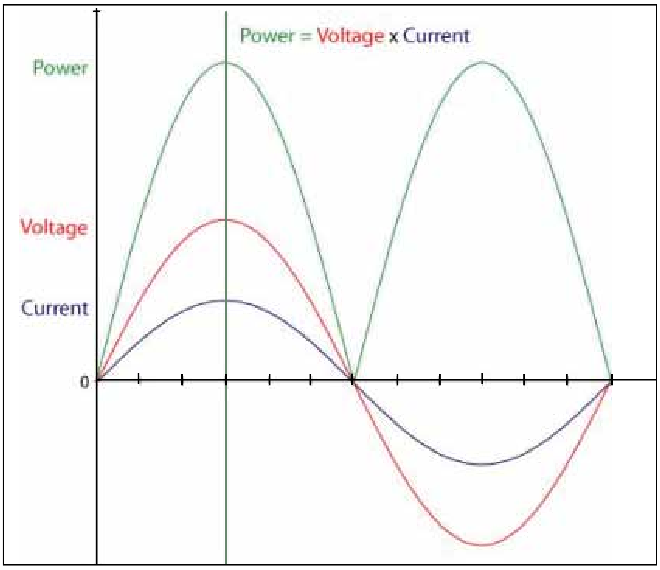

Figure 5—Ideal electrical loading conditions.

Figure 6—Copper rotor bars.

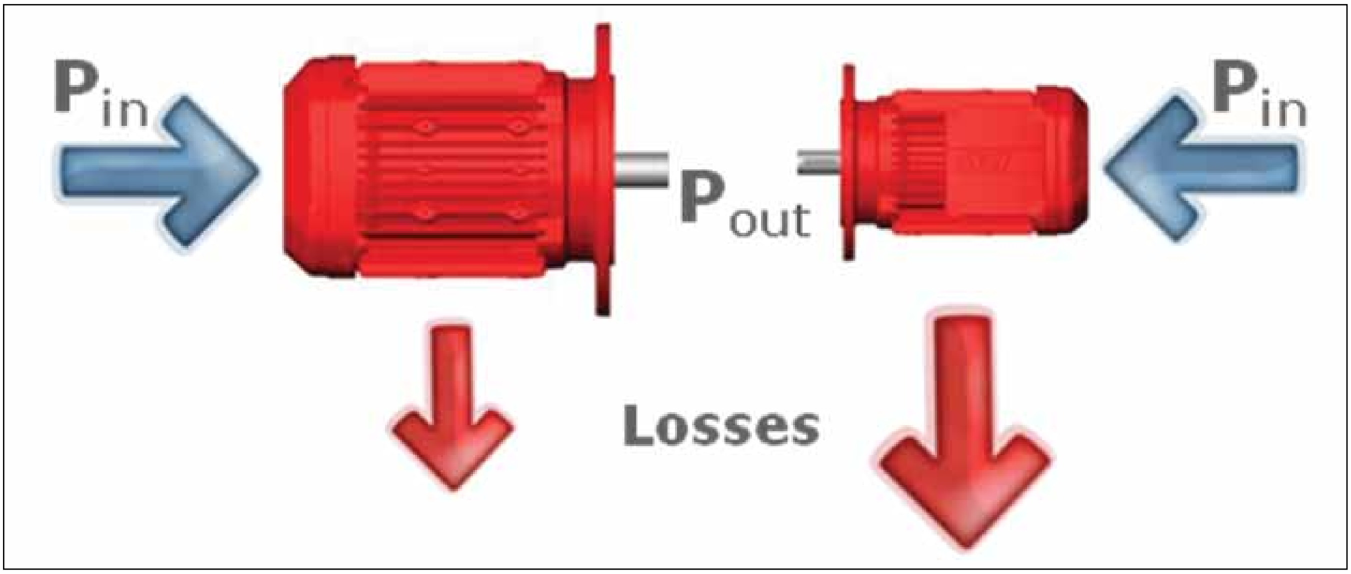

Figure 7—Over-dimensioning a motor to increase efficiency.

