# Cable Alternatives for PWM AC Drive Applications



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## Abstract

This paper describes an alternative solution for cables used with Insulated Gate Bipolar Transistor (IGBT) Variable Frequency Drives (VFDs). New IGBT technology has introduced voltage stresses on motors and cables that leads to unpredictable system performance and reliability. This paper includes a performance and cost comparison between a continuously welded armored option, the option of lead wire in conduit, and a proposed shielded tray cable. Unique physical characteristics of the cables are discussed. A proposed cable with increased insulation thickness is discussed that insures long-term cable service life under VFD operation, while the shielded coaxial braid contains VFD EMI emissions. Other applications, options, and termination considerations with respect to the petro-chem industry is discussed. Cable performance is documented with theoretical and experimental support.

## Index Terms

VFD cable, Insulation dielectric strength, reflected wave voltage, conducted and radiated emissions

## I. INTRODUCTION

Advantages of IGBT VFD's are well known, as are some of the problems associated with their operation. Motor insulation failure was first identified as the "weakest link" in the IGBT drive system. As a solution, new motor insulation technology provided motors with repetitive 1,600 Vpk withstand capability per NEMA MG-1 part 31 [1]. Careful selection of the VFD cable is necessary to insure it does not become the next "weakest link" in the system. The cable technology selected must guarantee a minimum 20-year cable life in the presence of the repetitive 1,600 Vpk voltage spikes from 600V IGBT drives. The cable must also minimize the effect of high frequency noise induced into the plant ground system as a result of faster switching speeds of the new IGBT drives. As a result of customer demand, another option for VFD to motor cabling was developed to provide an alternate to continuously welded aluminum armored cable [2,3] or conduit [4]. It is shown that this cable also provides advantages when used as the connection method between the VFD and input power source. This paper discusses other application specific considerations, conducted and radiated noise, environmental concerns, installation difficulties, cost, and plant layout that should be addressed when choosing a cable type.

### A. Drive System Longevity

Drive system longevity has been the subject of many papers since the advent of the VFD. Subjects of failure consist of motor winding insulation failure, cable failure, motor bearing failure, and unexpected drive over-current alarms, susceptible external circuit malfunction, and more. As part of the system, the cable plays an integral role in optimizing longevity and performance. The role of the cable consists of two parts: (i) It's ability to withstand the operating conditions caused by the drive system (ii) How it influences the life of other drive system components.

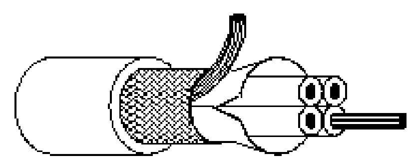

Fig. 1 Focus Cable is a UL Shielded Tray Cable with 3 XLPE increased insulation conductors (black with white T1, T2, T3 marking), full insulated green ground wire, one or more drain wires for ease of braid / foil shield connection, and 90oC wet or dry rating with an external PVC outer jacket.

### B. Application Specific Considerations

As longevity of the system is a goal for nearly every application, there are some applications which may require additional cable properties, and some that may not be as demanding.

Application specific issues are industry independent and can be summed into a list that is manageable. From this list, several tables have been developed in the paper for use as a quick reference when choosing a cable construction. All connection methods have their benefits, but they must all first meet the requirements of expected system longevity before the application specific attributes are considered. All components of a cable type are critical.

### C. Cables Compared

Cables compared in this paper are those that have had some history in industrial applications and have been found as a recommended cable type for VFD applications. The components of cables have physical characteristics and electrical characteristics that are dependent. What may have good electrical characteristics, may also be very structurally weak and vice versa. The tables and cross-references contained in this paper only compare the following three constructions. Two of the constructions are UL Type Tray Cables, and differ mostly with respect to conductor dielectric insulation and use of an overall shield.

(1) Focus Cable

The Focus cable is a 90$^{o}$C, wet or dry, direct burial Underwriter's Lab (UL) listed, Type Tray Cable (TC) with three labeled Cross-Linked Poly-Ethylene (XLPE) insulated conductors and a full-sized fully insulated green ground conductor. XLPE insulation is intentionally oversized for extended life on VFD drives. EMI performance is enhanced with a full size tinned copper drain wire between a 100% coverage foil shield and 85% coverage tinned copper braid shield. The overall jacket is sunlight resistant Poly-Vinyl Chloride (PVC). All conductors are tinned and finely stranded for extreme flexibility. Chemical resistant jackets and armor covering are possible design options available.

(2) VNTC®:

Vinyl Nylon Tray Cable (VNTC) is a generic representation for the insulation system that is used in this cable. The conductor's insulation utilizes PVC with a Nylon skin, referred to as "PVC-Nyl". PVC-Nylon is also an insulation system that is used with National Electric Code (NEC) listed THHN single conductors in conduit, which can be approximated by the values seen in the testing and tables as "VNTC."

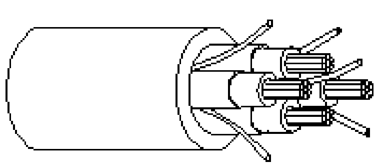

Fig. 2 Vinyl Nylon Tray Cable using 4 PVC-Nylon THHN conductors, fillers and an overall PVC outer jacket.

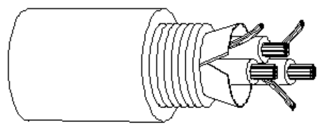

Fig. 3 Type MC continuous welded aluminum armor cable with 3 XLPE insulated conductors, ground wires and external PVC outer jacket.

(3) Type MC Cable:

Metal Clad (Type MC) cable is another cable referred to as a preferred cable for VFD applications, and is another viable alternative. It also uses XLPE insulation, however, it is much thinner than the Focus Cable. It may incorporate one or more ground conductors as allowed by UL, and is constructed specifically with a continuously welded impervious aluminum sheath and PVC outer jacket.

## II. CABLE IMPACT ON DRIVE APPLICATIONS

### A. Understanding Reflected Waves

Fig. 4 shows a single pulse from a PWM drive output waveform and the associated waveform as seen at the motor terminals, where it is not necessarily the drive dc bus voltage ($V_{bus}$) but a much larger value. Drive peak output voltage is the $V_{bus}$ value which is ~ 1.37*($V_{ac\_rms\_input}$). The peak transient voltage at the motor in Fig. 4 is caused by "Reflected Waves" on the cable as a result of motor and cable surge impedance mismatch, and the effects of the extremely small rise times associated with PWM drives [5,6]. Although this theory could be examined more closely, it can be summarized that a reflected wave may occur at the motor-cable connection, if there is a Motor surge impedance ($Z_{motor}$) to Cable surge impedance ($Z_{cable}$ ) impedance mismatch at that point [5,6]. Peak reflected wave voltage is then defined by the formula below:

$$V_{motor\ peak} = V_{bus}(1+\Gamma) \quad where\ \Gamma = \frac{Z_{motor} - Z_{cable}}{Z_{motor} + Z_{cable}}$$

As the cable is a contributing factor to this increase in reflected wave voltage from (1), it can also be designed differently to reduce its affect of this phenomenon. As seen above, if the impedance mismatch of the cable was smaller, (the cable more closely matched the impedance of the motor), the reflected waves would be smaller than those seen on a cable-motor combination with a larger impedance mismatch. As impedance mismatch is related to standing waves, cable impedance calculations show that common cables used in VFD applications to date may have a wide variety of impedance values. To illustrate this impedance mismatch, Fig. 5 shows the average difference of cable surge impedance between industry standard cables and motors. Motor Surge Impedance $Z_{motor}$ of Fig. 5 was experimentally derived in [7]. Cable Surge

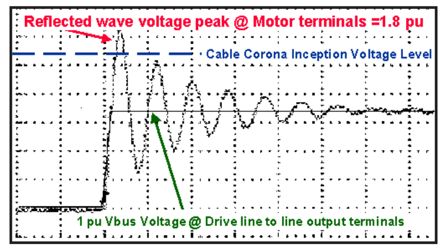


Fig. 4 PWM Drive output voltage waveform and resulting motor terminal voltage with 1.8x the drive output voltage peak caused by reflected wave cable to motor surge impedance mismatch

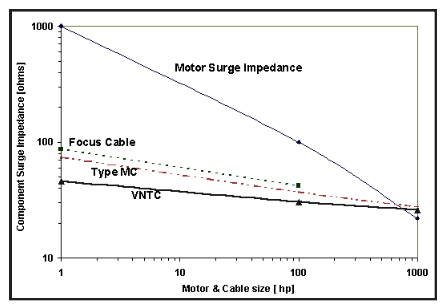


Fig. 5 Surge impedance of ac motor, Focus Cable, Type MC cable and VNTC cable vs. Motor hp range.

Impedance $Z_{cable}$ of Fig. 5 was experimentally measured for the XLPE Focus cable, PVC - VNTC cable and the XLPE Type MC armor cable.

As shown in Fig. 5, the largest difference is between the motor and the 0.019 inches of PVC-Nylon. Substitution of VNTC $Z_{cable}$ and $Z_{motor}$ into (1) yields theoretical peak motor voltages in per unit (pu = $V_{peak}$ / $V_{bus}$) for the low hp drives between 1.85 pu to 1.9 pu. Based on the impedance mismatch of the motor to cable, the reflected wave phenomenon difference between the two cables using XLPE is insignificant. However, as seen in Section II-B, it is important to note that motor life stress reduction of even 5% may result in a significant increase in the insulation life expectancy of some motor manufacturer's windings.

