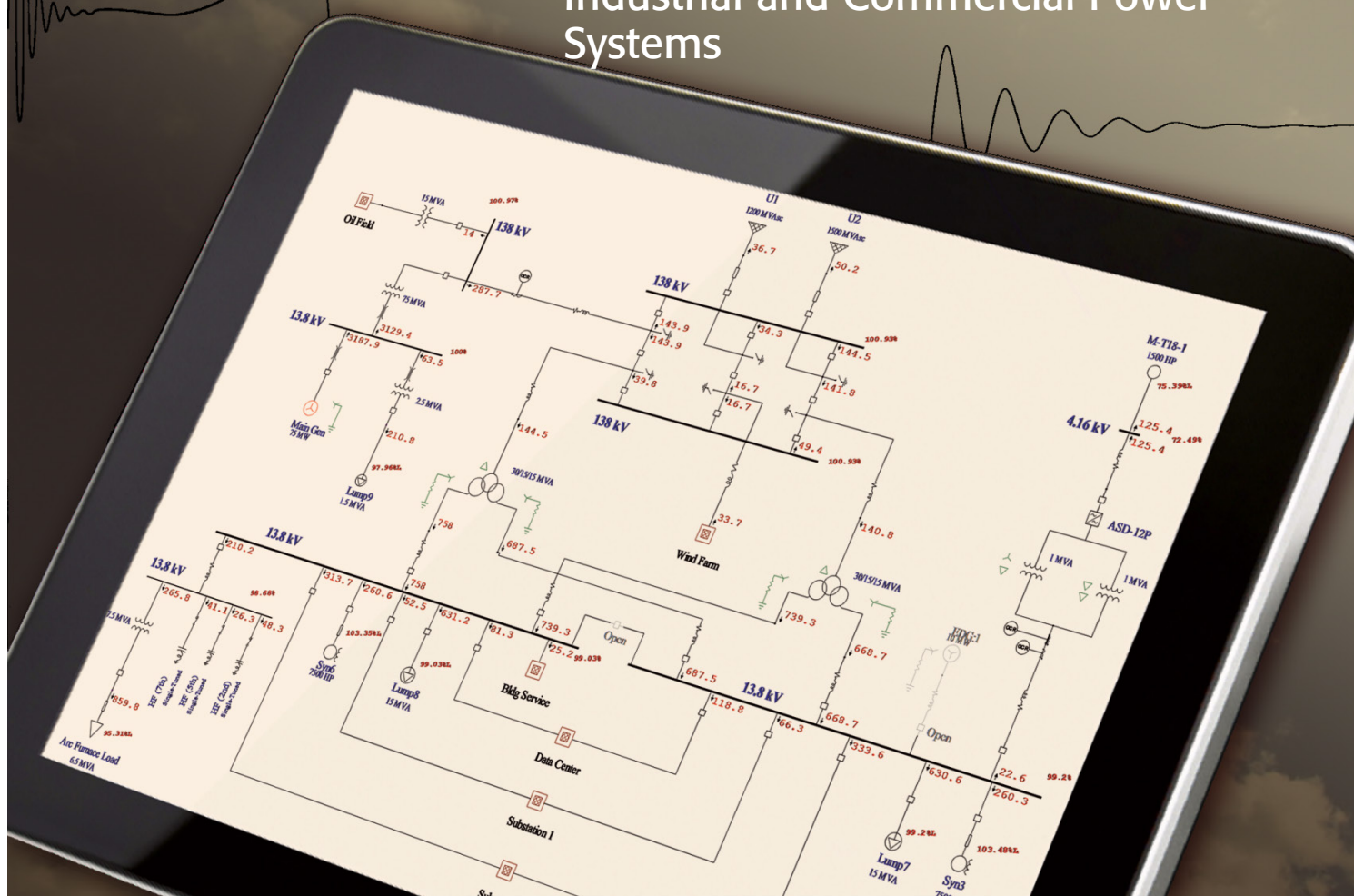


IEEE Std 3002.7™-2018

Recommended Practice for Conducting
Motor-Starting Studies and Analysis of
Industrial and Commercial Power
Systems



IEEE Recommended Practice for Conducting Motor-Starting Studies and Analysis of Industrial and Commercial Power Systems

Sponsor

**Technical Books Coordinating Committee
of the
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Abstract: Activities related to motor-starting studies, including design considerations for new systems, analytical studies for existing systems, as well as operational and model-validation considerations for industrial and commercial power systems are described. Motor-starting analysis includes evaluation of motor-starting current and voltage drop. Accuracy of calculation results primarily relies on system modeling assumptions and methods used. The use of computer-aided analysis software, with a list of desirable capabilities recommended to conduct a modern motor-starting study, is emphasized. Examples of system data requirements and result-analysis techniques are presented. Benefits obtained from motor-starting studies are discussed, and various types of computer-aided motor-starting studies are examined. Data or information required for these studies, as well as the expected results of a motor-starting study effort, are also reviewed.

Keywords: adjustable speed drive, dynamic motor starting, IEEE 3002.7, motor acceleration, motor protection, motor reacceleration, motor starting, reduced-voltage starters, soft-starters, static motor starting, variable frequency drive, voltage flicker

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This introduction is not part of IEEE Std 3002.7-2018, IEEE Recommended Practice for Conducting Motor-Starting Studies and Analysis of Industrial and Commercial Power Systems.

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This recommended practice was developed by the Technical Books Coordinating Committee of the Industrial and Commercial Power Systems Department of the Industry Applications Society, as part of a project to repackage the popular IEEE Color Books®. The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material included in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Standby Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

IEEE Std 3002.7

This recommended practice, from the commonly known *IEEE Brown Book*™, is intended as a practical, general treatise on motor-starting analysis and as an engineer's reference source on the techniques that are most commonly applied to the computer-aided motor-starting analysis of electric power systems in industrial plants and commercial buildings. IEEE Std 3002.7™ is a useful supplement to several other power system analysis texts that appear in Clause 2 (Normative reference) and Annex A (Bibliography). IEEE Std 3002.7 is both complementary and supplementary to the rest of the Color Book series.

This recommended practice describes how to conduct motor-starting studies and analysis of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in this area. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

All sections have been revised and updated—in some cases quite substantially—to reflect current technology and methodology for the computer simulation of power systems.

To many members of the working group who wrote and developed the original recommended practice, the *IEEE Brown Book* was a true labor of love. The dedication and support of each individual member was clearly evident in every chapter of the *Brown Book* and is also reflected in IEEE Std 3002.7. These individuals deserve our many thanks for their excellent contributions.

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IEEE Recommended Practice for Conducting Motor-Starting Studies and Analysis of Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice describes how to conduct motor-starting studies and analysis of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in this area. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

2. Normative reference

The following referenced document is indispensable for the application of this document (i.e., it must be understood and used, so it is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 399™, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (*IEEE Brown Book™*).^{1, 2}

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² IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.³

accelerating torque: The amount of torque available to accelerate the motor and load at any instant in time. Accelerating torque is the difference between the torque available from the motor at the motor output shaft, and the required load torque of the load system as seen at the connection to the motor shaft. Accelerating torque varies with the instantaneous speed of the system.

armature resistance: R_a , the direct-current armature resistance. This is determined from a dc resistance measurement.

armature: The main current carrying winding of a machine, usually the stator.

breakdown torque or maximum torque: The maximum shaft output torque that an induction motor (or a synchronous motor operating as an induction motor) develops when the primary winding is connected for running operation, at normal operating temperature, with rated voltage applied at rated frequency. This is also the peak of the torque-slip curve at rated voltage.

