TRAINING COURSE 1

890037-01-00

The Basics of AC Motor Control

Basic Physics

Basic Motor Theory

AC Induction Motor Starting Methods

Variable Frequency Drives

Harmonics

Eliminating Motor Failures

Installation & Troubleshooting RVSS

Installation, Maintenance & Troubleshooting VFDs

BENSHAW

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BASIC PHYSICS

1

In this chapter, you will learn about:

- Force
- Torque
- Inertia
- Power

Overview

A fundamental understanding of basic physics terminology is needed in order to apply AC motors and controls for any application. Many of these terms may be familiar to you in some context. In later chapters we will learn how these terms apply to AC motor controls.

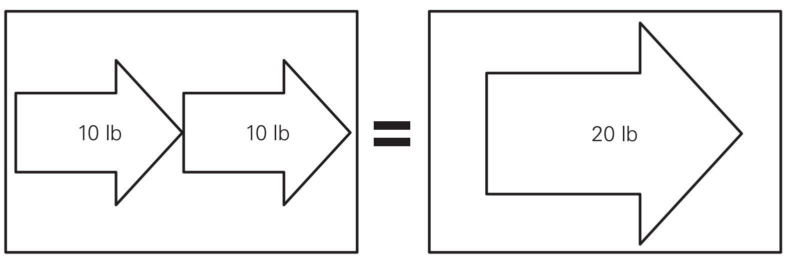
Basic Terminology

Force

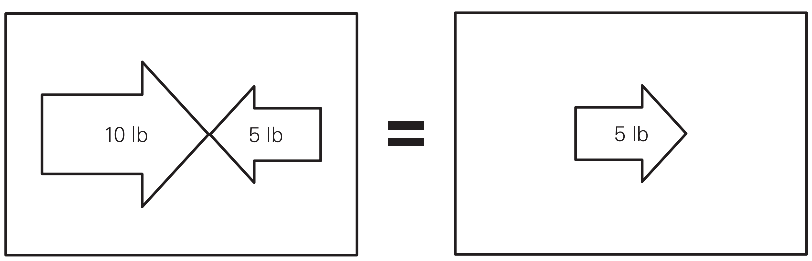
In simple terms, a *force* is a push or a pull. Force may be caused by electromagnetism, gravity, or a combination of physical means.

Net Force

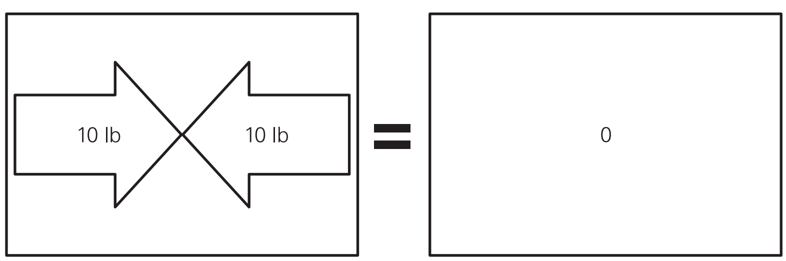
Net force is the vector sum of all forces that act on an object, including friction and gravity. When forces are applied in the same direction they are added. For example, if two 10 lb forces were applied in the same direction the net force would be 20 lbs.



If 10 lbs. of force were applied in one direction and 5 lbs. of force applied in the opposite direction, the net force would be 5 lbs. and the object would move in the direction of the greater force.



If 10 lbs. of force were applied equally in both directions, the net force would be zero and the object would not move.



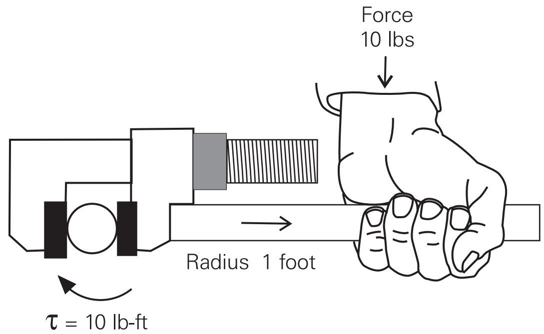
Torque

Torque is a twisting or turning force that tends to cause an object to rotate. A force applied to the end of a lever, for example, causes a turning effect or torque at the pivot point.

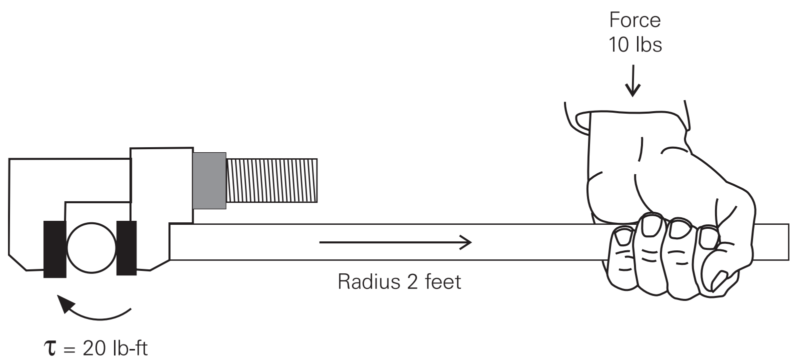
Torque () is the product of force and radius (lever distance).

Torque () = Force x Radius

In the English system torque is measured in pound-feet (lb.-ft.) or pound-inches (lb.-in.). If 10 lbs. of force were applied to a lever 1 foot long, for example, there would be 10 lb.-ft. of torque.



An increase in force or radius would result in a corresponding increase in torque. Increasing the radius to 2 feet, for example, results in 20 lb.-ft. of torque.



Speed

An object in motion travels a given distance in a given time. *Speed* is the ratio of the distance traveled to the time it takes to travel the distance.

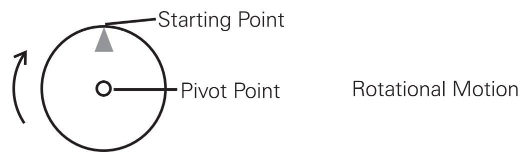
$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

Linear Speed

The *linear speed* of an object is a measure of how long it takes the object to get from point A to point B. Linear speed is usually given in a form such as meters per second (m/s). For example, if the distance between point A and point B were 10 meters, and it took 2 seconds to travel the distance, the speed would be 5 m/s.

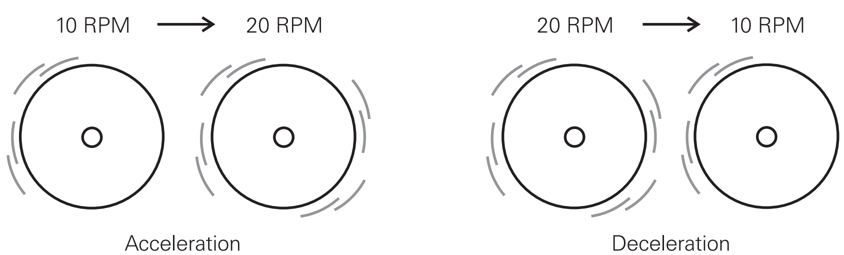
Angular (Rotational) Speed

The *angular speed* of a rotating object is a measurement of how long it takes a given point on the object to make one complete revolution from its starting point. Angular speed is generally given in revolutions per minute (RPM). An object that makes ten complete revolutions in one minute, for example, has a speed of 10 RPM.



Acceleration

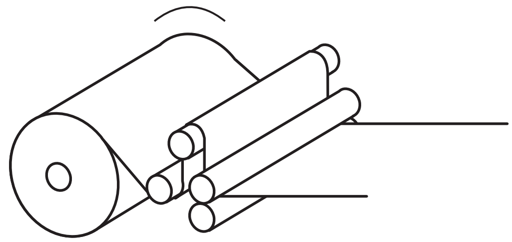
An object can change speed. An increase in speed is called *acceleration*. Acceleration occurs only when there is a change in the force acting upon the object. An object can also change from a higher to a lower speed.This is known as deceleration (negative acceleration). A rotating object, for example, can accelerate from 10 RPM to 20 RPM, or decelerate from 20 RPM to 10 RPM.



Law of Inertia

Mechanical systems are subject to the *law of inertia*.The law of inertia states that an object will tend to remain in its current state of rest or motion unless acted upon by an external force. This property of resistance to acceleration/deceleration is referred to as the *moment of inertia*. The English system of measurement is pound-feet squared (lb.-ft.^{2}).

If we look at a continuous roll of paper, as it unwinds, we know that when the roll is stopped, it would take a certain amount of force to overcome the inertia of the roll to get it rolling.The force required to overcome this inertia can come from a source of energy such as a motor. Once rolling, the paper will continue unwinding until another force acts on it to bring it to a stop.



Friction

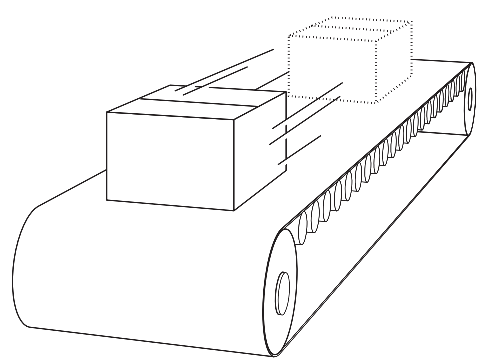
A large amount of force is applied to overcome the inertia of the system at rest to start it moving. Because *friction* removes energy from a mechanical system, a continual force must be applied to keep an object in motion.The law of inertia is still valid, however, since the force applied is needed only to compensate for the energy lost.

Once the system is in motion, only the energy required to compensate for various losses need be applied to keep it in motion. In the previous illustration, for example, these losses include:

- Friction within motor and driven equipment bearings
- Windage losses in the motor and driven equipment
- Friction between material on winder and rollers

Work

Whenever a force of any kind causes motion, *work* is accomplished. For example, work is accomplished when an object on a conveyor is moved from one point to another.



Work is defined by the product of the net force (F) applied and the distance (d) moved. If twice the force is applied, twice the work is done. If an object moves twice the distance, twice the work is done.

$$W = F \times d$$

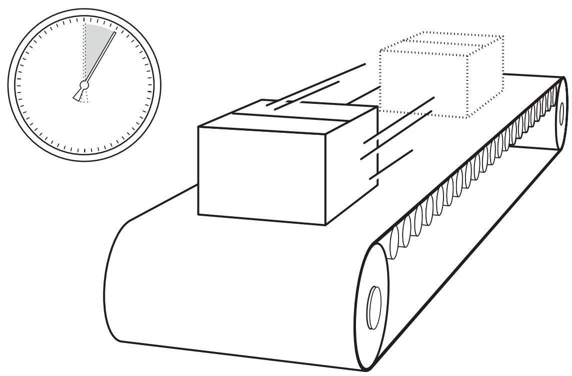
Power

Power is the rate of doing work, or work divided by time.

$$\text{Power} = \frac{\text{Force} \times \text{Distance}}{\text{Time}}$$

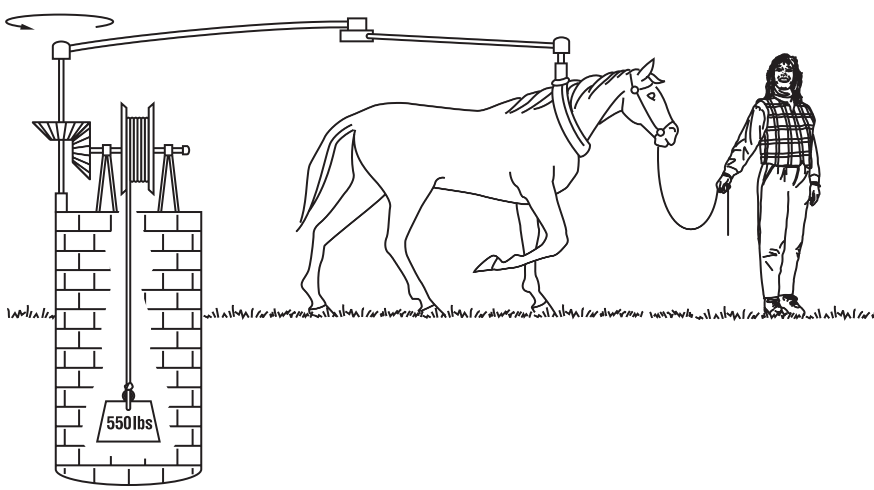
$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

In other words, power is the amount of work it takes to move the package from one point to another point, divided by the time.



Horsepower

Power can be expressed in foot-pounds per second, but is often expressed in *horsepower* (HP).This unit was defined in the 18th century by James Watt. Watt sold steam engines and was asked how many horses one steam engine would replace. He had horses walk around a wheel that would lift a weight. He found that each horse would average about 550 foot-pounds of work per second. One horsepower is equivalent to 500 foot-pounds per second or 33,000 foot-pounds per minute.



The following formula can be used to calculate horsepower when torque (lb-ft) and speed (RPM) are known. It can be seen from the formula that an increase of torque, speed, or both will cause a corresponding increase in horsepower.

$$\text{HP} = \frac{\text{T} \times \text{RPM}}{5250}$$

Electrical Energy

When voltage is applied to a conductor in an electrical circuit, electrons begin to flow. Voltage is the *force* and the electron flow is the *motion*.

The rate which work is done is called *power* which is represented by the symbol *P*. Power is measured in watts which is represented by the symbol *W*. The definition of a watt is the rate of work done in a circuit when one (1) amp flows with one (1) volt applied.

Power in a DC Circuit

The Power (*P*) consumed in a DC (or pure resistive) circuit is determined by the amount of current flow (*I*) through a resistor for a given voltage (*V*).

$$P = E \times I$$

Example:
$$P = 12 \text{ volts} \times 2 \text{ amps}$$
$$P = 24 \text{ watts}$$

Power in an AC Circuit

Resistance is only one of the circuit properties that effects the power in an AC circuit. Power consumed by a resistor is dissipated in heat and not returned to the source. This is known as *True Power*. True power is the rate at which energy is used measured in watts (*W*). AC, or alternating current circuits, change the current flow and voltage polarity many times per second. The energy stored within the magnetic field of an inductor or plates of a capacitor is returned to the power source when the current changes direction. This power is not consumed and is called *Reactive Power*. Reactive Power is measured in volt-amps reactive units or *VAR*. The power in an AC circuit is the vector sum of true power and reactive power. The product is called *Apparent Power*. Apparent power is measured in volt-tamps or *VA*.

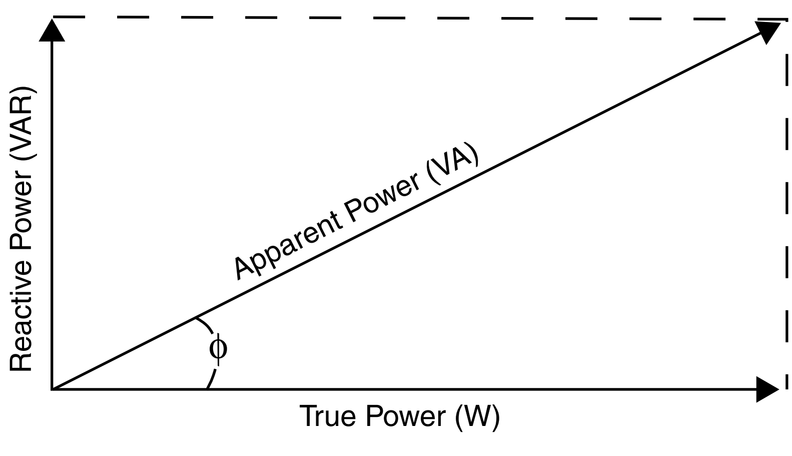


Figure 1-1: True Power / Reactive Power / Apparent Power

The formula for apparent power is:

$$P = E \times I$$

True power is calculated using a trigonometry function, the cosine (ϕ) of the phase angle. The formula for true power is:

$$PF = E \times I \cos\phi$$

Power Factor

Power Factor is the ratio of true power to apparent power; the measurement between how much power is consumed and how much power is returned to the source. Power factor is equal to the cosine of the phase angle.

$$PF = \cos\phi$$

In a purely resistive or DC circuit where the current and voltage are in phase, there is one angle of displacement, or zero degrees displacement. The cosine of a zero degree angle is one. Therefore, the power factor is one. All of the energy delivered to the circuit by the source is consumed by the circuit in the form of heat.

Horsepower and Kilowatts

AC drives and motors manufactured in the United States are generally rated in horsepower (HP). Equipment manufactured in Europe is generally rated in kilowatts (KW). Horsepower can be converted to kilowatts with the following formula:

$$KW = .746 \times HP$$

For example, a 25 HP motor is equivalent to 18.64 KW.

$$18.65\ KW = .746 \times 25\ HP$$

Kilowatts can be converted to horsepower with the following formula:

$$HP = 1.341 \times KW$$

Chapter Review

1. *Force* is a ______________________.

2. An object that has a force of 50 pounds applied in one direction and a force of 10 pounds in the opposite direction. The *net force* is ______________________.

3. A twisting or turning force that causes an object to rotate is known as ____________________.

4. *Torque* is measured as ______________________.

5. The law of ___________________ states that an object will tend to remain in its current state of rest or motion unless acted upon by an external force.

6. ______________________ is the ratio of distance traveled and time.

7. The speed of a rotating object is generally given as __________ per _______________.

8. ______________________ is accomplished whenever force causes motion.

9. ______________________ is the rate of doing work.

10. In an electrical circuit, the amount of *force* applied is known as ______________________.

11. *Power* to do work is called ______________________.

12. *True power* is measured in ______________________ and *apparent power* is measured in ______________________.

13. *Power factor* is the ratio of ______________________ to ______________________.

BASIC MOTOR THEORY

2

In this chapter you will learn about…

- Basic Motor Construction
- Motor Components
- Motor Characteristics
- Motor Types

AC Motor Construction

AC induction motors are commonly used in industrial applications.The following motor discussion will center around three-phase, 460 VAC, asynchronous, induction motors. An asynchronous motor is a type of motor where the speed of the rotor is other than the speed of the rotating magnetic field.This type of motor is illustrated. Electromagnetic stator windings are mounted in a housing. Power connections, attached to the stator windings, are brought out to be attached to a three-phase power supply. On three-phase, dual-voltage motors nine leads are supplied for power connections.Three power connection leads are shown in the following illustration for simplicity. A rotor is mounted on a shaft and supported by bearings. On self-cooled motors, like the one shown, a fan is mounted on the shaft to force cooling air over the motor.

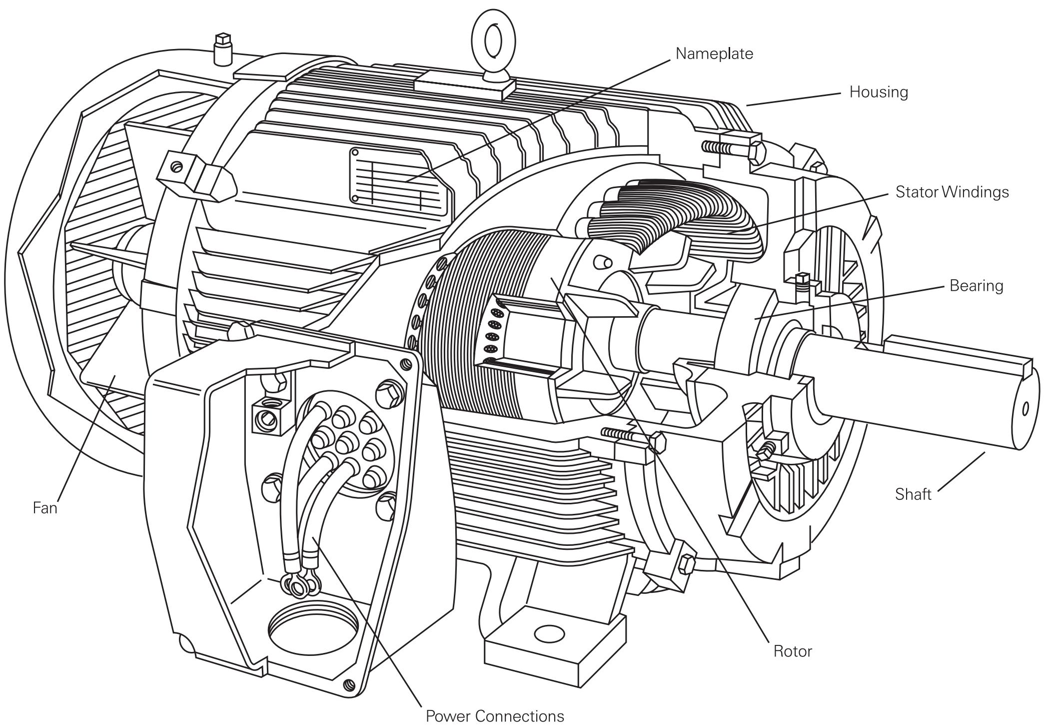


Figure 2-1: AC Induction Motor

Nameplate

The *nameplate* of a motor provides important information necessary when applying a motor to an AC drive. The following drawing illustrates the nameplate of a sample 25 horsepower AC motor.

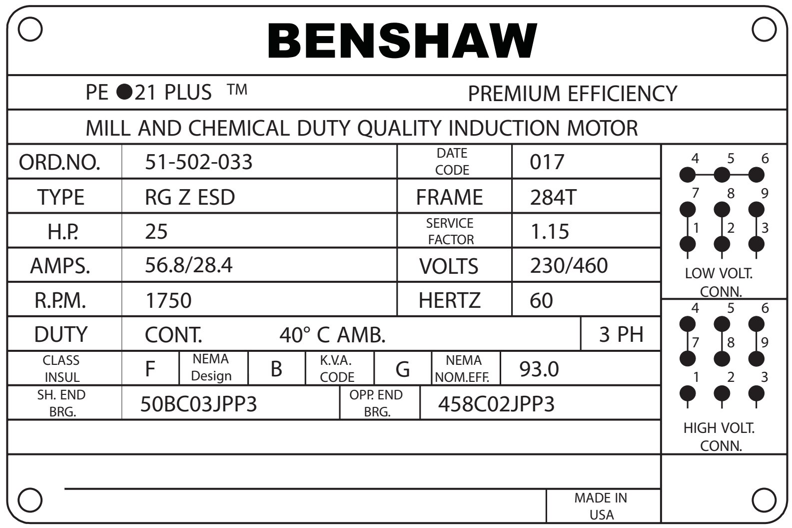


Figure 2-2: Nameplate for Motor Designed for NEMA B Specifications

Connections

This motor can be used on 230 VAC or 460 VAC systems. A wiring diagram indicates the proper connection for the input power leads.The low voltage connection is intended for use on 230 VAC with a maximum full load current of 56.8 Amps. The high voltage connection is intended for use on 460 VAC with a maximum full load current of 28.4 Amps.

Base Speed

Base speed is the nameplate speed, given in RPM, where the motor develops rated horsepower at rated voltage and frequency. It is an indication of how fast the output shaft will turn the connected equipment when fully loaded and proper voltage is applied at 60 hertz. The base speed of this motor is 1750 RPM at 60 Hz. If the connected equipment is operating at less than full load, the output speed will be slightly greater than base speed.

It should be noted that with European and Asian motors and many special motors, such as those used in the textile industry, base speed, frequency and voltage may be different than standard American motors. This is not a problem, however, because the voltage and frequency supplied to a variable speed drive does not have to be the same as the motor. The supply voltage to a variable speed drive has nothing to do with motor voltage, speed or frequency. A variable speed drive can be set up to work with any motor within a reasonable size range and rating.

Service Factor

A motor designed to operate at its nameplate horsepower rating has a service factor of 1.0. Some applications may require a motor to exceed the rated horsepower. In these cases a motor with a service factor of 1.15 can be specified.The *service factor* is a multiplier that may be applied to the rated power. A 1.15 service factor motor can be operated 15% higher than the motor's nameplate horsepower. Motors with a service factor of 1.15 are recommended for use with AC drives. It is important to note, however, that even though a motor has a service factor of 1.15 the values for current and horsepower at the 1.0 service factor are used to program a variable speed drive.

Insulation Class

The National Electrical Manufacturers Association (NEMA) has established insulation classes to meet motor temperature requirements found in different operating environments. The four insulation classes are A, B, F, and H. Class F is commonly used. Class A is seldom used. Before a motor is started, its windings are at the temperature of the surrounding air. This is known as ambient temperature. NEMA has standardized on an ambient temperature of 40° C, or 104° F for all motor classes.

Temperature rises in the motor as soon as it is started. The combination of ambient temperature and allowed temperature rise equals the maximum winding temperature in a motor. A motor with Class F insulation, for example, has a maximum temperature rise of 105° C.The maximum winding temperature is 145° C (40° ambient plus 105° rise). A margin is allowed for a point at the center of the motor's windings where temperature is higher. This is referred to as the motor's hot spot.

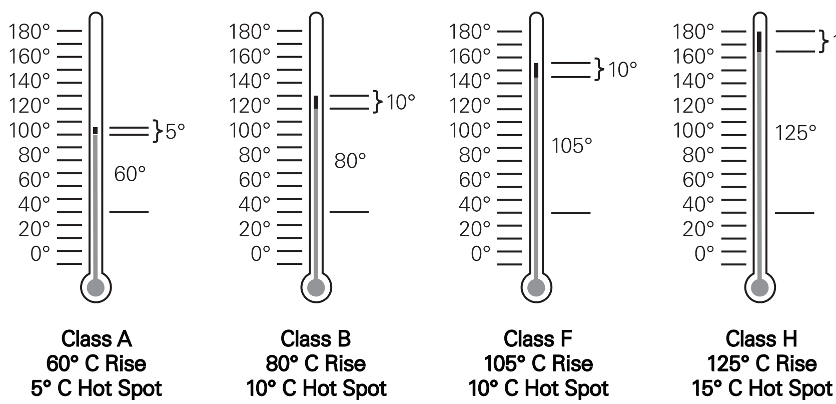


Figure 2-3: NEMA Insulation Classes for Motor Temperatures

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

NEMA Design

The National Electrical Manufacturers Association (NEMA) has established standards for motor construction and performance. The nameplate shown in Figure 2-2 on page 2-3 is for a motor designed to NEMA B specifications. NEMA B motors are commonly used with AC drives. Any NEMA design (A, B, C, or D) AC motor will work perfectly well with a properly sized variable speed drive.

Efficiency

AC motor efficiency is expressed as a percentage. It is an indication of how much input electrical energy is converted to output mechanical energy.The nominal efficiency of this motor is 93.0%.

Converting Kilowatts (KW) to Horsepower (HP)

Motor manufacturers may also use kilowatts (KW) instead of horsepower. To convert KW to HP use the following equation:

$$HP = 1.341 \times KW$$

Example:
$$HP = 1.341 \times 18\ KW$$
$$HP = 24$$

Developing a Rotating Magnetic Field

There is no direct electrical connection between the stator and the rotor or the power supply and the rotor of an induction motor. To see how a rotor works, a magnet mounted on the shaft can be substituted for the squirrel cage rotor. When the stator windings are energized, a rotating magnetic field is established. The magnet 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 magnet and the south pole of the rotating magnetic field attracts the north pole of the magnet. As the rotating magnetic field rotates, it pulls the magnet along causing it to rotate. This type of design is used on some motors and is referred to as a permanent magnet synchronous motor.

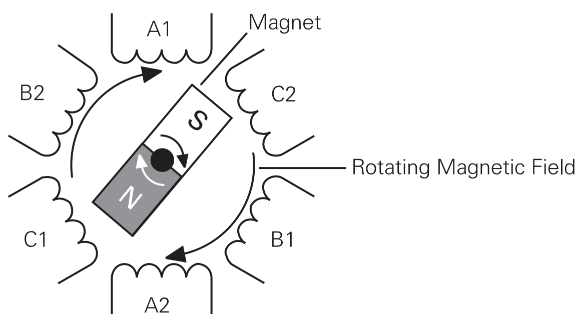


Figure 2-4: Rotating Magnet

Rotation of a Squirrel Cage Rotor

The squirrel cage rotor of an AC motor acts essentially the same as the magnet. When a conductor, such as the conductor bars of the rotor, passes through a magnetic field a voltage (emf) is induced in the conductor. The induced voltage causes current flow in the conductor.The amount of induced voltage (E) depends on the amount of flux (Φ) and the speed (N) at which the conductor cuts through the lines of flux. The more lines of flux, or the faster they are cut, the more voltage is induced. Certain motor constants (k), determined by construction also affect induced voltage. These constants, such as rotor bar shape and construction, do not change with speed or load.

$$E = k\Phi N$$

Current flows through the rotor bars and around the end ring. The current flow in the conductor bars produces magnetic fields around each rotor bar. The squirrel cage rotor becomes an electromagnet with alternating north and south poles. The magnetic fields of the rotor interact with the magnetic fields of the stator. Keep in mind that the current and magnetic fields of the stator and rotor are constantly changing. As the stator magnetic field rotates, the rotor and shaft follow.

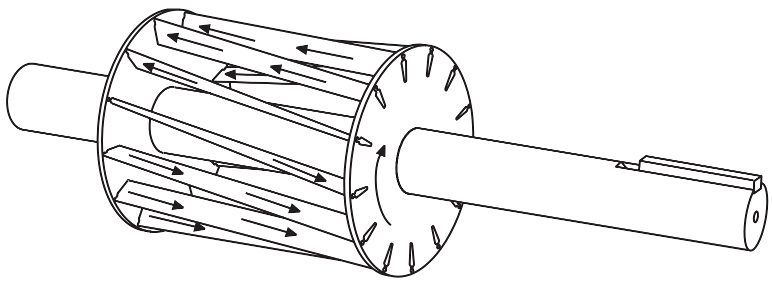


Figure 2-5: Rotation of a Squirrel Cage Rotor

Slip

There must be a relative difference in speed between the rotor and the rotating magnetic field. The difference in speed of the rotating magnetic field, expressed in RPM, and the rotor, expressed in RPM, is known as *slip*.

Slip is necessary to produce torque. If the rotor and the rotating magnetic field were turning at the same speed no relative motion would exist between the two; therefore, no lines of flux would be cut and no voltage would be induced in the rotor. Slip is dependent on load. An increase in load will cause the rotor to slow down or increase slip. A decrease in load will cause the rotor to speed up or decrease slip. Slip is expressed as a percentage.

$$\% \text{ Slip} = \frac{NS - NR}{NS} \times 100$$

For example, a four-pole motor operated at 60 Hz has a synchronous speed of 1800 RPM. If the rotor speed at full load were 1750 RPM, the slip is 2.8%.

$$\% \text{ Slip} = \frac{1800 - 1750}{1800} \times 100$$

$$\% \text{ Slip} = 2.8\%$$

Electrical Components of a Motor

Up to this point we have examined the operation of an AC motor with rated voltage and frequency applied. Many applications require the speed of an AC motor to vary, which is easily accomplished with an AC drive. However, operating a motor at other than rated voltage and frequency *has an effect on motor current and torque*. In order to understand how a motor's characteristics can change we need a better understanding of both AC motors and AC drives.

The following diagram represents a simplified equivalent circuit of an AC motor. An understanding of this diagram is important to comprehending how an AC motor is applied to an AC drive.

VS	Line voltage applied to stator power leads
RS	Stator resistance
LS	Stator leakage inductance
IS	Stator current
E	Air gap or magnetizing voltage
LM	Magnetizing inductance
IM	Magnetizing current
RR	Rotor resistance (varies with temperature)
LR	Rotor leakage inductance
IW	Working or torque producing current

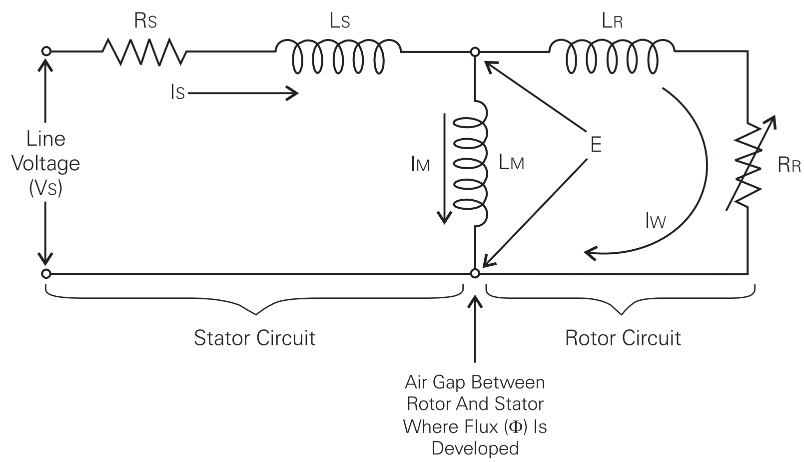


Figure 2-6: Simplified AC Motor Circuit

Line Voltage

Voltage (VS) is applied to the stator power leads from the AC power supply. Voltage drops occur due to stator resistance (RS). The resultant voltage (E) represents force (cemf) available to produce magnetizing flux and torque.

Magnetizing Current

Magnetizing current (IM) is responsible for producing magnetic lines of flux which magnetically link with the rotor circuit. Magnetizing current is typically about 30% of rated current. Magnetizing current, like flux (Φ), is proportional to voltage (E) and frequency (F),

$$IM = \frac{E}{2\pi F\ LM}$$

Working Current

The current that flows in the rotor circuit and produces torque is referred to as *working current* (IW). Working current is a function of the load. An increase in load causes the rotor circuit to work harder increasing working current (IW). A decrease in load decreases the work the rotor circuit does decreasing working current (IW).

Stator Current

Stator current (IS) is the current that flows in the stator circuit. Stator current can be measured on the supply line and is also referred to as line current. A clamp-on ammeter, for example, is frequently used to measure stator current. The full-load ampere rating on the nameplate of a motor refers to stator current at rated voltage, frequency and load. It is the maximum current the motor can carry without damage. Stator current is the vector sum of working current (IW) and magnetizing current (IM). Typically magnetizing current (IM) remains constant. Working current (IW) will vary with the applied load which causes a corresponding change in stator current (IS).

$$IM = \sqrt{IM^2 + IW^2}$$

Starting Current

When a motor is started, it must perform work to overcome the inertia of the rotor and attached load.The starting current measured on the incoming line (IS) is typically 600% of full-load current when rated voltage and frequency is first applied to a NEMA B motor. Stator current decreases to its rated value as the rotor comes up to speed.The following graph applies to “across the line” operation, not variable speed drive operation.

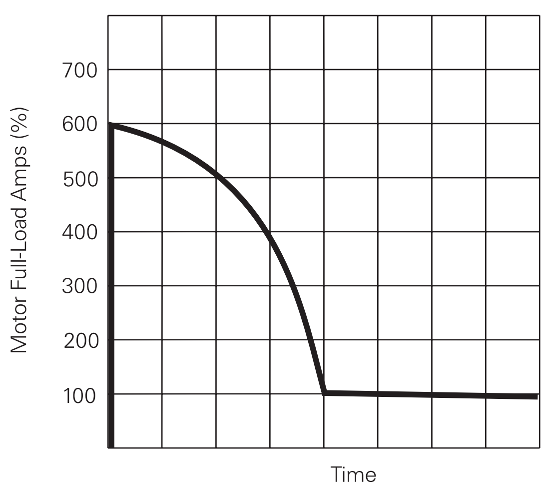


Figure 2-7: Starting Current for “Across the Line” Operation

NEMA Rotor Characteristics

The National Electrical Manufacturers Association (NEMA) classifies motors according to locked rotor torque and current, pull up torque, breakdown torque and percent slip. In addition, full-load torque and current must be considered when evaluating an application.

Most NEMA terms and concepts apply to motors operated from 60 Hz power lines, not variable speed drive operation. In following sections we will see how an AC variable speed drive can improve the starting and operation of an AC motor.

Locked Rotor Torque

Locked rotor torque, also referred to as *starting torque*, is developed when the rotor is held at rest with rated voltage and frequency applied. This condition occurs each time a motor is started. When rated voltage and frequency are applied to the stator, there is a brief amount of time before the rotor turns.

Locked Rotor Current

Locked rotor current is also referred to as *starting current*. This is the current taken from the supply line at rated voltage and frequency with the rotor at rest.

Pull Up Torque

Pull up torque is the torque developed during acceleration from start to the point breakdown torque occurs.

Breakdown Torque

Breakdown torque is the maximum torque a motor develops at rated voltage and speed without an abrupt loss of speed.

Full-Load Torque

Full-load torque is the torque developed when the motor is operating with rated voltage, frequency and load.

Full-Load Current

Full-load current is the current taken from the supply line at rated voltage, frequency and load.

Motor Types

Performance requirements for various types of induction motors for use on standard sinewave power supplies are identified in NEMA MG1. Some of these types of motors are suitable for use in variable speed applications, dependent on the type of application. Performance requirements are also identified for motors for specific use in variable speed applications.

Design A

NEMA MG1 does not impose any limits on the magnitude of the locked-rotor current on Design A motors except that the locked-rotor current is greater than the upper limit for Design B motors. They are usually used in situations where higher locked-rotor current is used for the purpose of obtaining higher running efficiency and higher breakdown torque. Such motors typically require the use of reduced voltage starting techniques for starting across the standard utility power source. However, normal adjustable frequency control function limits motor operation to the portion of its torque speed characteristic that lies between no-load and breakdown, even during starting. Because of this, the higher locked rotor current of Design A motors is generally of little concern and the motors are well suited for variable speed operation, exhibiting low slip and high efficiency. The potentially higher breakdown torque of a Design A motor will extend its constant horsepower speed range beyond that achievable by a Design B motor. However, caution should be used when applying Design A motors in by-pass operation, as their high locked-rotor current can increase starter, thermal overload, and short circuit protection device sizing. Design A motors may also suffer greater thermal and mechanical stress than other designs when started across-the-line. Design A motors with very low slip may also exhibit instability under lightly loaded conditions.

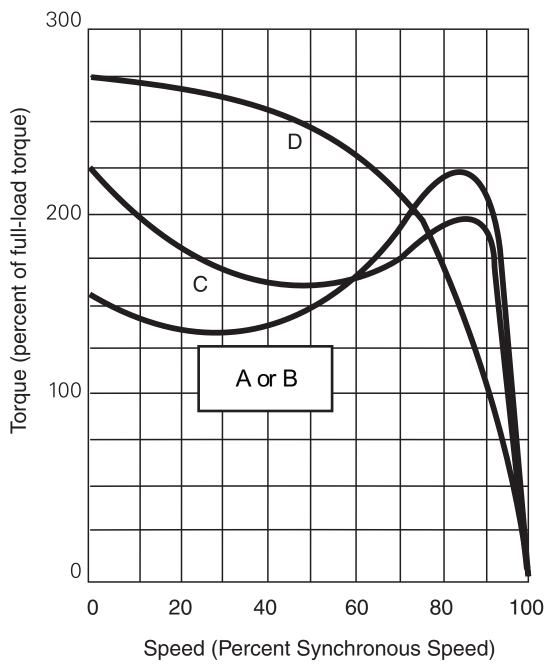


Figure 2-8: Typical Motor Speed Torque Curves

Design B

Design B motors are applied in variable torque, constant torque, and constant horsepower applications. Adjustable frequency control algorithms are generally optimized to the speed-torque-current characteristics of Design B motors. They exhibit good efficiency and low slip, and are suitable for across-the-line starting in bypass mode. Design B motors with very low slip may also exhibit instability under lightly loaded conditions.

Design C

Design C motor speed-torque-current characteristics were defined to address across-the-line applications requiring high starting (locked-rotor) torque while generally maintaining Design B locked-rotor current but slightly higher slip. Since a Design B motor operated from an adjustable frequency control can provide the same breakaway torque as a Design C motor operated from a control, it is usually preferred because of its industry-standard availability and higher running efficiency. Also, since an adjustable frequency control driven motor normally operates at speeds above the breakdown speed, the high locked-rotor and pull-up torque of a Design C motor serves no benefit in most adjustable speed drive applications. Because Design C motors usually achieve high starting torque with a double or pseudo-double cage rotor slot, they may exhibit higher rotor losses if the control output current waveform has significant low order harmonic content. This can result in additional heating in Design C motors over that in Design B and a corresponding greater decrease in system efficiency. Design B motors may not be suitable for bypass operation in an application that normally requires use of a Design C motor for fixed frequency application.

Design D

Design D motors were developed specifically for high impact, high starting torque, or high inertia loads. They exhibit very high locked-rotor torque but suffer in running efficiency due to their high slip characteristic. By employing negative slip compensation with an adjustable frequency control, a Design A, B or C motor can be made to emulate the speed-torque characteristic of a Design D motor while providing higher running efficiency. As a result, Design D motors are seldom used in general ASD applications. Design A, B or C motors cannot be used for bypass operation on an application that normally requires a Design D motor for fixed frequency application.

NEMA Classifications

Three-phase AC motors are classified by NEMA as NEMA A, B, C and D. NEMA specifies certain operating characteristics for motors when started by applying rated voltage and frequency (across the line starting). A NEMA B motor, for example, typically requires 600% starting current and 150% starting torque.These considerations do not apply to motors started with an AC drive. NEMA B design motors are the most common and most suitable for use on AC drives.

Speed and Torque

A graph, similar to the one illustrated in Figure 2-9, is used to show the relationship between motor speed and torque of a NEMA B motor. When rated voltage and frequency are applied to the motor, synchronous speed goes to 100% immediately. The rotor must perform a certain amount of work to overcome the mechanical inertia of itself and the connected load.

Typically a NEMA B motor will develop 150% torque to start the rotor and load. As the rotor accelerates the relative difference in speed between synchronous speed and rotor speed decreases until the rotor reaches its operating speed. The operating speed of a NEMA B motor with rated voltage, frequency and load is approximately 97% (3% slip) of synchronous speed. The amount of slip and torque is a function of load. With an increase in load there is a corresponding increase in slip and torque. With a decrease in load there is a corresponding decrease in slip and torque.

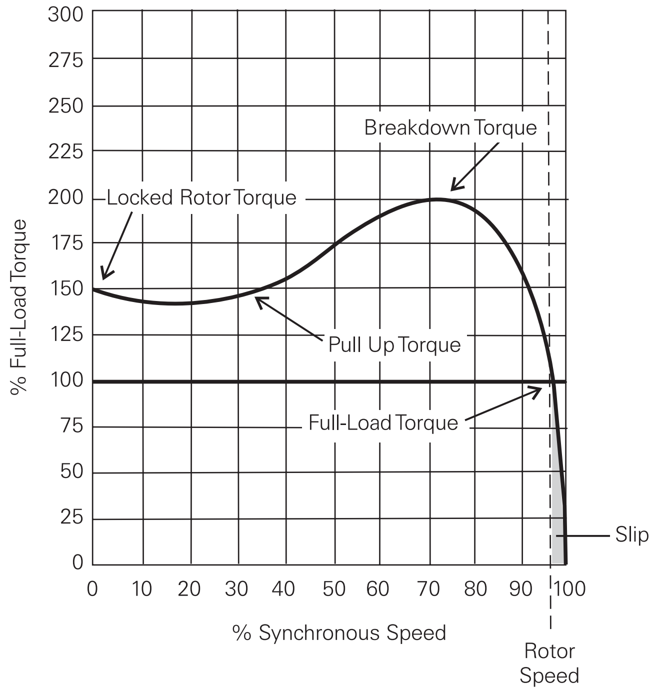


Figure 2-9: Relationship between Motor Speed and Torque of a NEMA B Motor

Chapter Review

1. On the nameplate of the NEMA B AC motor, the FLA is listed as 10/5 and the voltage is listed as 230/460. If the motor is wired for 460 volt operation, the FLA is _______________.

