Chapter 1

Overview and Summary

A sizable percentage (15–25%) of U.S. electricity (see calculations in Chapter 7) can be saved by optimizing the performance of electric motors and their associated wiring, power-conditioning equipment, controls, and transmission components. These networks of devices are also known as motor systems.

Electric motors are remarkable machines: rugged, reliable, and far more efficient than the animals and steam-powered equipment that motors have replaced over the past century. A well-designed and well-maintained electric motor can convert over 90% of its input energy into useful shaft power, 24 hours a day, for decades. The popularity of motors attests to their effectiveness: they provide more than four-fifths of the nonvehicular shaft power in the United States, and use upwards of 60% of the nation's electricity as input. It is this popularity that makes electric motor systems such an important potential source of energy savings: because more than half of all electricity flows through them, even modest improvements in their design and operation can yield tremendous dividends.

Touring a Motor System

The key to making motor systems more efficient and economical is to take advantage of high-performance technologies and the synergism among the various system components. To illustrate, let's take a brief tour of a system. Starting from the point at which electricity enters the facility, we will move downstream through the wiring, power-conditioning equipment, and controls to the motor. Finally, we will continue through the transmission hardware to the driven devices. Along the way, we will identify some of the major opportunities for savings.

In theory, electricity arrives at a customer's facility as perfectly balanced and synchronized single- or three-phase power of constant voltage, free of harmonics and other kinds of distortion. In reality, this ideal condition is almost never reached. Phases are often slightly out of balance, voltages may dip and rise, and various kinds of distortion commonly occur. This less-than-perfect power provision is subject to further unbalance and distortions from equipment inside customers' facilities (e.g., welders, lighting ballasts, arc furnaces, and variable-frequency motor controls). Sometimes problems can arise from a poor arrangement of equipment, such as the uneven distribution of single-phase and three-phase devices on a circuit. Such deviations from the pure, ideal electric waveform can reduce the efficiency, performance, and life of motors and other electric equipment.

Avoiding and correcting such problems requires careful monitoring of power quality, repair of faulty devices, and in some cases, installation of specialized power-conditioning equipment. Some analysts believe that such tune-ups may be among the largest reservoirs of untapped drivepower savings, although the scanty data available allow only rough estimates of the overall potential. Field studies suggest that the effort and expense of electrical tune-ups can be worthwhile due to reduced energy costs, better equipment performance, improved process control, and reduced downtime from damaged equipment. Further details of some major opportunities in this area are discussed in Chapter 3.

Just as it pays to streamline the power flowing through the wires, so too it is important to optimize the efficiency of the wires themselves. In most facilities, distribution wiring is sized according to the National Electrical Code, which principally addresses safety, not energy efficiency. Wires that are larger than the minimum size requirement of the code have lower resistance to the flow of electricity, and hence fewer energy losses. Therefore, in new installations or major renovations, it often pays to exceed code standards. Unfortunately, the benefits of doing so are not widely appreciated by architects, designers, electricians, and facility managers, so considerable amounts of energy and money are being wasted through in-plant distribution losses, before the electricity even does any work. Details on wire sizing are covered in Chapter 3.

Motor-driven processes frequently require some form of control over the motor's start-up, speed, or torque (rotational force). For example, fan-, compressor-, and pump-driven systems moving gaseous or liquid loads may require frequent changes in the rate of flow. This is the case for fans and chillers for ventilation and cooling of commercial buildings, pumps for hydronic heating and/or cooling systems, fans and feed water pumps for industrial and power plant boilers, and municipal water and wastewater pumps. Modern adjustable speed drives (ASD), discussed in Chapter 4, allow the motor's speed to be precisely controlled, which can significantly reduce energy consumption. This device precisely controls the speed of alternating current (AC) motors, eliminating the need for wasteful throttling devices in fluid flow applications and rendering many traditional controls and uses for direct current (DC) motors obsolete. ASDs yield sizable energy savings (15–40% in many cases) and extend equipment life by allowing for gentle start-up and shutdown.

Most systems with variable flow, however, have not been updated and continue to use mechanical devices such as inlet vanes, outlet dampers, or throttling valves to control fluid flow while the motor continues to run at full speed. These techniques are analogous to driving a car with the accelerator pushed to the floor while controlling the vehicle's speed with the brake. Such methods yield imprecise control and waste a lot of energy.