Reflected wave phenomenon has always been possible with VFD applications, but smaller pulse rise times of IGBT technology have now led to motor voltages of ~ 2 x $V_{bus}$ or 2 pu at very short cable distances [5,6]. Fig. 6 is a plot of motor pu overvoltage vs. output cable distance for typical IGBT pulse risetimes of 100 ns to 400 ns. Fig. 6 is generated by determining the (l/4) critical wavelength where 2 pu reflected voltage peak occurs from (2). The equivalent pulse frequency ($f_u$), is where the transient energy of the pulse risetime ($t_{rise}$) is concentrated and is defined as (1/ p $t_{rise}$). The reflected wave velocity is a function of the speed of light (c = 3.0 E+8 m/s) and insulation dielectric constant $e_r$. For wires separated in air, $e_r$ =1.0, while $e_r$ =5.5 for bundled PVC wires and $e_r$ =3.2 for bundled XLPE wire insulation.

$$\lambda = [wave\ velocity]\left(\frac{1}{f_u}\right) = \left[\frac{c}{\sqrt{\varepsilon_r}}\right](\pi t_{rise})$$

[meters] (2)

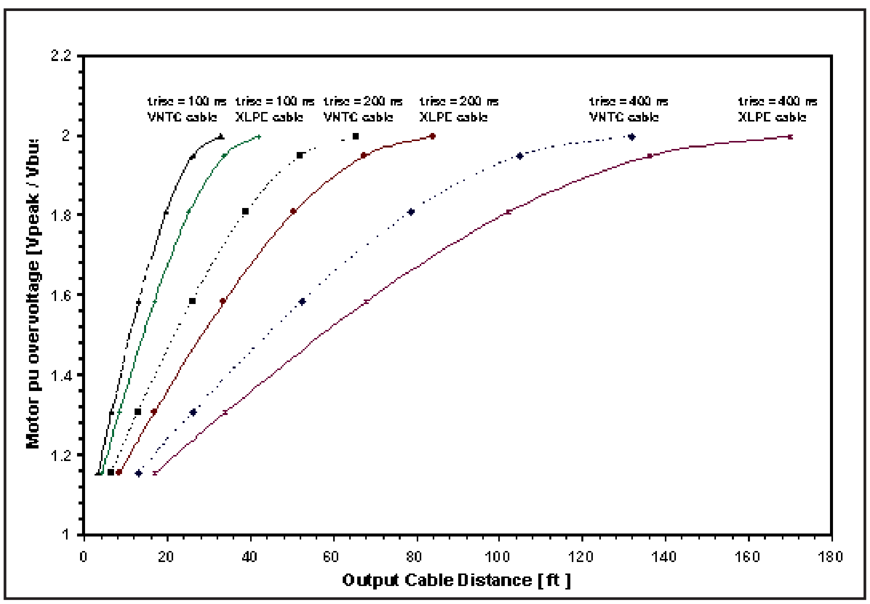


Fig. 6 Predicted Motor Overvoltage transient vs. output cable distance for typical IGBT risetimes when using bundled PVC cable or bundled XLPE cables.

Fig. 6 data shows that for various IGBT risetimes used with short drive to motor cable runs, the XLPE bundled cables have ~ 5% to 10 % lower peak reflected wave voltage than bundled VNTC cables for the same output cable length.

Thus, the motor insulation stress is reduced with the Focus cable used in short application lengths. Field site testing of the Focus Cable versus a VNTC construction, showed average reflected wave voltages, seen line to line at the motor, were reduced by 4.1% for a 100 ft run of #12 AWG cables with a 5 hp IGBT drive and 3 hp 460V AC induction motor. This agrees with Fig. 6 information provided.

Use of high PWM carrier switching frequencies and application cable lengths longer than the critical cable length shown, may have up to 3 pu reflected wave motor voltage for all cable types. This is due to a complex interaction of repetitive PWM pulses and cable dynamics not allowing the transient reflected wave voltage to decay to zero before arrival of the next PWM pulse [8]. The 3 pu stress at the switching edge only occurs a few times during a complete fundamental cycle, but must be taken into account in terms of cable and motor dielectric withstand capability. There are some PWM drives available that can reduce the 3 pu stress down to the theoretical 2 pu voltage stress by appropriate PWM control methods.

## B. Reflected Wave Impact on Motor Insulation

Motor insulation failures may occur depending on reflected wave peak voltage magnitude and risetime [9-12]. The fast ristimes of IGBT drives place a higher non-linear voltage stress across the phase winding, such that the first few turns in a random wound machine may be stressed above the insulation CIV limit. Likewise, the first coil wire end to the line end wire is also a place of maximum voltage stress that might be above the insulation CIV limit. None of the cable types listed will significantly or beneficially slow down the reflected wave pulse risetime. However, the XLPE insulations from Fig. 5 have a lower reflected wave magnitude, which aid in voltage stress reduction. XLPE type insulated cables also extend the output cable distance where 2 pu voltage stress occurs as compared to PVC - VNTC cables.

A CIV test method of the winding insulation was done to determine the average and statistical variances of typical motor insulation CIV limits [13]. Predicting motor life leads to a comparison of the percentage probability of motor failure based on the motor insulation CIV statistical quality variation with an applied peak reflected wave voltage determined by the cable-motor combination. Fig. 7 shows the probability that various motor manufacturer's will fail, relative to motor peak transient voltages of 2 pu and 3 pu voltages on a 480 V system.

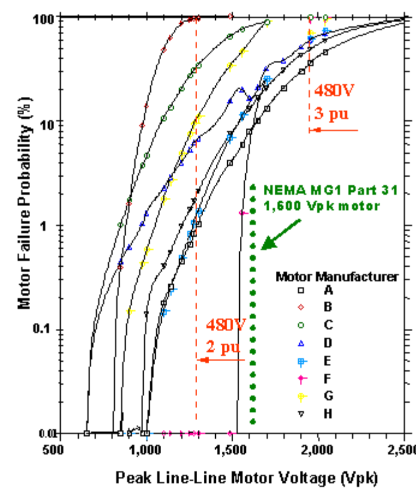


Fig. 7 Predicted Motor Failure Probability vs. applied peak line to line reflected wave voltage for various motor manufacturer's tested.

The 5% to 10% difference in lower peak reflected wave voltage of the two XLPE constructions, as compared to the PVC cable, may have a significant impact on motor life in the low grade range of standard duty motors of Fig. 7.

The preferred system solution is to: (i) use the Focus cable to mainly control EMI conducted and radiated emissions, while simultaneously guaranteeing a 20-year dielectric withstand to the repetitive 2 pu to 3 pu transient stress. (ii) use a PWM drive that reduces the 3 pu stress in Fig. 7 down to 2 pu by use of an intelligent PWM controller. (iii) chose a 1600 Vpk inverter duty motor per Nema specs [1] for 480 V systems and a 1,850 Vpk motor for 600 V systems. As seen the probability of motor failure is not as much cable dependent, if the motor has a higher insulation rating.

### C. Reflected Wave Impact on Cable Insulation

Predicting in-service cable life for the various cable types requires a comparison of the insulation material properties, insulation thickness and cable geometrical construction. The comparison must also consider the mechanical, environmental and electrical stresses applied to the cable insulation material. The combined stresses will dictate where the cable will fail, if at all, as a direct result of operation on the PWM drive. Table 1 summarizes some of the mechanical and environmental properties of the PVC, CPE and XLPE compounds as used on insulation or outer jacket [14].

The dielectric (conductor insulation) directly affects the cable surge impedance value and therefore impacts the reflected wave voltage magnitude that a given motor-cable combination will have. Ultimately, the dielectric must withstand the repetitive 2 $V_{bus}$ to 3 $V_{bus}$ electrical transient voltage spike stress, occurring at the drive-switching rate, that is caused by the reflected wave phenomenon.

The stronger the dielectric strength, the less likely the insulation will break down under extreme voltage stress. However, rated dielectric breakdown voltage and rated volts/mil dielectric strength are not necessarily the only insulation parameter to coordinate with applied stress. Firstly, the breakdown value is an instantaneous failure point and secondly partial discharge and corona inception voltage (CIV) failure mechanisms may start at a voltage much lower than the breakdown voltage value. Therefore, the conductors must be capable of maintaining insulation resistance at the repetitive 2 $V_{bus}$ to 3 $V_{bus}$ values. Thus, the cable will have long term life if the applied repetitive 2 $V_{bus}$ to 3 $V_{bus}$ voltage is less than the corona inception voltage of the cable [2,6]. Section III measures the CIV levels for various cable insulation types and insulation thickness available and estimates the effect of the VFD induced reflected wave transient 2 pu and 3 pu over-voltage on cable life.

The Focus Cable, using 0.045 inches of XLPE, was found to have a long-term dielectric withstand of 550 v/mil under load cycling tests. The actual in-service life expectancy of this cable type should be a minimum of 40 years. Also, Section III shows measured CIV of the 0.045" XLPE insulation is well above applied 2 pu to 3 pu transient voltage stress for a 600 Vac drive system. Section III shows how the insulation CIV level degrades with environments containing moisture. From Section III, predicted in-service life expectancy of 0.045" XLPE insulated single conductors is > 55 years, when used with a 600 Vac drive with 2 pu voltage spikes. A 480 V drive with 2 pu voltage spikes will have a predicted cable life in excess of 100 years under wet or dry conditions. The 0.045 inches of XLPE also affords the single conductors a RHW-2 rating, which is rated for 90 degree C in wet or dry locations, compared to typical PVC or PVC-Nylon rating, which is only rated at 75 degree C for wet locations.