the induction motor can be the greatest contributor to inefficiency. There are various losses associated with any component in a system. The main contributors of gearbox losses in order of importance are:

Meshing between the teeth

Gears churning through oil (or grease)

Friction of bearings and seals

Gear Mesh Losses. Gears mesh through a combination of rolling contact and sliding contact. Spur, helical, and bevel gears are considered rolling contact gears, because the majority of the contact is of the rolling type. A typical estimate of the power loss in rolling contact gearing is 1.5 percent per stage. Worm gear sets use mostly sliding contact to transfer torque. The efficiency of a worm gear set is mainly determined by the number of threads on the driver (Fig. 8).

As you can see from the numbers in Table 2, the efficiency of a worm gear set can vary drastically. Without question, certain applications that must withstand heavy shock load or provide increased back-driving resistance may require a worm gear set. But, in comparison to the single-tooth worm gear efficiency (approx. 50 percent in some cases), there are alternatives that can improve the total cost of ownership. Wasting 50 percent of the input energy seems a bit much when the worm gear is not required by the demands of the application (which is not often). Of course, the initial cost of a helical-bevel gearbox is much higher than that of a worm gearbox, but the majority of lifetime cost will be the electricity purchased to run the system. Therefore, it makes sense to think of the total cost, not just the initial purchase price (Fig. 9).

The type of lubricant selected also contributes to the efficiency of a gearbox. Synthetic lubrication can reduce the amount of mesh loss per stage by approximately 33 percent. Using a the rule of thumb that rolling contact gears have a loss of approximately 1.5 percent per stage, using synthetic oil would reduce this loss to around 1.0 percent per stage. How much impact can 0.5 percent really make? Over the life of a

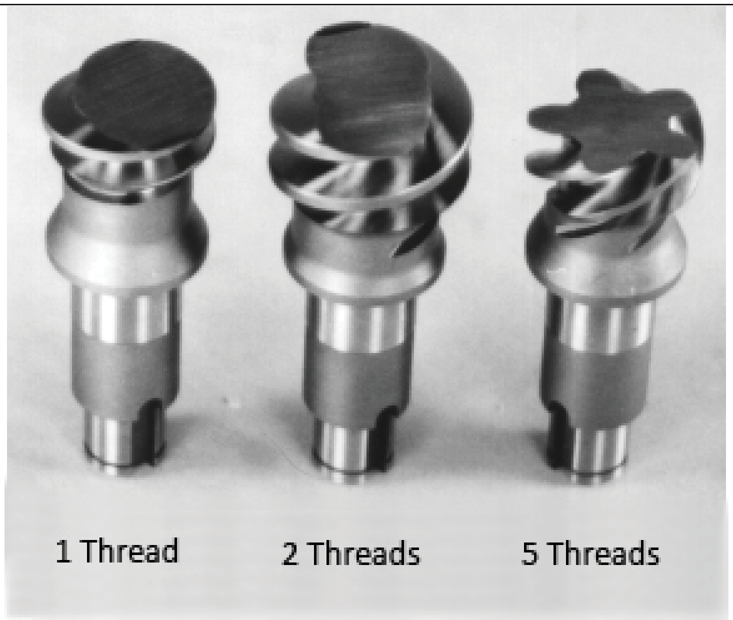

Figure 8—Cross-section view of a worm gear.

