

## Building a Reliable VFD System

Brian Shuman  
Senior Product Development Engineer  
Belden

A Variable Frequency Drive (VFD) regulates the speed of a 3-phase AC electric motor by controlling the frequency and voltage of the power it delivers to the motor. Today, these devices (also known as Adjustable Speed Drives or Variable Speed Drives) are becoming prevalent in a wide range of applications throughout industry, from motion control applications to ventilation systems, from wastewater processing facilities to machining areas, and many others.

VFDs offer many benefits; principle among them the ability to save a substantial amount of energy during motor operation. In that sense, these devices represent both an attractive, "green" engineering solution, and an economical choice. Other benefits worth mentioning include the following: they can maintain torque at levels to match the needs of the load, improve process control, reduce mechanical stress on 3-phase induction motors by providing a "soft start," and improve an electrical system's power factor. What's more, legacy systems that now use throttling devices to regulate motor speed can be retrofitted with VFDs to make speed regulation much more efficient and precise.

Special consideration must be given to the proper installation and operation of the overall system that comprises the VFD, the motor it controls, and the cable that connects them. See *Figure 1* for a schematic depicting a generalized VFD system. The way in which VFD-based systems are constructed and operated will have an impact on both the longevity and reliability of all the components of the system, as well as nearby or adjacent systems.

This paper is primarily concerned with the motor-supply cable in the VFD/motor system. It looks at some fundamental cable design considerations, and presents suggestions for installation. However, to give the reader some context, it makes sense to first describe VFDs, their benefits and potential problems, and their relationship to the motors they control.

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### Overview of VFD technology

VFDs are solid state devices for converting 3-phase AC line voltage to a quasi-sinusoidal pulse width modulated (PWM) waveform in which the frequency and voltage level can be varied. The output is a series of narrow voltage pulses having constant amplitude but sinusoidally-varying widths. Internally, VFDs consist of three main sections: an AC-to-DC converter based on a rectifier bridge of diodes, a DC bus that filters and smoothes out the rectifier output, and a DC-to-AC inverter to change the DC back to AC. The inverter, which is most typically based on insulated gate bipolar transistor (IGBT) technology, creates the variable voltage and frequency output that will control the motor's speed. A microprocessor in the VFD, with programming resident in firmware, governs the overall operation of the device.

VFDs allow a motor's speed to be varied electrically instead of by mechanical means. This permits much greater efficiency and flexibility of operation. They are capable of controlling both the speed of the motor and the torque. Without a VFD, industrial induction motors run at full speed continuously; valves, or other mechanical methods, are employed to control the machine output. Unfortunately, running a motor at maximum speed regardless of the varying demands of production means a great deal of electric power is wasted.

Another benefit of VFDs is their soft-start capability in which motors are ramped up to speed instead of being abruptly thrown on line. This useful feature reduces mechanical stresses on the entire motor system and leads to lower maintenance costs, as well as a longer motor life. Still another benefit is improved process control. Since industrial process throughput in most operations depends on a range of variables, a motor that is only able to operate at a constant speed even when one or more process variables change might contribute to creation of scrap, not to mention wasted energy. With a VFD, motor speed can be changed almost instantaneously to adapt to changing process conditions.

