Southwire Company:  
VFD Cables, Essential or Overkill?  
– Presented by Steve Wetzel, Sr. Product Engineer
A Engineer from Rockwell Automation once said to me...

- “Please tell me you don’t make a VFD cable with PVC insulation”
- It just caused him problems
- Why would anyone make such a cable?
Three quick Stories

- When things go well…
- When things do not go well…
- When things might go well but then again they may not…
A Rockwell Automation engineer once said to me...

- “Please tell me you don’t make a VFD cable with PVC insulation”
- It just caused him problems
- Why would anyone make such a cable?
Why would anyone make such a cable?

“In those days, there was no king in Israel; everyone did what was right in his own eyes.”

– Judges 21:25
Why would anyone make such a cable?

“In those days, there was no VFD cable standard in America; everyone did what was right in his own eyes.”

– Wetzel 1:1
Confusion abounds because:

- There is no US standard for VFD cable
- Anyone can make anything and call it a VFD cable.
- There is no such thing as a “VFD Rated Cable”
  (but we are asked to supply one all the time)
Southwire is working to fix this!

- Southwire chairs a working group to create a VFD Cable Standard that will help to end the confusion

Insulated Cable Engineers Association
Potential Problems

- Motor Failures
- Drive Failures
- PLC Failures
- Shock Hazards
- Drive Trips
- Radio Problems
- Control Issues
- Communication Challenges
- EMI
- Wasted Energy
- Cable Failure
- Decreased Productivity

Why would anyone make such a cable?
What people want to know

- When do I need to use a VFD Cable?
How to know if you need a VFD cable?

- Shield Type
- Number of Grounds
- Ground Grid
- Termination Type
- Frequency
- Cable Impedance
- Insulation Type
- voltage Rating
- Cable Capacitance
- dV/dT
- Noise Immunity
- Cable Length
- Motor Impedance
- Switching Speed
- Transfer Impedance
- VFD Type
- And More…

And More…
How to know if you need a VFD cable?

**Answer**

\[ \text{Insulation Type} \times \text{Cable Impedance}^2 \times \left( \frac{\text{Cable Capacitance}^4}{\text{VFD Type}} \right)^{\text{Cable Length}} \]

\[ \times \left\{ \begin{array}{c}
\text{Termination Type} \\
\text{Switching Speed} \\
\text{Frequency} \\
\text{Ground Grid} \\
\text{Switching Speed} \\
\text{Ground Grid} \\
\end{array} \right\} \]

\[ \times \int \frac{dV/dT}{\text{Shield Type}} \times \text{Transfer Impedance} \times \text{Noise Immunity} \]

\[ - \text{Limit}_{f \rightarrow \infty} \left( \frac{\text{Number of Grounds}}{\text{Voltage Rating}} \right) \times \text{Motor Impedance} \]
It’s not that simple.
The Basics: VFD Cable can help reduce

- Motor Failures
- Drive Failures
- PLC Failures
- Shock Hazards
- Drive Trips
- Radio Problems
- Control Issues
- Communication Challenges
- EMI
- Wasted Energy
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- Decreased Productivity
We are dealing with frequencies about one million times higher.
Why is high frequency a problem?

- Impedance changes at high frequency

<table>
<thead>
<tr>
<th>500 kcmil Shielded 5kV Conductor</th>
<th>60Hz</th>
<th>10MHz</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Resistance</td>
<td>0.013 mΩ/1000 ft.</td>
<td>3.457 mΩ/1000 ft.</td>
<td>266 times higher</td>
</tr>
<tr>
<td>Capacitive Reactance</td>
<td>16,370 Ω/1000 ft.</td>
<td>0.1 Ω/1000 ft.</td>
<td>163,700 times lower</td>
</tr>
</tbody>
</table>
What is a VFD Cable?

- VFD Cables Three Main Components:
  - Overall Shield: 100%
  - Robust Insulation: < 100%
  - Symmetrical Design: <<100%

Why?
“In those days, there was no VFD cable standard in America; everyone did what was right in his own eyes.”

– Wetzel 1:1

Let’s look at these three VFC Cable components in detail
At high frequency, an unshielded power cable can act as a large loop radiating antenna, broadcasting interference throughout your facility.
Overall Shield

- At high frequency, a shielded power cable reduces EMI and problems.
Safety

Shielded Cable

Overall Shield
Controlling Common Mode Current

- It’s the sum of all currents flowing in the cable

\[ i_{cm} = i_{phase\ A} + i_{phase\ B} + i_{phase\ C} + i_{grounds} + i_{shield} \]

- Should be close to zero or we can have problems
In a balanced 60Hz system $i_{cm} \approx Zero$

- Phase currents sum to Zero

\[
\sin \left(x - \frac{2\pi}{3}\right) + \sin \left(x - \frac{4\pi}{3}\right) + \sin \left(x - \frac{6\pi}{3}\right) = 0
\]

- Ground currents are Zero

- Shield currents are Zero

\[0 + 0 + 0 = 0\]
In a VFD System...