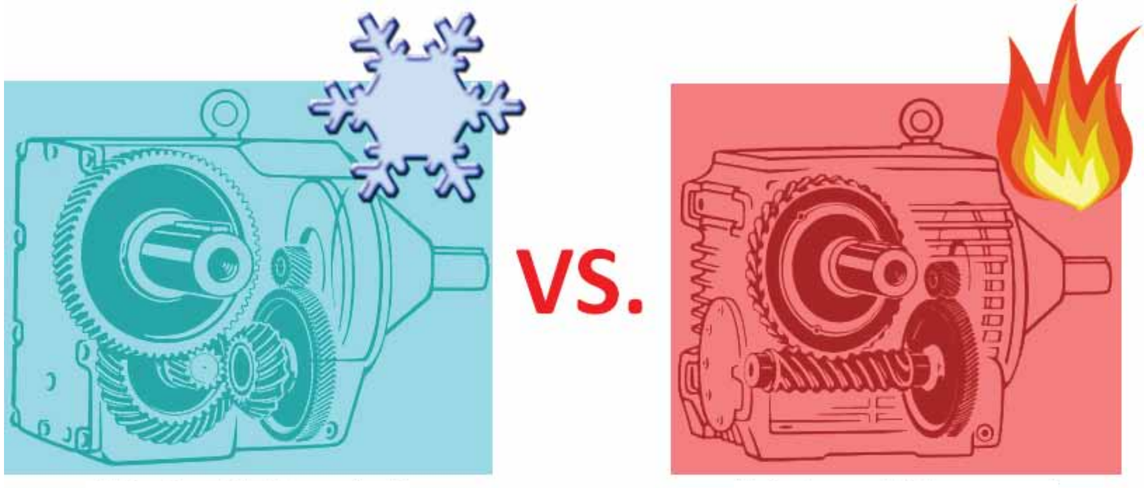

Figure 9—Helical-bevel rolling contact versus helical-worm sliding contact.

system, it can make a significant difference. Take a look at the following example of a three-stage helical-bevel gearbox with mineral oil in Equation 3.

Changing the oil (and nothing else) results in an energy savings of 1,172.5 kW hours per year. That's on one gear motor. Imagine a plant with 100 units like this. That would be an annual savings of 1.1725 MW-hours (not to mention the $11,725). Synthetic oil, shown in Equation 4, also lasts longer than mineral oil. The decreased change interval leads to more savings (not to mention lower disposal costs).

Churning Losses. The second largest loss in a gearbox deals with churning. Churning losses are caused by internal friction between the lubricant molecules. There is also friction between the lubricant and the gears themselves. The gears have to constantly "plow through" the lubricant during operation. Lubricant must be applied to all gear teeth mating surfaces during operation to prevent metal-to-metal contact. The amount of lubrication used is determined by the mounting position of the gearbox, and this determines the amount of churning losses that will be present, as shown in Figure 10. Consider the same gearbox mounted in two different positions requiring different lubrication levels. The amount of churning loss in a vertically mounted gearbox is greater than that in a horizontal one (because one gear set will always be completely submerged in lubrication). The difference in efficiency is not astronomical (on the order of a few percent), but every percentage point adds up to large energy savings over the lifetime of a system.

Bearing and Seal Friction. Bearings and seals make up a smaller percentage of the overall losses in a gearbox. Anti-friction bearings can be selected to reduce their contribution

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Table 2—Worm Gear Efficiency Based on Teeth

Number of Teeth on Worm Gear	Typical Efficiency Range
1	≈ 50-69%
2	≈ 70-79%
5	≈ 80-88%

EXAMPLE: High efficiency motor (10 Hp = 7.5 kW) 87.50%
3 stage helical bevel gearbox (mineral oil) 95.50%
Shaft mounted 100.00%

$$\eta_{System} = 87.50\% * 95.50\% * 100.00\% = 83.56\%$$

$$7.5\text{kW} * (24\text{ hour/day}) * (350\text{ days/year}) / (0.8356) = 75394.93\text{ kW-hour / year}$$

$$(75394.93\text{ kW-hour / year}) * (10¢\text{ / kW-hour}) = \$7539.49\text{ / year}$$

$7539.49 annual operating cost with mineral oil

Equation 3—Operating cost with mineral oil.

EXAMPLE: High efficiency motor (10 Hp = 7.5 kW) 87.50%
3 stage helical bevel gearbox (synthetic oil) 97.00%
Shaft mounted 100.00%

$$\eta_{System} = 87.50\% * 97.00\% * 100.00\% = 84.88\%$$

$$7.5\text{kW} * (24\text{ hour/day}) * (350\text{ days/year}) / (0.8488) = 74222.43\text{ kW-hour / year}$$

$$(74222.43\text{ kW-hour / year}) * (10¢\text{ / kW-hour}) = \$7422.24\text{ / year}$$

$7422.24 annual operating cost with synthetic oil

Equation 4—Operating cost with synthetic oil.