## Ten Things to Consider Before Selecting Your VFD

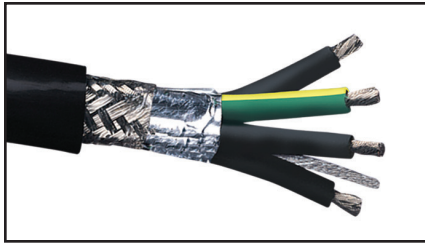
- 1. What will be the torque demands of the loads or processes in your planned system? Will any of the loads be hard to start?** Keep in mind, VFDs have limited over-current capacity. Hard-to-start loads may require an over-sized the unit to cover higher current demands.
- 2. How many motors will the drive have to control? If more than one, will they start up sequentially or simultaneously?** You should calculate the total peak currents of all motor loads under the worst operating conditions your planned system will see. Size your VFD according to this maximum current requirement.
- 3. Will your applications require a quick start or an emergency stop of the load?** If so, high currents will be demanded of the VFD. Over-sizing of the drive may be necessary.
- 4. Is motor overheating a potential concern for any of your planned VFD applications?** It may be, for reduced speed, constant torque applications.
- 5. What range of motor sizes will your process or processes require the VFD to handle?** Keep in mind that smaller motors are not as efficient as larger ones, so improvements due to the VFD will likely be readily apparent. However, since large motors consume much more power, even small increases in efficiency can, over the life of the motor, lead to appreciable savings.
- 6. Will the VFD system be operating in an environment containing volatiles, airborne particulate matter, high ambient temperatures?** In the case of volatiles, be sure all materials in use are resistant to chemical attack and are properly grounded; for an atmosphere full of particulates, ensure proper sealing; for high temps, allow for cooling.
- 7. Do you need equipment or drive protection features that will ensure a continuity in your processing?** Be aware that you can have a drive that trips instantly in an over-current condition, or one that maintains constant motor torque and reduces motor speed to maintain current required
- 8. Do you want or need a lot of diagnostic capability in your unit?** How critical is it to get a handle on load downtimes and be able to do a detailed fault analysis?
- 9. Are power factor correction capacitors present on the motor loads your VFD system will have to handle?** When these are switched, they typically generate power disturbances, and VFDs can be negatively impacted. Isolation transformers or line reactors may be necessary.
- 10. Is it possible the power source for your planned system will occasionally be switched while the VFD is operating?** This might happen, for example, when loads are switched to standby generators during a power outage. Some drives can handle a brief power outage, others can't.

However, VFDs are not without drawbacks. For example, the very fast voltage rise times associated with IGBT technology contributes to precise motor speed control but can also lead to voltage spikes that damage cables of poor quality, or ones that are improperly insulated. Other possible concerns with use of VFDs are the potential for acoustical motor noise and motor heating, when currents, induced by pulse width modulated switching, flow in improperly grounded motor shafts. The result can be damaged bearings. In addition, the purchase cost for a new VFD can be steep, though this must be balanced with the fact that the payback period can be a matter of just a few months to under three years.

### Evaluation of Cable Types Used for VFDs

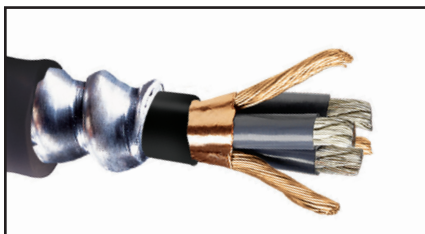
In order to better understand the variables involved with the cables that are a key part of any VFD system and to formulate a useful guide to cable selection, the most commonly recommended cables for VFD applications have been studied by Belden, in both a lab and working application.<sup>1</sup> Some wiring methods were not examined, however, such as THHN building wire in conduit, since their use has been shown to have detrimental effects, as outlined in other studies.<sup>2,3</sup> An exception to this exclusion was the use of PVC-Nylon insulated, PVC jacketed tray cables. These cables are the most commonly-installed type of industrial control cable, and though they are often misapplied for use in VFD applications, they were included in the tests for purposes of comparison. The PVC-Nylon designs (PVC-Nylon/PVC Type TC and PVC-Nylon/PVC Foil Shield Type TC) were evaluated in both unshielded and foil shielded versions.

The commonly-specified cables evaluated in the study included the following:



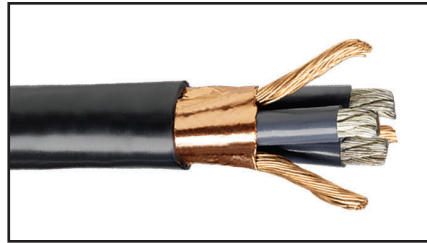
**XLPE (cross-linked polyethylene) insulated, foil/braid (85%) shielded, Industrial PVC jacketed cable designed for VFD applications.**

