Technical Article

Improving the Efficiency and Sustainability of Electric Motors

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Abstract

The motor efficiency drop caused by motor faults or motor anomalies has drawn increasing attention since they can persist over long time periods and can lead to significant economic losses. This article describes how common motor failures affect the efficiency of motor operation. It will discuss how the OtoSense™ Smart Motor Sensor (SMS), a predictive diagnostic maintenance solution, enables motors to operate at high efficiency. Two case studies are presented to show how the application OtoSense™ SMS can reduce CO_2 and electric energy costs.

Introduction

Industry 4.0 is seen as the new era of manufacturing, combining technology, robotics, artificial intelligence, and automation to create an efficient and effective manufacturing process. Industrial use cases represent 37% of energy used worldwide, with 70% consumed by motors. If motors run at maximum efficiency, a 10% reduction in global electricity is possible.[1,2,3,4] But what does that mean? Increasing operational efficiency through condition-based monitoring and predictive maintenance (CbM/PdM) can significantly increase business performance in terms of productivity, quality, and logistics management to meet sustainability metrics and other goals. Analog Devices OtoSense™ Smart Motor Sensor (SMS) technology is one of the leading CbM/PdM technologies in the market today. This article outlines how OtoSense SMS technology can make electric motor operation more energy efficient.

Electric Motor Efficiency and Motor Health Condition

Over recent years, there has been an intensive effort in the design of induction motors with enhanced efficiencies due to the amount of energy consumed by motors. However, there is another factor that strongly affects motor efficiency, which is often disregarded. Typically, industrial electric motors operate between 50% and 85% efficiency.[5] The motor health condition can cause a significant loss of energy efficiency. The rated efficiency values provided by the manufacturer are only valid assuming the motor condition is optimum, that is, there are no significant anomalies, defects, or faults during the operation. If a fault is present in the machine, even if it is in its early stages of fault development, motor efficiency will be reduced.

It is well known that electric motor efficiency is defined as the ratio of its useful power output to its total power input. Figure 1 shows the energy converting from electrical input energy to mechanical output energy and relevant energy losses, which include intrinsic power loss and anomaly power loss. Equation 1 calculates motor efficiency.

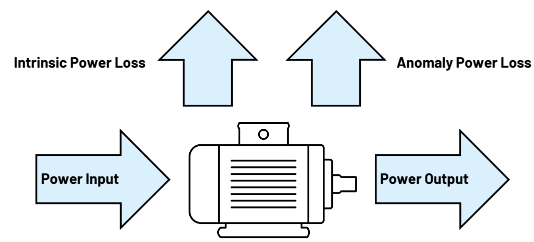

Figure 1. Electric motor energy converting efficiency.

The two major motor power losses are:

- Intrinsic power loss

  Includes copper losses (resistive, skin effect), iron losses (eddy current, hysteresis), and mechanical losses (friction, windage). Intrinsic power losses can be reduced in the motor design phase.

- Anomaly power loss

  Includes extra power losses caused by unhealthy motor conditions, such as any one or multiple motor faults listed in Table 1. Anomaly power losses can be minimized by keeping the motor operation in optimum condition and this is heavily related to motor maintenance schemes.

Studies on electric motor efficiency have shown that if a motor runs in an unhealthy condition, the motor's efficiency is lower than the rated efficiency.[6] Motors in an unhealthy condition can run at low efficiency for a long time before the motor faults become a motor failure and cause the machine to breakdown. This can cause a significant loss of energy. The effect of different types of bearing faults on the efficiency of induction motors has been investigated. Four types of bearing faults have been tested: Fault 1—a crack in the outer race, Fault 2—a

$$Efficiency\ \eta = \frac{Power\ Input - Intrinsic\ Power\ Loss - Anomaly\ Power\ Loss}{Power\ Input} \tag{1}$$

hole in the outer race, Fault 3—deformation of the protective shield, and Fault 4—a corrosion of the bearing. Example photo of bearing fault type of Fault 1 is shown in Figure 2. An experimental setup consisted of a 2.2 kW three-phase induction motor fed by the main power supply control unit and coupled with a break. Motor input current, voltage, and phase were measured to calculate the motor input power. Motor load torque and rotation speed were measured to calculate the motor output power. The motor efficiency is calculated as the ratio between the motor output mechanical power and motor input electrical power. Figure 2 shows how the motor efficiency changes over the different load condition. As illustrated, bearing faults can cause a 1.5% efficiency reduction in full load condition and a 4% efficiency reduction in light load condition.

