

Choosing the Right Cable for Your Variable Frequency Drive (VFD) System

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Table of Contents

Introduction	1
Benefits of Variable Frequency Drives	1
Why Choose a Purpose-designed VFD Cable.....	1-2
Attributes of a Well-Designed VFD Cable	3-5
Choosing a VFD Cable	5
Conclusion/References	6
Belden Industrial-grade VFD Cable Matrix	7
VFD System Glossary	8

Introduction

Variable Frequency Drives (VFDs) are among the most useful devices in the industrial world. They allow the speed of a 3-phase AC electric motor to be altered whenever the behavior of the motor's load change. By changing its output frequency and voltage, the VFD allows the motor to modify its RPMs to respond to those demands.

Benefits of Variable Frequency Drives

- Improved process control
- Energy savings
- Higher reliability
- Reduced wear and tear

AC (induction) motors are very common in discrete manufacturing and processing plants throughout the world. Imagine if all those motors could only spin at one speed, even when their loads are modifying their demands, and even when process variables (temperature, pressure, force, etc.) are changing. With motors delivering products at a constant speed regardless of new, changing conditions, scrap would pile up and energy would be wasted. (See Sidebar, "Torque, Speed, Horsepower and Load," on page 2.)

The pulse width modulation (PWM) VFD Drive design is the most common because of its ability to work with motors that range in size from fractional to hundreds of horsepower. It is reliable, affordable, and offers significant electrical energy savings. When a motor is run at half its maximum speed, it consumes significantly less energy than it does at full speed. Depending on the load characteristics, the power at half speed can be as little as 1/8th the base speed power.

When using a VFD, motor speed can be changed almost instantaneously to address load and process changes. An added benefit is its ability to increase the precision of process control with the ability to control motor speeds to within 0.1% tolerance.

A VFD can provide a "soft start" capability for a motor (that is, the motor can be ramped up to desired speed instead of being turned on at full RPMs), decreasing the mechanical stresses associated with full-voltage start-ups. This results in lower maintenance costs and a longer motor life. In cyclic loads the VFD also helps to avoid motor overheating.

Why Choose a Purpose-designed VFD Cable?

Like many engineering solutions, VFDs present not only benefits, but also drawbacks. For example, the same fast switching rate of the transistors inside a pulse-width modulated VFD that can accommodate an abrupt speed change in a motor (and offer precise control of processes) is also capable of generating unwanted noise in the drive system cable and in the drive itself.

Electrical energy flowing in the cable contains frequencies as high as 30 MHz. If this high frequency energy is not contained within the cable, it can radiate out to interfere with the proper operation of nearby equipment. Examples include electronic equipment, less-than-robust, or commercial grade Ethernet systems and simple instrumentation wires—even circuits that have absolutely nothing to do with the VFD system itself.

This noise emission can sometimes be difficult to track down and eliminate and is likely the single most significant problem associated with VFD systems today. Unless a proper cable shielding design is present to control it, noise emission from a drive system cable can disrupt plant and factory operations. Moreover, because a longer cable radiates more noise, the length of cable runs must be limited. That, in turn, puts a limitation on factory layout. (See Sidebar, "Tips for Better Management of Cable Noise Interference," on page 3.)

The way in which the components of a VFD system (drive, cable and motor) are selected, aligned and operated will impact system reliability. The cable connecting the VFD to the motor, positioned center stage within the drive system, plays an especially vital role in optimizing VFD system component longevity and performance. (See Figure 1, page 2.)

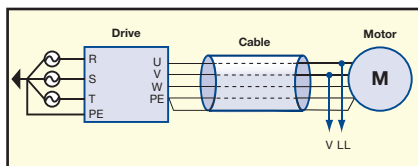


Figure 1. Diagram of a typical VFD system.

There are 4 key cable related issues that commonly effect variable frequency drive systems:

- Common mode current
- Cable charging and capacitive coupling
- Reflected wave voltage
- Installation safety and reliability

Common mode current is sometimes known as current noise. It is defined as any current that leaves the drive on the primary motor leads and returns through any ground path (including the cable grounds and shield).

