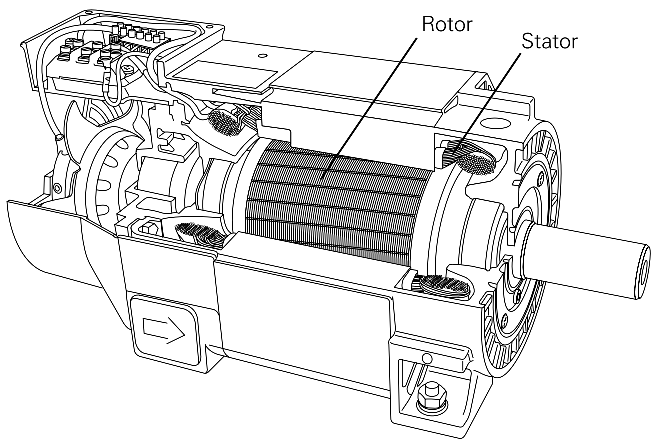
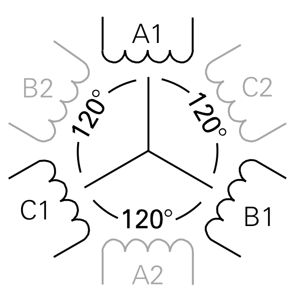
Servomotor Construction

There are two types of AC servomotors used with motion control drives: synchronous and induction. Induction motors are also referred to as asynchronous motors. The two basic elements of all AC motors are the stator and rotor. The principle of operation of a stator is the same in asynchronous and synchronous motors. There are, however, differences in rotor construction.



Stator and a Rotating Magnetic Field

A rotating magnetic field must be developed in the stator of an AC motor in order to produce mechanical rotation of the rotor. Wire is coiled into loops and placed in slots in the motor housing. These loops of wire are referred to as the stator windings. The following drawing illustrates a three-phase stator. Phase windings (A, B, and C) are placed 120° apart. In this example, a second set of three-phase windings is installed. The number of poles is determined by how many times a phase winding appears. In this example, each phase winding appears two times. This is a two-pole stator. If each phase winding appeared four times it would be a four-pole stator.



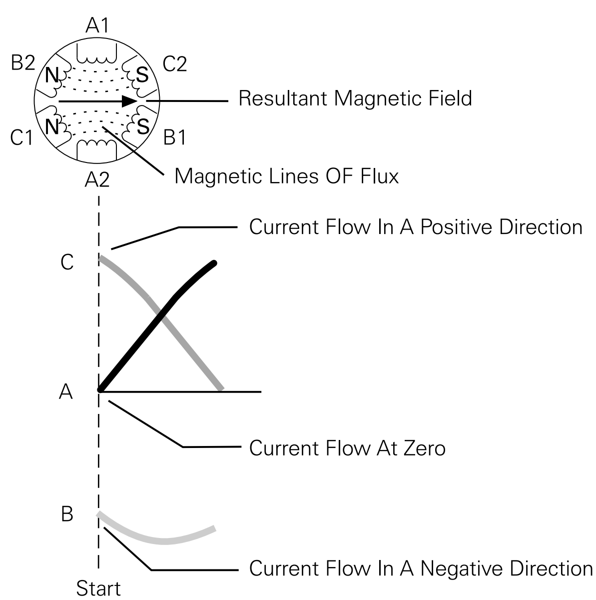
2-Pole Stator Winding

Magnetic Field

When AC voltage is applied to the stator, current flows through the windings. The magnetic field developed in a phase winding depends on the direction of current flow through that winding. The following chart is used here for explanation only. It assumes that a positive current flow in the A1, B1 and C1 windings result in a north pole.

Winding	Current Flow Direction	
	Positive	Negative
A1	North	South
A2	South	North
B1	North	South
B2	South	North
C1	North	South
C2	South	North

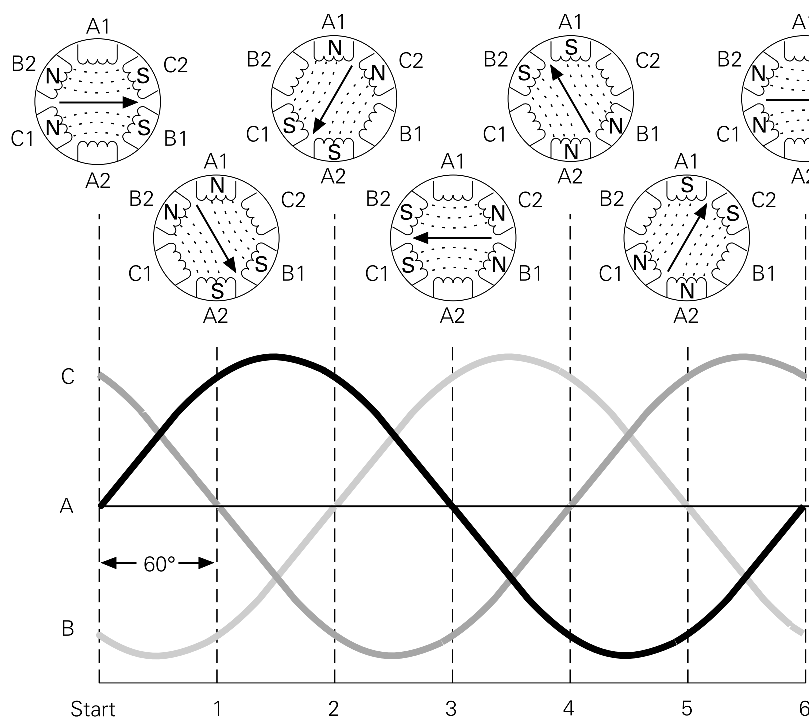
It is easier to visualize a magnetic field if a time is picked when no current is flowing through one phase. In the following illustration, for example, a time has been selected during which phase A has no current flow, phase B has current flow in a negative direction, and phase C has current flow in a positive direction. Based on the above chart, B1 and C2 are south poles and B2 and C1 are north poles. Magnetic lines of flux leave the B2 north pole and enter the nearest south pole, C2. Magnetic lines of flux also leave the C1 north pole and enter the nearest south pole, B1. A magnetic field results as indicated by the arrow.



