Electrical Tech Note — 314

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Induction Motor Characteristics

Introduction: The majority of electric motors in use are induction motors where windings in the frame or stator of the motor are supplied with either single-phase or three-phase alternating current and those windings create a rotating magnetic field within the motor. That rotating magnetic field induces a current flow in a winding within the rotor or more commonly a conducting structure sometimes called a “squirrel cage”. That current induced within the rotor “squirrel cage” creates it’s own magnetic fields which are both pushed and pulled by the stator rotating magnetic field. The speed at which the rotor turns depends upon the rotational speed of the stator magnetic field and the load applied to the motor shaft. It is important for personnel specifying, installing, and maintaining induction motor drive systems to understand their basic operating characteristics. For example an induction motor generally draws from five to eight times as much current when it is starting as it does when it is running at full operating speed. Current increases as the motor load increases, which if excessive will result in premature winding failure. Motor efficiency is important and a value is usually provided on the motor nameplate, but that value is not a constant. The efficiency changes dramatically depending upon whether the motor is properly matched to the load. The nameplate also provides something called the “design” letter which must be understood when matching a motor to a load as well as installing the electric motor circuit. Torque is twisting force and the power provided at the shaft is proportional to the torque times the revolutions per minute (rpm) the shaft is turning. This torque changes as the rotational speed of the shaft changes. Two important parameters for an indiction motor are full-load torque and locked-rotor or starting torque. The design letter designates the general shape of the curve for torque from zero rpm to full load rpm. It is essential to understand this characteristic when matching an induction motor to a load.

Torque-Speed Curves: In this Tech Note the term “torque-speed curve” will be used rather than “torque-rpm curve.” This is a graph of the value of the torque developed by the induction motor shaft verses the revolutions per minute of the motor shaft. The graphs in this Tech Note will plot torque on the vertical axis and revolutions per minute (rpm) on the horizontal axis. However, this characteristic of an induction motor is often plotted with rpm on the vertical axis and torque on the horizontal axis. Motors are designed with certain torque-speed characteristics to match the requirements of various loads. A motor must be able to develop enough torque to start, accelerate and operate a load at rated speed. A graph like the one shown in Figure 314.1 shows the relationship between torque and shaft rpm for a “design B” three-phase induction motor from the moment of start until the motor reaches its designed full-load operating speed.

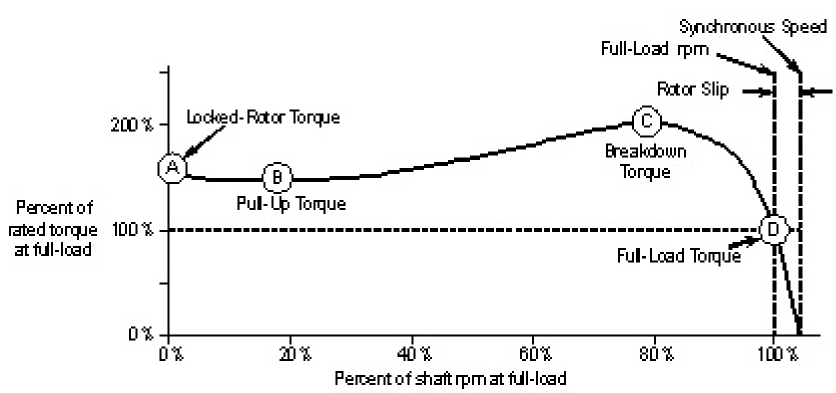

Figure 314.1. Common torque-rpm characteristic curve for a typical three-phase design B induction motor. The values are on the basis of the motor rating at full-load which is point “D” on the graph.