The role of VFD cable is to provide the most attractive path for these potentially harmful currents to return to the drive with minimal disturbance to the surrounding networks and instrumentation. A cable that provides the lowest impedance ground path will be most effective in reducing common mode currents. It is Belden's observation that systems with a significant number of smaller drives tend to be proportionally more likely to see issues with common mode noise. We attribute this tendency to faster switching devices and reduction of output filtering in the more cost sensitive drive products.

Capacitive coupling and cable charging are effects which consume some of the drive output currents in capacitive interaction with either the other motor leads, or other adjacent cable systems. These phenomena can consume drive power and result in reduced motor torque, drive overload trips,

and induced voltages on adjacent cable systems. The keys to reducing the cable losses associated with capacitive coupling and cable charging are: Having the lowest practical cable capacitance, and ensuring that motor lead sets are effectively shielded from each other to prevent capacitive interaction. Capacitive charging losses are proportional to the length or run, and the number of conductors with which a given set of motor leads can capacitively interact. A worst case scenario is when multiple motor leads with high capacitance (THHN for example) are ganged together in conduit.

Reflected wave voltage is a problem common in VFDs with longer motor leads. The mismatch between the cable and motor impedance leads to a voltage reflection at the point where the leads enter the motor windings. This reflection leads to a standing wave effect, and a potential doubling of

Load, Torque, Speed, and Horsepower

Key terms that describe the operation of an industrial AC motor controlled by a VFD are: load, motor speed, motor torque and motor horsepower rating (see glossary on page 8 for detailed definitions).

- **Load:** Device that a motor must move
- **Torque:** Twisting force that leads to rotation
- **Speed:** Rate of the turning of the motor shaft
- **Horsepower rating:** The maximum rate at which the motor can perform

Every load in an industrial setting presents its own varying torque demands on the motor, and motor loads can be categorized as constant torque load, variable torque load or constant horsepower load. Further, torque varies with the operation required:

- Break-away torque (to start a load moving)
- Acceleration torque
- Running torque
- Peak torque
- Holding torque

Power = Speed x Torque

At a constant horsepower operation, when motor torque goes up, motor speed goes down, and vice versa. The formula that describes this is: Power = Speed x Torque

Properly Matching a VFD & VFD Cable

- **Understand the nature and requirements of the load.** The VFD and cable must have sufficient current capacity so that the power they supply to the motor is able to meet the torque requirements that the load will demand. Motor torque ultimately depends on the current passing through the motor, while the motor's speed depends on the frequency applied to it.
- **Select the right cable** Noise emissions, voltage reflections and motor cable failures can be substantially reduced or even avoided by choosing the appropriate VFD cable. There are essentially 2 types of VFD cable in the marketplace, construction grade VFD cables, and high performance VFD cables.

Construction grade VFD cables tend to be those with building wire type stranding and conforming minimally to the standards of UL/CSA Tray Cable(UL 1277) Typically construction grade VFD cables have a single layer of copper tape shielding, and have bare grounds conforming to the minimum requirements of the NEC. High performance VFD cables are highly suitable to more noise sensitive applications and environments. These cables tend to have significantly enhanced ground and shielding systems, and may have as much as 3 times lower ground impedance. These cable typically have flexible stranding with 4-8 times more surface area, and the resultant improvements in high frequency performance, along with tinned conductors for more reliable and stable connections. With an improperly selected cable, voltage waves reflected back from the motor toward the VFD along the cable can produce excessively high voltages in the cable's conductors. Peak voltages of up to 2.5 times the nominal system voltage can be present in the cable, resulting in voltage reflections that can cause in-service motor failures. There is also concern over long-term cable damage while under high voltage, most notably with VFDs operating at 575 volts and above.

