CHALLENGES AND REQUIREMENTS IN VFD CABLE DESIGN

BASTIAN GÖRICKE

STEFAN GRUNWALD

CHARLOTTE, NC

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Systematic Technology

Lutze, Inc.
13330 South Ridge Drive
Charlotte, NC 28273

www.lutze.com
info@lutze.com
+1-800-447-2371

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Charlotte, NC 28273

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info@lutze.com
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1 What is a variable-frequency drive?

In the United States the most common alternating current (AC) for industrial applications has a constant voltage of 460 volts and a constant frequency of 60 hertz in a sinusoidal waveform. Due to the constancy of the voltage and the frequency, an electric motor connected to this current would rotate at a constant rotational speed.
However, industrial applications very often require variable rotational speeds as well as acceleration and braking features.
Examples of such applications include:

- Metal industry and production
- Automotive industry
- Chemical industry
- Power plants
- Paper and printing industry
- Mining
- Oil and gas extraction
- Polymer industry
- Water treatment plants
- Textile industry
- Heating, ventilation, and air conditioning (HVAC)
- Food industry
- Machine shops
- Theme parks and fairs

In these industries it is required to:

- coordinate speeds and accelerations of multiple motors working together in one machine
- limit acceleration, speed, start up currents, torque or inrush currents, e.g. in elevators or when handling fragile goods
- conserve energy, e.g. by reducing the speed of ventilation fans
- controlling air or water flow with electrical pumps or fans.

Figure 1: Picture of a variable-frequency drive

A variable-frequency drive (VFD) is a device designed to alter a motor's rotational speed by changing the frequency and the voltage of the electrical power supplied to it. This way, the rotational speed can be adjusted within a wide range from standstill to above the nominal rotation speed at 60 hertz.

The second main feature of a VFD offers is that it can control the motor's torque. To avoid an overload of the motor the torque has to decrease when running the motor at speeds above the nameplate rating and vice versa.

This can easily be understood from the following equation:

$$\text{Power} = \text{torque} \times 2\pi \times \text{rotational speed}$$

where:

torque is in Newton meters
rotational speed is in revolutions per minute
power is in watts

Considering the maximum permissible power of the motor, the rotational speed has to decrease when the torque increases in order to satisfy the equation.

Hereafter, the terms either VFD or drive will be used. However, in the industry several terms are used having basically the same meaning with some minor differences in features and function:

- (AC) drive
- Variable-speed device
- Adjustable-frequency drive
- AC inverter
- (IGBT) PWM drive
- Servo inverter
- Adjustable Speed AC drive

Due to the high efficiency of modern drives (95% and above) the device housings of modern drives are very compact compared to the motors they are operating.

The U.S. Department of Energy stated that 60-65% of all energy produced in the U.S. is consumed by electric motors. 20% of the energy these motors consume is lost due to inefficient rotational speed control.
The power consumption of an electric motor used in a pumping or ventilation application is proportional to the cube of its speed. Thus the option of adjusting the rotational speed of these motors will save energy. This is possible because in many applications it is not necessary to run the motor constantly at its maximum speed.

Figure 2 shows the power consumption of an electric motor as a function of its rotational speed. If this motor is running at 100% speed it consumes 100% of its rated power. Now, if the motor speed would be reduced to 80%, almost half of the energy could be saved. Reducing the speed to 50% would save more than 80% energy.