- Four Conductor (three conductors plus green/yellow ground)
- XLPE Insulation (.045 in. wall) 100% Foil +85% Tinned Copper Braid Shield
- Full Size Tinned Copper Drain Wire (sectioned in #8 and larger)
- Full Size Insulated Tinned Copper Ground Conductor
- Industrial PVC Jacket
- 600V/1000V Rated



**XLPE insulated, continuously welded aluminum armored, Industrial PVC jacketed cable designed for VFD applications**

- Three Conductor #12
- XLPE Insulation (.030 in. wall)
- Continuously Welded Aluminum Armor
- Three Symmetrical #16 Bare Ground Conductors
- Industrial PVC Jacket
- 600V MC Rating



**XLPE insulated, dual-copper tape shielded, Industrial PVC jacketed cable designed for VFD applications**

- Three Conductor #12
- XLPE Insulation (.030 in. wall)
- (2) .002" Cu Tapes Spiral Wrapped with 20% overlap
- Three Symmetrical #16 Bare Ground Conductors
- Industrial PVC Jacket
- 600V Rated

The cables investigated were used to interconnect a VFD to the AC motor. All testing was conducted using a current generation, IGBT-based, 480VAC, 5HP VFD, an inverter-duty rated AC motor, and relevant lab equipment, such as an LCR meter to characterize the cables and an oscilloscope to make voltage measurements.

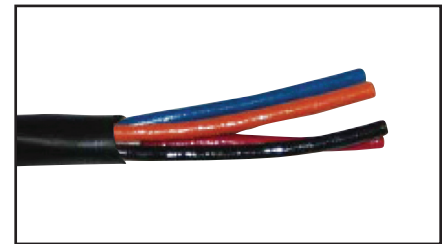
### Impact of Cable Design on Motor and Cable Life

Reflected waves caused by a cable-to-motor impedance mismatch are prevalent in all AC VFD applications. The magnitude of the problem depends on the length of the cable, the rise-time of the PWM (pulse width modulated) carrier wave, the voltage of the VFD, and the magnitude of the impedance difference between the motor and cable.

Under the right conditions, a pulse from the VFD can add to a pulse reflected back from the motor to result in a doubling of voltage level, which could damage the cable or the components inside the drive. A solution is



PVC-Nylon/PVC Foil Shield Type TC



PVC-Nylon/PVC Type TC

use of XLPE cable insulation, a material with high impulse voltage breakdown levels, that makes it more immune to failure from reflected wave and voltage spikes in a VFD application than, say, PVC, a material which is not recommended in these applications.

Because cable length is mostly determined by the layout of the application, while rise times vary with the VFD output semiconductor and the voltage of the VFD is determined by the application, the impedance of the cable relative to the motor will be the primary mechanism outlined in this paper.

First, let's look at estimated motor impedance relative to motor size in HP over a range of horsepower ratings, as indicated in *Figure 2*. Note that the cable impedance for 1HP motor/drive combinations would need to be roughly 1,000 ohms to match the corresponding motor's impedance. Unfortunately, a cable with such high characteristic impedance would require conductor spacing in excess of several feet. Obviously, this would be both impractical and very expensive.

In addition to other benefits, such as reduced capacitance, a more closely matched impedance can improve motor life. Table 1 lists the observed line-to-line peak motor terminal voltages, as well as the impedance of the cables under test. The voltage measurements were taken using 120 ft. cable lengths.

Table 1 shows typical impedance values for #12 AWG circuit conductors and is based on actual data. Cable impedance is influenced both by its geometry and materials used in its manufacture. The characteristic impedance of a cable is calculated using the following formula, where  $Z_c$  = characteristic impedance,  $L$  = cable inductance, and  $C$  = cable capacitance.

$$Z_c = \sqrt{L/C}$$

In Table 1, note the inversely proportional relationship between the cable's impedance and the peak motor terminal voltage: cables with higher impedance tended to result in lower peak motor terminal voltages. A cable's design for impedance also impacts its useful life. Lower voltages across the motor terminals translate into the cable being exposed to lower voltages, increasing its life expectancy.