2. An AC motor has a service factor of 115% and a listed FLA of 110 amps. The maximum permissible running current is _______ amps.

3. A 37 KW motor will have an equivalent horsepower of _______ HP.

4. The synchronous speed of a six pole stator with 60 Hz applied is _______ RPM.

5. The squirrel cage is the most common type of ________________________.

6. The difference in stator speed and rotor speeds is known as __________________.

7. A two-pole motor on a 60 Hz power at 3450 RPM has ________% slip.

8. Current that actually produces torque to turn the rotor is known as _____________________ current.

9. Stator current is the vector sum of ___________ and ____________.

10. The starting torque of a NEMA B motor is approximately __________ % of full load torque and the starting current is approximately ___________ % of full load amps.

AC INDUCTION MOTOR STARTING METHODS

3

In this chapter you will learn about…

- The Advantages and Disadvantages of the Different Starting Methods
- Reduced Voltage Starting
- Solid State Reduced Voltage Starting
- Silicon Controlled Rectifiers (SCRs)

Overview

In this chapter we will discuss the principles of different AC motor starting methods from the most simple to the more complex. You will learn about Across-The-Line (ATL) starting, Autotransformer starting, Wye/Delta starting and Reduced Voltage Solid State starting. After learning the starting basics, you will learn how to properly select and apply a starter based on the effects of each starting method on the motor, load and power distribution system.

❖***Note:*** *While VFDs might be considered "starters" by some they will be discussed later in Chapter 4*

Comparison of Starting Methods

Across The Line Starting

There are various methods that can be used to start an AC induction motor. The simplest method is by closing a contactor and allowing the motor to start at full voltage, or *Across The Line* (ATL). This is the oldest method used to start a motor and, although compact and inexpensive, it is far from the best. ATL starting is marked by inrush currents of six to eight times the motor's full load amp value, on average. Premium efficiency motors can have inrush currents greater than ten times full load amps. These high inrush currents result in electrical as well as mechanical problems for the motor and the application.

The diagram below is a current/speed curve for a motor started at full voltage. Note the amount of current that is drawn by the motor to accelerate the connected load. The motor produces maximum torque in less than three seconds. The majority of applications require less than half this amount of torque to accelerate the connected load. For many applications, this excess amount of torque will create premature mechanical and electrical failures in the drive train of the application. Starting a motor in this manner is very similar to "dropping the clutch" in your car or truck while revving the engine.

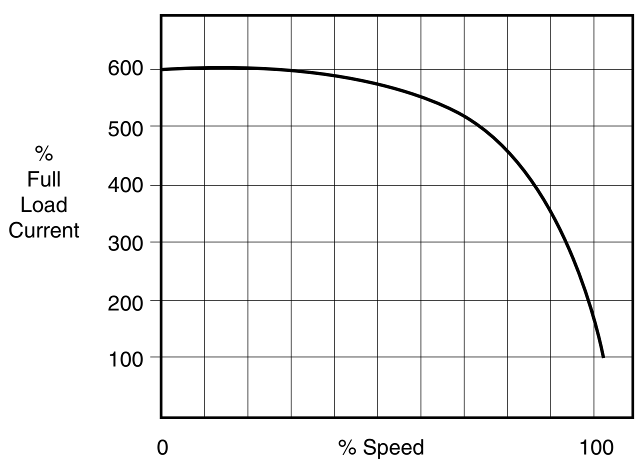


Figure 3-1: Current/Speed Curve for Motor Started at Full Voltage

These problems prompted changes in the motor control industry. Soon companies were examining means to start motors while reducing high inrush currents. The results were a large variety of starters, utilizing a combination of transformers, resistors, and contactors. Although there are numerous variations of these electromechanical starters, the most common is the Autotransformer.

Disadvantages of Full Voltage ATL Starting

1. High inrush currents create stress on the motor's windings. This stress will cause the windings to move in the end turns of the stator. This will cause the insulation to break down. Eventually, phase to phase shorts will occur and result in early motor failure.
2. Full voltage starting will cause damage to belts, sheaves, gearboxes, and other mechanical components throughout the application drive train, thus causing downtime and replacement costs. For the most part, it is the down time that proves to be the most costly in any industry.
3. Full voltage starting can create line drops/voltage dips which may result in penalties from the utility company. The line drops that large motors can create may also cause problems with other applications throughout the plant.
4. Across The Line starting puts large amounts of stress on the contactor contacts which, in turn, require a relatively large amount of maintenance.
5. Poor motor protection with the use of bimetallic overload with 20% accuracy.
6. No capability to control the deceleration.

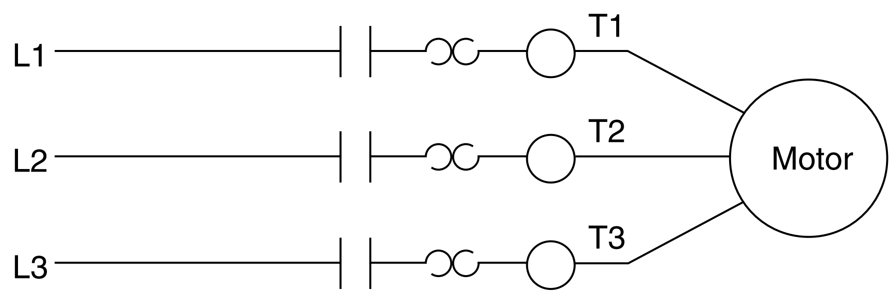


Figure 3-2: Full Voltage Electromechanical Non-Reversing Start

Autotransformer Reduced Voltage Starting

The Autotransformer starter is simply a transformer configured with contactors to allow a stepped acceleration to full speed. This is accomplished by "tapping" the transformer at 50, 65, or 80 percent of full voltage. One of these taps is the first step of voltage applied to the motor and is subsequently followed by a second step to full voltage.

Offered below are current/speed curves for the two types of Autotransformer Starters. The first is an open transition type. With this type, the motor is disconnected from the voltage source during the transition step to full voltage. Even though this is very quick, a large current spike and torque transient is created. The second is for a closed transition starter. This type of starter does not disconnect the motor from the voltage source during the transition step to full voltage. Although this is an improvement over the open transition, a significant current surge and torque transient is still experienced.

Disadvantages of Autotransformer Starting

1. Limited adjustability to load conditions.
2. Mechanical shock to system between steps.

3. Large size; takes up control room space.
4. High contactor maintenance.
5. High purchase cost.
6. Unable to compensate easily for input voltage variations.
7. Uncontrolled deceleration.
8. Poor motor protection with the use of bimetallic overload with 20% accuracy.

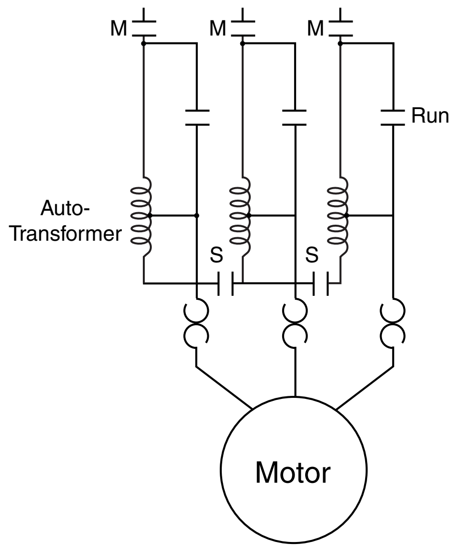


Figure 3-3: Reduced Voltage Autotransformer Starter

Wye-Delta (Also Called Star Delta) Starting

A Star Delta starter utilizes a special wound motor that has the wires from each of the sets of windings brought out to the terminal leads. These windings can be connected in a "Delta" pattern for full motor starting torque, or in a "Y" (Star) pattern for reduced starting torque. In the Delta pattern, all of the windings are connected phase-to-phase in series, just as they would be in a standard motor.

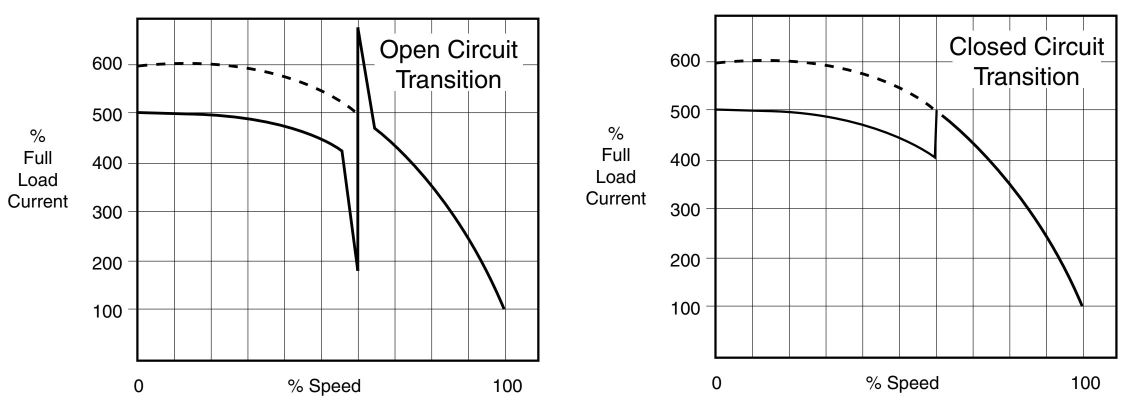


Figure 3-4: Current/Speed Curves for Open and Closed Circuit Transition Types

In the "Y" configuration, each set of phase windings is brought together at a common point. This increases the impedance of the motor itself, reducing the current and torque to 33% of normal. Three contactors and a timer are used to switch the six leads brought out of the motor into the Y-then-Delta configuration in a two-step starting process.

During the "Open Transition" from Y to Delta, the motor is taken offline in order to avoid short circuiting the contactors. This transition time can cause significant deceleration of the motor in situations when the motor is heavily loaded. It can also cause the motor to stall or create a current spike that trips the circuit breakers or blows the fuses when reconnected to Delta. Because of this, "Closed Transition" versions of Y-Delta starters are available that put shunt resistors in the circuit during the transition to avoid this problem. This scheme uses four contactors in three steps and requires large starting resistors.

To illustrate the disadvantages with the electromechanical type of starters, let's look at a speed/torque curve for a typical variable torque load started at full voltage, at 65% voltage with an Autotransformer and Wye-Delta. The area between the typical load torque curve and the full voltage, Wye-Delta or Autotransformer torque curve is the excess torque that is created during starting. Electromechanical reduced voltage starters reduce the inrush current and applied torque when compared to starting with full voltage; unfortunately the motor still produces an excess of torque compared to the torque actually required to start the connected load.

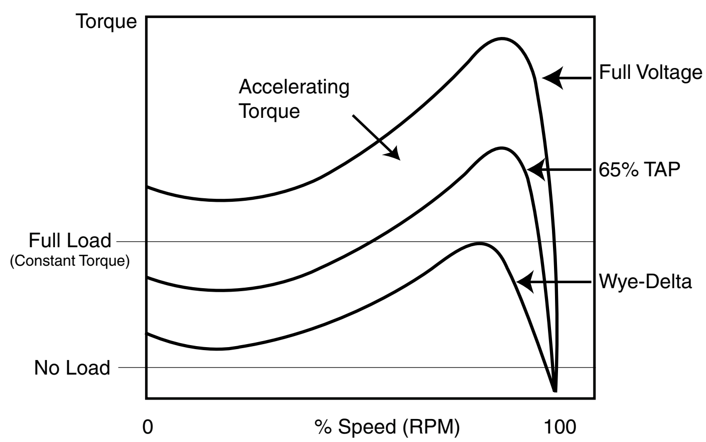


Figure 3-5: Typical Motor Speed Torque Curves for Electromechanical Starting

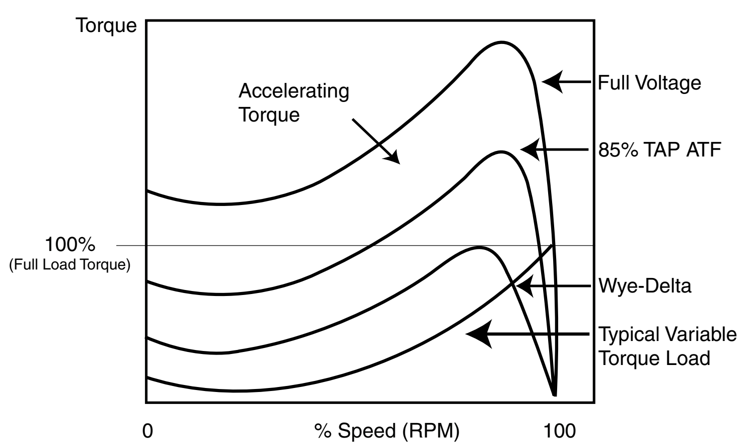


Figure 3-6: Typical Constant Torque Motor Speed Torque Curves for Electromechanical Starting

For a better understanding of the effects associated with full voltage starting and the voltage steps associated with electromechanical reduced voltage starters like the Autotransformer and Wye-Delta, let's look at the relationship between applied motor voltage and motor output torque:

❖***Rule of thumb:*** *Torque varies as (voltage)*^{2}

Thus, if only 50% of nominal voltage is applied, the motor's starting torque is only 25%. The following examples apply for a 480 or 575 volt induction motor and various applied voltages.

Table 3-1:

Starting Voltage (480)	Starting Voltage (575)	% Input Voltage	% Starting Torque
120V	150V	25%	12.5%
240V	300V	50%	25%
Wye-Delta		57%	33%
360V	450V	75%	51%
480V	600V	100%	100%

Disadvantages of Wye-Delta Starting

1. Limited adjustability to load conditions.
2. Mechanical shock to system between steps.
3. High contactor maintenance.
4. Unable to compensate easily for input voltage variations.
5. Uncontrolled deceleration.
6. Poor motor protection with the use of bimetallic overloads with 20% accuracy.

The Full Voltage Starter produces maximum torque, which is typically unnecessary to start the motor. The Autotransformer Starter does reduce the inrush current and applied torque to a certain extent. However, the Autotransformer's main disadvantage is its inability to adjust to different load conditions. From what has been shown so far, the most effective starter would be a starter that not only reduces the inrush currents, but that is also adjustable to different load conditions.

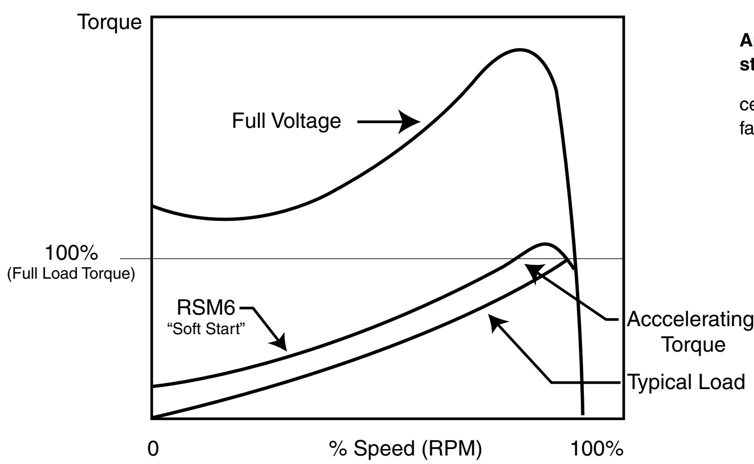
Solid State Reduced Voltage Starting

Solid State Reduced Voltage Starters (Soft Starts) provide smooth, stepless acceleration and deceleration of induction, synchronous, and wound rotor motors. This method of control is obtained through the use of Silicon Controlled Rectifiers (SCRs) which increase and decrease the motor terminal voltage within given, user-adjustable parameters. The benefits of solid state starters are numerous. Two of the most important advantages are listed below.

Advantages of Solid State Starters

1. High inrush currents can be reduced to less than 50 percent of those seen during full voltage starting. The inrush current can be held to a programmable limit through the entire start—for example, 300% of the motor's rated FLA. This will eliminate excessive line dips caused by a full voltage start and the transition step to line voltage with an Autotransformer.
2. Mechanical stress is greatly reduced due to a tremendous reduction of applied torque. Moreover, a soft start can replicate the actual starting torque requirements of the application because of the smooth, and programmable stepless current/torque ramp.
3. Metering is available to monitor the starter's status.
4. Electronic motor protection from ground faults, shearpin currents, a short in the wiring, the loss of a phase, or other events which could damage the motor.
5. Communication for remote starting and stopping and/or starter status information.
6. Maintenance jog for inspections.
7. Relays can be added to indicate the current state of the starter.

The following are speed/torque curves showing a motor connected with a Full Voltage Starter and a Solid State Starter. Note that the Solid State Starter follows the typical load, providing just enough torque to accelerate the motor to full speed.



Applications for variable torque starting:

centrifugal pumps
fans

Figure 3-7: Soft Start Speed Torque Curve for Solid State Starting

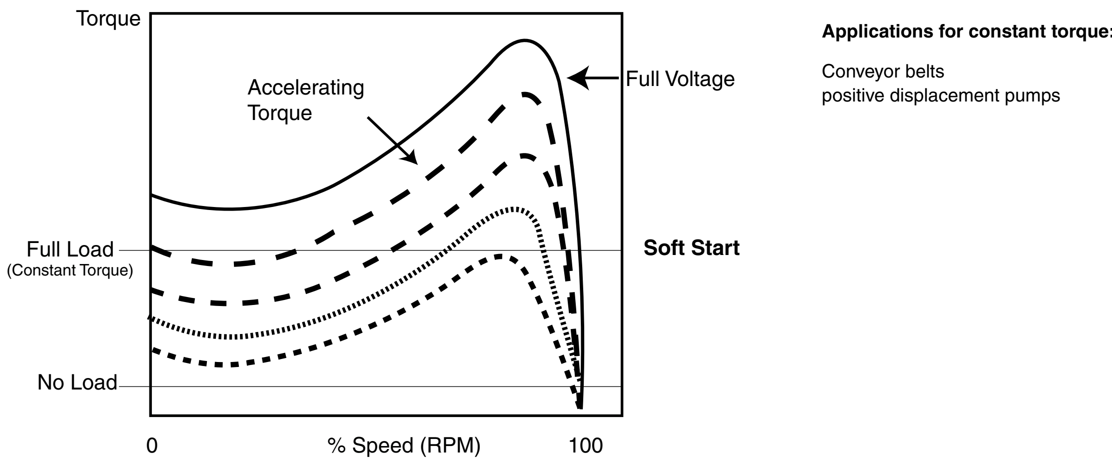


Figure 3-8: Typical Constant Torque Motor Speed Torque Curves for Solid State Starting

Shown below is a current/speed curve for a Solid State Starter. A Solid State Starter is adjustable using three main parameters which determine the starting profile. They are the initial current, maximum current, and ramp time. The current provided to the motor is slowly increased from the initial current setting (100% in this example) to a preset maximum current setting (300%). The increase in current is called the *ramp*. The ramp is linear, and the *slope* of the ramp is determined by the amount of time that is programmed during starter setup (0-120 seconds). The linear ramp eliminates the sudden torque transients such as those caused by Full Voltage, Wye-Delta and Autotransformer type starters, thus providing a soft start.

By holding the inrush current below a set level (such as 300%), the demand on the entire power system is also greatly reduced. The diagram below illustrates a typical ramp profile for a Solid State Starter.

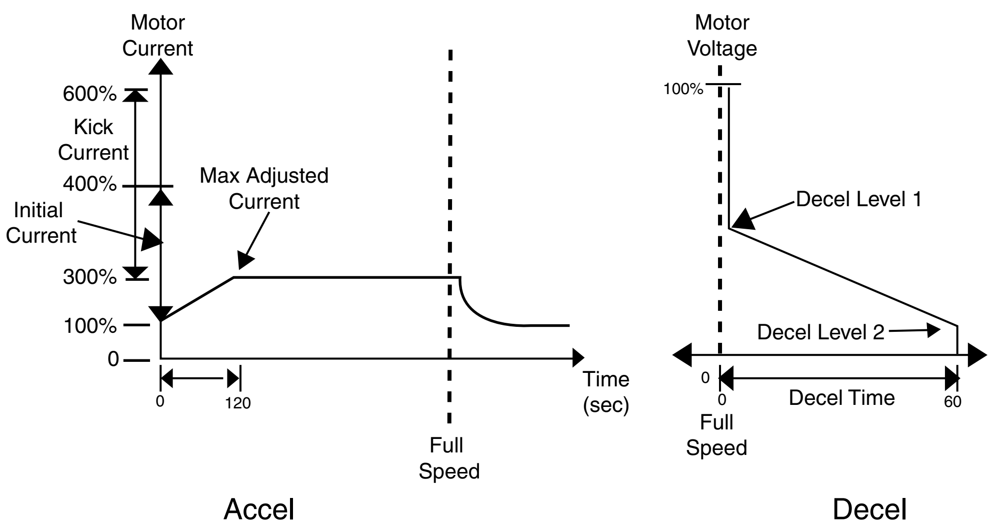


Figure 3-9: RediStart Micro Solid State Starter Ramp Profiles

To fully understand how all of this is possible, we must first understand the main component of a solid state starter. As we mentioned earlier, Solid State Starters use devices called SCRs. But what exactly is an SCR?

Silicon Controlled Rectifier (SCR)

SCRs are compact devices which control current and voltage to the motor. When properly applied and protected, they have a virtually unlimited life.

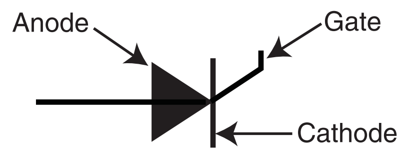


Figure 3-10: SCR Symbol

The SCR consists of three basic elements: the anode, the cathodes, and the gate. The SCR can conduct only when a positive voltage is applied to the anode with respect to the cathode, and a gating current is, or has been established from the gate to the cathode. At all other times, the SCR blocks the current flow.

The SCRs are used in inverse parallel operation, meaning that one SCR is used for the negative half of the sine wave, and one SCR is used for the positive half of the sine wave. In a three phase system, six SCRs are required.

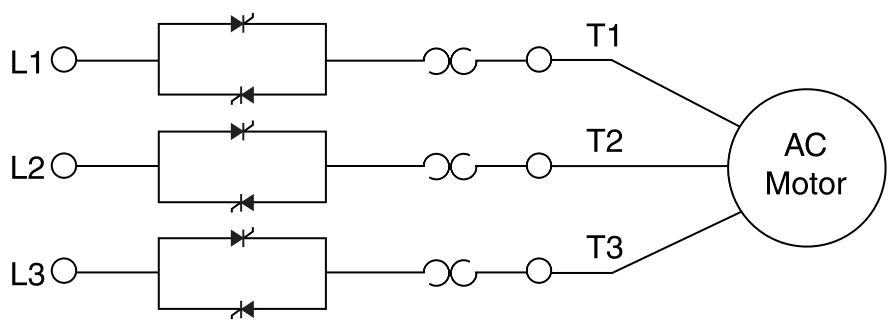


Figure 3-11: Basic Power Schematic of Solid State Reduced Voltage Starter

Voltage control is achieved by gating the SCRs on at different times in the AC sine wave cycle. Gating later in the cycle produces a lower output voltage. Gating earlier will increase the output voltage.

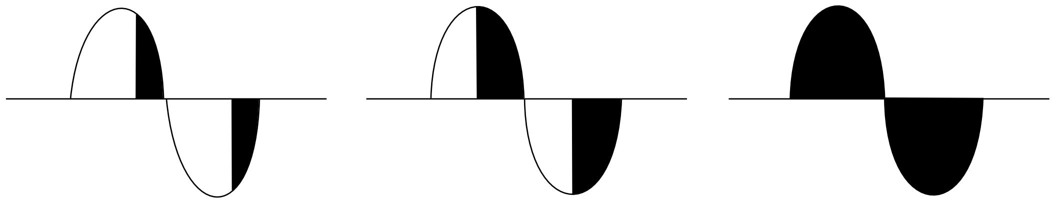


Figure 3-12: Voltage Control by Gating SCRs

To summarize, the chart below shows the relationship between line current, motor current, and motor torque for different types of starting methods.

Table 3-2: Relationship Between Line Current, Motor Current and Motor Torque for Starting Methods

	% Voltage	**Line Current as a % of**		**Motor Starting Current as a % of**		**Motor Starting Torque as a % of**	
Starting Method	at Motor	Locked	Full	Locked	Full	Locked	Full
	Terminals	Rotor	Load	Rotor	Load	Rotor	Load
		Current	Current	Current	Current	Torque	Torque
Full Voltage	100	100	600	100	600	100	180
Autotransformer							
80% Tap	80	64	384	80	480	64	115
65% Tap	65	42	252	65	390	42	76
50% Tap	50	25	150	50	300	25	45
Part Winding	100	65	390	65	390	50	90
Wye-Delta	100	33	200	33	200	33	60
Solid State	0-100	0-100	0-600	0-100	0-600	0-100	0-180

Medium Voltage Solid State Starters (MVSSRVS)

In a medium voltage soft start assembly; SCR's are assembled in a series string to provide the PIV rating that is required for the nominal line voltage. This PIV rating establishes the necessary voltage blocking capability.

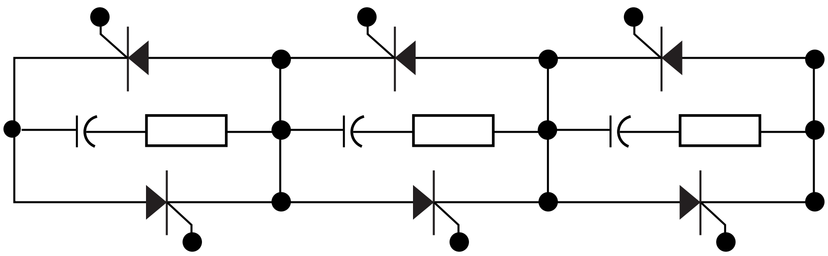


Figure 3-13: One Phase of a Medium Voltage SSRVS

This single line drawing shows the SCR Power Pole package with Micro Processor Controller and the additional necessary components that make up a complete medium voltage combination solid state reduced voltage motor starter.

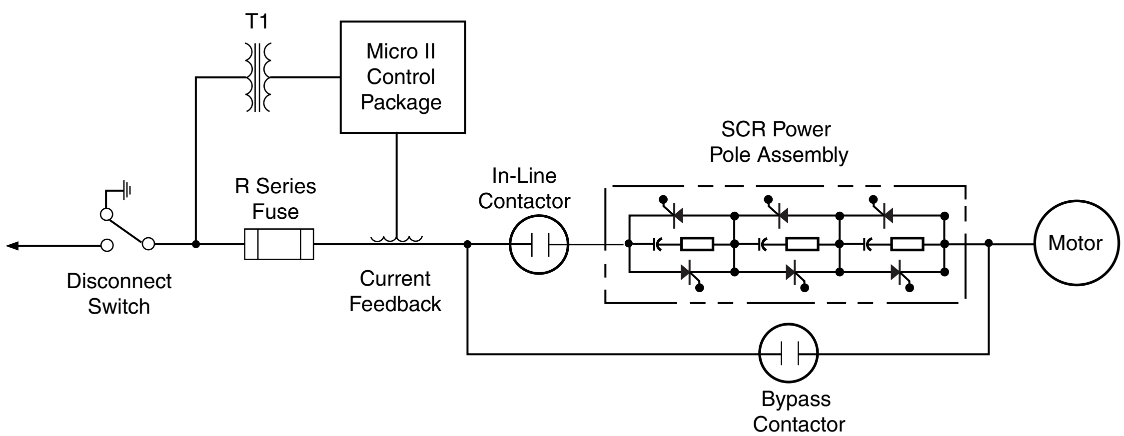


Figure 3-14: SCR Power Pole Package

Motor Characteristics

There are several characteristics that serve to define a motor's capabilities.

Speed

The *speed* of a motor is the number of revolutions in a given time frame, typically revolutions per minute (RPM). The speed of an AC motor depends on the frequency of the input power and the number of poles for which the motor is wound. The synchronous speed in RPM is given by the following equation, where the frequency is in hertz:

$$\text{Synchronous Speed (RPM)} = \frac{60 \times 2 \times \text{Frequency}}{\text{Poles}}$$

The actual speed which the motor operates will be less than the synchronous speed. The difference between synchronous and full load speed is called slip and is measured in percent. It is calculated using this equation:

$$\text{Slip (\%)} = \frac{\text{Synchronous Speed} \times \text{Full Load Speed}}{\text{Synchronous Speed}} \times 100$$

Induction motors can be manufactured with slip as high 20%. Motors with a slip of less than 5% are called normal slip motors. Motors with 5% or more slip are called high slip motors. They are used in applications that require high starting torque.

Torque

Torque is the turning power of a motor, and is measured in foot-pounds. One foot-pound is equal to a force of one pound turning a shaft at a distance of one foot. Torque produced by a motor varies as the speed of the motor increases from zero to full speed. This phenomenon is depicted by a motor's speed-torque curve, as shown below. There are several points on the speed-torque curve that are of interest.

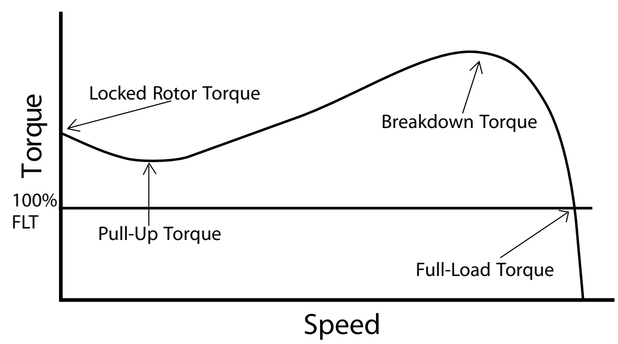


Figure 3-15: Torque

Locked Rotor Torque (LRT): Also known as starting torque. LRT is the torque generated by a motor with rated voltage and frequency applied while the rotor is at zero speed. It is usually measured as a percentage of full-load torque.

Pull-Up Torque (PUT): The PUT of a motor is the minimum amount of torque developed between Locked Rotor Torque and Breakdown Torque. It is usually expressed as a percentage of full-load torque.

Breakdown Torque (BDT): The maximum torque that a motor will develop at rated voltage and frequency, without an abrupt drop of speed, is called the Breakdown Torque.

Full Load Torque (FLT): FLT is the torque produced when the motor is running at full-load speed with rated voltage and frequency applied.

Horsepower

Horsepower represents the combination of both torque and speed. It can be calculated with this formula where torque is measured in foot-pounds:

$$\text{Horsepower} = \frac{\text{RPM} \times \text{Torque}}{5250}$$

Given the RPM and the horsepower of a motor, the full-load torque can be calculated with the following equation:

$$\text{Full Load Torque} = \frac{\text{Horsepower} \times 5250}{\text{RPM}}$$

Time for the motor to reach operating speed:

$$\text{Seconds} = \frac{(\text{Motor Wk}^2 \times \text{LoadWk}^2)\ \text{Speed Change}}{308\ \text{Avg. Accelerating Torque}}$$

$$\text{Avg. Accelerating Torque} = \frac{\text{FLT BDT / 2 BDT LRT}}{3}$$

FLT	Full Load Torque
LRT	Locked Rotor Torque
BDT	Breakdown Torque

$$\text{Load Wk}^2\ (\text{at motor shaft}) = \text{Load Wk}^2 \times \text{Load RPM}^2$$

Motor Output for NEMA Design Designations

NEMA has designated several types of motors, each having unique speed/torque relationships. Below is a description of each of the designations, along with a summary of the performance characteristics and some typical applications.

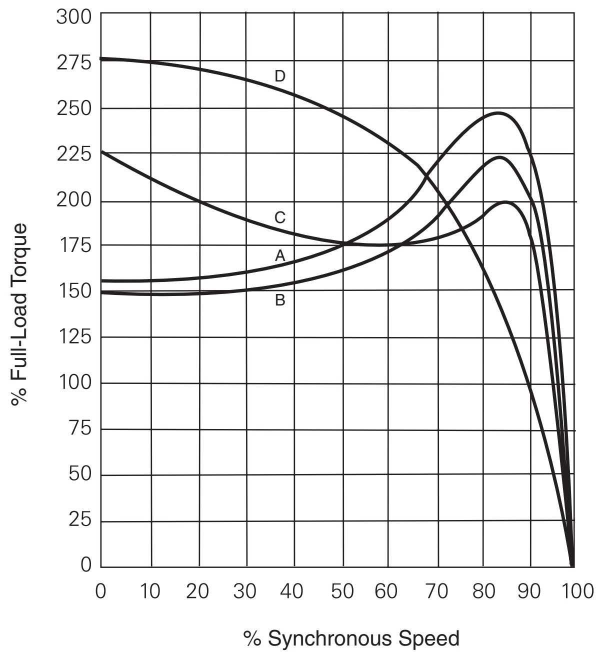


Figure 3-16: Motor Output for NEMA Design Designations

Summary of NEMA Design Designations

Table 3-3: NEMA Design Designations

<table>
<tr><th>NEMA Design</th><th>Starting Current</th><th>Locked Rotor Current</th><th>Breakdown Torque</th><th>% Slip</th><th>Example Applications</th></tr>
<tr><td>A</td><td>Normal</td><td>High</td><td>High</td><td>< 5%</td><td>Fans, blowers, pumps, and machine tools</td></tr>
<tr><td>B</td><td>Normal</td><td>Normal</td><td>High</td><td>< 5%</td><td>Fans, blowers, rotary pumps, unloaded compressors, conveyors, metal cutting, machine tools, miscellaneous machinery</td></tr>
<tr><td>C</td><td>Normal</td><td>Normal</td><td>Normal</td><td>Low</td><td>Large centrifugal blowers, fly wheels, crusher drums, piston pumps, compressors and conveyors</td></tr>
<tr><td rowspan="3">D</td><td rowspan="3">Extra High</td><td rowspan="3">Normal</td><td rowspan="3">Low</td><td>High</td><td>Very high inertia and loaded starts. Choose slip range to match application</td></tr>
<tr><td>5-8%</td><td>Punch press, sheers, and forming machine tools</td></tr>
<tr><td>8-13%</td><td>Cranes, hoists, elevators and oil well pumping jacks</td></tr>
</table>

Locked-Rotor Current

Locked-rotor current is the steady state current of a motor locked at zero speed with the rated voltage and rated frequency applied. NEMA has specified locked-rotor KVA per horsepower using a set of letters. The rated KVA/HP (Kilovolt-amperes-per-horsepower) code is stamped on the nameplate of all AC squirrel cage induction motors.

Calculating KVA/HP for Single Phase Motors

$$\text{kVA / HP} = \frac{\text{Current Volts}}{\text{HP 1000}}$$

Calculating KVA/HP for Three Phase Motors

$$kVA / HP = \frac{1.73 \text{ Current Volts}}{\text{HP } 1000}$$

NEMA Locked-Rotor Current Code Letters

Table 3-4: NEMA Locked-Rotor Current Code Letters

Letter Designation	kVA/HP (Up to, but not including the upper limit)
A	0 -3.15
B	3.15 -3.55
C	3.55 -4.0
D	4.0 -4.5
E	4.5 -5.0
F	5.0 -5.6
G	5.6 -6.3
H	6.3 -7.1
J	7.1 -8.0
K	8.0 -9.0
L	9.0 -10.0
M	10.0 -11.2
N	11.2 -12.5
P	12.5 -14.0
R	14.0 -16.0
S	16.0 -18.0
T	18.0 -20.0
U	20.0 -22.4
V	22.4 and up

Chapter Review

1. The four methods of AC induction motor starting are:

   ____
   ____
   ____
   ____

2. In rush current of an Across-The-Line (ATL) starter can be _____ to _____ times the FLA of the motor.

3. Full Voltage starting can create ____________/____________, which may result in penalties from the utility company.

4. An Autotransformer starter uses contactors configured to all for a _____________________ to full speed.

5. The autotransformer starter allows high _______________ to the system between steps.

6. Autotransformer starters can be either __________ or ___________ transition.

7. The Wye-Delta starter connects the motor windings in the ____________ configuration first followed by the ____________ configuration to obtain full speed.

8. In the Wye configuration, the current and torque are reduced to _______% of normal.

9. During the "Open Transition" from Wye to Delta, the motor is __________________ in order to avoid short-circuiting the contactors.

VARIABLE FREQUENCY DRIVES 4

In this chapter, you will learn about:

- VFD Components and Relationships
- Interaction between the Motor and the Control

Overview

A VFD changes fixed AC Voltage and Frequency into variable voltage and variable frequency. This transition is performed in three primary blocks: 1) Diode Bridge Rectifier–front end 2) Capacitors–DC Bus and 3) Transistors–Output Stage.

Motor Speed

The speed of a motor is the number of revolutions in a given time frame, typically revolutions per minute (RPM). The speed of an AC motor depends on the frequency of the input power and the number of poles for which the motor is wound. The synchronous speed in RPM is given by the following equation, where the frequency is in hertz:

$$\text{Synchronous Speed (RPM)} = \frac{120 \times \text{Frequency}}{\text{Poles}}$$

The actual speed, which the motor operates, will be less than the synchronous speed. The difference between synchronous and full load speed is called slip and is measured in percent. It is calculated using this equation:

$$\text{Slip (\%)} = \frac{\text{Synchronous Speed} - \text{Full Load Speed}}{\text{Synchronous Speed}} \times 100$$

As shown from the formula above, the speed of an AC motor is determined by the number of motor poles and by the input frequency. It can also be shown that the speed of an AC motor can be varied infinitely by changing the frequency. Notice that with the addition of a Variable Frequency Drive, the speed of the motor can be decreased as well as increased.

Volts/Hz Relationship

It has been shown that by changing the frequency, you can change the speed of the motor. However, frequency is not the only item that must be changed to the motor. Notice in the motor model below that the impedance of a motor will change with frequency since the impedance of an inductor is $= 2\pi\ fl$. At low frequencies this impedance approaches zero making the circuit appear to be a short circuit.

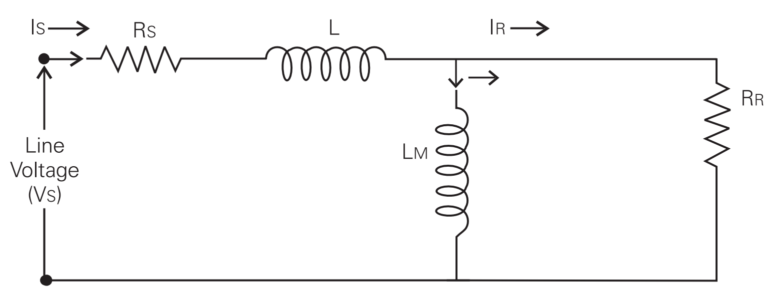


Figure 4-1: Basic Electric Circuit of AC Motor

To maintain a constant flux in the motor, the voltage to the motor must also be changed. This ratio is constant over most of the entire speed range. By keeping the ratio constant, a fixed speed induction motor can be made to run variable speed. At low speeds, due to the motor having inherent resistance in the windings, the ratio must be altered to provide enough magnetizing flux to spin the motor. The Benshaw VFD allows this relationship to be altered by changing the voltage boost parameter.

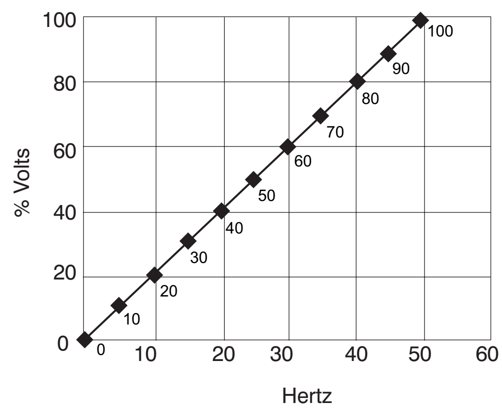


Figure 4-2: Volts/Hz Relationship

Diode Bridge Rectifier

The first section of a VFD is a full wave diode bridge rectifier. The function of this section of the VFD is to convert AC power into DC power. A 460 Vac VFD will have 650Vdc on the bus (460 x 2).

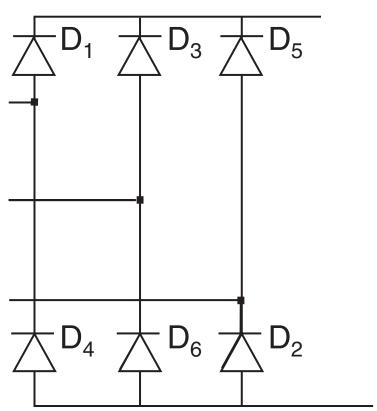


Figure 4-3: Wave Diode Bridge Rectifier

Capacitors

The second section of the VFD utilizes *capacitors* to filter dc bus ripple. After the diode section, the waveform is dc, however there is a high ripple content in the waveform. Capacitors are added to smooth out this dc ripple.

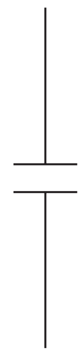


Figure 4-4: Capacitor

Transistors

The third section of the VFD utilizes transistors to change the dc waveform back into AC. By utilizing six or more transistors, the drive is able to recreate a sine wave to the motor. This method of power conversion is called *pulse width modulation*.

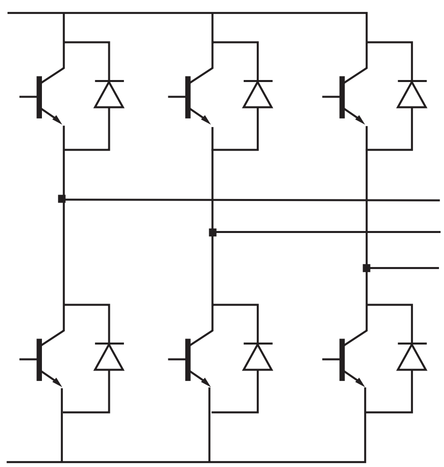


Figure 4-5: Transistors

Pulse Width Modulation

Notice by firing the transistors on the output of a variable frequency drive, a sinusoidal waveform can be created. By varying the time the pulses are on, and which transistors are firing, the frequency can be increased or decreased. Also, by changing the width and duration of the pulses, the average voltage to the motor can also be increased or decreased.