The electronic ASD is not the only new control technology, although it may be the most important one. Other technologies include microprocessor-based controllers that monitor system variables and adjust motor load accordingly, and power-factor controllers that can trim the energy use of small motors driving grinders, drills, and other devices that idle at nearly zero loading most of the time. There are also application-specific controls such as those that sequence the operation of multiple compressors in a compressed air system.

Other developments enlarge the range of control applications. For instance, advanced sensors are allowing ASDs to be used in applications (lumber drying kilns, for example) where they previously would not work due to limitations in sensing or in matching the response time required by a control loop. Electronic advances also are allowing lumber mills to control cuts better and to mill more product from raw stock without increasing energy use. These developments and others in the controls area represent the largest slice of the drivepower savings pie and are discussed in Chapter 4.

In other kinds of loads requiring varying speed or torque—winders, mills, conveyors, elevators, cranes, and servodrivers—motor users have employed various kinds of mechanical, electromechanical, or hydraulic speed controls in conjunction with AC motors, or have used DC motors where the speed can be easily controlled. However, most of these speed control options have pitfalls, including high cost, low efficiency, or poor reliability. New motor technologies, discussed in Chapter 2, are emerging that may address these applications' needs while improving energy efficiency at the same time.

Motors are available in a range of efficiencies, as discussed in Chapter 2. Higher-efficiency motors are available for most applications. These motors are typically 2 to 10 percentage points more efficient than standard-efficiency motors, with smaller motors at the high end of this range and larger motors at the low end. Due principally to their better materials, high-efficiency units cost 10–30% more but tend to last longer than standard models. While a few percentage points of efficiency do not sound like much, such an improvement can add up to sizable savings over the life of a motor. A heavily used motor can easily have electricity bills ten times its purchase price each year. If cars were comparable, a $l0,000 car would use $100,000 worth of gasoline annually. With so much of the life-cycle cost in operating expense, each increment of efficiency is extremely valuable. Therefore, the payback on the added cost of high-efficiency motors is often very attractive. However, these more efficient motors have been a small part of the market. As presented in Chapter 6, efficient motors accounted for 16% of 1 to 200 horsepower (hp) motor sales on a unit basis and 32% on a value basis in 1997.

The most important recent development has been the implementation of the minimum efficiency standards for industrial motors that were in the Energy Policy Act of 1992 (EPAct) that went into effect in 1997. As discussed in Chapter 2 and Appendix B, this law eliminated the lest-efficient industrial motors from the new motors market. However, efficient motors comprised only 9.1% of the integral motor stock in U.S. manufacturing plants in 1997. Consequently, significant economically attractive opportunities exist for replacing less efficient motor now in service with new, more efficient motors.

While EPAct eliminated the least-efficient products from the market, a range of efficiencies above the minimum levels continue to exist. In many cases, choosing these *premium efficiency* motors (PEMs) is attractive when a motor is bought for a new application, or to replace a failed motor. In some cases, the retrofit of an operating motor can be justified. Unfortunately, these motors are not well labeled, as is discussed in Chapter 2. This lack of labeling has resulted in market confusion, and made it more difficult for motor purchasers to identify the most efficient products in the market.

As we replace older, less efficient motors with more efficient models, we can capture savings bonuses by correcting for two problems endemic to the existing motor stock: oversizing and rewind damage. Many motors are oversized for their applications, and because motor efficiency drops off sharply below about 40% of rated load, oversized motors often run far below their nameplate efficiency. In addition, many motors are repaired at least once and often several times before they are discarded. While quality repair practices can maintain the efficiency of a motor, less attention to detail can reduce the motor's efficiency and life significantly. The proper sizing of new motors and either the use of quality rewind practices or the adoption of replace-instead-of-rewind policies can thus add significant savings. These matters are covered in Chapters 2 and 3.