In addition, this reduces the likelihood of either the cable or the motor reaching its corona inception voltage (CIV). That's the point at which the air gap between two conductors in the cable, or two windings on the motor, breaks down via arcing or a spark under the high potential difference. If the CIV is reached, insulation failure can occur in the windings of the motor.<sup>4</sup>

Corona discharge occurring between conductors of the cable can produce very high temperatures. If the insulation system of the cable is a thermoplastic material such as PVC, the phenomenon can cause premature cable burn-out or a short circuit due to a gradual, localized melting of the insulation. For this reason alone, thermoplastic insulations should not be used for VFD applications.

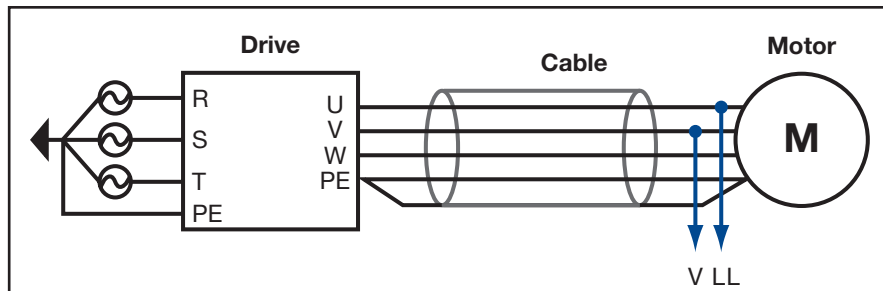


Figure 1: Schematic of a VFD setup.

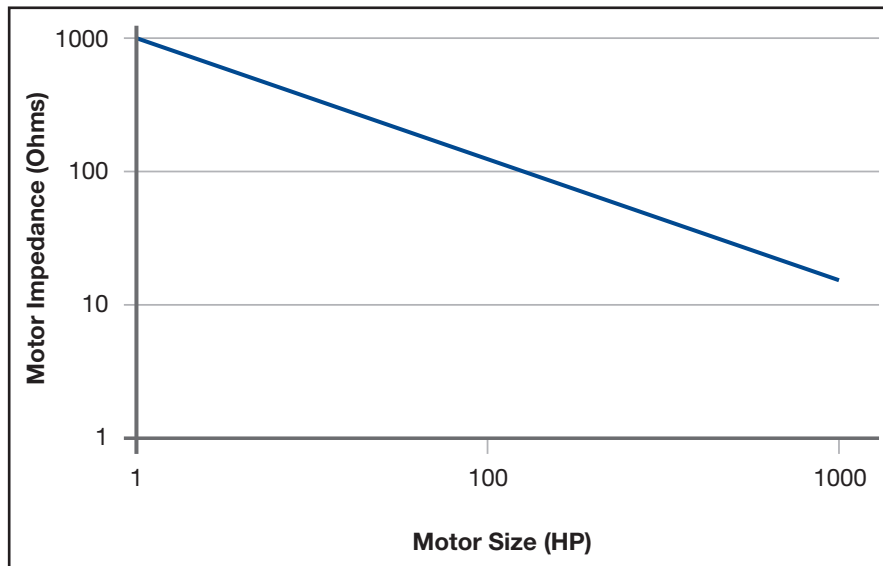


Figure 2: Motor impedance relative to motor size.

Cable Type	Impedance (ohms)	Voltage at Motor Terminals
Continuous Aluminum Armored Cable	87	1080 V
Belden Foil/Braid VFD Cable 2950X Series	78	1110 V
Cu-Tape Shielded Belden VFD Cable	58	1150 V
Unshielded PVC-Nyl/PVC	58	1150 V
Shielded PVC-Nyl/PVC	38	1260 V

Table 1. Impedance impact on motor terminal voltage using 120 ft. of cable.

On the other hand, thermoset insulation systems such as those based on XLPE are ideal materials for these applications because of the high temperature stability they exhibit. In their case, the heat generated from corona forms a thermally-isolating charred layer on the surface of the insulation, preventing further degradation. All cables used for VFDs should use a thermoset insulation system as a precautionary measure.