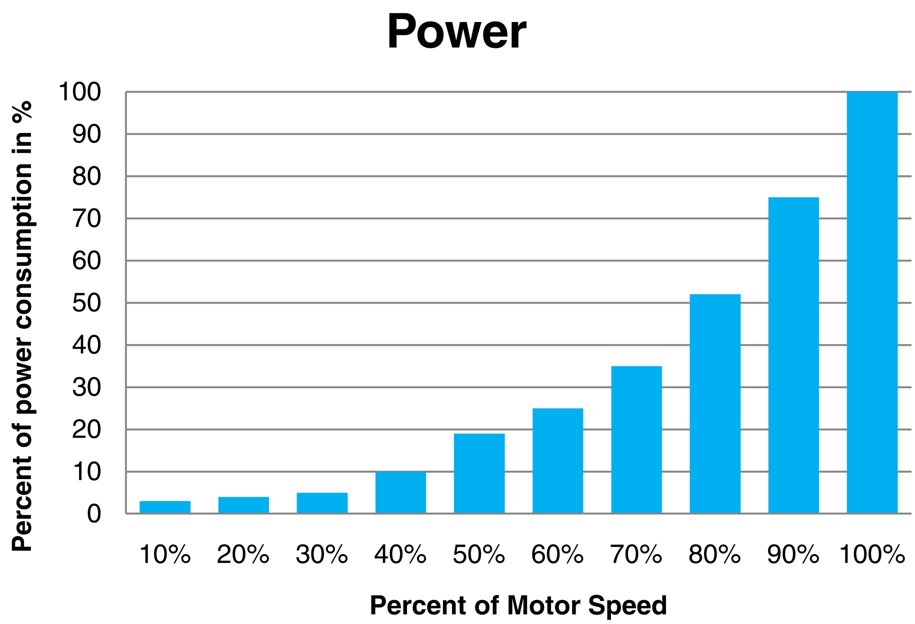

Figure 2: Power consumption of an electric motor in pumping or ventilation applications as function of the motor’s speed

The use of a VFD would save a significant amount of energy and money. Instead of connecting the motor directly to the mains supply and running it at 100 % speed all the time, a VFD would adjust the motor’s speed to required values that are often a lot less than 100 %. The VFD will quickly pay for itself by saving energy.

2 Description of a VFD System

A functional VFD system consists of at least three components:

- VFD device
- VFD cable
- VFD motor

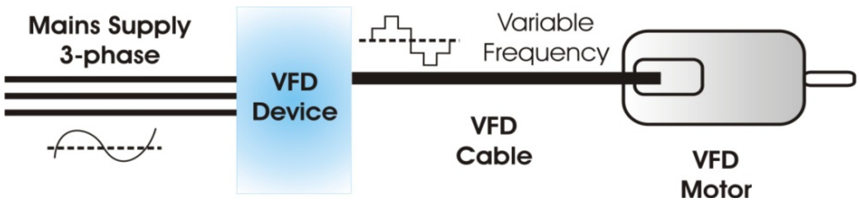

Figure 3: Overview of an entire VFD system

2.1 VFD Device

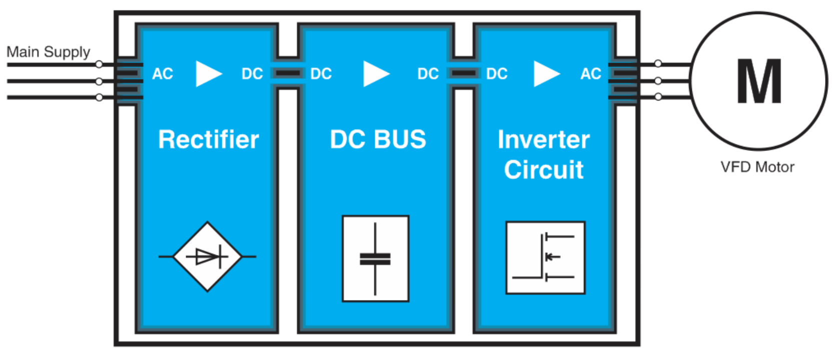

Figure 4: Block diagram of a VFD device

A typical VFD device consists of the drive controller and the operator interface. In the controller, the AC input power is first rectified into a DC intermediate power (DC bus) and stored in capacitors. An inverter circuit, which typically contains a 6-diode bridge network, subsequently transforms this DC bus power back to a "Quasi" AC signal with adjustable voltage and frequency. The DC bus voltage is calculated by AC line voltage x 1.414 (sqrt. of 2)