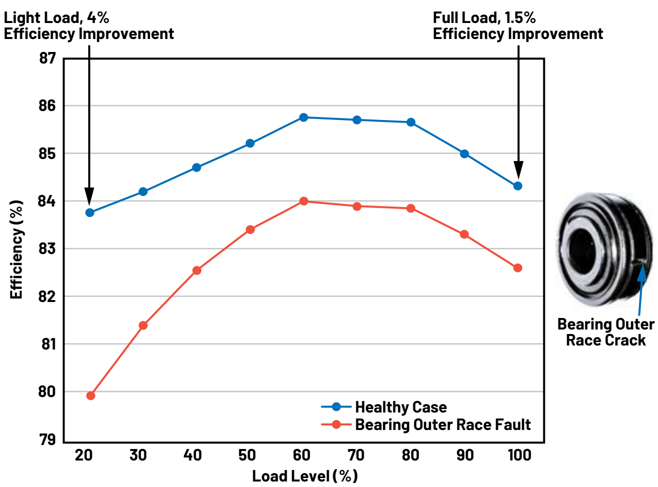

Figure 2. Bearing fault's impact on motor efficiency.

It has been shown that motor faults, such as rotor bar faults, stator winding faults, motor shaft misalignment faults, and soft foot and cooling fan motor faults can cause motor efficiency reduction.[7,8] Figure 3 shows how different motor faults affect motor efficiency.

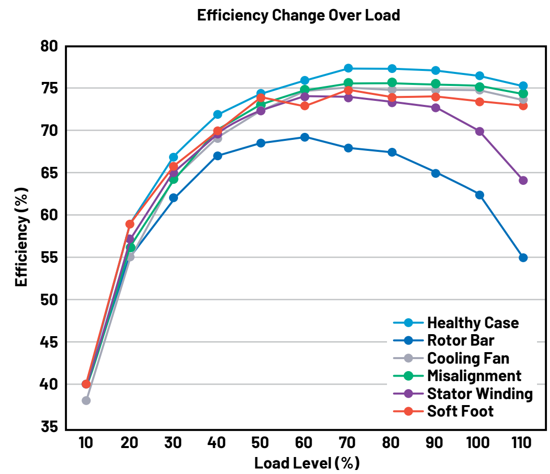

Figure 3. Different types of motor faults' impact on motor efficiency.

ADI OtoSense SMS Explained

OtoSense SMS is an AI-based, full turnkey, hardware and software solution for CbM and predictive maintenance of industrial electrical motors. It monitors the condition of electric motors by combining best-in-class sensing technologies with state-of-the-art data analysis.

The solution consists of a hardware subsystem and a software subsystem, which includes a cloud platform, web application, and mobile application. A machine learning-based motor fault diagnosis AI algorithm is part of the cloud platform. Figure 4 shows the OtoSense SMS system diagram.