Predicted life expectancy of 15-mil PVC-Nylon THHN insulated single conductors under 480V drive operation is 10 years from Section III and could be as low as 3 years with 3 pu voltage spikes applied. Life expectancy predicted for 600 V operation with of 15-mil PVC-Nylon THHN insulation and 2 pu voltage spikes is an unacceptable 5-year life. For this reason, VNTC constructions and lead wires are not recommended for drive applications.

### D. Cable Impact on Motor Bearing Failure

Motor bearing failure due to bearing currents induced by VFD operation has become a recent concern with users and has been addressed in literature [15-19]. Balanced motor operation on a 60 Hz utility system has a stator neutral voltage to ground near zero volts and has an electro-magnetically induced rotor shaft voltage of < 1 volt. The low rotor voltage implies a bearing race to ground voltage that cannot charge the bearing oil film through bearing currents and therefore cannot cause bearing damage. The motor stator neutral to ground voltage waveform under VFD operation is not at zero volts but has modulation steps of ($V_{bus}$ /2) peak magnitude possible [20] and, which can electro-statically induce a rotor shaft voltage up to 30 volt. The high rotor voltage implies a bearing race to ground voltage that can charge the bearing oil film to a 7 to 15 Volt breakdown level and cause Electrical Discharge Machining (EDM) currents to flow that damage and pit the bearing race [15]. Reflected wave voltages may appear on the step like edges of the stator neutral to ground voltage waveform and may increase the potential for EDM breakdown. Section II-A shows CWA armor or the Focus cable may reduce the reflected wave voltage peaks depending on cable length and drive risetime. However, for a solidly grounded VFD source input, the output cables cannot effectively change the modulated ($V_{bus}$ /2) peak stator neutral to ground voltage magnitude step, so that the rotor shaft eventually will charge to 30 Volts, with the potential for damaging EDM currents to occur.

A paper mill recently verified this fact at a field site that was initially experiencing motor bearing failures with VFDs. The output Type TC tray cable was replaced with Type MC Continuous Welded Aluminum Armor cable grounded per installation recommendations. Motor bearing failures returned within 6 months. Thus, cable construction may help reduce transient voltage peak magnitudes on the modulation neutral to ground voltage waveform, but cannot be expected to eliminate bearing failures due to bearing currents induced by VFDs. It is important to note that reduction of EDM bearing currents is possible through several other mitigation techniques [21].

### E. Impact of Cable Charge Current on VFD IOC Trips

Small drives < 5 hp are susceptible to Instantaneous Over-Current (IOC) trips as a result of cable charging currents caused by capacitive coupling of conductors of the motor cable [5]. Any two conductors if not shielded will have a capacitive interaction. From the capacitor theory, the higher the frequency, or in this case the faster the rise times, the more likely that a small capacitance between two conductors is likely to allow a current flow. Fig. 8 shows capacitive coupled charging current spikes approaching overcurrent trip levels that may occur on a low hp phase current lead, which are due to the numerous 2 kHz PWM voltage switching instants.

The smaller the capacitance is, the less likely that a current will flow at a given frequency or rise time. Cable capacitance for a three wire cable can be approximated in (3) and is a function of the insulation thickness, a constant known as stranding factor (a), insulation dielectric constant (er), conductor diameter (d), physical spacing of the conductors (h), and frequency.

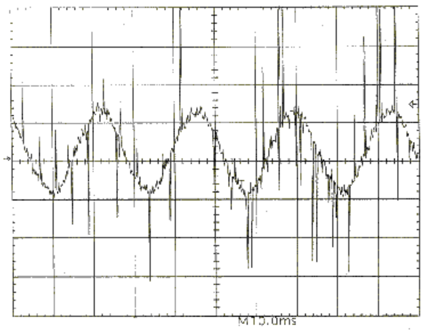

Fig. 8 Output Phase current of a low hp VFD showing capacitivly coupled line to line and line to ground current spikes.

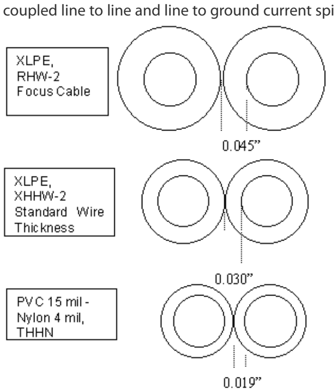


Fig. 9 Cross section of three types of cables compared for capacitance calculations and testing. Shaded conductors are of equal diameter with drawings to scale.

$$C = \frac{3.68 \varepsilon_r \, d \bullet a}{1.2h} \quad \text{pf / ft} \qquad (3)$$

Thus, from (3), capacitance will decrease as the insulation thickness is increased and the dielectric constant is decreased (assuming near uniform zero spacing between conductors). Fig. 9 is a graphical representation of two isolated conductors used in each of the three conductor types listed and highlights the dimensional differences of the insulation systems used in each of the cables.

The Focus cable's increased XLPE insulation and lower dielectric constant of XLPE compared to PVC will reduce the cable charging currents in a given application and reduce possible overcurrent trips. Table 2 below has typical capacitance values for PVC-Nylon insulated conductors in a Tray Cable and XLPE insulated conductors in a Tray Cable or armored cable for the popular #12 awg conductor used in low hp drives.

Table 2 Cable Capacitance Values

| AWG | VNTC | Type MC | Focus Cable |
|---|---|---|---|
| #12 | 79-85 pF/ft | 38-40 pF/ft | 30-32 pF/ft |

Another contributing factor to capacitance is the cable shield or armor. It has an additive affect to the cable capacitance and can increase the capacitance from conductor to all other conductors of the cable. This can offset the effectiveness of the increased insulation thickness and improved dielectric constant. However, using a shielded cable prevents capacitive coupling between conductors of multiple motor leads routed in the same tray or conduit. This is because the only capacitive interaction is between adjacent cable shields, which are grounded. The shielding only carries the noise current elements, and is not considered to be a current carrying conductor in system operation. The number of shielded Focus cables per tray or conduit is only limited by standard NEC ampacity derating factors.

### F. Cable Influence on Failure of Susceptible External Circuits

The largest cause of external susceptible circuit failure is electrical Electro Magnetic Interference (EMI) noise. Electro Magnetic Interference is defined as unwanted electrical signal that produces undesired effects in a system, such as errors, degraded performance and malfunction or even non-operation [22]. This noise can be radiated EMI or conducted in the ground reference grid as Common Mode (CM) noise. CM noise is an electrical interference with respect to a reference ground, or in most cases a portion of the ground grid of the plant.

CM noise caused by a PWM drive is due to the fast rise times associated with the high speed switching transistors used in new drives. The capacitance between both the motor line to ground and the cable line to ground acts as an open to low frequencies and as a high impedance path to frequencies in the range of most PWM carrier frequencies. However, the equivalent frequency of the fast rise time of the pulses used in IGBT based PWM drives is so high, that the capacitance between both phase conductors to ground and motor stator winding capacitance to ground now looks like a low impedance path to ground. This causes a ground current to flow, but mostly at the higher frequencies. Therefore, smaller conductor to ground capacitance will reduce the amount of ground current that is coupled and reduce the CM noise problems.

Some of the circuits that are most susceptible to CM noise are 0 - 10V interface circuits and 4 - 20 mA current loop sense [5]. Other circuits with high levels of susceptibility are communication links, and equipment such as temperature sensors, vision systems, proximity or photoelectric sensors and computers [5]. Some of these same circuits are susceptible to radiated EMI, but not as large of a degree as the CM noise. These specific circuits are capacitive proximity, photoelectric sensors and thermocouple temperature sensors. However, most difficulties with radiated EMI noise can be resolved by using appropriate equipment spacing and shielded components and instrumentation cables.

Most equipment failures are caused by CM noise of a high level present on the ground plane. Equipment is designed to operate with a solid zero potential ground reference, and this is not the case when high frequency noise exists on the ground grid. Causes and implications of this phenomenon are discussed more in [5].

Properly designed cables can further contribute to the reduction of this CM noise by having a shield and ground conductors that can carry the noise back to the drive with an impedance that is several orders of magnitude smaller than the ground grid impedance. The Focus cable's low ground circuit impedance diverts any current flow from the ground grid to the shield / ground of the cable. At most low frequencies, cable ground circuit impedance is composed mostly of DC resistance, that is generally very low in comparison to the ground grid. At higher frequencies, the phenomenon of common mode noise becomes more difficult to combat, as the cable insulated ground conductor between drive and motor begins to look like a high impedance path back to the drive from motor ground. The obvious cable design solution is to incorporate a return path in the cable that has low impedance at high frequencies, and does not negatively impact the capacitance or other performance features of the cable. The Focus cable uses a coaxial-type shield that has comparable or improved ground circuit impedance in the noise frequency range of interest corresponding to pulse risetime and follow on cable CM noise oscillation frequency. Equivalent noise pulse frequency is centered at (1/ p $t_{rise}$), or 1 MHz to 10 MHz for 50 ns to 400 ns IGBT risetimes. CM noise oscillation frequencies are typically 1 MHz for 100 ft. cable and 50 kHz for 1000 ft. output cable runs.