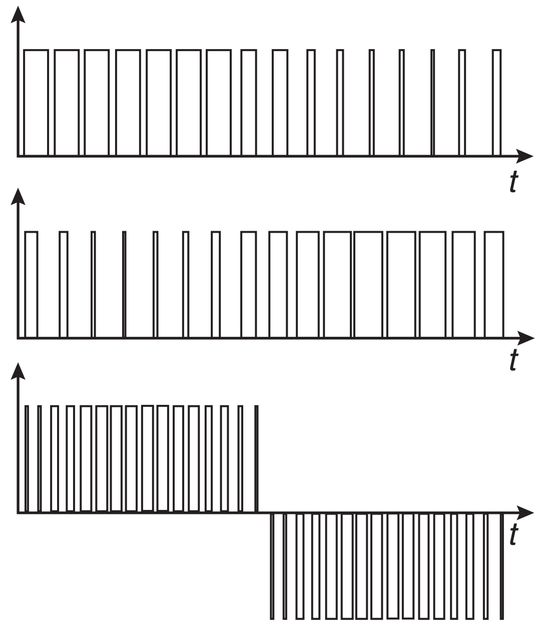


Figure 4-6: Voltage Waveform

The above voltage waveform is high in harmonic content. However, the current waveform to the motor more closely represents a sine wave. In fact with the higher switching frequencies of the IGBT, the more closely the current output waveform represents the true sine wave.

IGBT

The most recent advances in AC drive technology have been improvements in the size and performance of IGBTs (Insulated Gate Bipolar Transistors). IGBTs have displaced other types of power switching devices. Losses of the new devices are lower than earlier types of switching devices. The advantages of IGBT's are as follows:

- Fast switching capability
- Quieter motor operation
- Closer approximation of a sine wave
- More efficient motor operation
- Small Packages
- Increased reliability and better performance

Voltage And Frequency

Volts per Hertz

A ratio exists between voltage and frequency.This ratio is referred to as *volts per hertz* (V/Hz). A typical AC motor manufactured for use in the United States is rated for 460 VAC and 60 Hz.The ratio is 7.67 volts per hertz. Not every motor has a 7.67 V/Hz ratio. A 230 Volt, 60 Hz motor, for example, has a 3.8 V/Hz ratio.

$$\frac{460}{60} = 7.67 \text{ V/Hz} \qquad \frac{230}{60} = 3.8 \text{ V/Hz}$$

Flux (Φ), magnetizing current (I_M), and torque are all dependent on this ratio. Increasing frequency (F) without increasing voltage (E), for example, will cause a corresponding increase in speed. Flux, however, will decrease causing motor torque to decrease. Magnetizing current (I_M) will also decrease. A decrease in magnetizing current will cause a corresponding decrease in stator or line (I_S) current.These decreases are all related and greatly affect the motor's ability to handle a given load.

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

$$T = k\Phi I_W$$

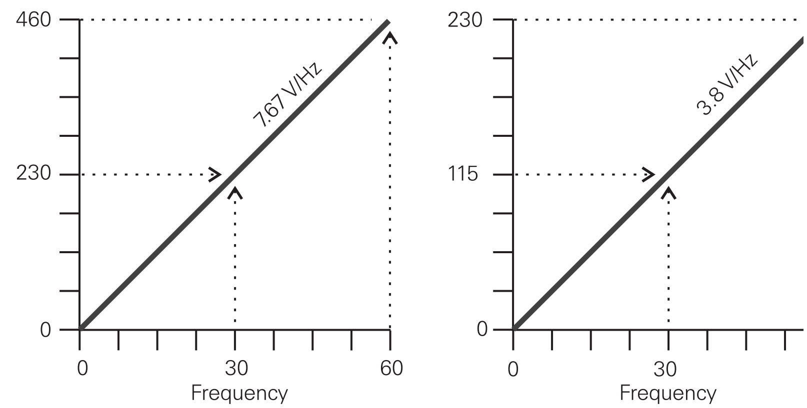
$$I_M = \frac{E}{2\pi F L_M}$$

Constant Torque

AC motors running on an AC line operate with a constant flux (Φ) because voltage and frequency are constant. Motors operated with constant flux are said to have constant torque. Actual torque produced, however, is determined by the demand of the load.

$$T = k\Phi I_W$$

An AC drive is capable of operating a motor with constant flux (Φ) from approximately zero (0) to the motor's rated nameplate frequency (typically 60 Hz).This is the *constant torque* range. As long as a constant volts per hertz ratio is maintained the motor will have constant torque characteristics. AC drives change frequency to vary the speed of a motor and voltage proportionately to maintain constant flux.The following graphs illustrate the volts per hertz ratio of a 460 volt, 60 hertz motor and a 230 volt, 60 Hz motor. To operate the 460 volt motor at 50% speed with the correct ratio, the applied voltage and frequency would be 230 volts, 30 Hz.To operate the 230 volt motor at 50% speed with the correct ratio, the applied voltage and frequency would be 115 volts, 30 Hz.The voltage and frequency ratio can be maintained for any speed up to 60 Hz. This usually defines the upper limits of the constant torque range.



$$\frac{460}{60} = 7.67\text{ V/Hz} \qquad \frac{230}{60} = 3.8\text{ V/Hz}$$

$$\frac{230}{30} = 7.67\text{ V/Hz} \qquad \frac{115}{30} = 3.8\text{ V/Hz}$$

Figure 4-7: Volts/Hz Ratios

Reduced Voltage and Frequency Starting

You will recall that a NEMA B motor started by connecting it to the power supply at full voltage and frequency will develop approximately 150% starting torque and 600% starting current. An advantage of using AC drives to start a motor is the ability to develop 150% torque with a starting current of 150% or less. This is possible because an AC drive is capable of maintaining a constant volts per hertz ratio from approximately zero speed to base speed, thereby keeping flux (Φ) constant.Torque is proportional to the square of flux developed in the motor.

$$T = \Phi^2$$

The torque/speed curve shifts to the right as frequency and voltage are increased.The dotted lines on the torque/speed curve illustrated below represent the portion of the curve not used by the drive.The drive starts and accelerates the motor smoothly as frequency and voltage are gradually increased to the desired speed. Slip, in RPM, remains constant throughout the speed range. An AC drive, properly sized to a motor, is capable of delivering 150% torque at any speed up to the speed corresponding to the incoming line voltage.The only limitations on starting torque are peak drive current and peak motor torque, whichever is less.

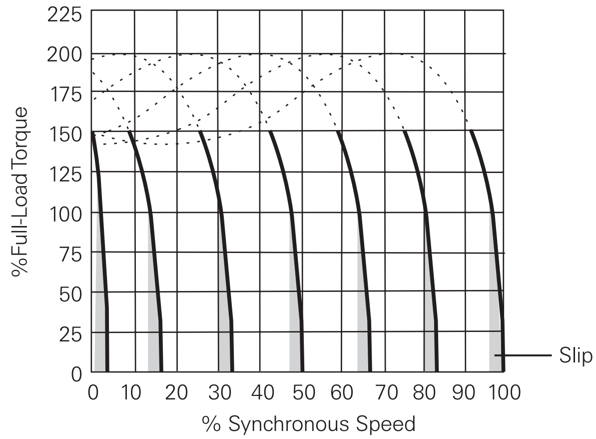


Figure 4-8: Torque/Speed Curve From Zero to Base Speed

Some applications require higher than 150% starting torque. A conveyor, for example, may require 200% starting torque. If a motor is capable of 200% torque at 200% current, and the drive is capable of 200% current, then 200% motor torque is possible.Typically drives are capable of producing 150% of drive nameplate rated current for one (1) minute. A drive with a larger current rating would be required. It is appropriate to supply a drive with a higher continuous horsepower rating than the motor when high peak torque is required.

Constant Horsepower

Some applications require the motor to be operated above base speed.The nature of these applications requires less torque at higher speeds. Voltage, however, cannot be higher than the available supply voltage.This can be illustrated using a 460 volt, 60 Hz motor. Voltage will remain at 460 volts for any speed above 60 Hz. A motor operated above its rated frequency is operating in a region known as a constant horsepower. Constant volts per hertz and torque is maintained to 60 Hz. Above 60 Hz the volts per hertz ratio decreases.

Table 4-1: V/Hz ratio up to and beyond base speed

Frequency	V/Hz
30 Hz	7.67
60 Hz	7.67
70 Hz	6.6
90 Hz	5.1

Flux (Φ) and torque (T) decrease:

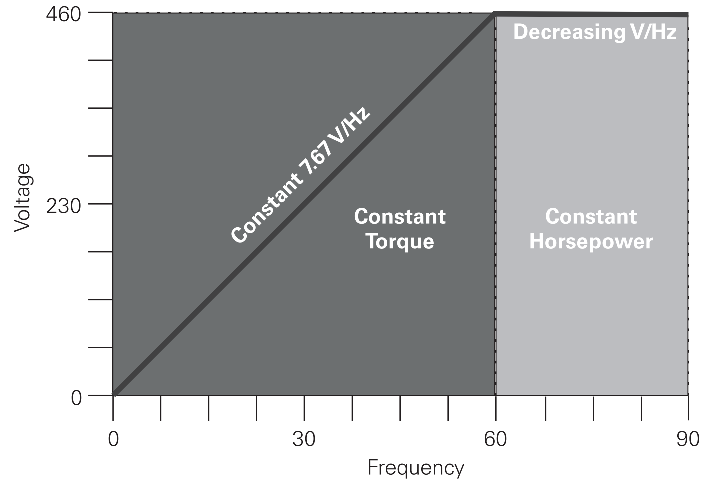


Figure 4-9: Example of Operating Motor Above Base Speed

Horsepower remains constant as speed (N) increases and torque (T) decreases in proportion.The following formula applies to speed in revolutions per minute (RPM).

$$\text{HP (remains constant)} = \frac{\text{T (decreases)} \times \text{N (increases)}}{5250}$$

Field Weakening

Motors operated above base frequency can also be said to be in *field weakening*. Field weakening occurs whenever there is an increase in frequency without a corresponding increase in voltage. Although an AC drive could be setup for field weakening at any speed, it typically only occurs beyond base frequency.

We have seen that below base speed, in the constant torque region, a motor can develop rated torque at any speed. However, above base speed, in the constant horsepower region, the maximum permissible torque is greatly reduced.

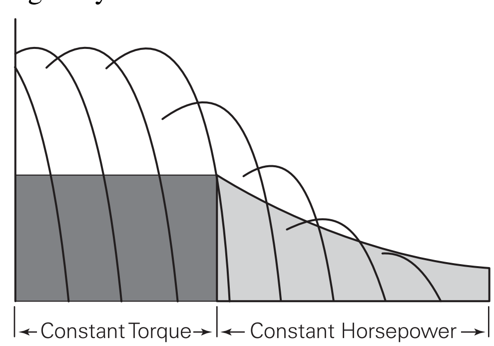


Figure 4-10: Reduction in Maximum Permissible Torque

Field Weakening Factor

A field weakening factor (FFW) can be used to calculate the amount of torque reduction necessary for a given extended frequency.

$$^{F}FW = \left(\frac{\text{Rated Frequency}}{\text{Extended Frequency}}\right)^2$$

For example, a 60 Hz motor can only develop 44% rated torque at 90 Hz and 25% rated torque at 120 Hz.

$$^{F}FW = \left(\frac{60}{90}\right)^2 = 44\%$$

$$^{F}FW = \left(\frac{60}{120}\right)^2 = 25\%$$

Selecting a Motor

AC drives often have more capability than the motor. Drives can run at higher frequencies than may be suitable for an application. In addition, drives can run at low speeds. Self-cooled motors may not develop enough air flow for cooling at reduced speeds and full load. Consideration must be given to the motor.

The following graph indicates the speed and torque range of a sample motor. Each motor must be evaluated according to its own capability.The sample motor can be operated continuously at 100% torque up to 60 Hz. Above 60 Hz the V/Hz ratio decreases and the motor cannot develop 100% torque.This motor can be operated continuously at 25% torque at 120 Hz.The motor is also capable of operating above rated torque intermittently.The motor can develop as much as 150%* torque for starting, accelerating or load transients, if the drive can supply the current. At 120 Hz the motor can develop 37.5% torque intermittently.

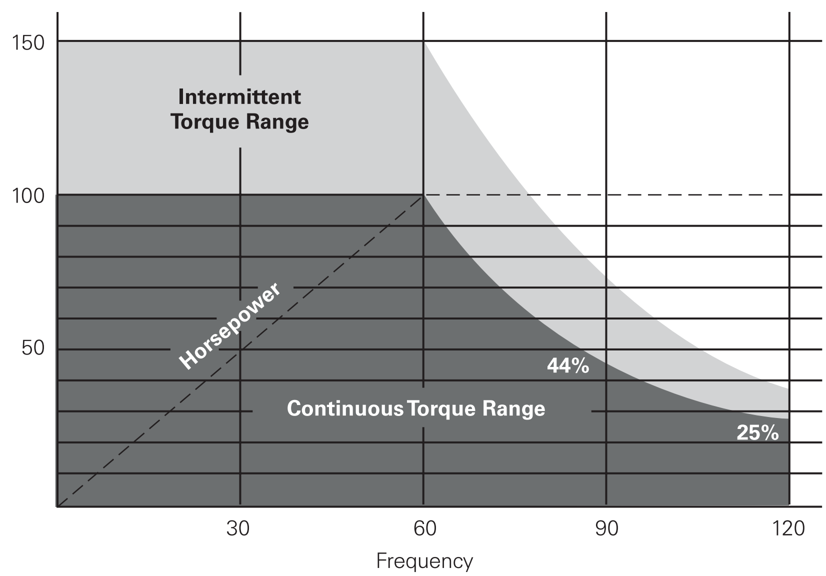


Figure 4-11: Speed and Torque Rance of Sample Motor

The sample motor described above is capable of operating at 100% rated torque continuously at low frequencies. Many motors are not capable of operating continuously at 100% continuous torque at low frequencies. Each motor must be evaluated before selecting it for use on an AC drive.

❖***Note:*** ** Torque may be higher than 150% if the drive is capable of higher current.*

Interaction Between Motor and Control

Thermal Considerations - Inverter Losses

Inverter losses are composed of two components: conduction losses and switching losses. Conduction losses are the product of the voltage drop across and the current through the device while the device is conducting current. Conduction losses do not vary with switching frequency. Switching losses are the product of the voltage across the device and current through the device during turn on and turn off. Switching losses increase proportionally to switching frequency. This results in higher operating temperatures, reduced efficiency of the control, and the possible need to derate maximum continuous horsepower at higher switching frequencies. Higher horsepower controls typically use lower switching frequencies.

Non-Fundamental Currents

Distortion of the motor currents varies inversely with switching frequency because of the low pass filtering effect of the leakage inductances of the motor windings. The higher the switching frequency the lower the total distortion and the better the current waveform, up to a point. As switching frequency is increased higher and higher, distortion of the motor currents about their zero crossings caused by the switch deadband (intentionally built-in time delay between upper and lower switch conduction) becomes significant. Usually, however, tradeoffs between current distortion and switching loss are such that little is to be gained above approximately 5 kHz.

Motor temperature is a function of both cooling and the magnitude of heat producing losses in the motor. These losses are increased, when compared to operation on line power, because of the current distortion. The non-fundamental currents contribute very little to useful torque, but do increase several components of motor losses. Core losses are increased due to eddy currents and hysteresis. Rotor conductor losses are increased due to high frequency surface losses. The high frequency component also adds to the total rms current and thus the I^2R loss in the stator conductors. The magnitude of this increase in losses depends on the switching frequency of the control and the motor design characteristics.

Reduced Speed

There are two general methods of motor cooling or ventilation: 1) speed dependent, 2) speed independent. These methods may be affected by operation on variable frequency.

In the case of speed dependent ventilation (totally-enclosed fan cooled or open drip-proof motors) where the rotation of the cooling fan is supplied by the motor, cooling depends on motor speed. Therefore, cooling will decrease as motor speed decreases. The magnitude of the decrease depends on the speed range. The rate of decrease depends on motor construction. Motors in this group may have only 20 to 50 percent of base speed cooling at very low speeds. Care should be taken to be certain that unidirectional motors are operated only in the intended direction of rotation.

In the case of speed independent ventilated motors (totally-enclosed non-ventilated, totally-enclosed air-over, blower-cooled, etc.), cooling variation with speed is minimal, effectively staying constant. As a result, motors of this type are better suited for operation at very low speeds or for wide constant horsepower speed ranges.

Voltage Boost

Voltage boost is often used on volts per Hz controls at frequencies below 20 Hz for the purpose of obtaining sufficient breakaway torque or running torque without requiring excessive current. At very low frequencies, such as 6 Hz or lower, this voltage boost may be as great as 100 percent of the prescribed voltage at that frequency based on a constant volts per Hz relationship. At rated torque, this additional voltage compensates for the voltage drop across the stator winding impedance when rated current flows in the motor. However, when the load is removed from the motor operating at such low speeds, the current is reduced and the higher (boosted) voltage may then result in operation of the motor in a highly saturated condition. This can result in overheating of the motor. It is recommended that, when necessary to provide breakaway torque in excess of 140 percent of rated torque, the motor should not be operated at no load under a fixed voltage boost condition at frequencies less than 10 Hz for more than one minute without careful observation of motor temperature or consulting with the motor manufacturer. When extended operation at no-load is required, a control providing compensation in relation to the IR drop should be used.

Motor Thermal Protection

Since the operating conditions of a motor used on a control vary across wide speed and torque ranges, motors often use some type of thermal protection.

Thermal protection devices built into the motor come in either line interrupting or pilot devices.

Line interrupting devices open the power supply circuit when the motor overheats. They are protectors that sense both motor temperature and current and offer inherent protection against all abnormal stalled and running conditions. They are supplied with the motor and may be either automatic or manual reset. These protectors are typically only available with motors under 5 HP.

Because these protectors are current sensitive and may be sensitive to airflow, extreme caution should be used in applying a motor with this type of protection on a control. Underwriters Laboratories Recognized protector/motor combinations are traditionally selected based on sinewave power at the rated line frequency such as 60 or 50 hertz. The change in the heating rate in the protector as a result of additional harmonic currents or variable frequency operation when a motor is operated on a control may result in improper protector operation.

Pilot devices open the holding coil of a magnetic switch to take the motor off line, or energize alarm bells or warning lights. Motors taken off line by pilot devices typically cannot be restarted until an operator re-closes the magnetic starting switch. Typical examples include thermostats, thermistors, and RTDs (resistance temperature devices.) When pilot motor thermal protection is supplied, it is ineffective as a motor trip device unless the pilot leads are wired into the control logic circuit.

Connecting the pilot devices into the control logic circuit is mandatory in hazardous location applications. In these applications, the agency listing may have been obtained assuming the pilot protectors will cause the motor to be disconnected from the line when the protectors trip. In these cases, not connecting the pilot devices for their intended purposes may invalidate the agency listing in addition to the hazard of causing damage to equipment and personnel.

Most adjustable frequency controls have overload protection built into them that will shut off the motor if the current versus time profile built into them is activated in software. Care should be taken, when using this feature, to assure that the current setpoint is based on the motor nameplate current and not the default current programmed into the control software.

Voltage

AC motors are rated by NEMA standards to operate at 100 percent output torque when the voltage applied to the motor terminals is within ±10 percent of the rated voltage. Although some control designs may operate when the supply voltage is beyond these limits, their output voltage may vary more than ±10 percent under these conditions and could result in damage to the motor.

Allowable Temperature Rise for General Purpose Motors - Designs A, B, C and D

General-purpose motors are designed such that the temperature rise when operating under sinewave power at the nameplate rating is within the limits given in Table 4-2. Some derating of the motor may be required when used with a control in order for the temperature rise to remain within these limits.

Table 4-2: Temperature Rise for General-Purpose Motors—Designs A, B, C and D

Class of Insulation System	A	B	F	H
Time Rating (continuous or any short-time rating) Temperature Rise (based on a maximum ambient temperature of 40°C), Degrees C Windings, by resistance method				
Motors with 1.0 service factor other than those given in items a.3 and a.4	60	80	105	125
All motors with 1.15 or higher service factor	70	90	115	
Totally-enclosed non-ventilated motors with 1.0 service factor	65	85	110	130
Motors with encapsulated windings and with 1.0 service factor, all enclosures	65	85	110	

❖**Notes:** *Abnormal deterioration of insulation may be expected if the ambient temperature of 40°C is exceeded in regular operation.*

The foregoing values of temperature rise are based upon operation at altitudes of 3300 feet (1000 meters) or less. For temperature rises for motors intended for operation at altitudes *above 3300 feet (1000 meters),The equipment must be derated 1% for every 330 feet above 3300 feet.*

Allowable Temperature Rise for Definite-purpose Inverter-fed Motors

Maximum Temperature Rise for Continuous Duty Rated Motors

The maximum temperature rise of the windings, above the temperature of the cooling medium, does not exceed the values given in Table 4-3.

Table 4-3: Temperature Rise for Continuous Duty Definite-Purpose Inverter-Fed Motors

Maximum Temperature Rise Degrees C		
Method of Temperature Determination		
Insulation Class	Resistance	Embedded Detector
A	60	70
B	80	90
F	105	115
H	125	140

Maximum Temperature Rise for Variable Speed Duty Rated Motors

The maximum intermittent temperature rise of the windings, above the temperature of the cooling medium, does not exceed the values given in Table 4-3 when tested at any rated load within the rated speed range with the identified control. All temperature rises in the table are based on a maximum ambient temperature of 40^{o}C.

Chapter Review

1. The three primay blocks of a variable frequency drive are:
   ____
   ____
   ____

2. The function of the of the diode rectifier section is to convert _______________ into ____________.

3. The capacitor section's primary function is to smooth out ___________________________.

4. The third section utilizes ________________ to change the DC waveform back into AC.

5. Pulse Width Modulation varies the time the transistors are turned on thereby changing the ________ ________ to the motor.

6. As the frequency to the motor is decreased toward zero the impedance of the motor ____________ and appears to be a short circuit.

7. The ratio between the voltage and frequency to the motor is known as the ____________.

8. In order to maintain a constant motor flux in the motor over the entire speed range, the Volt/Hz ratio must remain constant. For a 460 volt system, the Volt/Hz is ___________

9. As speed increases from zero to base speed, the motor operates in the constant __________ range. Above base speed, the motor operates in the constant __________ range.

10. Voltage boost is often used on volts per hertz controls below 20Hz for the purpose of obtaining ___________ ___________ torque without requiring excessive currents.

HARMONICS 5

In this chapter, you will learn about:

- The Effects of Harmonic Current on Equipment
- Voltage Distortion
- Harmonic Limits

BENSHAW U

Overview

By the operation of their input rectifiers, Variable Frequency Drives (VFDs) draw distorted input currents. These distorted currents contain the 60Hz fundamental current plus additional harmonic currents. The primary problem with harmonic current is its effect on other equipment connected to the same AC bus and its effect on the electric utility's equipment. The supply transformer and distribution network will now need to supply the additional harmonic current to the drive which increase losses and creates additional heat. Also depending on the bus impedance, the current harmonics can cause voltage distortion that can cause problems with computers, UPSs, telephone systems and other sensitive equipment. Further, external to the user's facility, neighboring facilities and homes can also be affected. Because these harmonics can sometimes cause significant problems, there is a standard limiting current harmonic production and that standard is IEEE-519-1992.

IEEE-519-1992 is a very commonly quoted specification for VFD packages. IEEE-519-1992 is also one of the most misunderstood specifications. IEEE-519-1992 sets limits for the overall harmonic current present at the point of common coupling (PCC) of a facility. This point is usually the metering point of the building/facility. The harmonic limits are also dependent on the source capability of the utility supply and can range from a maximum Total Harmonic Distortion (THD) of 20% down to only 5%. Some customers/consultants specify that IEEE-519-1992 must be met at the drive input rather than at the PCC. Technically, application of IEEE-519-1992 limits right at the drive input rather than at the PCC is not the intent of IEEE-519-1992. However this is primarily specified by customers and consultants when drives and other harmonic loads make up a large share of a facility overall electrical load. In order to better understand VFD input current harmonics tests were performed in the Benshaw Power Lab and the results are shown below to show the effects of various methods to reduce input current harmonics.

Test Results

Tests were performed in the Benshaw Power Lab to illustrate how VFDs can induce input current harmonic distortion. The figures in this chapter show how the distortions appear. A Power Analyzer was used to quantify the distortions and test the effectiveness of various methods to reduce it. Testing was performed using a RSi 075-H-4-L variable frequency drive. The drive was connected to a 75hp test motor and loaded to the NEMA 75hp current rating of 96 A_{rms} on the Benshaw power lab dynamometer. Various three phase input reactors that are available in the Benshaw lab were used to test the drive under various input impedance conditions. Below are the test results.

No Input Inductor

With no input inductor the only source impedance that the input of the drive sees is generally the impedance of the building's supply transformer. In the case of the Benshaw Power Lab, the equivalent source impedance is even lower than the building's 300kVA supply transformer because the lab utilizes a 5th harmonic trap filter and power factor correction system. This filter presents a very low impedance to the drive especially at the fifth and seventh harmonics. This results in an equivalent per phase source impedance at 75hp of only 0.5% per phase. If a customer has power factor capacitors installed this can cause a similar low impedance situation. This low equivalent impedance can also occur when a drive is placed on a very "stiff" bus relative to the size of the drive (i.e. 50 hp drive on a 5MVA source).

The effect of this very low source impedance can be seen in the results below. The scaling for all the current traces is 5Amps per millivolt (mv). The input phase current waveform consists of two 230+ Amp peak current pulses and the input diodes are not in continuous conduction. Other than resulting in a great deal of current harmonics the DC bus ripple will also be larger and cause addition heating of the input diodes and DC bus capacitors. The average input current was 109 A_{rms} and because of the large harmonic content the PF is a poor 0.70. As you will see below as the harmonic content is decreased the rms input current will decrease and the overall PF will improve.

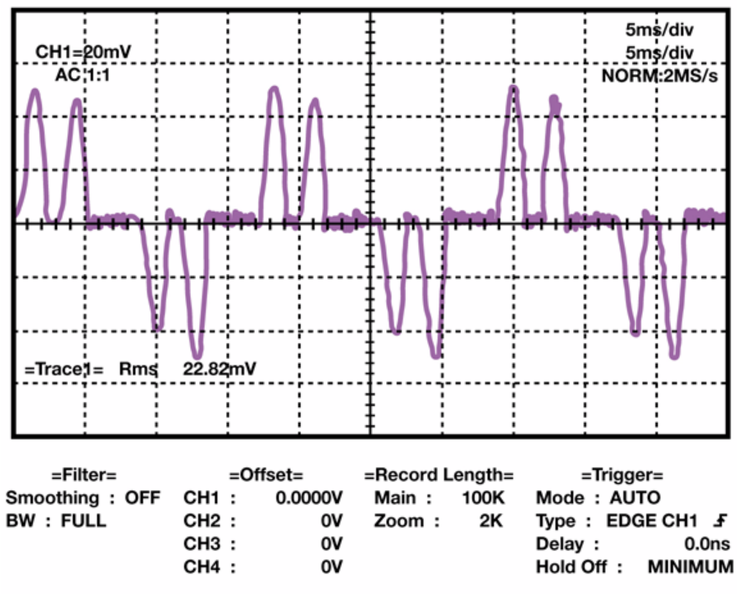


Figure 5-1: Input Phase Current No Added Reactance

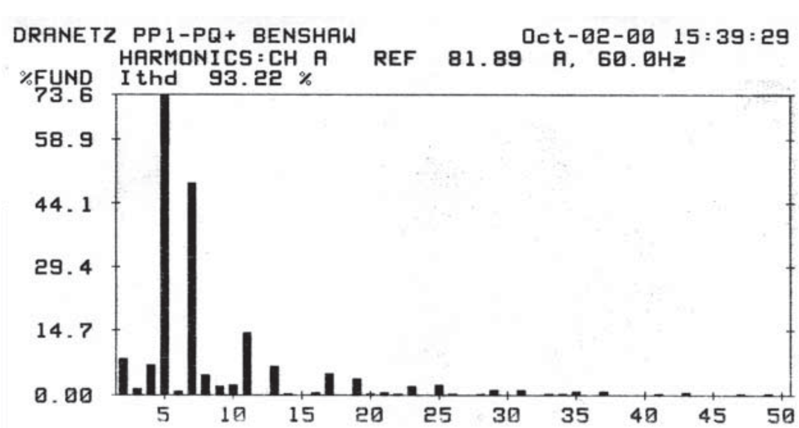


Figure 5-2: Harmonic Spectrum No Added Reactance

With only the building's source impedance the THD of the input current is a very high 93.22%. Looking at the bar graph the 5th and 7th harmonics (as expected with the standard 6-pulse input rectifier) are the dominant harmonics. The 5th alone is 73.6% of the fundamental 60Hz current.

1.5% Input Reactor

A 0.15mH three-phase reactor was added in series with the input supply to the drive. In many cases a line reactor sold as a 1.5% reactor may actually provide slightly higher than specified reactance. This occurs because the manufacturers design the reactors with extra impedance so that they can specify the same reactor for different voltage and load situations and still meet the impedance specification. Also slight differences in ratings are also seen depending on what "base" voltage and current the manufacturer uses to calculate the impedance. In practice this slight variation when used for VFD input or output reactors is negligible. During this test the 1.5% rated reactor actually provided approximately 2% impedance per phase with respect to a 75hp, 96 A_{rms}, 480V base. So the overall input impedance seen by the drive is that of the reactor and of the source, which is ~ 2.5% per phase.

In Figure 5-3, it can be seen that with 2.0% additional input reactance that the diodes are now conducting for a full 120°. However the current still has two obvious current peaks. Compared to Figure 1 the peaks are now noticeably lower with a 180Amps peak (note that the vertical scaling is half that of Figure 5-1). The average measured input current was 93.7 A_{rms} at a PF of 0.852.

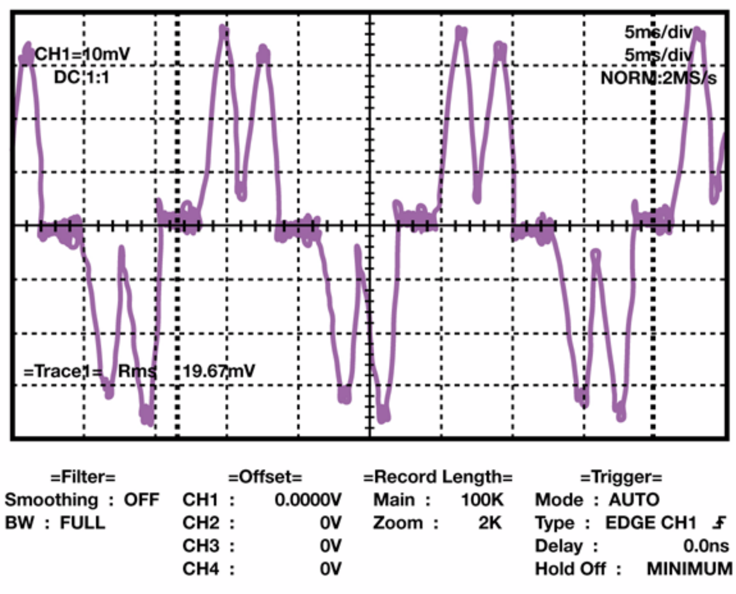


Figure 5-3: Input Phase Current 1.5% Input Reactor

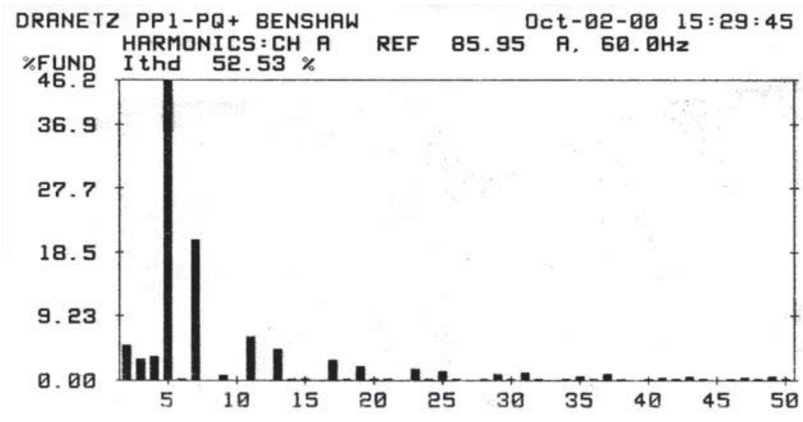


Figure 5-4: Harmonic Spectrum 1.5% Input Reactor

As shown, the THD with a 1.5% reactor is 52.53% (which is not very good although it is a drastic improvement over no reactor).

3% Input Reactor

A 0.3mH three-phase reactor was connected in series with the input supply to the drive. This inductor actually provides ~4% impedance per phase with respect to a 75hp, 96A, 480V base. The overall input impedance seen by the drive is about 4.5% per phase.

In the figure below, the current is looking even better than above. The peaks are lower at approximately 145Apeak and the current is looking slightly more rounded. The average input current is down to 88.5 A_{rms} at an improved PF of 0.899.

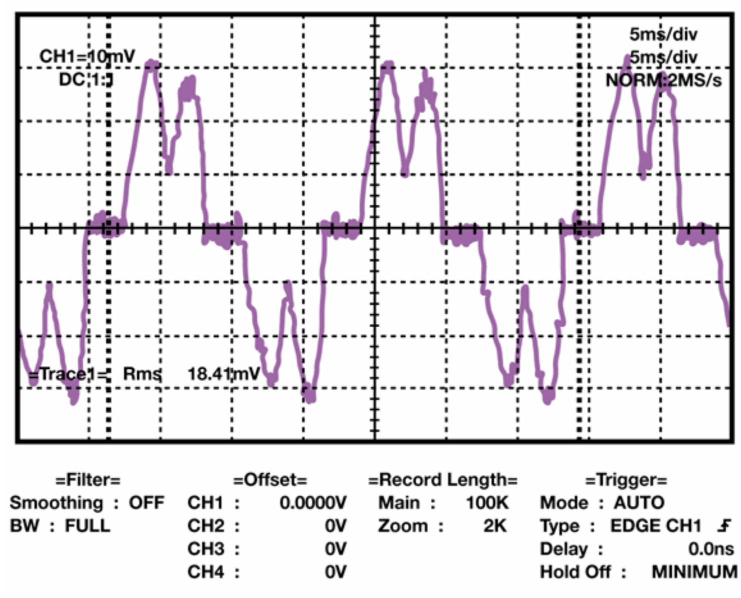


Figure 5-5: Input Phase Current 3% Input Reactor

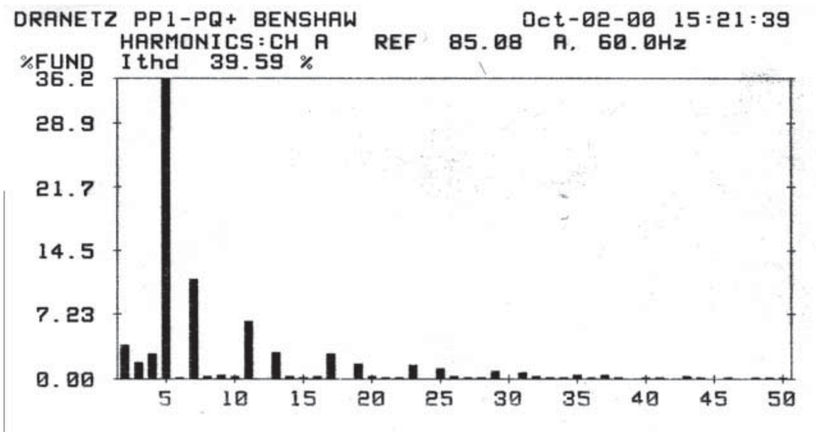


Figure 5-6: Harmonic Spectrum 3% Input Reactor

With the 3% input reactor the THD has been reduced down to 39.59%. In many cases this reduction in the THD can be enough to meet harmonic requirements at the Point of Common Coupling (PCC).

5% Input Reactor

A 0.45mH three-phase reactor was connected in series with the input supply to the drive. The calculated impedance of this reactor is 5.8% per phase with respect to a 75hp, 96A, 480V base.

Visually the current waveform is a very slight improvement over the 3% reactor case. The peak currents are very slightly down to 138Apeak. The average input current is 87.1A_{rms} at a reasonable 0.914 PF

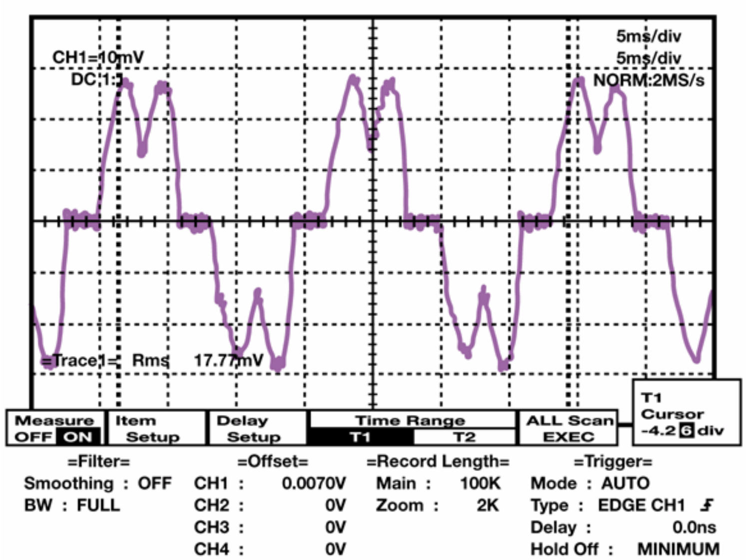


Figure 5-7: Input Phase Current with 5% Input Reactor

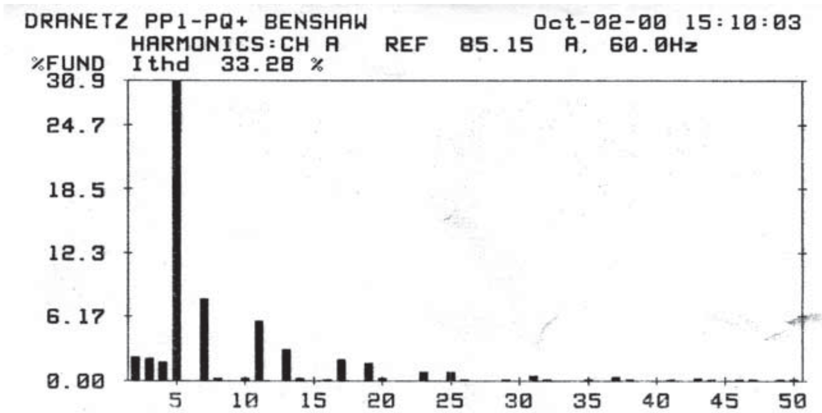


Figure 5-8: Harmonic Spectrum 5% Input Reactor

With a 5% reactor the THD has been reduced down to 33.28%. Unfortunately this is only a small reduction from using a 3% reactor. This shows that there are diminishing improvements in THD as the reactance is increased past 4-5%.

Benshaw's 18-pulse Package

The ultimate in harmonic reduction comes from using the Benshaw 18-pulse front-end package. It can be seen from the above test results that the minimum THD by using large input reactors is limited to 30-35%. As discussed in other training material, the 18-pulse package can reduce harmonic distortion to meet any of the IEEE519 requirements. Unfortunately, the Benshaw Power Lab has an input voltage imbalance of ~1% between phases and the DC load drive slightly distorts the input voltage going to the VFD under test. These two factors result in slightly imbalanced input currents that contribute even and 3rd order harmonics to the harmonic spectrum of the input current. Therefore the lowest harmonics value achieved for this test is ~7%. Plans are underway to balance the phase voltages in the Benshaw Power Lab so that more precise testing can be conducted.

In Figure 5-9, the input current of an 18-pulse system can be seen. It is a stark improvement over the currents seen above. Current flows for the full 180° of each half cycle and it is very close to sinusoidal. The average phase current was 81.96 A_{rms} and the input PF was an excellent 0.982.

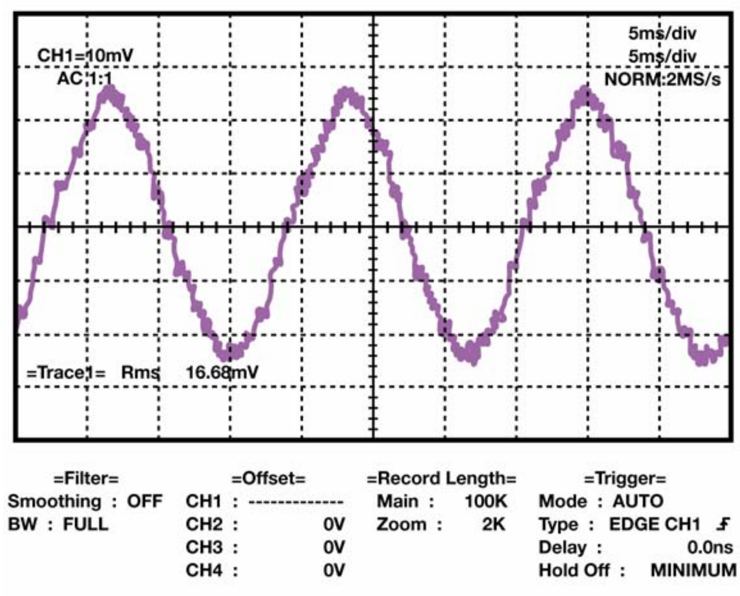


Figure 5-9: Input Phase Current 18-Pulse

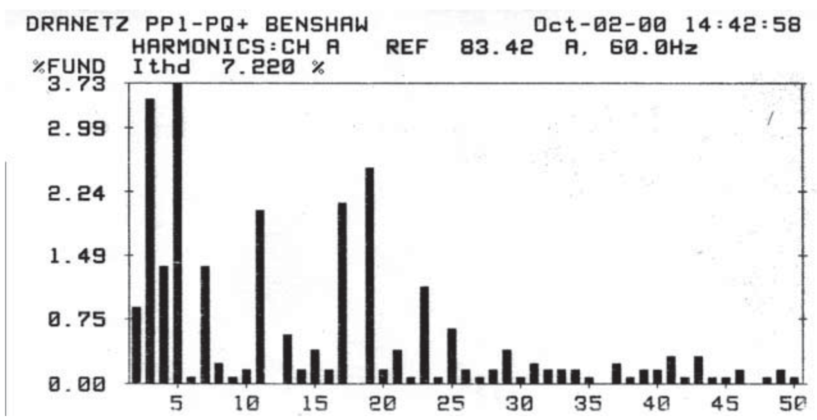


Figure 5-10: Harmonic Spectrum 18-Pulse

As can be seen the magnitude of harmonic spectrum is overall very low. The dominant harmonics in an 18-pulse system theoretically should be the 17th and 19th harmonic. Unfortunately because of our current imbalance the 3rd and 5th are also high in our test example.

