



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 its own magnetic fields which 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 to understand electric alternating current motor basic operating characteristics. For example an *induction motor generally draws five to eight times as much current when starting when 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 to understand because it is not a constant value. The efficiency changes dramatically depending upon whether the motor is properly matched to the load. Torque is a twisting force and the power provided at the shaft is proportional to the torque times the revolutions per minute (RPM) of the turning shaft. This torque changes as the rotational speed of the shaft changes. Two important parameters for an induction motor are full-load torque and locked-rotor or starting torque. The nameplate also provides something called the “design” letter which must be understood when matching a motor to a load. The *design letter designates the shape of the torque curve from zero rpm to full load rpm*. It is essential to understand this characteristic when matching an induction motor to a load.

Torque-RPM Curves: There are several types of motors presently in use that have different torque-RPM characteristics from zero RPM to operating RPM. *Figure 314.1* is a graph of level of torque developed and revolutions per minute of a motor shaft of a typical 3-phase motor. The graphs plots *torque on the vertical axis and revolutions per minute (RPM) on the horizontal axis*. Motors are designed with certain torque-RPM 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 RPM. A graph like the one shown in *Figure 314.1* shows the relationship between torque and shaft RPM for a design **B** 3-phase induction motor from the moment of start until the motor reaches full-load operating RPM.

Starting torque is identified as point **A** on *Figure 314.1*. This point is commonly referred to as **locked-rotor torque** which is the moment a motor is started. The magnetic attraction and repulsion of the rotating magnetic field of the stator will accelerate the rotor. 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** 3-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. *Full-load torque* identified at point **D** is developed when the motor is operating at rated voltage, frequency, and design full-load. If the load is increased 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 variations.

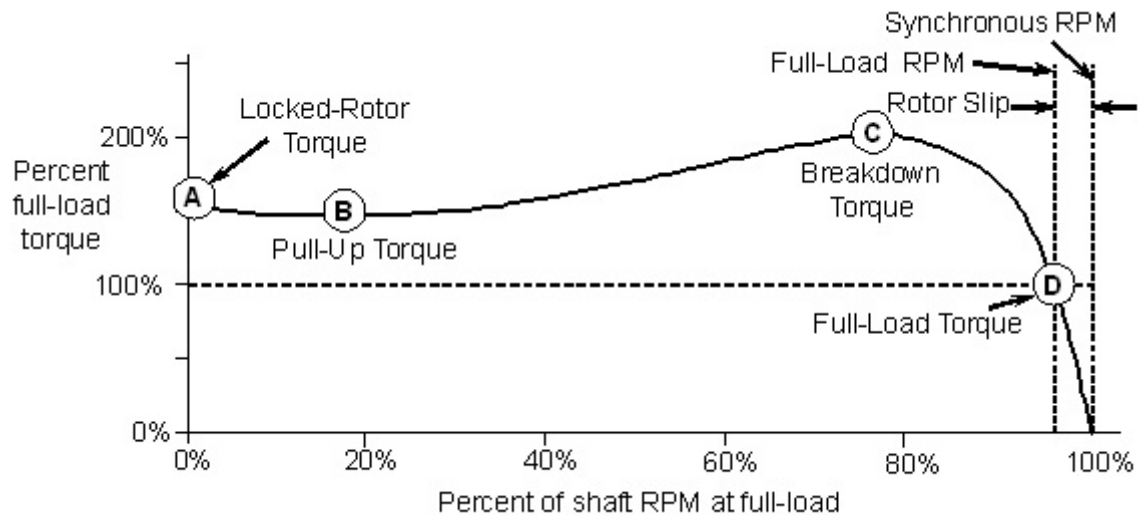


Figure 314.1. Common torque-rpm characteristic curve for a typical 3-phase design **B** induction motor. The values are on the basis of the motor rating at full-load which is point **D** on the graph.

Synchronous RPM is the speed at which the magnetic field is rotating in the stator. For a typical motor supplied 60 Hz alternating current, synchronous RPM is typically 1,800 RPM for a four-pole motor and 3,600 RPM for a two-pole motor. The shaft RPM at full-load as shown on the motor nameplate is less than synchronous RPM 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 rotor slip increases. Increased load requires an increase in motor current and a decrease in RPM.

