THE CONTROL OF COSTS OF ELECTRIC MOTOR OPERATION IN INDUSTRY

It is well recognised that the induction motor is the workhorse of all industry and is the pre-eminent source of rotating mechanical power to drive industries' machines. The operation and maintenance of the many motors used represents a major proportion of the operating expenses of any industrial organisation. This paper discusses the sources of these costs and the various methods by which they can be mitigated.

Most of the motors in use today are controlled using the techniques which have become established as standard practice over the past hundred years or so, that is, by using electro-mechanical switches known as contactors to connect and disconnect them from the supply. Although these devices are familiar and relatively low-cost, their inflexibility and simplicity of operation impose severe demands as well as introducing a variety of problems. These manifest themselves as voltage dips, excessive accelerating torque, oversized power supplies etc., - and create a persistent need for maintenance of the electrical and mechanical components of a machine.

Over the years methods have evolved to relieve some of these damaging effects and involve strategies, amongst others, such as the deliberate over-sizing of motors and other equipment, using fluid couplings, incorporating star-delta or auto-transformer starting.

Electricity supply systems have evolved to provide energy at a fixed voltage and frequency, whether it is derived from a local generator or from a public supply network. Motors connected to such a supply can only run at a single, unchanging speed, consequently, varying the speed of a machine usually involves changing gears, slipping clutches, "variators" or other inflexible or power-wasting devices.

THE COST COMPONENTS OF INDUCTION MOTOR OPERATION

1 Maintenance Costs

Maintenance costs are frequently difficult to quantify. Although an overall cost of maintenance is usually readily obtainable, specific maintenance costs related a machine or group of machines are usually "buried". Nevertheless, it is possible to identify the sources of maintenance requirements since they arise from the nature of the machine and its operation. Generally, they fall into three groups, electrical, mechanical and environmental: -
Electrical

The inflexible, fixed voltage and frequency characteristic (400V, 50 Hz. AC.) of electrical power supplies means that excess currents flow through the contactor switching surfaces during the starting process giving rise to erosion, pitting and burning. In extreme cases contacts can weld, thereby removing a vital element of the motor control and protection process. In direct-on-line starting currents are equal to the locked rotor current of the motor and ranges between 6 - 8 x full-load current. At the transition point of a star-delta starter, the out-of-phase nature of the transfer can cause currents of twice the locked rotor value to flow. These “switching transients” occur every time a motor is started electro-mechanically, and also cause the voltage dips and surges on the supply system. Within a motor, higher than necessary partial-load currents due to excess flux, keep the motor body and surrounding air temperature high so that additional cooling may be needed. Separately, but importantly, induction motors exhibit worsening power-factors as their load falls and this can lead to inadvertent breaching of tariff minimum power-factor thresholds.

Mechanical

Conventional, full supply-voltage starting methods frequently cause a rapid and destructive acceleration of the motor due to the excessive torque generated by the motor over that usually required by the mechanical load. The result is persistent wearing of couplings, belts, chains and gears and the gradual loosening of the motor stator and rotor laminations. In many instances, transmission systems, shafts, bearings etc., are deliberately over-sized to compensate for these effects, all of which, nevertheless, need constant monitoring and routine replacement if catastrophic failure is to be avoided. Furthermore, partially loaded motors frequently exhibit vibration and noise due to excessive flux. In star-delta controlled motors, the transition transient can cause a massive torque surge (up to 10 x full load torque) often resulting in sheared drive shafts etc.

Environmental

Although environmental effects relate to the location and protection given to a machine, they are usually well understood at the outset, and maintenance provisions are made accordingly. However, for the purposes of this paper, the environment also includes the nature and type of the power supply from which the energy is drawn to power the production process. The fixed voltage and frequency characteristic of the vast majority of supplies inhibits the use of speed-changing systems. When speed-changing systems are unavoidable, complex, and often-inefficient mechanisms are used which increase the need for specialist maintenance forces.

B Operational Costs

Unlike maintenance costs, the operational costs of motors are relatively easy to quantify and the electricity bill usually provides a strong indication of the amount spent on powering the production process.

The modern induction motor is a highly developed, relatively high efficiency machine, easily achieving efficiencies greater than 90%. New ‘high efficiency’ motors are now available which improve efficiencies further by 0.3 to 2%.

