

Basic Soft Starter Principles

The Principles of Fixed-Speed Induction Motor Control

Since its invention one hundred years ago, the standard 3-phase induction motor has become one of the most familiar items of industrial equipment ever known. Due to its simplicity of construction, low cost, reliability and relatively high efficiency, it is likely to remain the prime source of mechanical energy for industrial applications.

Introduction

The conversion of energy from the electrical supply to rotating mechanical energy is the primary purpose of all motors. To regulate energy flow, most motor circuits require a mechanism to connect and disconnect them from their electrical power source and, electro-mechanical switches, known as 'Contactors', are the standard means of achieving this control. Even today, more than one hundred years after their introduction, contactor-based systems remain the most widely used method of motor control. Nevertheless, there is a definite trend towards more sophisticated electronic systems of control being applied to fixed-speed motor drives and here we discuss the newest form of control - namely, electronic, microprocessor-controlled, optimising soft-starters.

The Induction Motor

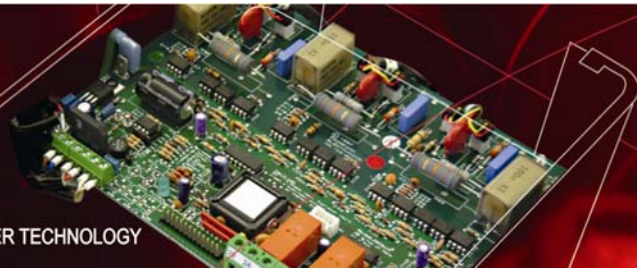
In order to appreciate the benefits of using an electronic controller, it is important to have some understanding of the characteristics and limitations of the induction motor and the electro-mechanical systems currently used to control them.

The standard, fixed-speed induction motor has to fulfil two basic requirements: -

To accelerate itself and its load to full speed (or speeds in the case of multi-speed motors)

To maintain the load at full speed efficiently and effectively over the full range of loadings.

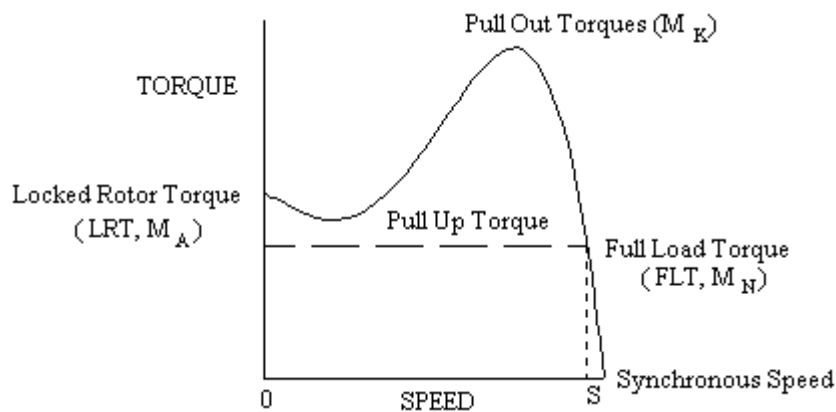
Due to the constraints of materials and design, it can be difficult to achieve both objectives effectively and economically in one machine.



So, how does a motor start in the first place?