High voltage levels in the cable can also cause a corona discharge to occur between the conductors. This can damage the cable and the motor, as well as the motor bearings and the drive, leading to a failure of the entire system, with ensuing production downtime.

motor terminal voltages. Higher voltages increase the probability of either a motor or drive failure. Using cables with the lowest capacitance will increase the critical distances (the distance where the cable is fully rung up to twice the drive bus voltage), thus potentially reducing the stresses on motor windings and VFD cable.

Installation safety and reliability is ensured when a properly designed cable system is selected. It is critical to select a system that can withstand the challenges associated with harsh environments, and electrical challenges, as well as one that will provide the highest degree of safety.

Induced voltages and system failures as a result of unsuitable cable selection create both risk to personal safety, and operational reliability.

Attributes of a Well-designed VFD Cable

It is important to select a motor drive cable that has been properly designed and engineered to address all the key technical issues that such a component faces. (See Figure 2 below for a closer look at the anatomy of three types of VFD cable and to aid in understanding the following descriptions of essential cable attributes.)

A well-designed grounding configuration: An electrical grounding system provides a reference voltage, ideally zero, for other VFD system voltages. It is not always possible to bring the ground voltage to a true 0V level, but the ideal reference can be approximated by bringing all grounded points to the same very low potential.

Creating a low impedance ground path between the motor and drive is essential to reducing potential(voltage) differences, and thus harmful common mode currents.

When the VFD cable provides the lowest impedance ground path, it will mitigate common mode current flowing into other devices/systems. Having a suitable ground means it is possible to control where the potentially harmful energy from the VFD goes.

Ground sizes allowed by the National Electrical Code (NEC) vary by conductor size, but, except in smaller cables, they are typically required to be significantly smaller than the circuit conductors. In order for a VFD cable to be optimally effective, it should have significantly more copper at

Tips for Management of Cable Noise Interference

Unshielded VFD cables can radiate more than 80V of noise to other unshielded communication wires and cables, and more than 10V of noise to shielded instrumentation cables. When VFD cables are installed close to low-level communications cables and other susceptible devices, it is necessary to ensure that shielding is present in the VFD cable.

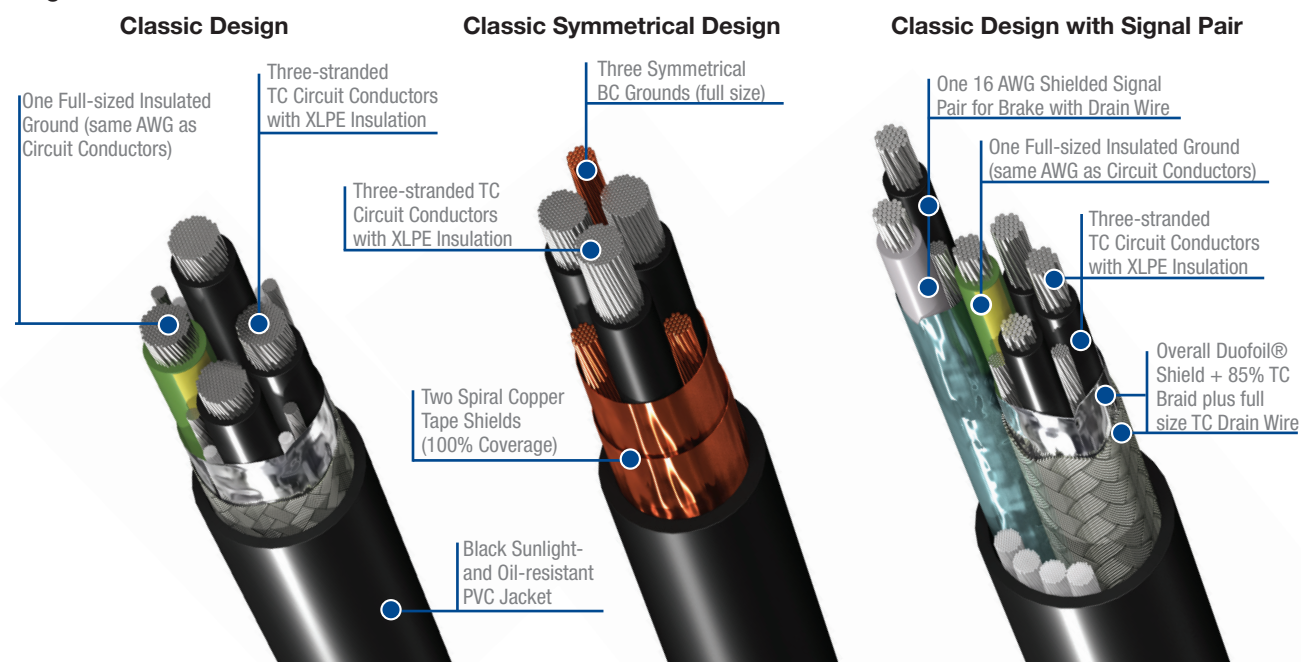
The use of unshielded cables in conduits around a VFD setup should be limited or eliminated completely, since the conduit is an uncontrolled path to ground for the noise it captures.