NOTE—A motor with a continually-increasing torque as the speed decreases to standstill is not considered to have a breakdown torque.⁴

direct axis: The machine axis that represents a plane of symmetry in line with the no-load field winding.

direct-axis saturated subtransient reactance: X''_{dv} (rated voltage) is the apparent reactance of the stator winding at the instant short-circuit occurs with the machine at rated voltage, no load. This reactance determines the current flow during the first few cycles after short-circuit.

direct-axis unsaturated subtransient reactance: X''_{di} (rated current) is the reactance that is determined from the ratio of an initial reduced-voltage open-circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open-circuit voltage is adjusted so that rated current is obtained for the level of the short-circuit current. The impedance is determined from the currents during the first few cycles.

direct-axis saturated synchronous reactance: X_d (machine base) is the ratio of reactive armature voltage to direct-axis armature current at rated frequency and voltage.

direct-axis saturated transient reactance: X'_{dv} (rated voltage) is the apparent reactance of the stator winding several cycles after initiation of the fault with the machine at rated voltage, no load. The time period for which the reactance may be considered X'_{dv} can be up to a half second or longer, depending upon the design of the machine and is determined by the machine direct-axis transient time constant.

direct-axis unsaturated transient reactance: X'_{di} (rated current) is the reactance that is determined from the ratio of an initial reduced-voltage open-circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open-circuit voltage is adjusted so that rated current is obtained for the level of the short-circuit current. The initial high decrement currents during the first few cycles are neglected.

³ *IEEE Standards Dictionary Online* subscription is available at: <http://dictionary.ieee.org>.

⁴ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

ferroresonance: A type of resonance in electric circuits which occurs when a circuit containing a non-linear inductance is fed from a source that has series capacitance, and the circuit is subjected to a disturbance such as the opening of a switch.

field: The exciting or magnetizing winding of a machine.

frequency: The operating frequency of a circuit.

full-load torque: The shaft torque necessary to produce rated output power at full-load speed.

inrush current: The rapid change of current with respect to time upon motor energization. Inrush current depends on the voltage impressed across the motor terminals and the motor inductance by the relationship

$$V = L \times \frac{di}{dt} \quad V = L \times \frac{di}{dt}$$

load torque: The shaft torque necessary to produce the required power output at required speed.

locked-rotor current: The steady-state current taken from the line with the rotor locked and with rated voltage and rated frequency applied to the motor.

motor slip: The quotient of the difference between the synchronous speed and the actual speed of a rotor, to the synchronous speed, expressed as a ratio, or as a percentage.

motor-starting torque, breakaway, or locked-rotor torque: The torque output capability of the motor at zero speed and rated voltage and frequency. It may also be defined as the minimum torque of a motor developed for all angular positions of the rotor when at rest, and with rated voltage and frequency applied.

positive sequence: A set of symmetrical components that have the angular phase lag from the first member of the set to the second and every other member of the set equal to the characteristic angular phase difference and rotating in the same phase sequence of the original vectors. For a three-phase system, the angular different is 120°.

positive sequence machine resistance: R_1 is that value of rated frequency armature resistance that, when multiplied by the square of the rated positive-sequence armature current and by the number of phases, is equal to the sum of the copper loss in the armature and the load loss resulting from the flow of that current.

pull-in torque: The maximum load torque under which the motor will pull its connected inertia (WR^2) into synchronism at rated voltage and frequency when excitation is applied. Note that inertia of the rotating system consists of motor, load, and coupling inertia.

pull-out torque: The maximum steady-state torque developed by the motor for 1 minute before it pulls out of step due to overload.

pull-up torque: The minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs with rated voltage applied at rated frequency.

quadrature axis: The machine axis that represents a plane of symmetry in the field that produces no magnetization. This axis is 90° ahead of the direct axis.

quadrature-axis saturated subtransient reactance: X''_{qv} (rated voltage) is the apparent reactance of the stator winding at the instant short-circuit occurs with the machine at rated voltage, no load, in quadrature axis. This reactance determines the current flow during the first few cycles after short-circuit..

quadrature-axis unsaturated subtransient reactance: X''_{qi} (rated current) is the reactance in quadrature axis that is determined from the ratio of an initial reduced-voltage open-circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open-circuit voltage is adjusted so that rated current is obtained for the level of the short-circuit current. The impedance is determined from the currents during the first few cycles.

quadrature-axis synchronous reactance: X_q is the ratio of reactive armature voltage to quadrature-axis armature current at rated frequency and voltage.

quadrature-axis saturated transient reactance: X'_{qv} (rated voltage) is the apparent reactance of the stator winding several cycles after initiation of the fault with the machine at rated voltage, no load, in quadrature axis.

quadrature-axis unsaturated transient reactance: X'_{qi} (rated current) is the reactance that is determined from the ratio of an initial reduced-voltage open-circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency in quadrature axis. The initial open-circuit voltage is adjusted so that rated current is obtained for the level of the short-circuit current. The initial high decrement currents during the first few cycles are neglected.

rating: The designated operating characteristics of a device, usually at some prescribed load.

rms: The square root of the average value of the square of the voltage or current taken throughout one period. In this text, rms will be considered total rms unless otherwise noted.

service factor: It is the percentage of overloading the motor can handle for short periods when operating normally within the correct voltage tolerances.

stator: The stationary member of a machine.

symmetrical components: A symmetrical set of three vectors used to mathematically represent an unsymmetrical set of three-phase voltages or currents. In a three-phase system, one set of three equal magnitude vectors displaced from each other by 120° in the same sequence as the original set of unsymmetrical vectors. This set of vectors is called the positive sequence component. A second set of three equal magnitude vectors displaced from each other by 120° in the reverse sequence as the original set of unsymmetrical vectors. This set of vectors is called the negative sequence component. A third set of three equal magnitude vectors displaced from each other by 0° . This set of vectors is called the *zero sequence component*.

symmetrical current: That portion of the total current that, when viewed as a waveform, has equal positive and negative values over time, such as is exhibited by a pure single-frequency sinusoidal waveform.

synchronous torque: Steady-state (load dependent) torque developed during operation.

X/R ratio: The ratio of rated frequency reactance and effective resistance to be used for short-circuit calculations.

4. Introduction

4.1 Overview

Motors on modern industrial systems are becoming increasingly larger. Some are considered large even in comparison to the total capacity of large industrial power systems. Starting large motors, especially across-the-line, can cause severe disturbances to the motor and any locally-connected load, and also to buses electrically remote from the point of motor starting. Improper motor start-up can cause damage to the motor, power quality problems (such as brownouts), or even service disruptions.

Ideally, a motor-starting study should be conducted before a large motor is purchased, such that the motor can be installed with confidence that the motor's life and applications performance will be satisfactory and the remainder of the power distribution system will not be adversely affected. It may also be performed anytime a change in the power supply is implemented. A starting voltage requirement and preferred locked-rotor current should be stated as part of the motor specification.

This recommended practice, from the commonly-known IEEE Std 399™ (*IEEE Brown Book*™), discusses benefits obtained from motor-starting studies and examines various types of computer-aided studies normally involved in motor-starting studies. Data or information required for these studies as well as the expected results of a motor-starting study effort are also presented and reviewed.

4.2 Motor fundamentals

An electric motor is an electromechanical device that converts electrical energy into mechanical energy. Most electric motors operate through the interaction of magnetic fields and current-carrying conductors to generate force. The reverse process, producing electrical energy from mechanical energy, is done by generators such as an alternator or a dynamo; some electric motors can also be used as generators; for example, a traction motor on a vehicle may perform both tasks. Electric motors and generators are commonly referred to as *electric machines*.

4.3 Motor horsepower versus torque

When ordering a motor, one refers to its basic ability for converting electrical to mechanical energy by specifying its horsepower (see Figure 1.) Yet, it will be found that most of the manufacturer's data deal with torque. A little contemplation reveals the reason for this. It turns out that torque, the turning effort, is more fundamental than horsepower, which is the rate of supplying energy. Horsepower is the product of torque multiplied by speed, so that a given horsepower can correspond to a high torque and low speed, or to the converse combination. In practical applications, one is usually specifically interested in knowing the torque and the speed separately as they apply to the load on the motor. One should note that speed is very easily measured. Because of these considerations, the graphs of motor performance will either depict torque as the function of some other parameter, such as armature current, or alternatively some parameter, such as speed, as a function of torque. More quantitatively, torque itself is the product of the force developed at the rim of a disc, cylinder, or wheel multiplied by the distance to the center. Thus, pound-feet is a common unit for this measurement. The relationship between motor-rated power and its rated torque is given below:

$$T = \frac{33\,000 \times HP}{2\pi \times RPM} \text{ in lb-ft} \quad (1)$$

$$T = \frac{59\,994 \times kW}{2\pi \times RPM} \text{ in N-m} \quad (2)$$

where

T is motor-rated torque

HP is motor-rated output power in horsepower

kW is motor-rated power

RPM is motor-rated speed

A practical manifestation of what has been said is that the horsepower output of a motor at standstill is zero. Even giant motors develop zero horsepower at the instant an attempt is made to start them. On the other hand, torque, and specifically starting torque, tells us what we want to know about starting capability. Indeed, this performance characteristic is one of the primary considerations in motor selection and application.