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The starting torque is identified as point "A" of Figure 314.1. This point is commonly referred to as *locked-rotor torque*. This is the torque produced by the motor at the instant voltage is applied to the motor. This locked rotor condition occurs whenever the rotor is not spinning, which includes motor start-up. The magnetic attraction/repulsion of the rotating magnetic field in the stator will accelerate the rotor. As the rotor accelerates from its resting position, a slight dip in torque often occurs. At point "B", both the torque and the speed will increase. Between points "B" and "C" is known as the *pull-up torque*. Torque and speed continue to increase until point "C" is reached, which is the maximum torque a design B three-phase motor can develop. Point "C" is known as the *breakdown torque*. If the motor is overloaded, when breakdown torque is reached the motor will stall and the shaft will stop turning. When examining Figure 314.1, note that as the speed increases from point "C," a drop in torque occurs. *Full-load torque*, identified at point "D", is developed when the motor is operating at rated voltage, frequency, and design full-load. Note that if the load is increases above full-load, rotor rpm will decrease. When the motor is operating at less than full-load, rotor rpm will increase. Induction motor shaft rpm varies slightly depending upon load.

Synchronous speed is the speed at which the magnetic field is rotating in the stator. For a typical motor supplied 60 Hz alternating current, synchronous speed is typically 1800 rpm for a four-pole motor and 3600 rpm for a two-pole motor. The shaft speed at full-load as shown on the motor nameplate is less than synchronous speed as illustrated in Figure 314.1. The difference between the full-load shaft rpm and the synchronous magnetic field rpm is called *rotor slip*. When load on the shaft increases, the rotor rpm will decrease and thus rotor slip increases. Increased rotor slip results in increased induced rotor current which is necessary to increase the additional shaft torque necessary to power the load.

Motor Design Letter: Induction motors are standardized for specific applications by the National Electrical Manufactures Association (NEMA). These standards can be found in *NEMA Standard Publication No. MG 1*. Motor design specifies the relationship of the output torque of a three-phase induction motor compared to the motor shaft rpm from zero up to full-load rpm. There are four common three-phase induction motor design letters, A, B, C, and D. The basic shape of the torque verses rotor rpm curves are illustrated in Figure 314.2. The most common three-phase induction motor is design B illustrated in Figures 314.1 and 314.2. A characteristic of the Design B induction motor is that breakdown torque is generally higher than starting or locked-rotor torque. The design A motor also has lower starting torque than breakdown torque generally greater pull-up torque than the design B motor. The design B motor has characteristics that fit a wide range of applications. Design A motors are not common. A distinguishing characteristic of the design C motor is that starting torque is generally higher than breakdown torque. An application for this type of motor would be powering a very hard starting load requiring high torque at low rpm. Some motors power highly variable loads where rapid acceleration or rapid change in rpm is not desirable. Examples of such loads would be lifts, elevators, and oil well pump motors. The design D motor would be a good match for such loads because it's rotor rpm varies considerably with change in load torque as illustrated in Figure 314.2. Design D is considered a high rotor slip motor. If there is a sudden increase in load the rotor rpm decreases much more than other motor designs. For the design D motor maximum torque is locked-rotor torque, and as shaft rpm increases there is a steady decrease in output torque.

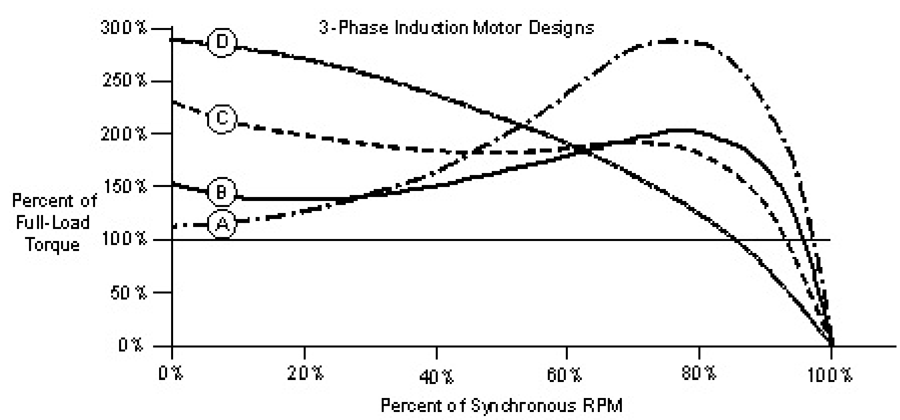

Figure 314.2. The design letter on the motor nameplate designates the relationship of shaft rpm and shaft output torque. The most common general purpose three-phase motor is design B.