The conduit plus PE wire system has an internal return wire bonded at both ends of the conduit. The ground return wire in close proximity to the phase wire results in a lower effective wire inductance that is in parallel with low inductance coaxial steel tube. This system has a substantial reduction in impedance in the 100 kHz to 1 MHz range. However, skin effect resistance of the steel tube and wire inductance

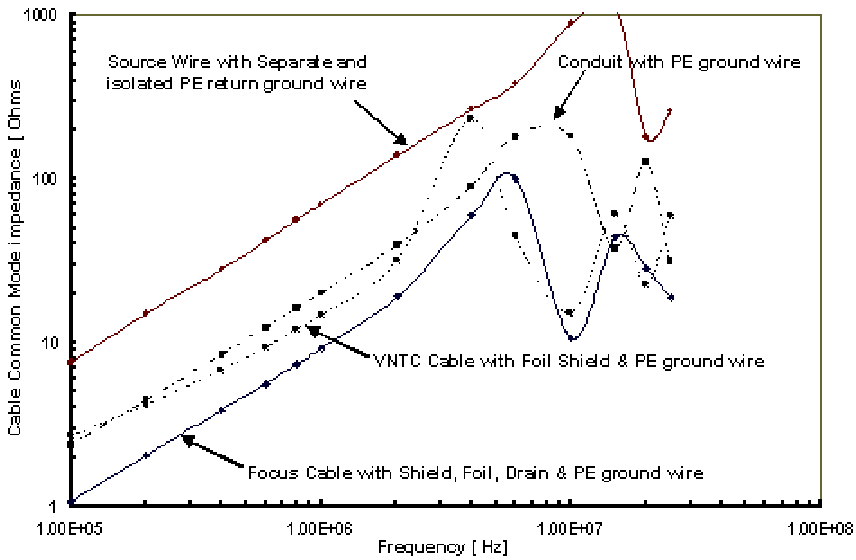


Fig. 10 Comparison of measured common mode impedance vs. frequency for 30 ft. cable lengths of VNTC cables, Conduit with PE ground wire, Focus cable and use of a source wire with isolated PE return wire.

still forms unacceptable high impedance in the 10 MHz range. In addition, the non-isolated conduit system suffers from the fact that HF CM noise can jump from the conduit surface to the ground grid at the conduit strap points, if the grid HF impedance is lower than the conduit HF impedance.

Section IV-A shows that CM noise exiting at the motor winding to ground will take the path of least resistance back to the drive. CM current magnitude flowing in the ground grid is determined by impedance divider rule between cable ground / shield impedance and ground grid resistance. The ideal cable has a common mode surge impedance at both low and high frequency (HF) noise that is less than the typical 1 to 5 ohms dc resistance of the ground grid system. Fig.10 measures the common mode surge impedance of various cable constructions.

The first configuration uses a phase source wire that has an isolated PE ground return wire. This setup has acceptable impedance only below 100 kHz. The wire self inductance presents high impedance to HF noise and is not useful for diverting and containing HF noise.

The VNTC without a shield has unacceptable impedance characteristics and follows the separate PE wire discussion of the first configuration. A VNTC with a foil shield and PE ground wire was tested to have similar impedance to the conduit system at 100 kHz to 1 MHz, while providing a lower CM impedance than the conduit at high 10 MHz frequency. The shielded VNTC system is not recommended because of the PVC dielectric degradation problems of Section III-B and because the foil shield resistance still presents higher impedance than desired.

The Focus cable has an internal PE ground wire for low frequency noise, foil shield/drain wire for 2 MHz to 10 MHz high frequency noise and a low inductance / low resistance coaxial tinned copper braid covering both low and high frequency noise ranges. The Focus cable has the lowest CM impedance over the entire frequency range and is best suited to divert HF CM noise out of the user ground grid.

The CWA cable was not tested at this writing, but is expected to have slightly higher impedance than the Focus cable. This is due to high frequency ac skin effect and the higher dc resistance of the aluminum armor as compared to the Focus cable tinned copper braid.

## III. IMPACT OF VFD OPERATION ON CABLE LIFE

This section estimates the effect of the VFD induced reflected wave transient 2 pu and 3 pu over-voltage on cable life for various cable insulation types and insulation thickness available.

### A. Dielectric Degradation of XLPE Cable Insulation

The ac dielectric breakdown strength of insulation decreases with time when a continuous dielectric stress is applied [23]. Thus, the tested dielectric strength of a new installation will be lower a year later when operated under continuous voltage stress. A predominant aging mechanism is electrochemical treeing or "water treeing". The insulation absorbs moisture over time leading to "tree like" growth within the insulation. This mechanism occurs at an electrical stress much lower than breakdown value and leads to reduced dielectric strength versus time as shown in Fig. 11 for XLPE insulation [23]. Utility companies prefer XLPE and EPR insulation to PVC insulation because of their reduced water tree effect. Fig. 11 is well documented and based on actual utility field experience under continuous voltage operation and where the presence of moisture or water is possible. Use of Fig. 11 curve represents worst case condition even though an individual application site may not contain moisture to a similar extent. The rate of PVC dielectric degradation with time under same conditions is accelerated due to PVC insulation absorbing water at a faster rate than XLPE.

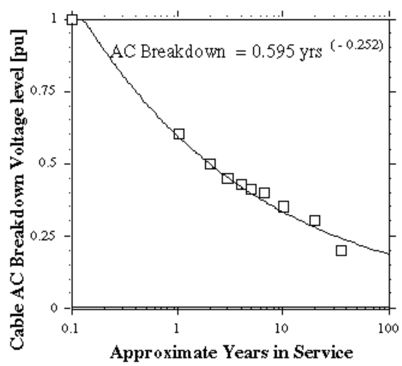


Fig. 11 Degradation of XLPE dielectric breakdown voltage strength vs. life under utility based service conditions [23]

### B. Measured CIV of PVC & XLPE Insulation

Industrial plants expect a 20-year cable service life while power utilities expect 50 to 100 years service life [23]. To get this life, a larger thickness insulation than initially thought necessary must be used to account for aging, so that the breakdown strength at 20 years is still above the dielectric stress imposed by the application. The following corona test procedure proposed verified this known field proven result.

The corona inception voltages (CIV) between two-bundled insulated phase wires of PVC & XLPE insulation types and of various insulation thickness' were measured with a corona tester. Table 3 shows typical variation of insulation thickness with wire AWG and insulation type of 600 V rated wire. Previously unstressed and bundled PVC wires of 15, 20 and 30-mil insulation and XLPE wires insulation of 15, 30 and 45-mil thick insulation were tested in a 25ºC ambient with a Relative Humidity of < 50%.

"BEGIN CORONA" measurements were made by adjusting the sinewave 60 Hz test voltage from zero voltage upward, until the corona tester detected some partial discharges occurring in the sample. Peak sinewave voltage where the discharges occurred was recorded in Fig. 12 for each insulation type and thickness. Although discharges start at this point, BEGIN CORONA measurements represent the point at which a small % probability of insulation failure may occur. Factors such as high humidity and high temperature will lower the BEGIN CORONA point.

"EXTREME CORONA" measurements were made by adjusting the sinewave 60 Hz test voltage upward from the "BEGIN CORONA" value, until the corona detector screen was full of partial discharges. Peak sinewave voltage where this discharge magnitude occurred was recorded in Fig. 12 EXTREME corona is an indicator of a corona process leading to a large 90% probability of cables with short-term end of life failure.

Measured test results of Fig. 12 prove XLPE has superior corona resistant properties as compared to PVC at the low temperature 25ºC, low humidity test condition. XLPE CIV values exceed PVC by 1.4x when comparing BEGIN corona measurements for the same insulation thickness. Interpolation curves for both XLPE and PVC BEGIN corona data have exponents of ~ 0.4 in Fig. 12. The 0.4 exponent measured follows the generic dielectric strength rule for solid organic insulation [24], where dielectric strength typically increases as the square root (0.5 power) of the insulation thickness ratio.

$$\begin{pmatrix} Dielectric \\ Strength \end{pmatrix}_{\#2} \propto \begin{pmatrix} Dielectric \\ Strength \end{pmatrix}_{\#1} \sqrt{\frac{(InsulationThickness)_{sample\,\#2}}{(InsulationThickness)_{sample\,\#1}}}$$

(4)

Also, the thinner XLPE insulation thickness has an EXTREME corona value 1.5x higher than the BEGIN CIV value, while the thicker XLPE insulation has a 1.32x higher EXTREME value as compared to the BEGIN CIV value.

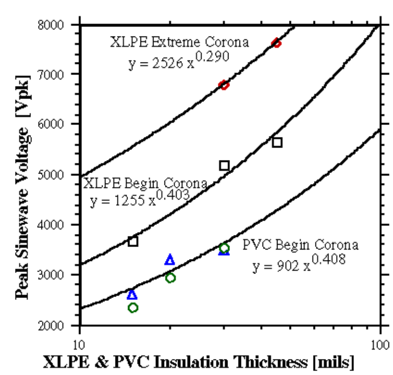


Fig. 12 Measured XLPE & PVC Corona Inception Voltage Level vs. Insulation Thickness for 600V rated cable

Assignment of a 10% cable failure probability to the BEGIN CIV value and 90% cable failure probability to the EXTREME CIV value is based on medium voltage XLPE testing [Fig. 2, Ref. [23]. Reference data exhibits a greater probability of breakdown failure as the volts/mil dielectric stress is increased beyond a BEGIN volts/mil value. Referenced data shows volts/mil stress increases of 1.32x to 1.55x from a "BEGIN" value to an "EXTREME" value will change the % probability of cable insulation failures from 10% to 90%. Since corona inception is a precursor to AC breakdown of dielectric strength and since the ratio of EXTREME / BEGIN corona measurements also span an identical 1.32x to 1.55x ratio, it appears that the BEGIN corona measurements may predict the onset of a small number of failure possibilities in the field. Likewise, the measured EXTREME corona which is 1.32x -1.55x greater than the BEGIN value may tend to predict that 90% of the cables are certain to fail.