If radiated noise is an issue in an existing VFD installation, consider how the instrumentation and control cables are routed and their location related to other cables and machines. Maintain as much separation as possible between noise-susceptible cables and VFD cables—a minimum of 1 ft. for shielded instrumentation cables and 3 ft. for unshielded instrumentation cables.

If the two types of cable must lie close to each other, try to minimize the amount of parallel runs between them; it is wise to limit these stretches to 10 ft. or less to reduce the likelihood of picking up radiated noise. Finally, if the two types of cable must unavoidably cross, it is preferable to cross them perpendicularly, at a single point.

Belden's Classic, Classic Symmetrical and Classic with Signal Pair VFD Cables

Figure 2



Why Choose the Lowest Impedance Cables?

Engineers should select the VFD cables with the lowest impedance possible. This is done for two main reasons.

First, when the conductor impedances is lower, maximum power is transferred from the VFD to the motor to do useful work, with only a small amount of energy reflected. However, if there is a substantial mismatch between the impedances of the cable and motor, damaging reflected wave voltages are generated, and energy is lost. This reduces the stress on the motor windings and cable, and leads to greater system reliability and life.

Having the lowest impedance ground path (i.e., one with a large cross-sectional area of copper in the ground wires and shielding (see the matrix on page 7), means a low ground resistance from one end of the cable to the other to minimize ground loops and common mode current. (See the glossary on page 8.) By contrast, with the higher resistance of a smaller sized grounding/shielding system, a voltage difference between the motor and drive is more likely. Such an offset in potential encourages ground loops. It is possible to get by with a single ground conductor of a small gauge size, but this may ultimately have a negative impact on instrumentation or communication circuits in the local area if energy leaks out and is conducted into adjacent systems

ground potential than is required by the NEC. Belden's research has shown that the common mode noise released is inversely proportional to the amount of copper at ground potential, and the amount of surface area in the ground potential copper. Cable designs vary from those which have 1 or less full sized grounds to 4 conductor foil braid and drain combinations which offer 3 or more circuit equivalents at ground potential.

One approach for grounding a cable is to use an insulated ground conductor, terminated both at the motor and at the drive. The shield surrounding the circuit conductors should be tied both physically and electrically to the insulated ground at the point where the cable enters the motor housing and the drive proper. (See Belden VFD Termination Guide)

Alternatively, in what is known as a symmetrical-design cable (see cable matrix, page 7), three conductors are used for the ground—each relatively small in gauge size, though when taken together they add up to the equivalent gauge size of the circuit conductors. These are connected to the shield, so when they are terminated together at the ground lug on the motor case, the shield is automatically terminated.

Noise immunity: Noise radiated from a VFD cable is proportional to the amount of varying electric current in it, as well as cable length. A higher current and/or greater length produces higher levels of radiated noise. By properly shielding the VFD cable, noise can be controlled. Belden's research

has concluded that the lowest impedance shielding and grounding systems are the most appropriate for VFD applications. This is due to the low impedance path provided for common-mode noise to return to the drive. Foil shields are not robust enough to restrict the volume of noise generated by VFDs.