### Understanding Radiated Noise in VFD applications

Noise radiated from a VFD cable is proportional to the amount of varying electric current within it. As cable lengths grow, so does the magnitude of reflected voltage. This transient over voltage, combined with the high amplitudes of current associated with VFDs, creates a significant source of radiated noise. By shielding the VFD cable, the noise can be controlled. In the tests presented in this paper, relative shielding effectiveness was observed by noting the magnitude of noise coupled to 10 ft. of parallel unshielded instrumentation cable for each VFD cable type examined. The results of the shielding effectiveness testing are documented in *Figure 3*.

As demonstrated by its trace in that figure, foil shields are simply not robust enough to capture the volume of noise generated by VFDs. Unshielded cables connected between a VFD and a motor can radiate noise in excess of 80V to unshielded communication wires/cables, and in excess of 10V to shielded instrumentation cables. Moreover, the use of unshielded cables in conduits should be limited, as the conduit is an uncontrolled path to ground for the noise it captures. Any equipment in the vicinity of the conduit or conduit hangers may be subject to an injection of this captured, common-mode noise. Therefore, unshielded cables in conduit are also not a recommended method for connecting VFDs to motors.

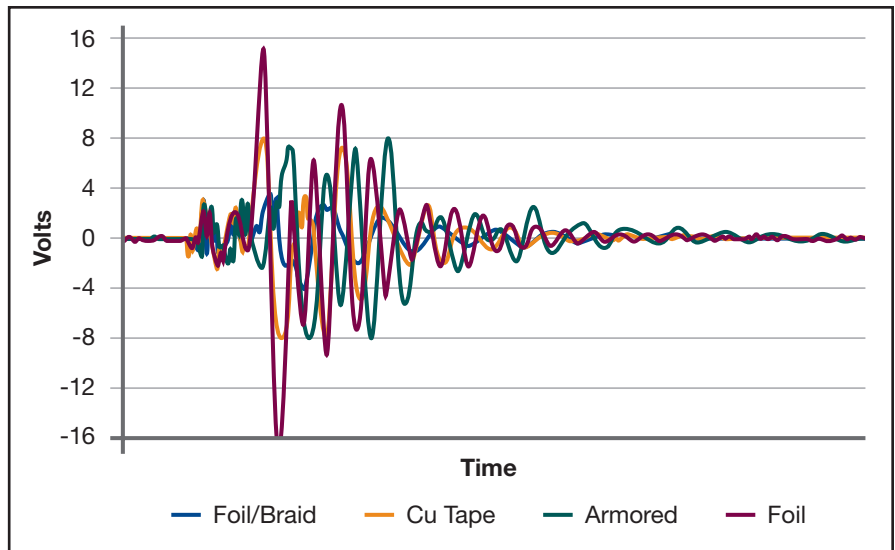


Figure 3: Noise coupled from VFD cables to unshielded instrumentation cable.

If radiated noise is an issue in an existing VFD installation, care should be taken when routing instrumentation/control cables in the surrounding area. Maintain as much separation as possible between such cables and VFD cables/leads. A minimum of one foot separation for shielded instrumentation cables, and three feet for unshielded instrumentation cables, is recommended. If the cables must cross paths, try to minimize the amount of parallel runs, preferably crossing the instrument cable perpendicularly with the power/VFD cable.

If noise issues persist after these precautions are taken, use a non-metallic, vertical-tray flame rated fiber optic cable and media-converters or direct-connect fiber communication equipment for the instrumentation circuit. Other mitigation techniques may also be required, such as, but not limited to, use of band-pass filters/chokes, output reactors, motor terminators, and metallic barriers in cable trays or raceways.

### Impact of Common Mode Noise in VFD Applications

Radiated noise from a VFD cable is a source of interference with adjacent systems that is often easier to identify and rectify than common mode noise. In the latter, high levels of noise across a broad frequency range, often from 60 Hz to 30 MHz, can capacitatively couple from the windings of the motor to the motor frame, and then to ground.