### C. Estimated Cable Life under Sinewave Voltage Stress

Once corona starts in any insulation, dielectric failure is usually rapid due to the formation of ozone attacking the insulation and high electric fields, which create ionic bombardment of the insulation and change its chemical composition. Since the degradation of XLPE dielectric breakdown strength vs. time is known to reduce at the rate of Fig. 11 and since corona inception voltage is always lower than the breakdown strength, it follows that the CIV also degrades by the same time rate curve. Thus, by determining the CIV of a new insulation thickness sample and applying Fig. 11 time degradation curve to the initial CIV value, it is possible to speculate when a given application peak voltage exceeds the degraded CIV curve of the insulation. The intersection point marks the end of cable service life. Un-aged samples of 15-mil PVC and 20-mil XLPE 600V cable were corona tested under 60 Hz sinewave voltage between phase wires. BEGIN corona peak voltage values are plotted in Fig. 13 @ 0.1 years.

The 20-mil XLPE insulation is the minimum thickness value for 600V rated cable of Table 3. A 100-year cable service life is predicted from Fig. 13 when operated on a 575 Vrms (813 Vpk) sinewave system voltage, since peak corona inception level of the degraded insulation is always higher than the peak application voltage. This has historically been proven by field experience. Initial AC hypot testing of this cable at [$2V_{rated\ (rms)}$ + 1000 Vrms] = 2,200 Vrms

(3,111 Vpk) also does not degrade insulation, since applied peak voltage is less than 4,150 Vpk BEGIN corona value. Basic Impulse Level (BIL) testing at (1.25*Peak Voltage) or 3,889 Vpk also does no damage to this cable. The 15-mil THHN insulation is the minimum PVC insulation thickness allowed for UL 600V cable. Fig. 13 predicts no insulation failures with 15 mil PVC at 100 years on a 480V sinewave system (678 Vpk). However, 575 V sinewave system operation may have a small % of failures at 20-year life, since a BEGIN corona value corresponding to < 10% failure was used. UL should specify the 3,111 Vpk 60 second, hypot test, but rather specifies initial peak test voltage as 2,828 Vpeak. Fig. 13 verifies this practice, since BEGIN corona voltage where damage can start to occur was measured at exactly 2,800 Vpeak. Applying a BIL impulse test of 3,111 Vpk clearly degrades the 15-mil PVC wire.

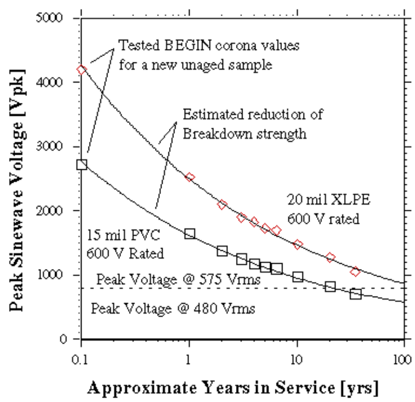


Fig. 13 Conservative estimate of 600V PVC and XLPE insulation service life under sinewave system voltage stress obtained by using measured corona inception values for each material and applying the well documented time aging degradation factor from Fig. 11.

### D. Correlation of Sinewave to Reflected Wave Voltage Stress

This section correlates peak corona inception voltage levels under sinewave operation with PWM twice dc bus over-voltages that occur at every edge of the PWM waveform as in Fig. 4.

Insulation that is dielectrically tested at (2 Vrated + 1,000 V) with 60 Hz sinewave voltage may have as many as 6,000 partial discharges occurring at the positive and negative peaks over a 1 minute interval [24]. This corona discharge quantity is possibly more than ever transiently seen in its sinewave system voltage life. Thus, manufacturers discard equipment after four AC hypot tests, since insulation life is reduced 20% after each test.

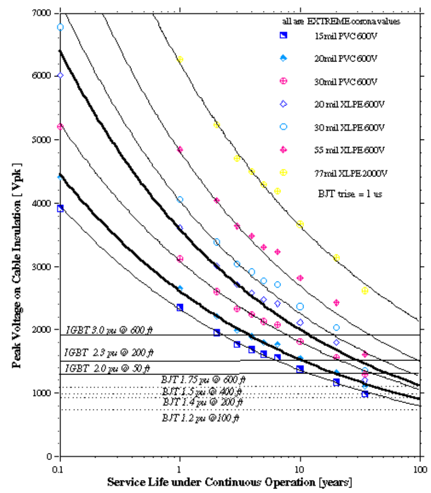


Fig. 14Prediction of 600V PVC and XLPE insulation service life and 2 kV XLPE insulation service life obtained by using measured corona inception values for each material type and thickness, and applying the well documented time aging degradation factor from Fig. 11. Cable life predictions are for 480V BJT & IGBT peak reflected wave cable voltage stress.

IGBT PWM drives with output cables as low as 50 ft. may have peak transient microsecond voltages at twice the Vdc bus level and occur at the carrier rate. The voltage-time dielectric stress is not present long enough to affect the normal long-term cable aging breakdown failure mode effect. However, the peak transient may invoke a corona discharge failure mode that is a precursor to cable failure. Consider the PWM drive output with a peak over-voltage equal in value to the tester sinewave peak where discharges occurred. The reflected wave transient overvoltage peaks that reach the same sinewave peak voltage where corona discharge voltage level occurred should also have partial discharges. These discharges occur at the PWM carrier frequency rate, for IGBT drives 4,000 to 12,000 times a second or 240,000 to 720,000 in 1 minute interval. Thus, using the known cable life curves under peak sinewave corona inception voltage and applying the degradation curve to PWM 2 pu transient over-voltages should be acceptable, since the number of partial discharges are at least equal to or greater than those under sinewave operation.

IGBT PWM drives with long output cables may have peak transient microsecond voltages at 2.5 to 3 times the Vdc bus level depending on the drive manufacturer PWM modulator used. Some drive manufacturers now have PWM modulators which inhibit the generation of voltage spikes > 2 pu on the cable, so this higher stress is never seen [8]. However, if the > 2 pu voltage spikes on the cable appears, it occurs at a rate of several times per fundamental output cycle. This is due to interaction between PWM pulse spacing and cable dynamics [8]. Ultimately, the large quantity of 2 pu voltage spikes predominantly determine cable life, while the effect of the lower quantity of 2.5 pu - 3 pu peak spikes should still be analyzed for effect on cable life.

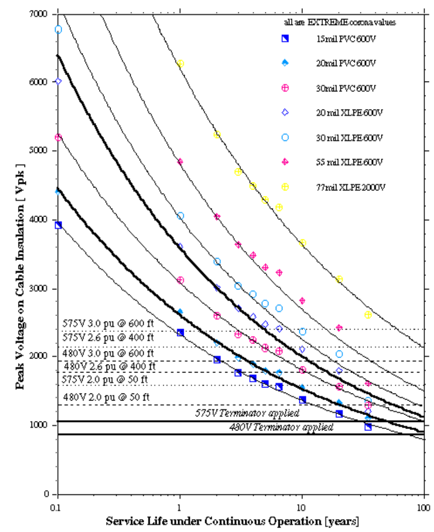


Fig. 15Prediction of 600V PVC and XLPE insulation service life and 2 kV XLPE insulation service life obtained by using measured corona inception values for each material type and thickness, and applying the well documented time aging degradation factor from Fig. 11. Cable life predictions are for 480V & 575V IGBT peak reflected wave cable voltage stress, as well when used with reflected wave reduction solutions.

### E. Analysis of Reflected Wave Voltage Stress on Cable Life

Fig. 14 is a plot of peak application voltage vs. cable service life for various PVC and XLPE standard insulation thickness'. Fig. 14 is generated by measuring the initial CIV level of the insulation and applying Fig.11 life degradation curve to the initial CIV value. The following statements can be made from Fig. 14 graph.

• 230V IGBT drives with even 3 pu transients (900 Vpk = 3*300 Vdc) have an acceptable 50-year life when using 15-mil PVC wire from Fig. 14.

- 480V BJT drives of 1985 vintage had a 1 ms PWM pulse risetime so that a typical cable length of 400 ft. only had a 1.5 pu peak reflected wave voltage (1.5 * 650 Vdc = 975 Vpk). This results in a 40-year life with 15-mil PVC. The last 15 years of operation without cable failure incidence has field proven this result.

- 480V IGBT drives of 1995 vintage have a 0.1 ms PWM pulse risetime so that a typical cable length of 50 ft. has a 2 pu peak reflected wave voltage (2 * 650 Vdc = 1,300 Vpk). The graph predicts a low 10-year life with 15-mil PVC insulation. However, larger drives which use PVC cables of 30-mil insulation or greater may have an acceptable life of 40 years. The proposed Focus cable with 45-mils of XLPE has a predicted life > 100+ years for the same condition.

- 480V IGBT drives of 1995 vintage and cable length of 400 ft. may see a 2.5 pu peak reflected wave voltage (2.5 * 650 Vdc = 1,625 Vpk). Fig. 14 predicts an unacceptable 3-year life with 15-mil PVC insulation. The proposed 45-mil XLPE Focus cable has a predicted life > 35+ years.

- 575V IGBT drive cables will have a 2.0 pu peak reflected wave voltage (2.0 * 800 Vdc = 1,600 Vpk) at 50 ft. Fig. 15 graph predicts an unacceptable 5-year life with 15-mil PVC insulation, 20 year life with 30-mil PVC insulation, and 55-year life with 45-mil XLPE insulation of the proposed Focus cable. Fig. 15 shows a 77-mil XLPE 2 kV rated cable is in excess of what is required for acceptable cable life on a 600V system. The 45-mil XLPE Focus still provides an acceptable 20-year life for those drive modulators that generate a 2.5 pu reflected wave voltage spike at the cable terminations.