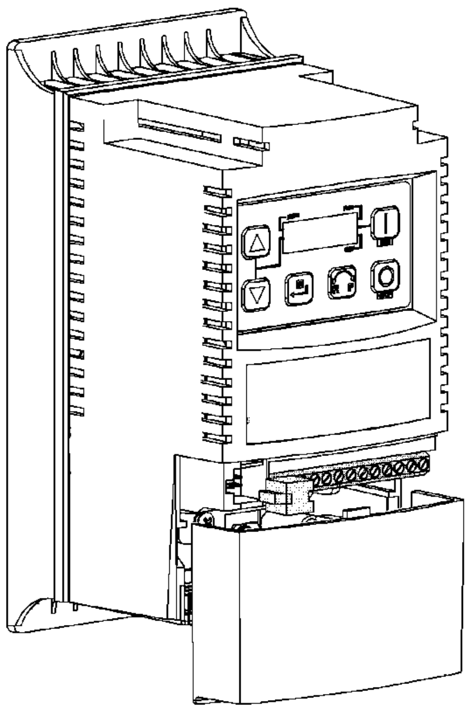

Figure 5: Drawing of a generic drive with a simple operator interface

The insulated gate bipolar transistor (IGBT) is the most commonly used solid-state switch in modern VFD inverter circuits. These switches, in combination with a method to adjust the motor voltage called Pulse Width Modulation (PWM), may cause severe problems to both the motor and the cable. These issues will be discussed later.
Another important component of a VFD device is the operator interface. It consists of a combination of displays, meters, and indication lights and provides status information during the operation of the drive.

A keypad offers the option to change drive parameters. Since more complex drives can require over several hundred parameters to be set up, a communications port is often available to allow the use of a computer or laptop. Figure 6 shows a sample of a keypad that allows the user to turn the drive on and off and to change its parameters.

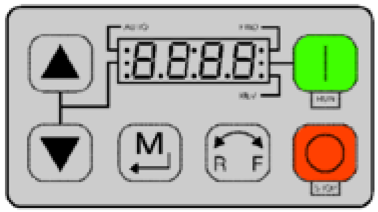

Figure 6: Operator interface with a keypad, allowing the adjustment of parameters and a seven-segment display

During the normal operation of the drive, the keypad is usually not needed. The drive is then controlled by a computer or a PLC (programmable logic controller) which is connected to it by a networking cable or other signal wires.

2.2 VFD Cable

Figure 7: VFD cable

Variable Frequency Drive applications are the causing unique electrical issues that are unlike other standard power transmission in machine applications. Thus there are higher demands on the cable connecting the motor to the drive. Standard multi-conductor cables rated for 600V will most likely not meet the requirements of VFD applications, and can cause operating malfunctions and early failures.
Cable is often an afterthought in the planning process but represents actually a very important component in the whole application.
What is a Ferrari worth without the proper road to drive on? Similarly, the best VFD requires a cable that takes all the unique electrical issues into consideration and in the end improves the application.

Instead of just any standard power cable the use of a special VFD Power cable is required because the construction and insulation is designed to cope with the harsh demands of a VFD Application.

A more detailed discussion of VFD cables and their implementation is given later on. Proper installation of the VFD cable is also crucial for the correct functioning of the whole VFD system.

2.3 VFD Motor

It is common In VFD applications to use electric motors that were originally designed for fixed-speed main voltage operation (general purpose AC motor). This is due to the fact that pre-existing machinery is often upgraded later to be used with a VFD device. In most cases it is not necessary to replace the motor although motors that are designed specifically for VFD operation would offer better performance and higher reliability.

Today, the most common motor type used with VFD is a three-phase AC induction motor. However, special variable-frequency motors (inverter duty rated motors) are becoming more popular because they are capable of handling higher voltage spikes created by the VFD. In addition they are able to run at slow speeds for a long time without overheating.

In any case the motor is typically supposed to be installed close to the Drive because a long cable length can amplify the electrical issues which are discussed throughout this paper.

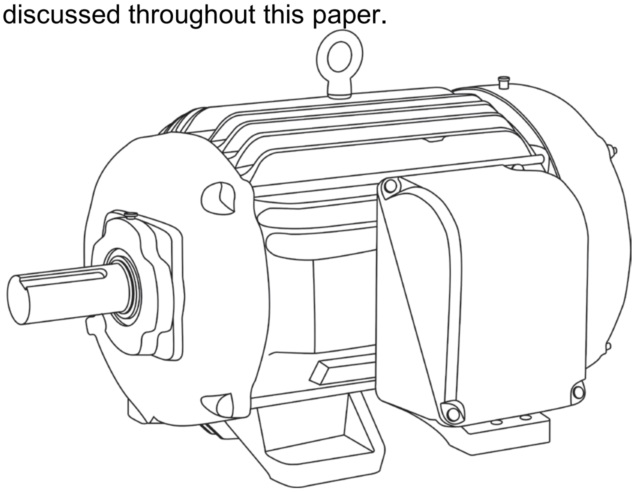

Figure 8: Motor for use with variable-frequency drives

An electric motor consists of two main components: the turning rotor (also called armature) and the fixed stator (also called field winding) that is stationary and connected to the VFD cable. When an AC current is applied to the stator, a rotating electromagnetic field develops and causes the rotor to turn.

