Evaluating Critical VFD Cable Parameters

Specifying cables for VFD applications

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VFDs

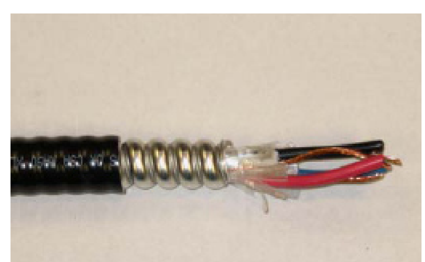
VFDs (Variable Frequency Drives) seem to be ever present in applications ranging from motion control to commercial flow/pumping. VFDs, also known as Adjustable Speed Drives or Variable Speed Drives require special considerations for the proper installation and operation of the drive system as well as the proper operation of nearby or adjacent systems. The nature of their operation impacts both longevity and reliability of these systems. This paper examines the motor-supply cable's impact on VFDs and surrounding equipment. Included are some fundamental guidelines for their installation and design.

Evaluation of Cable Types Used for VFDs

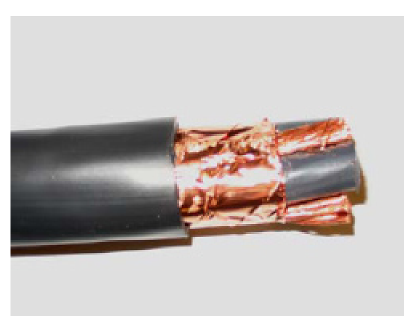
In order to provide an understanding of the variables and a guide in cable selection, the most commonly recommended cables for VFD applications were studied in both a lab and working application. Some wiring methods were not examined, such as THHN building wire in conduit, as their use has been shown to have detrimental effects, as outlined in other studies.[1 2] The exception to this was the use of PVC-Nylon insulated, PVC jacketed, tray cables. These cables are the most commonly installed industrial control cable and are often misapplied for use in VFD applications. For this purpose they are included for comparison. The PVC-Nylon designs were evaluated in both unshielded and foil shielded versions with their photos included below. Other cables evaluated were:

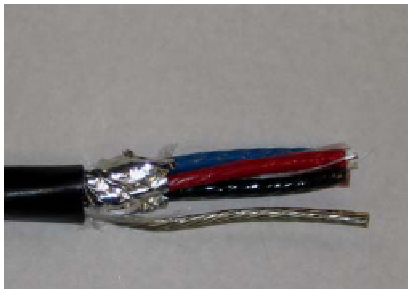
- XLP insulated, foil/braid(85%) shielded, PVC jacketed cable designed for VFD applications.
  - ◊ Four Conductor (three conductors plus green/yellow ground)
  - ◊ XLPE Insulation (.045" wall) 100% Foil +85% Tinned Copper Braid Shield
  - ◊ Full Size Tinned Copper Drain Wire (sectioned in #8 and larger)
  - ◊ Full Size Insulated Tinned Copper Ground Conductor
  - ◊ Industrial PVC Jacket
  - ◊ 600V/1000V Rated

- XLP insulated, continuously welded aluminum armored, PVC jacketed cable designed for VFD applications
  - ◊ Three Conductor #12
  - ◊ XLPE Insulation (.030" wall)
  - ◊ Continuously Welded Aluminum Armor
  - ◊ Three Symmetrical #16 Bare Ground Conductors
  - ◊ PVC Jacket
  - ◊ 600V MC Rating



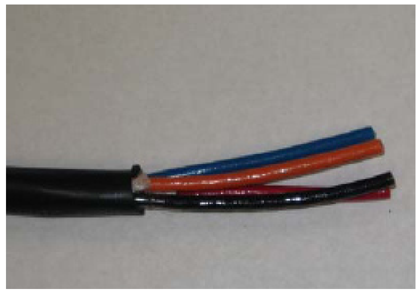
- XLP insulated, dual-copper tape shielded, PVC jacketed cable designed for VFD applications
  - ◊ Three Conductor #12
  - ◊ XLPE Insulation (.030" wall)
  - ◊ (2) .002" Cu Tapes spiral wrapped with 20% overlap
  - ◊ Three Symmetrical #16 Bare Ground Conductors
  - ◊ PVC Jacket
  - ◊ 600V Rated





PVC-Nylon/PVC Foil Shield Type TC

In order to better illustrate the application, a schematic is included in Figure 1. The cables discussed are used to interconnect the VFD to the AC motor(s). All testing was conducted using a current generation, IGBT-based, 480V, 5HP, AC, VFD, a inverter-duty rated AC motor and relevant lab equipment such as an LCR meter used to characterize the cables and an Oscilloscope used to make voltage measurements.



PVC-Nylon/PVC Type TC

Note that the cable impedance for 1HP motor/drive combinations would need to be roughly 1,000 ohms in order to match the corresponding motor's impedance. A cable with such high characteristic impedance would require conductor spacing in excess of several feet, implying that such a cable would be both impractical and very expensive, if it were available.