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Single-Phase Motor Characteristics: A single-phase induction motor is supplied alternating current in the form on one sine wave using two conductors to supply the motor stator windings. These stator windings produce a magnetic field that simply alternates it's polarity, North and South, back and forth inside the motor. In order for the motor to rotate, it must be exposed to a rotational magnetic field. In the case of a three-phase motor there are three sets of windings located around the inside of the stator and each is supplied a different sine wave that is off-set from the others by 120 electrical degrees. The result is a rotating magnetic field inside the motor for the rotor to follow. In the case of a single-phase motor, some method must be devised to create magnetic field rotation for the rotor to follow. To learn more about how this is done refer to Tech Note 313. The most common method is to provide a special starting winding in the motor stator and get the alternating current to flow through the starting winding out of phase with the current in the main stator winding. There are different methods of accomplishing this task, but a common method is to add a series capacitor to the starting winding. In most cases the starting winding as well as the capacitor are not rated for continuous duty, so there is a device called a centrifugal switch that disconnects power to the starting winding when the motor shaft reaches about 80 percent of full speed. Common torque verses shaft rpm curves for single-phase motors is illustrated in Figure 314.3. When the motor is energized, both the main winding as well as the starting winding accelerate the load. Usually when the shaft reaches about 80% of full speed the centrifugal switch opens and the starting winding is disconnected. This results in a sudden drop in torque when the main winding must power the load by itself. At this point it is common for the stator magnetic field to stop rotating and the North and South poles simply flip-flop back and forth inside the motor. The shaft will continue to rotate even though the magnetic field is not rotating. Also shown in Figure 314.3 is a permanent split capacitor single-phase motor where the starting winding is not disconnected and remains operating continuously. A common application for these motors is a furnace blower.

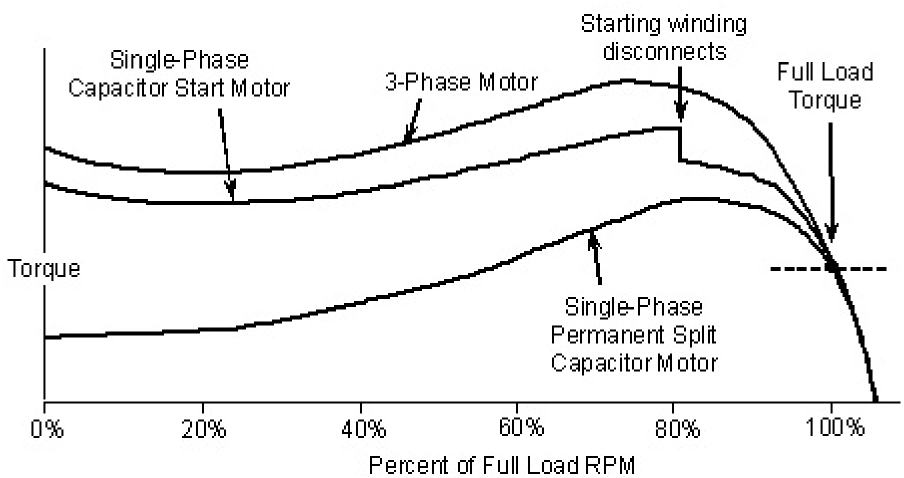

Figure 314.3. There will be a decrease in torque at the point where the starting winding disconnects for a single-phase induction motor. The auxiliary winding of a single-phase permanent split capacitor motor is rated for continuous duty and is not disconnected.