The amount of flux lines (Φ) the magnetic field produces is approximately equal to the voltage (E) divided by the frequency (F). Increasing the supply voltage increases the flux of the magnetic field. Decreasing the frequency increases the flux.

$$\Phi \approx \frac{E}{F}$$

If the field is evaluated at 60° intervals from the starting point, at point 1 it can be seen that the field will rotate 60°. At point 1 phase C has no current flow, phase A has current flow in a positive direction and phase B has current flow in a negative direction. Following the same logic as used for the starting point, windings A1 and B2 are north poles and windings A2 and B1 are south poles. At the end of six such intervals the magnetic field will have rotated one full revolution or 360°.



Synchronous Speed

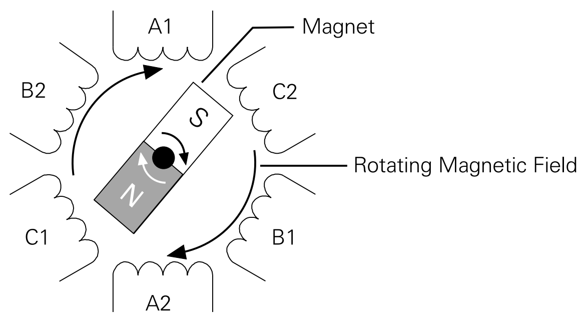
The speed of the rotating magnetic field is referred to as synchronous speed (N_S). Synchronous speed is equal to 120 times the frequency (F), divided by the number of poles (P). If the applied frequency of the two-pole stator used in the previous example is 60 hertz, synchronous speed is 3600 RPM.

$$N_S = \frac{120F}{P} \qquad N_S = \frac{120 \times 60}{2} \qquad N_S = 3600 \text{ RPM}$$

Synchronous Rotor

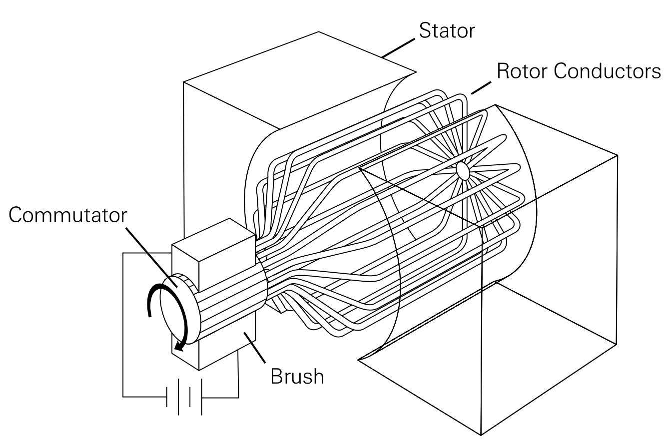
Synchronous motors are not induction motors. They are called "synchronous" because the rotor operates at the same speed as the rotating magnetic field. There are different methods to achieve synchronization between the rotor and the rotating manetic field. The most common method in servomotor applications is the use of a permanent magnet rotor. Permanent rare-earth magnets are glued onto the rotor. This type of rotor is found on smaller synchronous motors. A synchronous motor of this design is relatively small with low rotor inertia. The smaller, low inertia rotor provides fast acceleration and high overload torque ratings.

When the stator windings are energized, a rotating magnetic field is established. The permanent magnet rotor has its own magnetic field that interacts with the rotating magnetic field of the stator. The north pole of the rotating magnetic field attracts the south pole of the permanent magnet rotor. As the rotating magnetic field rotates, it pulls the permanent magnet rotor, causing it to rotate.



DC Motor Comparison

A permanent magnet synchronous motor can be compared to a standard DC motor. A DC motor consists of a stator and rotor. The rotor windings are made up conductors that terminate at a commutator. DC voltage is applied to the rotor thru carbon brushes which ride on the commutator.