- Fig. 15 shows the use of cable termination devices, or possibly line reactors, dv/dt filters and sinewave filters will reduce the peak reflected wave voltage to < 1,000 Vpk and increase the cable life even for 15-mil PVC insulation.

### F. Finite Element Analysis of Voltage Spikes on PVC cable

FEA's were performed on three random lay #12 AWG 15-mil PVC insulated wires installed in a grounded conduit and operated on a 575V IGBT drive with a long cable. Fig 16 shows a shaded contour plot of the Electric field magnitude between two phase conductors with 1,950 Volts peak reflected wave voltage between copper phase conductors. The FEA revealed that a high electric field intensity of 400 V/mil exists in the 1mil air gap between the PVC insulation, and that it exceeds the 110 V/mil to 150 V/mil corona inception stress for air @ 1-mil distance with #12 awg wire. Corona breakdown actually starts on the insulation outer surface and works inward. The V/mil stress in the 15-mil PVC insulation is higher than normal but not sufficient to cause short-term cable failure in itself. The reason is that dielectric stress is inversely proportional to dielectric constant $e_r$. Thus, the high $e_r$'s of PVC ($e_r$ = 5.5 dry to 9 wet) and 4 mil Nylon ($e_r$ = 6-11) shift voltage stress to the air gap ( $e_r$ = 1), which has low corona inception tolerance at close spacing. The Focus cable has a low XLPE $e_r$ = 3 which reduces voltage stress in the air gap and which itself has a higher corona inception voltage level.

The FEA plots confirmed a few field failures of THHN wire used in high humidity locations. The sections of wire failure were analyzed to initially have localized damaged spots on the outer nylon where the two wires were close but not completely touching. Sections of the cable that were more damaged actually had the nylon and PVC insulation eroded with a carbon track remaining between two exposed bare conductors.

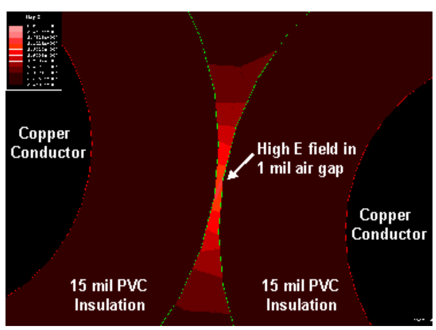


Fig. 16 Finite element Electric field magnitude plot of two THHN #12 awg conductors (15 mil PVC plus 4 mil Nylon) separated by a 1-mil air gap and showing the Electric Field intensity is greater than the CIV of the air gap.

## IV. CABLE IMPACT ON CONDUCTED & RADIATED EMISSIONS

The latest generation of PWM drives use IGBTs that have output voltage waveforms with risetimes an order of magnitude faster (e.g. 0.1 ms vs. 1 ms). The faster dv/dt during output voltage switching now creates a higher, capacitively coupled, transient noise current to ground that does not return on the output phase leads [5,20,25]. This ground noise current pollutes the ground grid and is called Common Mode (CM) or zero sequence current. The flexible shielded cable is one viable alternative solution to control the drive's high frequency noise current path and divert it from conducting into the plant system ground. Shielded cable also reduces radiated cable emissions.

### A. Reduction of Conducted VFD Ground Noise Current

Fig. 17 shows a possible wiring installation with previous generation VFD drives in which the 3 output wires or unshielded tray cable were randomly laid in cable tray. NEC motor grounding requirements were met with a separate wire taken to the closet ground pole of the plant ground grid. Due to the slower switching speed of old VFDs, the system may not have had a system ground noise problem. However, the high dv/dt outputs of the new drive technology now capacitively couples noise into ground from the stray output cable capacitance ($C_{cable\ stray}$) and from the motor stator capacitance to ground ($C_{slot}$). The motor ground wire as shown in Fig.17 permits noise current to flow into the full ground grid. These transients CM noise currents must flow through the ground grid to the drive feed transformer, drive input wires and back to the drive where they are sourced. Fig. 17 shows drive logic ground Potential #1 is elevated from Building Steel Ground by the CM noise voltage developed. Thus, this wiring method is not recommended, since drive interface signals to susceptible equipment, which is grounded at a quieter True Earth (TE) Ground Potential #4, will see a CM voltage impressed on it and may malfunction.

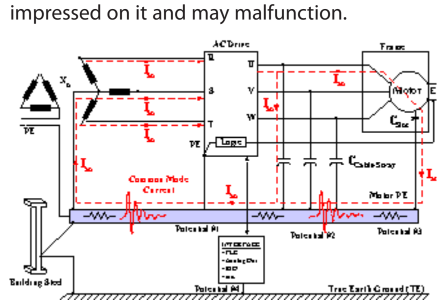

Fig. 17 CM high frequency noise path taken for a Non-Recommended drive installation with 3 random output wires or unshielded tray cable laid in cable tray and connected to a motor with separate ground wire to the closet pole ground.

Fig. 18 shows the CM high frequency noise path taken during drive switching for an improved drive installation using 3 output wires and insulated Power Earth (PE) ground wire in steel conduit. The PE ground wire bonded at both ends meets NEC Article 250 motor ground requirement. An additional motor ground wire to closet pole ground is sometimes used to insure the motor frame is grounded. The conduit PE ground wire provides a low resistance path back to the drive for the lower frequency CM noise current, which hopefully is lower than the ground grid impedance. However, at high noise frequencies the ground wire skin effect resistance increases ten to fifty-fold. Also, ground wire inductance at high frequencies contributes to high ground impedance. Thus, CM current tends to flow on the conduit tube, which acts as a coaxial return of CM noise current. Conductivity of the steel is low at high frequencies and many conduit coupling joints may be corroded or not in proper contact, so that CM noise may return to the ground grid via conduit straps or conduit accidental contact with grounded surfaces. Thus, control of the CM noise path is not guaranteed with conduit and system ground noise problems may or may not occur. This is verified by a computer malfunction incident, in which conduit mounting straps accidentally grounded the VFD output conduit to the same pole ground where a computer network was grounded. The CM noise found a lower return impedance path via a computer ground wire that was connected back to plant system ground, and injected high frequency ground noise into the computer network.

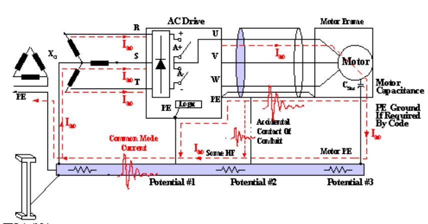


Fig. 18 CM high frequency noise path taken for an improved drive installation with 3 output wires and insulated ground in a conduit and connected to a motor with an additional motor ground wire to the closet pole ground.

Fig. 19 shows the CM high frequency noise path taken with a preferred IGBT drive installation using shielded output wires plus insulated ground in a PVC jacket. Shield and ground wires are bonded at both drive and motor grounds to prevent motor winding CM noise entering the ground grid. The low resistance full rated ground wire meets motor grounding requirements, while conducting some of the lower frequency components of the CM noise current. The tinned copper braid shield acts as a low resistance and low inductance impedance coaxial return for the higher frequency CM noise currents. The insulated PVC jacket insures most of the CM noise current returns back to the drive on the shield and out of accidental contact with the ground grid.

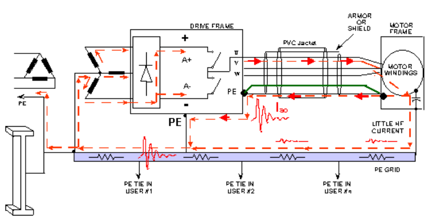


Fig. 19CM high frequency noise path taken for preferred IGBT drive installation with shielded output wires plus insulated ground in a PVC jacket. Shield and ground wires are bonded at both drive and motor grounds.

Fig. 20 shows the CM high frequency noise path taken when using the Best installation practices possible for a low noise IGBT drive installation. Shielded input and shielded output wires, with their respective insulated ground wires and PVC jacket are used. Shield and ground wires are bonded at both drive and motor grounds to prevent motor winding CM noise entering the ground grid between the drive and motor. Shield and ground wires are bonded at both drive PE and input transformer PE grounds to prevent drive CM noise entering the ground grid between drive PE and transformer PE ground. Shielded input wires are recommended for installations where AM radio interference is not acceptable, when the drive input transformer is physically located far away from the drive or when a large amount of sensitive equipment referenced to ground exists at the application site.

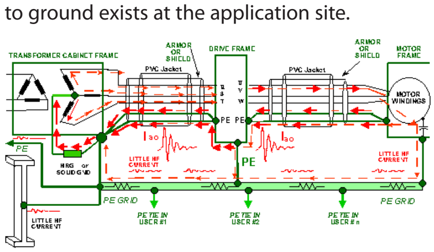


Fig. 20CM high frequency noise path taken for recommended IGBT drive installation with shielded output wires with insulated ground in a PVC jacket and shielded input wires with insulated ground in a PVC jacket. Output Shield and ground wires are bonded at both drive PE and motor PE ground. Input Shield and ground wires are bonded at both drive PE and transformer PE ground to reduce CM noise current in the user ground grid.