In a general way, horsepower, because it is specified at a rated speed, motor current, and motor voltage (and frequency), can provide guidance in selection of the size of the motor. However, in order to know whether it will serve a particular application, we must ascertain that the right combination of speed and torque can be delivered.

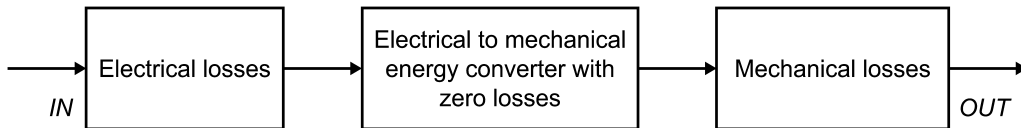


Figure 1—Motor electric power to mechanical power conversion

4.4 Starting torque and acceleration

The motor must provide sufficient torque to accelerate within its thermal rating. The torque available to accelerate at any point on the speed–torque curve is the difference between the motor torque and the load torque (see Figure 2). Because the motor torque varies approximately with the voltage squared, it must be adjusted for voltage drop during starting. If the acceleration torque produced by the motor is insufficient to bring the machine to its operating speed within the permissible time, the motor may suffer from rotor or stator damage.

Note that, typically, torque and speed characteristics can be obtained from motor manufacturers at 100% and 80% starting voltage.

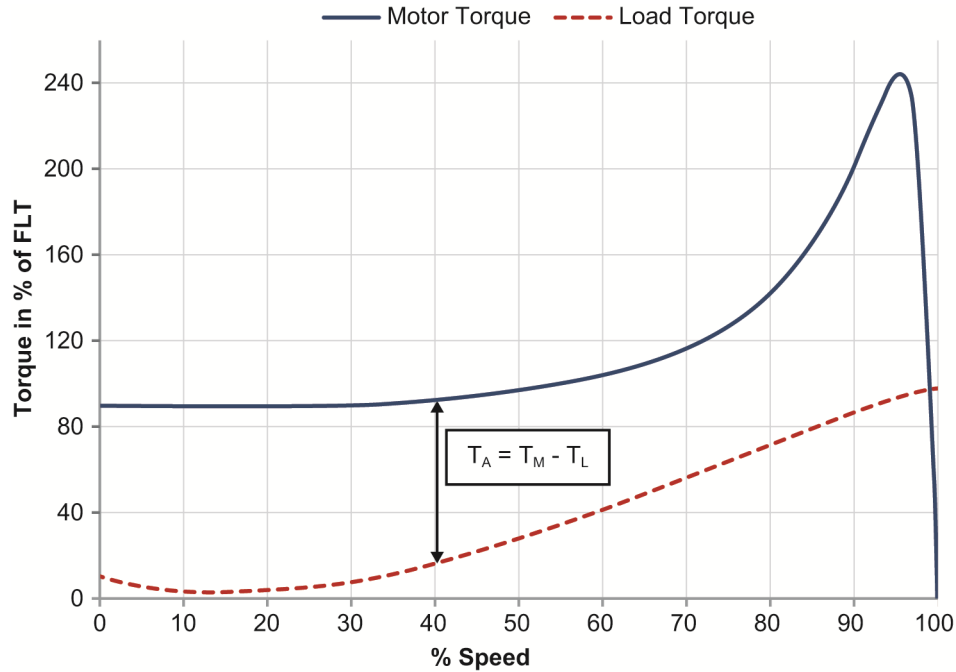


Figure 2—Motor torque/speed curve

Where

- T_L is load torque (N-m or lb-ft)
- T_M is motor torque (N-m or lb-ft)
- T_A is $(T_M - T_L)$ accelerating torque (N-m or lb-ft)
- N is operating speed in RPM
- n_s is synchronous speed in RPM
- 1 lb-ft is 1.355 818 N-m

4.5 AC and DC machines

Electric motors represent an important fraction of residential, commercial, and industrial loads; approximately 60% of the electrical energy in the United States is utilized by motors of some kind. Motor loads comprise fans, pumps of all kinds, including refrigerators and air conditioners, power tools from hand drills to lawn mowers, and even electric streetcars—basically, anything electric that moves.

Aside from differences in size and power, there are three distinct types of motors; namely induction, synchronous, and direct current (dc). Besides motor type, another important distinction is between single-phase and three-phase motors. A three-phase motor benefits from the constant torque afforded by three separate windings, staggered in space and time, that in combination produce a rotating magnetic field of

constant strength (this applies only to alternating-current [ac], not dc machines). Three-phase motors, therefore operate more smoothly and much more efficiently than single-phase motors.

Three-phase motors are commonly used for large industrial and commercial applications where high performance, including high horsepower output and high efficiency, is essential, and where three-phase utility service is standard. Smaller commercial and almost all residential customers receive only single-phase service because of the significant cost difference in distribution. It is technically possible, however, to operate a three-phase motor on single-phase service by inserting an electronic phase-shifting device that effectively splits the voltage and current along several circuits and changes their relative timing to produce three staggered sine waves. Motor-generator apparatus can also be used to operate three-phase motors on single-phase services.

4.6 AC machines

4.6.1 Overview

Two classes of ac motors are recognized—induction (asynchronous) motor and synchronous motor. An asynchronous or induction motor requires slip—relative movement between the magnetic field generated by the stator and a winding set (the rotor) to induce current in the rotor by mutual inductance. The most ubiquitous example of asynchronous motors is the common ac induction motor which must slip to generate torque.

In the synchronous types, induction (or slip) is not a requisite for magnetic field or current production. In synchronous machines, rotor-winding currents are supplied directly from the stationary frame through a rotating contact or induced via a brushless excitation mechanism.

4.6.2 Induction motor

An induction machine is an asynchronous machine that comprises a magnetic circuit which interlinks with two electric circuits, rotating with respect to each other and in which power is transferred from one circuit to the other by electromagnetic induction. An induction motor is an induction machine which transforms electric power into mechanical power, and in which one member (usually the stator) is connected to the power source, and a secondary winding on the other member (usually the rotor) carries induced current.

The ac induction motor is the most common type of industrial motor. The common ac polyphase squirrel-cage induction motor does not require commutator, brushes, or slip rings. It has the fewest windings, least insulation, and lowest cost per horsepower when compared to other motors, such as single-phase or synchronous motors. Therefore, it has become the most widely used industrial motor (see Donner, Subler, and Evon [B10]⁵).

The two main electrical components of an ac induction motor are the stator and the rotor. The stator is the stationary primary side, and the rotor is the rotating secondary part of the motor. The power is transmitted to the rotor inductively from the stator through transformer action.

The polyphase ac induction motor is connected to a three-phase power supply. The currents in a three-phase power supply are displaced by 120 electrical degrees. The current in phase A reaches its positive maximum 120° ahead of phase B, and the current in phase B will be 120° ahead of phase C. A plot of three-phase current of an induction motor can be seen in Figure 3 (ABC rotation).

⁵ The numbers in brackets correspond to those of the bibliography in Annex A.