Matching Induction Motors to the Load: The load to be powered by the motor also has torque requirements that vary with load drive shaft revolutions per minute. Efficiency of motor operation is dependant upon matching the load power requirement to the motor. Motor efficiency decreases significantly when motor power is much higher than the load power requirement. Some loads have a relatively constant torque requirement from zero rpm to full load operating rpm. Other loads have a low torque requirement when they are started and torque builds up as the load reaches operating rpm. Other loads have a high torque requirement to get them started and torque decreases as full load rpm is obtained. The motor must be capable of developing torque in excess of the load torque from the moment of start-up to full load. Figure 314.4 illustrates three common types of loads: (1) fan motor, where the torque requirement increases with speed; (2) hoist motor, where the torque requirements remain constant, and (3) rolling mill, where the high torque requirements are at start up.

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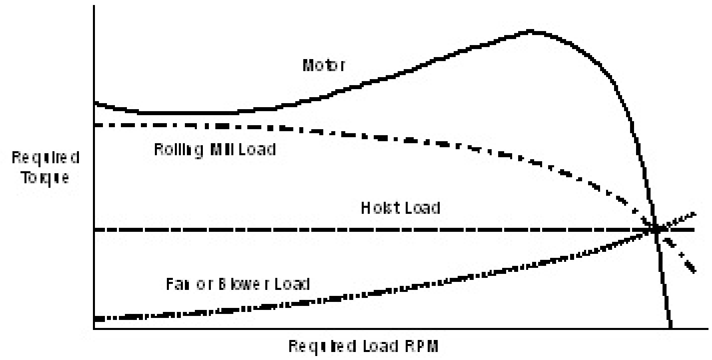

Figure314. 4. The drive motor must be capable of providing sufficient torque from start-up to full operating rpm. It is necessary to match the torque verses rpm capabilities of the motor with that of the load.

Motor Current: A unique characteristic of an alternating current induction motor is that it experiences a high inrush of current the instant it is energized. After a short time, usually only a few seconds, full-load current is reached which is only about one-fifth to one-eighth of the level of inrush current. This is illustrated in Figure 314.5. The initial inrush current is called the *locked-rotor current (LRC)* of the motor. The rotor has a magnetic field induced by the stator magnetic field. As the rotor begins to turn, it's magnetic field cuts across the stationary stator winding and induces a reverse voltage into the stator windings. That reverse voltage opposes the supply voltage. The faster the rotor turns the greater the reverse voltage in the stator winding causing the current flow in the stator winding to decrease until it reaches full-load operating current. The current drawn by the stator windings when the rotor is operating at rated rpm and torque is called *full-load current (FLC)*. Provided the torque of the load remains constant, the motor full-load current remains constant. The elevated current during the start-up of a motor may occur in a fraction of a second or it may take several seconds depending upon the load. The locked-rotor current is typically five to eight times the full-load current for most induction motors. High efficiency induction motors generally have a higher inrush current. These are often known as *premium efficiency* motors.

Even though efficiency of all electric motors has increased in recent years, premium efficiency motors are available with very high efficiency at converting electrical power to mechanical power. Improved design, materials, and manufacturing techniques enable electric motors to accomplish more work per unit of electricity consumed. High energy-efficient motors have low winding electrical resistance and thus exhibit higher inrush currents than standard models. The number of cycles to decrease current from inrush level to full-load level also depends upon the load. A premium efficiency design B motor will have a higher starting inrush current than a standard design B motor of the same horsepower rating.

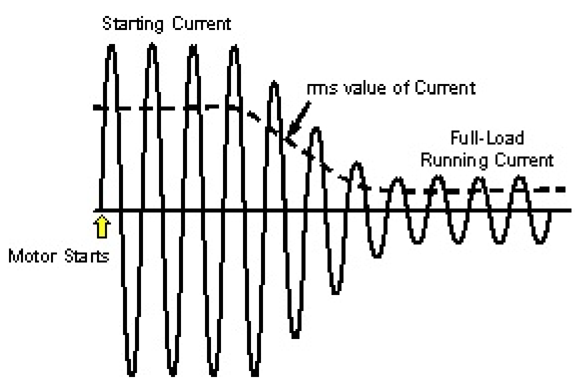

Figure 314.5. Starting current or locked-rotor current of an induction motor is usually five to eight times the level full-load current. This must be taken into consideration by the system designer and electrician when specifying and installing overcurrent protection for electric motor circuits.