3 Variable-frequency drive manufacturers in North America

Manufacturer	Series	230 V supply voltage				460 V supply voltage				575 V supply voltage			
		Power in kW		Output Current in A		Power in kW		Output Current in A		Power in kW		Output Current in A	
		min	max	min	max	min	max	min	max	min	max	min	max
Allen-Bradley	PowerFlex 400	5.6	37.3			5.6	74.6						
Allen-Bradley	PowerFlex 40	0.4	11			0.4	11			0.4	11		
Allen-Bradley	PowerFlex 4	0.2	3.7			0.2	3.7						
Allen-Bradley	1336 PLUS	0.75	11	4.5	48	1.2	45	2.8	77	3.7	45	8	62
Allen-Bradley	1336 PLUS 2	0.4	93	2.3	325	0.4	448	1.1	670	0.75	448	2	600
ABB	ACS350 machinery drives	0.37	4	2.4	17.6	0.37	7.5	1.2	15.6				
ABB	ACS50, ACS150	0.2	2.2	1.4	9.8	0.4	4	1.2	8.8				
ABB	ACS5xx general purpose	0.56	74.6	4.6	192	0.75	410	2.4	645	1.11	112		
Lenze AC Tech	SMVector series	0.25	0.75	1.7	29	0.4	7.5	1.1	14	0.75	7.5	1.7	11
Lenze AC Tech	MC1000 series	0.2	45	1.4	177	0.75	110	2.3	207				
Lenze AC Tech	8220/8240 HVAC series					0.55	110	1.5	171				
Lenze AC Tech	821x series					1.1	11	3	23.5				
Siemens	Micromaster 4xx series	0.12	45	0.9	154	0.37	250	1.3	370	1	100	1.4	99
SEW-Eurodrive	Movidrive	1.5	29.8	7.3	95	0.6	130	2	250				
Hitachi	L100 series	0.2	7.5	1.4	32	0.4	7.5	1.5	16				
Polyspede	PSV4 series	0.4	55	3	220	0.75	200	2.5	260				
Polyspede	PSV6 series	0.2	7.5	1.6	32	0.4	7.5	1.5	16				
Polyspede	XLT6 series	11	75	44	270	11	132	22	230				
AutomationDirect	GS2 series	0.4	2.2	2.5	25	0.75	7.5	3	18	0.75	7.5	1.7	12.2
AutomationDirect	Durapulse	0.75	37	5	145	0.75	75	2.7	150				
Yaskawa	F7 series	1.2	140	3.2	360	1.4	450	1.8	590				
Yaskawa	E7 HVAC series	0.37	112	3.6	415	0.37	373	1.8	675				
Danfoss	VLT AutomationDrive	0.25	3.7			0.37	700			37	1000		
Danfoss	HVAC Drive	1.1	3.7										
Danfoss	VLT 2800	0.37	3.7			0.56	18.6						
SECO	SL3000 series	1.4	6	3.6	15.1	1.4	16.7	1.8	21				
Baumueller	b maXX 1000	2.4	36	0.2	11	2.4	36	0.2	11				
Baldor	Series 11	5.5	7.5	24	32	2.2	7.5	5.5	16				
Baldor	Series 15P	0.75	3.7	4.2	15.2	0.75	5.6	2.1	11				

Figure 9: Overview of VFD devices

Figure 9 shows an overview of low voltage VFD devices. It is not feasible to include all available Drive-manufacturers in one table. A selection has been made due to availability of drive specifications and the compatibility to cables discussed in this paper. All details are as specified in the drive datasheets. All ratings are for continuous current and power. If several chopper frequencies were given in the datasheet, the ratings for 8 kHz were chosen.

