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

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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 – i.e., the device the motor is driving, such as a pump, fan, conveyor belt or lathe – changes its demands on the motor. By changing its output frequency and voltage, the VFD allows the motor to modify its RPMs to respond to those demands.

What Are the Benefits of Using VFD Motors?

Why is this motor speed-changing ability so important? AC (induction) motors are extremely common in discrete manufacturing and processing plants throughout the world. Imagine that all those motors could only spin at one speed, even when their loads are modifying their demands, and even when process variables – like temperature, pressure, force, etc. – are varying. With motors delivering products at a constant speed regardless of new, changing conditions, scrap would pile up and energy would be wasted. *(See Sidebar entitled "Torque, Speed, Horsepower and Load"* on *page 2.)*

However, when using a VFD, motor speed can be changed almost instantaneously to address load and process changes. And, as a bonus, VFDs can increase the precision of process control, given their ability to control motor speeds to within 0.1% tolerance.

Several types of VFDs are available, but the pulse width modulation (PWM) design has become the most common, because it works well with motors that range in size from about a half horsepower on up to 500 hp. It is also reliable and affordable, and offers significant electrical energy savings. When a motor is run at half its maximum speed, it consumes only about a fourth of the energy it needs at full speed. In this sense, you could say VFDs represent a "green" engineering solution.

The list of benefits goes on. A VFD can provide a "soft-start" capability for a motor, decreasing the mechanical stresses associated with full voltage start-ups. In other words, a motor can be ramped up to desired speed instead of being abruptly thrown on line at full RPMs. The result is lower maintenance costs and a longer motor life. Use of a VFD can also help avoid overheating that can gradually destroy a motor.

The way in which the components of a VFD system – drive, cable and motor – are selected, matched to each other, and operated will impact reliability of all of the components of the system, as well as of adjacent systems. 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.)* The cable must be able to withstand the operating conditions caused by the drive system itself, yet at the same time influence in a positive way the life of other drive system components.

Why Choose a Purpose-designed VFD Cable?

Like many engineering solutions, VFDs present not only benefits, but drawbacks as well. 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 megahertz. If this radio frequency energy is not contained within the cable, it can radiate out to interfere with the proper operation of nearby 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 very 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 entitled "A Few Tips for Better Management of Cable Noise Interference" on page 5.)*

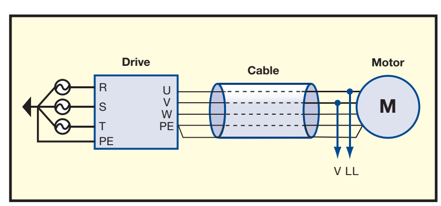

Figure 1. Diagram of a typical VFD system.

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Load, Torque, Speed, and Horsepower

A handful of terms are used to describe the operation of an industrial AC motor controlled by a VFD: load, motor speed, motor torque and motor horsepower rating.

- **Load:** The device that a motor must drive or move, that offers resistance to the motor's turning action.
- **Torque:** The twisting force that a motor shaft applies to a load, a force that tends to produce rotation. An electrical motor's task is to develop enough twisting force to meet the requirements of its load.
- **Speed:** The rate of turning of the motor shaft expressed in revolutions per minute.
- **Horsepower rating:** The maximum rate at which the motor can perform the mechanical work it is assigned, given the way the motor is designed.

Motor loads can be categorized by one of the following general types:

- **Constant torque loads:** These are comprised of 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.
- **Variable torque loads:** Mostly found in variable flow applications, like those using fans and pumps. Applications include fans, centrifugal blowers, propeller pumps, centrifugal pumps, turbine pumps, axial compressors and agitators.
- **Constant horsepower loads:** Most often found in the machine-tool industry and certain winder applications. Examples include core-driven reels, winders, wheel grinders, lathes, large driller machines, planers, core extruders and boring machines.