• In a VFD System $i_{cm} \neq Zero$
• Phase currents sum to:

• The math is not pretty
It’s a lot of current!

• To scale…

Common Mode Currents of 100A have been measured
What’s the problem?

- $i_{cm}$ gets pushed to the motor
- $i_{cm}$ must travel back to the drive to the motor
- What path will it take?

Input Transformer

Big Factory Machine

Cable

Cable

Not Likely

Overall Shield
Why Not?

- Because of High Frequency
  - Currents flows on the surface (skin effect)
  - Building steel has:
    - Lots of surface area
    - Low impedance at high frequency
  - Copper ground wires have:
    - Small surface area
    - High impedance at high frequency

- So where will the current go?
Why is this an Issue?

- Input Transformer
- Cable
- Unshielded Cable
- Big Factory Machine
- Motor Failure

100A CMC has been measured

Overall Shield
About Motor failure

- Can be caused by premature bearing failure
- Caused by current flowing through the bearing
- It’s called bearing fluting
- Bearing fluting scars the bearing and looks like this:
How do we fix it?

- Use a properly terminated VFD cable
  - The cable connector must provide good **360° contact** and low transfer impedance from the shield or armor of the cable to the conduit entry plate at both the motor and the drive (or drive cabinet) for electrical bonding.

- Use an “EMC” type cable gland or a constant force spring to terminate the shield.

- The shield must be terminated at both ends.

- Consult Southwire’s application note “Terminating VFD Cables”.

- Southwire terminating kits will be coming!
How do we fix it?

- We need to control the path of the common mode current

Input Transformer → Cable → Big Factory Machine

Conduit Alert!!!

Properly Terminated VFD Cable

Overall Shield
Conduit Alert

- Conduit is installed and maintained as mechanical protection, not electrical.
- It does not provide a safe path for the common mode current
  - No low impedance at high frequency terminations
  - Bare “Shield” contacts building infrastructure allowing for jumping off points for the common mode current
A symmetrical design also helps
About Symmetrical Design

- To help minimize common mode current
- Let's look at the common mode ground current
- \( i_{cm} = i_{phase\ A} + i_{phase\ B} + i_{phase\ C} + i_{grounds} + i_{shield} \)
Sine Wave Magic!

\[
\sin \left( x - \frac{2\pi}{3} \right) + \sin \left( x - \frac{4\pi}{3} \right) + \sin \left( x - \frac{6\pi}{3} \right) = 0
\]

\[
+ \quad + \quad \text{ZERO!}
\]
4 Conductor Cable

Symmetrical Design
3+3 Cable

Symmetrical Design
Symmetrical cables reduce common mode current!
The difference

- The Symmetrical 3+3 design minimizes common mode current

The best design for VFD Cable
We can reduce common mode problems by:

- Controlling the path of the common mode current
- Minimizing the common mode current
About Insulation

- Anyone here use a 2000 volt cable in a 4160 volt application?
- So why use a 600 volt cable between and inverter and motor?
THHN cable is not your friend

- THHN is
  - The most popular alternative to using VFD Cable
  - Not good to use
Why Not?

- It's rated 600V
- A drive cable can see higher voltage than that
The voltage your cable sees

- Function of:
  - Cable length
  - Drive pulse rise time

- In Theory, the voltage doubles. In practice, it can be higher
It can get worse

- 2 to 2.4 times the DC link voltage according to one IEEE paper

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1 Riding the Reflected Wave - IGBT Drive Technology Demands New Motor and Cable Considerations
Will you see over voltage?

- Robust Insulation

Graph showing the relationship between motor overvoltage and cable length for different risetimes. The graph includes data points and curves for different cable lengths (4 feet, 35 feet, 320 feet, > 3200 feet) and risetimes (4 μs, 2 μs, 1 μs, 600 ns, 400 ns, 200 ns, 100 ns, 50 ns).
The solutions obvious

We need really really small factories

Or we need to use system components rated to handle the voltages they will see.
480V System

- RMS (its easy!)
  - 480 V<sub>rms</sub>
  - 480 V<sub>rms</sub> < 600 V<sub>rms</sub> Cable Rating
  - Life is good!

- Peak Voltage
  - 480√2 = 679 V<sub>p</sub>
  - 679 V<sub>p</sub> < 850 V<sub>p</sub> Cable Rating
  - Life is still Good!