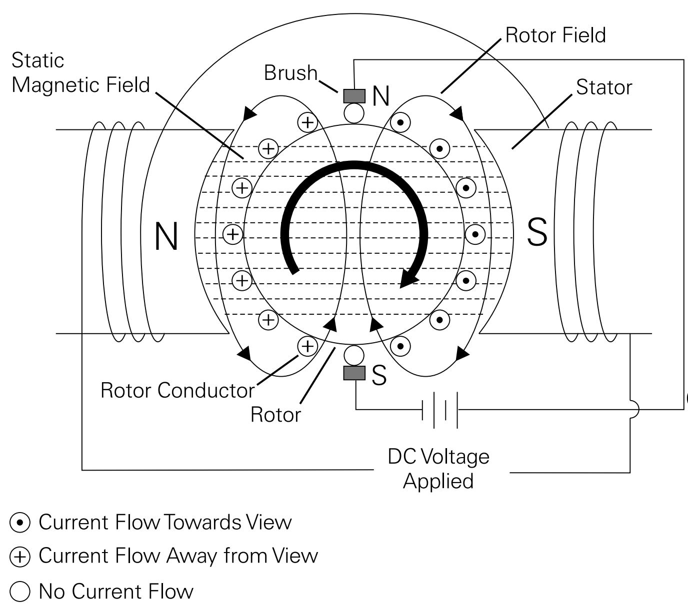


A permanent electromagnet with north and south poles is established when DC voltage is applied to the stator. The resultant magnetic field is static (non-rotational).

The DC voltage applied to the rotor conductors causes current to flow. This current reverses direction twice per revolution. Voltage polarity is such that during one half of a revolution current flows through half the conductors in one direction and half of the conductors in the opposite direction.

Current flow momentarily decreases to zero in a conductor when a brush is in direct contact with it. Polarity of the applied voltage is reversed. This is known as commutation. Current flow through the conductor increases in the opposite direction. The resultant magnetic field reverse polarity for the second half of a revolution.

The resultant magnetic armature fields are of opposite polarity to the main stator field. The north pole of the rotor is attracted to the south pole of the stator and rotation results.



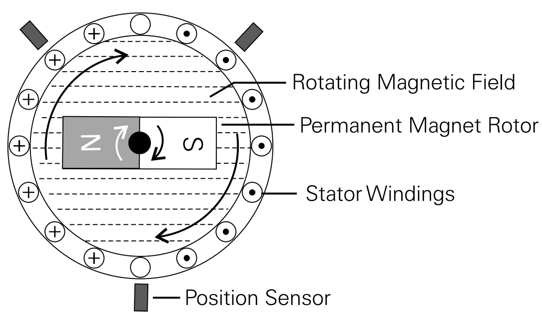
conductor.

There are weak points with this design. The commutator adds significant weight to the rotor, increasing inertia and reducing acceleration capability. The design of the commutator also limits the maximum speed of the motor. Current flow through rotor windings generates heat in the center of the motor that requires some method of cooling, such as intenal ventilation. In addition, there are added maintanance cost, such as brushes, which must be checked and replaced regularly.

Synchronous Servomotor

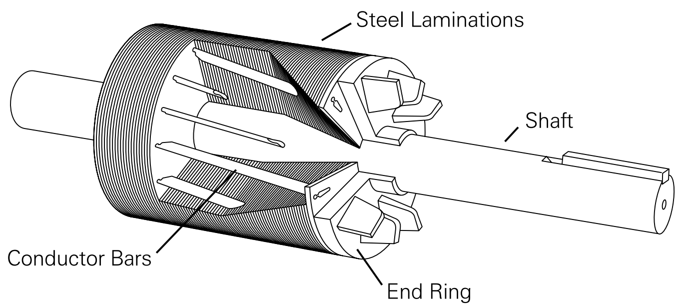
Permanent magnet synchronous servomotors offer many advantages over DC motors. The permanent magnetic field is generated by the rotor instead of the stator. There is no current flow to generate heat in the rotor. Instead, heat is generated in the stator windings which are close to the surface of the motor. In many applications natural convection cooling is all that is required. In some more demanding applications an external blower provides sufficient cooling. Since no internal ventilation is required, servomotors can be built to higher degrees of protection. Servomotors have a higher efficiency since there are no losses in a rotor/armature winding.

In addition, there is no commutator to limit speed or acceleration. Instead of switching rotor current mechanically to establish the correct polarity of the rotor's magnetic field, the MASTERDRIVE MC commutates the magnetic field of the stator electronically. In order to accomplish this the drive must monitor the position of the permanent magnet rotor with respect to the rotating magnetic field of the stator. This information is provided to the drive by a feedback device known as an enccoder. On permanent magnet type synchronous motors, the encoder must give the absolute position of the rotor within one revolution.