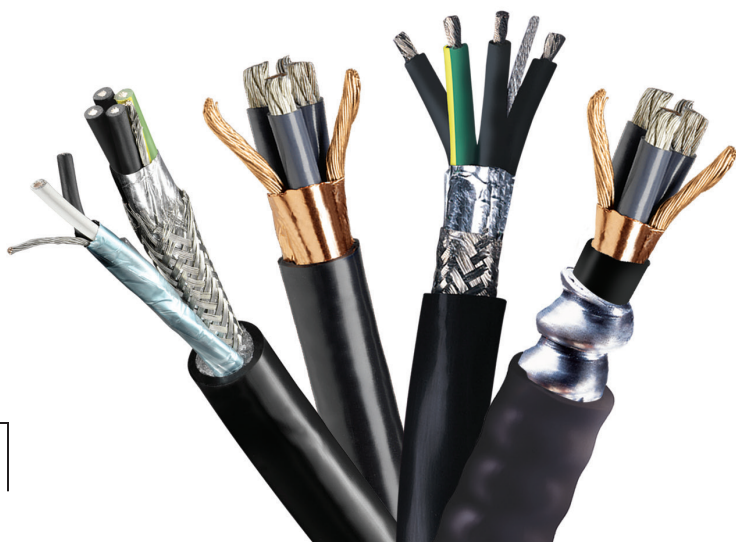
Low dielectric constant: An important property of the cable insulation is its dielectric constant, or relative permittivity. In a cable, the dielectric constant should have a low value if the cable is to have a low capacitance, and consequently, minimize voltage reflections from the motor back to the drive. Of course, shielding helps suppress noise, but cross-linked polyethylene (XLPE) insulation, with its low dielectric constant, also helps to diminish noise.

An insulation with a low dielectric constant, such as XLPE, effectively reduces the energy stored in the cable and thus increases the critical distances required to ring up full (2x) reflected wave voltages. As a result, a low dielectric-constant insulation, such as XLPE, permits longer cable runs.

Suppression of reflected wave voltage: Without a proper cable design, reflected waves caused by a cable-to-motor impedance mismatch can be problematic in a VFD application. The magnitude of this problem depends on: cable length, rise-time of the pulse-width modulated carrier wave coming from the drive, VFD voltage, and the degree of the impedance mismatch between the motor and cable. XLPE insulation, a material with a high-impulse voltage breakdown rating significantly reduces the risk of failure from reflected waves and voltage spikes. It is much more robust than PVC (PVC is not recommended for VFD applications).

Thick insulation wall: A thicker, industrial-grade XLPE insulation provides:

- More stable electrical performance than PVC
- Lower cable capacitance, providing for:
 - Longer cable runs



- Reduced peak motor terminal voltages for extended motor life
- Greatly reduced likelihood of corona discharge
- Reduced magnitude of standing waves
- Increased efficiency of power transfer from drive to motor

Low risk of corona discharge: Use of XLPE insulation reduces the likelihood of either the cable or the motor voltage reaching its corona inception voltage (CIV). CIV is the point at which the air gap between two conductors in the cable, or between two windings on the motor, breaks down via electrical arcing. A corona discharge produces extremely high temperatures. If the insulation system of the cable is a thermoplastic material (i.e., PVC), the effect can cause premature cable burnout or a short circuit due to a gradual, localized melting of the insulation. By contrast, the heat generated from corona discharge forms a thermally-insulating charred layer on the surface of XLPE insulation in the cables, preventing further degradation.

Proper bonding: Bonding refers to how the components of grounding systems are physically connected or joined in order to tie them together electrically. In a VFD cable, this has implications for how well the shield and the ground conductors are connected to the motor case or drive enclosure, and ultimately, to earth ground potential. VFD cables perform best when the grounds and shields are connected at the motor and drive, with no intermediate bonding of the ground to introduce "jumping of points" for the current noise that has been captured by the carefully designed ground and shielding system inside the VFD cable.