Motor Design Letter: Induction motors are standardized for specific applications by the *National Electrical Manufacturers Association (NEMA)*. Motor design specifies the relationship of the output torque of a 3-phase induction motor compared to the motor shaft RPM from zero up to full-load RPM. There are presently four common 3-phase induction motor design types **A**, **B**, **C**, and **D**. The basic shape of the torque versus rotor RPM curves are illustrated in *Figure 314.2*. The most common 3-phase induction motor is *design B* illustrated in *Figures 314.1* and *Figure 314.2*. A characteristic of the design **B** induction motor is that breakdown torque is generally higher than starting torque known as *locked-rotor torque*. The design **A** motor has lower starting torque and higher breakdown torque than the design **B** motor. The design **B** motor has characteristics that fit a wide range of applications. A distinguishing characteristic of the design **C** motor is that starting torque is higher than breakdown torque. An application for this type of motor is powering a very hard starting load requiring high torque at low rpm. Some motors power highly variable loads where rapid acceleration is not desirable. Examples of such loads would be lifts, elevators, and oil well pump motors. The design **D** motor is best suited for these applications. These types of motors torque-RPM curves are illustrated in *Figure 314.2*.

Whatever the load a motor will increase torque and current to power the load. If a properly sized current shut-off device is not installed inside the motor or in the circuit supplying the motor the motor current will increase until the motor destroys its windings. A motor is an electrical device that must be protected from self destruction due to overloading. This current overload capability of a motor is illustrated in *Figure 314.4*.

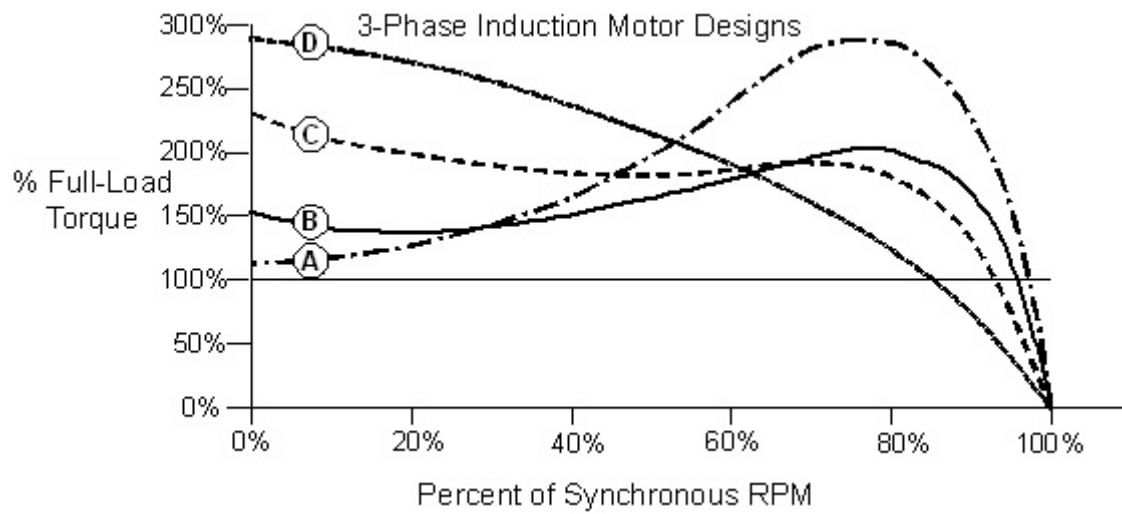


Figure 314.2. The design letter on the motor nameplate designates the relationship of shaft rpm and shaft output torque. The most common general purpose 3-phase motor is design **B**.

Single-Phase Motor Characteristics: A single-phase induction motor is supplied alternating current in the form of one sine wave using two conductors to supply the motor stator windings. These stator windings produce a magnetic field that simply alternates its North South polarity back and forth inside the motor. In order for the motor to rotate there must be a rotating magnetic field. Torque versus RPM curves for two types of single-phase motors is illustrated in *Tech Note 313*. There are different methods of creating magnetic field rotation for single-phase motors. In most cases the *starting winding* is not rated for continuous duty and must be disconnected when the motor approaches full-load RPM. A centrifugal switch usually is used to disconnect the starting winding. A common torque versus shaft RPM curves for single-phase motors is illustrated in *Figure 314.3*. When the motor is energized both the main winding and the starting winding accelerate the load. Usually when the shaft reaches about 80% of full load RPM the centrifugal switch opens and the starting winding disconnects. There is a small drop in motor torque when the starting winding disconnects. This drop in torque when starting winding disconnects can be seen in one of the motor diagrams of *Figure 314.3*. 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 this type of motor is a furnace blower. The blower is easy to start and the load builds as a synchronous blower RPM increases. The starting winding remains in the circuit because a rotating magnetic field is needed to power the load.