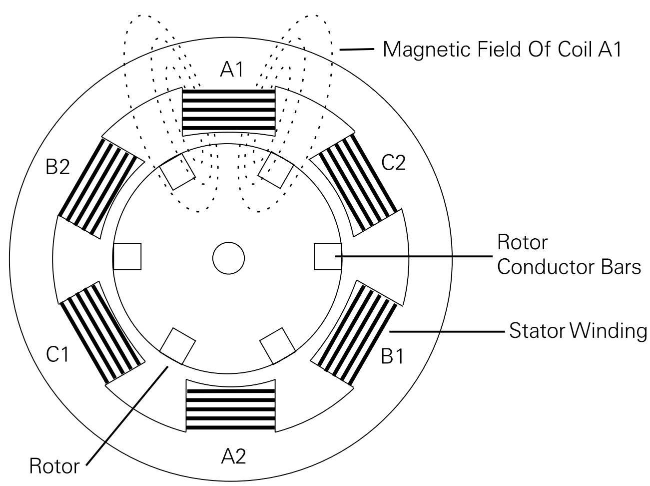


Asynchronous Rotor

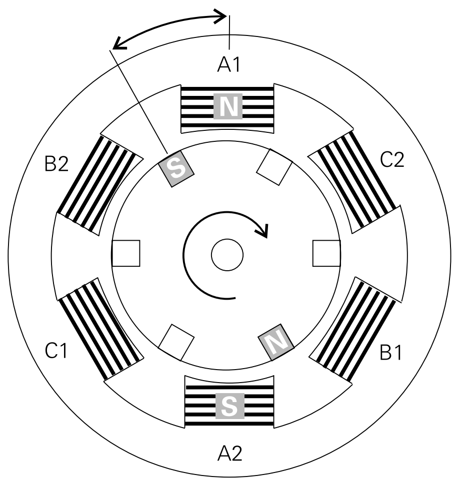
Siemens also offers asynchronous (induction) servomotors. The most common type of rotor used with asynchronous motors is the "squirrel cage" rotor. The construction of the squirrel cage rotor is reminiscent of the rotating exercise wheels found in cages of pet rodents. The rotor consists of a stack of steel laminations with evenly spaced conductor bars around the circumference. The conductor bars are mechanically and electrically connected with end rings. A slight skewing of the bars helps to reduce audible hum. The shaft is an integral part of the rotor construction.



There is no direct electrical connection between the stator and the rotor or between the power supply and the rotor of an asynchronous motor. When a conductor, such as a conductor bar of the rotor, passes through a magnetic field, a voltage (emf) is induced in it. The induced voltage causes current flow in the conductor.



Current flow in the conductor bars produces magnetic fields around each rotor bar. The rotor becomes an electromagnet with alternating north and south poles. It must be remembered that current and magnetic fields of the stator and rotor are constantly changing. The following drawing illustrates one instant in time during which current flow through winding A1 produces a north pole. The expanding field cuts across an adjacent rotor bar, inducing a voltage. The resultant magnetic field in the rotor tooth produces a south pole, which is attracted to the stator's north pole. As the stator magnetic field rotates the rotor follows.



Asynchronous Slip

There must be a difference in speed between the rotor of an asynchronous motor and the rotating magnetic field. This is known as slip. If the rotor and the rotating magnetic field were turning at the same speed, no relative motion would exist between the two and no lines of flux would be cut. With no flux lines cut no voltage would be induced in the rotor. The difference in speed is called slip. Slip is necessary to produce torque.

Slip is dependent on load. An increase in load will cause the rotor to slow down, that is to increase the slip. A decrease in load will cause the rotor to speed up or decrease slip. The following formula is used to calculate slip. For example, a four-pole motor operated at 60 Hz has a synchronous speed of 1800 RPM. If rotor speed at full load were 1765 RPM, slip is 1.9%.

$$\% \text{ Slip} = \frac{N_S - N_R}{N_S} \times 100$$

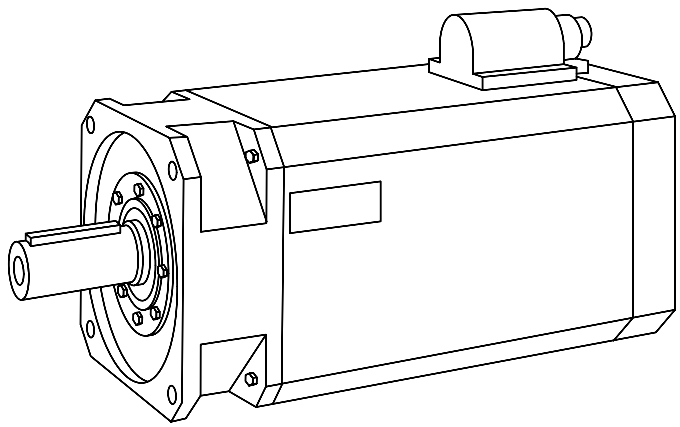
$$\% \text{ Slip} = \frac{1800 - 1765}{1800} \times 100$$

$$\% \text{ Slip} = 1.9\%$$

Servomotor Ratings

Siemens Servomotors

Servomotors, like the Siemens servomotor shown below, are high-performance motors specifically designed for use with the high demand of variable speed drives and motion control applications.