Energy enters a motor as electricity and emerges as mechanical power in the form of a rotating shaft. To put that energy to use often requires a transmission provided typically by belts, gears, or chains. Such devices are often overlooked in efficiency analyses. They also typically receive unsophisticated installation and maintenance. This neglect is unfortunate, because, as discussed in Chapter 3, the proper selection, installation, and maintenance of transmission hardware can profoundly affect the performance and efficiency of a motor system. For example, too loose a belt will slip, wasting energy. Too tight a belt can place extreme loads on a bearing, causing it to fail prematurely and lead to costly downtime. Such problems can be avoided in some applications by using synchronous belts, which run on toothed sprockets and are generally more efficient than V-belts, which run on smooth pulleys.

Optimized drivetrains are also important because they are far downstream in the drivepower system. Even modest improvements can ripple back through the system to yield significant savings. For instance, a unit of energy saved in the drivetrain means the motor doesn't have to work as hard, so it draws less energy, which reduces losses in the distribution wiring, and so on, back to the power plant. An additional, potentially large bonus comes in the form of indirect savings from reduced building cooling load due to lower current flow and less heat dissipation from the more efficient equipment.

The shaft of the motor drives some types of equipment, such as fans, pumps, compressors, and conveyors. No matter how efficient the system is up to that point, if the system does unnecessary work, significant amounts of energy can be wasted. In Chapter 5, we discuss what is needed to optimize the motor-driven system. Savings approaching 50% can often be realized at little cost just by matching the operation of the system to the end-use requirements.

The need for careful, ongoing monitoring and maintenance applies to the entire motor system. A high-efficiency system will only stay that way if given proper care, from simple cleaning and lubrication to sophisticated troubleshooting of power quality problems. While the energy savings from top-notch maintenance are substantial, the greatest dividend comes in the form of more reliable, trouble-free operation and extended equipment life. When equipment downtime can mean thousands of dollars per hour in lost production, quality maintenance is worthwhile.

We have completed our tour of the motor system and touched on some of the major technical areas that later chapters will deal with in greater depth. If nothing else, this brief survey is designed to emphasize the notion of a motor *system* and to underscore the critical importance of the interactions and synergism among the various system components.

A Note on Lost Opportunities

Most of the efficiency options discussed here are more economical in new installations than in retrofits. These options are termed "lost opportunity" resources because if they are not implemented during new construction or renovation, they are much more costly to install later. In some cases, however, it makes economic sense to replace and upgrade operating equipment rather than to wait for it to fail. Where load factors are very high, for instance, it often pays to scrap standard-efficiency motors and replace them with efficient models. As described in Chapter 2, Stanford University did this with 73 motors, with average paybacks of less than 3 years. Energy conservation program planners and facility managers should remember this distinction between new and retrofit efficiency opportunities as they implement programs.

Barriers to Drivepower Savings

If the potential savings are so large, why are so few motor users aggressively pursuing them? The answer lies in a maze of barriers to investment in energy efficiency in general and to drivepower improvements in particular. Some of the most important of these barriers are highlighted below and discussed in detail in Chapter 8.

Aversion to Downtime

In many businesses, particularly in industry, shutting down equipment for upgrading or replacement can mean losing thousands of dollars per hour in forgone production. Such penalties may induce an understandable aversion to downtime. Because of this, many facility managers shy away from new, unfamiliar technology that they fear might be less reliable than the equipment they are used to. Furthermore, if a high-efficiency substitute for a failed motor is not stocked by the distributor, in order to save time the user is likely to buy a standard replacement or simply repair the old motor.

Purchase Practices

Existing equipment is usually replaced or repaired without engineering analysis and is often replaced with the same size, brand, and model number. Only in the case of large motors (over approximately 250 hp) with high operating costs does an engineering or economic analysis usually precede decisions concerning replacement equipment.

Customers commonly believe that motors under approximately 200 hp and other drivepower components are commodity items, meaning that models produced by different manufacturers are interchangeable. While this is true from the functional perspective, it could not be further from the truth from an energy efficiency perspective. For many customers, purchase decisions are made based primarily on reliability, price, and availability, not on efficiency. Consequently, energy cost saving is a factor in decisions, but not a primary concern. Some large companies (and a few smaller ones) have formal motor-purchase policies that address motor efficiency; however, most do not.