Every load in an industrial setting presents its own individual, varying torque demands on the motor. Here are the main types of torque:

- **Break-away torque:** The torque needed to start a load moving from a motionless state (this is usually greater than the torque required to maintain motion once it is going).
- **Acceleration torque:** The torque necessary to bring the load up to operating speed within a given time frame.
- **Running torque:** The torque required to keep a load moving once it is functioning at any speed.
- **Peak torque:** The maximum torque occasionally demanded by the load. For example, the torque demanded when an especially heavy crate is suddenly dropped on a moving conveyor when the motor had previously only been dealing with small boxes.
- **Holding torque:** The torque required by the motor when it serves as a brake, as when loads are moving downhill and must be slowed.

These important concepts are related by the following formula:

Power = Speed x Torque

At a constant horsepower rating, when motor torque goes up, motor speed goes down, and vice versa.

The first thing to do to properly match a VFD and VFD cable to a motor tasked with driving a given load is to understand the nature and requirements of the load. The VFD and cable must have sufficient current capacity so that the motor to which they supply power can produce the required torque its load will demand at any time. Motor torque ultimately depends on the current passing through the motor (while the motor's speed depends on the voltage applied to it).

The VFD and cable should be sized to the motor based on the maximum current required by the motor under peak torque demand — not on the basis of horsepower considerations. Failure to adhere to this can lead to problems in many applications.

There is another potentially serious concern with use of VFDs: 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, because they add to the voltage that is already there. Peak voltages of up to 2.5 times the nominal system voltage are sometimes present in the cable. As a result, voltage reflections have been known to cause a number of in-service motor failures. There is also some concern over possible long-term cable damage under high voltage — especially with VFDs operating at 575 volts and above.

In addition, high voltage levels in the cable can sometimes cause a corona discharge to occur between the conductors, an effect that can damage not only the cable itself but also the motor, motor bearings and the drive. This can lead to failure of the entire system, with ensuing production downtime.

The problems of noise emissions, voltage reflections, overvoltages, and corona discharge can be substantially reduced or even avoided by choosing the appropriate VFD cable. Special attention should be paid to the cable's insulation type, impedance, and shield/grounding system. The payoff will be drive/motor system longevity and reliability.

Unfortunately, some users attempt to use unshielded tray cables or hookup wire for their drive system cabling. VFD installations with these products can suffer from low reliability, a complex, costly installation, or both. Neither construction effectively mitigates the problem of noise emissions generated by VFDs, nor do they properly address corona discharge.

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 faced by such a component. *(See Figure 2 on page 3 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 all other VFD system voltages. Sometimes it is not possible to bring the ground voltage to a true 0 V level, but the ideal reference can be approximated by bringing all grounded points to the same very low potential.

As long as a VFD cable is well-grounded, it can avoid the problem of excess current flowing into other devices or other systems. In other words, having a suitable ground means it is possible to control where all the energy from the VFD drive goes. Any extraneous induced voltage in the system is undesirable because a certain amount of useful power is lost. Proper grounding also helps to overcome the problem of impedance mismatches and overvoltages.

One approach for grounding a cable is the use of 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 or drive enclosure. The goal is "360 degree coverage" at this connection. This prevents openings in the shield where electromagnetic energy can possibly radiate out.

A less effective approach would be to connect a single conductor drain wire from the shield to the motor housing or connector. Unfortunately, this creates an opening in the shield — a place where the shield is no longer continuous — where energy can leak out.

One way to assure 360 degree coverage is to use a coupler — a mechanical fitting with male and female components. It is threaded into the motor or drive enclosure housing and the cable end passes through its middle. The portion of the cable jacket that lies inside the fitting is removed so that the braid or the copper tape of the shield is exposed for mechanical contact. A conductive spring or gasket in the coupler touches the shield in this exposed zone and also contacts the housing to complete the ground circuit.