Nameplate

The nameplate of a motor provides important information necessary when applying a motor to an AC drive and motion control application.

SIEMENS
MADE IN GERMANY
Brushless - Servomotor
1FT6082-8AF71-1AG1
Nr E J899 1745 01 001 EN 60034
M_n = 10.3 Nm 3000/min Ui(eff) = 240 V Y
(M = 11.7 Nm 1500/min Ui(eff) = 120 V Y)
M_0 = 10.4/13.0 Nm $I_{0(eff)}$ = 8.20/10.7 A 60/100K
IMB5 IP 64 Th.CL.F. N_{max}: 4160/min KTY 84
Optical-Encoder 2048 S/R

Note: M = τ = Torque

Catalog and Serial Number

The catalog number gives important information about the motor. The first four digits of the catalog number are the model number. In this case it is a 1FT6 synchronous servomotor. In addition to the 1FT6 Siemens also manufactures a 1FK6 synchronous servomotor. There is also the 1PH7, 1PL6, and 1PH4 asynchronous servomotors.

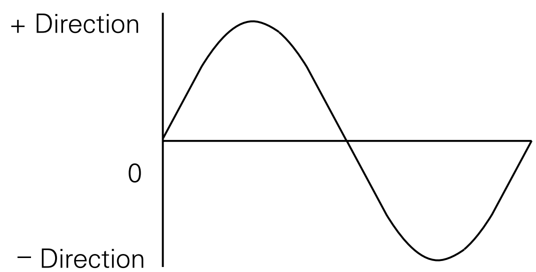
1FT6082-8AF71-1AG1

The serial number (Nr) is used to identify the motor.

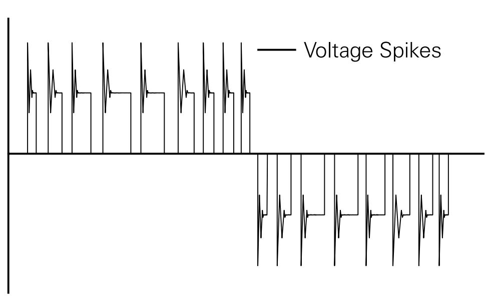
E J899 1745 01 001 EN 60034

Voltage

The example motor, like all 1FK6 and 1FT6 motors, is rated for 380 to 460 VAC, which correlates to an effective voltage in the stator windings of 240 VAC. Induction motors are designed to operate on a voltage source that supplies a smooth sinusoidal sine wave, such as the one shown below.



AC variable speed drives, unfortunately, do not produce a smooth sinusoidal waveform. Modern drives produce a PWM (pulse width modulation) waveform. This technology produces very rapid changes in voltage, resulting in high voltage spikes that can shorten the life of a motor. In addition, motion control applications typically incorporate quick starts and stops which add further stress to a standard motor. Siemens servomotors are specifically designed to operate with the PWM waveform produced by modern AC variable-speed motion control drives.



Speed and Torque

Rated speed is the nameplate speed, given in RPM, where the motor develops rated torque (τ_n) at rated voltage. This motor, for example, is rated to develop 10.3 Nm of torque at 3000 RPM with a supply voltage range of 380 to 460 VAC, which correlates to an effective voltage in the stator windings of 240 VAC. The nameplate of the 1F.6 motors also shows ratings when the supply voltage is reduced 50%. At 50% supply voltage rated speed is 1500 RPM, rated torque is 11.7 Nm, and the effective stator winding voltage is 120 VAC. This information is put in parenthesis because this supply voltage is outside the rated voltage of the MASTERDRIVE MC drive.

The nameplate on this motor also gives a maximum speed of 4160 RPM. Maximum speed is the fastest speed the motor can operate at and still develop enough torque to maintain that speed with some amount of load. Variable speed drives are capable of running a motor at various speeds. When a variable speed drive is set to turn a motor faster than rated speed, the motor's ability to develop continuous and overload torque is diminished. A variable speed drive should not be set to operate a servomotor above its maximum speed.

Current

Stall (Stand still) current is 8.2 amps at zero speed and stall torque (τ_o) with 60 K rise. The Current at stall is 10.7 amps with a 100 K rise.

Stall Torque and Current

Stall describes a condition where power is supplied to the motor but the rotor is at zero speed. This condition occurs when an AC drive is causing the motor to act as an electrical brake to hold the connected load at a specific position.

Stall Current (I_o) is the current drawn by the motor that is required to produce the given stall torque (τ_0).

Stall torque is also a thermal limiting torque when the motor is at standstill, corresponding to 60 K or 100 K temperature rise. Stall torque is available at zero speed for an unlimited time.