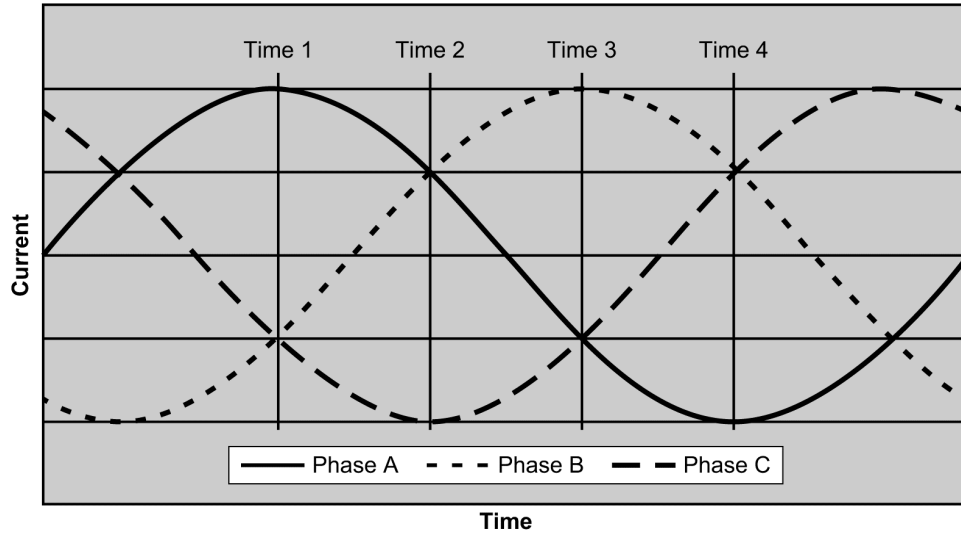


Figure 3—Plot of three-phase current of an induction motor

The stator for a two-pole three-phase ac induction motor is schematically represented in Figure 4. The pole pairs for each phase are represented in the schematic where the direction and magnitude of the fluxes in all three phases (Φ_A , Φ_B , and Φ_C) are shown as vectors. The vectors represent four moments in time as indicated in Figure 3. The resultant flux vector is represented as Φ_R . The rotation of the resultant flux vector is clockwise.

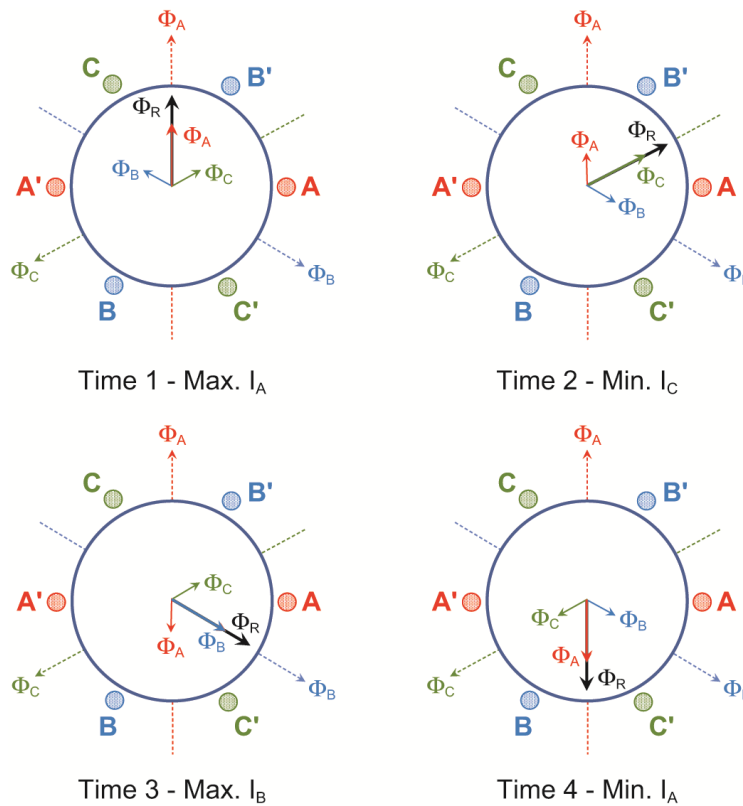


Figure 4—Flux vectors versus time

Time 1: The current in phase A is at its positive maximum as seen in Figure 3. The currents for phases B and C are at half of their negative maximums. The flux vectors for each phase can be seen in Figure 4, time 1. Using vector addition, the resultant flux vector (Φ_R) is equal to 3/2 of the maximum flux per phase and located at the 12 o'clock or 0° position.

Time 2: Phase C current is now at its negative maximum with phases A and B at half of their positive maximums. The resultant flux vector is then equal to 3/2 of the maximum and located at 2 o'clock or 60° position. The resultant vector has rotated clockwise 60° from the position in time 1. Therefore, for a 60° change in time the resultant vector has rotated 60°.

Time 3: Phase B current is now at its positive maximum with phases A and C at half of their negative maximums. The resultant flux vector is then equal to 3/2 of the maximum and located at the 4 o'clock or 120° position.

Time 4: Phase A current is now at its negative maximum with phases B and C being at half of their positive maximums. The resultant flux vector is again 3/2 of the maximum and located at the 6 o'clock or 180° position.

The resultant flux vector rotated 180° clockwise from time 1 to time 4 or half of a cycle. This half of a cycle caused the resultant flux vector, which represents the rotor, to rotate one pole. The rotor would then rotate two poles for the entire cycle or 360°. Therefore, for a two-pole motor, one cycle will produce one rotation. If the motor was a four-pole motor, the resultant flux vector would also rotate two poles for one cycle. However, a rotation of two poles in a four-pole motor is equal to a 180°. The four-pole motor would require 2 cycles for one revolution.

Therefore, the relationship between motor speed and number of poles can be seen as:

$$n_s = \frac{120 \times f}{P} \quad (3)$$

where

n_s is synchronous speed in RPM

f is frequency

P is the number of poles

The synchronous speed (revolutions per minute, RPM), is inversely proportional to the number of poles. Also, motor slip can be expressed as:

$$\% \text{ slip} = \frac{n_s - n}{n_s} \times 100 \quad (4)$$

where

n_s = synchronous speed in RPM

n = motor speed in RPM

Note that there are two common variations of induction motor: squirrel-cage and wound rotor:

- Squirrel-cage induction motor: The rotor circuit consists of a number of conducting bars shorted by rings at both ends.

- Wound rotor induction motor: The rotor circuit consists of an insulated winding whose terminals are either short-circuited or closed through external circuits. The rotor has a winding the same as stator, and the end of each phase is connected to a slip ring. Also, three brushes contact the three slip-rings to three connected resistances for reduction of starting current and speed control.

4.6.3 Synchronous motor

A synchronous machine is an alternating-current machine in which the speed of operation is exactly proportional to the frequency of the system to which it is connected. The stator winding is similar to the induction-motor winding. The rotor consists of salient poles, field pole winding, and amortisseur or damper or cage windings. Infrequently-used high speed (typically 3600 RPM) synchronous motors may use cylindrical rotors. The amortisseur winding consists of cage bars embedded in the pole faces and short-circuited at each end by the end rings. Field poles are magnetized by dc from the rotating exciter mounted on the same shaft. The rotor winding consists of an insulated-field winding, wound to produce the magnetic poles equal in number to the poles for which the stator is wound.

The motor starts as an induction motor, and the shape of the speed–torque curve depends on the resistance and reactance of the amortisseur winding. DC excitation is applied to the field winding at a speed known as pull-in speed when the motor torque equals the load torque. The dc field excitation keeps the rotor speed in synchronism with that of the rotating field produced by the stator. The motor will pull the connected load into synchronism upon the application of the dc field. During starting, the field winding is short-circuited through a field-discharge resistor to limit the induced voltage.

Synchronous motors are classified as high-speed machines when RPM is > 500 , and low-speed machines when RPM is < 500 . In certain applications, the synchronous motors are preferred over squirrel-cage induction motors for the following reasons:

- Operate at a leading power factor and thereby improve the overall power factor of the plant power system
- Less costly in certain horsepower and speed ranges, especially at speeds less than 600 RPM. Synchronous motors are cost effective when HP/RPM is > 5 or kW/RPM is > 6.7
- Constructed with wider air gaps than induction motors, which make them more robust mechanically and facilitates ease of maintenance
- Higher efficiency, on the order of 1.5% to 2% higher.