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Induction Motor Operating Characteristics: An alternating current induction motor is considered to be a constant speed or rpm motor, but it must be noted that shaft rpm does vary somewhat as the load on the shaft varies. The nameplate states the design shaft rpm for the motor under full load operating at the supply power values stated on the nameplate. The actual shaft rpm may be slightly different. If the motor is operated at less than full load, the shaft rpm will increase and the full-load current will decrease slightly. This as well as other important characteristics are illustrated in Figure 314.6. Efficiency may be listed on the nameplate, but listed efficiency is the intended value at full-load with the motor operating under conditions as listed on the nameplate. Examine the efficiency curve of Figure 314.6 which often increases slightly as the motor is operated at 10% to 20% less than rated horsepower. If the motor is oversized for the load, the efficiency is generally less than the value stated on the nameplate. To achieve high efficiency of operation it is recommended to select a motor with a horsepower rating between 80% and 100% of expected load horsepower. The center vertical line on the graph represents a typical alternating current induction motor operating at full load. Note the curve representing full-load current. Operating at over-load conditions, current increases to supply the required load torque. This elevated full-load current will cause winding overheating and will result in shorter than expected motor life.

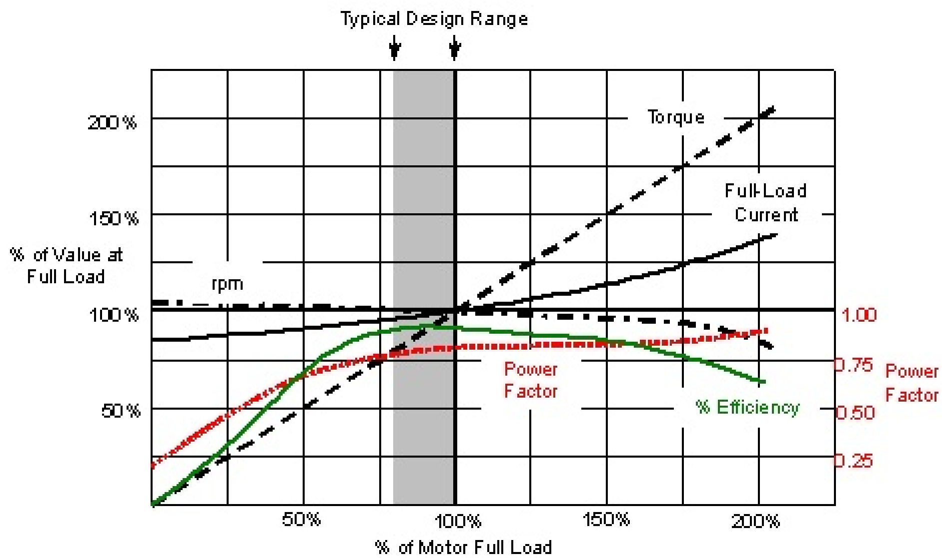

Figure314. 6. Typical operating characteristics of an alternating current induction motor powering a load ranging from less than nameplate horsepower to more than nameplate horsepower. Note in particular that operating efficiency varies significantly with load, and full-load current increases if the load is greater than the horsepower rating of the motor.