Few Drive manufacturers have detailed specifications for VFD cabling. The following list of common requirements can be found in most Drive manufacturer's manuals:

- Four tinned copper conductors shielded for Drives up to 50-100 HP
- Three conductors with three symmetrical split grounds for larger Drives and Motors especially 100HP and up.
- Low capacitance insulation
- Foil and braid shield combination (foil for high frequencies and braid for low frequencies)
- Ruggedized PVC jacket, preferably oil and sunlight resistant.

4 Issues and difficulties during VFD Operation

This section will point out some important issues regarding the cable used to connect the motor to the drive in a VFD application.
As mentioned before, PWM is a commonly used technology to adjust the resulting voltage and frequency of the power applied to the motor.

In VFD devices, semiconductor switches are used to switch the DC bus power to the output. These switches only have two states: “on” or “off”. The PWM continually switches between these two states with a constant frequency but with variable pulse widths. The widths of the pulses determine the effective output voltage. Smaller pulse widths result in lower effective voltage and larger pulse widths result in higher effective voltage. Depending on the drive, the frequency of these pulses is between 4 and 20 kHz. Instead of steep pulses, a sinusoidal waveform of the voltage and current is desired at the motor. The pulses are smoothed by the motor’s inductance.

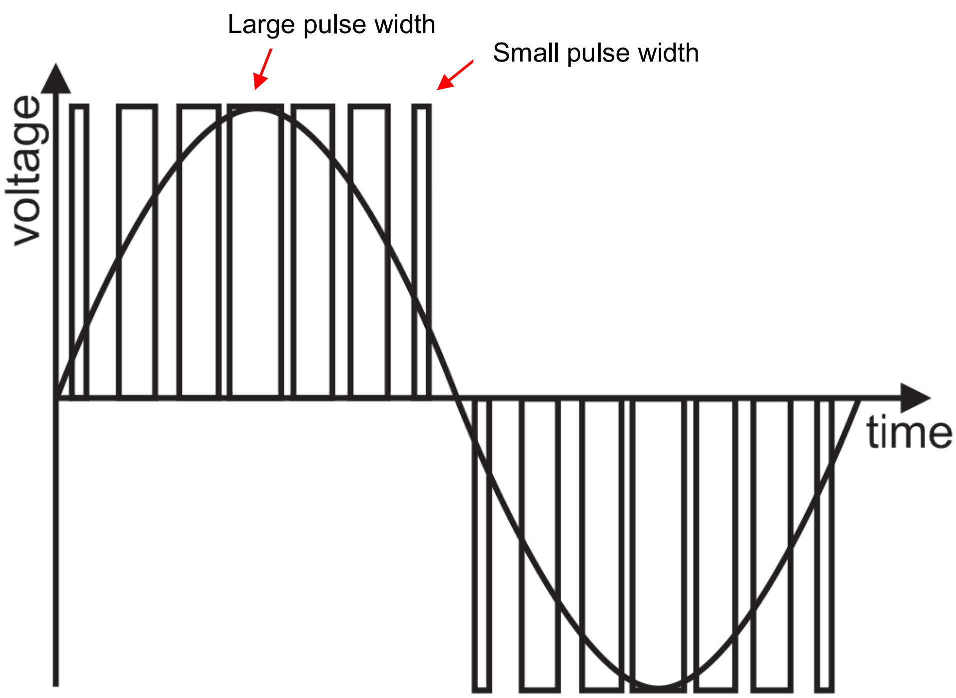

Figure 10: Pulse Width Modulation: Voltage pulses of different widths and the resulting sinusoidal waveform

Modern semiconductor switches (IGBTs) are very sophisticated and allow for high pulse rise times of more than 3 kV/µs in VFD applications with cable lengths of several hundred feet (compare: a standard 74ACT00 integrated circuit mounted on a printed circuit board has a rise time of only 1 kV/µs and the conductor length is limited to a few inches). These constantly occurring steep voltage impulses stress the cable insulation.

As a result of the above mentioned, binary switching, high switching frequency, and fast rise time; the length of VFD cable used in an installation becomes an important issue. An electrical characteristic called the cable capacitance indicates how much electrical charge the cable can store between its three power conductors, and between the conductors and the cable shielding.