The synchronous motor is further classified as the direct-current excited synchronous motor (usually called the synchronous motor), the permanent-magnet synchronous motor, and the reluctance synchronous motor. The different types of torques developed by a synchronous motor are as follows:

- Starting or breakaway torque
- Pull-up torque
- Synchronous torque
- Pull-out torque
- Maximum torque
- Pull-in torque

During starting and acceleration as an induction motor, the synchronous motor develops a pulsating or oscillating torque superimposed on the average torque. The frequency of this torque is equal to twice the slip frequency. For a 60 Hz system, the oscillating torque will go through all frequencies from 120 Hz to 0 Hz. The inertia system of a rotating motor which has one or more natural torsional frequencies at or

below twice the line frequency will be excited. When this condition occurs, there is a possibility of torsional resonance occurring with torque amplifications. A steady-state and dynamic analysis is required for the complete drive train (including motor, coupling, gear, and driven equipment) to determine the magnitude of the torque amplification. Either the mechanical or electrical equipment vendor, or both, shall be asked to carry out this analysis. If excessive torque amplification is identified, then necessary steps must be taken to reduce its magnitude to an acceptable level. This analysis however is outside the scope of IEEE Std 3002.7™.

4.7 DC machines

4.7.1 Overview

A direct-current machine is a machine consisting of a rotating armature winding connected to a commutator and stationary magnetic poles that are excited from a direct-current source or permanent magnets. Direct-current motors are of four general types: shunt-wound, permanent-magnet, series-wound, and compound-wound (Beaty and Kirtley [B2]).

4.7.2 DC shunt motor

A shunt-wound motor may be a straight shunt-wound or a stabilized shunt-wound motor. In a straight shunt-wound motor, the field winding is connected in parallel with the armature circuit or to a source of separate excitation voltage. The shunt field is the only winding supplying field excitation. The stabilized shunt motor has two field windings: the shunt and the light series. The shunt-field winding is connected either in parallel with the armature circuit or to a separate source of excitation voltage. The light series winding is connected in series with the armature winding, and is added to prevent a rise of speed or to obtain a slight reduction of speed with increase in load.

A salient feature of the dc shunt motor is its reversibility. The direction of rotation may be reversed by changing the direction of current flow in either the shunt field winding or in the armature, but not in both. Moreover, such rotational reversal can be accomplished by “plugging,” that is by reversing one of the currents while the motor is in normal operation. In this way, it becomes unnecessary to wait while the motor coasts down to a standstill. The general characteristics of a dc shunt motor is shown in Figure 5.

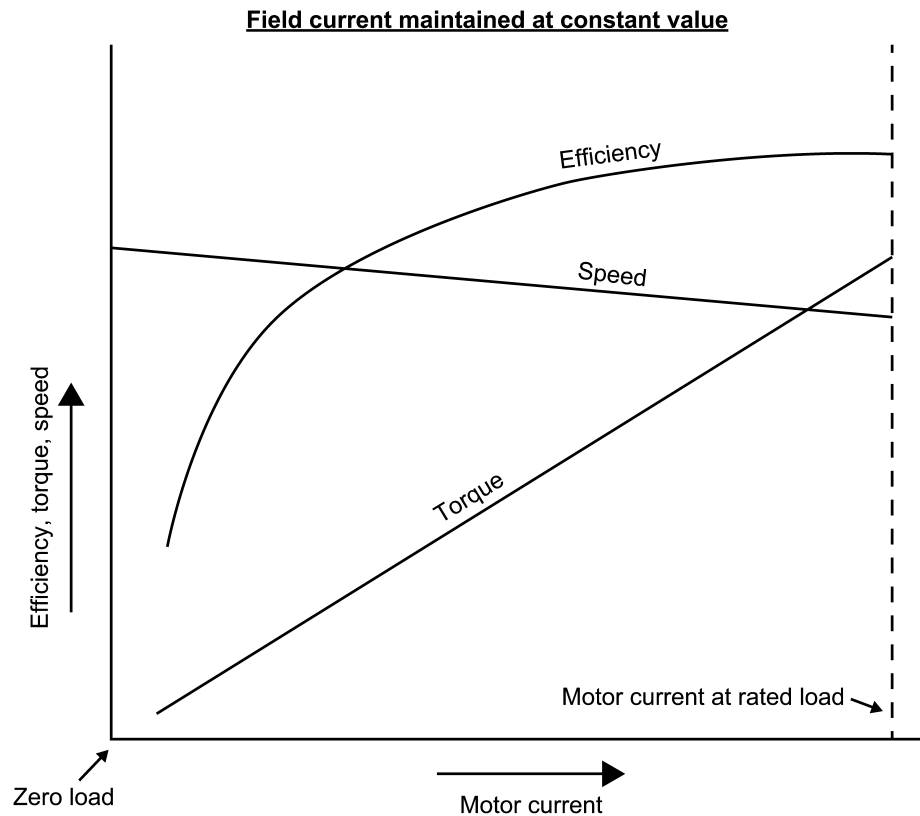


Figure 5—General characteristics of a dc shunt motor

4.7.3 DC permanent magnet (PM) motor

More recently, PM motors have benefited greatly from advanced-technology ceramic and alloy magnetic materials. On a horsepower-output basis, the PM motor can now be appreciably smaller and lighter than an equivalently-rated shunt motor. The starting torque can be several times greater than a shunt motor with otherwise-similar ratings. Their speed–torque relationship is very linear over a wide range, and therefore is easy to predict.

These characteristics of the dc PM motor are depicted graphically in Figure 6(a). It is interesting to observe from Figure 6(b) that, for a wide range of applied armature voltages, the speed–torque characteristics remain linear all the way down to a standstill as more torque is delivered.

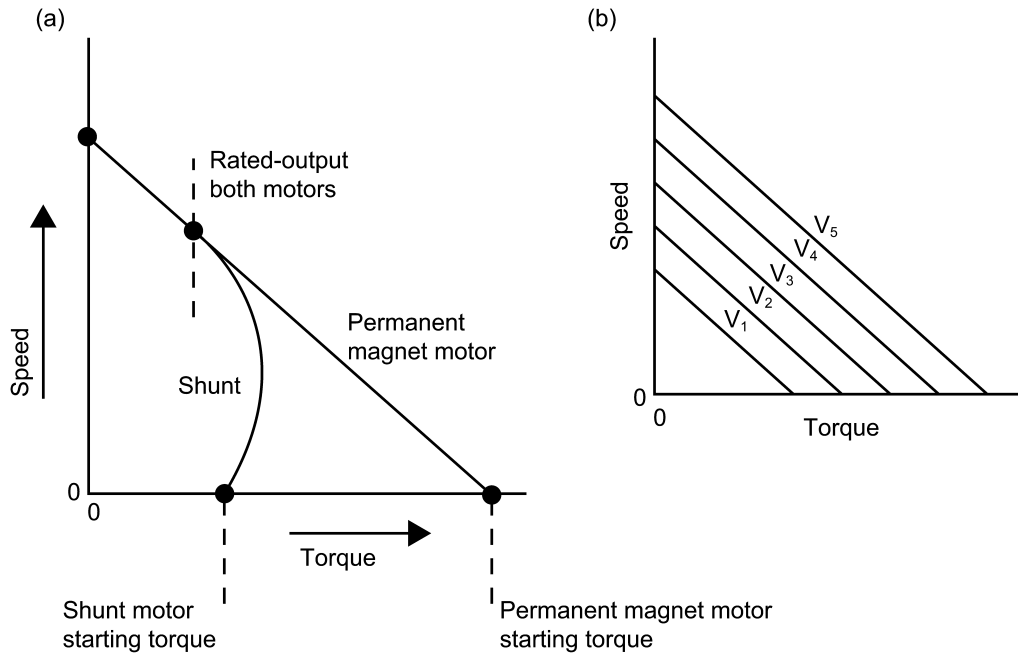


Figure 6—Unique torque-speed characteristics of a PM motor

Permanent magnet dc motors tend to exhibit better (lower) speed regulation than do shunt motors. In this regard, they compare favorably with ac induction motors. Their operating efficiency, too, tends to exceed that of shunt motors. Not only is the PM motor amenable to armature voltage control of its speed, but usually its good performance is also continuous when its direction of rotation is reversed by reversal of the polarity of the applied armature voltage. It has also been observed that when the PM motor is controlled by an audio-frequency pulse-width-modulation wave, operation is quieter than it would be in a similarly-controlled shunt motor. There, the need to use higher operating frequencies for the sake of noise reduction can be electrically undesirable.