6 ELIMINATING MOTOR FAILURES

In this chapter, you will learn:

- How to Eliminate Motor Failures due to IGBT-Based Drives
- What Causes Motor Failures
- How to Avoid Effects of Shaft Voltage and Bearing Currents

Eliminating Motor Failures Due to IGBT-Based Drives when Connected with Long Leads

The application of new generation Variable Frequency Drives (VFDs), utilizing Insulated Gate Bipolar Transistors, (IGBTs), in the inverter section with motors connected by long leads has been a source for concern and expense. Motors controlled by VFDs installed some distance away often fail due to high voltage-induced insulation breakdown. This chapter offers an analysis of this phenomenon and recommends some practical solutions for correcting existing problems and for protecting against future failure.

Drives and motors often need to be separated by distance. Motors in wells must be controlled above ground: the deeper the well, the longer the leads between the drive and the motor. In some plants, motors can withstand the harsh surroundings. However, sensitive VFD electronics cannot tolerate such environments, forcing long distances between the motor control centers that house the drives and the motors that they control. Conveyors and presses often utilize single drives to operate multiple motors that are positioned along the length of the conveyor. The length of the conveyor often dictates the longest distance between a drive and a motor.

Most manufacturers of VFDs publish a maximum recommended distance between their equipment and the motor. The restriction of that maximum distance often makes application difficult, impractical, or unfeasible. Maximum tolerable distances vary by manufacturer, but might be 100 to 250 feet. Many users of VFDs have elected, or have been forced, to disregard the maximum recommended distance. These users are now replacing or rewinding motors after a 2-week, a 6-week, or a 6-month life span. In some cases, motor failure occurs even though the installation is within, but close to, the maximum recommended distance. Both the cost of these repairs and the downtimes that they demand are mounting quickly.

The PWM Voltage

VFDs generate the useful “fundamental” voltage and frequency via a modulation technique known as *Pulse Width Modulation (PWM)*. For a 480V system, the typical fundamental voltage ranges from 0 to 460V and the fundamental frequency varies from 0 to 60Hz. The inverter circuit “switches” rapidly, producing a carrier upon which is contained the useful fundamental voltage and frequency. This switching is quite similar to an AM or FM radio where the useful information, music or talk, is transmitted to the radio receiver at some assigned radio frequency. The carrier, or switching frequency used for IGBT-based VFD, generally ranges between 3 to 15 kHz.

Switching time is the time required for the IGBT inverter to transition from the “off” (high impedance) state to the “on” (low impedance) state and visa-versa. For the latest generation of IGBTs, the switching time varies from 100 to 200 nanoseconds,(ns). Because these devices are used in circuits fed by approximately 650 V DC, for a 480V system, the rate of change of voltage with respect to time, (dV/dT), can exceed 7500 volts per microsecond, (V/µs).

IGBTs

The relatively recent availability of high voltage, high current IGBTs has led to the wide use of these devices as the main switching element in the D-C to AC inverter section of 1-phase and 3-phase AC Pulse Width Modulated VFDs. Virtually all of the manufacturers of these types of power conversion circuits have developed, or are developing, product lines that utilize these relatively new devices. One of the main reasons for the widespread use of these devices is their extremely fast switching time. This results in very low device transition losses and, therefore, in highly efficient circuits. In addition, a fast switching time allows drive carrier frequencies to be increased above the audible range. (Slower switching topologies operating at a range of 1 to 2kHz often induced irritating mechanical noise in a motor.)

The Reflected Wave Phenomenon

Voltage wave reflection is a function of the voltage rise time (dV/dT) and of the length of the motor cables which behave as a transmission line. Because of the impedance mismatch at both ends of the cable (cable-to-inverter and cable-to-motor), some portion of the waveform high frequency leading edge is reflected back in the direction from which it arrived. As these reflected leading edges encounter other waveform leading edges, their values add, causing voltage overshoots. As the carrier frequency increases, there are more leading edges present that “collide” into one another simultaneously, causing higher and higher voltage overshoots. If the voltage waveform was perfectly periodic, it might be possible to “tune” the length of the wire. However, since the width of the pulses varies throughout the PWM waveform, it is not possible to find any “null” points along the lead length where the motor may be connected without the fear of damage.

The Resonant Circuit Phenomenon

Another way to analyze the problem is with respect to system resonance. Because multiple conductor wire runs contain both distributed series inductance and distributed parallel capacitance, the conductors can be viewed as a resonant tank circuit.

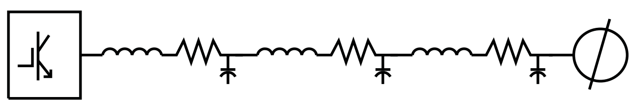


Figure 6-1: Equivalent Resident Tank Circuit

Knowledge of the Inductance (L) and the Capacitance (C) values of any circuit allows for the calculation of the circuit’s natural resonant frequency. As wire lengths grow, L and C will both increase, reducing the resonant frequency as described by the equation:

$$\mathrm{Fr} = \frac{1}{2 \times 3.14159 \times \sqrt{L \times C}}$$

In those applications where the physical length of conductors connecting the motor to the inverter exceeds 50 ft., L and C values combine to form a typical resonant frequency range between 2 to 5 MHz, depending on wire characteristics. If the length is longer than 250 ft., the resonant frequency will be lowered to the range of 500 kHz to 1.5 MHz. These self-resonant frequency ranges are at, or below, the high frequency components of the voltage waveform produced by the IGBT inverter. (A spectral analysis of the voltage waveform generated by inverters employing IGBTs would reveal frequency components ranging in excess of 1 to 2 MHz). Furthermore, whenever the self-resonant frequency of the conductors approximates the frequency range of the IGBT voltage waveform, the conductors themselves go into resonance. The conductor resonance then creates a

Gain, or an amplification of the voltage components at, or near, the conductor's natural resonant frequency. This results in voltage spikes at the waveform transition points. These voltage spikes can readily reach levels in excess of 2 to 2.5 times the DC voltage feeding the inverter.

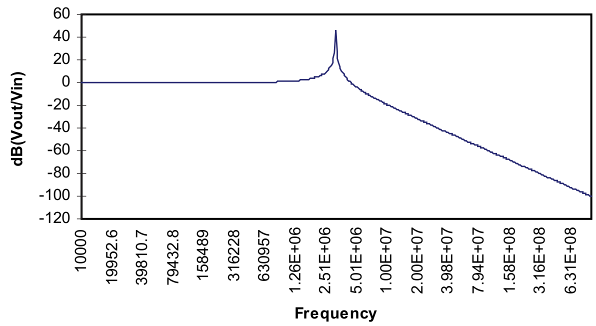


Figure 6-2: Bode Plot of 100 ft. Long Motor Leads

Voltage Overshoot

For a 480 V system, it is common to find voltage spikes at the motor terminals ranging between 1200 to 1550 V. (575/600V systems are even more vulnerable, as peak voltages are further amplified by the higher system voltage.)

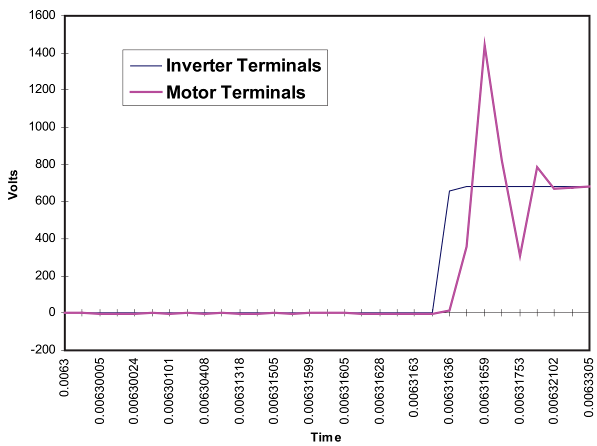


Figure 6-3: 480V Motor Terminal Peak Voltage

Also, recall that these voltage spikes can have a rise time, dV/dT, in excess of 7500 V/μs. This can have an extremely detrimental effect on the motor windings and on the insulation system, often causing premature motor failure. Most motor manufacturers believe that the life of the motor will be greatly extended by limiting both the magnitude of the voltage spikes to levels below 1000V and the dV/dT at the motor terminals to levels less than 1000 V/μs.

Motor Failures

Compare the Voltage Overshoot to a Mini-Dielectric Test

All manufacturers of motors and of other electromagnetic components, such as inductors, perform one or two dielectric tests on their equipment during the manufacturing stage in an attempt to detect any defects in the insulation system components. For 600V class equipment, these tests consist of applying a relatively high voltage, 2500 to 3000V, for a short period of time. These types of tests stress the insulation system components and, if applied too many times or for too long a period of time, damage the insulation system. When long motor leads create a voltage overshoot, each spike acts like a little dielectric test. If enough of them occur, the insulation system will fail and the motor will need to be repaired or replaced.

Insulation Punch-Through Failures

Seldom, if ever, do large motors fail due to insulation punch-through. This is because they are usually “perfect” wound, which means that the location of each turn of wire in the phase winding is precisely controlled. Therefore, the level of voltage from turn to adjacent turn is controlled. In smaller motors, however, the wire size is quite small and the number of turns is large. Usually, these motors are “random” wound and do not lend themselves to control over the proximity of adjacent turns. Therefore, it is quite possible to have two turns of wire next to each other with a high voltage potential that is close to the maximum allowable limit of the insulation system. Even in the absence of an overshoot voltage, when a high dV/dT is applied, the insulation components may experience punch-through, causing motor failure. Normally, these types of failures occur within hours or weeks of start-up.

Partial Discharge (Corona Inception) Failures

As the voltage associated with the high dV/dT increases, the likelihood of partial discharge, or “corona”, also increases. When corona is present, highly unstable ozone,O_3, is generated. This very reactive by-product then attacks the organic compounds in the insulation system. Corona can easily develop whenever the dV/dT and the resulting voltage overshoot are not controlled. Even the larger motors, whose turn-to-turn voltage can be controlled with perfect winding techniques, are vulnerable to corona. Overall, this corona effect will lead to motor failure.

Some Techniques for Correction

The addition of a Line Reactor

Applying a line reactor at the drive terminals has been attempted. Unfortunately, adding inductance merely reduces the resonant frequency of the total circuit. Because there are additional losses associated with the inductor, both in the copper and in the core, overall circuit dampening increases. This dampening may reduce the overshoot slightly, but it will also increase the duration of the overshoot voltage, applying additional stress on the motor windings.

Applying a line reactor at the motor terminals has also been attempted. Since line reactors and motors share common construction materials, line reactors applied in front of motors simply become sacrificial lambs. They will eventually fail due to the same voltage-induced stresses.

Carrier-Stripping Filters

A tuned low-pass filter can be designed to remove all carrier frequency voltages. These application-specific, custom filters were originally designed to strip low frequency carrier energy from Bipolar and Darlington transistor-based drives to limit audible motor noise. While this approach removes all frequencies above the fundamental and affords the ultimate in motor protection, it comes at a severe price. These filters are large, costly and consume large amounts of power. In addition, they reduce the fundamental voltage due to high inductor insertion losses and force the motor to draw higher fundamental currents to produce rated horsepower. Finally, the specific tuning frequency of a carrier-stripping filter greatly restricts the ability to alter carrier frequencies after installation. This limits fine-tuning of the drive application.

Voltage Clippers, Snubbers, Etc.

These energy-consuming devices must be applied at the motor terminals which is difficult in most industrial and commercial applications. They require the addition of extra junction boxes or equipment enclosures as well as alterations and additions to the conduit scheme.

The Dampened Low-Pass KLC Filter

A Benshaw KLC filter combines inductance, capacitance, and resistance to form a dampened low-pass filter with a break frequency in the range of 25 to 55 kHz.

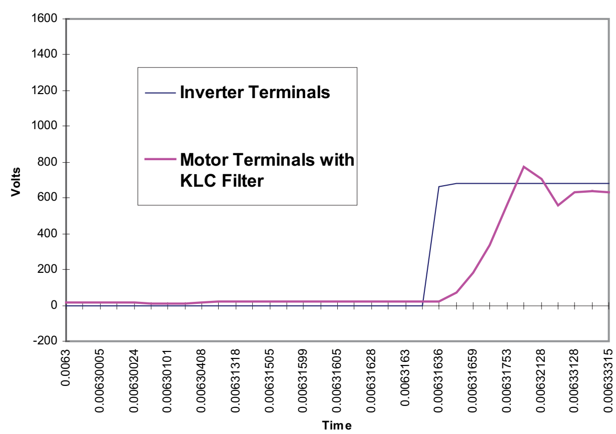


Figure 6-4: 480V Motor Terminals-Low Pass Filter

The KLC filter does not attempt to strip the entire carrier frequency. Instead, it is designed to simply slow down the steep edges of the PWM voltage waveform, (see Figure 6-5). It is not the carrier itself that produces motor failures. Rather, it is the high dV/dT (steep edge) of the PWM waveform that induces a damaging voltage overshoot. The KLC filter is specifically designed to reduce voltage waveform dV/dT. By doing so, it will also lower the dV/dTs associated frequency to levels well below the expected natural resonant wire frequency for runs ranging from 50 to 3000 ft. Consequently, the wire will no longer be able to resonate because the higher frequency components are gone, as shown below.

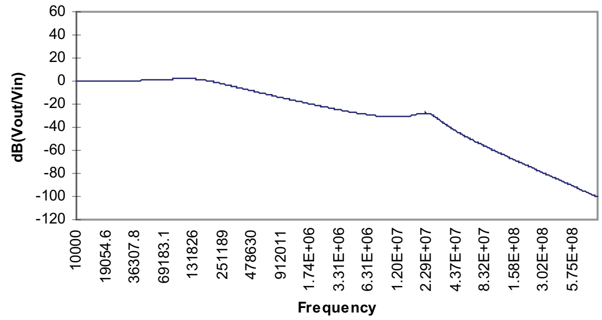
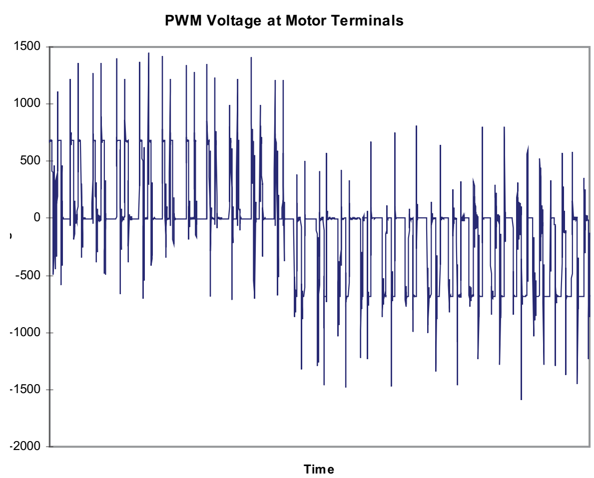


Figure 6-5: Bode Plot of 100 Ft. Motor Leads with KLC Filter

KLC's high coefficient of dampening ensures minimal overshoot on even the longest leads. Figure 6-6 offers a full cycle view of the PWM voltage measured before and after the application of KLC.



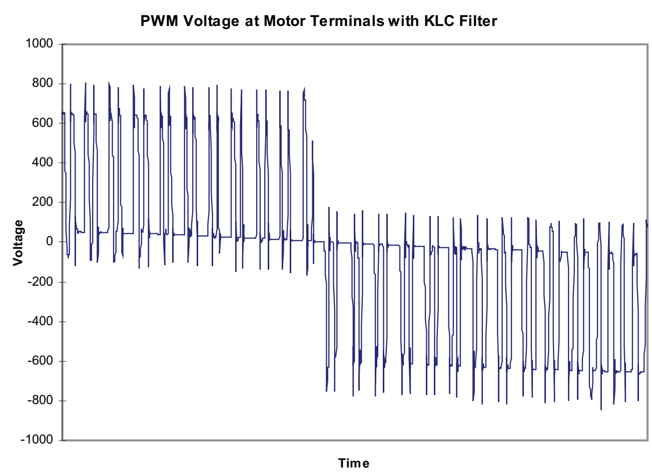


Figure 6-6: Full Cycle View of PWM Voltage Before & After KLC Application

Careful consideration was given to the selection of series inductance to minimize the insertion loss and, therefore, the voltage drop. System losses are held to well below 1% of the drive/motor rating.

Both the break frequency and the high level of dampening ensure that *KLC can be confidently applied with any drive and motor.*

Summary

Benshaw recommends that a dampened low-pass filter be applied at the terminals of an inverter any time there is a risk of motor damage due to voltage overshoot. Refer to your drive's manufacturer's operation manual for recommended maximum installation lengths and apply KLC when you either approach or exceed them.

KLC should also be considered as an after-market correction in VFD/motor installations where the motor fails prior to its anticipated life cycle and where long wire lengths exist.

Finally, KLC creates an opportunity to continue to apply cost-saving variable frequency drives in environments and applications that were previously considered inappropriate.

Avoiding Detrimental Effects of Shaft Voltages and Bearing Currents

In some applications, controls have been found to produce currents in the bearings of motors they control. At this point, there has been no conclusive study that has served to quantify the type of application most prone to bearing currents. In general, these guidelines can minimize the detrimental effects of shaft voltages and bearing currents:

1. Use a lower voltage supply (for example, 230 volts instead of 460 volts) and the appropriately rated motor and control.
2. Run the control at the lowest carrier frequency that satisfies any audible noise and temperature requirements.
3. Add a shaft grounding device to the motor. Some devices have a brush that rides on the motor shaft. Current does not go through the bearing but is instead conducted directly to ground through the brush. These brushes are especially selected to tolerate misalignment and maintain rotating contact throughout the brush's life when properly maintained.
4. Use a motor with both bearings insulated. This approach will avoid damage to the motor's bearings.

Other non-insulated bearings connected to the shaft with a conductive coupling (such as tachometers or gearboxes) may be damaged by the shaft voltage.

Insulation for bearings must provide a high impedance to high frequency signals in order to be effective against common mode voltage induced bearing currents.

5. Use non-conductive couplings for loads or devices which may be damaged by bearing currents.) Ensure that the control and motor are grounded per the manufacturers' instructions.
6. Use a filter that reduces common mode voltage.

Examples of Bearing Current Damage

Figure 6-7 shows the inner race of a bearing from a 20 horsepower motor operated on a VFD. The serration pattern is called *fluting*. The flutes are the source of audible bearing noise and reduced bearing service life.

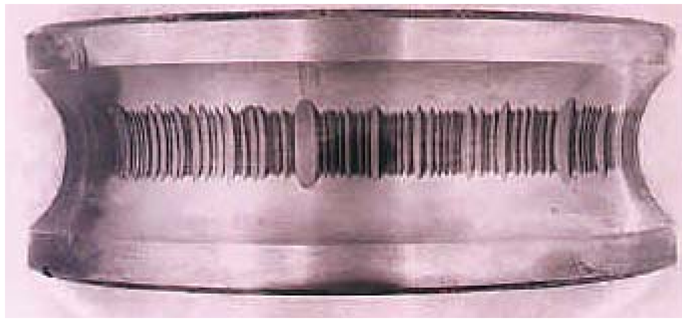


Figure 6-7: Typical "Fluting"

The image from a scanning electron microscope, Figure 6-8, shows a one-micron diameter pit in the fluted area of the bearing. It is caused by current flowing during a single discharge. As electrical discharges continue to occur the pits begin to overlap each other. Ultimately, if the bearing operates with current long enough, the groove like configurations called flutes will form.

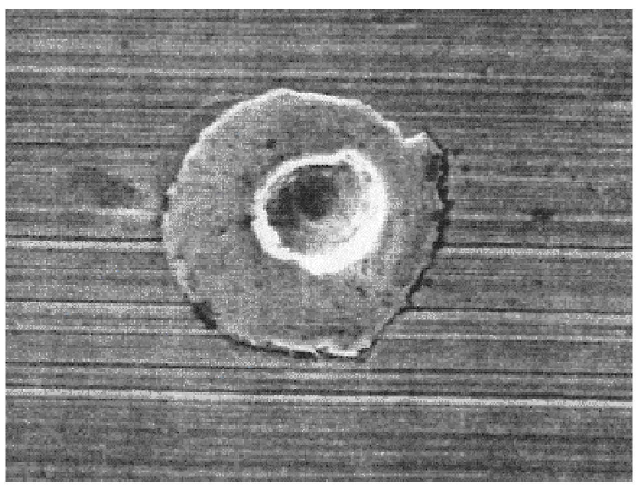


Figure 6-8: Single Discharge Pitting

Sources of Bearing Current

Bearing current will flow when voltage is developed across the bearing sufficient to break down the insulating capacity of the grease. There are several sources of this voltage:

1. Dissymetery in the magnetic circuit of a motor creates a situation that causes bearing currents. This is more common in motors greater than 75 HP. The unbalanced magnetic circuit results in unwanted time-varying circumferential flux in the motor that induces ac voltage along the length of the motor shaft. The shaft, bearings, end brackets, and outer shell form a closed circuit which may allow current to flow. If the induced voltage is sufficient to break down the grease, current will flow through the bearing.

2. A voltage can be caused by an electrostatic build up on the shaft due to friction with the driven load (such as paper on rollers). This situation does not normally lead to fluting.
3. A voltage across the bearings can be the result of common mode voltage created through the interaction of the motor and control.
4. The common mode voltage also causes current to flow from the stator winding to ground via parasitic capacitances between the winding and ground. These currents generate a radial time varying magnetic flux which links the shaft and induces voltage along its length end-to-end. Although this voltage is rooted in a different source than that caused by magnetic dissymmetries described in 1, the resulting current path is the same. In contrast to the phenomenon described in 2, these circulating currents may cause bearing problems in frame sizes smaller than 500 frame (most likely in the 400 and larger frames).

Common Mode Voltages

Controls produce adjustable frequency by switching their three outputs alternately from the positive to the negative potential rails of a DC voltage bus. The switching occurs at a high rate on modern controls, typically 1 kHz to 20 kHz. Since there is an odd number of outputs, there can be only four possible control output states: 1) two high and one low, 2) two low and one high, 3) all high, and 4) all low. Note that none of these states is balanced, resulting in a fluctuation of the motor neutral voltage with respect to ground. This voltage fluctuation is typically referred to as common mode voltage.

Unwanted current pulses are driven by fast-rising common mode voltages through unintentional (parasitic) capacitance that exists from the lead to ground. Parasitic capacitance exists between the leads and the metal conduit, for example, and between the motor's windings and its frame. Since the common mode voltage contains high frequency AC components, a current will flow into the lead and to ground through these capacitances.

Shaft Voltage and Bearing Current

A primary cause of bearing currents in motors driven by controls is common mode voltage. A capacitive coupling exists between the stator winding and the rotor surface, Figure 6-9 shows High frequency common mode voltage, produced by the control, forces current to ground through a circuit path consisting of this capacitance, the rotor, the shaft, the bearings, and the grounded end bracket.

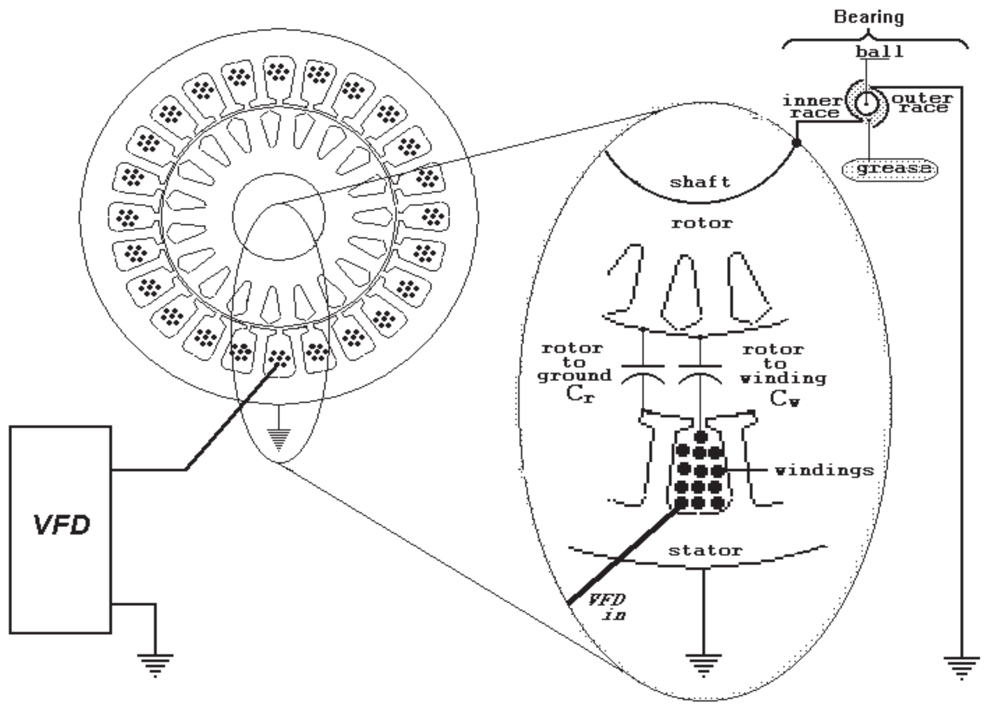


Figure 6-9: Parasitic Coupling

The Common Mode Circuit

The control forces current through the capacitor divider formed by the winding-to-rotor capacitance (C_w) and the rotor-to-ground capacitance (C_r). The result is an ac voltage on the rotor and shaft, with respect to ground. The amplitude of this voltage is proportional to the source common mode voltage at the motor terminals and the ratio of C_w to ($C_r + C_w$). (See Figure 6-10.) C_w is normally much smaller than C_r, so the shaft voltage is lower than the applied common mode voltage. The shaft voltages can reach 25 V when the control is fed with 460 V.

The balls, races and grease film in the bearing form a "switch" across C_r , capable of discharging it. If the shaft voltage reaches a high enough level, the bearing will conduct and C_r will discharge through the ball and races.

The rotor is supported by bearings with a grease film that is not normally conductive. At high speeds, an even distribution of the grease film exists, and the rotor is not in contact with the outer (grounded) bearing race. The rotor voltage is free to oscillate with respect to ground. The voltage that the grease film can support is constantly changing due to thickness, surface roughness, load, temperature, etc. When the shaft voltage reaches a level capable of breaking down the grease film, electrical conduction occurs and C_r discharges through the bearing.

The entire circuit can be simplified as shown below.

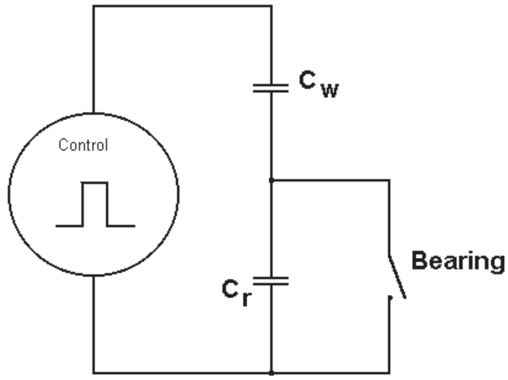


Figure 6-10: Basic Circuit Common Mode

Experimental Evidence

Figure 6-11 is an oscillograph of the shaft voltage on a 20 HP 6-pole induction motor excited by a control. Note the shaft voltage is an ac voltage and continues to vary in amplitude while no current flows through the bearings.

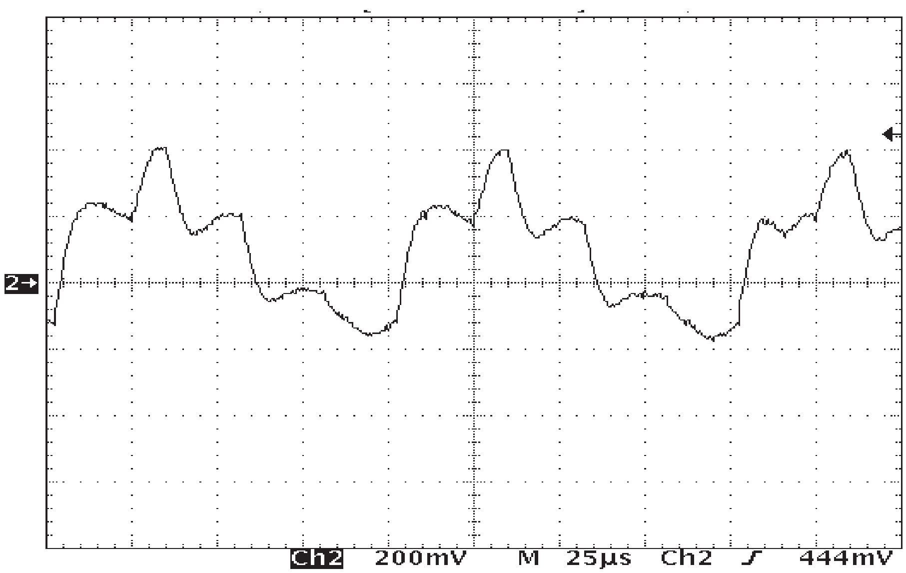


Figure 6-11: Shaft Voltage With Bearing Current

Eventually the voltage exceeds the value that the grease can support and it breaks down. Then the bearing conducts and the rotor and shaft are discharged. The oscillograph in Figure 6-12 shows such a discharge. Note that the shaft voltage collapses at the instant of discharge. Such a discharge can cause a pit such as the one shown in Figure 6-8.

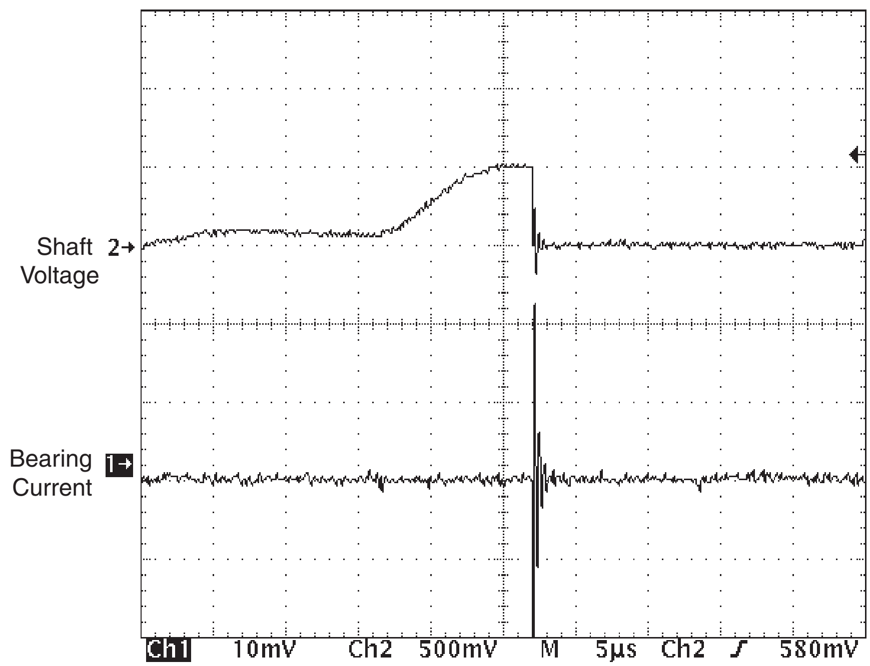


Figure 6-12: Shaft Voltage With Bearing Current

Shaft Mounted Accessories

Once there is voltage on the shaft, a current may flow in any bearing electrically connected to the shaft system, such as the bearing in a tachometer, encoder, or gearbox. Care should be taken to ensure that possible flow of bearing currents through those devices is prevented or at least minimized.

Load Reactors and Filters

It is possible to reduce the peak voltage at the motor's terminals by using a filter or reactor connected between the control and the motor. Successful operation depends on selecting the correct size and on the high frequency performance of the device. The manufacturer should be consulted for the proper application of such filters. This may require measurements of the peak voltage at the motor terminals both before and after installation of a filter.

Such filters and reactors may have an effect on reducing common mode voltage.

Multiple Motors

Motors are not typically line-started when used with a control; the control and motor are usually started together. When started in this manner, the motor is not subjected to the inrush current associated with an across-the-line start. When more than one motor is used with a control there may be a requirement to connect additional motors while the control is operating. Under this condition of starting a motor while the control is operating other motors, the control must provide the inrush current associated with the motor being connected. Under this condition the control may need to be oversized to provide the required starting current of the motor being started when the control is already operating.

INSTALLATION & TROUBLESHOOTING RVSS

7

In this chapter, you will learn:

- Installation and Troubleshooting Techniques for Reduced Voltage Solid State Starters (RVSS)

Installation

Before You Start: Installation Precautions

Inspection

Before storing or installing the RediStart MX Series Starter, thoroughly inspect the device for possible shipping damage. Upon receipt:

- Remove the starter from its package and inspect exterior for shipping damage. If damage is apparent, notify the shipping agent and your sales representative.
- Open the enclosure and inspect the starter for any apparent damage or foreign objects. Ensure that all of the mounting hardware and terminal connection hardware is properly seated, securely fastened, and undamaged.
- Ensure all connections and wires are secured.
- Read the technical data label affixed to the starter and ensure that the correct horsepower and input voltage for the application has been purchased.

General Information

Installation of some models may require halting production during installation. If applicable, ensure that the starter is installed when production can be halted long enough to accommodate the installation. Before installing the starter, ensure:

- The wiring diagram (supplied separately with the starter) is correct for the required application.
- The starter is the correct current rating and voltage rating for the motor being started.
- All of the installation safety precautions are followed.
- The correct power source is available.
- The starter control method has been selected.
- The connection cables have been obtained (lugs) and associated mounting hardware.
- The necessary installation tools and supplies are procured.
- The installation site meets all environmental specifications for the starter NEMA/CEMA rating.
- The motor being started has been installed and is ready to be started.
- Any power factor correction capacitors (PFCC) are installed on the power source side of the starter and not on the motor side.

Failure to remove power factor correction or surge capacitors from the load side of the starter will result in serious damage to the starter that will not be covered by the starter warranty. The capacitors must be connected to the line side of the starter. The up-to-speed (UTS) contact can be used to energize the capacitors after the motor has reached full speed.

Safety Precautions

To ensure the safety of the individuals installing the starter, and the safe operation of the starter, observe the following guidelines:

- Ensure that the installation site meets all of the required environmental conditions (Refer to "Site Preparation" on page 7-3).

- LOCK OUT ALL SOURCES OF POWER.
- Install circuit disconnecting devices (i.e., circuit breaker, fused disconnect or non-fused disconnect) if they were not previously installed by the factory as part of the package.
- Install short circuit protection (i.e., circuit breaker or fuses) if not previously installed by the factory as part of the package.
- Consult Power Ratings for the fault rating.
- Follow all NEC (National Electrical Code) and/or C.S.A. (Canadian Standards Association) standards or Local Codes as applicable.
- Remove any foreign objects from the interior of the enclosure, especially wire strands that may be left over from installation wiring.
- Ensure that a qualified electrician installs wiring.
- Ensure that the individuals installing the starter are wearing ALL protective eye wear and clothing.
- Ensure the starter is protected from debris, metal shavings and any other foreign objects.

The opening of the branch circuit protective device may be an indication that a fault current has been interrupted. To reduce the risk of electrical shock, current carrying parts and other components of the starter should be inspected and replaced if damaged.

Site Preparation

General Information

Before the starter can be installed, the installation site must be prepared. The customer is responsible for:

- Providing the correct power source
- Providing the correct power protection
- Selecting the control mechanism
- Obtaining the connection cables, lugs and all other hardware
- Ensuring the installation site meets all environmental specifications for the enclosure NEMA rating
- Installing and connecting the motor

Power Cables

The power cables for the starter must have the correct NEC/CSA current rating for the unit being installed. Depending upon the model, the power cables can range from a single #14 AWG conductor to four 750 MCM cables. (Consult local and national codes for selecting wire size).

Site Requirements

The installation site must adhere to the applicable starter NEMA/CEMA rating. For optimal performance, the installation site must meet the appropriate environmental and altitude requirements.

EMC Installation Guidelines

In order to help our customers comply with European electromagnetic compatibility standards, Benshaw Inc. has developed the following guidelines.

This product has been designed for Class A equipment. Use of the product in domestic environments may cause radio interference, in which case the installer may need to use additional mitigation methods.

Enclosure. Install the product in a grounded metal enclosure.

Grounding. Connect a grounding conductor to the screw or terminal provided as standard on each controller. Refer to layout/power wiring schematic for grounding provision location.

Wiring. Refer to "Wiring Practices" on page 7-5.

Filtering. To comply with Conducted Emission Limits (CE requirement), a high voltage (1000V or greater) 0.1 uF capacitor should be connected from each input line to ground at the point where the line enters the cabinet.

Use of Power Factor Capacitors

Power factor correction capacitors and surge capacitors CAN NOT be connected between the starter and the motor. These devices can damage the SCRs during ramping. These devices appear like a short circuit to the SCR when it turns on, which causes a di/dt level greater than the SCR can handle. If used, power factor correction capacitors or surge capacitors must be connected ahead of the starter and sequenced into the power circuit after the start is completed. A programmable relay can be configured as an up-to-speed (UTS) relay and then used to pull-in a contactor to connect the capacitors after the motor has reached full speed.

❖ ***Note:*** *If the motor manufacturer supplies surge capacitors they must be removed before starting.*

Use of Electro-Mechanical Brakes

If an electro-mechanical brake is used with the starter, it must be powered from the line side of the starter to ensure full voltage is applied to the brake during a start so it will properly release. A programmable relay can be configured as a run relay and then used to pull-in a contactor to power the brake whenever the starter is providing power to the motor.

Reversing Contactor

If the application requires a reversing contactor, it should be connected on the output side (load) of the soft starter. The contactor must be closed before starting the soft starter. The soft starter must be off before switching the direction of the reversing contactor. The reversing contactor must never be switched while the soft starter is operating.

Mounting Considerations

Bypassed Starters

Provisions should be made to ensure that the average temperature inside the enclosure never rises above 50°C. If the temperature inside the enclosure is too high, the starter can be damaged or the operational life can be reduced.

Non-Bypassed Starters

Provisions should be made to ensure that the temperature inside the enclosure never rises above 50°C. If the temperature inside the enclosure is too high, the starter can be damaged or the operational life can be reduced. As a general rule of thumb, the following ventilation guidelines can be followed.

Table 7-1: Ventilation Requirements

Current Range	Bottom of Enclosure	Top of Enclosure
< 200 amps	Fans or grills depending on enclosure size	
200 to 300 amps	2 x 4” grills (12 sq. in.)	2 x 4” grills (12 sq.in.)
301 to 400 amps	1 x 4” fan (115 cfm)	2 x 4” grills (12 sq.in.)
401 to 600 amps	2 x 4” fan (230 cfm)	2 x 6” grills (28 sq.in.)
601 to 700 amps	2 x 6” fan (470 cfm)	2 x 6” grills (28 sq.in.)
> 700 amps	Consult factory	Consult Factory

The starter produces 4 watts of heat per amp of current and 26 square inches of enclosure surface is required per watt of heat generation. Contact Benshaw and ask for the enclosure sizing technical note for more information concerning starters in sealed enclosures. Benshaw supplies starters under 124 amps non-bypassed, with the heat sink protruding from the back of the enclosure. This allows a small enclosure size while still maintaining the cooling capability of the starter.

Wiring Considerations

Wiring Practices

When making power and control signal connections, the following should be observed:

- Never connect input AC power to the motor output terminals T1/U, T2/V, or T3/W.
- Power wiring to the motor must have the maximum possible separation from all other wiring. Do not run control wiring in the same conduit; this separation reduces the possibility of coupling electrical noise between circuits. Minimum spacing between metallic conduits containing different wire groups should be three inches (8cm).
- Minimum spacing between different wiring groups in the same tray should be six inches.
- Wire runs outside an enclosure should be run in metallic conduit or have shielding/armor with equivalent attenuation.
- Whenever power and control wiring cross it should be at a 90 degrees angle.
- Different wire groups should be run in separate conduits.
- With a reversing application, the starter must be installed in front of the reversing contactors.

❖ ***Note:*** *Local electrical codes must be adhered to for all wiring practices.*

Considerations for Control and Power Wiring

Control wiring refers to wires connected to the control terminal strip that normally carry 24V to 115V and Power wiring refers to wires connected to the line and load terminals that normally carries 200VAC - 600VAC respectively. Select power wiring as follows:

- Use only UL or CSA recognized wire.
- Wire voltage rating must be a minimum of 300V for 230VAC systems and 600V (Class 1 wire) for 460VAC and 600VAC systems.

- Grounding must be in accordance with NEC, CEC or local codes. If multiple starters are installed near each other, each must be connected to ground. Take care to not form a ground loop. The grounds should be connected in a STAR configuration.
- Wire must be made of copper and rated 60/75°C for units 124 Amps and below. Larger amp units may use copper or aluminum wire.

Refer to NEC table 310-16 or local codes for proper wire selection.

Considerations for Signal Wiring

Signal wiring refers to the wires connected to the control terminal strip that are low voltage signals, below 15V.

- Shielded wire is recommended to prevent electrical noise interference from causing improper operation or nuisance tripping.
- Signal wire rating should carry as high of a voltage rating as possible, normally at least 300V.
- Routing of signal wire is important to keep as far away from control and power wiring as possible.

Meggering a Motor

If the motor needs to be meggered, remove the motor leads from the starter before conducting the test. Failure to comply may damage the SCRs and WILL damage the control board, which WILL NOT be replaced under warranty.

High Pot Testing

If the starter needs to be high pot tested, perform a DC high pot test. The maximum high point voltage must not exceed 2.0 times rated RMS voltage + 1000VAC (High pot to 75% of Factory). Failure to comply WILL damage the control board, which WILL NOT be replaced under warranty. An example to find the high point voltage is (2.0 * rated RMS voltage + 1000) * 0.75.