Fig. 21 shows field test results of an IGBT VFD with output voltage risetimes of 50 ns, connected through 300 ft. of Focus cable that is wired per Fig. 19 with an additional motor ground wire. A CT measured output CM noise ground current of 6 Apk, during a voltage switch transition, by placing all phase leads through the CT. The current in the braid and foil was found to capture most of the high frequency CM noise current and return it back to the drive out of the ground grid. The PE ground wire absorbs some but not all of the higher frequency noise during the voltage transition, but is found to be ineffective during the CM noise high frequency oscillation period as predicted. Net CM current conducted into the actual ground grid is determined by placing the entire Focus cable through a CT. Fig 21 verifies a substantial reduction of CM ground noise current and shows the Focus cable is a viable installation solution to VFD induced noise problems.

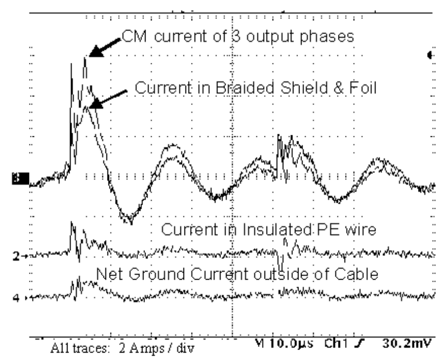


Fig. 21 Measured VFD CM output current, return shield current, PE wire current & net ground current flowing outside of Focus cable (all traces 2 amp /div) for Fig. 19 field installation.

## B. Radiated Noise Reduction with Shielded Cables

There is a large radiating loop antenna area formed between the unshielded phase leads and ground of Fig. 17, with CM noise current frequency as the driving source. The large loop antenna occurs on both output as well as input leads. The conduit system of Fig. 18 is better in terms of radiated emission area due to the internal ground wire return reducing the effective loop area and the attenuation properties of steel conduit. However, the CM noise exiting to ground at incidental ground contact may still allow RF emissions to escape. The Focus cable of Fig. 19 and Fig. 20, uses an internal PE ground wire, coaxial 85% coverage braided shield and 100% coverage Mylar / foil film to form a tight closed loop area that minimizes external RF emissions.

Both low and high frequency shielding effectiveness tests were done to address the issue of radiated noise from the cable. Fig. 22 contains test results of voltage induced on a loop antenna that is in direct contact to a standard tray cable and a Focus cable with a braided copper shield of 85% coverage, but without a foil shield. The unshielded cable couples a direct square wave voltage replica of the 10 kHz PWM pulses onto the pickup coil antenna, while the braided shielded cable substantially attenuates the low carrier frequency components and most other frequencies. Fig. 22 shows an attenuation ratio of 30 dB as defined by 20*LOG(0.1div/3.6 div) when braided cable emissions (0.1 div) is compared to unshielded (3.6 div) coupled RF emissions. There is some cable high frequency emissions during the rising and falling edges of the PWM waveform, probably due to CM currents on the shield developing shield voltages during the high frequencies associated with the fast PWM voltage risetime. A high frequency analysis was done to further investigate the risetime effect.

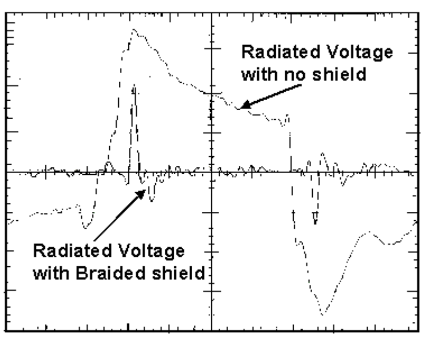


Fig. 22 Relative low frequency shielding effectiveness of standard unshielded cable compared to Focus cable using only 85% coverage braid. Data obtained for one complete PWM cycle using a voltage pickup antenna coil in direct contact with outer cable surface.

The high frequency shielding effectiveness associated with the steep dv/dt voltage switching edge was investigated by passing the VFD output cable through a RFI chamber, lined with absorption tiles, and returning the cable to a motor connected outside the RF chamber. A high gain dipole antenna measured 10 MHz to 50 MHz RF emissions at 10 feet from the output cable for both standard shielded tray cable (TC) and the Focus cable. Fig. 23 shows a relative attenuation comparison of the shielded TC to the Focus cable.

Attenuation peaks and valleys of Fig. 23 most likely correspond to the cable's minimum and maximum impedance nodes that occur at multiples of the cable's resonant frequency. An average attenuation of 26 dBuV is obtained from the cable with the (Mylar / Foil) shield accounting for 7 dbuV. Foil shield attenuation is predominant over the braided shield for frequencies > 40 MHz. It is seen the variation of shielding effectiveness with frequency makes it difficult to test rank various cables unless a desired frequency is identified as the comparison base. In terms of actual applications, the Focus cable will have a radiated noise of 30mV or less at real world distances from adjacent cables or components.

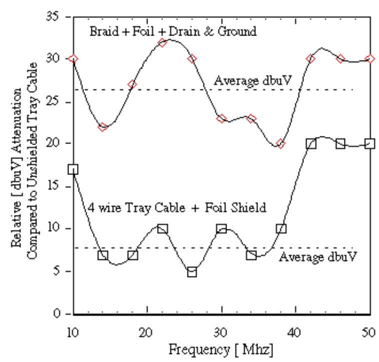


Fig. 23 Relative high frequency shielding effectiveness of tray cable compared to Type TC plus foil vs. Focus cable braid/foil/ground wire system.

The high frequency CM noise current path of Fig.20 shielded input / shielded output system results in the lowest loop antenna areas between input and output phase leads to ground due to the coaxial shields. Therefore, system RF emissions are reduced with this wiring installation.

## V. APPLICATION SPECIFIC CABLE CONSIDERATIONS

Non-electrical considerations such as environmental, mechanical and installation considerations are also important aspects when choosing the correct cable type for an application. Tables 4 through Table 6 include such information that aid in the cable selection process. In order to use the tables, you must have a good understanding of external factors that affect cable life. The tables include information such as compound suitability with respect to temperature, chemical exposure, abrasion, impact, moisture, and flame exposure. There are other factors covered as well, such as vibration, ease of installation, allowed usage according to the National Electrical Code (NEC) and installed cost of cabling system.

Termination is another very important installation consideration, as improper termination could negate any benefits of a good design. Termination of the MC cable is very crucial to proper shielding and grounding effectiveness, but is not the intended scope of this paper [2,25]. The unshielded VNTC construction is not a preferred cabling solution for VFD applications, so termination methods need not be discussed.

Termination of the Focus Type TC construction is also important, yet quite simple. The shield, drain wire, and ground wire combination is critical for proper cable system performance as discussed in the paper. A solid termination must be made of the drain and ground wire at the PE (Power Earth) ground of the drive and motor.

The minimum cable termination recommendation for typical industrial applications is to use a sealed, moisture resistant gland to attach the cable at the drive cabinet and the motor junction box as in Fig. 24. Glands that are explosion proof and nickel plated, (for corrosion resistance), are superior, but add cost to the installation. For an installed cost comparison of the XLPE constructions, refer to Table 6. Termination of the shield is satisfactorily done with the drain wire, as the full size drain wire has extremely low resistance. If this method is chosen, the shield should be trimmed and taped at the same point the jacket is cut away, so as to prevent stray strands from shorting other electrical circuits in the motor cabinet.

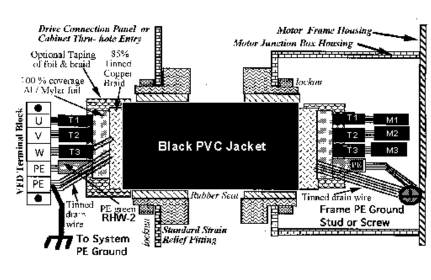

Fig. 24 Recommended Focus cable and connector installation at drive and motor when CE compliance is not required.

The shield should be terminated as in Fig. 25 for applications requiring full conformity to European CE noise interference levels. A shield termination gland should be selected that has a shield termination ring that slides over the core of the cable and makes 360º contact with the shield. The termination gland should also have a low contact resistance to the cabinet mounting. It is important that the shield integrity be maintained well within the metallic portion of the gland and the motor junction box or drive cabinet. This will insure maximum shield effectiveness.

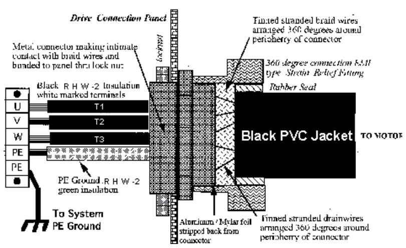


Fig. 25 Recommended Focus cable and special 360o shield connector installation at drive and motor when CE compliance is required.

The Focus Cable can be made to meet an OPEN WIRING rating according to NEC article 340, by UL. This allows installation of the cable without the use of conduit or cable tray for the first and/or last 50 feet of the run. The benefit realized is both cost reduction and an isolation of a conduit from the motor PE to the drive frame ground that could cause accidental ground contact of conduit and potential increase in Common Mode noise.

## VI. FIELD COMPARISON, SO vs. FOCUS CABLE

Figs. 26 and 27 shows a comparison of an actual field application of the Focus cable (Fig. 27), vs. the same identical installation of an unshielded 4 conductor SO cord. The comparison is from an OEM machine builder who used the Focus cable to reduce supply and encoder noise in a new process. The outputs compare noise coupled to the motor position encoder signal while the motor was sitting still and the signals were high. As seen in Fig. 26 the noise could result in false encoder feedback using the unshielded cable, even with the ground wire in place. Under the same situation but using the Focus cable, the encoder feedback has near zero coupled noise, allowing error free encoder feedback to the controller as a result of reduced radiated and Common Mode noise.