THE WAY AHEAD

With the advent of reliable electronic control systems and power-switching semiconductors in the past two or three decades, new systems of controlling induction motors have developed which fundamentally alter the approach to induction motor operation and potentially allow for a much reduced life-cycle cost of motor ownership. Electronic control of motors impacts on both the maintenance and operational cost aspects that were highlighted earlier. Maintenance costs can, indeed, be dramatically reduced because all of the deleterious electrical and mechanical effects of simple electro-mechanical starting are removed at a stroke - provided high quality and reliable electronic controllers are selected. However, it is in the area of operational costs that electronic controllers offer the most interesting prospects and the greatest controversy arises.

Renewed interest in the wider aspects of energy saving and the effects on greenhouse gas emissions has re-awakened the topic of energy consumption by electric motors. In order to understand how reductions in energy use may be achieved, a review of the principles of work and energy is appropriate, because an awareness of how electrical and mechanical energy are related is often lacking: -

In a motor,

- Work *or* Energy is the application of power over time, measured in units of watts x seconds, although for the purposes of billing, kilowatt-hours (kWh) is usual.
- Power is the rate of doing work measured in watts. Electrically, power = 3 x voltage x current x power factor. Mechanically, power = torque x rotational speed (rpm).
- Efficiency is the ratio of output power to input power and is always less than 100%. Output power = Input power minus the power necessary to meet the internal requirements of the motor. So, Input power x (% efficiency / 100) = Output power.
- Torque is the mechanical turning moment at the motor shaft necessary to maintain the load in steady motion.

Energy then, has two components, time and power. For a given amount of energy, reducing time or power requires a corresponding increase in the other component. Mechanical power also has two components, speed and torque. Consequently, reducing speed for a given torque will reduce the instantaneous value of energy, but it will take longer to complete a finite amount of work.

With this understanding, if speed could be matched to a varying load requirement, it would be possible to reduce energy consumption in those applications where the torque is related to speed. In particular, fans and some pumps follow the ‘affinity laws’ where the demand power is proportional to the $speed^3$, for example, at half speed, the power required is 12.5% of the power at full speed.

Energy consumption is also affected by efficiency. If a motor's efficiency can be improved without reducing it's ability to supply the demand torque at a given speed, then the input power will be reduced and running costs reduced.

Electronic Control Systems for Induction Motors.

It is not the purpose of this paper to enter into the details of how the electronic systems achieve their control since a large body of technical information exists elsewhere, but there are two basic types to consider: variable-, and fixed- frequency controllers.

Variable Frequency Controllers.

In an induction motor, the shaft speed is directly related to the number of poles built into the stator and the frequency of the supply. Variable-frequency controllers change the frequency of the supply presented to the motor in response to some control parameter such as air pressure, so that the motor speed follows. In this way significant reductions in energy consumption are possible in fans and those centrifugal pump applications where the static head is low. In addition, very good control over starting, stopping and reversing is inherent in these devices. However, they have a relatively high first cost compared with other forms of control device but it remains possible to achieve rapid pay-back from energy savings alone, sometimes less than a year, *provided the correct application is sought.* The Good practice Guide No 2 prepared by ETSU for the Dept. of Environment, Transport and Regions (DETR) gives many examples of the successful application of V-F controllers.

Fixed Frequency Controllers.

Fixed-frequency controllers are known as "soft starters". This type of controller is much cheaper than the V-F version, and operate by controlling the motor torque during the acceleration and stopping phases of motor operation to match that demanded by the mechanical load thereby eliminating virtually all of the maintenance costs associated with electro-mechanical starters.

The "optimising soft starter" version offers the additional advantage of improving motor efficiency at part loads which reduces energy consumption during the run phase of operation.

Although induction motors are relatively efficient machines, - motors larger than 11kW, purchased from reputable suppliers are rarely less than 90% efficient at full load - it is well known that a motor connected to the normal fixed-voltage supply network will experience a worsening power-factor and efficiency as the motor load reduces. However, even at half load the efficiency remains close to that of full-load. Below this level, efficiency does tail off, falling to zero at zero loads.

How much energy saving?
In theory, the potential for energy savings can arise in all aspects of a motor’s operation, and we will examine the cost recovery prospects in each of the following areas:-

During the starting process.

During motor operation at part loads.

As a result of reduced downtime, maintenance, equipment replacement etc.