Power and Control Drawings for Bypassed and Non Bypassed Power

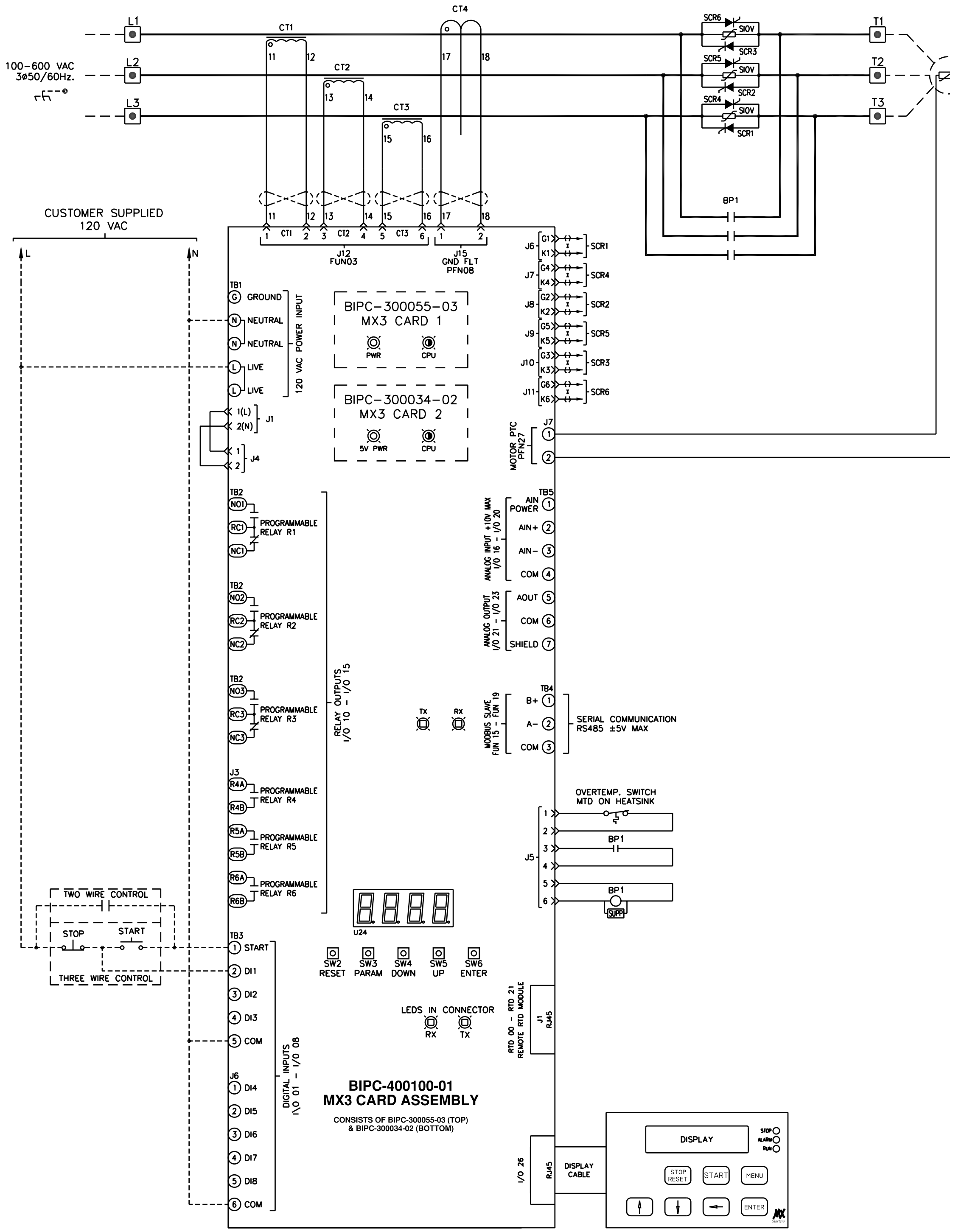


Figure 7-1: Power Schematic for RB3 Low HP

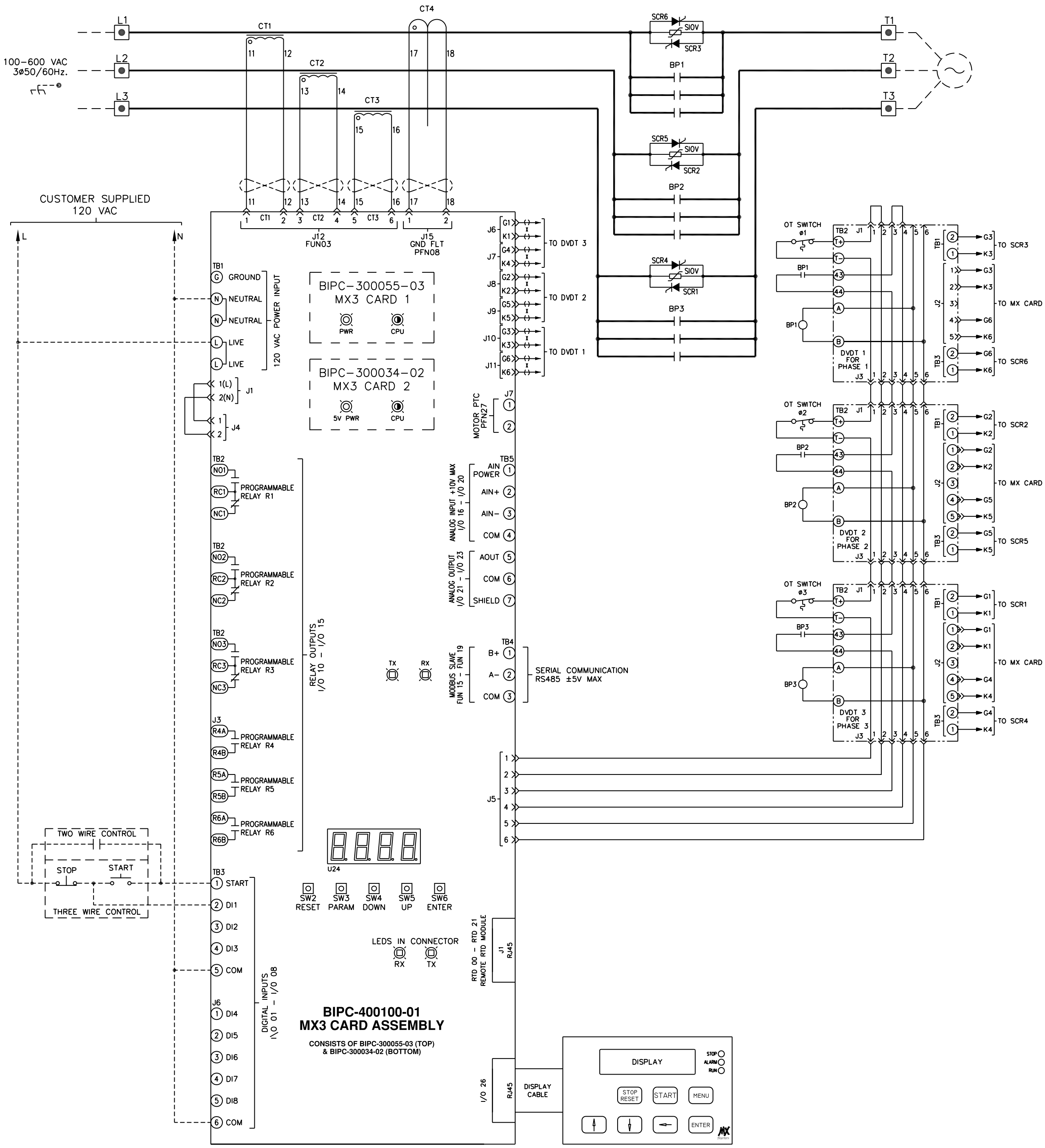


Figure 7-2: Power Schematic for RB3 High HP

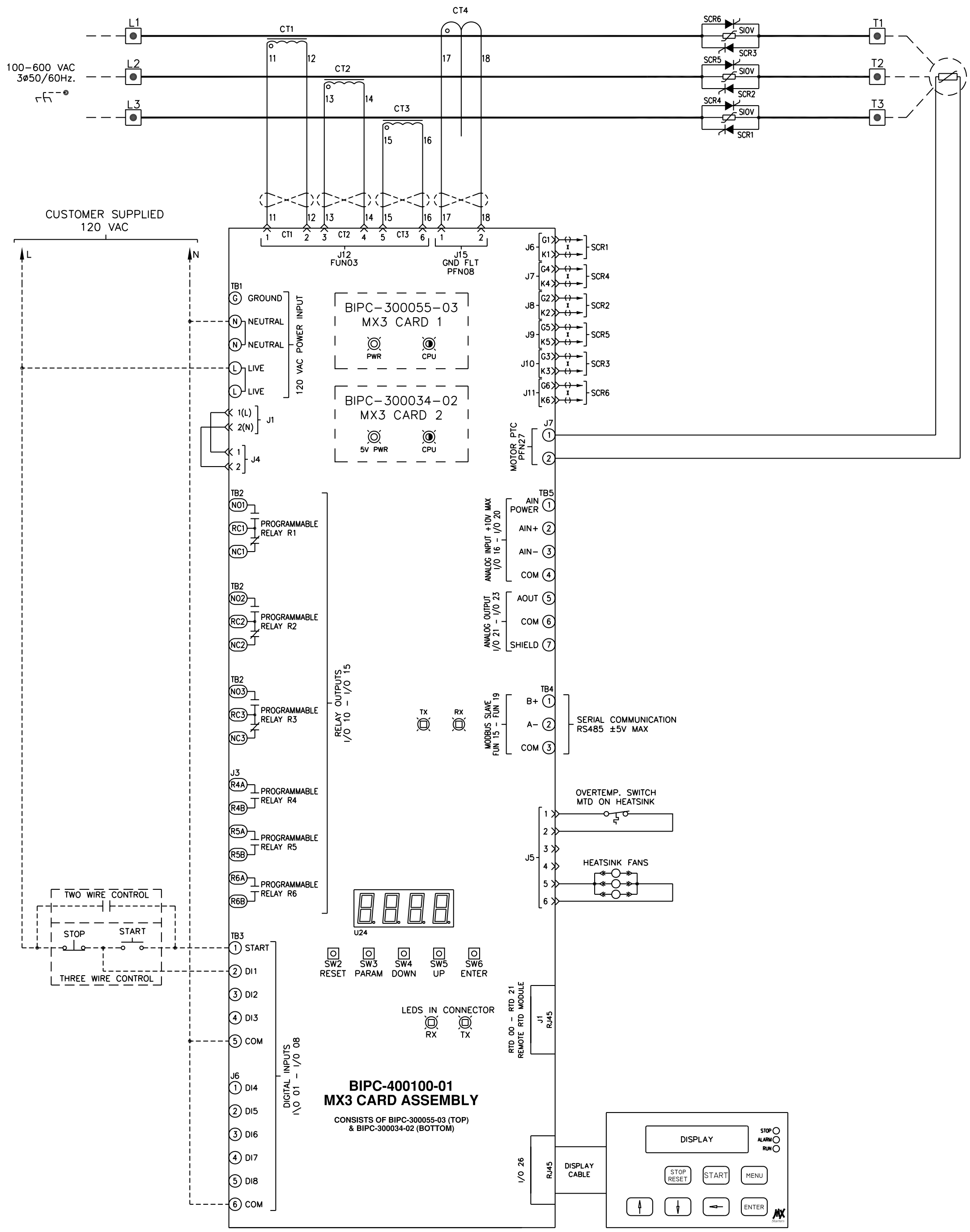


Figure 7-3: Power Schematic for RC3

Power Wiring

Recommended Incoming Line Protection

Fuses or Circuit Breaker

Input Line Requirements

The input line source needs to be an adequate source to start the motor, generally 2 times the rating of the motor FLA. (This may not apply in some cases such as being connected to a generator).

Recommended Wire Gauges

The wire gauge selection is based on the FLA of the motor. Refer to NEC table 310-16 or CEC Part 1, Table 2 or local code requirements for selecting the correct wire sizing. Ensure appropriate wire derating for temperature is applied. If more than three current carrying conductors are in one conduit, ensure NEC table 310.15(B)(2) or CEC Part 1 Table 5C is adhered to. In some areas local codes may take precedence over the NEC. Refer to your local requirements.

Power Wire Connections

Attach the motor cables:

- Use the T1, T2 and T3 terminals. Use lugs/crimps or terminals. (Lugs and Crimps are to be provided by the user)

Attach the power source cables:

- Use the L1, L2 and L3 terminals. Use lugs/crimps or terminals (Lugs and Crimps are to be provided by the user).

Motor Lead Length

The standard starter can operate a motor with a maximum of 2000 feet of properly sized cable between the “T” leads of the starter and that of the motor. For wire runs greater than 2000 feet contact Benshaw Inc. for application assistance. If shielded cable is used, consult factory for recommended length.

Compression Lugs

The following is a list of the recommended crimp-on wire connectors manufactured by Penn-Union Corp. for copper wire.

Table 7-2: Single Hole Compression Lugs

Wire Size	Part #	Wire Size	Part #
1/0	BLU-1/0S20	500 MCM	BLU-050S2
2/0	BLU-2/0S4	600 MCM	BLU-060S1
3/0	BLU-3/0S1	650 MCM B	LU-065S5
4/0	BLU-4/0S1	750 MCM	BLU-075S
250 MCM	BLU-025S	800 MCM	BLU-080S
300 MCM	BLU-030S	1000 MCM	BLU-100S
350 MCM	BLU-035S	1500 MCM	BLU-150S
400 MCM	BLU-040S4	2000 MCM	BLU-200s
450 MCM	BLU-045S1		

Table 7-3: Two Hole Compression Lugs

Wire Size	Part #	Wire Size	Part #
1/0	BLU-1/0D20	500 MCM	BLU-050D2
2/0	BLU-2/0D4	600 MCM	BLU-060D1
3/0	BLU-3/0D1	650 MCM	BLU-065D5
4/0	BLU-4/0D1	750 MCM	BLU-075D
250 MCM	BLU-025D	800 MCM	BLU-080D
300 MCM	BLU-030D	1000 MCM	BLU-100D
350 MCM	BLU-035D	1500 MCM	BLU-150D
400 MCM	BLU-040D4	2000 MCM	BLU-200D
450 MCM	BLU-045D1		

Torque Requirements for Power Wiring Terminations

Table 7-4: Slotted Screws and Hex Bolts

Wire size installed in conductor		Tightening torque, pound-inches (N-m)							
		Slotted head NO. 10 and larger				Hexagonal head-external drive socket wrench			
AWG or kcmil)	(mm2	Slot width-0.047 inch (1.2mm) or less and slot length ¼ inch (6.4mm) or less		Slot width-over 0.047 inch (1.2mm) or slot length – over ¼ inch (6.4mm) or less		Split- bolt connectors		Other connectors	
18 – 10	(0.82 – 5.3)	20	(2.3)	35	(4.0)	80	(9.0)	75	(8.5)
8	(8.4)	25	(2.8)	40	(4.5)	80	(9.0)	75	(8.5)
6 – 4	(13.3 – 21.2)	35	(4.0)	45	(5.1)	165	(18.6)	110	(12.4)
3	(26.7)	35	(4.0)	50	(5.6)	275	(31.1)	150	(16.9)
2	(33.6)	40	(4.5)	50	(5.6)	275	(31.1)	150	(16.9)
1	(42.4)	—	—	50	(5.6)	275	(31.1)	150	(16.9)
1/0 – 2/0	(53.5 – 64.4)	—	—	50	(5.6)	385	(43.5)	180	(20.3)
3/0 – 4/0	(85.0 – 107.2)	—	—	50	(5.6)	500	(56.5)	250	(28.2)
250 – 350	(127 – 177)	—	—	50	(5.6)	650	(73.4)	325	(36.7)
400	(203)	—	—	50	(5.6)	825	(93.2)	375	(36.7)
500	(253)	—	—	50	(5.6)	825	(93.2)	375	(42.4)
600 – 750	(304 – 380)	—	—	50	(5.6)	1000	(113.0)	375	(42.4)
800 – 1000	(406 – 508)	—	—	50	(5.6)	1100	(124.3)	500	(56.5)
1250 – 2000	(635 – 1010)	—	—	—	—	1100	(124.3)	600	(67.8)

❖ ***Note:*** *For a value of slot width or length not corresponding to those specified above, the largest torque value associated with the conductor size shall be marked. Slot width is the nominal design value. Slot length is measured at the bottom of the slot.*

⚠ WARNING

HAZARD OF ELECTRIC SHOCK, EXPLOSION, OR ARC FLASH

Only qualified personnel familiar with low voltage equipment are to perform work described in this set of instructions.

Apply appropriate personal protective equipment (PPE) and follow safe electrical work practices. See NFPA 70E.

Turn off all power before working on or inside equipment.

Use a properly rated voltage sensing device to confirm that the power is off.

Before performing visual inspections, tests, or maintenance on the equipment, disconnect all sources of electric power.

Assume that circuits are live until they have been completely de-energized, tested, and tagged. Pay particular attention to the design of the power system. Consider all sources of power, including the possibility of backfeeding.

Replace all devices, doors, and covers before turning on power to this equipment.

⚠ WARNING

Failure to follow these instructions will result in death or serious injury.

Table 7-5: Socket size across flats Tightening torque

Socket size across flats		Tightening torque	
inches	**(mm)**	**Pound-inches**	**(N-m)**
1/8	(3.2)	45	(5.1)
5/32	(4.0)	100	(11.3)
3/16	(4.8)	120	(13.6)
7/32	(5.6)	150	(16.9)
1/4	(6.4)	200	(22.6)
5/16	(7.9)	275	(31.1)
3/8	(9.5)	275	(42.4)
1/2	(12.7)	500	(56.5)
9/16	(14.3)	600	(67.8)

❖***Note:*** *For screws with multiple tightening means, the largest torque value associated with the conductor size shall be marked. Slot length shall be measured at the bottom of the slot.*

Current Transformers

CT Mounting

For starters larger than 124 amps, the CTs are shipped loose from the power stack and need to be mounted on the power wiring. Thread the motor or incoming lead through the CT with the polarity mark towards the line side. (The polarity marks may be a white or yellow dot, an “X” on the side of the CT, or the white wire.) Each phase has its own CT. The CT must then be attached to the power wiring, at least three inches from the power wire lugs, using two tie-wraps.

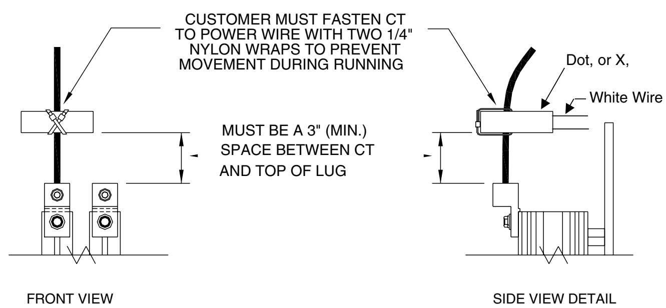


Figure 7-4: Typical CT Mounting

CT Polarity

The CT has a polarity that must be correct for the starter to correctly measure Watts, kW Hours, Power Factor, and for the Power and TruTorque motor control functions to operate properly.

Each CT has a dot on one side of the flat surfaces. This dot, normally white in color, must be facing in the direction of the line.

CT1 must be on Line L1, CT2 must be on Line L2, CT3 must be on Line L3.

Zero Sequence Ground Fault Current Transformer

The Zero Sequence Ground Fault CT can be installed over the three phase conductors for sensitive ground current detection or for use with high resistance grounded systems.

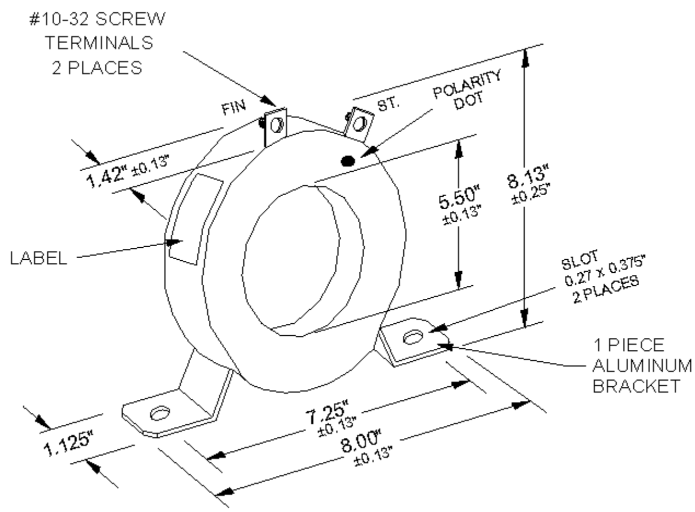


Figure 7-5: BICT 2000/1-6 Mechanical Dimension

The correct installation of the current transformer on the motor leads is important. The shield ground wire should also be passed through the CT window if the motor conductors use shielded cable. Otherwise, capacitive coupling of the phase current into the cable shield may be measured as ground fault current. See Figure 7-6 and Figure 7-7 for proper installation.

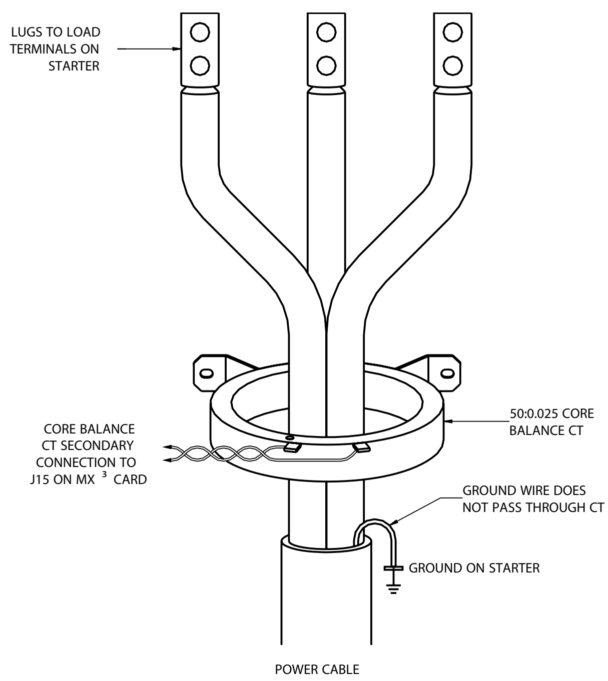


Figure 7-6: Zero Sequence CT Installation Using Unshielded Cable

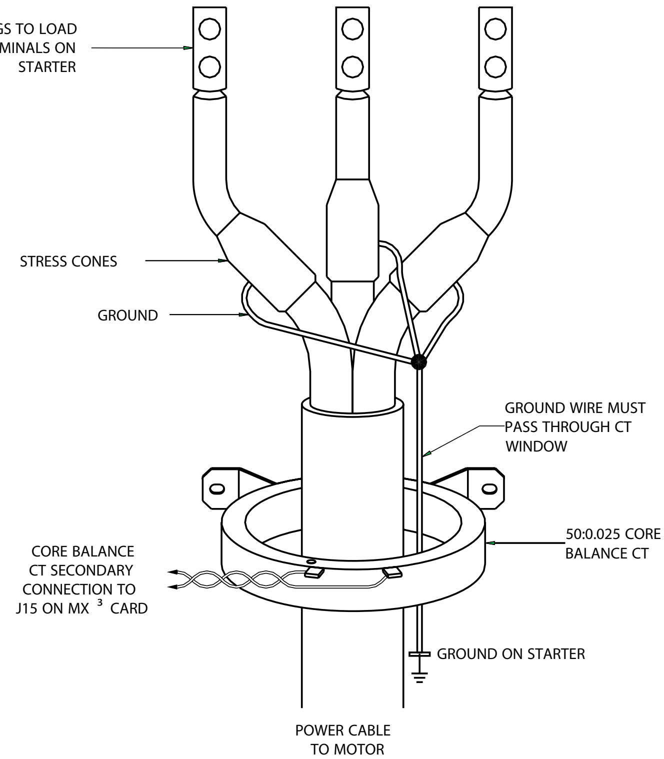


Figure 7-7: Zero Sequence CT Installation Using Shielded Cable

Control Card Layout

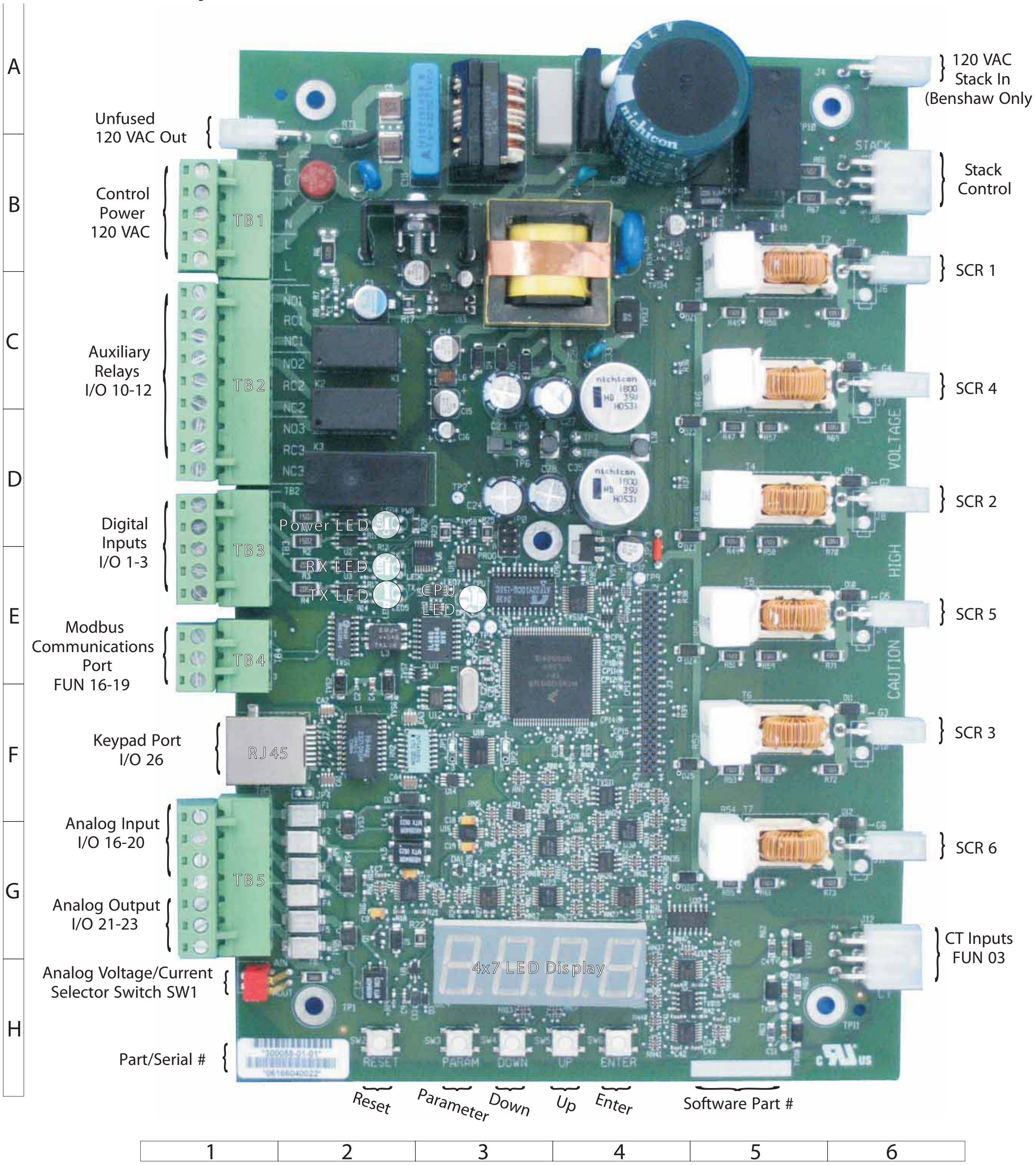


Figure 7-8: Control Card Layout

I/O Card Layout

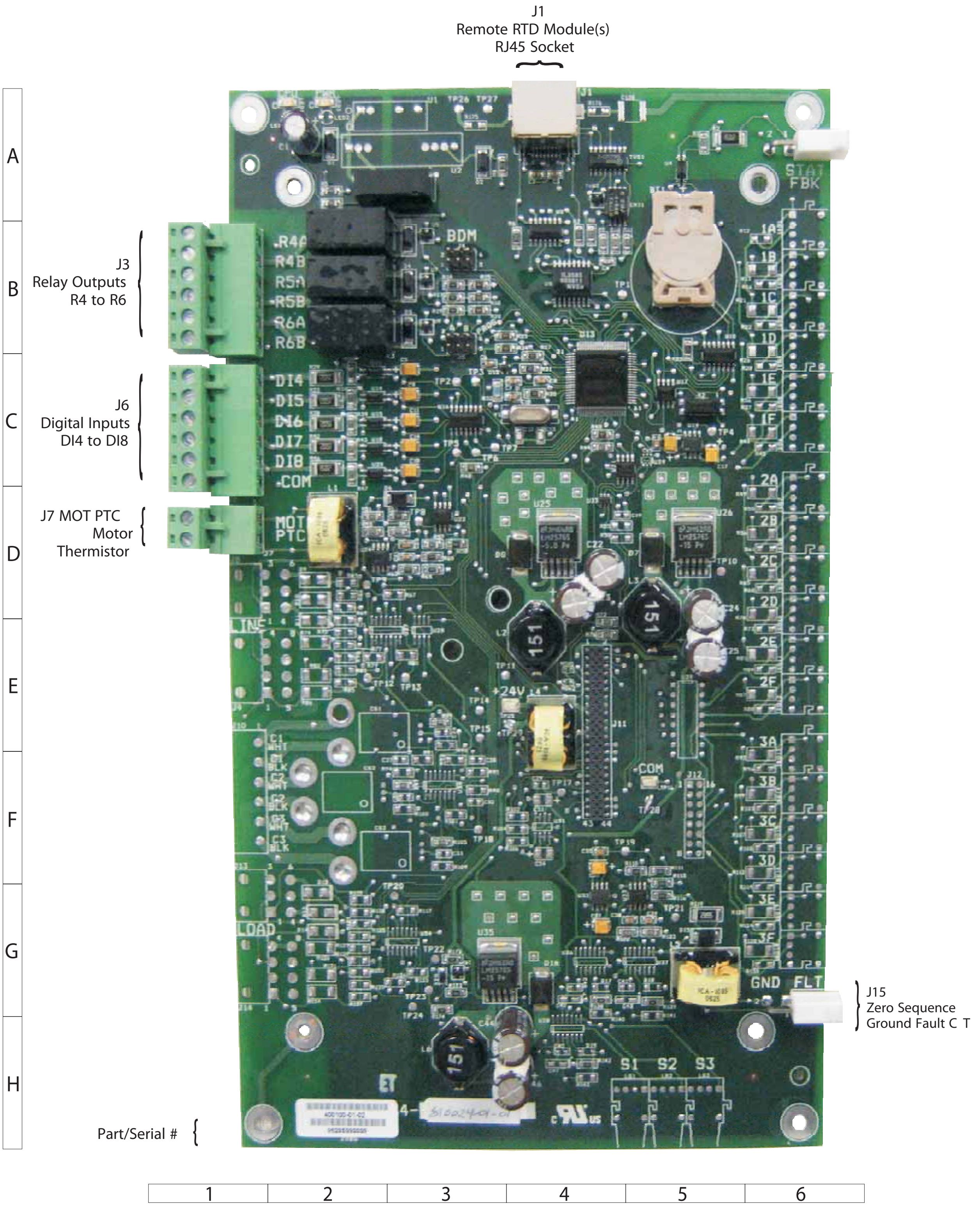


Figure 7-9: I/O Card Layout

Terminal Block Layout

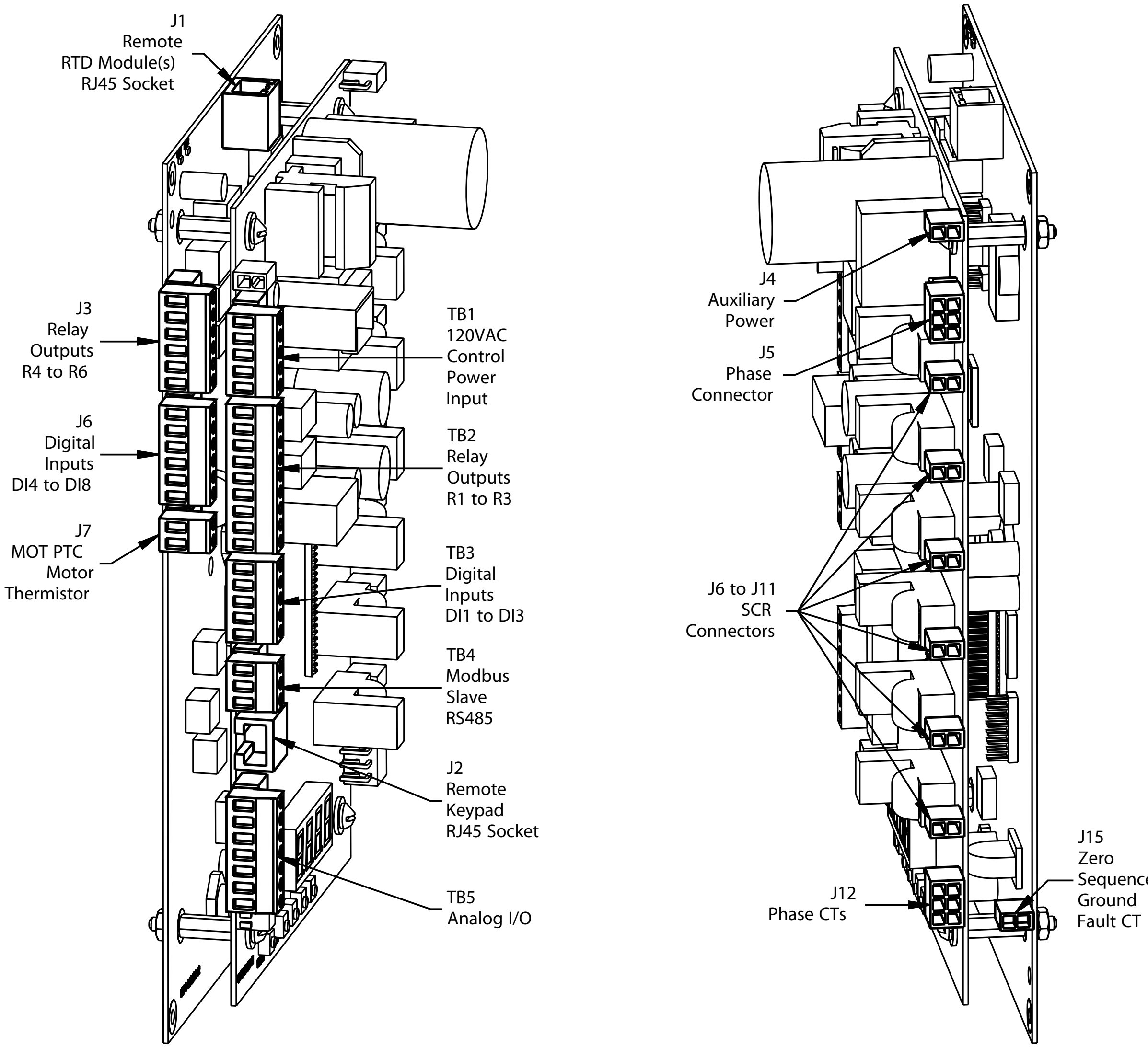


Figure 7-10: Terminal Block Layout

Control Wiring

Control Power

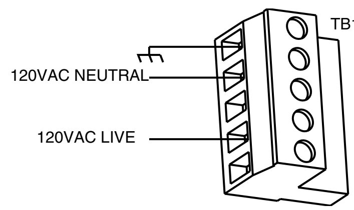


Figure 7-11: Control Power Wiring Example

The 120VAC control power is supplied to TB1. The connections are as follows:

1	Ground
2.	Neutral
3	Neutral
4	Line (120VAC)
5	Line (120VAC

Output Relays

TB2 is for output relays R1, R2 and R3. These relays connect as follows:

1	NO1: Relay 1 normally open
2	RC1:Relay 1 common
3	NC1:Relay 1 normally closed
4	NO2: Relay 2 normally open
5	RC2:Relay 2 common
6	NC2:Relay 2 normally closed
7	NO3:Relay 3 normally open
8	RC3:Relay 3 common
9	NC3:Relay 3 normally closed

Terminal block J3 is for output relays R4, R5 and R6. These relays connect as follows:

1	R4A: Relay 4 common
2	R4B:Relay 4 open
3	R5A: Relay 5 common
4	R5B: Relay 5 open
5	R6A:Relay 6 common
6	R6B: Relay 6 open

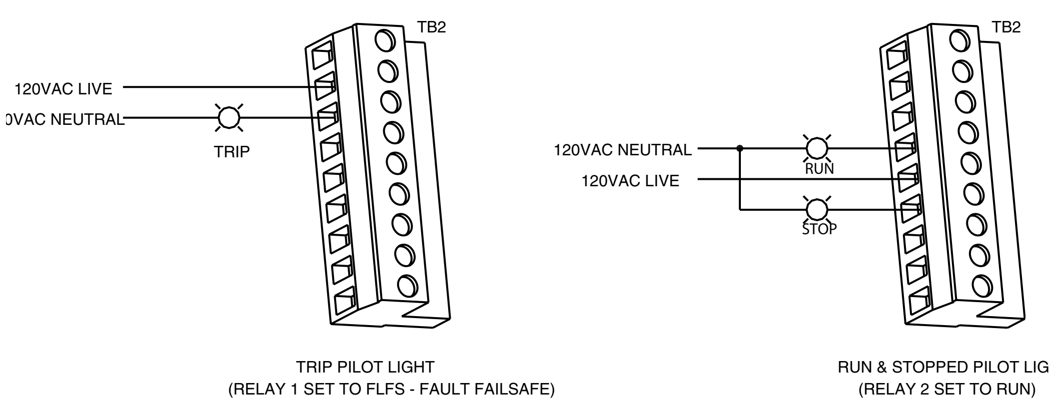


Figure 7-12: Relay Output Configuration (I/O 10-15)

Digital Input

TB3 is for digital inputs Start, DI1, DI2 and DI3. These digital inputs use 120VAC. These digital inputs connect as follows:

1	Start: Start Input
2	DI1: Digital Input 1
3	DI2: Digital Input 2
4	DI3: Digital Input 3
5	COM: 120VAC neutral

Terminal block J6 is for digital inputs DI4 to DI8. These digital inputs use 120VAC. These digital inputs connect as follows:

1	DI4: Digital input 4
2	DI5: Digital input 5
3	DI6: Digital input 6
4	DI7: Digital input 7
5	DI8: Digital input 8
6	Com: 120 VAC neutral

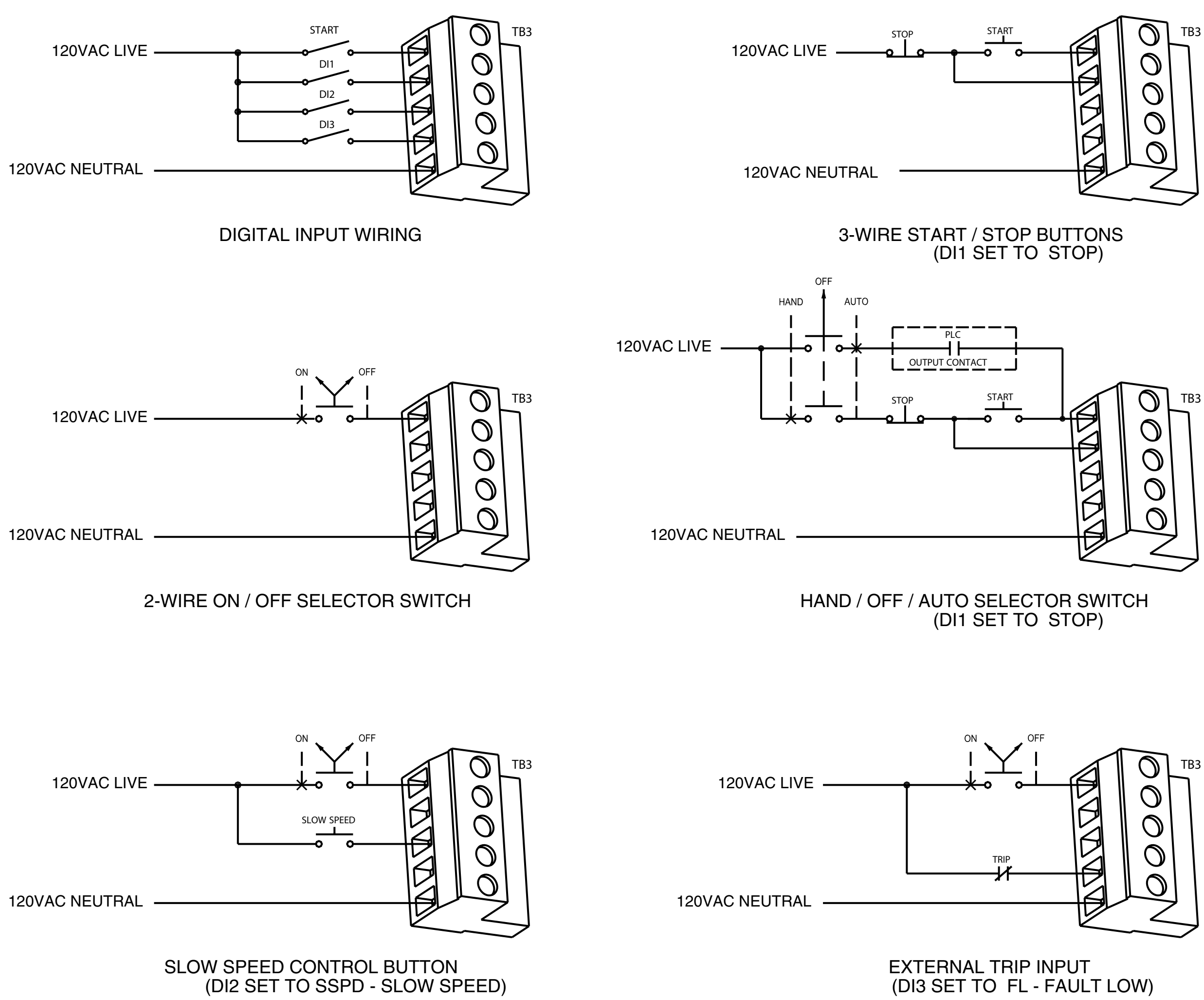


Figure 7-13: Digital Input Wiring Examples

Analog Input

The analog input can be configured for voltage or current loop. The input is shipped in the voltage loop configuration unless specified in a custom configuration. Below TB5 is SW1-1. When the switch is in the on position, the input is current loop. When off, it is a voltage input. The control is shipped with the switch in the off position.

