Application Note

About VFD Cables

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A variable-frequency drive (VFD) cable is a special cable construction for the inverter-to-motor cable that has some or all of the following attributes:

- An overall shield that keeps bad stuff such as electrical magnetic interference (EMI) from escaping.
- A robust insulation system that keeps good stuff such as voltage and current from escaping.
- A symmetrical design that reduces the amount of bad stuff in the cable, such as common mode current and EMI.

Not all VFD cables offer each attribute mentioned; but each attribute helps the cable operate in such a way as to reduce problems that occur in installations that use VFDs. These problems aren't restricted to premature cable failure. They include interference with radios, controls and communication systems; shock hazards; premature motor failure; bearing fluting; drive trips; drive failures; and even having that precious magic smoke leak out of programmable logic controllers (PLCs), causing them to fail!

All these problems can make it harder to keep a facility up and running, and the wrong inverter-to-motor cable can contribute to any or all of these issues. How can a power cable at one end of a plant affect a PLC at the other end of the plant when it's not even connected to it? No, it's not the mystical "We Are All Connected" philosophy, although, in a way, that's not too far off. Before I discuss this mystery of the universe, here's the simple stuff.

A VFD Cable Has an Overall Shield

VFD cables have an overall shield. Unlike traditional slow 60-Hz power systems, the newer lightning-fast VFD waveforms have frequency measured in tens of MHz. Electrical Engineering 101 taught us that higher frequency means more energy. We need a way to stop that high energy from escaping the inverter-to-drive system, and a shield is a great way to limit electromagnetic radiation, interference and cross-talk.

Consider, for instance, two inverter-to-motor cables traveling together for a good distance in cable tray. One is energized, and the other is locked out. The locked-out circuit may receive enough electromagnetic coupling from the energized cable to produce a combination of voltage and current that can be dangerous or even fatal. It may shock you to learn that not using shielded (VFD) cable can result in safety issues. I'm pretty sure you don't need additional safety issues. Of course, with a VFD cable, this safety issue goes away!

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A VFD Cable Has Robust Insulation

While not all of VFD cables have this attribute, most of them do. Robust insulation means:

- Adequate thickness to handle the higher than traditional voltage peaks the cable sees.
- A high corona inception voltage (CIV) so the cable insulation is not damaged by corona discharge.
- A low dielectric constant to minimize cable capacitance.

This may seem like a lot of cable manufacturer mumbo-jumbo, but it's important. The first two items, insulation thickness and CIV, are important because inverter-to-motor cables see much higher voltages than you would expect because of reflected (also called standing) waves. These waves are caused by an impedance mismatch between the cable and the motor. I won't bore you with all the math, but in a 480V drive system, the cable can see voltage peaks of 1,300V, and that is a conservative number.

Add ringing and normal voltage fluctuations on the incoming line and the cable may see more than 1,500V. With a 575V system, that number jumps up to more than 1,900V. Using a 600V-rated cable in these applications makes about as much sense as using a 2,000V-rated cable in a 4,160V application. Personally, I believe that the cable's rated voltage should be higher than the voltage the cable sees. I would hope you agree.

Thicker insulation is a good thing but it alone will not combat the destructive effects of corona discharge. Corona discharge is simply an electrical discharge. The Corona Inception Voltage (CIV) is the voltage required to initiate a visible corona discharge from a conductor. Once the CIV is reached, corona discharge will occur, and that discharge will affect the insulation. As corona discharge produces heat, thermoplastic insulations (like the PVC insulation used in THHN cables) are melted by this discharge. Melted insulation does not work very well and cables with melted insulation will experience a short circuit when voltage breakdown occurs in this area of damage. There are other insulation materials that will not melt called thermoset insulations (like Cross-Linked Polyethylene, XLPE). Thermoset insulations are not susceptible to premature failure from corona discharge like thermoplastic insulations are. Most VFD cables have a thermoset insulation like XLPE. Some VFD cables actually use PVC insulation which not only can be damaged by corona discharge but also has other problems like increased capacitance. But why is capacitance a problem? Read on to find out!