In addition to other benefits such as reduced capacitance, more closely matching 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 120ft cable lengths.

Table 1 lists typical impedance values for #12 AWG circuit conductors and is based on actual data. Impedance is influenced by the geometry and materials used in the manufacture of the cable. The characteristic impedance of the cable is calculated using the following formula:

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

Note the inversely proportional relationship between the cable's impedance and the peak motor terminal voltage. The cables with higher impedance tended to result in lower peak motor terminal voltages. The cable design for impedance also impacts the cable's useful life. Lower voltages across the motor terminals also translate into the cable being exposed to lower voltages, increasing the life expectancy of the cable. In addition, this reduces the likelihood of reaching either the cable or motor's CIV (corona inception voltage). CIV is the point at which the air gap between two conductors in the cable or two windings on the motor breaks down. If the CIV level is reached, insulation failure can occur in the windings of the motor.[3]

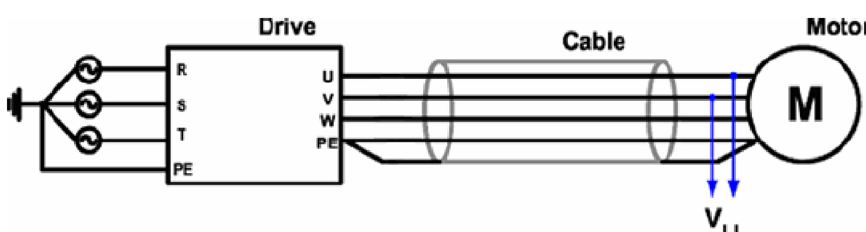


Figure 1. Schematic of VFD setup

Cable Design Impact on Motor and Cable Life

Reflected waves caused by a cable-to-motor impedance mismatch are prevalent in all AC VFD applications. It is dependent 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. Because cable length is mostly determined by the application, the rise times vary by VFD output semiconductor, and the voltage of the VFD is driven 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 over a range of horsepower ratings as indicated in Figure 2.

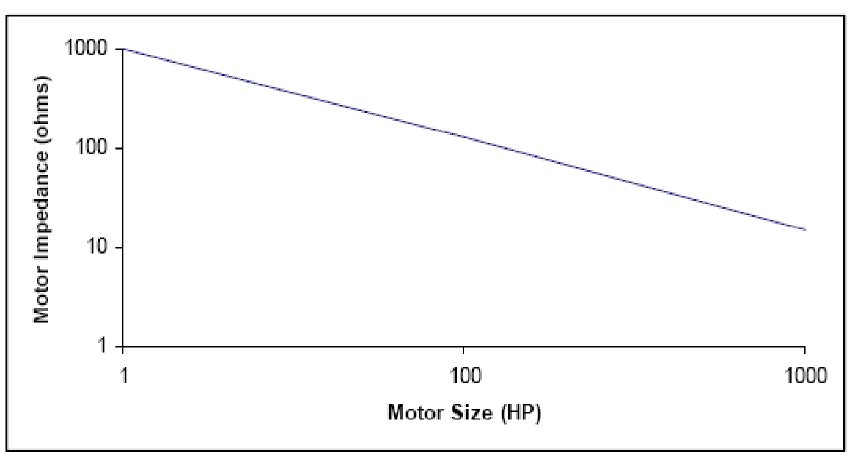


Figure 2. Motor impedance relative to motor size

The corona discharge occurring between conductors of the cable can reach very high temperatures. If the insulation system of the cable is a plastic material, such as PVC, corona inception can cause premature failure due to a gradual localized melting of the insulation. For this reason alone, thermoplastic insulations should not be used for VFD applications. Thermoset insulation systems such as XLP are ideal materials for such small localized temperature extremes because of the high temperature stability that they exhibit. The heat generated from possible 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

Radiated noise is proportional to the amount of varying electric current within the VFD cable. 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 source of significant radiated noise. By shielding the VFD cable, noise can be controlled. Relative shielding effectiveness was observed by noting the magnitude of noise coupled to 10' of parallel unshielded instrumentation cable for each VFD cable type. The results of the shielding effectiveness testing are documented in Figure 3:

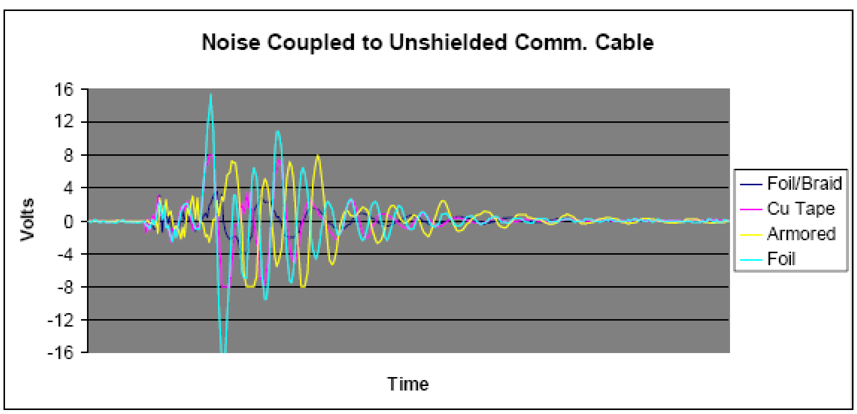


Figure 3. Noise coupled from VFD cables to unshielded instrumentation cable

As demonstrated by the pale green/blue trace in Figure 3, foil shields are simply not robust enough to capture the volume of noise generated by VFDs. Unshielded cables between VFDs and motors 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.