❖***Note:*** *The analog input is a low voltage input, maximum of 15VDC. The input will be damaged if control power (115VAC) or line power is applied to the analog input.*

The terminals are as follows:

1	+10VDC Power (for POT)
2	+ input
3	- input
4	common
7	shield

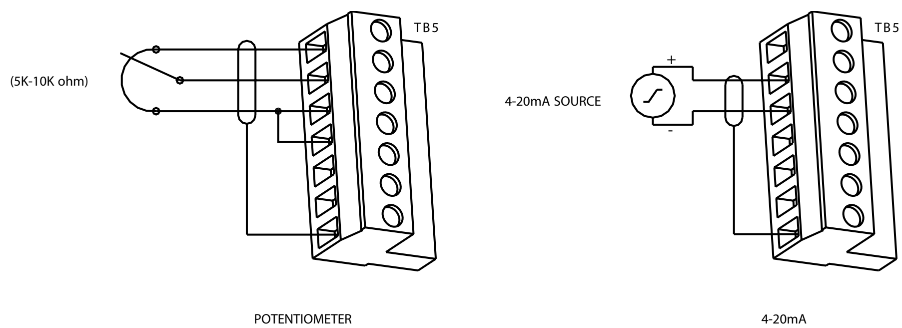


Figure 7-14: Analog Input Wiring Examples

Analog Output

The analog output can be configured for Voltage or Current loop. The output is shipped in the Voltage loop configuration unless specified in a custom configuration. Below TB5 is SW1-2. When the switch is in the off position, the output is current. When on, it is a Voltage loop output. The control is shipped with the Switch on.

❖***Note:*** *The analog output is a low voltage output, maximum of 15VDC. The output will be damaged if control power (115VAC) or line power is applied to the analog output.*

The terminals are as follows:

5	analog output
6	common
7	shield

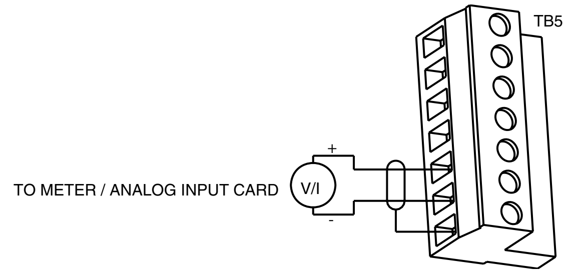


Figure 7-15: Analog Output Wiring Example

SW1 DIP Switch

The SW1 DIP switch on the card
changes the analog input and analog output between 0-10V or 0-20mA. Figure 7-16 shows how to adjust the switch to select the desired signal.

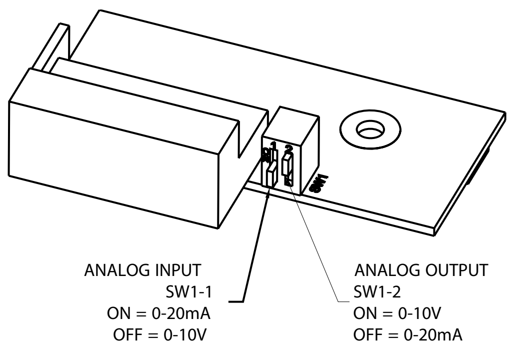


Figure 7-16: SW1 DIP Switch Settings

Motor PTC

Terminal block J7 is for a PTC (positive temperature co-efficient) motor thermistor. This input is designed to use standard DIN 44081 or

DIN 44082 thermistors. The specifications of the input are as follows;

- Trip resistance 3.5K, ± 300 Ohms.
- Reset resistance 1.65K, ± 150 Ohms.
- Open terminal voltage is 15V.
- PTC voltage at 4Kohms = 8.55v. (>7.5V)
- Response time adjustable between 1 and 5 seconds.
- Maximum cold resistance of PTC chain = 1500 Ohms.

An example of the thermistor wiring is shown below.

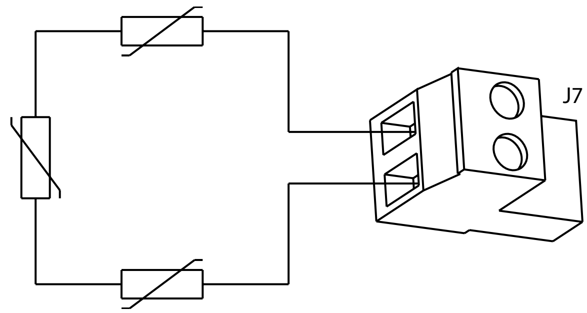


Figure 7-17: PTC Thermistor Wiring

RTD Module Connector

Connector J1 is for the connection of Benshaw Remote RTD Modules. These modules can be mounted at the motor to reduce the length of the RTD leads. The connector is a standard RJ-45. The wires connect as follows;

4	B(+)
5	A(-)
8	common

Remote LCD Keypad/Display

The display has a NEMA 13 / IP65 service rating. The display is available in 2 versions, a small display as P/N KPMX3SLCD and large display as P/N KPMX3LLCD.

Remote Display. The LCD keypad is mounted remotely from the MX^3 Control via a straight through display cable which connects between the MX^3 RJ45 terminal and remote display's RJ45 terminal.

Installing Display. The remote display is installed as follows:

- Install the gasket onto the display
- Insert the display through the door cutout
- Insert the mounting clips into the holes in each side of the display
- Tighten the mounting clips until they hold the display securely in place. Torque requirements for the display screen is 0.7 NM (6.195 in lbs)
- Plug the cable into the display connector on the MX^3 card.“I/O Card Layout” on page 7-17 for the connector location
- Route the cable through the enclosure to the display. Observe the wiring considerations as listed in “Considerations for Signal Wiring” on page 7-6.
- Plug the other end of the cable into the LCD display

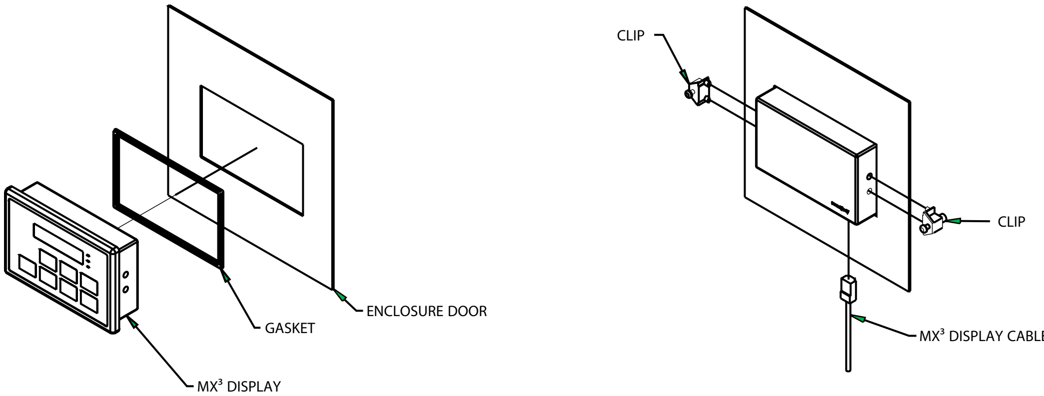


Figure 7-18: Mounting Remote Keypads

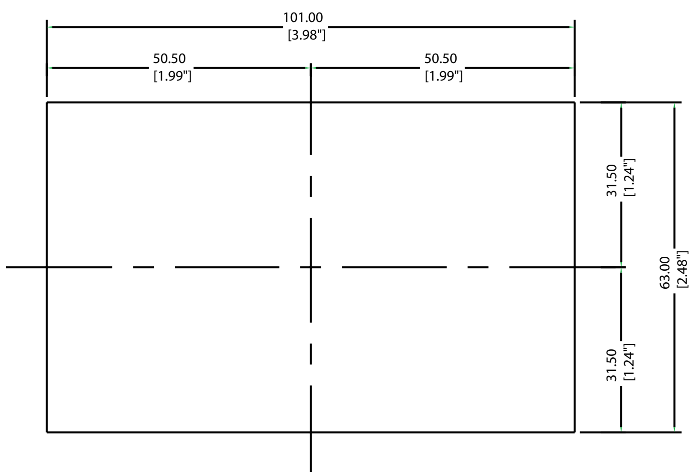


Figure 7-19: Small Display Keypad Mounting Dimensions Part #: KPMX3SLCD

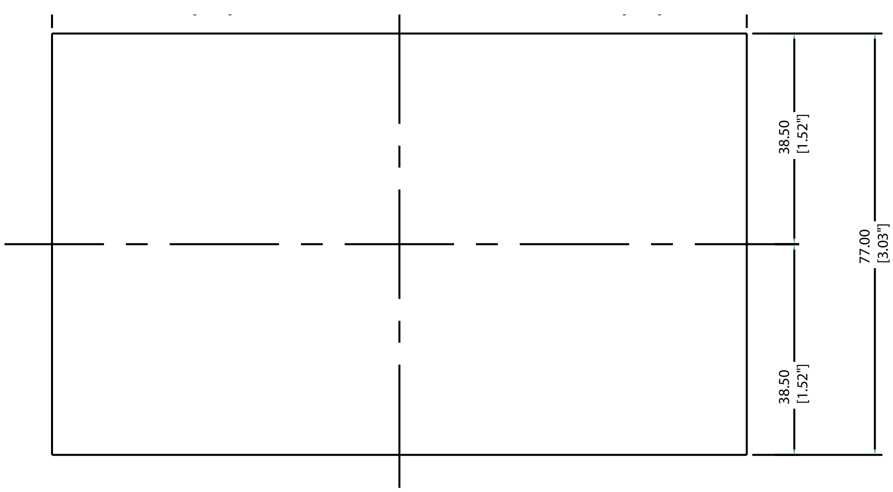


Figure 7-20: Large Display Keypad Mounting Dimensions Part #:KPMX3LLCD

RTD Module Installation

Location

The mounting location for the Remote RTD Module should be chosen to give easy access to the RTD wiring, control terminals and indicator LEDs as well as providing a location to mount the power supply. The Remote RTD Module is specifically designed to be mounted close to the equipment it is monitoring. This eliminates long RTD wire lengths which save time and money on installation and wiring. The Benshaw Remote RTD Module is designed to mount on industry standard 35mm wide by 7.5mm deep DIN rail.

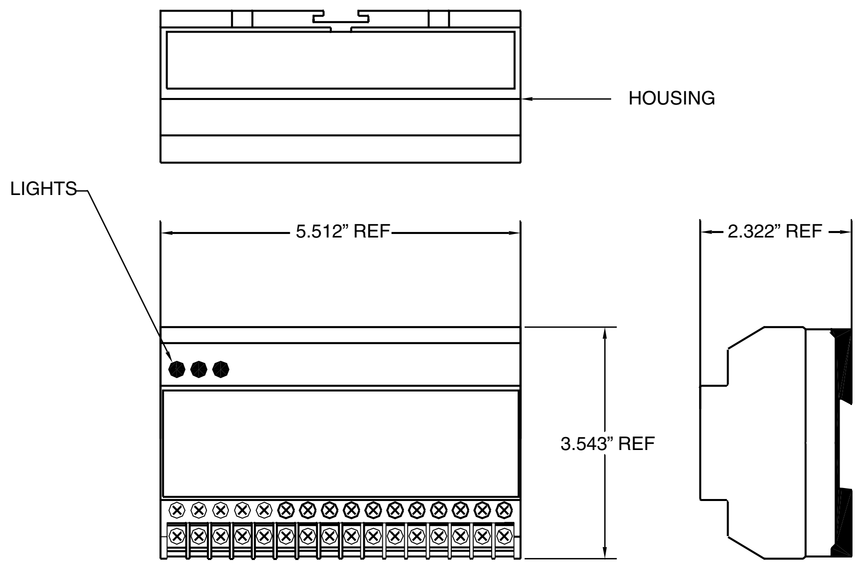


Figure 7-21: Remote RTD Module Mechanical Layout

Modbus Address

Set the rotary switch on the top of the Remote RTD Module to the desired Modbus address. Up to 2 modules can be connected to the MX^3 starter. The address set by the rotary switch must match the setting in RTD 01 or RTD 02. For example, setting both the rotary switch and RTD 01 to 16 would make the connected module be module #1. The connected RTDs would then represent #1 to #8 in the RTD programming.

Power Connections

The 24VDC power source is connected to the following terminals:

24VDC-	Negative connection to 24VDC power supply
24VDC+	Positive connection to 24VDC power supply
"g"	Chassis ground connection

RS-485 Communication

The RS-485 communications wiring should use shielded twisted pair cable. The shield should only be terminated at one end. The connections are as follows:

MX RJ45	Module	Description
pin 5	A(-)	RS-485 negative communications connection.
pin 4	B(+)	RS-485 positive communications connection.
pin 8	Com	RS-485 common connection.

RTD Connections

Each Remote RTD Module has connections for up to 8 RTDs. The terminals for the RTD wires are as follows:

R	RTD return wire
C	RTD compensation wire
H	RTD hot wire

Each RTD is connected to the three terminals with the common number. For example, RTD number 5 connects to the terminals numbered 5R, 5C and 5H.

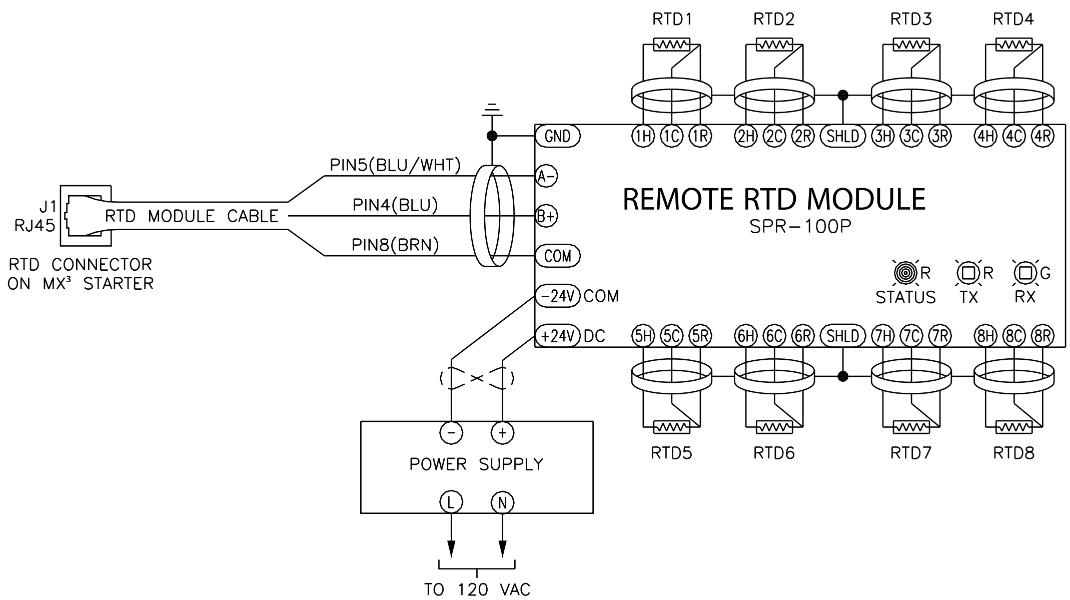


Figure 7-22: Remote RTD Module Wiring

Table 7-6: RTD Temperature vs. Resistance

Temperature		100 Ω Pt (DIN 43760)	ˆC	ˆF	100 Ω Pt
ˆC	ˆF		100	212	138.50
-50	-58	80.13	110	230	142.29
-40	-40	84.27	120	248	146.06
-30	-22	88.22	130	266	149.82
-20	-4	92.16	140	284	153.58
-10	14	96.09	150	302	157.32
0	32	100.00	160	320	161.04
10	50	103.90	170	338	164.76
20	68	107.79	180	356	168.47
30	86	111.67	190	374	172.46
40	104	115.54	200	392	175.84
50	122	119.39	210	410	179.51
60	140	123.24	220	428	183.17
70	158	127.07	230	446	186.82
80	176	130.89	240	464	190.45

Troubleshooting

Preventative Maintenance

Preventative maintenance performed on a regular basis will help ensure that the starter continues to operate reliably and safely. The frequency of preventative maintenance depends upon the type of maintenance and the installation site's environment.

❖ ***Note*** *A trained technician should always perform preventative maintenance.*

During Commissioning:

- Torque all power connections during commissioning. This includes factory wired equipment.
- Check all of the control wiring in the package for loose connections.
- If fans are installed, ensure proper operation

One month after the starter has been put in operation:

- Re-torque all power connections. This includes factory wired equipment.
- Inspect the cooling fans to ensure proper operation.

After the first month of operation:

- Re-torque all power connections every year.
- Clean any accumulated dust from the starter using a clean source of compressed air.
- Inspect the cooling fans every three months to ensure proper operation.
- Clean or replace any air vent filters on the starter every three months.

❖ ***Note:*** *If mechanical vibrations are present at the installation site, inspect the electrical connections more frequently.*

General Troubleshooting Charts

The following troubleshooting charts can be used to help solve many of the more common problems that may occur.

Table 7-7: Motor does not start, no output to motor

Condition	Cause	Solution
Display Blank, CPU Heartbeat LED on MX2 board not blinking.	Control voltage absent.	Check for proper control voltage input. Verify fuses and wiring.
	MX2 control board problem.	Consult factory.
Fault Displayed.	Fault Occurred.	See fault code troubleshooting table for more details.
Start command given but nothing happens.	Start/Stop control input problems.	Verify that the start/stop wiring and start input voltage levels are correct.
	Control Source parameters (QST 04-05, P4-5) not set correctly.	Verify that the parameters are set correctly.
NOL or No Line is displayed and a start command is given, it will fault in F28.	No line voltage has been detected by the MX2 when a start command is given.	Check input supply for inline contactor, open disconnects, open fuses, open circuit breakers, or disconnected wiring.
		Verify that the SCR gate wires are properly connected to the MX2 control board.
		On medium voltage systems, verify wiring of the voltage feedback measurement circuit.
		See fault code troubleshooting table for more details.

Table 7-8: During starting, motor rotates but does not reach full speed

Condition	Cause	Solution
Fault Displayed.	Fault Occurred.	See fault code troubleshooting table for more details.
Display shows Accel or Run.	Maximum Motor Current setting (P7/ QST07) set too low.	Review acceleration ramp settings.
	Motor loading too high and/or current not dropping below 175% FLA indicating that the motor has not come up to speed	Reduce load on motor during starting.
	Motor FLA (P1/QST01) or CT ratio (P78/FUN03) parameter set incorrectly.	Verify that Motor FLA and CT ratio parameters are set correctly.
	Abnormally low line voltage.	Fix cause of low line voltage.
	A mechanical or supplemental brake is still engaged.	Verify that any external brakes are disengaged.
Motor Hums before turning.	Initial current to low.	Increase initial current.
	FLA or CT incorrect.	Verify FLA and CT settings.

Table 7-9: Starter not accelerating as desired

Condition	Cause	Solution
Motor accelerates too quickly.	Ramp time (P8/QST08) too short.	Increase ramp time.
	Initial current (P6/QST06) set too high.	Decrease Initial current.
	Maximum current (P7/QST07) set too high.	Decrease Maximum current.
	Kick start current (P13/CFN10) too high.	Decrease or turn off Kick current.
	Kick start time (P14/CFN11) too long.	Decrease Kick time.
	Motor FLA (P1/QST01) or CT ratio	Verify that Motor FLA and CT ratio
	(P78/FUN03) parameter set incorrectly.	parameters are set correctly.
	Starter Type parameter (P64/FUN07) set	Verify that Starter Type parameter is set
	incorrectly.	correctly.
Motor accelerates too slowly	Maximum Motor Current setting	Review acceleration ramp settings.
	(P7/QST07) set too low.	
	Motor loading too high.	Reduce load on motor during starting.
	Motor FLA (P1/QST01) or CT ratio	Verify that Motor FLA and CT ratio
	(P78/FUN03) parameter set incorrectly.	parameters are set correctly.
	Abnormally low line voltage.	Fix cause of low line voltage.
	Ramp time to long.	Decrease ramp time.

Table 7-10: Starter not decelerating as desired

Condition	Cause	Solution
Motor stops too quickly.	Decel Time (P18/CFN17) set too short.	Increase Decel Time.
	Decel Begin and End Levels (P16/CFN15 and P17/CFN16) set improperly.	Increase Decel Begin and/or Decel End levels.
Decel time seems correct but motor surges (oscillates) at beginning of deceleration cycle.	Decel Begin Level (P16/CFN15) set too high.	Decrease Decel Begin Level until surging is eliminated.
Decel time seems correct but motor stops before end of deceleration cycle.	Decel End Level (P17/CFN16) set too low.	Increase Decel End Level until motor just stops at the end of the deceleration cycle.
Water hammer still occurs at end of cycle.	Decel End Level (P17/CFN16) set too high.	Decrease Decel End Level until water hammer is eliminated.
	Decel Time (P18/CFN17) too short.	If possible, increase Decel Time to decelerate system more gently.
Motor speed drops sharply before decel	Decel begin level to low.	Increase the Decel Begin Level until drop in speed is eliminated.

Table 7-11: Motor stops unexpectedly while running

Condition	Cause	Solution
Fault Displayed.	Fault Occurred.	See fault code troubleshooting table for more details.
Ready Displayed.	Start command lost.	Verify start command input signal is present or serial communications start command is present.
		Check any permissive that may be wired into the run command. (Start/Stop)
Display Blank, Heartbeat LED on MX2 card not blinking.	Control voltage absent.	Check for proper control voltage input. Verify wiring and fuses.
	MX2 control card problem.	Consult factory.

Table 7-12: Metering incorrect

Condition	Cause	Solution
Power Metering not reading correctly.	CTs installed or wired incorrectly.	Verify correct CT wiring and verify that the CTs are installed with all the White dots towards the input line side. CT1=L1 CT2=L2 CT3=L3
	CT ratio parameter (P78/FUN03) set incorrectly.	Verify that the CT ratio parameter is set correctly.
PF Meter not reading correctly.	CTs installed or wired incorrectly.	Verify correct CT wiring and verify that the CTs are installed with all the White dots towards the input line side.
Motor Current or Voltage meters fluctuating with steady load.	Energy Saver active.	Turn off Energy Saver if not desired.
	Loose connections.	Shut off all power and check all connections.
	SCR fault.	Verify that the SCRs gate leads are connected properly and the SCRs are ok.
	Load actually is not steady.	Verify that the load is actually steady and that there are not mechanical issues.
	Other equipment on same power feed causing power fluctuations and/or distortion.	Fix cause of power fluctuations and/or distortion.
Voltage Metering not reading correctly.	In medium voltage systems, Rated Voltage parameter (P76/FUN05) set incorrectly.	Verify that Rated Voltage parameter is set correctly.
Current Metering not reading correctly.	CT ratio parameter (P78/FUN03) set incorrectly.	Verify that the CT ratio parameter is set correctly.
	CTs installed or wired incorrectly.	Verify correct CT wiring and verify that the CTs are installed with all the White dots towards the input line side.CT1=L1 CT2=L2 CT3=L3

Table 7-12: Metering incorrect

Condition	Cause	Solution
Ground Fault Current Metering not reading correctly.	CT ratio parameter (P78/FUN03) set incorrectly.	Verify that the CT ratio parameter is set correctly.
	CTs installed or wired incorrectly.	Verify correct CT wiring and verify that the CTs are installed with all the White dots towards the input line side.CT1=L1 CT2=L2 CT3=L3

Table 7-13: Other Situations

Condition	Cause	Solution
Motor Rotates in Wrong Direction.	Phasing incorrect.	If input phasing correct, exchange any two output wires.
		If input phasing incorrect, exchange any two input wires.
Erratic Operation.	Loose connections.	Shut off all power and check all connections.
Motor Overheats.	Motor overloaded.	Reduce motor load.
	Too many starts per hour.	Allow for adequate motor cooling
		between starts. Set Hot/Cold ratio higher or lengthen cooling time.
	High ambient temperature.	Reduce ambient temperature or provide for better cooling. Set OL class lower to compensate for ambient temperature.
	Acceleration time too long.	Reduce starting load and/or review acceleration ramp settings.
	Incorrect motor OL settings.	Review and correct motor OL settings.
	Motor cooling obstructed/damaged.	Remove cooling air obstructions. Check motor cooling fan.
Starter cooling fans do not operate. (When Present)	Fan power supply lost.	Verify fan power supply, check fuses.
	Fan wiring problem.	Check fan wiring.
	Fan failure.	Replace fan.
Analog Output not functioning properly.	Voltage/Current output switch (SW1-2) not set correctly.	Set switch SW1 to give correct output.
	Wiring problem.	Verify output wiring.
	Analog Output Function parameter (P60/ I/O12) set incorrectly.	Verify that the Analog Output Function parameter is set correctly.
	Analog Output Offset and/or Span parameters (P61/ I/O13 and P62/ I/O14) set incorrectly.	Verify that the Analog Output Span and Offset parameters are set correctly.
	Load on analog output too high.	Verify that load on analog output meets the MX_2 analog output specifications.
	Ground loop or noise problems.	Verify correct grounding of analog output connection to prevent noise and/or ground loops from affecting output.

Table 7-13: Other Situations

Condition	Cause	Solution
Remote Keypad does not operate correctly.	Keypad cable not plugged in properly or cable is damaged.	Verify that the remote keypad cable has not been damaged and that it is properly seated at both the keypad and the MX^2 control card.
	Remote display damaged.	Replace remote display.
Cannot change parameters.	Passcode is set.	Clear passcode.
	Starter is running.	Stop starter.
	Modbus is overriding.	Stop communications.
	Heater Level (P73 / FUN08) parameter is "On"	Turn Heater Level (P73 / FUN08) parameter "Off"

Fault Code Table

The following is a list of possible faults that can be generated by the MX starter control.

Table 7-14: Fault Code Table

Fault Code	Description	Detailed Description of Fault/Possible Solutions
F01	UTS Time Limit Expired	Motor did not achieve full speed before the UTS timer (P9/ QST09) expired.
		Check motor for jammed or overloaded condition.
		Verify that the combined kick time (P14/CFN11) and acceleration ramp time (P8/QST08) is shorter than the UTS timer setting.
		Evaluate acceleration ramp settings. The acceleration ramp settings may be too low to permit the motor to start and achieve full speed.
		If so, revise acceleration ramp settings to provide more motor torque during starting.
		Evaluate UTS timer setting and, if acceptable, increase UTS timer setting (P9/QST09).
F02	Motor Thermal Overload Trip	Check motor for mechanical failure, jammed, or overloaded condition.
		Verify the motor thermal overload parameter settings (P3/ QST03 and P44-P47/PFN12-PFN16,) and motor service factor setting (P2/QST02).
		Verify that the motor FLA (P1/QST01) and CT ratio (P78/ FUN03) are correct.
		If motor OL trip occurs during starting, review acceleration ramp profile settings.
		Verify that there is not an input line power quality problem or excessive line distortion present.
F03	Slow Speed Timer Limit Expired	Verify that PF caps, if installed, are ahead of CTs.
		Reset overload when content falls below 15%.
F10	Phase Rotation Error, not ABC	Input phase rotation is not ABC and Input Phase Sensitivity parameter (P77/FUN04) is set to ABC only.
		Verify correct phase rotation of input power. Correct wiring if necessary.
		Verify correct setting of Input Phase Sensitivity parameter (P77/FUN04).
F11	Phase Rotation Error, not CBA	Input phase rotation is not CBA and Input Phase Sensitivity parameter (P77/FUN04) is set to CBA only.
		Verify correct phase rotation of input power. Correct wiring if necessary.
		Verify correct setting of Input Phase Sensitivity parameter (P77/FUN04).
F12	Low Line Frequency	Line frequency below 23 Hz was detected.
		Verify input line frequency.
		If operating on a generator, check generator speed governor for malfunctions.
		Check input supply for open fuses or open connections.
		Line power quality problem / excessive line distortion.

Table 7-14: Fault Code Table

Fault Code	Description	Detailed Description of Fault/Possible Solutions
F13	High Line Frequency	Line frequency above 72 Hz was detected.
		Verify input line frequency.
		If operating on a generator, check generator speed governor for malfunctions.
		Line power quality problem / excessive line distortion.
F14	Input power not single phase	Three-phase power has been detected when the starter is expecting single-phase power.
		Verify that input power is single phase.
		Verify that single-phase power is connected to the L1 and L2 inputs. Correct wiring if necessary.
		Verify that the SCR gate wires are properly connected to the MX^2 control card.
F15	Input power not three phase	Single-phase power has been detected when the starter is expecting three-phase power.
		Verify that input power is three phase. Correct wiring if necessary.
		Verify that the SCR gate wires are properly connected to the MX^2 control card.
		On medium voltage systems, verify wiring of the voltage feedback measurement circuit.
F21	Low Line L1-L2	Low voltage below the Under voltage Trip Level parameter setting (P39/PFN08) was detected for longer than the Over/ Under Voltage Trip delay time (P40/PFN09).
		Verify that the actual input voltage level is correct.
		Verify that the Rated Voltage parameter (P76/FUN05) is set correctly.
		Check input supply for open fuses or open connections.
		On medium voltage systems, verify wiring of the voltage measurement circuit.
F22	Low Line L2-L3	Low voltage below the Under voltage Trip Level parameter setting (P39/PFN08) was detected for longer than the Over/ Under Voltage Trip delay time (P40/PFN09).
		Verify that the actual input voltage level is correct.
		Verify that the Rated Voltage parameter (P76/FUN05) is set correctly.
		Check input supply for open fuses or open connections.
		On medium voltage systems, verify wiring of the voltage feedback measurement circuit.
F23	Low Line L3-L1	Low voltage below the Under voltage Trip Level parameter setting (P39/PFN08) was detected for longer than the Over/ Under Voltage Trip delay time (P40/PFN09).
		Verify that the actual input voltage level is correct.
		Verify that the Rated Voltage parameter (P76/FUN05) is set correctly.
		Check input supply for open fuses or open connections.
		On medium voltage systems, verify wiring of the voltage feedback measurement circuit.

Table 7-14: Fault Code Table

Fault Code	Description	Detailed Description of Fault/Possible Solutions
F24	High Line L1-L2	High voltage above the Over voltage Trip Level parameter setting (P35/PFN07) was detected for longer than the Over/ Under Voltage Trip delay time (P40/PFN09).
		Verify that the actual input voltage level is correct.
		Verify that the Rated Voltage parameter (P76/FUN05) is set correctly.
		Line power quality problems/ excessive line distortions.
F25	High Line L2-L3	High voltage above the Over voltage Trip Level parameter setting (P38/PFN07) was detected for longer than the Over/ Under Voltage Trip delay time (P40/PFN09).
		Verify that the actual input voltage level is correct.
		Verify that the Rated Voltage parameter (P76/FUN05) is set correctly.
		Line power quality problems/ excessive line distortions.
F26	High Line L3-L1	High voltage above the Over voltage Trip Level parameter setting (P38/PFN07) was detected for longer than the Over/ Under Voltage Trip delay time (P40/PFN09).
		Verify that the actual input voltage level is correct.
		Verify that the Rated Voltage parameter (P76/FUN05) is set correctly.
		Line power quality problems/ excessive line distortions.
F27	Phase Loss	The MX^2 has detected the loss of one or more input or output phases when the starter was running. Can also be caused by line power dropouts.
		Check input supply for open fuses.
		Check power supply wiring for open or intermittent connections.
		Check motor wiring for open or intermittent connections.
		On medium voltage systems, verify wiring of the voltage feedback measurement circuit.
		Check Gate and Cathode connections to MX^2 card.
F28	No Line	No input voltage was detected for longer than the Inline
		Configuration time delay parameter setting (P63/ I/O16) when a start command was given to the starter.
		If an inline contactor is being used, verify that the setting of the Inline Configuration time delay parameter (P53/ I/O16) allows enough time for the inline contactor to completely close.
		Check input supply for open disconnects, open fuses, open circuit breakers or disconnected wiring.
		Verify that the SCR gate wires are properly connected to the MX^2 control card.
		On medium voltage systems, verify wiring of the voltage feedback measurement circuit.

Table 7-14: Fault Code Table

Fault Code	Description	Detailed Description of Fault/Possible Solutions
F30	I.O.C. (Instantaneous Over current)	During operation, the MX^2 detected a very high level of current in one or more phases.
		Check motor wiring for short circuits or ground faults.
		Check motor for short circuits or ground faults.
		Check if power factor or surge capacitors are installed on the motor side of the starter.
		Verify that the motor FLA (P1/QST01) and CT ratio (P78/FUN03) settings are correct.
F31	Overcurrent	Motor current exceeded the Over Current Trip Level setting (P32/PFN01) for longer than the Over Current Trip Delay Time setting (P33/PFN02).
		Check motor for a jammed or an overload condition.
F34	Undercurrent	Motor current dropped under the Under Current Trip Level setting (P26/PFN03) for longer than the Under Current Trip Delay time setting (P27/PFN04).
		Check system for cause of under current condition.
F37	Current Imbalance	A current imbalance larger than the Current Imbalance Trip Level parameter setting (P36/PFN05) was present for longer than ten (10) seconds.
		Check motor wiring for cause of imbalance. (Verify dual voltage and 6 lead motors for correct wiring configuration).
		Check for large input voltage imbalances that can result in large current imbalances.
		Check motor for internal problems.
F38	Ground Fault	Ground current above the Ground Fault Trip level setting (P37/PFN06) has been detected for longer than 3 seconds.
		Check motor wiring for ground faults.
		Check motor for ground faults.
		Megger motor and cabling (disconnect from starter before testing).
		Verify that the motor FLA (P1/QST01) and CT ratio (P78/FUN03) settings are correct.
		Verify that the CTs are installed with all the White dots towards the input line.
		In Single phase applications, verify that only two CTs are being used; that they are installed with all the White dots or Xs in the correct direction; and that the CTs are connected to the L1 and L3 CT inputs on the MX2 control card.

Table 7-14: Fault Code Table

Fault Code	Description	Detailed Description of Fault/Possible Solutions
F39	No Current at Run	Motor current went below 10% of FLA while the starter was running.
		Verify Motor Connections.
		Verify the CT wiring to the MX2control card.
		Verify that the motor FLA (P1/QST01) and CT ratio (P78.FUN03) settings are correct.
		Check if load is still connected to starter.
		Check if motor may have been driven by the load (a regeneration condition).
		Check Gate and Cathode connections to MX^2 for loose connections.
		Check for inline contactor or disconnect.
F40	Shorted / Open SCR	A shorted or open SCR condition has been detected.
		Verify that all SCR gate leads wires are properly connected at the SCR devices and the MX^2 control card.
		Check all SCRs with ohmmeter for shorts.
		Verify that the Input Phase Sensitivity parameter setting (P77/FUN04) is correct.
		Verify that the Starter Type parameter setting (P74/FUN07) is correct.
		Verify the motor wiring. (Verify dual voltage motors for correct wiring configuration).
F41	Current at Stop	Motor current was detected while the starter was not running.
		Examine starter for shorted SCRs.
		Examine bypass contactor (if present) to verify that it is open when starter is stopped.
		Verify that the motor FLA (P1/QST01) and CT ratio (P78/FUN03) settings are correct.
F46	Disconnect Fault	A signal on the disconnect digital input was not present when a start was commanded
		Verify that disconnect feedback wiring is correct.
		Verify that the disconnect is not faulty.
F47	Stack Protection Fault (stack thermal overload)	The MX^2 electronic power stack OL protection has detected an overload condition.
		Check motor for jammed or overloaded condition.
		Verify that the CT ratio (P78/FUN03) and burden switch settings are correct.
		Motor load exceeds power stack rating. Consult factory

Table 7-14: Fault Code Table

Fault Code	Description	Detailed Description of Fault/Possible Solutions
F48	Bypass /2M Contactor Fault	An incorrect bypass feedback has been detected for longer than the Bypass Confirm time parameter setting (P64/ I/O17).
		Verify that the bypass/2M contactor coil and feedback wiring is correct.
		Verify that the relay connected to the bypass/2M contactor(s) is programmed as the UTS function.
		Verify that the bypass/2M contactor power supply is present.
		Verify that the appropriate Digital Input Configuration parameter has been programmed correctly.
		Verify that the bypass contactor(s) are not damaged or faulty.
F49	Inline Contactor Fault	Verify that the appropriate Digital Input Configuration parameter has been programmed correctly.
		Verify that the inline contactor(s) are actually not damaged or faulty.
F50	Control Power Low	Low control power (below 90V) has been detected while running.
		Verify that the control power input level is correct, especially during starting when there may be significant line voltage drop.
		Check control power transformer tap setting (if available).
		Check control power transformer fuses (if present).
		Check wiring between control power source and starter.
F51	Current Sensor Offset Error	Indicates that the MX^2 control card self-diagnostics have detected a problem with one or more of the current sensor inputs.
		Verify that the motor FLA (P1/QST01), CT ratio (P78/FUN03) and burden switch settings are correct.
		Verify that no actual current is flowing through any of the starter's CTs when the starter is not running.
		Consult factory if fault persists.
F54	BIST Fault	The starter has detected a voltage or a current. Remove line power from input of starter. Disconnect must be open.
F55	BIST CT Fault	Verify CT location, CT1 on L1, CT2 on L2, CT3 on L3. or CTs are connected backwards (the polarity dot must be facing the supply line).
F60	External Fault on DI#1 Input	DI#1 has been programmed as a fault type digital input and the input indicates a fault condition is present.
		Verify that the appropriate Digital Input Configuration parameter has been programmed correctly.
		Verify wiring and level of input.
F61	External Fault on DI#2 Input	DI#2 has been programmed as a fault type digital input and input indicates a fault condition is present.
		Verify that the appropriate Digital Input Configuration parameter has been programmed correctly.
		Verify wiring and level of input.

Table 7-14: Fault Code Table

Fault Code	Description	Detailed Description of Fault/Possible Solutions
F62	External Fault on DI#3 input	DI#3 input has been programmed as a fault type digital input and input indicates a fault condition is present.
		Verify that the appropriate Digital Input Configuration parameter has been programmed correctly.
		Verify wiring and level of input.
F71	Analog Input Level Fault Trip	Based on the Analog Input parameter settings, the analog input level has either exceeded or dropped below the Analog Input Trip Level setting (P56/ I/O 09) for longer than the Analog Input Trip Delay time (P57/ I/O 010).
		Measure value of analog input to verify correct reading.
		Verify settings of all Analog Input parameters (P55-P59/ I/O 08-I/O 12).
		Verify correct positioning of input switch (SW1)
		(Voltage or Current) on the MX^2 control card.
		Verify correct grounding of analog input connection to prevent noise or ground loops from affecting input.
F81	SPI / Keypad Communication Fault	Indicates that communication has been lost with the remote keypad. (This fault normally occurs if the remote keypad is disconnected while the MX^2 control card is powered up. Only connect and disconnect a remote keypad when the control power is off).
		Verify that the remote keypad cable has not been damaged and that its connectors are firmly seated at both the keypad and the MX^2 control card.
		Verify that the display interface card (when present) is firmly attached to MX^2 control card.
		Route keypad cables away from high power and/or high noise areas to reduce possible electrical noise pickup.

SCR Testing

Resistance

The SCRs in the starter can be checked with a standard ohmmeter to determine their condition.

- Remove power from the starter before performing these checks.
- Check from L to T on each phase. The resistance should be over 50k ohms.
- Check between the gate leads for each SCR (red and white twisted pair).
  The resistance should be from 8 to 50 ohms.

❖ ***Note:*** *The resistance measurements may not be within these values and the SCR may still be good. The checks are to determine if an SCR is shorted "L" to "T" of if the gate in an SCR is shorted or open. An SCR could also still be damaged even though the measurements are within the above specifications.*

Voltage

When the starter is running, the operation of the SCRs can be confirmed with a voltmeter.

Extreme caution must be observed while performing these checks since the starter has lethal voltages applied while operating.

While the starter is running and up to speed, use an AC voltmeter, check the voltage from "L" to "T" of each phase. The voltage should be less than 1.5 Volts. If the starter has a bypass contactor, the voltage drop should be less than 0.3 volts.

Using a DC voltmeter, check between the gate leads for each SCR (red and white twisted pair). The voltage should between 0.5 and 2.0 volts.

Integral Bypass

A voltage check from "L" to "T" of each phase of the RediStart starter should be preformed every 6 months to confirm the bypass contactors are operating correctly.

Extreme caution must be observed while performing these checks since the starter has lethal voltages applied while operating.

Built In Self Test Functions

The MX has two built in self test (BIST) modes. The first test is the standard self test and is used to test many of the basic functions of the starter without line voltage being applied. The second test is a line powered test that is used to verify the current transformer’s locations and connections and to test for shorted SCRs/power poles, open or non-firing SCRs/power poles, and ground fault conditions.

Standard BIST Tests

(P67 / #7) / FUN 15 -Std BIST. The standard BIST tests are designed to be run with no line voltage applied to the starter. In selected low voltage systems where a disconnect switch is used, the Disconnect Switch must be opened before starting the standard tests. Standard BIST mode can be initiated by entering the appropriate value into P67 or FUN 15 -Misc Command user parameter.

In order to prevent back feeding of voltage through the control power transformer (if used), control power must be carefully applied to the MX control card and contactors so that self testing can occur safely. In low voltage applications, the user must verify that the applied test control power cannot be fed backwards through the system. “Run/Test” isolation switches, test power plugs, and wiring diagrams are available from Benshaw.

In low voltage systems with an inline/isolation contactor. Before the inline test is performed verify that no line voltage is applied to the line side of the inline contactor. Otherwise when the inline test is performed the inline contactor will be energized, applying line voltage to the starter, and a BIST test fault will occur.

The standard BIST tests comprise of:

Programming / Test Instructions:

Step 1.

LED Display	LCD Display
Go to P67 and press [ENTER]. Press [UP] button to #7 and press [ENTER]. Powered BIST test will commence.	Go to FUN 15-misc commands and press [ENTER]. Increment up to "Std BIST" and press [ENTER]. Std BIST test will commence.

```
FUN:  Misc Command
 15   Std BIST
```

❖***Note:*** *Designed to run with no line voltage applied to starter.*

Step 2. RUN relay test and Inline Feedback Test: In this test, the RUN assigned relays are cycled on and off once and the feedback from an inline contactor is verified. In order to have a valid inline contactor feedback, a digital input needs to be set to Inline Confirm and the input needs to be wired to an auxiliary contact of the inline contactor. The feedback is checked in both the open and closed state. If the feedback does not match the state of the RUN relay within the amount of time set by the Inline Config parameter an "Inline" fault will occur.

❖***Note:*** *If no digital input is assigned as an Inline Confirm input this test will always pass.*

❖***Note:*** *If the Inline Config (I/O 16) parameter on page 120 is set to "Off" this test will be skipped.*

LED Display	LCD Display
b ic (inline closed) b ic (inline open)	Inline Closed Inline open.

```
BIST Mode
Inline Closed
```

```
BIST Mode
Inline Open
```

Step 3. UTS relay test and Bypass Feedback Test: In this test, the dedicated bypass relay (if assigned) and the UTS assigned relays are cycled on and off once, and the feedback from a bypass contactor is verified. In order to have a valid bypass contactor feedback, the individual bypass input and any other inputs set to Bypass Confirm input needs to be wired to an auxiliary contact of the bypass contactor. The feedback is checked in both the open and closed state. If the feedback does not match the state of the UTS relay within the amount of time set by the Bypass Feedback parameter a "Bypass/2M Fault" will occur.