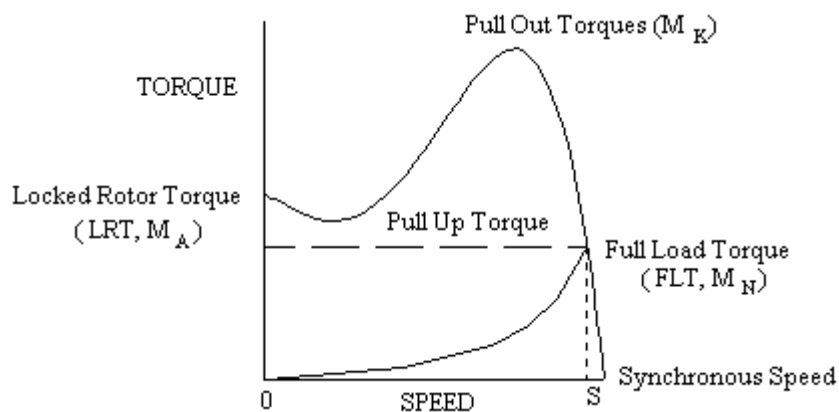
As mentioned earlier, motors convert electrical energy drawn from the power supply into a mechanical form, usually as a shaft rotating at a speed fixed by the frequency of the supply. The power available from the shaft is equal to the torque (moment) multiplied by the shaft speed (rpm). From an initial value at standstill, the torque alters, up or down, as the machine accelerates, reaching a peak at about two-thirds full speed, finally to become zero at synchronous speed. This characteristic means that induction motors always run at slightly less than synchronous speed in order to develop power - the 'slip speed' and, hence the term asynchronous. The graph below, which shows an induction motor torque/speed curve, illustrates this most important characteristic.

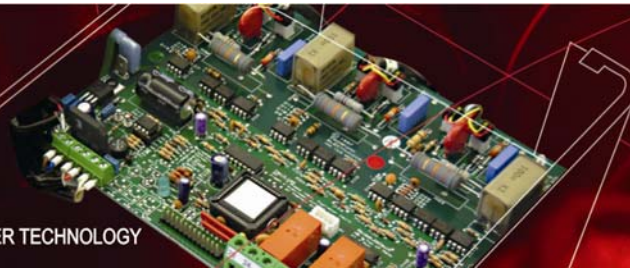
Torque/Speed curve for the induction motor



As for each type of motor, so each load coupled to an induction motor has its own speed/torque curve:

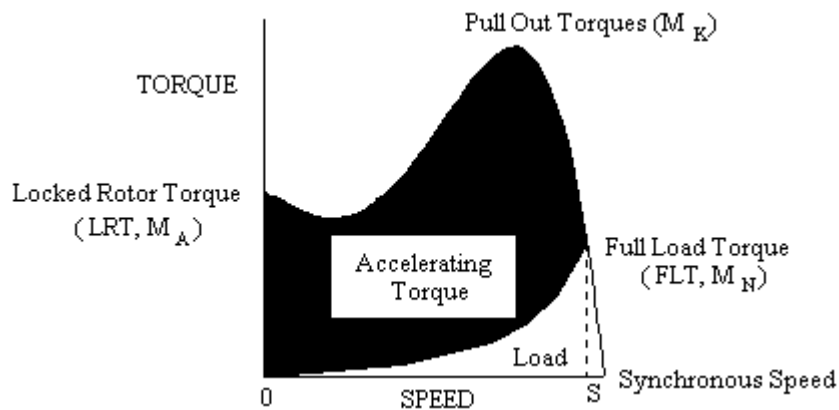
Torque/Speed Curve - Coupled load





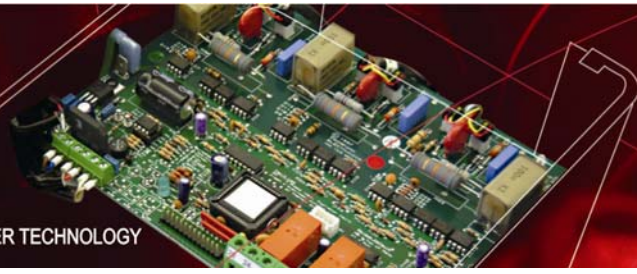
The acceleration of a motor-load system is caused by the difference between the developed torque (motor) and the absorbed torque (load) and is shown by the shaded area in the next figure:

Torque/Speed Curve - Accelerating Torque

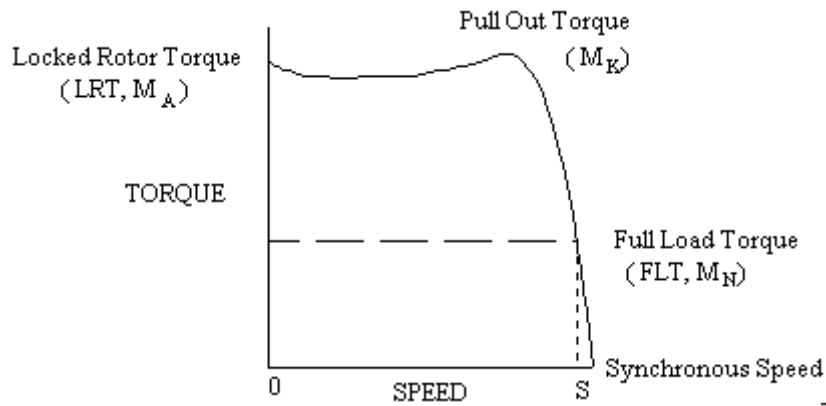


Obviously, the larger the difference, the faster the acceleration and the quicker full speed is reached - and, coincidentally, the greater the stresses experienced by the supply and drive systems during the acceleration process. An "ideal" start would accelerate the load with just sufficient force to reach full speed smoothly in a reasonable time, and with minimum stress to the supply and drive mechanisms.

Broadly speaking, the motor speed/torque characteristic is controlled by the rotor resistance - a motor with high rotor resistance can generate its peak torque (pull-out torque) at standstill giving the high break-away torque characteristic, which reduces steadily as the speed increases and becoming zero at synchronous speed. At the other end of the scale, a motor with a very low rotor resistance will produce a low starting torque but will generate its peak torque closer to the synchronous speed. Consequently this type of motor runs at full power with higher operating efficiency and low slip speed. Increasingly, modern induction motors to combine the twin requirements of high starting torque and efficient full-speed operation within a single motor by techniques such as double-cage or deep bar design, and this motor characteristic is ideal for use with soft starter control.

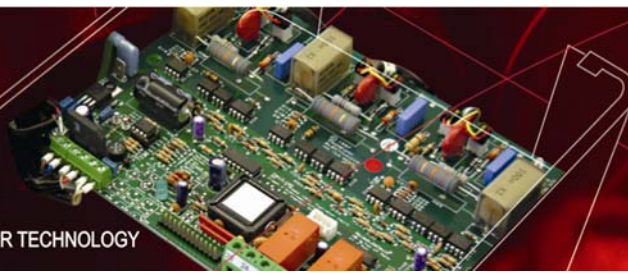


Torque/Speed Curve - High starting torque/High efficiency motor



Starting Induction Motors

Starting a de-magnetised induction motor from standstill is a demanding and complex process. At the instant of switching all the energy necessary to magnetise the motor, to provide the acceleration force, and to supply the kinetic energy of the rotor and load, must be present together with the energy to overcome the mechanical and electrical losses. To do so at full supply voltage places considerable stresses on the supply, the motor windings, and the iron cores of the stator and rotor. Excessive acceleration of a rotor when the mechanical load is small can produce torque oscillations in the shaft causing severe wear to transmissions, gears and drives. Excessive acceleration when the load inertia is high such as in centrifugal fans causes belts to slip in the pulleys, producing rapid wear and early failure.