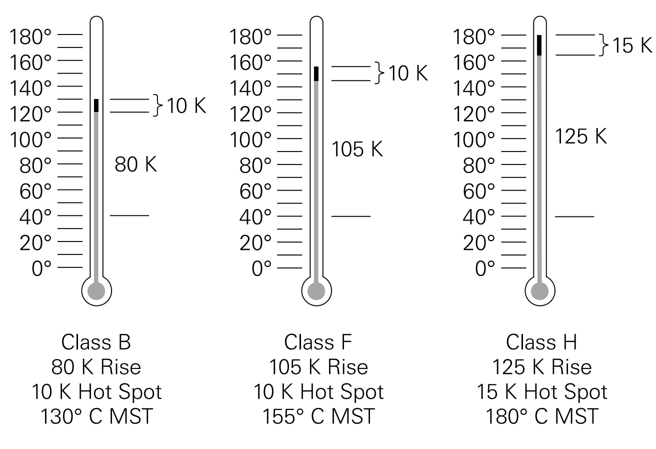
Insulation Class

In an electrical circuit, current causes heat. A certain amount of current will flow in the windings of a motor as soon as it is started. This will cause motor temperature to rise. DIN (Deutsche Industrie Normenausschuss) is a set of German standards now used in other countries. DIN VDE 0530 classifies the accepted amount of temperature rise. The three most commonly used classes are B, F, and H.

Before a motor is started its windings are at the temperature of the surrounding air. This is known as ambient temperature. The standard ambient temperature for electrical equipment is 40° C. Each insulation class has a specific allowable temperature rise. Ambient temperature and allowable temperature rise equals the maximum winding temperature in a motor. In addition, a margin is allowed to provide for a point at the center of the motor's windings where the temperature is higher. This is referred to as the motor's hot spot.

Temperature rise is always given in absolute values. The absolute value of Celsius is the Kelvin (K). Kelvin is the SI unit of temperature. The degree sign (°) is not used with Kelvin.

The insulation or thermal class (Th. CL. F.) of the example motor is Class F. Class F insulation has a maximum temperature rise of 105 K. The maximum winding temperature is 145° C (40° C ambient plus 105 K rise). The maximum steady-state temperature of a motor with Class F insulation is 155° C.



MST = Maximum Steady-State Temperature in ° C for the hottest spot in the winding

The operating temperature of a motor is an important factor in efficient operation and long life. Operating a motor above the limits of the insulation class reduces the motor's life expectancy. A 10 K increase in the operating temperature can decrease the life expectancy of a motor as much as 50%.

Stall Torque, Current, and Temperature Rise

There are two ratings for stall torque (τ_0), stall current (I_0), and temperature rise given for this motor. These ratings are related.

τ_0 = 10.4/13.0 Nm
I_0 = 8.20/10.7 A
Temperature Rise = 60/100 K

The motor begins developing torque to turn the connected load. If the load is such that it only requires 10.4 Nm of torque at stall, current will be 8.20 A and the temperature rise will be 60 K. If the load requires 13.0 Nm at stall, current will be 10.7 A and temperature rise will be 100 K. This is well within Class F temperature limitations.

IP Protection

The International Electrotechnical Commission (IEC) is an organization that, among other things, defines the degree of protection provided by enclosures. IEC is associated with electrical equipment sold in many countries, including the United States.

The IEC system of classification consists of the letters IP followed by two numbers. The first number indicates the degree of protection provided by the enclosure with respect to persons and solid objects entering the enclosure. The second number indicates the degree of protection against the ingress of water. The motor indicated by the sample nameplate is dust tight and protected against splashing water (IP 64).

1st Number	Description
0	Not Protected
1	Protected Against Objects Greater than 50 mm
2	Protected Against Objects Greater than 12 mm
3	Protected Against Objects Greater than 2.5 mm
4	Protected Against Objects Greater than 1.0 mm
5	Protected Against Dust
6	Dust Tight
2nd Number	
0	Not Protected
1	Protected Against Dripping Water
2	Protected Against Dripping Water when Tilted up to 15°
3	Protected Against Spraying Water
4	Protected Against Splashing Water
5	Protected Against Water Jets
6	Protected Against Heavy Seas
7	Protected Against the Effects of Immersion for Specific Time and Pressure
8	Protected Against Continuous Submersion Under Conditions Specified by the Manufacturer

Review 3

1. Two types of servomotors used in motion control drives are ___________ and ___________ .

2. Phase windings in a 3-phase motor are located ___________ degrees apart.

3. The speed of the rotating magnetic field is known as ___________ speed.

4. The difference between rotor speed and synchronous speed of an asynchronous motor is known as ___________ .

5. The output of a PWM type drive is ___________ .

   a. sinusoidal
   b. pulse width modulated

6. The temperature rise of insulation class F is ___________ K.

7. A motor that is dust tight and protected against splashing water would have an IP rating of ___________ .

Duty Cycle

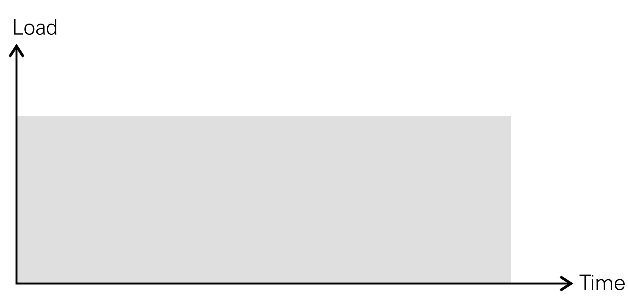
All motors are limited by the amount of heat that can develop in the motor windings. Speed-torque curves are based on standardized duty cycles which lead to the same temperature rise. The number of possible duty cycle types is almost infinite. To help promote a better understanding, duty cycles have been divided into nine standardized categories, which cover most of the applications encountered.