An important practical benefit of making use of a permanent magnet field structure is immunity to run away. As is well known, if for any reason the dc shunt motor is deprived of field current, the motor goes into a runaway mode. Even if it is fully loaded, the racing, together with abnormally-high armature current, can pose a hazardous situation.

Note that specialized ac permanent magnet motors are not part of the scope of this document. Refer to the motor manufacturer for additional details. In general, PM ac motors are inherently more efficient due to the elimination of rotor conductor losses, lower resistance winding, and a “flatter” efficiency curve. Due to their synchronous operation, these motors offer more precise speed control with higher power density due to the higher magnetic flux as compared with induction machines and generally operate cooler, resulting in longer bearing and insulation life.

4.7.4 DC series motor

The dc series motor is one of the traditional “workhorses” of electromechanical energy conversion. Its popularity with railway, automobile, and other traction applications largely stems from the very high torque developed by this motor at standstill and at low speeds. The torque is high because armature current flows through both; the armature and the series field giving rise to an exceptionally-strong magnetic field between the armature conductors and the pole faces. The motor obligingly supplies greater torque in

response to shaft loading until a limit is imposed because of magnetic saturation. The older control method via a series-connected resistance wasted energy and sufficed for trams, but is unacceptable for electric automobiles. On the other hand, control by duty-cycle modulation of pulsed waveforms is extremely efficient and allows smooth variation of speed and torque.

If deprived of its mechanical load, a dc series motor will accelerate to very high speeds. See Figure 7. Indeed, such racing can culminate in centrifugal explosion of the armature, and it would be hazardous for an operator to be anywhere close to such a self-destroying machine. One might say that the unloaded motor develops too much torque for its own good due to the multiplying effect of the internal field being the product of both the armature and series field current. This abundant torque manifests itself as speed acceleration. At some extremely high speed, the unloaded motor would develop enough counter electromotive force, so that armature and field current would again be relatively low; the acceleration would then come to a halt. Unfortunately, before such a new equilibrium can be attained, the motor could be expected to destroy itself.

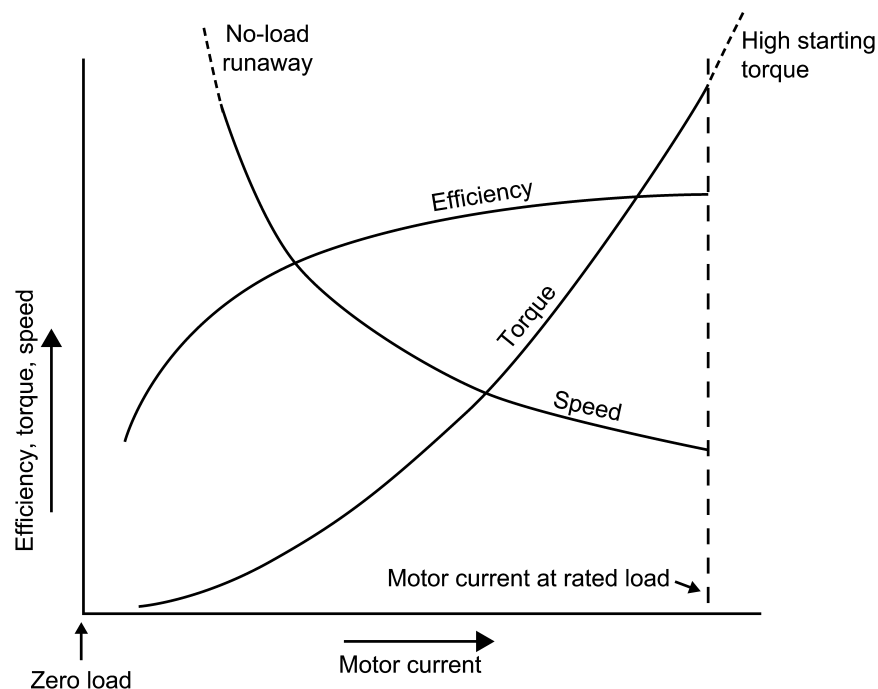


Figure 7—General characteristics of a dc series motor

4.7.5 DC compound motor

The dc compound motor has both series-connected and shunt-connected field windings. By varying the polarization and the current in these field windings, the motor can be made to behave as a series motor, a shunt motor, or a motor exhibiting various blends of series and shunt motor characteristics.

The current in the series-field winding can be diverted by means of a resistance connected across its terminals. Control of the current in the shunt-field winding is achieved by a series-connected rheostat, just as in a “plain vanilla” shunt-motor.

5. Motor standards

5.1 Overview

The motor standards can be grouped into two major categories: NEMA and IEC (and its derivatives). In North America, the National Electric Manufacturers Association (NEMA) sets motor standards, including what should go on the nameplate (NEMA MG1). In other parts of the world, the International Electrotechnical Commission (IEC) sets the standards, or at least many countries base their standards very closely on the IEC standards. For example, Germany's VDE 0530 standard and Great Britain's BS 2613 standard are close to IEC with minor exceptions. Note that the major IEC standard for motor is IEC 60034 series.

NEMA MG1 [B37] specifies that every motor nameplate must show these specific items:

- Manufacturer's type
- Rated volts and full-load amps
- Rated frequency and number of phases
- Rated full-load speed
- Rated temperature rise or the insulation system class
- Time rating
- Rated horsepower
- Locked-rotor indicating code letter
- Service factor
- Efficiency
- Frame size

Additional information may also normally appear on the nameplates depending on the motor vendor.

5.2 Comparison between NEMA and IEC motor standards

The IEC is the international counterpart to the NEMA standards. These two standards use different terms, but they are essentially analogous in ratings and, for most common applications, are largely interchangeable. In brief, NEMA standards tend to be more conservative, while IEC standards tend to be more precise, specific, and more categorized. For a more detailed comparison of these two motor standards, refer to Mistry, Finley, and Gaerke [B32]. Motor torque characteristics are compared and shown in Figure 8. Refer to Annex B for main differences between the two standards regarding motor description and testing.

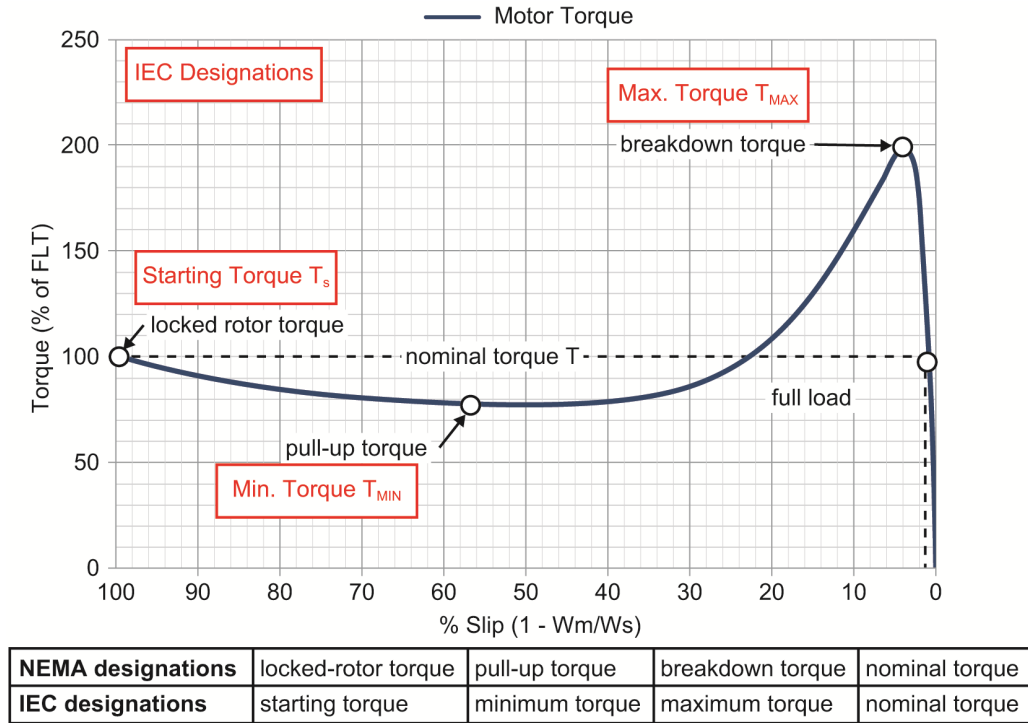


Figure 8—IEC and NEMA designations for the motor torque/speed curve

6. Analysis objectives

6.1 General purpose

A motor-starting study is performed to determine the voltages, currents, and starting times involved when starting large motors or a group of motors, either sequentially or simultaneously. Motor-starting studies are carried out to help ensure that:

- Motor(s) will start with appropriate/acceptable voltage drop
- Voltage drop at time of start will not disrupt other loads
- Motor feeder(s) are sized adequately
- Motor(s) will accelerate within acceptable start-up times
- An accurate evaluation of motor/load speed–torque characteristics and accelerating time is made
- An accurate evaluation of thermal damage characteristics of motors is made
- The motor will not experience nuisance tripping on the start
- In the event of direct on line (DOL) start is not possible, that the type and size of starter/drive required to start the motor is known
- Motor protective devices are sized/set properly

Following is a brief discussion of major problems associated with starting large motors, or groups of motors, and therefore, of significance in power system design and evaluation.