Repair Shops Compete on Speed and Price

When motors fail, most end-users replace small motors and repair large ones because repairing is generally more expensive than replacing a small motor and less expensive than replacing a large one. Repair-or-replace decisions are generally made at the plant level although a few large corporations have established guidelines for their plants. End-users select repair shops primarily on the basis of price and speed of service. Most motor repair shops do not provide the customer with any evaluation of the motor to be repaired or recommendations on replacement options unless the motor is severely damaged. To encourage competition and responsiveness, most end-users use more than one repair shop. Unless consistent reliability problems are encountered, the quality of the shops' repairs is not considered.

Maintenance Practices

Motor maintenance practices are generally limited to what is needed to keep equipment running rather than attempting to optimize performance and save energy. Most industrial plants and large commercial firms have full-time maintenance staff who regularly lubricate (and often overlubricate) motors, listen for bearing noise (a sign of wear or misalignment), and check and tighten belts as needed. Few firms do any more sophisticated monitoring or maintenance work on motor systems. According to some industrial observers, the time available for maintenance is becoming even more limited in some firms due to industrial company downsizing over the past decade, so the situation is likely to deteriorate.

Other Factors Influencing Decision-Making

Several other factors, in addition to those related specifically to motor systems, influence most efficiency-related investment. Some of the more important ones are discussed below.

- *Limited Information*. As noted above, most maintenance managers and other decision-makers are very busy, leaving little time to research new opportunities, including opportunities to save energy. This lack of time generally causes knowledge of energy-saving options to be limited. Only among large companies were the majority of decision-makers aware of the availability of premium-efficiency motors or decision-assisting tools. Adding to this confusion is publicity surrounding the EPAct motor standards, leading many users to mistakenly conclude that all motors are efficient and that they no longer need to pay attention to efficiency.

  To our knowledge, similar survey data are not available for other energy-saving measures, such as optimization of fan, pump, and compressed air systems. Given the fact that these other opportunities are usually more complicated than purchasing improved efficiency motors, the lack of information is likely to be even more of a problem for these other opportunities.

- *Limited Access to Capital*. The average end-user is more restrictive with capital than with operating funds. Generally, capital expenses are closely scrutinized and require approvals at multiple levels in a company. To minimize capital outlay, companies tend to choose the least expensive equipment that will do the job satisfactorily.

  Operating funds, on the other hand, are relatively easy to obtain, since they are required for production. Operating budgets are typically based on expenses in previous years and are only seriously examined when out of line with expectations. Moreover, unlike capital costs, operating costs are paid with pretax dollars.

- *Payback Gap.* It is a curious fact that most firms look for a simple-payback period of 2–3 years or less on energy projects and other operations and maintenance investments, even though longer paybacks are often considered when investing in new product lines. This difference, known as the payback gap, makes it difficult to implement all but rapid-payback energy-saving measures, although measures with longer paybacks will sometimes be considered as part of a major facility upgrade designed to improve the long-term competitiveness of the firm. The payback gap is most pronounced when viewed from the societal perspective—individual firms pass up energy-saving investments with paybacks of 3–4 years, while utilities invest in distribution lines with economic returns equivalent to 10- to 20-year paybacks.

- *Low Priority Assigned to Energy Matters.* For the average industrial firm, energy costs represent only a small percentage of total costs; labor and material costs are usually far greater. For example, in 1998 the U.S. Census' Annual Survey of Manufacturers estimated that on average, electricity accounts for a little over 1% of manufacturing costs. Since motors make up about 70% of manufacturing electricity use (see Chapter 6), they make up about 1% of total costs for the average industrial firm. Since energy costs represent a small proportion of an average end-user's total operating costs, motor and other energy-related operating costs are rarely examined in reviews of operating expenses.

- *Transaction Costs*. Contributing to the low priority that energy matters take is the fact that many energy-saving measures, including motor measures, have substantial transaction costs. Comparing equipment or optimizing a system takes time, which is a commodity in short supply in many firms. For larger projects, outside engineers can be brought in to help with project design and implementation, but for small projects, if existing staff are short on time, decisions are commonly made based on expediency rather than economic merit.

- *Misplaced Program Emphasis*. Since they generally have full-time maintenance staff or energy managers, large firms are more likely to be interested in energy efficiency. Even in firms with energy managers, however, motor systems historically have not received much attention because of (often incorrect) perceptions that motor system improvements have high capital expense, low rates of return, and low percentage savings. Energy managers tend to focus on low capital cost measures with high savings. While this approach is reasonable during the start-up stages of an energy management effort, many firms have not moved beyond high-savings, low-cost measures. Moreover, many drivepower saving measures are relatively inexpensive.