Starting:

The work needed to accelerate a motor and its load remains the same irrespective of the method by which it is achieved and savings are not possible. It is important to distinguish

between current (amps) and energy (watts hours), <u>halving the starting current does not halve the energy consumed</u>. Soft-starting, although very beneficial from the point of view of maintenance, voltage fluctuations etc., deliberately extends the starting time, and is slightly more <u>inefficient</u> due to the losses in the thyristor switches. However, since the difference may be between 1 or 2 seconds to start electro-mechanically and 10 to 15 seconds with a soft start, the additional energy consumption at normal starting frequencies is so low as not be significant.

The third area cannot be easily quantified, but the less stressful starting does extend component life and help in reducing unscheduled downtime through equipment failure. As an adjunct to the ability to save energy, the Fairford System of optimising has two useful additional effects - that of acting as an automatic voltage limiting device which reduces the chance of motor failure due to burn out and lowering the motor temperature at part-loads. By extending the motor life, each effect contributes to lowering the cost of motor ownership.

It is during the motor run phase that the optimising function will act to improve the overall efficiency of a motor, giving rise to an opportunity for energy cost reduction. However, it is important to keep in perspective the extent to which reductions in energy consumption are possible in fixed-speed applications since it is an area where many unsubstantiated claims are made.

Frequently, claims of “20% or more savings” are made for optimising fixed-speed motors, and it is important to treat such claims with suspicion because of the implication that much greater savings are available than can be scientifically achieved. “20% of what?” is a most pertinent question to ask. Despite this, as will be shown later, the QFE Optimising Controller generates real cash returns on partly loaded motors.

Let us pose the question “20% of what?”

The only plausible answer can be the losses, since they represent the only opportunity for savings without doing less work/hour, I.e., by reducing speed. For many applications, reducing speed is impractical since, with, for example, a finite amount of material to process, reducing the work rate will only increase time taken to complete the task, and at best, the energy (kWh) will be the same.

In order to optimise, a motor must be running at less than full load and here it is important to understand the nature of the losses within a motor and there are three elements to consider before we examine the “20% of what?” question: -

1. Mechanical losses arise from bearing friction, air friction within the rotor-stator gap and cooling fan energy. All these losses are proportional to the rotor speed and are independent of the motor load. They cannot be reduced except by lowering the speed of the machine, which is fixed by the frequency of the supply. They form about 15% of the total losses.
2. Excitation losses that arise from the passage of current needed to form the magnetic field within the motor. They are independent of the load and are proportional to the voltage at the motor terminals. They form approximately 35% of the total losses.
3. Losses which are proportional to the load. These are derived from the passage of current in the windings in order to create the mechanical output, and are at their greatest at the highest load. At full load, they form, with the stray losses (also predominantly load-dependent) around 50% of the total losses.

The table below is based on data taken from information published by two respected manufacturers of induction motors, one European, the other Asian.

Manufacturer	Power (kW)	Frame Size	Speed	100% Load Efficiency	Power Factor	Current (A)
European	200	315MLA	1484	96.1	0.87	365
Asian	185	315SB	1460	94.5	0.89	311

Consider the data for the 185kW, 4-pole machine. At full load the efficiency is 94.5%, therefore, the input kW required to deliver an output of 185kW will be 185/0.945 = 195kW. So, the maximum loss for this motor is - (195 -185) kW = 10kW.

Of this, 3.5kW represent the excitation losses. At half load, the efficiency has declined very slightly to 93,2% and the input energy now becomes 185/(2 x 0.932) = 99.2kW. The losses are now (99.2 - 92.5) kW = 6.7kW, and are made up from the excitation and mechanical losses (unchanged at 3.5kW and 1.5kW respectively), and the load losses which have fallen to 1.7kW.

The Fairford System QFE controller recovers approximately 45% of the excitation loss to give around 1.5kW saving in input energy, equivalent to a 0.8% improvement in efficiency at half load. At a typical energy cost of £0.04/kWh, this equals £480 in a 8000 hour working year, which is roughly equivalent to 3.7 years to recover the installed cost of the QFE starter.

Are there other ways of reducing motor operating costs?