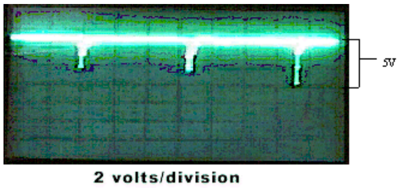


Fig. 26 Coupled noise to motor position encoder using SO cord with full size ground, but no shield.

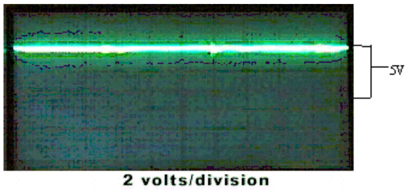


Fig 27 Coupled noise to motor position encoder using Focus cable with full size ground/drain/foil/braid shield.

## VII. CONCLUSION

The design and application of a 600 V shielded Tray Cable suitable for use on 600 V IGBT variable frequency drives was discussed. The main electrical feature discussed was increased XLPE insulation thickness on smaller gauge cables to guarantee long service life under wet or dry conditions with 600 V IGBT drives having 2 pu and 3 pu reflected wave transient voltage spikes. A methodology to predict cable life at 2 pu and 3 pu voltage spikes for various insulation thickness was proposed. Increased XLPE insulation thickness also minimizes cable capacitance, which reduces drive over-current trip problems due to cable charging current.

Another electrical feature of the Focus shielded Tray Cable is the low common mode surge impedance that was demonstrated to be effective in containing VFD conducted and radiate emissions. The VFD noise current paths were described for various wiring practices and cable constructions possible.

Mechanical and environmental application specific attributes of the Focus cable were compared to presently available cable technology, along with a cable-connector cost comparison for the various cable constructions.

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Table 1 Compound Comparison, Jacket Options and Insulation

| Property | PVC Insulation / Jackets | XLPE Insulation | CPE Jackets (optional) |
|---|---|---|---|
| Tensile Strength | 1,400 -- 3,500 psi | 2,000 psi | 1,500 psi |
| Elongation | 100 - 500 % (300 % typical) | 325 % typical | 465 % typical |
| Heat Aging % of original tensile strength | 80 % typical | 95 % typical | 97 % typical |
| Cold Temperature Brittleness | -30ºC typical | -55ºC | -35ºC |
| Dielectric Constant | 4 to 8 (5 to 6 typical) | 3.2 - 3.4 | NA |
| Limiting Oxygen Index (flame resistance higher better) | 27 to 28 | 28 to 30 | 32 |
| High Temp Deformation | 5 to 30 % | 10 % | 3 % max |
| Oil Resistance | Fair | Good | Excellent |
| Moisture Resistance | Fair | Excellent | Good - Excellent |
| Acid Resistance | Good - Excellent | Good - Excellent | Excellent |
| Hydrocarbon Resistance (aromatic and aliphatic) | Poor - Fair | Fair | Fair |
| Underground Burial | Poor - Good | Excellent | Excellent |
| Sunlight Resistance | Good | Good | Excellent |
| Ozone Resistance | Good | Good - Excellent | Excellent |

Table 3 Insulation Thickness of Commonly Used Drive Cables & Wire

| Voltage (rms) | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 90C | 90C | 90C | 90C | 90C | 90C | 90C | 105C | 105C | 105C |
| Type | MC | TC | TC | | wire | wire | wire | wire | wire | wire |
| Insulation | XLPE/XLP | XLPE / XLP | PVC | XLP | EPR | PVC | PVC | PVC | PVC | PVC |
| NEC listing | MC | TC | TC using THHN | VW-1 XHHW2 | VW-1 RHW2 RHH USE2 | THHN PVC (+) Nylon jacket | MTW, TW No nylon jacket | | | - |
| UL spec | 1569 | | | | | MTW | | 1015 & SO | 1015 | - |
| CSA spec | | | | | | | | TEW-105 | TEW-105 | - |
| Military spec | | | | | | | | W-76B | W-76B | 16878D |

| AWG | Insulation Thickness (mils) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 18 | | | | | | | 30 | 32 | 32 / 31 | 10 |
| 16 | | | | | | | 30 | 32 | 32 / 31 | 10 |
| 14 | 30 | 20 / 30 | 15 | 30 | | 15 + 4 | 30 | 45 | 32 / 31 | 10 |
| 12 | 30 | 20 / 30 | 15 | 30 | 45 | 15 + 4 | 30 | 45 | 32 / 30 | |
| 10 | 30 | 20 / 30 | 20 | 30 | 45 | 20 + 4 | 30 | 45 | 32 / 30 | |
| 8 | 45 | 30 / 45 | 30 | 45 | 60 | 30 + 4 | 45 | 45 | 32 / 45 | |
| 6 | 45 | 30 / 45 | 30 | 45 | 60 | 30 + 5 | 60 | | | |
| 4 | 45 | 35 / 45 | 40 | 45 | 60 | 40 + 6 | 60 | | | |
| 2 | 45 | 35 / 45 | 40 | 45 | 60 | 40 + 6 | 60 | | | |
| 1 | 55 | 45 / 55 | 50 | 55 | 80 | 50 + 7 | 80 | | | |
| 1 / 0 | 55 | 45 / 55 | 50 | 55 | 80 | 50 + 7 | 80 | | | |
| 2 / 0 | 55 | 45 / 55 | 50 | 55 | 80 | 50 + 7 | 80 | | | |
| 3 / 0 | 55 | 45 / 55 | 50 | 55 | 80 | 50 + 7 | 80 | | | |
| 4 / 0 | 55 | 45 / 55 | 50 | 55 | 80 | 50 + 7 | 80 | | | |
| 250 | 65 | 65 / 65 | 60 | 65 | 95 | 60 + 8 | 95 | | | |
| 350 | 65 | 65 / 65 | 60 | 65 | 95 | 60 + 8 | 95 | | | |
| 500 | 65 | 65 / 65 | 60 | 65 | 95 | 60 + 8 | 95 | | | |
| 750 | 80 | 80 / 80 | 70 | 80 | 110 | 70 + 9 | 110 | | | |
| 1000 | 80 | ?? / 80 | 70 | 80 | 110 | 70 + 9 | 110 | | | |

Note: "/" in Table implies multiple manufacturer's with different insulation thickness listed

Table 4 Application Specific Attributes

Table 4 Application Specific Attributes

| | TYPE MC CABLE 0.030" XLPE | TYPE TC CABLE 0.045" XLPE |
|---|---|---|
| IMPACT RESISTANCE | Per UL 1569 | Per UL 1569 |
| CRUSH RESISTANCE | Per UL 1569 | Per UL 1569 |
| VIBRATION SUITABILITY | Minimal vibration | Extreme vibration |
| EASE OF INSTALLATION | Standard cable type, can be difficult to route in tight locations | Standard cable type, easily bent by hand, simple termination |
| ABRASION RESISTANCE | Excellent to Outstanding | Excellent |
| MINIMUM BEND RADIUS | 12 X CABLE DIAMETER | 7 X CABLE DIAMETER |
| MOISTURE RESISTANCE | Excellent to Outstanding | Excellent |
| DESIGN OPTIONS | Jacket Compound changes | Jacket Changes, and addition of Shielding or Armor |

Table 5 Allowed Installation Environments According To NEC

| APPLICATION | TYPE MC CABLE 0.030" XLPE | TYPE TC CABLE 0.045" XLPE |
|---|---|---|
| Class I Division 1 (NEC art. 501-4(a) (1) Exception 2 ) | YES | YES (requires conduit) |
| Class II Division 1 (NEC art. 502-4(a) Exception) | YES | YES (requires conduit) |
| Class I Division 2 (NEC art. 501-4(b) ) | YES | YES |
| Class II Division 2 (NEC art. 502-4(b) ) | YES | YES |
| Indoor/ Outdoor | YES | YES |
| Intermediate Metal Conduit | YES | YES |
| Electrical Metallic Tubing | YES | YES |
| Direct Buried | YES | YES |
| Cable Trays | YES | YES |
| Raceways | YES | YES |
| Open Wiring (per NEC article 340) | YES | YES |
| Wet Locations | YES | YES |

Table 6 Cost Comparison Of XLPE Constructions (Average Cable plus Connection Costs)

| Type MC Construction | | | American Wire Gauge | Type TC w/0.045" XLPE Insulation | | |
|---|---|---|---|---|---|---|
| Cost/foot for 10 foot piece | Cost/foot for 50 foot piece | Cost/foot for 100 foot piece | | Cost/foot for 10 foot piece | Cost/foot for 50 foot piece | Cost/foot for 100 foot piece |
| N/A | N/A | N/A | #16 | $1.74 | $1.18 | $1.11 |
| $3.66 | $1.61 | $1.36 | #14 | $2.39 | $1.52 | $1.41 |
| $4.86 | $2.04 | $1.68 | #12 | $2.71 | $1.85 | $1.74 |
| $5.16 | $2.34 | $1.99 | #10 | $3.11 | $2.25 | $2.14 |
| $6.09 | $3.26 | $2.91 | #8 | $4.73 | $3.30 | $3.12 |
| $7.14 | $4.32 | $3.97 | #6 | $5.93 | $4.50 | $4.32 |
| $9.85 | $5.57 | $5.04 | #4 | $8.36 | $5.90 | $5.60 |
| $12.44 | $8.16 | $7.63 | #2 | $11.68 | $8.13 | $7.69 |

Note: Costs do not include labor rates or installation expertise requirements - expected to be lower for the focus cable.