In addition to allowing the cable to be rated for the voltage it actually sees, a thicker insulation will also help reduce the cable's capacitance. The main factors in calculating cable capacitance are the insulation's thickness and its dielectric constant. Thermoplastic High Heat-resistant Nylon coated (THHN) cable has a great price because it uses a thin PVC insulation rated at 600V, but PVC insulation has a high dielectric constant compared with thermoset materials. A 600V THHN cable may have about 10 times the capacitance of a 2,000V XLPE insulated cable.

"Why do I care about capacitance?" You say.

"Why did you buy a drive system in the first place?" I ask.

"To save energy and money!" You gladly respond.

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This is where I start shaking my head.

Think of what a capacitor does. It doesn't let low-frequency current pass, but it does allow high-frequency currents to flow freely. Remember the 60-Hz vs. multiple MHz discussion? At high frequency, a high-capacitance cable is leaking lots of current to ground and thereby is increasing energy usage and costs. In fact, enough current can leak to ground that a drive may shut down.

Ironically, some people "fix" this drive tripping problem by up-sizing the drive. They must be thinking the best way to reduce energy usage is to use more energy. A better, less costly, green energy solution would be to simply use a VFD cable that is not throwing so much of your drives energy away through capacitance coupling to ground.

Why THHN Is Not Your Friend

THHN cables not only have high capacitance, their PVC insulation is only rated for 600V and can melt when exposed to corona discharge. THHN, despite the fact that it is commonly used in drive applications, meets none of the three criteria set forth above for a robust insulation. Why do so many people use THHN? It's inexpensive and people don't know about the downsides of using it in drive systems. There are a few other reasons not to use PVC insulated cables, PVC is hydroscopic and it can cold flow but we don't need to discuss those negatives in detail. I think you already get the point.

Don't Skimp

Drives don't like to experience over-current trips, its not conducive to their long term well-being and it's my guess you would prefer that all your drives' energies get sent down the cable to the motor instead of bypassing the motor and going to ground. You probably don't want to be one of those people that will spend more money to buy drives to save energy and then spend less money on cable so that you can throw away some of that energy you paid more money to save in the first place. I suggest you spend a little more money on the cable to save energy – kind of like when you spent more money on a drive to save energy.

Don't Cause Problems

So far we have seen that using the incorrect cable between your inverter and motor can lead to:

- Premature cable failure due to over-voltage and corona discharge
- Operating issues with nearby equipment due to uncontrolled EMI
- Wasting energy by sending it to ground and bypassing the motor, via capacitive coupling
- Unnecessary drive trips due to high cable capacitance

A properly designed VFD cable will minimize all of these above issues. However, the wrong cable (or an improperly designed VFD cable) will not only NOT minimize all of these issues, an improperly designed VFD cable can actually contribute to the severity of drive related problems! It can do this by actually increasing the amount of common mode current (CMC) in the cable itself. But before we look at how a cable can actually increase the amount of CMC flowing let's look at what CMC is and why it's important? CMC is defined as the total sum of current flowing in the cable. Add up all the current flowing in all the conductors, grounds and shields and if you get a number close to zero, life is good. In traditional 60-Hz power systems the CMC flowing in the cable is very close to zero. In today's high speed drive systems, CMCs of 100 amps have been measured. That is a very big number.

100 amps is a problem and we will see why a little later but for now let's see how we can have such a large amount of CMC flowing in the cable in a VFD system. To simplify things, let's just look at the power conductors (where all the current is supposed to be flowing). In traditional 60-Hz power systems, each phase consists of a nice looking sine wave that is out of phase by 120° from the other phases. When we add up three equal amplitude sine waves that are 120° out of phase you get zero thanks to the wonders of trigonometry.
In the world of variable frequency drive pulse width modulated waveforms, things are not so nice. Imagine a simple two state drive that outputs either +V, or -V on each phase. Any way you look at it, you cannot add up the three phases to be anything close to zero. The closest you can come is +V + +V + -V or +V + -V + -V in either case, the amplitude is V and that is not going to equal zero unless V equals zero and if V equals zero we paid way too much money for this drive that has no output!