6.2 Criteria

Starting large motors can cause disturbances to the motor and other loads on other buses. In the worst cases, the starting motor may stall and be unable to start the driven load. In general, a motor-starting study should be made if the motor horsepower rating exceeds approximately 30% of the base kVA rating of the supplying transformer. Likewise, if a motor is to be started from an isolated generator, a motor starting study should be performed if the motor horsepower rating exceeds 10% to 15% (typical) of the generator kVA rating, depending on actual generator characteristics. The study should also recognize contingent condition(s), i.e., the loss of a source (if applicable).

Types of available motor-starting studies range from simple voltage drop calculation to a detailed waveform presentation of motor bus voltage; motor speed and motor torque; acceleration torque; load torque; power factor; rotor and stator currents; motor slip, real, reaction, and total power study that approaches a dynamic analysis in complexity. Each study has an appropriate use, and the selection of the correct study is as important a step in the solution process as the actual performance of the study itself. Examples presented here should serve as a guide for determining when to use each type of motor-starting study, what to expect in the way of results, and how these results can be beneficially applied. The examples should also prove useful in gathering the required information for the specific type of study chosen. Experienced consulting engineers and equipment manufacturers can give valuable advice, information, and direction regarding the application of motor-starting studies as well.

It may be necessary to make a study for smaller horsepower sizes depending on the daily fluctuation of nominal voltage, voltage level, size and length of the motor feeder cable, amount of load, regulation of the supply voltage, the impedance and tap ratio of the supply transformer(s), load torque versus motor torque, and the allowable starting time. Finally, some applications may involve starting large groups of smaller motors of sufficient collective size to impact system voltage regulation during the starting interval.

One of the most common side effects of starting large motors is a serious voltage dip on the buses throughout the facility. This voltage dip will cause other motors to slow down. In severe cases, other motors may reach the stall point causing a cascading drop in system voltage. Control relays may not hold, and auxiliary equipment may be affected. In addition to these secondary effects, the life of all motors on the system may be shortened. Motor-starting studies should determine the variation in voltage as a function of time during the period of acceleration of the motor. Motor-starting studies should be performed prior to the ordering of large motors, such that the motor can be installed with confidence that the motor's life and applications performance will be satisfactory, and the remainder of the power distribution system will not be adversely affected.

6.3 Voltage dips

Probably the most widely recognized and studied effect of motor starting is the voltage dip experienced throughout an industrial power system as a direct result of starting large motors. Available accelerating torque drops appreciably at the motor bus as voltage dips to a lower value, extending the starting interval and affecting, sometimes adversely, overall motor-starting performance. Acceptable voltage for motor starting depends on motor and load-torque characteristics. Requirements for minimum starting voltage can vary over a wide range, depending on the application (i.e., voltages can range from 80% or lower to 95% or higher). Refer also to Chapter 3 in IEEE Std 141™ for a discussion of voltage considerations.

A starting point for most motor-starting studies is an understanding of the minimum acceptable voltage that must be sustained on the system. During motor starting, the voltage level at the motor terminals should be maintained as specified by the motor manufacturer. This value is typically 80% of motor-rated voltage for a standard motor having a standard 150% starting torque at rated voltage (i.e., 100% voltage) and with a constant torque load applied. This value results from examination of speed–torque characteristics of a motor and the desire to successfully accelerate a fully-loaded motor at reduced voltage (i.e., torque varies

with approximately the square of the voltage, therefore, the new starting torque is about $T = 0.8^2 \times 150\% = 96\%$ of rated torque).

When other motors are affected, or when lower shaft loadings are involved, the minimum permissible voltage may be either higher or lower, respectively. The speed–torque characteristics of the starting motor along with any other affected motors and all related loads should be examined to specifically determine minimum acceptable voltage. Assuming reduced voltage permits adequate accelerating torque, it should also be verified that the longer starting interval required at reduced torque caused by a voltage dip does not result in the I^2t damage limit of the motor being exceeded.

Several other problems may arise on the electrical power system due to the voltage dips caused by motor starting. Motors that are running normally on the system, for example, will slow down in response to the voltage dip occurring when a large motor is started. The running machines must be able to reaccelerate once the machine being started reaches operating speed. When the voltage depression caused by the starting motor is severe, the loading on the running machines may exceed their breakdown torque (at the reduced voltage), and they may decelerate significantly, or even stall, before the starting interval is concluded. The decelerating machines all impose heavy current demands that only compound the original distress caused by the machine that was started. The result is a cascading voltage depression that can lead to the loss of all loads.

For example, if the motors on the system are standard NEMA B design, the speed–torque characteristics (e.g., 200% breakdown torque at full voltage) should prevent a stall, provided the motor terminal voltage does not drop below approximately 70% of motor nameplate voltage. This is a valid guideline to follow anytime the shaft load does not exceed 100% rated, since the developed starting torque is again proportional to the terminal voltage squared (V^2), and the available torque at 70% voltage would thus be slightly above 100%. Of course, if motors other than NEMA design B are used, a similar criterion can be established to evaluate reacceleration following a motor-starting voltage dip based on the exact speed–torque characteristics of each particular motor.

Other types of loads, such as electronic devices and sensitive control equipment, may be adversely affected during motor starting. There is a wide range of variation in the amount of voltage drop that can be tolerated by static drives and computers. Voltage fluctuations may also cause objectionable fluctuations in lighting. Tolerable voltage limits should be obtained from the specific equipment manufacturers. Table 1 summarizes some typical critical voltage levels when performing a motor-starting study and the effects of voltage dips (i.e., for information only, refer to NEMA MG1, NEMA ICS 1, NEMA ICS 2, UL 347, NEMA ICS 4, NEMA ICS 6, and specific equipment manufacturer for more details).

Table 1—Summary of representative critical system voltage levels when starting motors

Voltage drop location or problem	Minimum allowable voltage (% rated)
System voltage	95% to 105%
At terminals of starting motor	80%
All terminals of other motors that must reaccelerate	70%
AC contactor pick-up (by standard)	85%
DC contactor pick-up (by standard)	80%
Contactor hold-in (average of those in use)	60% to 70%
Solid-state control devices	90%

A motor-starting study can expose and identify the extent of a voltage drop problem. The voltage at each bus in the system can, for example, be readily determined by a computer study. Equipment locations likely to experience difficulty during motor starting can be immediately determined. In situations where a variety of equipment voltage ratings are available, the correct rating for the application can be selected. Circuit changes, such as off-nominal tap settings for distribution transformers and larger-than-standard conductor-sized cable, can also be readily evaluated. On a complex power system, this type of detailed analysis is very difficult to accomplish with time-consuming hand-solution methods.

Several methods of minimizing voltage dip on starting motors are based on the fact that during starting time, a motor draws an inrush current directly proportional to terminal voltage; therefore, a lower voltage causes the motor to require less current, thereby reducing the voltage dip.