❖***Note:*** *If one dedicated bypass is set to "fan" and if no digital input are assigned as a Bypass Confirm input, this test will always pass.*

LED Display	LCD Display
b bc (bypass closed)	Bypass Closed
b bo (bypass open)	Bypass Open.

```
BIST Mode
Bypass Closed
```

```
BIST Mode
Bypass Open
```

Step 4. Sequential SCR gate firing (L1+, L1-, L2+, L2-, L3+, L3-): In this test the SCR gate outputs are sequentially fired starting with the L1+ device(s) and ending with the L3-device(s). This test can be used to verify that the SCR gate leads are connected properly. In LV systems, the gate voltage can be verified using a DC voltage meter or oscilloscope. The voltage on each red and white wire pair should be between 0.5VDC and 2.0VDC.

LED Display	LCD Display
b 96 (gate 6 on)	Gate 6 On
b 93 (gate 3 on)	Gate 3 On
b 95 (gate 5 on)	Gate 5 On
b 92 (gate 2 on)	Gate 2 On
b 94 (gate 4 on)	Gate 4 On
b 91 (gate 1 on)	Gate 1 On.

```
BIST Mode
Gate G? On
```

Step 5. Simultaneous SCR gate firing: In this test the SCR gate outputs are simultaneously fired (all gates on). This test can be used to verify that the SCR gate leads are connected properly. The gate voltage can be verified using a DC voltage meter or oscilloscope. The voltage on each red and white wire pair should be between 0.5VDC and 2.0VDC.

Pressing [ENTER] on the keypad at any time will abort the current test in progress and proceed to the next BIST test.

During the standard BIST tests if line voltage or phase current is detected, the MXwill immediately exit BIST mode and declare a “BIST Abnormal Exit” fault.

LED Display	LCD Display
b 9A (all gates on)	All Gates On.

```
BIST Mode
All gates on
```

Step 6 .

LED Display	LCD Display
b--(tests completed)	Tests Completed. BIST Mode Test Completed

Powered BIST Tests

(P67 / #8) / FUN 15 -Powered BIST. The powered BIST tests are designed to be run with normal line voltage applied to the starter and a motor connected. Powered BIST verifies that the power poles are good, no ground faults exist, CTs are connected and positioned correctly and that the motor is connected. Powered BIST mode can be entered by entering the appropriate value into the FUN 15-Miscellaneous Command user parameter.

❖***Note:*** *The powered BIST test is only for use with SCR based reduced voltage soft starters. Powered BIST can not be used with wye-delta or ATL types of starters.*

❖***Note:*** *The motor wiring MUST be fully connected before starting the powered BIST tests. Also the motor must be at rest (stopped). Otherwise the powered BIST tests will not function correctly.*

❖***Note:*** *Before using the powered BIST test function, the following MX user parameters MUST be set for correct operation of the powered BIST test: Motor FLA (P1 / QST 01), CT Ratio (P78 / FUN 03), Phase Order (P77 / FUN 04), Rated Voltage (P76 / FUN 05), and Starter Type (P74 / FUN 07).*

The powered BIST tests comprise of:

Step 1.

LED Display	LCD Display
Go to P67 and press [ENTER]. Press [UP] button to #8 and press [ENTER]. Powered BIST test will commence.	Go to FUN 15 press [ENTER]. Increment up to “Powered BIST" and press [ENTER]. Powered BIST test will commence. FUN: Misc Command 15 Powered BIST

Step 2. Shorted SCR and Ground Fault Test: In this test each power pole is energized individually. If current flow is detected, the MXcontroller attempts to differentiate whether it is a shorted SCR/shorted power pole condition or a ground fault condition and either a "Bad SCR Fault" or "Ground Fault" will occur.

LED Display	LCD Display
b 59 (Gating individual SCRs)	Shorted SCR / GF.

```
BIST Mode
Shorted SCR/GF
```

Step 3. Open SCR and Current Transformer (CT) Test: In this test, a low-level closed-loop controlled current is selectively applied to various motor phases to verify that the motor is connected, all SCRs are turning on properly, and that the CTs are wired and positioned properly. If current is detected on the wrong phase then a "BIST CT Fault" fault will be declared. If an open motor lead, open SCR, or non-firing SCR is detected then a "Bad SCR Fault" will occur.

❖***Note:*** *When this test is in progress 6 audible humming or buzzing sounds will be heard from the motor.*

LED Display	LCD Display
b oc	Open SCR / CTs.

```
BIST Mode
Open SCR/CTs
```

Step 4.

LED Display	LCD Display
b -- (tests completed)	Tests Completed.

```
BIST Mode
Tests completed
```

Pressing [ENTER] on the keypad at any time will abort the current test in progress and proceed to the next BIST test.

❖***Note:*** *If line voltage is lost during the powered tests a "BIST Abnormal Exit" fault will occur.*

❖***Note:*** *The powered BIST tests will verify that the input phase order is correct. If the measured phase order is not the same as the "Phase Order" (FUN 04) parameter a phase order fault will occur.*

SCR Replacement

SCR Replacement This section is to help with SCR replacements on stack assemblies.Please read prior to installation.

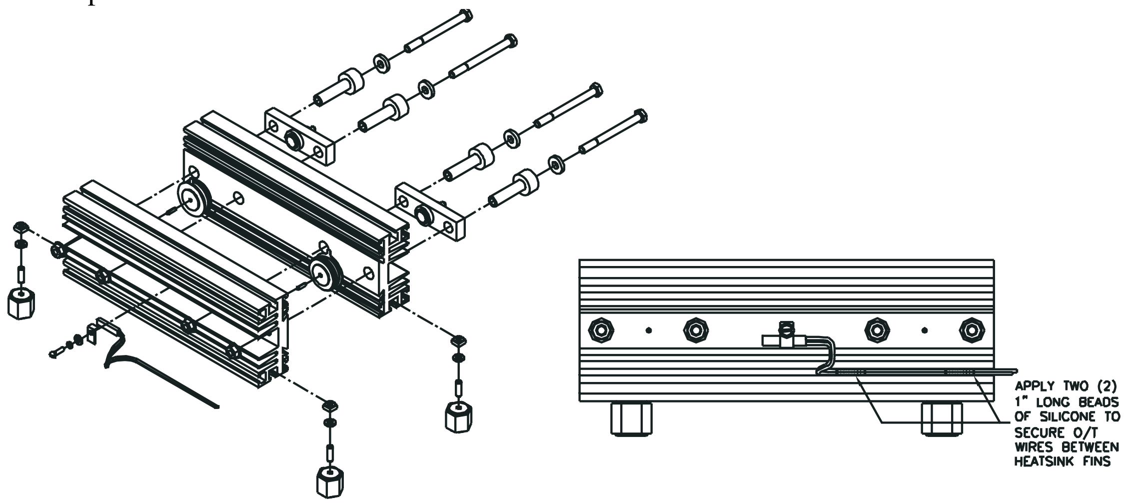


Figure 7-23: Typical Stack Assembly

SCR Removal

To remove the SCR fromthe heatsink, losen the two bolts (3) on the loader bar side of the clamp. Do not turn on the nuts (5). The nuts have a locking ridge that sink into the aluminum heatsink. So 1/4 turns until the SCR comes loose. Remove theh SCRs from the heatsink.

❖***Note:*** *Do not loosen nut on indicator washer (6). This will change the clamping pressure of the clamp and the clamp will be defective.*

SCR Installation

- Coat the faces of the SCRs to be installed with a think layer of EJC (Electrical Joint Compound).
- Place the SCRs onto the dowel pins. The top SCR will have the cathode to the left and the bottom SCR will have the cathode to the right. The SCR symbol has a triangle that points to the cathode.
- Finger tighten nuts on the bolts.

SCR Clamp

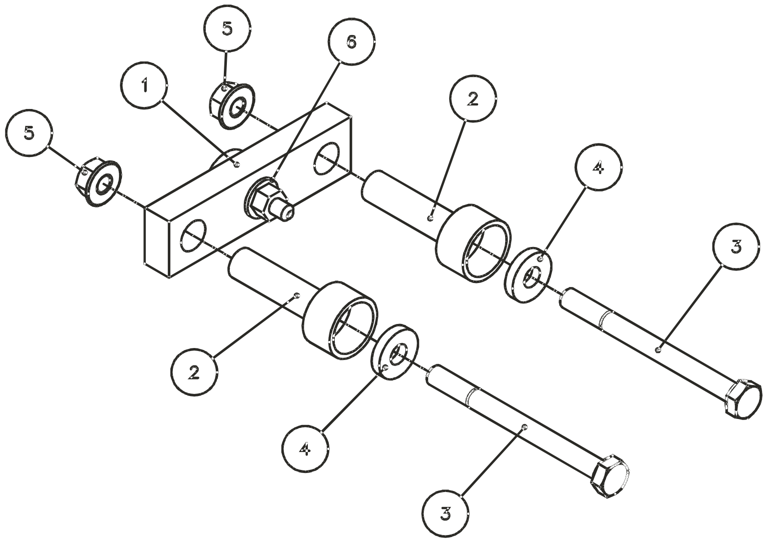


Table 7-15: SCR Clamp Parts

Item #	Quantity	Description
1	1	Loader Bar
2	2	Insulator cup
3	2	Bolt
4	2	Washer
5	2	Serrated nut (larger style clamp has 1 support bar)
6	1 or 2	Indicator Washer - Quantity dependant on style of clamp.

Tightening Clamp

Finger tighten the clamp. Ensure both bolts are tightened an equal amount so that the loader bar (item 1) is square in the heatsink. Tighten the bolts equally in 1/8 turn increments until the indicator washer(s) (item 6), which are under the nut(s) in the center of the loader bar, becomes loose indicating the clamp is tight. On the loader bars with two indicator washers, it may be necessary to tighten or loosen one side of the clamp to get both indicator washers free.

Testing SCR

After the SCRs have been replaced, conduct the resistance test.

Installation, Maintenance & Troubleshooting VFDs

8

In this chapter, you will learn:

- Installation, Maintenance and Troubleshooting Techniques for Variable Frequency Drives (VFDs)

VFD Installation

Precautions

1. Handle the drive with care to prevent damage to the plastic components. Do not hold the drive by the front cover.
2. Do not mount the drive in a location where excessive vibration (5.9 m/sec^2 or less) is present such as installing the drive on a press or other moving equipment.
3. Install in a location where temperature is within the permissible range (-10~40°C).

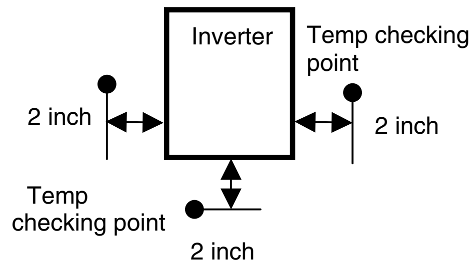


Figure 8-1: Installation Location Requirements

4. The drive will be very hot during operation. Install it on a non-combustible surface.
5. Mount the drive on a flat, vertical and level surface. Drive orientation must be vertical (top up) for proper heat dissipation. Also leave sufficient air space clearances around the drive. **On drives 40HP and larger, A= 20 inch and B= 8 inch.**

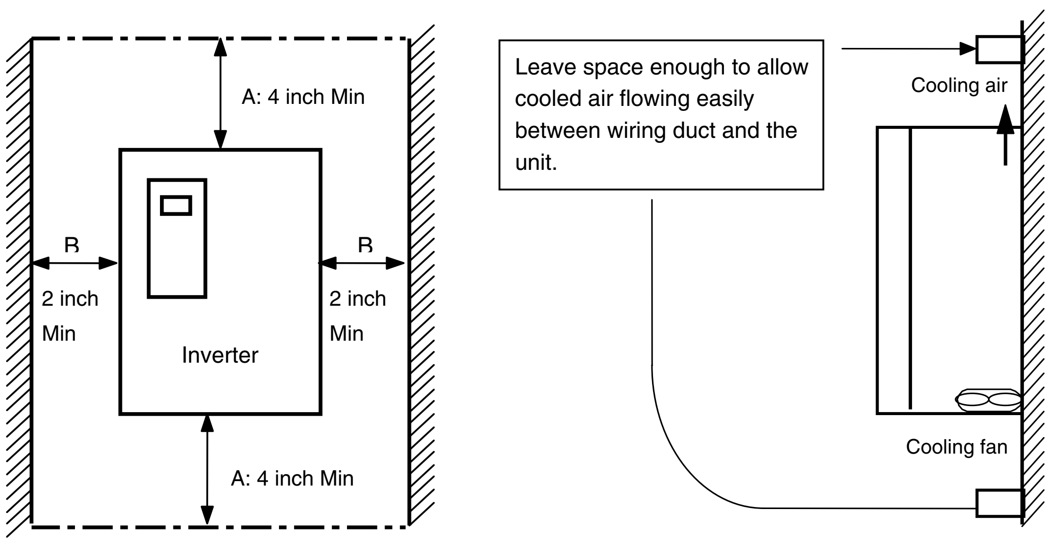


Figure 8-2: Drive Mounting Recommendations

6. Do not mount the drive in direct sunlight or near other heat sources.
7. The drive shall be mounted in a Pollution Class 2 environment. If the drive is going to be installed in an environment with a high probability of dust, metallic particles, mists, corrosive gases, or other contaminates, the drive must be located inside the appropriate electrical enclosure of the proper NEMA or IP rating.

8. When two or more drives are installed or a ventilation fan is mounted in the drive panel, the drives and ventilation fan must be installed in proper positions with extreme care taken to keep the ambient temperature of the drives below the permissible value. If they are installed in improper positions, the ambient temperature of the drives will rise.

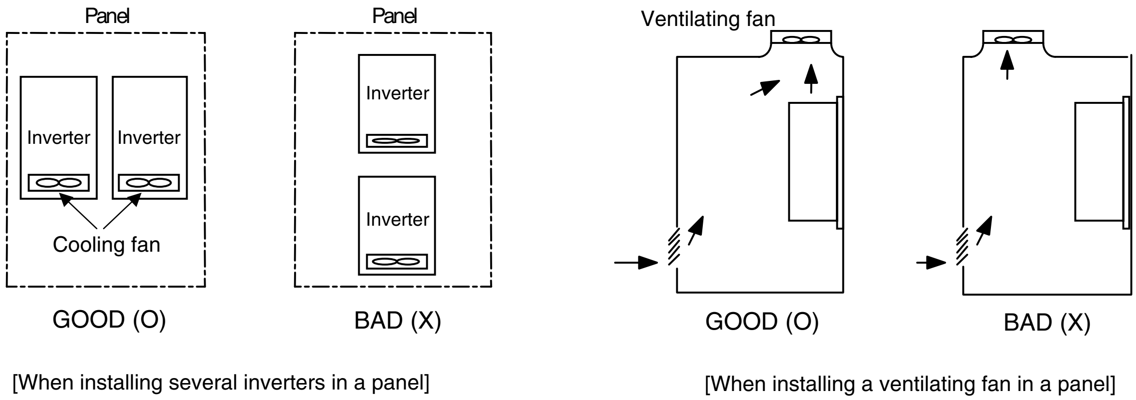


Figure 8-3: Recommended Drive Ventilation

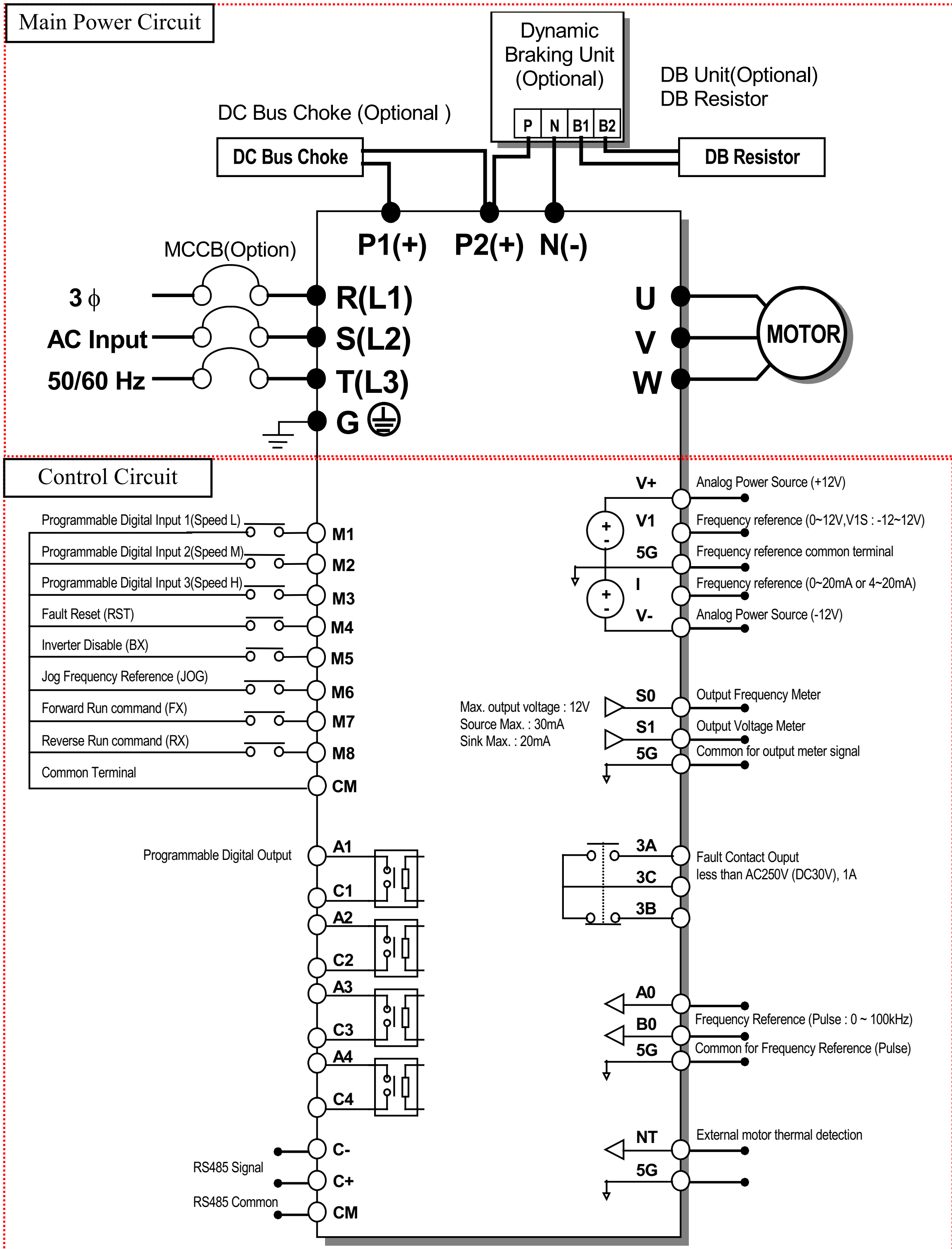
9. Install the drive using appropriate sized screws or bolts to insure the drive is firmly fastened.

CAUTION

Risk of Electric Shock More than one source of power may be present. More than one disconnect switch may be required to de-energize the equipment before servicing.

Wiring

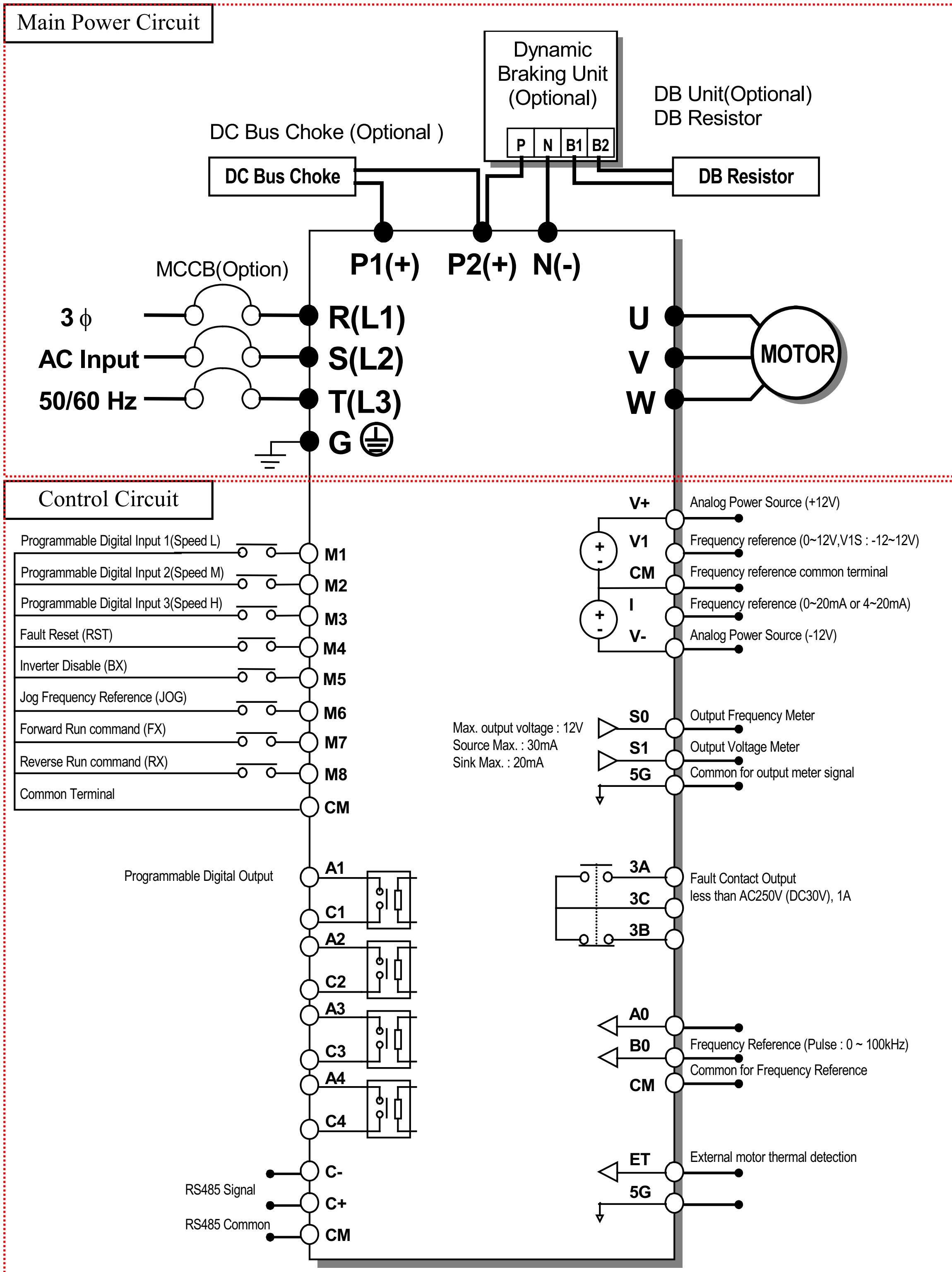
Basic Wiring For 7.5 ~ 40 HP



Note : 1) 5G is Common Ground for Analog Input/Output.
2) Use terminal V1 for V1, V1S (0~12V, -12 ~ 12V) input.

Figure 8-4: Wiring Diagram for 7.5~40 HP

Basic Wiring for 50 ~ 700 HP



Note : 1) 5G is Common Ground for Analog Meter Output(SO,S1) and External motor thermal detection(ET).
2) Use terminal V1 for V1, V1S (0~12V, -12 ~ 12V) input.

Figure 8-5: Wiring Diagram for 50~700 HP

Power Terminals

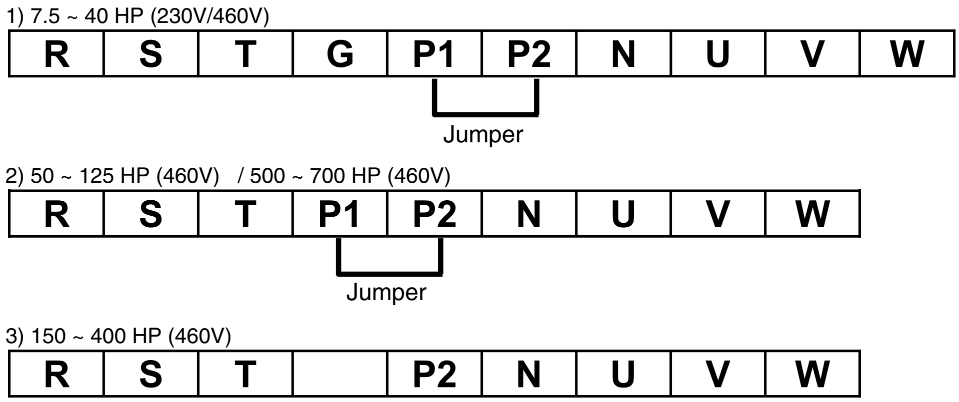


Figure 8-6: VFD Terminals

Table 8-1: Power Terminal Descriptions

Symbol	Description
R, S, T	AC Line Voltage Input
G	Earth Ground
P1, P2	External DC Reactor (P1-P2) Connection Terminals (Jumper must be removed).
P2, N	DB Unit (P2-N) Connection Terminals
U, V, W	3 Phase Power Output Terminals to Motor

Control Circuit Terminals

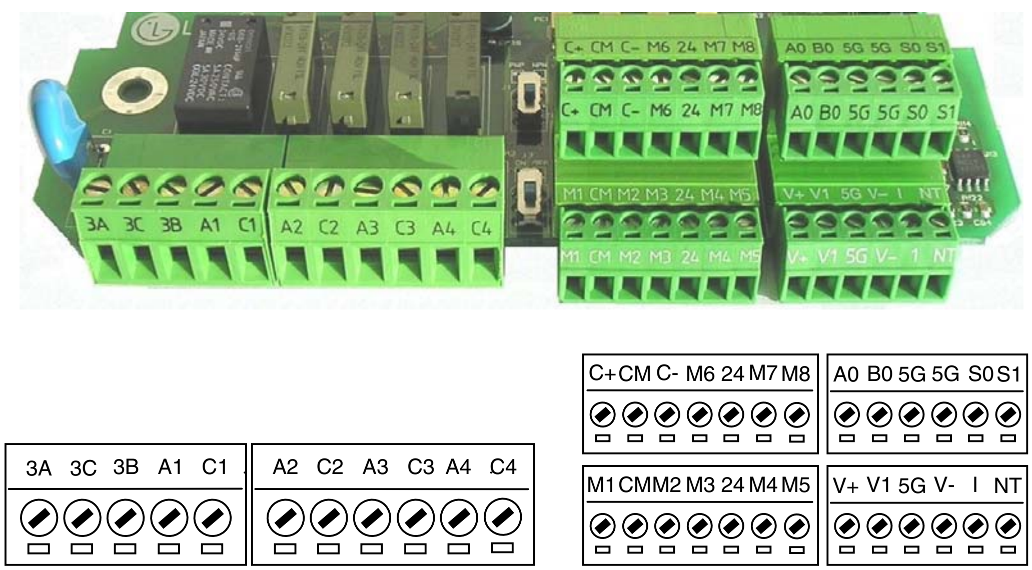


Figure 8-7: Control Circuit Terminal for 7.5 ~ 40 HP (230/460 V)

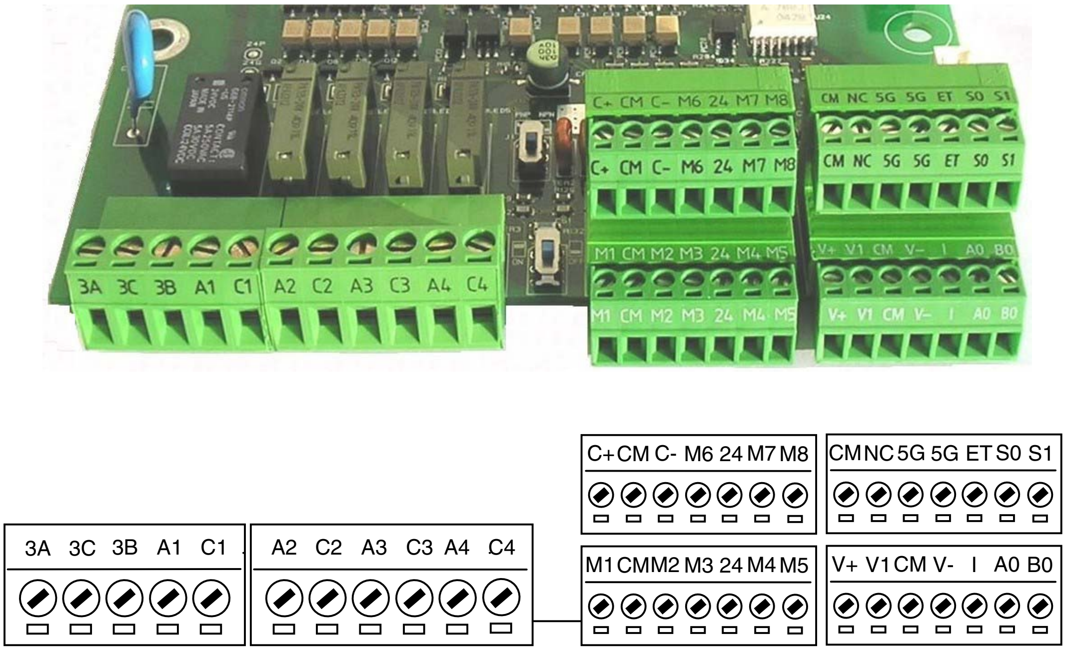


Figure 8-8: Control Circuit Terminal for 50 ~ 700 HP (460V)

Table 8-2:

Type		Symbol	Name	Description
Input signal	Starting Contact Function Select	M1, M2, M3	Multi-Function Input 1, 2, 3	Defines Multi-Function Inputs. (Factory setting: Multi-Step Frequency 1, 2, 3)
		FX [M7]	Forward Run Command	Forward Run When Closed and Stopped When Open.
		RX [M8]	Reverse Run Command	Reverse Run When Closed and Stopped When Open.
		JOG [M6]	Jog Frequency Reference	Runs at Jog Frequency when the Jog Signal is ON. The Direction is set by the FX (or RX) Signal.
		BX [M5]	Inverter Disable	When the BX Signal is ON the output of the drive is turned off. When the motor uses an Electrical Brake to Stop, BX can be used to turn off the output signal when the brake is applied.
		RST [M4]	Fault Reset	Used for fault reset.
		CM	Sequence Common (NPN) / 24V Com	Common terminal for NPN contact input and also common for the external 24V supply.
		24	Sequence Common (PNP) / Ext. +24VDC supply	Common 24 V terminal for PNP contact input. Can also be used as a 24VDC external power supply (maximum output: +24V, 50mA).
	Analog frequency setting	V+, V-	Frequency Setting Power (+12V,-12V)	Power supply for Analog Frequency Setting. (maximum output: +12V, 100mA, -12V, 100mA.)
		V1	Frequency Reference (Voltage)	Used by a DC 0-12V or –12~ 12 V input to set the frequency Reference. (Input Resistance 20 K).
		I	Frequency Reference (Current)	Used by a 0-20mA input to set the frequency reference. (Input Resistance 249).
		A0, B0	Frequency setting (Pulse)	Used by a pulse input to set the frequency reference.
		NT (~40HP) ET (50~ 125HP)	External motor thermal detection	Motor thermal sensor input. Used to prevent motor from overheating by using a NTC or PTC thermal sensor.
		5G	Frequency Setting Common Terminal	Common terminal for Analog Frequency Reference signals and FM (For Monitoring).
RS485 terminal		C+, C-	RS485 signal High, Low	RS485 signals (See RS485 communication in the manual for more details.)
		CM	RS485 common	Common And. Terminal for RS485 interface.

Table 8-2:

Type		Symbol	Name	Description
Output signal	Voltage	S0, S1	For external monitoring	Voltage output for one of the following: Output Frequency, Output Current, Output Voltage, DC Link Voltage. Default is set to Output Frequency. (Maximum Output Voltage and Output Current are 0-12V and 1mA).
	Contact	3A, 3C, 3B	Fault Contact Output	Energizes when a fault is present. (AC250V, 1A; DC30V, 1A) Fault: 3A-3C Closed (3B-3C Open) Normal: 3B-3C Closed (3A-3C Open)
		A1~4, C1~4	Multi-Function Output Relay	Use defined by Multi-Function Output terminal settings (AC250V, 1A; DC30V, 1A)

❖ **Note:** *M1~M8 terminals are User Programmable.*

Wiring Input and Output Power Terminals

General Power Wiring Precautions

1. The internal circuits of the drive will be damaged if the incoming power is connected and applied to the output terminals (U, V, W). If a drive bypass contactor is used, extreme care must be taken so that input voltage is never applied to the output terminals. An electrical or mechanical interlock of MC1 and MC2 is required for Inverter Bypass Operation.
2. Use ring terminals with insulated caps when wiring the input power and motor wiring.
3. Do not leave wire fragments inside the drive. Wire fragments can cause drive faults, short circuits, and other malfunctions.
4. Motor torque may drop when operating at low frequencies and with a long wire run between drive and motor.
5. The cable length between inverter and motor should be less than 150m (492ft). Due to increased leakage capacitance between cables, overcurrent protective feature may operate or equipment connected to the output side may malfunction. (But for products of less than 40 HP, the cable length should be less than 50m (164ft).)
6. The main power circuit of the drive may produce high frequency noise, and can hinder communication equipment near the drive. Do not run control wires in the same conduit or raceway with power wiring. To reduce noise, install line noise filters on the input and or output side of the drive.
7. Power wiring to the motor must have the maximum possible separation from all other power wiring. Do not run output wires in the same conduit as other wiring.
8. Cross wires at right angles whenever power and control wiring cross.
9. Do not use power factor capacitor, surge arrestors, or RFI filters on the output side of the drive. Doing so may damage the drive or the added components.
10. The input phase voltages must be balanced. Large input phase voltage imbalances can cause significantly imbalanced input currents that can result in excessive heating of the input diodes and the DC bus capacitors.
11. Always check whether the LCD keypad is off and the charge lamp for the power terminal is OFF before wiring terminals. The DC bus capacitors may hold high-voltage even after the power is disconnected. Use caution to prevent the possibility of personal injury.

Grounding

1. The drive contains high power and high frequency switching devices, leakage current may flow between the drive and ground. Ground the drive to avoid electrical shock.
2. Connect only to the dedicated ground terminal of the drive. Do not use the case or the chassis screw for grounding.
3. If multiple drives are installed near each other, each must be connected to ground directly. Take care not to form a ground loop between the drives and the grounding location.
4. The protective earth conductor must be the first one in being connected and the last one in being disconnected.
5. The grounding wire shall comply with all local regulations. As a minimum, the grounding wire should meet the specifications listed below. The grounding wire should be as short as possible and should be connected to a ground point as near as possible to the drive.

Table 8-3: Drive Capacities and Wiring Sizes

	Grounding wire Sizes, AWG or kcmil (mm^2)	
Drive Capacity	**230V Class**	**460VClass**
7.5 ~ 10 HP	10 (5.5)	12 (3.5)
15 ~ 20 HP	6 (14)	8 (8)
25 ~ 40 HP	4 (22)	6 (14)
50 ~ 75 HP	-	4 (22)
100 ~ 125 HP	-	2 (38)
150 ~ 200 HP	-	1/0 (60)
250 ~ 400 HP	-	4/0 (100)
500 ~ 600 HP	-	300 (150)
700 HP	-	400 (200)

Use of Isolation Transformers and Line Reactors

In most cases, the SG drive may be directly connected to a power source. However in the following cases a properly sized isolation transformer or a 3% or 5% line reactor should be used to minimize the risk of drive malfunction.

- When the source capacity exceeds ten (10) times the KVA rating of the drive.
- When power factor capacitors are located on the input source supplying the drive.
- When the power source experiences frequent power transients and/or voltage spikes.
- When the power source supplying the SG drive also supplies other large electrical devices such as DC drives that contain rectifiers or other switching devices.
- When the drive is powered from an ungrounded (floating) Delta connected source. In this case a drive isolation transformer utilizing a grounded secondary should be used.

Motor Lead Length Specifications

Excessive motor lead lengths may adversely effect the performance of the motor. The voltage of the pulses at the motor terminals can be almost double the input voltage of the drive. This in turn can cause additional stress on the motor insulation and shorten the life of the motor. The motor manufacturer should be consulted regarding the specifications of the motor insulation.

Lead lengths from the drive to the motor in excess of those listed below may require filters to be added to the output of the drive. Contact Benshaw for application assistance when using lead lengths in excess of those listed.

Table 8-4: Drive Voltage Specifications

Drive Voltage Rating	PWM Carrier Frequency	Suggested Max Motor Lead Length	
230V	All	150m (500 ft)	
460V	Less than or Default Frequency	More than 40 HP	150m (500 ft)
		40HP or Less	50m (170 ft)

If an output filter is used it is recommended that the output filter is wired as follows:

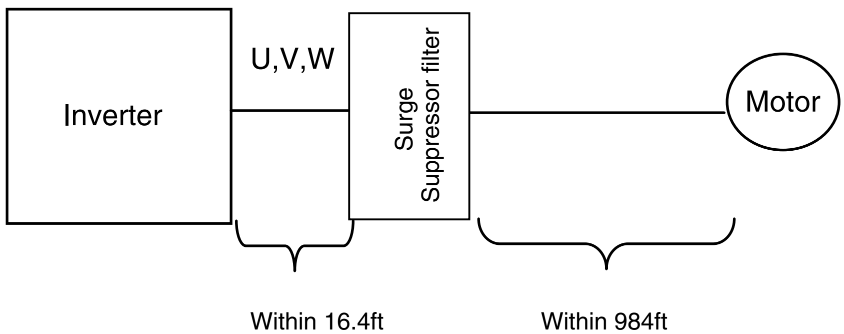


Figure 8-9: Motor Lead Length Specifications

- Wiring distance from drive output to filter input should not exceed 5 meters (16.4 feet).
- Wiring distance from filter to motor should not exceed 300 meters (984 feet).

Interference Suppression Measures

Electrical and electronic devices are capable of influencing or disturbing each other through their connection cables or other intended and unintended metallic connections. Interference suppression measures (electromagnetic compatibility) consist of two elements: raising interference resistance and suppressing interference emission.

Correct installation of the drive in conjunction with local interference suppression measures has a crucial effect on minimizing or suppressing mutual interference.

The following guidelines assume a power source that is not already contaminated by high frequency interference. Other measures may be necessary to reduce or suppress interference if the power source is already contaminated. Please consult Benshaw's Electrical Application Engineering Department if the following recommended interference suppression measures do not produce the desired result. Refer to Appendix C for more information.

- When dealing with RFI (radio frequency interference), the surface area of the conductors is a more critical consideration than its cross sectional area. Since high frequency interference currents tend to stay towards the outer surface (skin effect), braided copper tapes of equal cross section should be used.
- A central grounding (or earthing) point should be used for interference suppression. Route the ground cables radially from this point (star connection). Avoid making any ground loops that

may lead to increased interference. The drive and all components used for interference suppression, particularly the shield of the motor cable, should be connected over as large a surface area as possible when connecting it to ground. Remove the paint from contact surfaces if necessary to ensure a good electrical connection.

- Take care not to damage the shield's cross section and verify the continuity of the shield when splicing wires. Splices raise the RF resistance of the shield and can cause RF to radiate rather than continue in the shield. Shields, particularly those on control cables, must not be routed through pin contacts (pluggable connectors). When shielded cables must pass through a plug connection, use the metallic hand guard of the plug for the continuation of the shield. It is strongly recommended that the shield be uninterrupted whenever possible.
- Use a shielded motor cable that is grounded over a large surface area at both ends. The shield on this cable should be uninterrupted. If a shielded motor cable can not be used, the unshielded motor lines should be laid in a metal conduit or duct which is uninterrupted and grounded at both ends.

When selecting shielded cable for use as motor leads it is important to select a cable that is designed for operation at the frequencies and power levels involved with a variable frequency drive. Improper selection of motor cables can cause high potential to exist on the shield. This could cause damage to the drive or other equipment and can pose a safety hazard.

Many cable manufactures have shielded drive cable available. The following cables are acceptable for this purpose: OLFlex Series 150CY, 110CY, 110CS, 100CY, 100CS, and 540CP. Siemens CordaflexSM is also acceptable. Some of these cables are VDE-approved only; others carry VDE, UL, CSA, or a combination of these ratings. Be sure to confirm that the cables meet the appropriate local regulatory requirements.

OLFlex cables are available from OLFlex Wire & Cable, 30 Plymouth Street, Fairfield NJ 07004, 800-774-3539

Cordaflex cables are available from Siemens Energy and Automation, Inc., Power Cables, 3333 State Bridge Road, Atlanta GA 30202, 800-777-3539

If the installation requires the use of an output reactor, the reactor, as with a line filter, should be placed as close as possible to the drive.

Low voltage control wires longer than 1 meter (3ft) must use shielded cable and the shield must be terminated at the proper CM connection. Note that the connection to the CM rather than earth ground is allowed because the RSi SG drive has isolated control inputs. If the signal run exceeds 9 meters (30ft), a 020mA or 4-20mA signal should be used as it will have better noise immunity than a low-level voltage signal.

Other loads connected to the power source may produce voltage transients (spikes) that may interfere with or damage the drive. Input line reactors or input filters can be used to protect the drive from these transients.

If the drive is operated from switchgear devices or is in close proximity to switchgear devices (in a common cabinet), the following procedures are recommended as a precaution to prevent these devices from interfering with the drives operation.

- Wire the coils of DC devices with freewheeling diodes. The diodes should be placed as close as possible to the physical coil of the device.

- Wire the coils of AC devices with RC type snubber networks. Place the snubber as close as possible to the physical coil of the device.
- Use shielded cables on all control and monitoring signals.
- Route distribution cables (for example, power and contactor circuits) separately from the drive's control and monitoring signal cables.