There is a method where substantial savings can arise in fixed-speed applications by acknowledging the less savage effects of motor starting when using the Fairford QFE and MFE soft starters. The more gentle start allows a much higher frequency of starting which means that idling machinery can be switched on and off more frequently. Simple, automatic detectors are available which, when combined with a QFE controller can convert for example, conveyors, to a “die back” scheme whenever material is not being processed, during lunch breaks, etc. Contingent on the operational conditions, hours run etc., very acceptable payback periods can be assured from controlling fixed-speed motor applications in this way. With the relatively high no-load power requirements of much of the industry’s machinery, 20 - 40 kWh or more can easily be saved each hour by the simple act of switching off when no material is being processed. Using the QFE for this function, still preserves the opportunity to benefit from the reduction in excitation losses whilst the plant is in operation.

There are strong economic arguments for the replacement of traditional electro-mechanical motor control systems because of their inherent disadvantages. The use of both forms of electronic motor controller, variable-frequency drives and optimising soft starters, should form an integral part of an overall energy management strategy.

For historical and functional reasons, the great majority of motors operate at part-loads - even when “fully loaded” and the optimising function <u>will</u> generate a payback. However, it is unrealistic to expect a cost recovery in much less than 20,000 to 30,000 hours of operation. For this reason, it is not usually viable to retro-fit “optimisers” on the basis of their energy savings potential alone. However, it can be very cost effective to fit a Fairford QFE soft-starter with an optimising feature on a new or upgraded installations, where the marginal increase in cost over electro-mechanical systems can be swiftly recovered.

1. Electro-mechanical control methods for fixed-speed applications (conveyors, compressors, chillers, crushers etc.) are obsolescent and should be phased-out whenever a new or upgraded installation is planned.
2. Electro-mechanical and mechanical systems of speed control are crude or wasteful of power.
3. The smaller the power rating of a motor, the greater are the losses as a % of motor nameplate rating. Large motors inherently have lower losses because their electrical characteristics are less resistive in nature. Industrial motors rated at more than 7.5kW are rarely less than 85% efficient. (See the attached sheets).
4. Motor losses comprise mechanical, excitation and load-dependent losses. Excitation losses are 35 - 40% of total losses, <u>but do not change with load</u>, but depend on motor terminal voltage.

5. High efficiency motors are available at extra cost, but still need to be started. For fixed speed applications, unless a motor is being operated continuously at or near full power with few starts, it is usually more cost effective to fit an optimising soft-starter to a standard induction motor. High efficiency motors are characterised by lower locked rotor torque and higher locked rotor currents (8 - 10 x full load current).
6. All optimising controllers employ phase-control as a method of regulating energy input, and only operate on the excitation losses. Typically, depending on the motor characteristics, the maximum reduction that can be achieved is in the region of 45-50% of the excitation loss.
7. 3-phase motor efficiency tends to be flat over a load range from 100 - about 45% of rated output, but thereafter tends non-linearly towards zero as the load reduces to zero with a consequential worsening of the motor power-factor. Optimising will improve the power-factor at all part-loads.
8. The greater the numbers of hours run, the greater is the chance of recovering the capital cost of a controller.
9. The higher the unit cost of energy, the greater is the chance of recovering the capital cost of a controller.
10. Automatic no-load shutdown and start-up schemes of idling equipment such as found on baggage-handling conveyors should be considered as a method of energy management. The use of Fairford soft starters will allow for frequent stopping and starting without reducing the life of motors, control equipment and mechanical components. Depending on the residual mechanical load of a machine, it could be entirely possible to save 20kW or more during the time a motor is switched off
11. Where compressed-air ring mains exist, a similar strategy to 10 above can be used to control compressor motors.
12. Even when retro-fitted, the use of variable-frequency controllers (inverters) can be very cost effective in terms of energy cost reduction, on fans and low static head pumps.
13. Retrofitting “optimisers” for energy savings alone is rarely economic. However, fitting “soft starters” without an in-built optimising feature omits a valuable cash-generating feature.
14. Reliability should be a prime consideration in selecting a controller. The bulk of the cost of a controller lies in the power-handling components (semi-conductor devices, heatsinks etc). There is little point in fitting a product on the basis of first cost alone if device size is compromised and unreliability results. Soft starters should be shown to comply with IEC 947-4-2 and inverters with IEC 1800-3. In CENELEC countries (Europe, Australia and some of Asia), EN60947-4-2 and EN61800-3 apply.

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