- *Lack of Internal Incentives*. For many companies, energy bills are paid by the company as a whole and not allocated to individual departments. This practice gives maintenance and engineering staff little incentive to pursue energy-saving investments because the savings in energy bills show up in a corporate-level account where the savings provide little or no benefit to maintenance and engineering decision-makers. As is discussed in Chapter 10, mechanisms to improve internal incentives have been put into place in some facilities.

This listing of the barriers to motor system improvement is by no means exhaustive. It does cover, however, enough of the major impediments to clarify the nature of the challenge. Fortunately, there are many ways to remove or lower these hurdles to sound investment. Some of the more important options are outlined briefly below and are covered in greater depth in Chapter 9.

Overcoming the Hurdles

In the intervening decade since the first edition of this book was published, significant progress has been made in improving motor system efficiency. We have made many steps towards improving the quality and availability of information on motors and motor system efficiency. Utilities, energy agencies, manufacturers, universities, and private organizations have developed publications, videos, seminars, and design and calculation aids. These products have been used across the country in programs discussed in Chapter 9. These products and programs have begun to have a significant impact on the motor market.

While significant steps have been made, more is needed. We discuss the perspectives and needs of these various players in the motor market in detail in Chapter 8.

With EPAct, we have minimum efficiency and motor labeling standards in place in the United States Now educational efforts are needed to make the market aware of these standards and to assist motor owners in making sound motor decisions. While EPAct eliminated the least efficient industrial motors from the market, motors significantly more efficient that EPAct levels are available. These more efficient products are cost-effective in most replacement applications and many retrofit applications, as discussed in Chapter 2. What is needed now is a brand to easily identify these products in the marketplace. National Electrical Manufacturers Association (NEMA), motor manufacturers, and voluntary programs, such as ENERGY STAR®, need to step up and implement a national premium-efficient branding program.

Financial incentives have proven useful in certain instances to overcome the perverse effects of the payback gap and motor users' limited access to capital. The impacts of these programs have been modest but have yielded important visibility for motor efficiency. We have also learned important lessons that are presently leading to improved programs. Recently, programs have shifted their focus from rebates for individual motor purchases to strategically shifting the motor marketplace toward products and practices that are more efficient. Chapter 9 covers the experience to date with motor system programs.

In addition, the programs for increasing drivepower efficiency need to be broader in scope. Most drivepower efficiency programs have focused only on efficient motors instead of on the entire motor-decision process. A good program would address repair versus replace decisions, the implementation of life-cycle analysis of new motor purchase decisions, and the importance of demanding quality motor repairs.

Improved motor repair practices have long been identified as significant opportunities for energy efficiency. Unfortunately, we have only begun to see the first, tentative steps toward implementing programs to realize these savings. Research discussed in Chapter 2 has provided us with a foundation upon which programs can be built. We need to now focus on implementing programs that raise the standard of practice to the level of the best shops, which can restore a motor to near its original efficiency. Such programs need to work with repair shops to assist them to improve the quality of their services and also work with repair shop customers to help these customers understand why and how they can obtain quality repairs.

A number of programs were motivated by the opportunity created by ASDs, and have attempted to focus on motor-driven systems, particularly fan, pump, and compressed air systems. As discussed in Chapter 7, the largest opportunities for cost-effective saving are in improved optimization of these systems. The success of these programs has been mixed to date, largely because of the site-specific effort required to identify and implement projects. However, some recent efforts that build on the successes and failures in this area show promise and provide a foundation for new motor system program designs that can help capture huge savings potential in this area. This process is addressed in Chapter 9.

Finally, most programs have ignored other efficiency-related topics, such as motor sizing, rewinding, and controls other than ASDs. Few programs that we know of have addressed the savings available from electrical tune-ups, better selection and maintenance of drivetrains and bearings, better system monitoring, and the upsizing of distribution wires in new installations. While the savings from these measures may appear incremental, they are frequently among the most cost-effective, and they also offer significant nonenergy benefits in the form of improved reliability and productivity.