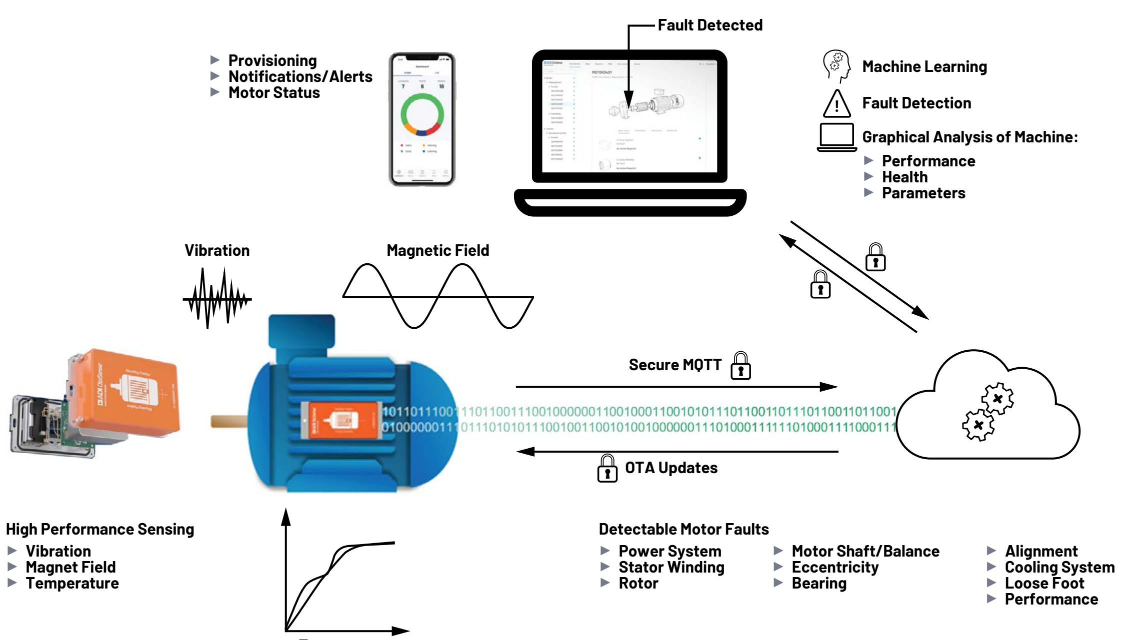

Figure 4. OtoSense SMS system diagram.

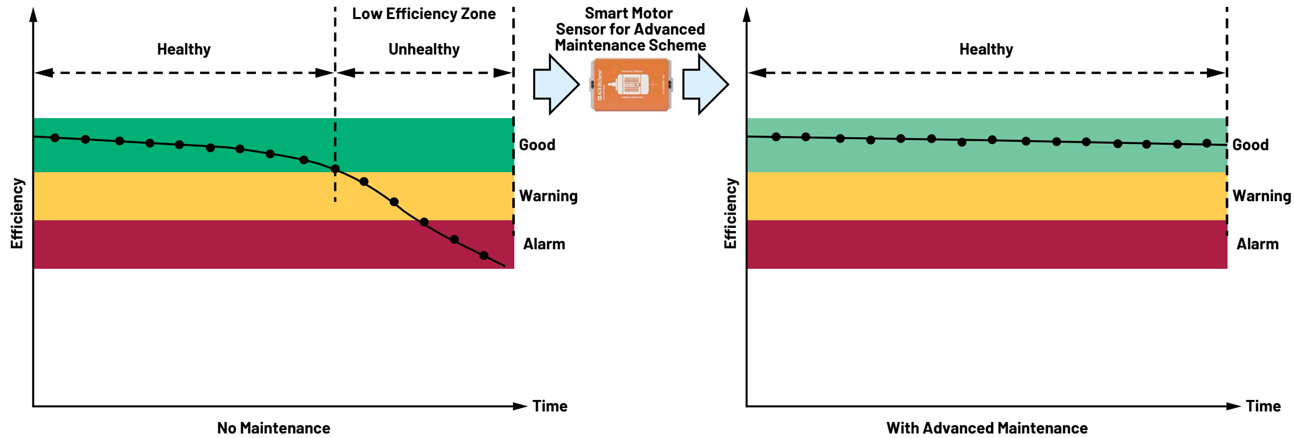

Figure 5. Motor operation efficiency optimum by OtoSense SMS.