- RMS (its hard!)
  - No sine wave magic here

- Peak Voltage
  - 2.4 x V<sub>dcLink</sub> = 1,629 V<sub>p</sub>
  - 1,629 V<sub>p</sub> > 850 V<sub>p</sub> Cable Rating
  - That’s above the cable rating!
575V System

- $575 \text{ V}_{\text{rms}}$
- $575\sqrt{2} \text{ V}_{\text{rms}} = 813 \text{ V}_p$
- $2.4 \times V_p = 1951 \text{ V}_p$ with reflected waves
- $1951 \text{ V}_p > 850 \text{ V}_p$ Cable Rating
- 130% to be exact

- $4160 \text{ V}_{\text{rms}}$
- $4160\sqrt{2} \text{ V}_{\text{rms}} = 5883 \text{ V}_p$
- $2000 \text{ V}_{\text{rms}}$ cable is 2828 Vp cable
- $5883 \text{ V}_p > 2828 \text{ V}_p$ Cable Rating
- 108% to be exact
Three Other Problems

- Voltage
- CIV
- Wet Withstand
- Cold Flow
- Capacitance
- Compliance with Standards
CIV

- Corona Inception Voltage
- A function of
  - Insulation Compound
  - Insulation Thickness
Wet Withstand Voltage

- PVC is Hydroscopic:
  - Absorbs moisture from the air, reducing voltage withstand by 55%
Cold Flow

- When pulled into conduit around a bend
Cold Flow

- When pulled into conduit around a bend
- PVC can be permanently deformed due to pressure or force.
Side Note: Medium Voltage Drives

- Different than Low Voltage Drives
- LV Drives are voltage sourced devices
- MV Drives can be either current or voltage sourced
- Current sourced drives do not output high frequency like voltage sourced drives.
- Talk to the drive manufacturer about cable requirements.
Cable Capacitance

- Cable acts like a capacitor
- Common cause of drive over-current trips
What happens
What happens

THHN cable can have 10 times the capacitance of VFD cable
One Solution

Buy a bigger drive!

Robust Insulation
Some People

- Buy a drive to save energy
- Save money and buy PVC insulated cable…
  - Which has a higher capacitance
  - And leaks current to ground
  - And Trips
  - And wastes energy
  - And may damage drives

DO NOT BE LIKE SOME PEOPLE!
A Better Solution

Buy a better cable!
But VFD Cable Costs More!

- Yes, just as buying a VFD cost more than not buying a VFD.
- A VFD **saves energy costs and increase efficiency**. You spend money up front, to save money long term.
- A VFD cable **saves energy costs and increase efficiency**. You spend money up front, to save money long term.
- **If you could reduce one drive trip per month**
  how long before you realized the payback of installing VFD cable?
The New NFPA 79

“Circuits Supplied From Power Conversion Equipment. Electrical conductors and equipment supplied by power conversion equipment as part of adjustable speed drive systems and servo drive systems shall be listed flexible motor supply cable marked type RHH, RHW, RHW-2, XHH, XHHW, or XHHW-2 or selected based on the equipment manufacturer’s instructions.”

NFPA 79 2018: Electrical Standard for Industrial Machinery 4.4.2.8
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**NFPA 79 2018: Electrical Standard for Industrial Machinery 4.4.2.8**

Note that THHN insulation is not allowed. All insulations listed are cross-linked.
What to do

- Use a VFD cable that has:
  - An overall shield
  - A symmetrical construction
  - A robust insulation of the proper voltage rating
  - Use a thermoset (cross-linked) insulation, not PVC (THHN)
What about Reactors and Filters?

All These are additional devices that you need to:

- Make Room and Find Time For:
  - Installation
  - Inspection
  - Maintenance

Reactor at Drive
- Expensive and bulky
- Voltage drop causing reduced torque
- Can cause nuisance tripping.

dV/dt Filter
- Expensive and Bulky
- Loss of Power
- Can make things worse

Reactor at Motor
- Does not address reflected waves in cable
Southwire VFD Cable Constructions

600V, 2400V, or 5kV

Class B or Flex Strand

w/ or w/o signal pair
Which construction is best (my Opinion)

- I don't like 4 conductor designs
  - we do it because others do
  - a drain wire is not needed if you properly terminate

- Copper tape works but...
  - if you over bend it you gap can gap the tape shield
  - because there is no standard, tape overlap varies
  - may be hard to terminate correctly

- Continuously corrugated welded cable (ArmorX)
  - termination of the shield is very easy and very good (we have glands)
  - you cannot gap the shield
  - the armor is an excellent shield
One More Thing… (a gross generalization)

- **Drive Sales Guys**
  - May overlook or minimize potential technical problems
  - Getting the order is the highest priority

- **Drive Application Engineers**
  - Look for areas where you may have problems
  - Getting a smooth operating system is the highest priority

Disclaimer: I have been in both Sales and Engineering!
Thank You!