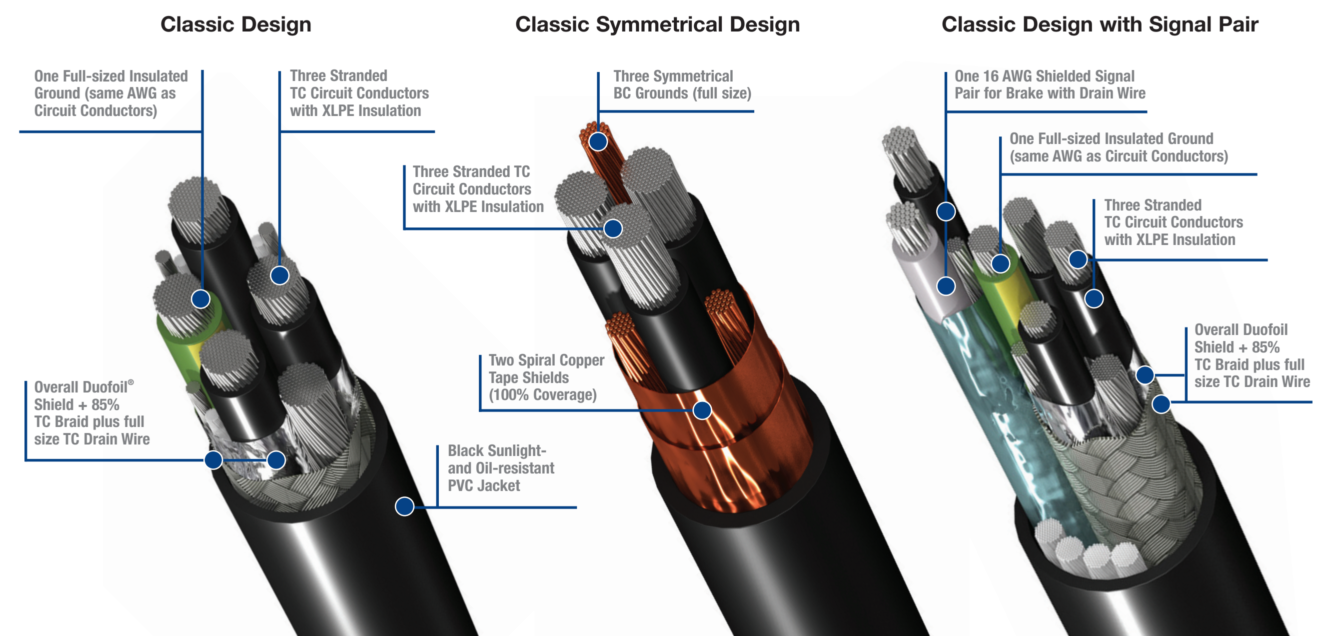
A Few Tips for Better Management of Cable Noise Interference

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 in close proximity to low-level communications cables and other susceptible devices, it is necessary to ensure that shielding is present in the VFD cable. In addition, the use of unshielded cables in conduits around a VFD setup should be limited or eliminated altogether, 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 physically routed and located in the surrounding area. Maintain as much separation as possible between noise-susceptible cables and VFD cables — a minimum of one foot for shielded instrumentation cables, and three feet 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' 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



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Why Match Impedances?

Engineers try (or *should* try) to match the impedance of the VFD cable to the impedance of the motor as closely as possible. This is done for two main reasons.

First, when the impedances match, maximum power is transferred from the VFD to the motor to do useful work, with only a small amount of energy lost. However, if there is a substantial mismatch between the impedances of the cable and motor, a lot of power is wasted. So, this is a "green" consideration.

Second, when there is an impedance mismatch, a substantial amplification of voltage will appear at the motor terminals and some of the power is reflected back toward the drive from the motor terminals. This problem is even more likely to occur when the cable run is longer. The over-voltage condition at the motor terminals can cause premature insulation breakdown in the motor windings.

Having a full-sized ground in a cable, i.e., one with a large cross sectional area of copper in the ground wires *(see the matrix table on page 6)*, 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 for these concepts on page 7.)* By contrast, with the higher resistance of a smaller sized grounding conductor, a voltage drop across the cable 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 those adjacent systems.

Alternatively, in what is known as a symmetrical design cable *(again, see matrix for an example)*, 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 within it, as well as cable length; more current and greater length mean more radiated noise. However, by properly shielding the VFD cable, noise can be controlled. Belden's research has concluded that shielding systems including copper tape and combination foil/braid types are the most appropriate for VFD applications, due to the low impedance path they provide for common-mode noise to return to the drive. Foil shields are simply not robust enough to restrict the volume of noise generated by VFDs.