Choosing a VFD Cable

There is no body or organization that decides if a cable is suitable for operation with VFDs and no standards for what can be called a VFD cable. Some manufacturers describe high capacitance PVC/Nylon insulated cables

as VFD cables when they have simply added shield to a 600V tray cable. In general; however, the market is comprised of cable which have effective XLPE insulation systems, and a variety of shielding systems that effectively reduce radiant noise and effectively withstand the dielectric stresses present due to reflected wave voltages. Beyond that the market for VFD cables is effectively broken into 2 distinct segments. We call those the construction grade products, and the high performance products. The distinction between these segment lays in a number of factors and attributes:

Stranding: High performance VFD cables tend to be constructed with flexible high flex (high strand count) tinned conductors, while construction grade products tend to be made with 7 or 19 strands of bare copper per construction product standards. The result is that the high performance product is more flexible, more thermally stable at connection points, and as a result of the 4-8 times increase in conductor surface area, much more attractive for the high frequency drive output components.

Insulation: While construction grade VFD products are usually XLPE insulated, and thus always sufficient from an insulation value perspective, most construction grade products are designed to comply with the minimum wall thickness requirements of UL1277 (Tray Cable) while high performance VFD cables often significantly exceed the specified minimum wall thickness to dramatically reduce capacitance and increase permissible cable distances.

Grounding and Shielding: An area where again significant distinctions exist between cables. Typically construction grade products will use a single helically applied copper tape in contact with 3 segmented grounds which in total comprise 1 ground meeting at least the minimum requirements of the NEC. High performance VFD cables tend to have significant excesses of copper at ground potential to best attract and contain common mode currents. High performance 4 conductor cables with foil braid and heavy

drains can have more copper in the ground and shielding system than they do at circuit potential. This excess ground copper ensures the lowest ground impedance, and the lowest common mode current emissions.

As cables increase in size, the need for excess copper at ground potential is reduced, and the ratio of ground potential copper to circuit conductor copper can be gradually reduced with increasing cable sizes without diminishing cable performance. As the need for excess copper diminishes with cable size, it is effective to transition premium cables to designs with dual copper tapes (for maximum surface area and HF performance) and full size equivalent symmetric bare copper grounds. Opinions vary among VFD manufacturers, but Belden's research suggests that the benefits of symmetric design to prevent internally generated ground currents begins to be a design factor for motors above 50hp with very long runs, but is typically more significant in motors greater than 100hp.

As a result of the distinctions in VFD cable design, the items below are discussed to help the specifier determine the most suitable grade of VFD cables for a given installation.

1. **How sensitive is the environment to Common mode current?** In highly noise susceptible environments such as those where the drives are connected directly to industrial network communications, the drives are mounded in close proximity to instruments or controllers, or the cabling may run close to sensitive devices like load cells or transducers, it is advisable to consider the type of VFD cable being used. High performance VFD cables with significant excesses of ground potential copper tend to be much more effective than copper-poor construction-grade products. In noise sensitive environments give strong consideration to the selection of a foil braid construction with enhanced common mode current control.
2. **What is the voltage rating of the VFD**

itself? The cable voltage rating must be high enough to support voltages generated by the VFD.

3. **Are there sealing requirements for the cable?** A round cable should be selected to provide a good seal as the cable passes through circular openings and connection glands.
4. **Do you need a line running between the drive and motor to carry brake signals (for slowing down or stopping the motor when necessary) or for thermal monitoring?** If so, consider a cable having a signal pair integrally packaged inside the same outer jacket as the drive cable. (See cable matrix, page 7)
5. **How long is the cable run?** Usually, the drive manufacturer can provide the specific information needed to make decisions about gauge size and cable run length. Note: if a cable length is too long, it will act like a large capacitor that must be charged up when the system is turned on. After that initial phase, electrical energy continually pumped into the cable from the drive can surge into the motor, possibly causing motor bearing burn-out or damage to windings.