Good Construction

Cable construction can make this situation even worse! To see how let's go back to our simple sine waves and look at the current flowing in the ground conductor of a 4 conductor cable.

There is no power being forced down the ground conductor but according to Michael Faraday's law of induction we will see a current flowing in this ground conductor from each of the phase conductors. The phases adjacent to the ground are closer to it than the phase opposite the ground. As long as the three phases are not equidistant from ground we don't get complete cancellation of the induced sine waves and we will have current flowing in the ground.

Compare that to the current we see flowing in a symmetrically designed VFD cable, sometimes called a 3+3 design. In this cable design we have three phase conductors and three grounds, one ground in each of the three interstices between the phases. As this construction is symmetrical, trigonometry magic occurs and we get a complete cancellation of the induced currents. We end up with zero current flowing in the ground.

So a "3+3" VFD cable will have less CMC flowing in it than a 4 conductor VFD cable. And less CMC is a good thing! So why do you want less CMC flowing? Because the CMC flowing from the inverter to the motor has to find a way back to the inverter.

Here is where you look at me like you have got me.

You say, "Well the CMC can simply flow back to the inverter through the ground wires".

I respond, "Why do you think the CMC will flow back through the ground wires?"

You reply, "because it's the lowest impedance return path".

"Not at high frequency!" I state with a smile.

This is what gets most engineers and electricians in trouble with these systems. They apply all their years of experience and knowledge about 60-Hz power systems directly to VFD systems and don't take into account that electrical systems operating at 60-Hz and 30MHz are quite different. If you remember this fact alone it will save you lots of trouble. It will help you question things that you otherwise might take for granted. Just keep reminding yourself that you are dealing with frequencies almost 1 million times greater than the power you are used to dealing with.

Surface Area Rules All

In calculating resistance at high frequency, surface area becomes king. Your little ground wires become a relatively high impedance path. The current is lazy and it wants to take the path of least resistance. The factory's infrastructure looks very appealing to it. Building steel with its large surface area is a very attractive path. The CMC may also choose to wander through large motor shafts (via the bearings,) to factory equipment and then through building steel on its way back to the inverter. If it chooses this path it often leaves tracks behind. Those tracks, also called bearing fluting are a common cause of premature motor failure.

What we need is a nice, short, low impedance at high frequency path for the CMC to flow to on its way back to the inverter. An overall shield, be it a copper braid, a copper tape, or a continuously welded aluminum armor, provides such a path. Now we have yet another reason to use shielded cable – to provide that controlled CMC path!

By the way, that nice, short, low impedance at high frequency shield is not going to do you a lot of good unless it has a nice, conductive, low impedance termination at both ends of it. By termination I am talking about terminating the shield. Rockwell recommends a shield termination that gives you 360° of electrical contact around the shield. But please understand, not all terminations are created equal. Some terminations are better than others just like some VFD cables are better than others. We could do a whole other paper just on that topic. Just remember that if you buy VFD cable but don't terminate it correctly, you lose many of the advantages VFD cable has to offer.

There you have it. Now you know about the issues of EMI, CIV, CMC in VFD systems. If you allow me to use CAP for Capacitance, we have yet another 3 letter acronym to make all this easier to remember!

Now imagine an innocent little PLC someplace far far away from the VFD system and cable. It seems isolated from the VFD system but it happens to be sitting next the return path for the CMC. How do you think that PLC is going to act when it's ground gets exposed to, say, 100 amps of high frequency noise? It's not going to be pretty. This is why you want to provide a controlled path for the CMC back to the inverter. You don't need or want lots of amps wandering around your building steel, smoking your PLCs and other control and communication equipment.

See? That mystical "We Are All Connected" philosophy has more to do with the wonderful world of VFD engineering than you ever thought. One more mystery of the universe explained!

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