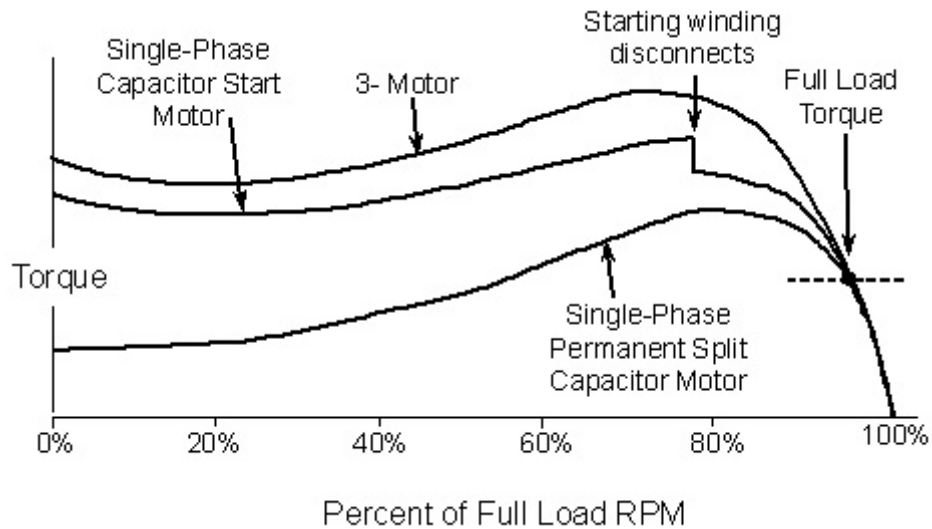


Figure 314.3. There will be a decrease in torque at the point where the starting winding disconnects for a single-phase induction motor. The auxiliary winding of a single-phase permanent split capacitor motor is rated for continuous duty and is not disconnected.

Matching Induction Motors to the Load: Figure 314.4 shows the torque-RPM curve for an induction motor and several characteristic types of loads the motor must power. 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 to full load 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 starting torque requirement to get started and torque decreases at full load RPM. 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 load where high torque is needed to start but eases off at full RPM.

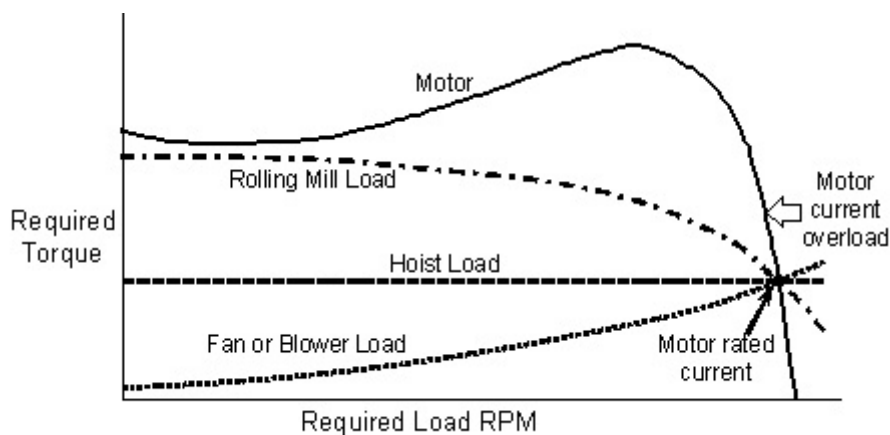


Figure 314.4. The drive motor must be capable of providing sufficient torque from start-up to full operating rpm. It is necessary to match the torque verses rpm capabilities of the motor and the load.

Motor Current: A unique characteristic of an alternating current induction motor is that it experiences a high inrush current the instant it is energized. After a short time, usually not more than 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 the rotor magnetic field cuts across the stationary stator winding and induces a reverse voltage into the stator windings. That reverse voltage opposes the supply voltage. When the rotor is just beginning to turn it does not have the ability to affect the current flow in the stator. The stator current of an induction motor is very high until the rotor has reached full load RPM. Motors are unique because of this starting inrush current and must be treated differently than other circuit loads. The rules for determining the ratings of the circuit overcurrent protection and the protective running overcurrent protection are usually separate devices. Motor rules are covered in the *National Electrical Code (NEC)* in *Article 430* for determining the rating components of electric motor circuit. Motors are prone to overload current. Overcurrent protection for electric motors is an *NEC* requirement.