Conclusion

Choosing well-designed, robust VFD cables ensures motor uptime and reliability of the VFD system and also provides protection for any sensitive instrumentation and adjacent control systems.

For more information on the variables involved with the cables that are a key part of any VFD system see "Specifying Cables for VFD Applications," a guide developed by Belden through both lab tests and working applications.³

References:

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Belden Industrial-grade VFD Cable Matrix

Physicals									Ratings								
Cable Type	No. of Circuit Conductors	Conductor AWG and Sizes	Tinned Copper Conductor	No./Type of Grounds	Shielding	Circuit Conductors Feature Heavy XLPE Insulation	Full-sized Drain Wire	PVC Jacket	ER Rating	1000V Flexible Motor Supply Rating	600V UL 1277 Type TC	2000V UL 1277 Type TC	Underground (burial)	MSHA	UL-WTTC	1000V CSA AWM	1000V CSA C22.2 TC
Classic	3	16-2	Yes	1 - Full-sized Insulated	Overall 100% Duofoil ® + 85% TC Braid	Yes	Yes	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	-
Classic Symmetrical	3	1-4/0	Yes	1 - Full-sized Segmented Into 3 - Bare CU Symmetrical	Dual Spiral Overlapping Copper Tape (100% Coverage)	Yes	-	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	-
Classic with Brake/Signal Pair	3	16-10 (16 AWG Signal Pair)	Yes	1 - Full-sized Insulated	Overall 100% Duofoil ® + 85% TC Braid	Yes	Yes	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	-
Classic for 2kV Applications	3	14-2	Yes	1 - Full-sized Insulated	Overall 100% Duofoil ® + 85% TC Braid	Yes	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	Yes	-
Classic Symmetrical for 2kV Applications	3	1-4/0	Yes	1 - Full-sized Segmented Into 3 - Bare CU Symmetrical	Dual Spiral Overlapping Copper Tape (100% Coverage)	Yes	-	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	Yes	-
Classic with Haloarrest® Low Smoke Zero Halogen Jacket	3	16-2	Yes	1 - Full-sized Insulated	Overall 100% Duofoil ® + 85% TC Braid	Yes	Yes	LSZH	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	-
Classic Symmetrical with Haloarrest Low Smoke Halogen Jacket	3	1-4/0	Yes	1 - Full-sized Segmented Into 3 - Bare CU Symmetrical	Dual Spiral Overlapping Copper Tape (100% Coverage)	Yes	-	LSZH	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	-
Classic Interlocked Armor	3	16-2	Yes	1 - Full-sized Insulated	Overall 100% Duofoil ® + 85% TC Braid	Yes	Yes	Yes	Meets MC	Yes	Yes	-	Yes	Yes	Yes	-	-
Classic Symmetrical Interlocked Armor	3	1-4/0	Yes	1 - Full-sized Segmented Into 3 - Bare CU Symmetrical	Dual Spiral Overlapping Copper Tape (100% Coverage)	Yes	-	Yes	Meets MC	Yes	Yes	-	Yes	Yes	Yes	-	-
C. Series Symmetrical	3	16-4/0	Yes	3 - Bare CU Symmetrical	Dual Spiral Overlapping Copper Tape (100% Coverage)	Yes	-	Yes	Yes	-	Yes	-	Yes	-	-	Yes	-
MCM Symmetrical	3	250 350 500	-	3 - Bare CU Symmetrical	Dual Spiral Overlapping Copper Tape (100% Coverage)	Yes	-	Yes	Yes	-	-	Yes	Yes	-	-	-	Yes

VFD System Glossary

Cable noise: Electromagnetic interference emitting from a motor cable. It occurs as the cable begins to act like a radio antenna when voltage reflections causing voltage spikes are present in the cable.