Electro-Mechanical Methods of Starting

Method A: Direct-on-Line/Across-the-line

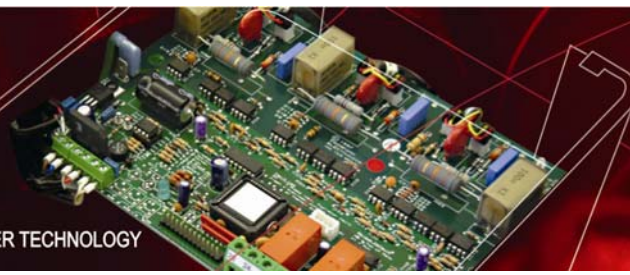
The simplest means of controlling energy flow to an induction motor is to interrupt the power supply by a single, solenoid operated, 3-phase switch, known as a contactor. Very widely applied, the method is known variously as "direct-on-line", "across-the-line", "direct" etc., and is the usual form of control where low cost is the first, and most important consideration. As a result, it is most often used on smaller motor sizes (7.5 up to 22kW), or where the supply is strong enough to withstand the inrush and starting current surges without causing unacceptable voltage drops. The harsh, damaging effects described earlier are all imposed by direct-on-line starting and, as a control method; it is the most destructive of equipment. Its simplicity and apparent low cost, although attractive at first sight, hide large cost penalties in the shape of increased maintenance, reduced transmission equipment life and higher risk of motor failure, particularly when frequent stopping and starting is needed. In larger sized motors special strengthening is necessary, at higher cost, before they can be safely used with direct-on-line starting. However, the shortcomings of the direct-on-line starter have been recognised ever since motors have been used and alternative systems have been developed over the years to reduce the damaging effects of this form of control.

Method B: Star-Delta and other Reduced Voltage Starting Systems

Reduced voltage starting makes use of the fact that motor torque is proportional to the square of the terminal voltage and the most familiar type of reduced-voltage starter is the star-delta or wye delta starter. Consisting of three contactors and a time switch (which can be mechanical, pneumatic, electrical or electronic), the star-delta starter changes the motor winding configuration from an initial star connection to a delta as the motor accelerates.

The change-over or transition point is controlled by the time switch and is usually arranged to be at 80% of full speed. The effect of starting in star is to alter the voltage across each stator winding to 58% of normal. This reduces the starting torque to a third of locked rotor torque (LRT) with a consequent reduction in starting currents and acceleration forces. Although an apparent improvement over the direct system, significant disadvantages still remain.

The transfer from star to delta momentarily removes the motor from the supply. During this time the motor is under the mechanical influence of the rotating load and, at the instant of disconnection, current will still flow in the rotor bars due to the time delay necessary for the magnetic flux to die away. Therefore, there is a residual flux "frozen" on the surface of the rotating rotor, which cuts the stator windings, generating a voltage whose frequency depends on the rotor speed. If the load inertia is small, such as in a pump, or if the friction is high, there could be a significant loss of speed during the time the supply is disconnected. In this case, when the reconnection to delta is made, a large phase differential can exist between the supply and the rotor fluxes.



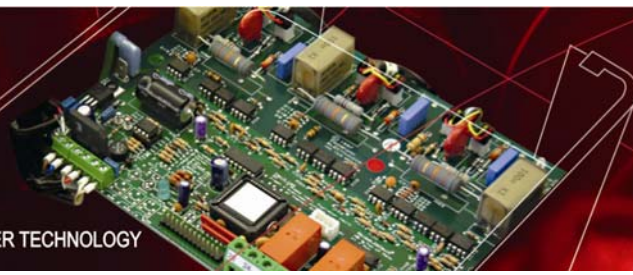
This can give rise to very large current surges (as much, or more than full-voltage locked rotor current), together with massive transient torque oscillations. (These oscillations can be as much as five times full-load torque.) Although the effects described are only present for a very short period of time (about one fifth of a second), they are sources of great stress and damage to the whole drive system, and where frequent starting is necessary, invoke high maintenance costs. There are methods of control, for example, the closed transition starter, which eliminate or reduce the reconnection transients. However, such starters are expensive and have reliability implications; for these reasons they are not widely applied. The star-delta starter also has disadvantages due to the restricted starting torque available (if you need 40% LRT to break-away, you can only increase the motor size, or revert to direct-on-line). Combined with the severe effects of the re-switching surges, and the additional costs of bringing six conductors from the motor to the starter instead of only three, star-delta only offers an imperfect solution to the problem of starting the induction motor.