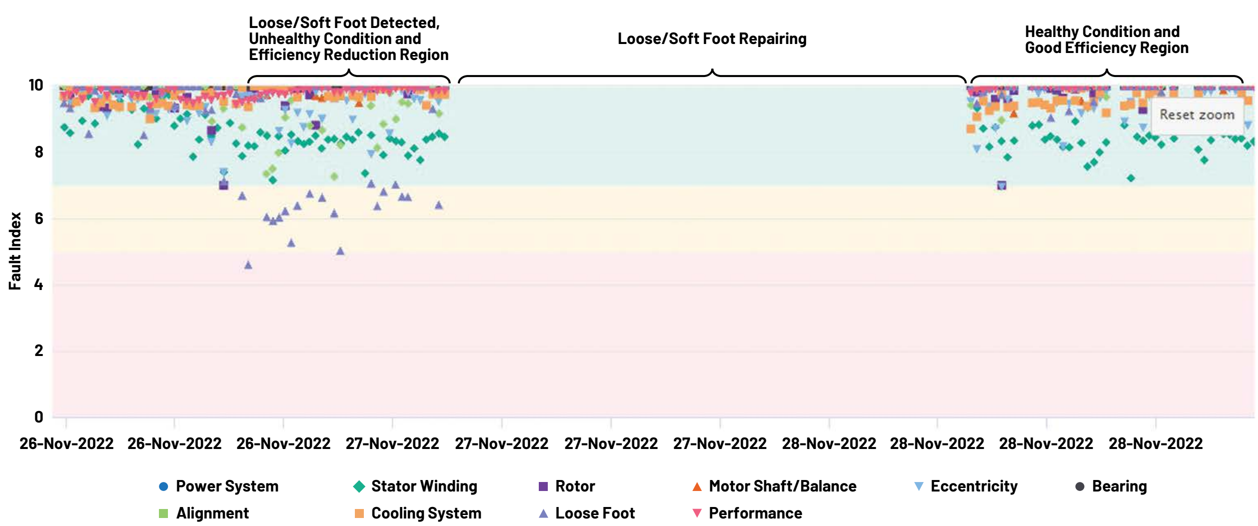

Figure 6. Example showing how OtoSense SMS keeps motors running in high efficiency.

OtoSense SMS integrates several high performance sensors developed by ADI, including:

- Two low noise, high frequency MEMS accelerometers ADXL1002 for both x- and z- axis vibration sensing.
- Two high accuracy, 16-bit digital temperature sensor ADT7420 for motor frame and ambient temperature sensing.

In addition to:

- One magnetic field sensor for motor speed sensing and motor electrical fault diagnosis.
- One Wi-Fi processor for data collection and data packing for 2.4 GHz Wi-Fi data transfer.

OtoSense SMS sensor is a leading solution in the market to sense and interpret machine data. Table 1 shows the most common motor faults that the OtoSense SMS sensor can diagnose and predict.

Table 1. Motor Faults OtoSense SMS Can Diagnose and Predict

Motor Fault	Fault Type	Description	Example
Power System	Electrical	Problems in the three phases of the power supply, which could lead to a motor current imbalance.	Lost Phase
Stator Winding	Electrical	Problems in one of the phases of the power motor, which could cause an imbalance of the motor currents.	Coil Short Circuit
Rotor	Electrical	Short-circuit ring or rotor bar related problems.	Broken Rotor Bar
Shaft Imbalance	Electromechanical	Unequal distribution of mass, causing the center of gravity to shift from the center of rotation.	Rotor Flexion
Eccentricity	Mechanical	Asymmetric air gap between the rotor and stator.	Bent Shaft; Improper Bearing Instillation
Bearing	Mechanical	Mechanical stress or contamination leading to small cracks or defects that occur in the bearing, creating vibration problems.	Pitting
Misalignment	Mechanical	Occurs when two rotating shafts (motor and load) are not aligned, creating external misalignment.	Angular or Parallel Misalignment
Loose/ Soft Foot	Mechanical	Structural looseness occurring when the motor base (or connection to the motor base) is not properly tightened.	Motor not fixed to base frame
Cooling Fan	Temperature	Problems with fans attached to the shaft or externally attached to the motor.	Fan Cover Collapse
Performance	Overall Vibration	Overall increase in vibrations. Indicates faults that do not correspond to any of the other nine fault categories.	Mechanical Faults

Electric Motor Operational Efficiency with OtoSense SMS

Proper maintenance helps to meet maximum economic profitability, as the occurrence of motor failures is reduced and unscheduled downtime can be avoided. Additionally, the efficiency of the motors plays a fundamental role in cost savings per operation since a high efficiency motor consumes less electrical energy than a motor with standard efficiency. Studies have shown the extent to which the efficiency of the machine is compromised by the presence of different types of failure, specifically, rotor failures, stator winding asymmetries, insulation system failures, imbalance/misalignments, and ventilation system failures.

Figure 5 shows the motor operation efficiency optimization with OtoSense SMS. The cloud platform provides unparalleled insight into the motor's operating conditions and maintenance needs. Due to proprietary OtoSense SMS predictive maintenance analytics, users can identify the nine most common motor faults at an early stage and remediate faults before they affect motor operation. For each motor fault, a fault score index (FSI) is calculated to represent the severity of motor faults. The FSI is a value between 0 and 10. FSI number above 7 means the motor is in good health condition. FSI number between 5 and 7 indicates that a motor fault is found at an early stage and low severity WARNING notification will be delivered to the user through email. A motor in WARNING status can still operate normally for a certain amount of time, however, since the motor is not in healthy status, motor operational efficiency is degraded. Figure 6 shows an example, in which a motor loose foot is detected at an early stage, and a WARNING notification is issued. When the user receives a notification, a quick repair action is recommended to bring the motor's operation back to the optimal condition so that the motor can continue to run at high efficiency.