NEMA Waits on Washington for Energy Bill

Who has the time in Washington to discuss energy efficiency these days? Democrats and Republicans are spending so much time on health care almost everything else has been put on the back burner. That's not to say energy advocates haven't tried. Late last year, Congresswoman Tammy Baldwin (D-WI) launched a $700 million motor rebate bill for an energy-efficient motor rebate program advocated by the National Electrical Manufacturers Association (NEMA). This "crush for credit" legislative proposal was introduced in the House of Representatives as HR 4031.

Similar to a previous legislative proposal, this bill authorizes a federal rebate program for the purchase of NEMA Premium motors. The newly introduced bill, however, doubles the authorized amount from $350 million to $700 million.

"NEMA and one of its member companies in my district, Regal Beloit, have been valuable resources and allies in crafting legislation that will help create jobs and protect our environment," says Congresswoman Baldwin, a member of the House Energy and Commerce Committee. "Offering incentives to purchase energy-efficient electric motors is a smart way to reach these goals."

The $700 million legislative proposal creates a federal rebate program that will provide a $25 per horsepower rebate for the purchase of NEMA Premium energy-efficient motors. It also provides for a $5 per horsepower rebate for the proper disposal of the less efficient, non-NEMA Premium motor.

"Since the energy/climate change bill continues to be held up due to partisan bickering, I applaud Representative Baldwin for taking a leadership role to ensure that the crush-for-credit proposal remains active," said NEMA President and CEO Evan Gaddis. "Not only does this program incentivize the purchase of NEMA Premium motors, it also vastly decreases the demand on our electric grid."

Dain Hansen, NEMA government relations, stresses the importance of both the House and Senate to pass an energy bill as soon as possible.

"There are many good energy policies that are currently getting tangled up in the controversial climate change debate and this is unfortunate. We're hoping Washington can move forward on many of these energy portions separately," Hansen says.

While energy and climate change policies were passed together in the House, the issues remain separate in the Senate. Hansen is hoping the House will take action on the energy portions of the bill, including renewable energy incentives, new lighting efficiencies, tax credits for smart technologies and the rebate program for motors.

"With all the current political agendas surrounding health care, it's hard to tell when we're going to move forward on energy," Hansen adds. "In a perfect world, an energy bill will be passed early this year. Realistically, it will probably happen toward the end of 2010."

NEMA continues to remind Washington that its new Premium Efficiency Program goes into effect December 19, 2010. At this time, all motors must meet or exceed the standards presented by NEMA that were passed in the Energy Independence and Security Act Of 2007 (EISA).

Based on U.S. Department of Energy data, it is estimated these efficiency standards will reduce CO_2 emissions by 238 million metric tons over equipment lifetimes and provide net present energy savings of $1.39 billion.

"The job and efficiency gains will be incredible," Hansen says. "If, however, companies don't have any sort of incentive to buy a new motor, they'll just repair the old ones."

Along with the motor rebate program, NEMA is working on an advanced motor systems tax credit as well as legislation for motor assessment. For more information about these programs, contact John Caskey, NEMA industry director, at *john.caskey@nema.org*.

—*Matthew Jaster*

to gearbox power loss. Polytetraflouroethylene (PTFE) seals can be used in some applications. PTFE seals actually lay down a sacrificial layer of material onto the shaft surface. This sacrificial layer fills in the micro-asperities of the surface, thus reducing friction. The reduced friction leads to reduced losses.

Transmission Elements

The final portion of our system is the transmission element between the gearbox and the load. Chain and sprocket, V-belt and sheave, timing belt and timing pulley—there are different methods for transmitting torque. As you can imagine, there are different efficiency levels available for each method. Of course, a transmission element that allows slip creates friction; friction creates heat, which is a loss. A positive engagement method will always be more efficient than one with slip. Even when a slip transmission element is needed for the application, increased efficiency models are available.