Autotransformer starters are a very effective means of obtaining a reduced voltage during starting with standard taps ranging from 50% to 80% of normal rated voltage. A motor-starting study is used to select the proper voltage tap and the lower line current inrush for the electrical power system during motor start. Other special reduced-voltage starting methods include resistor, reactor, partial-winding, and wye-delta (Y- Δ). All starting methods are examined by an appropriate motor-starting study, and the best method for the particular application involved can be selected. In all reduced-voltage starting methods, torque available for accelerating the load is a very critical consideration once bus voltage levels are judged otherwise acceptable. Only 25% torque is available, for example, with 50% of rated voltage applied at the motor terminals. Any problems associated with reduced starting torque imposed by special starting methods are automatically uncovered by a motor-starting study.

Another method of reducing high inrush currents is by using a capacitor starting system (see Harbaugh and Ponsting [B16]). This maintains acceptable voltage levels throughout the system. With this method, the high inductive component of normal reactive starting current is offset by the addition, during the starting period only, of capacitors to the motor bus. This differs from the practice of applying capacitors for running motor power factor correction. A motor-starting study can provide information to allow optimum sizing of the starting capacitors and determination of the length of time the capacitor must be energized. The study can also establish whether the capacitor and motor can be switched together, or because of an excessive voltage drop that might result from the impact of capacitor transient charging current when added to the motor inrush current, the capacitor must be energized momentarily ahead of the motor. The switching procedure can appreciably affect the cost of final installation.

Use of special starters or capacitors to minimize voltage dips can be an expensive method of maintaining voltage at acceptable levels (see Harbaugh and Ponsting [B16]). Where possible, off-nominal tap settings for distribution transformers are an effective, economical solution for voltage dips. By raising no-load voltage in areas of the system experiencing difficulties during motor starting, the effect of the voltage dip can often be minimized. In combination with a load flow study, a motor-starting study can provide information to assist in selecting proper taps and help ensure that light load voltages are not excessively high.

The motor-starting study can be used to prove the effectiveness of several other solutions to the voltage dip problem as well. With a wound rotor motor, differing values of resistance are inserted into the motor circuit at various times during the starting interval to reduce maximum inrush (and accordingly starting torque) to some desired value. Figure 9 shows typical speed–torque characteristic curves for a wound rotor motor. With appropriate switching times (dependent on motor speed) of resistance values, practically any desired speed–torque (starting) characteristic can be obtained. A motor-starting study aids in choosing optimum current and torque values for a wound rotor motor application whether resistances are switched in steps by timing relays or continuously adjusted values obtained through a liquid rheostat feedback starting control.

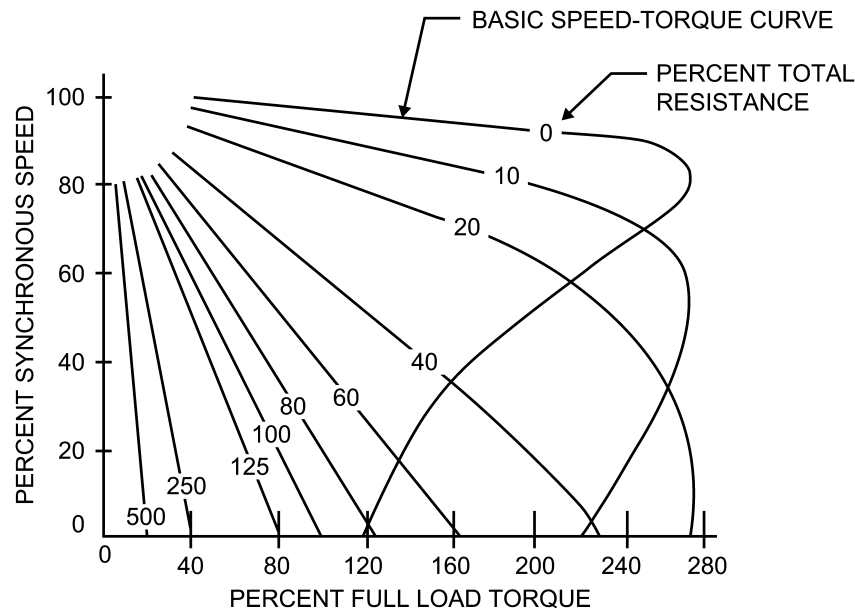


Figure 9—Typical wound rotor motor speed–torque characteristics

Motors with a specified lower-than-normal inrush characteristic can be used to manage applications in which the disturbance caused by motor starting is otherwise problematic. While more expensive than standard motors, the premium cost of so-called “low inrush” motors may offset the costs of other solutions to the voltage disturbance problem. These motors maintain nearly the same speed–torque characteristics as standard machines, but the inrush current is limited (usually to about 4.6 times full-load current compared with 6 times full-load current for a standard motor). Low-inrush motors are commonly used in applications where the electrical energy is supplied from local generators such as shipboard systems.

6.4 Weak source generation

6.4.1 Overview

Smaller power systems are usually served by limited capacity sources, which generally magnify voltage drop problems on motor starting, especially when large motors are involved. Small systems can also have on-site generation, which causes an additional voltage drop due to the relatively higher impedance of the local generators during the motor-starting interval. The type of voltage regulator system applied with the generators can dramatically influence motor starting as illustrated in Figure 10. A motor-starting study can be useful, even for analyzing the performance of small systems. Certain computer programs can accurately model generator transient behavior and exciter/regulator response under motor-starting conditions, providing meaningful results and conclusions.

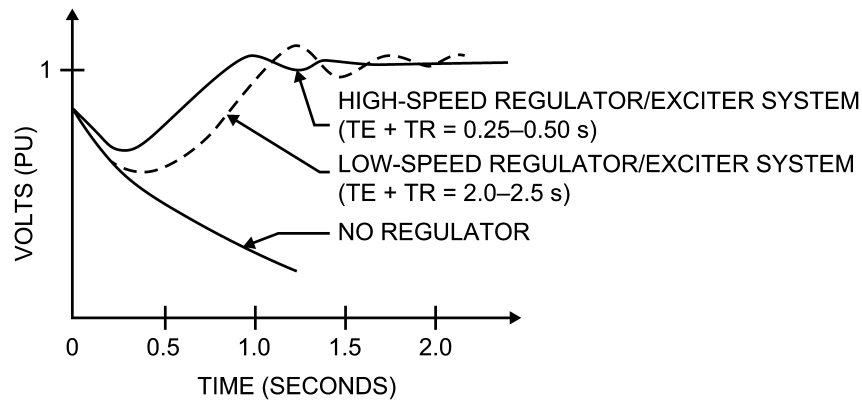


Figure 10—Typical generator terminal voltage characteristics for various exciter/regulator system;
TE = exciter time constant (in seconds),
TR = regulator input filter time constant (in seconds)

6.4.2 Special torque requirements

Sometimes special loads must be accelerated under carefully controlled conditions without exceeding specified torque limitations of the equipment. An example of this is starting a motor connected to a load through gearing. This application requires a special period of low-torque cushioned acceleration to allow slack in the gears and couplings to be picked up without damage to the equipment. Certain computer-aided motor-starting studies allow an instant-by-instant shaft output torque tabulation for comparison to allowable torque limits of the equipment. This study can be used for selecting a motor or a starting method, or both, with optimum speed–torque characteristics for the application. The results of a detailed study are used for sizing the starting resistors for a wound rotor motor, or in analyzing rheostatic control for a starting wound rotor motor that might be used in a cushioned starting application involving mechanical gearing or a coupling system that has torque transmitting limitations. High-inertia loads increase motor-starting time, and heating in the motor due to high currents drawn during starting can be intolerable. A computer-aided motor-starting study allows accurate values of motor current and time during acceleration to be calculated. This makes it possible to determine if thermal limits of standard motors will be exceeded for longer than normal starting intervals.

Other loads have special starting torque requirements or accelerating-time limits that require special high-starting torque (and inrush) motors. Additionally, the starting torque of the load or process may not permit low inrush motors in situations where these motors might reduce the voltage dip caused by starting a motor having standard inrush characteristics. A simple inspection of the motor and load speed–torque curves is not sufficient to determine whether such problems exist. This is another area where the motor torque and accelerating-time study can be useful.

7. Methodology and standards

7.1 Overview

From the previous discussion, it is apparent that, depending on the factors of concern in any specific motor-starting situation, more than one type of motor-starting study can be required.