Common-mode noise can also capacitatively couple from unshielded motor leads in a conduit to ground via conduit ground straps, supports or other adjacent, unintentional grounding paths. This common-mode ground current is particularly troublesome because digital systems are susceptible to the high-frequency noise generated by VFDs.

Signals susceptible to common-mode noise include those from proximity sensors, and signals from thermocouples or encoders, as well as low-level communication signals in general. Because this type of noise takes the path of least resistance, it finds unpredictable

grounding paths that become intermittent as humidity, temperature, and load change over time.

One way to control common-mode noise is to provide a known path to ground for noise captured at the motor's frame. A low-impedance path, such as a properly designed cable ground/shield system, can provide the noise with an easier way to get back to the drive than using the building ground grid, steel, equipment, etc.

In the study presented in this paper, tests were conducted on the five cable types to determine the ground path impedance of the shield and grounding system of each cable. The tests were conducted across a broad frequency spectrum. Results are outlined in Figure 4. Lower impedance implies a more robust ground path, and therefore relatively lower noise coupled to the building ground. Lower building ground noise means a reduced need for troubleshooting of nearby adjacent systems and components.

**Conclusion**

A cable should never be the weak link in a VFD system. It must be able to stand up to the operating conditions, and maintain the life of other components in the system. Selecting an appropriate VFD cable can improve overall drive system longevity and reliability by mitigating the impact of reflected waves.

Special attention should be paid to the cable's insulation type, impedance, and shield/ground system.

Cables employing a heavy wall of thermoset insulation are recommended because of the proven electrical benefits and improved high temperature stability it offers. Shielding systems, including copper tape, combination

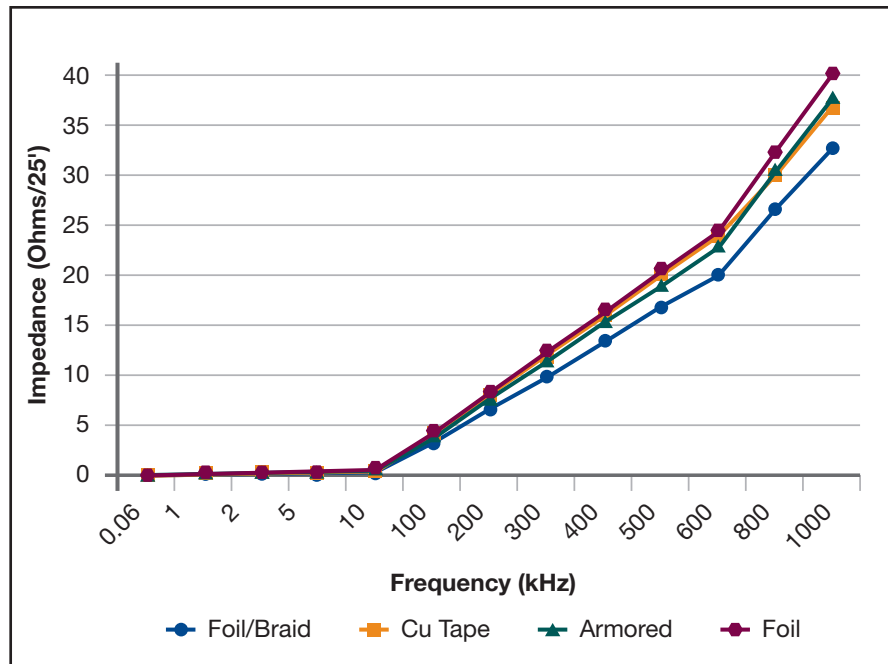


Figure 4: Shield/Ground impedance of the various cable types.

foil/braid, and continuous armoring types, are the most appropriate for VFD applications because of the low impedance path they provide for common-mode noise to return to the drive.

When VFD cables are installed in close proximity to low-level communications cables and other susceptible devices, shielded instrumentation cable should be used. It would also be prudent to limit the run length of VFD cable parallel to instrumentation cables to 10 ft. or less to reduce the likelihood of radiated noise issues.

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