S1 Continuous Running Duty
S2 Short-Time Duty
S3 Intermittent Periodic Duty Without Starting
S4 Intermittent Periodic Duty With Starting
S5 Intermittent Periodic Duty with Starting and Electric Braking
S6 Continuous Operation Periodic Duty
S7 Continuous Operation Periodic Duty with Starting and Electric Braking
S8 Continuous Operation Periodic Duty with Related Load/Speed Changes
S9 Continuous Operation Duty with Non-Periodic Load and Speed Variations

Duty cycle profiles can become complex. S1, S3, and S6, however, are three common duty cycles. Part 2 of the General Motion Control Catalog provides speed/torque curves for S1 and intermittent/periodic duty cycles where applicable.

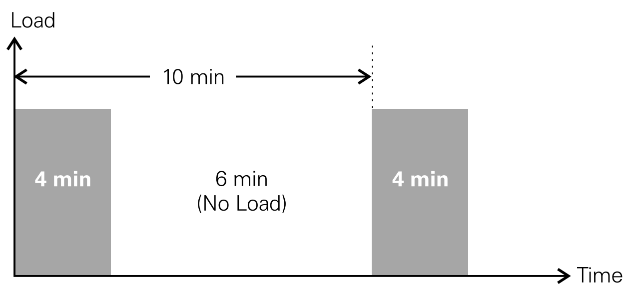
S1 Duty

Each duty cycle is characterized by cycle times, cycle durations, and load. S1 duty cycle, for example, characterizes a condition where the motor operates under constant load of sufficient duration for thermal equilibrium to be established. All motors listed in the Siemens catalog are designed for continuous duty type S1, unless otherwise indicated.



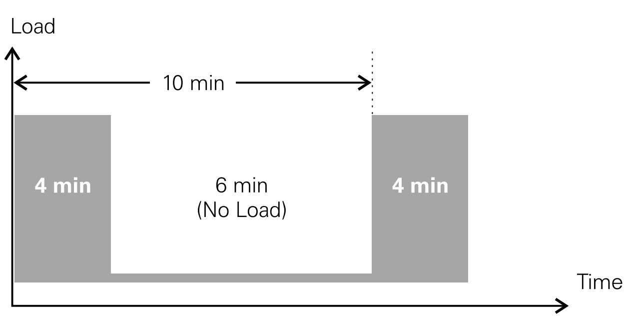
S3 Duty

S3 duty operation is comprised of a sequence of identical duty cycles, each of which consists of a period of constant load followed by an interval of no load. Starting current has no marked effect on the temperature rise of the motor. Operating time is given in minutes, such as 10 minutes, 30 minutes, or 60 minutes. If no time is given a 10 minute cycle time is assumed. Cycle duty is given in a percent such as 15%, 20%, 25%, 30%, or 40%. An S3 duty cycle of 40% for 10 minutes, for example, would indicate a motor load would be constant for 40% of the time (4 minutes). A no load condition would occur for 60% of the time (6 minutes).



S6 Duty

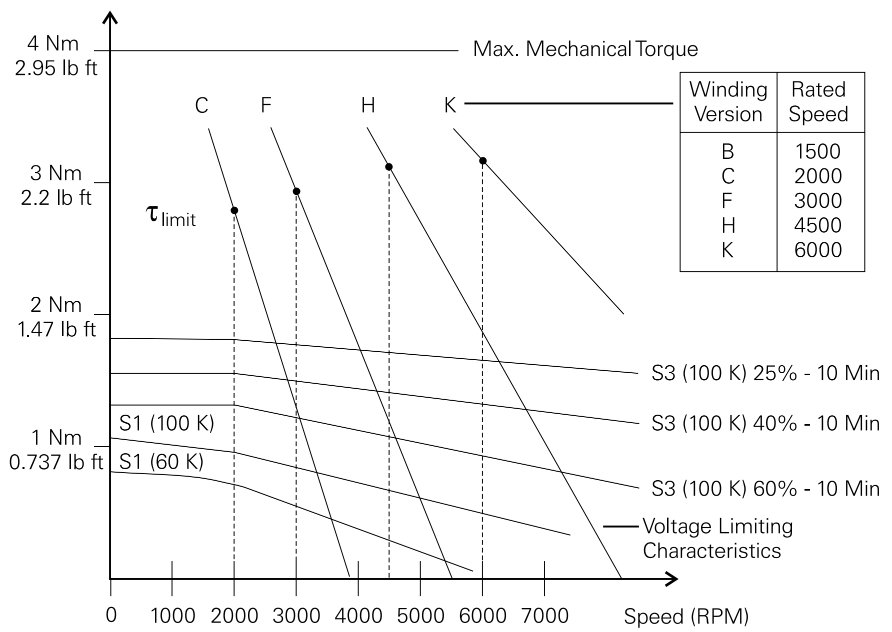
S6 duty operation is similar to S3 duty operation. The main difference is that there aren't any de-energized intervals. The motor remains energized during the no load interval. Operating time and cycle duration are given in the same manner as for S3 duty operation.