Method C: Primary Resistance Starter

It has long been recognised that the transition step in the star-delta system was a source of problems such as welded contactors, sheared drive shafts etc., and for many years a method of step less control has been available in the form of the primary resistance starter. This type of controller inserts a resistance in one, or more often in each, of the phase connections to the stator at start-up, after which it is progressively reduced and shorted out at the end of the acceleration process. Frequently, the resistances are movable blades that are gradually immersed in an electrolyte liquid. The mechanism is usually large and expensive, both to purchase and to maintain, and considerable heat is created by the passage of current through the electrolyte resistor. This limits the starting frequency (because the electrolyte has to condense back to liquid before a new start can proceed), and these restrictions prevent this starter from being a popular option when selecting a control system. However, it has the distinction of being the smoothest and least stressful method of accelerating an induction motor and its load.

Method D: Other Electro-Mechanical Systems

Other control methods such as auto-transformer starting (popular in North America), primary reactance starting etc., are employed to a greater or lesser extent, to compensate for some of the disadvantages of each type of starter discussed. Nevertheless, the fundamental problems of electro-mechanical starters remain, and it is only in the last decade or two that their dominance has been challenged by the introduction of power semiconductors controlled by electronics.



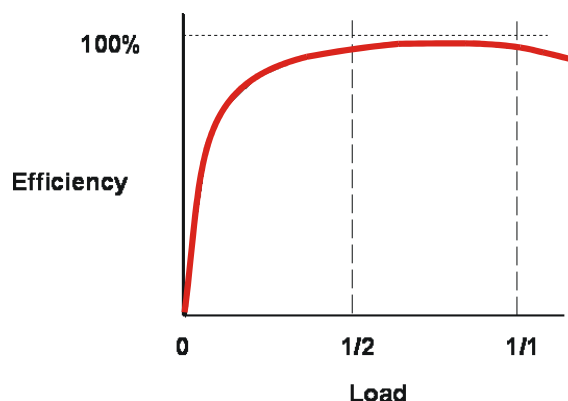
The Semiconductor Motor Controller

During the 1950's, much effort was put into the development of a four-layer transistor device which had the power to switch large currents at high voltages when triggered by a very small pulse of current. This device became known as the silicon controlled rectifier (SCR), or in Europe, the 'Thyristor'; it is the basis on which all soft starting systems are built. The characteristic of most interest is the ability of the thyristor to switch rapidly (in about 5 millionths of a second) from "OFF" to "ON" when pulsed, and to remain "ON" until the current through the device falls to zero, - which conveniently, happens at the end of each half-cycle in alternating current supplies. By controlling the switch-on point of a thyristor relative to the voltage zero crossing in each half wave of an alternating current, it is possible to regulate the energy passing through the device. The closer the turn-on point is to the voltage zero crossing point, the longer the energy is allowed to flow during the half-cycle. Conversely, delaying the turn-on point reduces the time for the energy to flow. Putting two thyristors back-to-back (or anti-parallel) in each of the phase connections to a motor, and by precisely controlling their turn-on points, an electronic soft starter continuously adjusts the passage of energy from the supply so that it is just sufficient for the motor to perform satisfactorily. So, for instance, by starting with a large delay to the turn on point in each half cycle, and progressively reducing it over a selected time period, the voltage applied to the motor starts from a relatively low value and increases to full voltage. Due to the motor torque being proportional to the square of the applied voltage, the starting torque follows the same pattern giving the characteristic smooth, step less start of the soft-starter.

Running Induction Motors

Once a start has been completed the motor operating efficiency becomes of interest. When working at or near full load, the typical 3-phase induction motor is relatively efficient, readily achieving efficiencies of 85% to 95%. However, as shown below, motor efficiency falls dramatically when the load falls to less than 50% of rated output.