Customer Case Study 1: OtoSense SMS for Compressor Monitoring

Compressors are one of the most important pieces of equipment in a manufacturing facility. In this use case, OtoSense SMS devices were installed on facility compressors to perform 24/7 continuous monitoring. Figure 7 shows this use case in which an OtoSense SMS device is installed on a compressor.

Figure 7. OtoSense SMS sensor installed on a customer facility compressor.

The compressor is 400 kW and runs 24 hours a day. Usually, every 4.5 years there will be an overhaul. Before the overhaul, the major motor fault is a bearing fault, which can cause 1.5% motor operation efficiency reduction as shown in Figure 2. After a trial evaluation, the customer adopted the OtoSense SMS solution on all critical compressors. OtoSense SMS detected early stage bearing faults and provided a warning notification to customer. The customer then took action to prevent permanent damage to the bearings and avoid unexpected production line down time.Meanwhile, because a quick repairing action is performed, the motor runs in a warning status for a brief period.

Previously, with OtoSense SMS installed, energy consumption reduction and CO_2 generation reduction were observed. When the quantity of compressors used increases, the CO_2 reduction effect can become significant. For example, if 1 million same size 400 kW compressors were monitored, this could result in about 147×10^9 kgr CO_2 reduction. Figure 8 shows the results achieved by using OtoSense SMS solution in one use case.