Speed-Torque Curve of Synchronous Servomotor

A motor can be identified by its frame size, which is associated with useful mounting information. The speed and torque characteristics for a given frame size depend upon the motor windings available. A common approach for representing the range of speed and torque characteristics available for a given motor frame size is the speed-torque curve.

A speed-torque curve, like the one shown in the following illustration, shows a motor frame which can be wound for various speeds and duty cycles. A letter in the catalog number is used to designate the speed of the motor. A speed-torque curve will show the expected torque performance of a motor for a specific duty cycle at a given speed. The motor frame for a permanent magnet synchronous motor illustrated by the following speed-torque curve is used on four different motor windings: 2000, 3000, 4500, and 6000 RPM. Torque ratings in this example are shown for S1 and S3 duty cycles.



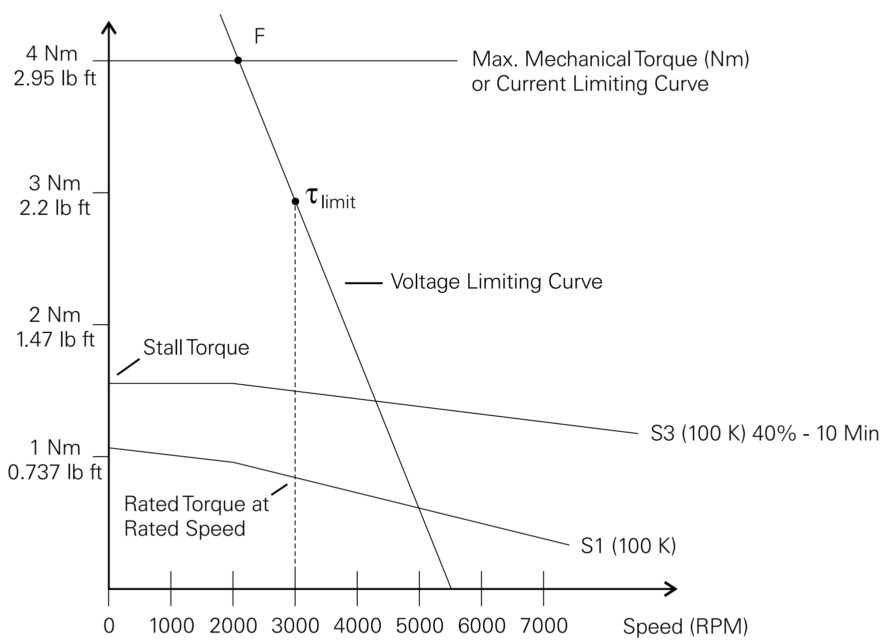
Winding Version	Rated Speed
B	1500
C	2000
F	3000
H	4500
K	6000

The speed-torque curve can be made less confusing by filtering out information so that only the applicable winding and duty cycles are shown. In the following illustration a motor with an F winding (3000 RPM) is used. The rated stall torque (zero speed torque) when operating the motor in S1 duty is about 1.1 Nm (0.81 lb ft). As the motor accelerates to rated speed, torque decreases to approximately 0.9 Nm (0.66 lb ft) due to friction (bearings) and stator losses (mainly eddy currents). The maximum torque that the motor can supply for a short period of time at rated speed is called τ_{limit}.

If the motor speed is increased beyond rated speed (3000 RPM) continuously available torque, indicated by the S1 line, continues to decrease. The maximum speed is defined by the intersection of the S1 line with the voltage limiting curve. The voltage limiting curve must be followed from that point on. Higher speeds result in reduced available torque.

The maximum torque or current limiting curve indicates the maximum available short-time torque of the motor. Exceeding the limit results in a sudden demagnetizing of the permanent magnets, destroying the synchronous motor.

The rated stall torque when operating the motor in S3 duty is approximately 1.5 Nm (1.1 lb ft). Torque will remain constant until about 2000 RPM. Torque will then decrease slightly to approximately 1.4 Nm (1.0) at 3000 RPM. Torque will continue to decrease as motor speed is increased above the rated speed of 3000 RPM.



Speed-Torque Curve for Specific Motors

Speed-torque curves can also be supplied for a specific motor. Larger motors are rated in Newton meters (Nm) and pound-feet (lb-ft). Smaller motors are rated in Newton meters (Nm) and pound-inches (lb-in). The following speed-torque curve, for example, shows the operating capabilities of a 1FT6082 motor. The motor associated with this curve can deliver 13 Nm (115 lb-in) at stall and 10.3 Nm (91.2 lb-in) at rated speed (3000 RPM) continuously. The region in the light grey area of the graph represents a continuous operating range (S1 duty cycle). The area represented by the dark grey region of the graph represents the intermittent operating region.