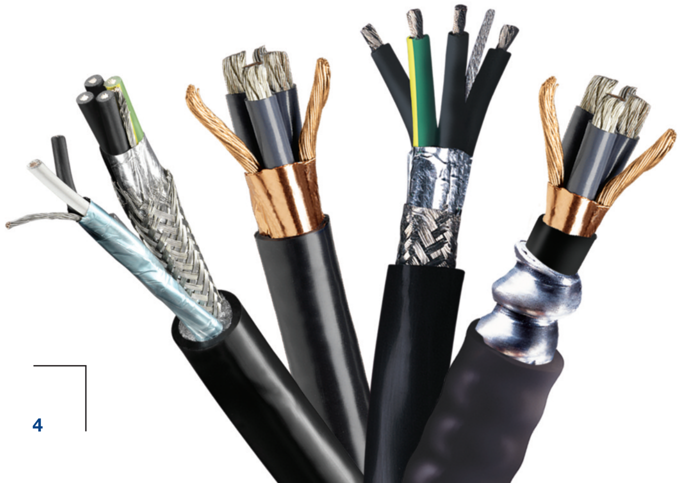
Low dielectric constant: An important property of the cable insulation is its dielectric constant, or relative permittivity. This refers to that property of the insulation which determines the amount of electrostatic energy that can be stored when a given voltage is applied. In a cable, the dielectric constant should have a low value if the cable is to have a low capacitance, and consequently, eliminate 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, allows engineers to closely match the impedance of the drive to the motor. *(See Sidebar entitled "Why Match Impedances?")* With a minimal mismatch, it is possible to substantially eliminate the occurrence of overvoltages and high frequency spikes, either of which can generate noise.

With better impedance matching between the drive, the motor and the cable, it is also possible to get an incrementally-higher degree of energy efficiency. In other words, more of the energy coming from the drive is converted into useful rotational energy in the motor, instead of being reflected back (which can heat up the cables and cause a corona effect and high voltages). This is yet another "green" benefit. As a bonus, a low dielectric constant insulation like XLPE permits longer cable runs.

Suppression of overvoltage: Without a proper cable design, reflected waves caused by a cable-to-motor impedance mismatch can be problematic in any VFD application. The magnitude of this problem depends on a number of factors: 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, a common insulation material that is not recommended for VFD applications.



Thick insulation wall: A thick insulation wall is an advantage because of its proven electrical benefits (e.g., lower cable capacitance) and the improved high temperature stability a heavier wall exhibits. Thicker cable insulation also helps guard against corona discharge.

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) — 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 — PVC, for example — 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-isolating 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 the case of a VFD cable, this has implications for how well you connect the shield and the ground conductors to the motor case or drive enclosure, and ultimately, to earth ground potential. Typically, bonding entails a mechanical connection involving a nut and bolt connection, though there are other possible methods. There is extensive literature available for more information on this topic.[1]

A Methodical Way to Choose a VFD Cable

When selecting a VFD cable, you should ask yourself a number of key questions about your application:

1. **Is it a VFD application? Does the motor speed need to be controlled?** If so, you must choose between several types of cable that provide different features and benefits. The product matrix selection chart following this section, as well as Belden's Product Bulletin on VFD Cables[2], gives some indication as to features to consider when choosing a VFD cable, and where they apply.
2. **What is the most suitable impedance of the cable to match the impedance of the motor?** The impedance realized by the cable at the motor is generally low, so it is desirable to choose the lowest cable impedance possible. However, it is not feasible to match cable impedance to motor impedance over a range of motor speeds since motor impedance varies with RPM.