Terminal Layout

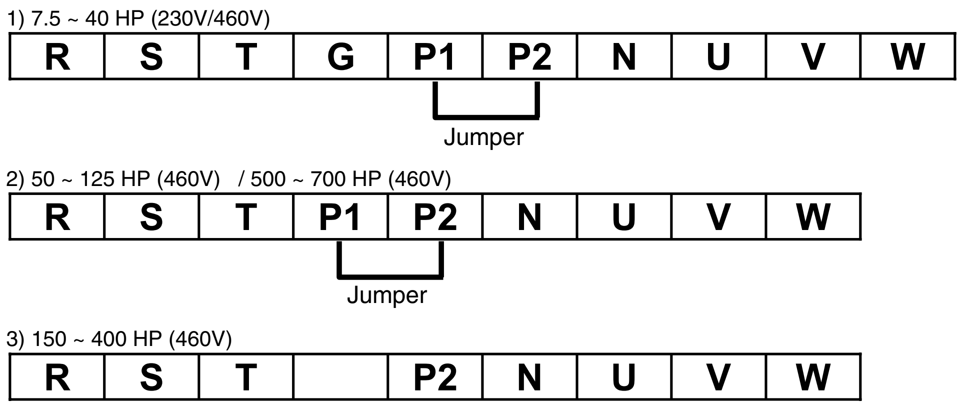


Figure 8-10: Terminal Layouts

Wires and Terminal lugs

The input power and motor cables must be of the appropriate type and dimensioned according to applicable national and local (NEC, etc.) regulations to carry the rated current of the drive. It is recommended that the cables be at least the size listed below in the following table.

Table 8-5: Terminal Specifications

Drive capacity		Terminal screw size	Screw torque 1)	Wire 2)			
				mm²		AWG or kcmil	
			Kgf·cm / lb-in	R, S, T	U, V, W	R, S, T	U, V, W
230v	7.5HP	M4	17 / 15.2	5.5	5.5	10	10
	10HP	M5	35 / 30.4	8	8	8	8
	15HP	M5	35 / 30.4	14	14	6	6
	20HP	M6	57 / 49.9	22	22	4	4
	25HP	M6	57 / 49.9	38	38	2	2
	30HP	M8	135 / 117.7	38	38	2	2
	40HP	M8	135 / 117.7	60	60	1/0	1/0

Table 8-5: Terminal Specifications

	Drive capacity	Terminal screw size	Screw torque 1)	Wire 2)			
				mm²		AWG or kcmil	
			Kgf·cm / lb-in	R, S, T	U, V, W	R, S, T	U, V, W
460v	7.5HP	M4	17 / 15.2	3.5	3.5	12	12
	10HP	M5	35 / 30.4	3.5	3.5	12	12
	15HP	M5	35 / 30.4	5.5	5.5	10	10
	20HP	M6	57 / 49.9	8	8	8	8
	25HP	M6	57 / 49.9	14	14	6	6
	30 ~ 40HP	M8	135 / 117.7	22	22	4	4
	50 ~ 75HP	M8	135 / 117.7	38	38	2	2
	100 ~ 125HP	M10	269 / 234.5	60	60	1/0	1/0
	150 ~ 200HP	M12	474 / 412.4	100	100	4/0	4/0
	250HP	M12	474 / 412.4	150	150	300	300
	350HP	M12	474 / 412.4	200	200	400	400
	400HP	M12	474 / 412.4	250	250	500	500

6. Apply the rated torque to terminal screws. Loose terminal screws can cause a short circuit or other malfunction. Over tightening the terminal screws/bolts may permanently damage the terminals.
7. Use copper (Cu.) wires only with 600V, 75 ratings. For 10~15HP 240V drives, R, S, T and U, V, W terminals are only for use with insulated ring type connectors.

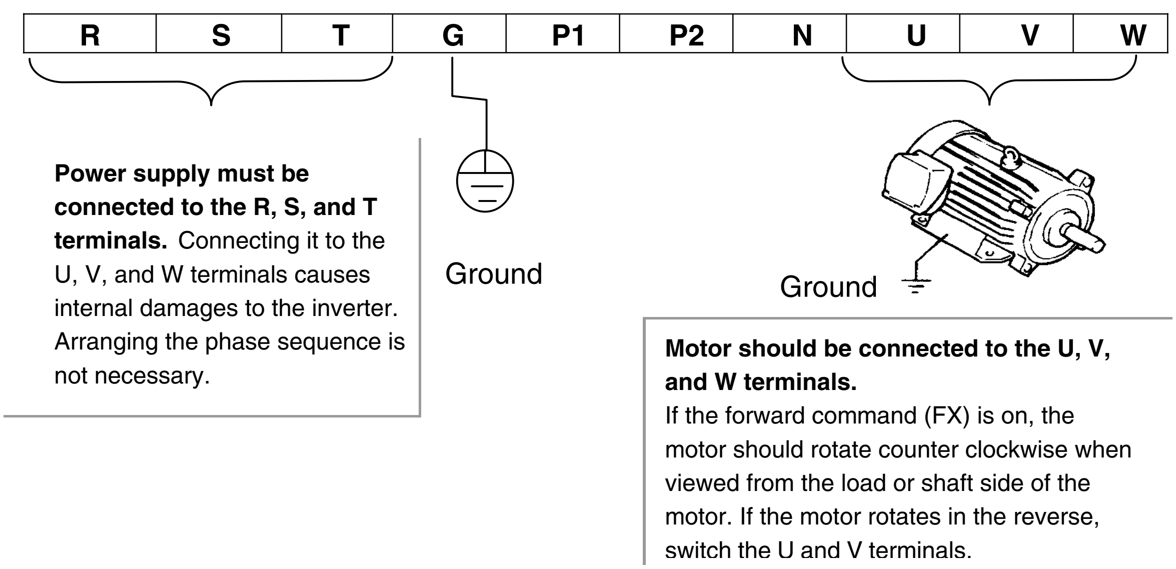


Figure 8-11: Power and Motor Connection Example (7.5~40 HP drives)

Control Circuit Wiring

Wiring Precautions

CM and 5G terminals are isolated from each other. Do not connect these terminals together or to the power or earth ground.

Do not apply voltage directly to control circuit input terminals such as FX, RX.

Use shielded wires or twisted wires for all control circuit wiring, and separate these wires from the main power circuits and other high voltage circuits (such as 120V or 240V relay circuits).

It is recommended to use the wires of 0.0804mm^2 (28 AWG) to 1.25mm^2 (16 AWG) for TER1 and TER2 control terminals and wires of 0.33mm^2 (22 AWG) to 2.0mm^2 (14 AWG) for TER3 and TER4 control terminals.

Terminal Layout

3 A	3 C	3 B	A 1	C 1	A 2	C 2	A 3	C 3	A 4	C 4

TER4 (22~14 AWG) TER 3 (22~14 AWG)

C+	CM	C-	M6	24	M7	M8
M1	CM	M2	M3	24	M4	M5

TER 2 (28~16 AWG)

A 0	B0	5 G	5 G	S0	S1
V +	V 1	5 G	V-	I	N T

TER 1 (28~16 AWG)
for 40HP and below

C M	N C	5G	5G	E T	S0	S1
V+	V1	C M	V-	I	A0	B0

TER 1 (28~16 AWG)
for 50HP and above

Control Circuit Operation

RSI-SG provides NPN/PNP modes for sequence input terminal on the control circuit. Connection method is shown in Figure 8-12.

NPN mode: When J1 switch is set to NPN (downward) mode, control circuit input terminal is turned ON using internal power supply (24V). CM terminal (24V GND) is common terminal for contact signal input.

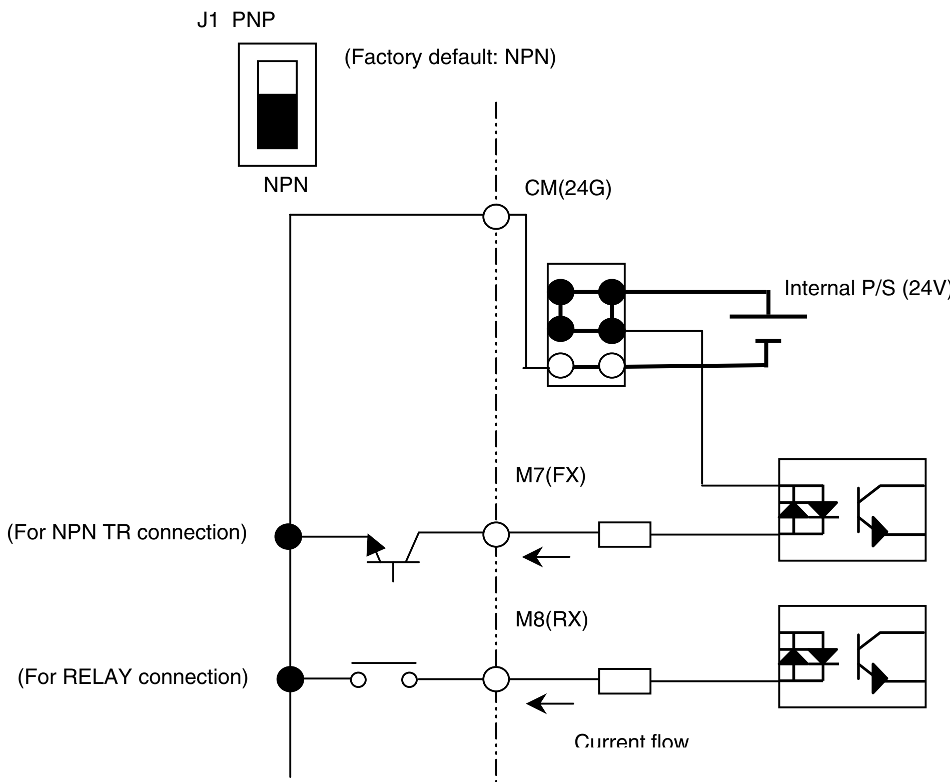


Figure 8-12: Control Circuit Operation: NPN Mode

PNP mode (Internal P/S used): When J1 switch is set to PNP (upward) mode, control circuit input terminal is turned ON. Terminal 24 (24V P/S) is common terminal for contact input signal.

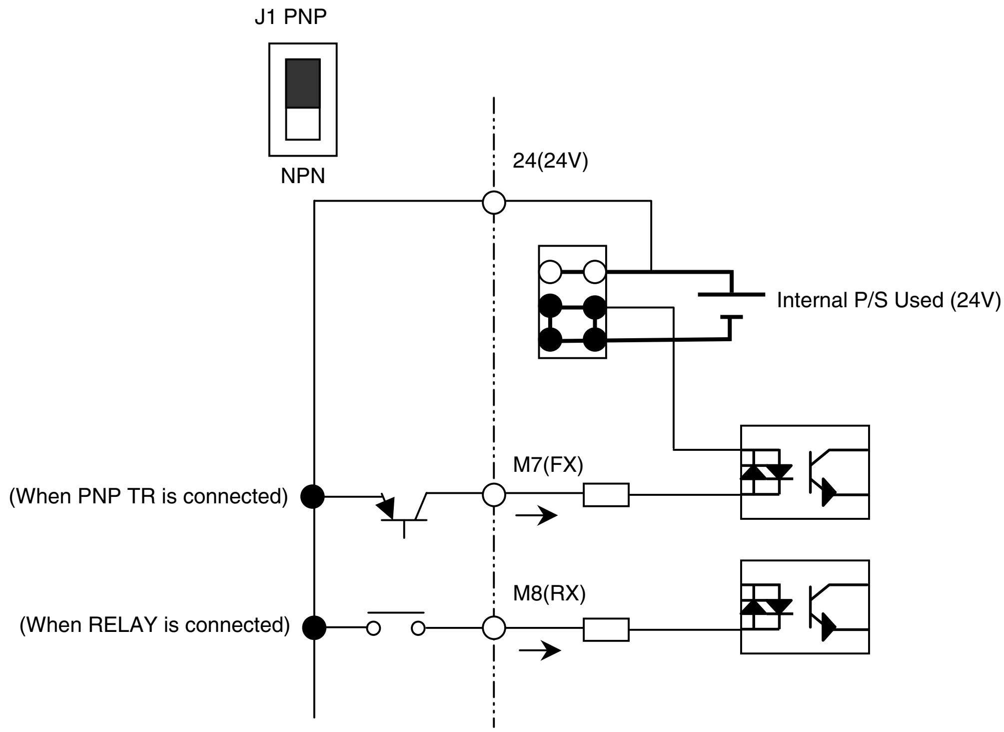


Figure 8-13: Control Circuit Operation: PNP Mode (Internal P/S used)

PNP mode (External P/S used): When J1 switch is set to PNP (upward) mode, control circuit input terminal is turned ON. To use external 24V P/S, make a sequence between external P/S (–) terminal and CM (24V GND) terminal.

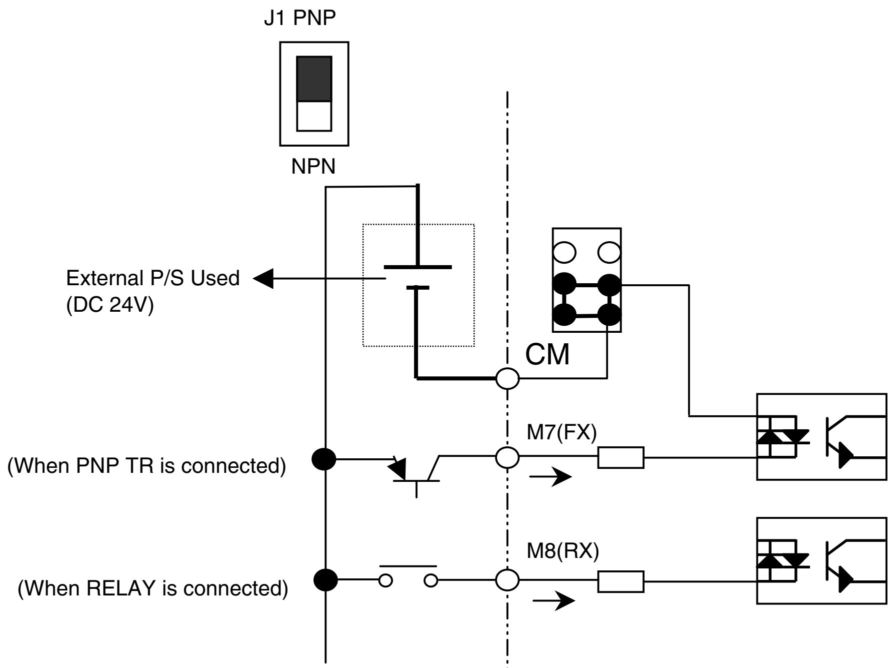


Figure 8-14: Control Circuit Operation: PNP Mode (External P/S Used)

RS485 Circuit Wiring

Use C+ (RS485 signal High) and C- (RS485 signal LOW) in TER 2. Turn the switch J3 ON (Upward) to connect the termination resistor (120 ohm) if required. J3 switch is on the left side of the TER2.

Table 8-6: RS485 Circuit Wiring

Item	Specification
Transmission type	Bus method, Multi drop Link System
Applicable drive	RSi-SG series
Number of drives	Max.31
Transmission distance	Within 3937ft Max. (2290ft recommended)
Recommendable cable	0.75mm2(18AWG), Shield Type Twisted-pair Wire
Installation	C+, C-, CM terminals on the control terminal block
Isolation	RS-485 port insulated from the drive power supply.

Keypad Wiring

Connect the keypad to the control board through keypad connector.

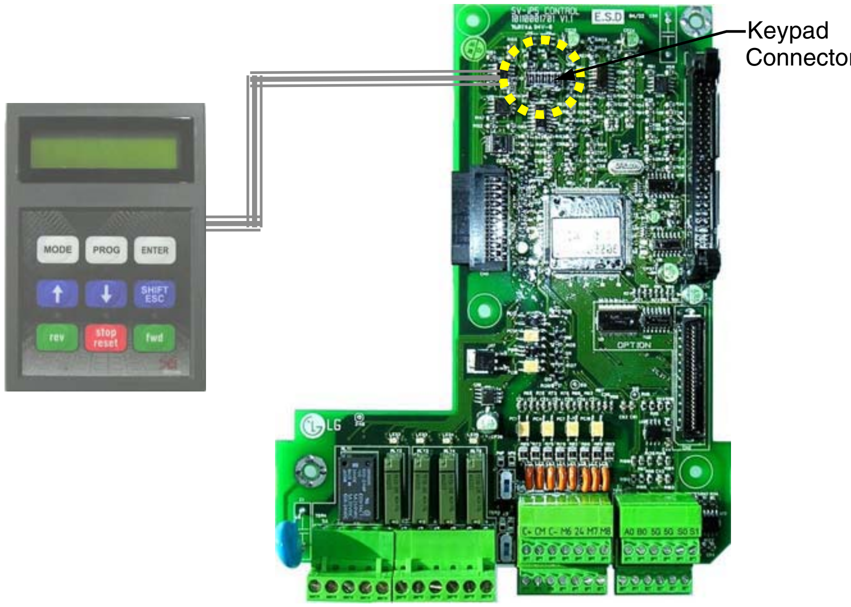


Figure 8-15: Keypad Wiring

VFD Troubleshooting

Fault Display

When a fault occurs, the drive turns off its output and displays the fault status in parameter DRV-13. The last five (5) faults are saved in parameter AFN-01 through AFN-05 along with the drive's operation status at the instance of the fault.

Table 8-7: Fault Display Codes

Keypad Display LCD	Protective Function	Description
Over Current 1	Over Current Protection	The drive turns off its output when the output current of the drive is more than 200% of the drive rated current.
Ground Fault	Ground Fault Protection	The drive turns off its output when a ground fault occurs and the ground fault current is more than a preset value. The over current trip function may also protect the drive when a ground fault occurs due to a low ground fault resistance.
Over Voltage	Over voltage protection	The drive turns off its output if the DC voltage of the main bus circuit increases higher than the rated value when the motor decelerates or when regenerative energy flows back to the drive due to a regenerative load. This fault can also occur due to a surge generated in the input power supply system.
Over Load	Current Limit Protection (Overload Protection)	The drive turns off its output if the output current of the drive is at greater than 120% (standard duty) or 150% (heavy duty) of the drive rated current.
Over Heat	Inverter Over Heat	The drive turns off its output if the heat sink is over heated due to a damaged cooling fan, a foreign substance blocking the heat sink or cooling fan(s), or operation in a high ambient temperature.
E-Thermal	Electronic Thermal	The internal electronic thermal overload protection of the drive has determined that the motor has over heated. The drive turns off the output. The drive cannot protect the motor when driving a multi-speed motor or when driving multiple motors, so consider thermal relays or other thermal protective devices for each motor. Overload capacity: 130% of user setting for 1 min.
Ext. Trip	External Trip	Multifunction input configured as "Ext_Trip" indicates a fault condition. Use this function if the user needs to turn off the output using an external trip signal. The external trip can be used to block the output to protect a motor if an external overload relay is used or to block operation if an motor or brake resistor overtemperature condition is indicated.
Low Voltage	Low Voltage Protection	The drive turns off its output if the DC bus voltage is below the detection level because insufficient torque and/or over heating of the motor can occur when the output voltage of the drive drops.
Over Current 2	IGBT Short	The drive turns off the output if an IGBT short through or an output short occurs.
Output Phase Open	Output Phase open	The drive turns off its output when the one or more of the output (U, V, W) phases is detected open. The drive checks the output current in all three phases to check for an open phase.

Table 8-7: Fault Display Codes

Keypad Display LCD	Protective Function	Description
BX	BX Protection (Drive Disable)	Used as an drive disable. The drive instantly turns off the output when the BX terminal is turned ON, and returns to regular operation when the BX terminal is turned OFF. Take caution when using this function.
HW-Diag	Inverter H/W Fault	A fault is indicated when an error occurs to the control circuitry of the drive. Possible causes are a Wdog error, a EEP error, a Input phase open, a NTC open and the ADC Offset.
COM Error CPU Error	Communication Error	This fault is displayed when the drive cannot communicate with the keypad.
Inv. OLT	Inverter Overload	The drive turns off its output when the output current of the drive flows more than the rated level (120% for 1 minute standard duty, 130% for 4 seconds) or (150% for 1 minute heavy duty, 162.5% for 4 seconds)
NTC open	NTC Open	This fault is displayed when drive internal NTC is opened.
LOP LOR LOV LOI LOX	Operating Method when the Frequency Reference is Lost	According to the I/O-48 [Operating Method when the Frequency Reference is Lost] setting, there are three modes: continuous operation, decelerate to stop, and free run, LOP: Displayed when option frequency reference is lost (DPRAM time out) LOR: Displayed when option frequency reference is lost (Communication network fault) LOV: Displayed when 'V1' analog frequency reference is lost. LOI: Displayed when 'I'analog frequency reference is lost. LOX: Displayed when sub-board (V2, ENC) analog frequency reference is lost.

To reset fault, Press **RESET** key, close RST-CM terminals or cycle the input power.

If a problem persists, please contact the factory or your local Benshaw distributor.

Fault Remedy

Table 8-8: Fault Causes and Suggested Remedies

Protective Function	Cause	Remedy
Over Current Protection 1	1) Acceleration/Deceleration time is too short compared to the inertial of the load. 2) Load is larger than the drive rating. 3) Drive turned output on when the motor is still rotating. 4) Output short or ground fault has occurred. 5) Mechanical brake on the motor is engaging too fast before the drive has actually turned off. 6) Components of the main circuit have overheated due to a faulty cooling fan or blocked cooling. 7) Power factor capacitors or other filters are connected to output of drive.	1) Increase Accel or Decel time. 2) Increase drive capacity. 3) Operate only after motor has completely stopped or use speed search function. 4) Check output wiring for shorts and ground faults. 5) Check mechanical brake operation. 6) Check cooling fan. 7) Remove capacitors or filters from output of drive. **Caution: Operating the drive prior to correcting the original cause of this fault may result in damage to the power section's IGBTs.**

Table 8-8: Fault Causes and Suggested Remedies

Protective Function	Cause	Remedy
Ground Fault Current Protection	1) A Ground fault has occurred in the output wiring of the drive. 2) A Ground fault has occurred in the motor.	1) Check the output wiring of drive for shorts. 2) Test and/or exchange motor.
Over Voltage Protection	1) Deceleration time is too short compared to the inertia of the load 2) Regenerative load 3) Line voltage too high	1) Increase deceleration time. 2) Use dynamic braking / regenerative resistor option if load is regenerative. 3) Check line voltage. Verify drive input voltage rating is correct. Reduce input voltage if necessary.
Current Limit Protection (Overload Protection)	1) Load is larger than the drive rating. 2) Incorrect drive capacity selected. 3) Incorrect V/F pattern or control mode set.	1) Increase capacity of motor and/or drive. 2) Select correct drive capacity. 3) Select correct V/F pattern or control mode.
Inverter Overheat	1) Cooling fan damaged or a foreign substance is blocking fan(s). 2) Foreign substance blocking heatsink. 3) Ambient temperature high. 4) Switching Frequency is too high for given loading and ambient condition.	1) Exchange cooling fans and/or eliminate foreign substance. 2) Check for foreign substances blocking heat sink. 3) Keep ambient temperature under 40 C. 4) Reduce PWM carrier frequency.
Electronic Thermal (ETH)	1) Motor has actually overheated. 2) Load is larger than drive rating. 3) ETH settings too low. 4) Incorrect drive capacity selected. 5) Incorrect V/F pattern. 6) Motor operated too long at low speeds.	1) Reduce load and/or running duty. 2) Increase drive capacity. 3) Verify motor and drive capability and adjust ETH level to a more appropriate level. 4) Select correct drive capacity. 5) Select correct V/F pattern or operating mode. 6) Install a motor cooling fan with a separate power supply and change ETH settings to forced air cooled motor.
External Trip	External Trip has occurred.	1) Eliminate trip condition of circuit connected to external trip terminal. 2) Disable external trip input.
Low Voltage Protection	1) Line voltage low. 2) Large loads are connected to same line as drive. (welding machine, motors with high starting current connected to the supply line) 3) Faulty inline contactor or one open phase at the input side of the drive	1) Check line voltage. Verify drive rating is correct for input voltage. 2) Increase line capacity if necessary to prevent low line condition. 3) Check for open circuit in wiring, open fuse, or bad contactor on input to drive.
Over Current 2	1) Short has occurred between the upper and lower IGBT. 2) Short has occurred at the output of the drive. 3) Acceleration/Deceleration time is too short compared to the inertial of load.	1) Check that the IGBTs are still good. 2) Check output wiring of drive for shorts. 3) Increase acceleration time.
Output Phase Open	1) Faulty contactor on output 2) Faulty output wiring	1) Check contactor at output of drive. 2) Check output wiring and connections for opens.
H/W Fault	Wdog error (CPU fault) EEP error (memory fault) ADC Offset (current feedback circuit fault)	Drive internal failure. Contact Benshaw Customer Service for more information.

Table 8-8: Fault Causes and Suggested Remedies

Protective Function	Cause	Remedy
Communication Fault	1) Faulty connection between drive and keypad 2) Drive CPU card malfunction	1) Check connector and wiring. 2) Replace drive CPU card.
Operating Method when the Speed Reference is Lost	LOP (Loss of reference from the Option), LOR (Remote) LOV (V1), LOI (I), LOX (Sub-V2, ENC)	Eliminate cause of fault.
Inverter Overload	1) Load is larger than drive rating. 2) Incorrect drive capacity selected.	1) Increase motor and/or drive capacity. 2) Select correct drive capacity.

Troubleshooting

Table 8-9: Troubleshooting Conditions and Remedies

Condition	Item to Check
The Motor Does Not Rotate.	1) Main circuit inspection: - Is the input (line) voltage normal? (Is the LED in the drive lit?) - Is the motor connected correctly? 2) Input signal inspection: - Check the operating signal input to the drive. - Check the forward and the reverse signal input to the drive? - Check the command frequency signal input to the drive. 3) Parameter setting inspection: - Is the reverse prevention (FUN-01) function set? - Is the Drive mode (DRV-03) set correctly? - Is the command frequency set to 0Hz? 4) Load inspection: - Is the load too large or is the motor jammed? (Mechanical brake) 5) Other: - Is an alarm or fault displayed on the keypad or is the alarm LED lit? (STOP LED blinks)
The Motor Rotates in Opposite Directions.	Is the phase sequence of the output terminal U, V, W correct? - Is the starting signal (forward/reverse) connected correctly?
The Difference Between the Rotating Speed and the Reference is too Large.	Is the frequency reference signal correct? (Check the level of the input signal) - Is the following parameter settings correct? Lower Limit Frequency (FUN-34), Upper Limit Frequency (FUN-35), Analog Frequency Gain (I/O-1~10) - Is the input signal line influenced by external noise or ground loops? (Use a shielded wire)
The Drive Does Not Accelerate or Decelerate Smoothly.	Is the acceleration/deceleration time is set too short a period of time? - Is the load too large? - Is the Torque Boost (AFN-68, 69) value is too high that the current limit function and the stall prevention function do not operate properly?
The Motor Current is Too High.	Is the load too large? - Is the Torque Boost Value (manual) too high? - Is the motor rated voltage parameter set correctly? - Is the input voltage low?
The Rotating Speed Does Not Increase.	Is the Upper Limit Frequency (FUN-35) value correct? - Is the load too large? - Is the Torque Boost (FUN-68, 69) value too high that the stall prevention function (FUN-70, 71) does not operate correctly?
The Rotating Speed Oscillates When the Drive is Operating.	1) Load inspection: - Is the load really oscillating? 2) Input signal inspection: - Is the frequency reference signal oscillating or being disturbed by noise? 3) Other: - Is the wiring too long when the drive is utilizing V/F control? (over 500m)

How to Check Power Components

Diode Module and IGBT Module Check (7.5~ 40 HP)

Before checking the power components, be sure to disconnect AC Input supply and wait until the Main Electrolytic Capacitors (DCP-DCN) is discharged. Note that more than one disconnect switch may be required to fully de-energize the equipment before servicing.

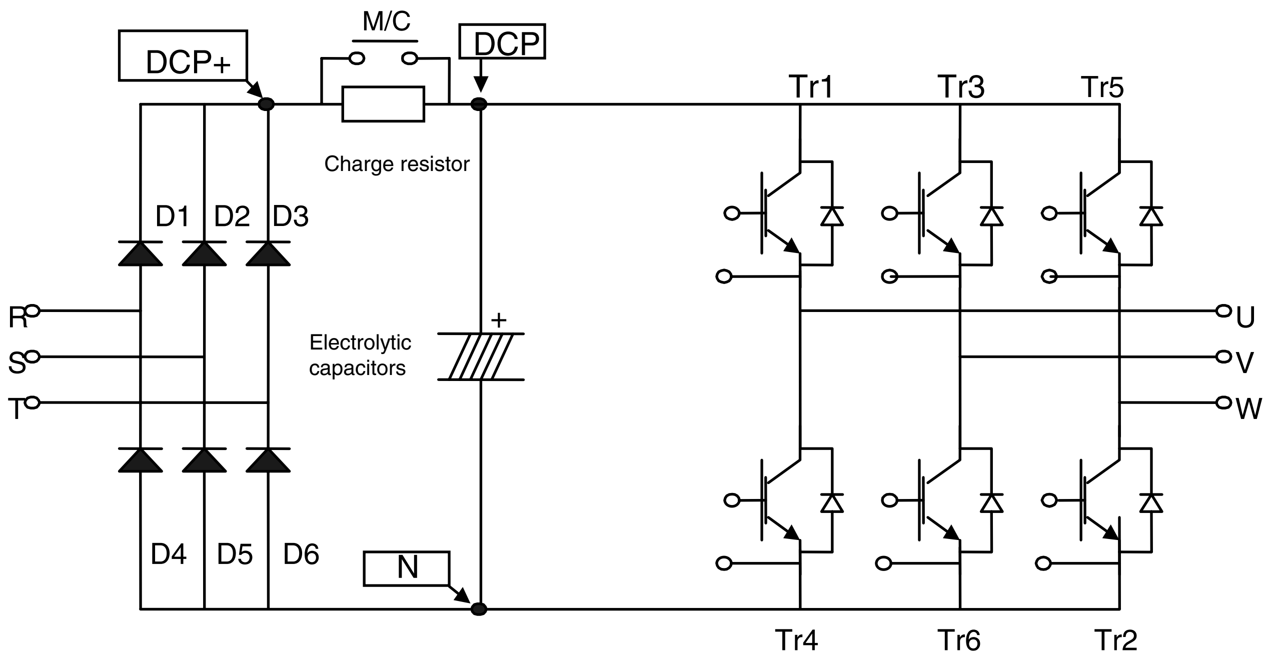


Figure 8-16: Diode module and IGBT Module Check (7.5~40 HP)

- Turn the power off and disconnect input (R,S,T) and output (U,V,W) wiring. Proper test results may not be achieved if any of the input or output wiring remain connected.
- Determine whether the drive terminals (R,S,T, U, V, W, P1(or P2),N) are energized or not by using a tester or meter.
- Wait until the Main DC Bus Electrolytic Capacitors (DCP-DCN) are discharged to a safe level. (The voltage between terminal P1-N (or P2-N) should be less than DC 30V).
- A large reading of resistance such as Mohegans will be displayed when the circuit is Open. When the circuit is closed, the resistance value will range from a few ohms to tens of ohms. Sometimes, a circuit will seem to be closed (or give negative resistance readings) due to the meter charging up the electrolytic capacitors within the circuit but high resistance will be eventually be displayed when the capacitors are charged.
- The measured values may not always be the exact same values depending on modules and tester types however they should be similar.

Table 8-10: Module Name and Test Points

Module		Test polarity +	Test polarity -	Check value	Number	Test polarity +	Test polarity -	Check value
Diode	D1	R	DCP+	Closed	D4	R	N	Open
		DCP+	R	Open		N	R	Closed
	D2	S	DCP+	Closed	D5	S	N	Open
		DCP+	S	Open		N	S	Closed

Diode Module and IGBT Module Check (50~ 125 HP)

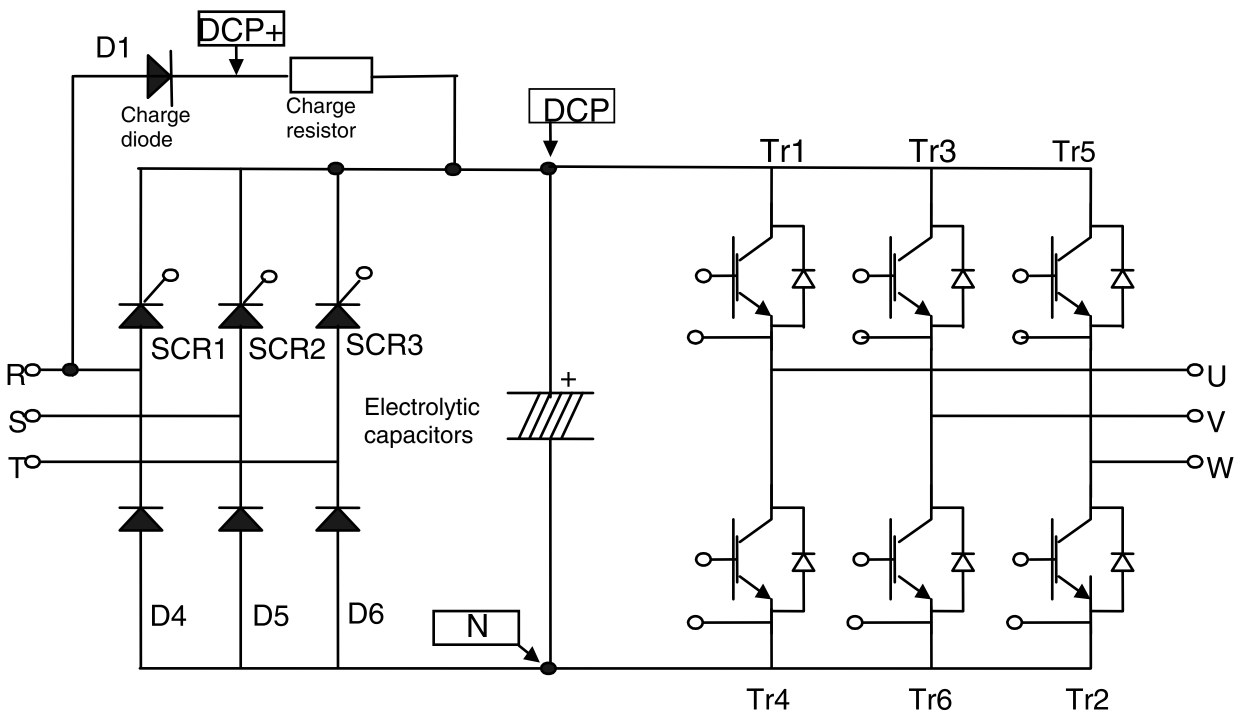


Figure 8-17: Diode Module and IGBT Module Check (50~125 HP)

- Turn the power off and disconnect input (RST) and output (UVW) wiring. Proper test results may not be achieved if any of the input or output wiring remain connected.
- Determine whether drive terminals (R,S,T, U, V, W, P1(or P2),N) are energized or not using a tester.
- Wait until the Main Bus Electrolytic Capacitors (DCP-DCN) is discharged to a safe level. (The voltage between terminal P1-N (or P2-N) should be less than DC 30V).
- A large reading of resistance such as Megaohms will be displayed when the circuit is Open. When the circuit is closed, the resistance value will range from a few ohms to tens of ohms Sometimes, a circuit will seem to be closed (or give negative resistance readings) due to the meter charging up the electrolytic capacitors within the circuit but high resistance will be eventually be displayed when capacitors are charged.

- The displayed values may not always be the exact same values depending on modules and tester types however they should be similar.

Table 8-11: Modules name and test points:

Module		Test polarity		Check value	Number	Test polarity		Check value
		+	-			-	+	-
		R	DCP+	Closed		R	N	Open
	D1	DCP+	R	Open	D4	N	R	Closed
Diode		S	N	Open		T	N	Open
	D5	N	S	Closed	D6	N	T	Closed
		U	DCP	Closed		U	N	Open
	Tr1	DCP	U	Open	Tr4	N	U	Closed
	Tr3	V	DCP	Closed	Tr6	V	N	Open
IGBT		DCP	V	Open		N	V	Closed
	Tr5	W	DCP	Closed	Tr2	W	N	Open
		DCP	W	Open		N	W	Closed

VFD Maintenance

The SG series drive is an industrial electronic product with advanced semiconductor elements. However, temperature, humidity, vibration and aging parts may still affect its operation. To avoid problems, it is recommended to perform routine inspections of the drive.

Precautions

- Be sure to remove the drive's power input while performing maintenance. Lock out all sources of power.
- Preventive maintenance should always be performed by a trained technician.
- Be sure to perform maintenance only after checking that the DC bus has discharged (The voltage between terminal P1-N (or P2-N) should be less than DC 30V). The DC bus capacitors in the electronic circuit can still be charged even after the power is turned off. A DC bus LED is not a definitive indication of the absence of DC voltage.
- The correct output voltage can only be measured by using a rectifier type voltage meter. Other voltage meters, including most digital voltage meters, are likely to display incorrect values due to the high frequency PWM output voltage of the drive.

Routine Inspection

- Be sure to check the following before operation:
- The conditions of the installation location
- The conditions of the drive cooling
- Abnormal vibration
- Abnormal heating

Periodic Inspection

- Are there any loose bolts, nuts, or rust caused by surrounding conditions? If so, tighten them or replace them.
- Are there any deposits or dirt inside the drive-cooling fan? If so, remove using compressed air.
- Are there any deposits or dirt on the drive's PCB (Printed Circuit Boards)? If so, remove using compressed air.
- Are there any abnormalities in the various connectors of the drive's PCB (Printed Circuit Boards)? If so, check the condition of the connector in question.
- Check the rotating condition of the cooling fan, the size and condition of the DC capacitors and the connections with the magnetic contactor. Replace them if there are any abnormalities.

Megger/Dielectric Test

Perform a megger test after the drive wiring has been disconnected. High test voltages should not be applied to the drive.

A Megger test should be conducted only for the main power circuit, never the low voltage control circuit. Connect the test jumpers as shown below and use a DC 500V megger voltage. Higher voltage dielectric tests should never be conducted on the drive. Otherwise, the power semiconductors, surge suppressors (MOVs), and/or other components may be damaged. Damage due to improper hi-pot or megger testing is not covered under warranty.

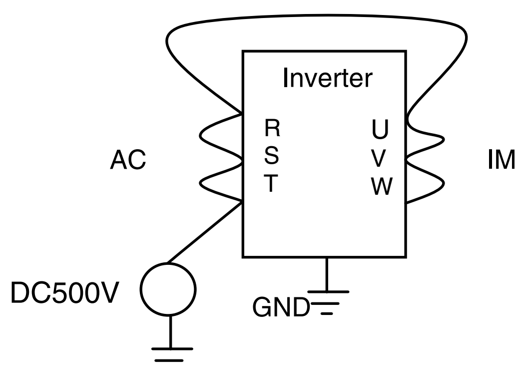


Figure 8-18: Megger/Dielectric Test

Daily and Periodic Inspection Items

Table 8-12: Inspection Items

Inspection Location	Inspection Item	Inspection	Period			Inspection Method	Criterion	Measuring Instrument
			Daily	1 Year	2 Year			
All	Ambient Environment	Is there any dust? Is the ambient temperature and humidity adequate?	✓			Refer to the precautions.	Temperature: -10~+40C. Humidity: Under 50% no dew	Thermometer, Hygrometer, Recorder
All	Equipment	Is there any abnormal oscillation or noise?	✓			Use sight and hearing.	No abnormality	
All	Input Voltage	Is the input voltage of the main circuit normal?	✓			Measure the voltage between the terminals R, S, T.		Digital Multi-Meter/ Tester
Main Circuit	All	Megger check (between the main circuit and the ground) Are any fixed parts removed? Are there any traces of overheating at each component's cleaning?		✓ ✓ ✓	✓	Undo the drive connections short the terminals R, S, T, U, V, W together and measure between these parts and the ground. Tighten the screws. Visual check.	Over 5MΩ No fault	DC 500V class Megger
Main Circuit	Conductor/ Wire	Is the conductor rusty or corroded? Is the wire coating damaged?		✓ ✓		Visual check	No fault	
Main Circuit	Terminal	Is there any damage?		✓		Visual check	No fault	
Main Circuit	IGBT Module /Diode Module	Check the resistance between each of the terminals.			✓	Undo the drive connection and measure the resistance between R, S, T and P, N and U, V, W and P, N with a tester.	(Refer 'How to Check Power Components")	Digital Multi-Meter/ Analog Tester
Main Circuit	DC Bus Capacitors	Is there any liquid coming out? Is the safety pin out, and is there any swelling? Measure the capacitance.	✓ ✓	✓		Visual check Measure with a capacitance-measuring device.	No fault Over 85% of the rated capacity	Capacitance Measuring Device
Main Circuit	Relay	Is there any chattering noise during operation? Is there any damage to the contact		✓ ✓		Auditory check Visual check	No fault	
Main Circuit	Resistor	Is there any damage to the resistor insulation? Is the wiring in the resistor damaged (open)?		✓ ✓		Visual check Disconnect one of the connections and measure with a tester.	No fault Error must be within ±10% the displayed resistance.	Digital Multi-Meter/ Analog Tester

Table 8-12: Inspection Items

Inspection Location	Inspection Item	Inspection	Period			Inspection Method	Criterion	Measuring Instrument
			Daily	1 Year	2 Year			
Control Circuit Protective Circuit	Operation Check	Is there any unbalance between each phases of the output voltage? Nothing must be wrong with display circuit after executing the sequence protective operation.		✓ ✓		Measure the voltage between the output terminals U, V and W. Short and open the drive protective circuit output.	The voltage balance between the phases for 230V (460V) class is under 4V (8V). The fault circuit operates according to the sequence.	Digital Multi-Meter/ Rectifying g Voltmeter
CoolingSystem	Cooling Fan	Is there any abnormal oscillations or noise? Is the connection area loose?	✓	✓		Turn OFF the power and turn the fan by hand. Tighten the connections.	Must rotate smoothly. No fault	
Display	Meter	Is the displayed value correct?	✓	✓		Check the meter reading at the exterior of the panel.	Check the specified and management values.	Voltmeter/ Ammeter etc.
Motor	All	Are there any abnormal vibrations or noise? Is there any unusual odor?	✓ ✓			Auditory, sensory, visual check. Check for overheat and damage.	No fault	
	Insulation Resistor	Megger check (between the output terminals and the ground terminal)			✓	Undo the U, V and W connections and tie the motor wiring.	Over 5MΩ	500V class Megger

❖***Note:*** *Values denoted with ✓ is for the 460V class drives. Note: Life cycle of the Main components indicated above is based on continuous operation with rated load. It may vary with surrounded environment.*

Parts Replacement

Table 8-13: Parts Replacement Expectancy

Part name	Period	Comments
Cooling fans	2-3 years	Exchange for a new fan after consulting Benshaw customer service center.
Electrolytic capacitors	5 years	Perform periodic inspections every year. Exchange after testing and consulting Benshaw customer service center. The Recommended capacitance level to replace a capacitor in the main/control circuit is when it has 85% or less of its initial value of capacitance.
Relays / Contactor	-	Exchange for a new part after consulting Benshaw customer service center.

The life expectancy of a part depends on the type of part, the environment it has been used in, and the operating conditions.