Common mode current: Undesirable current flow in a cable, which is not returned safely to the drive. This current produces radiation that could escape the cable and affect adjacent circuits.

Corona discharge: Electric arcing or sparking between a cable's conductors or motor windings. This takes place when the voltage between two points becomes great enough to finally break down the air or insulation separating them, causing a burst of current to jump between conductors to relieve the potential difference.

Ground loop: An unintended path through an electrical interconnection system in which potentials (voltages) measured with respect to ground at either end of the path differ from each other. Given even a small offset in potentials, extraneous currents can flow through the grounding system. To avoid this potentially damaging current, all grounding points must be tied to the same potential.

Horsepower: The time-rate at which mechanical work is being done. To get the same job done in less time, a motor must produce more power, though it will be limited by its maximum horsepower rating.

- **Horsepower rating:** Maximum rate at which the motor can perform the given mechanical work based on motor design.

Impedance: The opposition in an electrical circuit to the flow of an alternating current that is equal to the actual electrical resistance to a direct current when a voltage is applied.

Load: Device that a motor must drive or move offering resistance to the motor's turning of its shaft (e.g. pump, fan, conveyor belt, lathe, etc.).

Constant torque loads: Most loads present in general industrial machines (excluding pumps and fans). Examples include general machinery, conveyors, hoists, printing presses, positive displacement pumps, certain extruders and mixers, reciprocating compressors and rotary compressors.

- **Constant horsepower loads:** Most often found in the machine-tool industry and certain winder applications. Examples include core-driven wheels, winders, wheel grinders, lathes, larger drill machines, planers, core extruders, and boring machines.
- **Motor speed:** The revolutions per minute (RPM) turned by the motor shaft. Motor speed varies with the frequency and voltage of the pulse-width modulated (PWM) input it receives from the motor drive (VFD), which will attempt to keep the ratio of voltage to frequency constant.

Pulse-width modulation (PWM): A way to deliver energy via a series of pulses instead of an analog (i.e., continuously varying) signal. The advantage of PWM is efficiency, cooler operation, fast response to changing demands, and precision control.

Relative permittivity: Property of the insulation which determines the amount of electrostatic energy that can be stored when a given voltage is applied.

Torque: The twisting force a motor shaft applies to a mechanical device or piece of machinery that tends to produce rotation. The torque a motor produces at its turning shaft varies with the current flowing through it.

- **Break-away torque:** Torque needed to start a load moving from a motionless state. This is usually greater than the torque required to maintain motion.
- **Acceleration torque:** Torque required to bring the load up to operating speed within a given time frame.
- **Running torque:** Torque required to keep a load moving once it is functioning at any speed.
- **Peak torque:** Maximum torque demanded by the load, i.e. the torque required when a crate is suddenly dropped on a moving conveyor, given that the motor had previously only been dealing with small boxes.
- **Holding torque:** Torque required by the motor when it serves as a brake (to slow loads down when moving downhill).

VFD: Abbreviation for variable frequency drive.

This device is sometimes also called an adjustable speed drive or variable speed drive. VFDs control the speed and torque output of AC (induction) motors, and are now used in an enormous range of industries and applications. They use several stages and solid-state circuitry to convert 3-phase AC line voltage into the approximation of a sine-wave shape made up of narrow voltage pulses with constant amplitude but with sinusoidally-varying widths. The result is a variable voltage and frequency output to the motor, the two factors kept in a constant ratio to each other.

Voltage reflection: When the impedance of a cable, and the motor it is connected to, are not the same, part of the voltage waveform sent from the VFD will be rejected and pushed back into the cable. The situation is analogous to trying to force water under pressure from a garden hose into a straw adapted to the end of the hose. Some of the pressure will be fed back into the hose.

XLPE: Cross-linked polyethylene, a thermosetting plastic used as a conductor insulator inside a cable. Because of its electrical and mechanical properties, it is much better at this role than a thermoplastic material, such as PVC.



Variable frequency drives are increasingly used as a way to lower energy costs and increase the precision of a process control system.