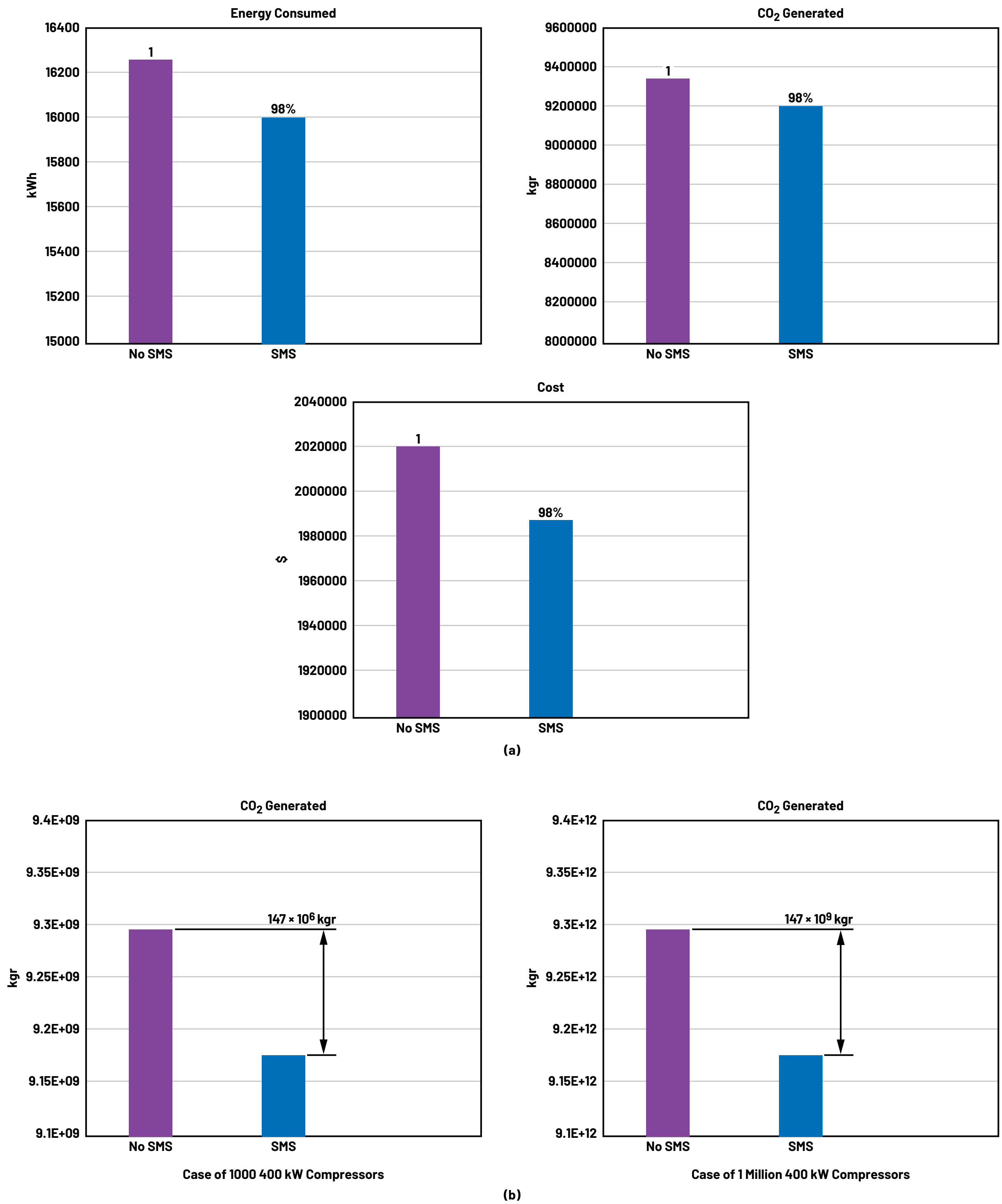

Figure 8. Energy/cost saving and CO_2 reduction with OtoSense SMS: (a) reduction effect in percentage; (b) an example of CO_2 reduction effect when quantity of 400 kW compressor increases.

Customer Case Study 2: OtoSense SMS for Material Handling System

The airport passenger baggage conveyor is an example of a high density motor-driven application. As shown in Figure 9, an airport passenger baggage conveyor system can be driven by thousands of motors.

If one assumes, the power of these motors is generally 5 HP and the life of the motors is usually five years. The cost of motor usage during the five-year period, or the total cost of ownership (TCO) is mainly composed of the motor purchase, maintenance, and electricity consumption. See Figure 9. In terms of specific dollar amounts: motor purchasing cost: $2000, 5% of TCO, maintenance cost: $8000, 20% of TCO, assuming electricity energy cost: $28,000, 70% of TCO.

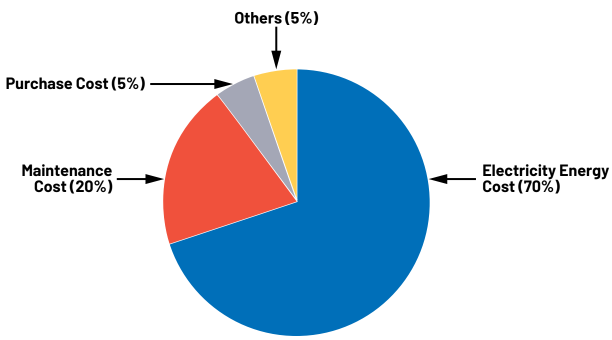

Figure 9. Conveyer motor drive system motor TCO.

The largest cost for motor use is motor energy consumption over lifetime. In the above example, if the efficiency of motor usage is increased by 2% through the adoption of OtoSense SMS, if 3000 motors are used in the airport baggage conveyor belt, then total electricity energy savings in dollars over 5 years is:

Electricity energy cost saving over 5 years = 3000 × 28000 × 2% = $1,680,000

When converted to annual savings this equates to 1680000/5 = $336 K, which is approximately the same cost as 168 new motors.

Conclusion

Cost reduction, due to the increased efficiency of motor operation, is a significant economic benefit of OtoSense SMS. With many enterprises focusing on operational efficiency, reduced unplanned downtime, and sustainability, the need to adopt CbM and predictive maintenance technologies has become a requirement. OtoSense SMS technology provides customers with the real-time monitoring of motor status, detection of early motor failures, and recommended actions for early troubleshooting. Early detection and elimination of motor faults not only ensures unanticipated motor failures and shutdowns but also ensures that the motor is running at high efficiency, resulting in energy savings. All are requirements as enterprises move to meet their goals for operational efficiency and sustainability in the next decade.

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About the Author

Bin joined Analog Devices in 2000 and has worked on motor controller DSP, Blackfin DSP, high speed ADC converter, and OtoSense smart motor sensor, participating in chip system architecture design, application reference design, and algorithm development. Bin Huo has experiences in motor controller inverter system design, motor closed-loop control algorithm, time-of-flight camera module design, and algorithm development. Bin Huo holds a Ph.D. degree in electrical engineering from the University of Tokyo and invented more than 10 patents in related R&D areas.

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