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
Un-Shielded 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

If radiated noise is an issue in an existing VFD installation, care should be taken when routing instrumentation/control cables in the area. Maintain as much separation as possible between instrumentation cables and VFD cables/leads. A minimum of one foot for shielded instrumentation and three feet for unshielded instrumentation cables is recommended. If the cables must cross paths, try to minimize the amount of parallel cable in the runs, preferably crossing the instrument cable perpendicularly with the power/VFD cable. If noise issues persist, 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, band-pass filters/chokes, output reactors, motor terminators, and metallic barriers in cable trays or raceways.

Impact of Common Mode Noise in VFD Applications

Noise radiating from the cable is one method for interference of adjacent systems, but is often easier to identify and rectify. Common-mode noise is more difficult to diagnose as the point of failure in adjacent systems, but it is often the cause and most difficult situation to rectify. High levels of noise across a broad frequency range, often from 60Hz to 30MHz, can capacitively couple from the windings of the motor to the motor frame and then to ground. Common-mode noise can also capacitively couple from unshielded motor leads in a conduit to ground via the conduit ground straps, supports or other adjacent and unintentional grounding paths. This common-mode ground current is troublesome because digital systems are susceptible to the high-frequency noise generated by VFDs.

Components and systems susceptible to common-mode noise are capacitive sensors such as proximity sensors, thermocouples signals, low-level communication signals, and encoders. Because this noise takes the path of least resistance, it finds unpredictable grounding paths that change and are often intermittent as humidity, temperature and load all change over time.

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

Tests were conducted on the five cable types to determine the ground path impedance of the shield and grounding system of each cable. These tests were conducted across a broad frequency spectrum and 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 reduced troubleshooting of nearby adjacent systems and components.

Conclusion

Selecting an appropriate VFD cable can improve overall drive system longevity and reliability by mitigating the impact of reflected waves on the overall drive system. 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 that they exhibit. Shielding systems including: copper tape, combination foil/braid, and continuous armoring types are the most appropriate shielding systems for VFD applications because of the low impedance path that 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 parallel runs of VFD cable with instrumentation cables to 10' or less in order to reduce the likelihood of experiencing radiated noise issues.

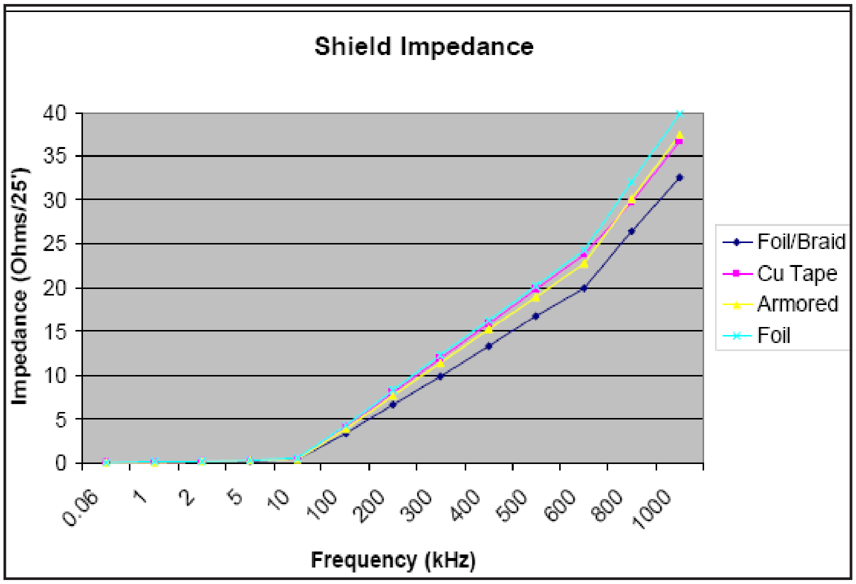


Figure 4. Shield/Ground impedance of the various cable types

[1] E. J. Bartolucci, B.H. Finke, "Cable Design for PWM Variable Speed AC Drives", IEEE Petroleum and Chemical Industry Conference, Sept, 1998
[2] E. Bulington, S. Abney, G. Skibinski, "Cable Alternatives of PWM AC Drive Applications", IEEE Petroleum and Chemical Industry Conference, Sept, 1999
[3] Evon, S., Kempke, D., Saunders, L., Skibinski, G., "Riding the Reflected wave - IGBT Drive Technology Demands New Motor and Cable Considerations", IEEE Petroleum and Chemical Industry Conference, Sept, 1996