Efficiency v Load



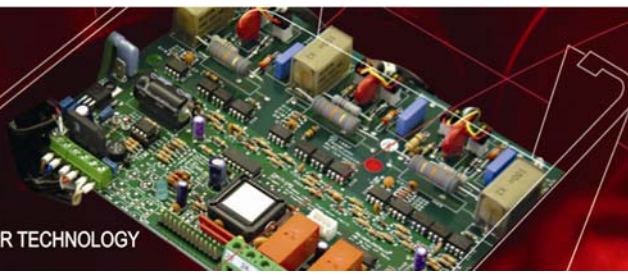
In fact, very few motors actually experience consistent fully rated operation, the vast majority operate at much lower loads due to either over-sizing (a very frequent situation), or natural load variations. For Fan and Pumping applications, the affinity laws will allow the inverter drive to show very considerable energy savings over virtually all other methods of control through varying the speed of the motor in response to changes in load. Where motor speeds cannot be varied, the optimising version of the semiconductor motor controller will also produce energy savings in lightly loaded motors. Less sophisticated systems of soft-starter remain at full conduction and the motor then behaves as if it were connected directly to the mains supply. However, at light loads and mains voltages, induction motors always have excess magnetic flux, and suffer efficiency loss and power factor degradation as a result. By detecting the load at any instant, and adjusting the motor terminal voltage accordingly, it is possible to save some of the excitation energy and load loss, and improve motor power factor when the motor is running inefficiently at light loads.

All Fairford soft-starters are microprocessor controlled, and this gives them a number of advantages. Firstly because of our patented method, there are no adjustments to be made for the energy saving function: all calculations necessary to find the best degree of phase-back of the thyristors for any load condition is made by the micro-computer. Secondly, the start always synchronises with the supply voltage and a special structure of turn-on pulses virtually eliminates the inrush currents normally associated with motor start-up; this happens every time. Lastly, there is the absolutely step less starting process, found only with the primary resistance or reactance electro-mechanical starters - but without the wasted energy, and with the opportunity to control the maximum current allowed to flow during the starting process. Other features such as soft stopping are included, or are available, to give considerable control over all modes of induction motor operation.

Reliability Considerations

One aspect of electronic controllers for induction motors which is of increasing concern is that of reliability. There is little point in installing an expensive item of electronic equipment to save potentially considerable amounts of money if the device is unreliable to the point that vital processes are constantly interrupted.

There are electronic products in the market place which appear to offer soft starting cheaply. They almost always rely on less advantageous technologies such as analogue control, or half-control, where one of the two thyristors in the phases is replaced with a diode. There are systems which only control the energy flow in one phase while the other two are directly connected. Owing to the variable quality and performance of many so-called inverters and soft-starters available to the unsuspecting purchaser, international standards for these products have been, or are being, developed.



An international standard, IEC 60947-4-2 - 'AC Semiconductor Motor Controllers and Starters' defines the soft-starter in every important respect, including thermal and overload performance as well as electromagnetic compatibility. By ensuring that any motor controller equipment purchased conforms to IEC 60947-4-2, a user should be reasonably safeguarded from shoddy or inadequate products when specifying equipment for future installations.

A particular advantage of the use of the optimising soft starter is its impact on the maintenance requirements of associated electro-mechanical equipment. Optimising lowers the surface temperature of the motor by reducing the losses within the motor. This prolongs the motor life - and reduces heating of the surrounding atmosphere in the process. If the atmosphere is subject to air conditioning, reducing the heat input will reduce the air conditioning costs. Reduced starting and running currents reduces cable losses and, contactor switching operations are carried out under the most advantageous conditions. No current flows on switch-on since all switching is carried out by the thyristors - virtually eliminating the need for contact replacement.

Indeed, there are a growing number of installations where contactors are no longer employed, being replaced by controllable circuit breakers or isolators instead.

In summary, electronic controllers for most fixed-speed applications are opening new ways of increasing the efficient operation of induction motors, as well as offering significant benefits in control. Intending users need to ensure themselves of the quality and performance of any products they expect to fit and this can be reasonably expected if compliance with the appropriate IEC standards is demanded.