Effects of Over Voltage and Under Voltage on Motor Operation: It is important for the electrical supply to an electric motor operating under full-load conditions to have circuit voltage close to nominal values. Depending upon the electrical supply and the motor, typical nominal alternating current circuit values. Typical nominal single-phase motor circuit values are 120, 208, and 240 volts. Typical nominal three-phase motor circuit values are 208, 240, and 480 volts. Motors are designed to operate at other nominal circuit voltage especially high horsepower motors that operate at high-voltage. A common problem that can have an effect on motor performance as well an motor life is circuit voltage drop. Motor circuit wire size must be increased for motors located a considerable distance from the source of the circuit. When an electric motor is powering a load, the motor must develop the torque required. Motor output torque and horsepower are proportional to the product of voltage and current. If the electric motor does not get sufficient voltage, current will increase to make up the loss to provide the horsepower required by the load. This is illustrated in Figure 314.7 which shows the typical full-load current, locked-rotor torque, and locked-rotor current of an alternating current induction motor. The increased full-load current due to insufficient circuit voltage will result in motor winding overheating and reduced operating life. Some circuit over-voltage is acceptable, but excessive circuit over-voltage will eventually result in excessive winding current and overheating.

It might seem that increased winding current would result in increased torque during motor start-up, but remember that start-up current is typically five times full-load current which results in an even higher

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voltage drop in the circuit. As illustrated in Figure 314.7, locked-rotor torque or start-up torque is significantly lower if there is insufficient circuit voltage supplied to the motor. This reduced torque capability during motor start-up results in a longer starting time which means inrush current is applied to the motor windings for a longer time which can result in winding overheating.

An alternating current induction motor is designed to tolerate a plus or minus 10% deviation from circuit nominal voltages. The increased full-load current resulting from insufficient circuit voltage leads to increased stator and rotor conductor heating of a fully loaded motor. Insufficient circuit voltage also results in a significant reduction in the starting current. A slight increase in the voltage supply to the motor will cause an increase in the starting current as well as the locked-rotor torque. However, as the voltage increases well above rated voltage, magnetic saturation of the stator iron core occurs, resulting in an increase in motor full-load current.

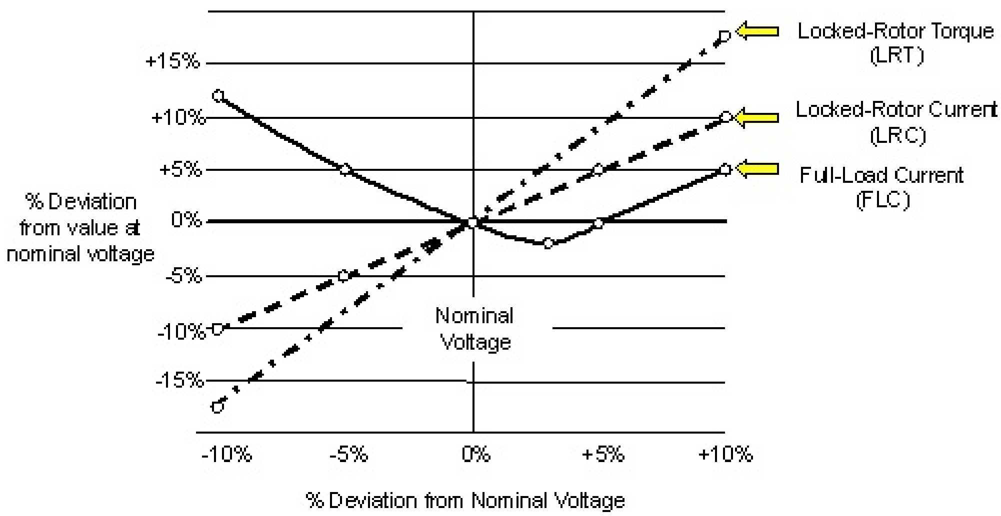

Figure314. 7. An insufficient supply voltage to an alternating current induction motor can result in an increase in full-load current and winding overheating. Insufficient supply voltage can reduce starting torque allowing starting inrush current to be applied to the windings for a longer time.

References: *NEMA Standards Publication No. MG 1-1993, Motors and Generators,* National Electrical Manufactures Association, 2101 L Street, N.W., Washington, DC, 20037. http://www.nema.org.

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