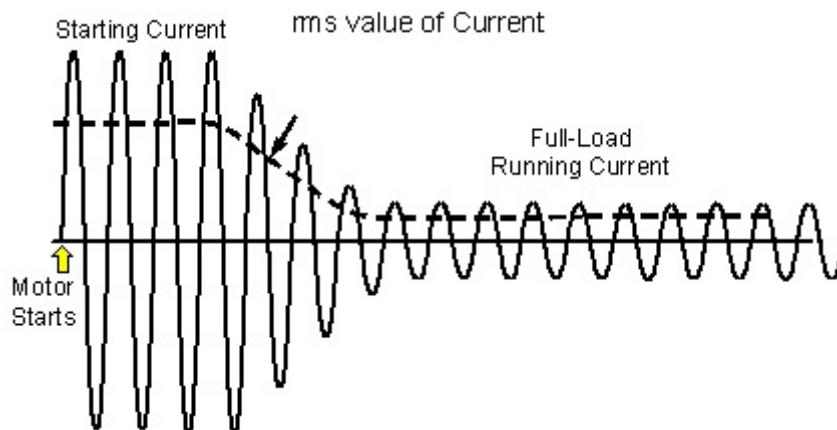


Figure 314.5. Starting current or locked-rotor current of an induction motor is usually five to eight times the level full-load current. This must be taken into consideration by the system designer and electrician when specifying and installing overcurrent protection for electric motor circuits.

Induction Motor Operating Characteristics: An alternating current induction motor is considered to be a constant RPM device but 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 condition. 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 will be 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 full-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*. Some motors can handle overloads and others cannot. The indicator is the *service factor (SF)* on the motor nameplate. For some motors the *SF* is 1.0 and others the *SF* is 1.15 or even higher.

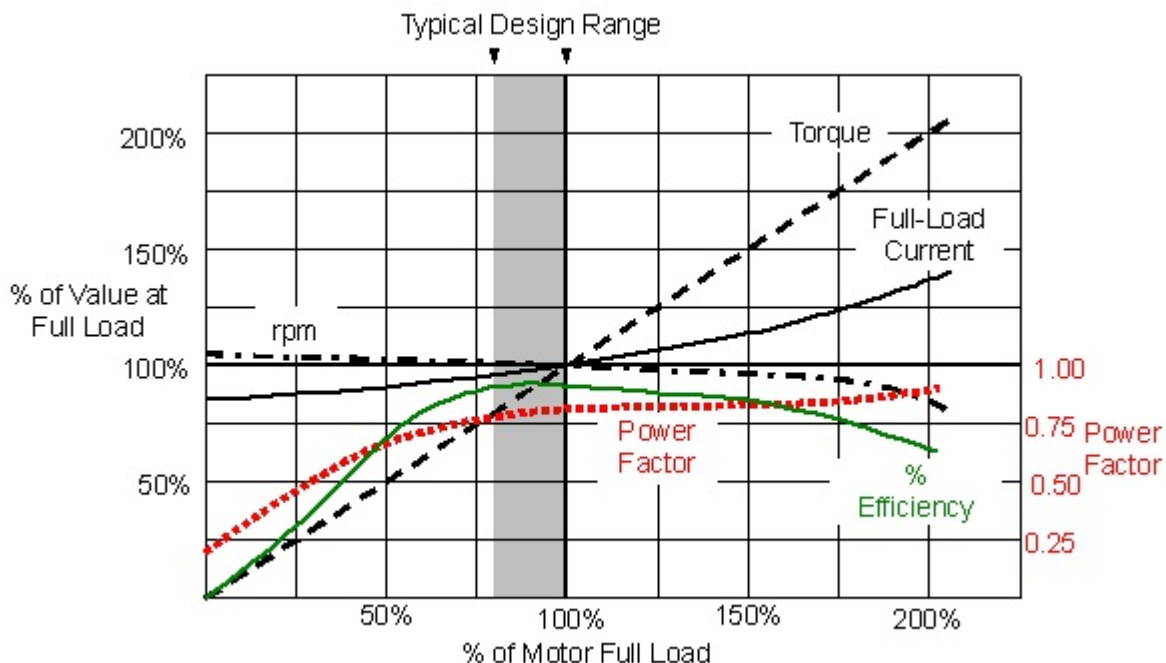


Figure 314.6. Typical operating characteristics of an alternating current induction motor powering a load ranging from less than nameplate horsepower to more than nameplate horsepower. Note in particular that operating efficiency varies significantly with load, and full-load current increases if the load is greater than the horsepower rating of the motor.

For more information on motor nameplates see *Tech Note 103*.

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