Summary

The big picture is that a system needs to be examined as a whole. Remember that each component's efficiency is multiplied together to obtain the entire system efficiency. A high efficiency motor is a great idea to save energy, but when it's mounted to a worm gearbox driving a V-belt, there is the potential to save more energy by being mindful of the entire system. An electronic speed controller is a great idea to save energy, but only when you take advantage of its energy saving capabilities.

Efficiency has a give-and-take relationship with performance and cost. To gain a little bit of efficiency, you have to give up some performance or maybe pay a little more for the component. Somewhere in the middle lies a level of performance, cost, and efficiency that can deliver results without excessive waste. That's a relationship we can all live with.

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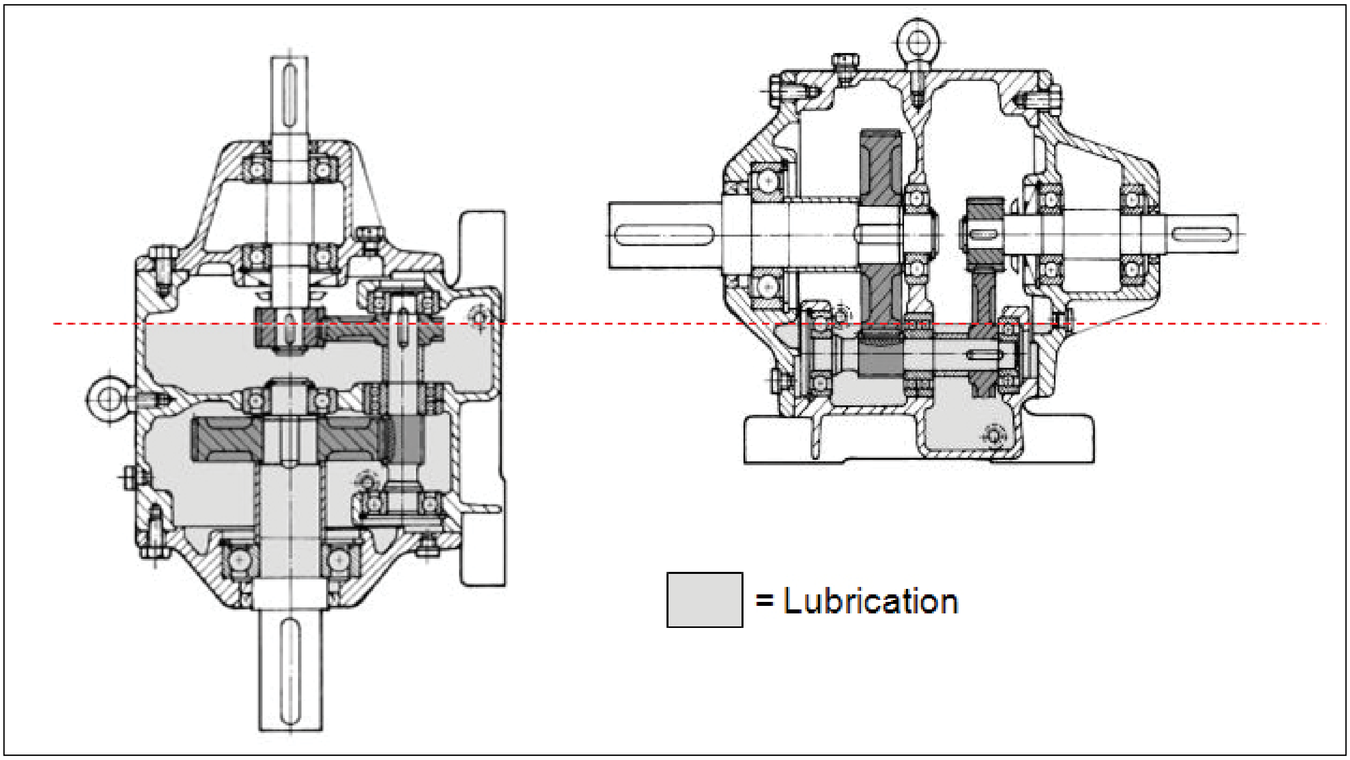

Figure 10—Oil level by mounting position.