   Therefore, the appropriate strategy is to minimize the impedance mismatch. By choosing an insulation with a low dielectric constant and thick wall, such as XLPE, the impedance mismatch can be minimized successfully.
3. **Does the motor in your system have a fairly high horsepower rating — 100 HP or more?** A higher motor horsepower translates to a higher current flow through the cable. Users with a high horsepower motor should consider a cable like the Symmetrical design described in the product matrix following this section. This construction features a larger conductor gauge size to handle more amperage.
4. **What is the voltage rating of the VFD itself?** The cable must be able to support it.
5. **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.
6. **Are there instrumentation and communication applications located close to where the motor drive and cable will be installed?** If they are far away, there is less concern about any possible emissions from the VFD cable, but if they are close, a cable with the Classic design shown in the matrix table should be considered. Its foil and braid shielding provides extra coverage against the impact of radiation on neighboring circuits.
7. **Do you need a line running between the drive and motor to carry brake signals, for example for slowing down or stopping the motor when necessary?** If so, consider a cable having a signal pair integrally packaged inside the same outer jacket as the drive cable. *(See matrix.)*
8. **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. Keep in mind, if a cable length is too long, the cable acts 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 burnout or damage to windings.

Conclusion

The user should be suspicious of a low-cost cabling solution which in the long run may end up costing more — as much as the price of a new motor or drive. By choosing well-designed, robust VFD cables, an investment is made in the uptime and reliability of the VFD system, as well as that of any sensitive instrumentation and control systems adjacent to it that need protection.

*(**Note:** In order to better understand the variables involved with the cables that are a key part of any VFD system and to formulate a useful guide to cable selection, the most commonly recommended cables for VFD applications were studied by Belden in both a lab and working application.[3] Also, see Belden's more technically-oriented white paper on the subject of VFD systems and components.[4])*

References

1. **IEEE standard no. 1100: "Recommended practice for powering and grounding electronic equipment" January 6, 2010.**
2. **"Variable Frequency Drive (VFD) Cable Solutions," Belden Product Bulletin 316.**
3. **Brandon L. Phillips and Eric J. Burlington, "Specifying Cables for VFD Applications,"** 2007.
4. **Brian Shuman, "Building a Reliable VFD System,"** 2009.

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Belden Industrial-grade VFD Cable Matrix

Physicals										Ratings					
Cable Type	No. of Circuit Conductors	Conductor AWG	Tinned Copper (TC) 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	Under-ground (burial)	MSHA	UL-WTTC
Classic	3	16-2	Yes	1 - Full-sized Insulated	Overall 100% Duofoil® + 85% TC Braid	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
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
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
Classic Symmetrical for 2kV Applications	3	1-4/0	Yes	1 - Full-sized Segmented Into 3 - Bare CU Symmetricall	Dual Spiral Overlapping Copper Tape (100% Coverage)	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
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
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
Basics Symmetrical	3	16-4/0	No	3 - Bare CU Symmetrical	Dual Spiral Overlapping Copper Tape (100% Coverage)	Yes	–	Yes	Yes	–	Yes	–	Yes	–	–

CU = Copper • TC = Tinned Copper

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.

Load: The machinery an electric motor drives or operates via the turning motion of its shaft, e.g., a pump, fan, conveyor belt, lathe — and a wide range of other devices.

Motor speed: The revolutions per minute 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.

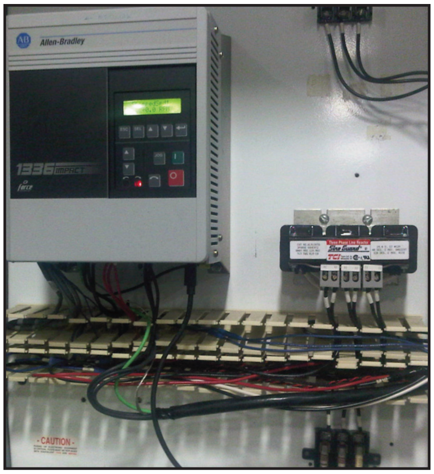
Pulse width modulation (PWM): A way to deliver energy via a series of pulses instead of an analog (i.e., continuously varying) signal. The advantage of PWM is efficiency, cooler operation, fast response to changing demands, and precision control.

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.

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 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 an 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 as a way to increase the precision of a process control system.