The level of capacitance is determined by the implemented insulation material, the insulation thickness, and the shielding type. A higher cable capacitance results in higher charging currents. Therefore, low cable capacitances are desired. However, even with a low capacitance VFD cable, the capacitive cable charging current can reach 0.6 A/m. For longer cables this effect can easily cause a capacitive charging current of more than 20 A. This current stresses the cable without providing any usable power to the motor. This issue becomes especially serious for smaller drives with a power of less than 10kW, for which shielded cables are necessary. The drive voltage is also a concern. Drives that operate at 460V lead to higher charging currents than those that operate at 230V.

> **During the design process of machinery with motors and VFD devices, the cable lengths must be considered. The VFD device should always be installed in close proximity to the motor.**

Another issue with cables that connect VFD devices to motors is known as the reflected wave phenomenon. Both the cable and the motor have an electrical characteristic, which is called the electrical surge impedance. The electrical impedance applies to sinusoidal AC currents and is comparable to the electrical resistance in a DC circuit. When the motor impedance is larger than the conductor cable impedance, the voltage wave form will reflect at the motor terminals, creating a so called “standing wave” or also known as “reflected wave”.

The cable insulation and cable construction will have an effect on the cable impedance. It is desired to use a cable with impedance values as close as possible matched to the motor impedance. Please note that especially for smaller motors it is impossible to design a cable that matches the motor impedance, but the goal is to use a cable with the best possible match to the motor’s impedance.

The following algorithmic chart shows the large delta between motor and cable impedance but also shows that XLPE insulation offers a closer match than for example PVC. For that reason it is recommended to use XLPE in particular with smaller motors.

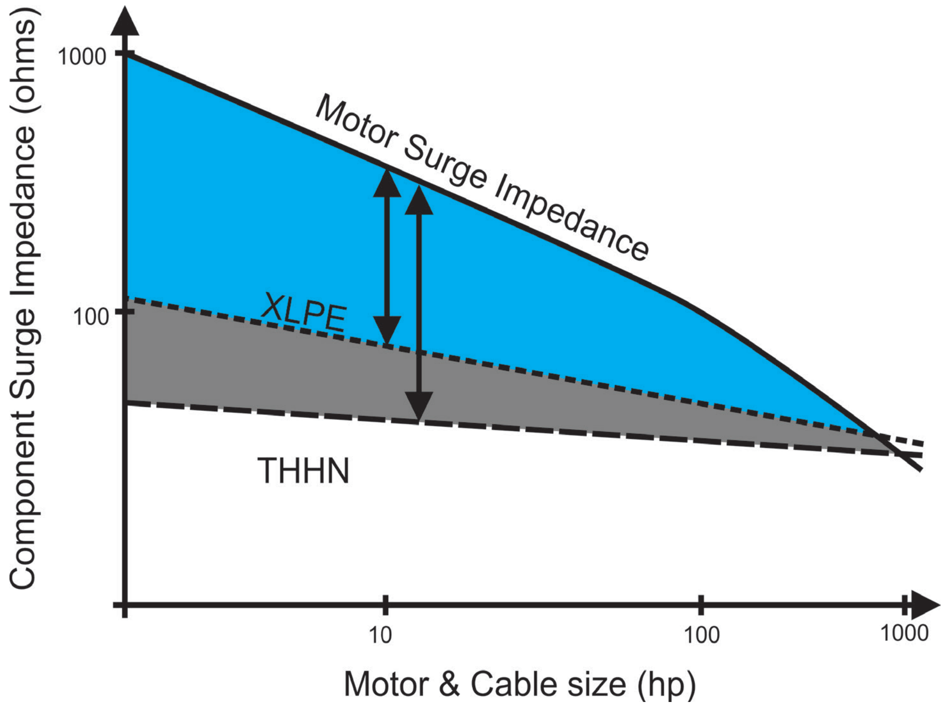

Figure 11: Algorithmic chart and impedance Delta between THHN insulated cable vs. XLPE insulated cable.

This reflected wave results in a voltage pulse reflected back from the motor to the drive. Long cable lengths between the motor and drive increase the probability of the reflected wave. A reflected pulse combined with a second pulse coming from the drive may raise the voltage at the cable to up to 2 times of its nominal voltage (DC bus voltage), even for very short cable lengths. This over voltage increases with the cable length.

In some cases voltage spikes have been reported to peak values as high as 2150 volts in a 460 V system. High voltage spikes can lead to insulation breakdown on the motor or cable insulation, resulting in short circuits.

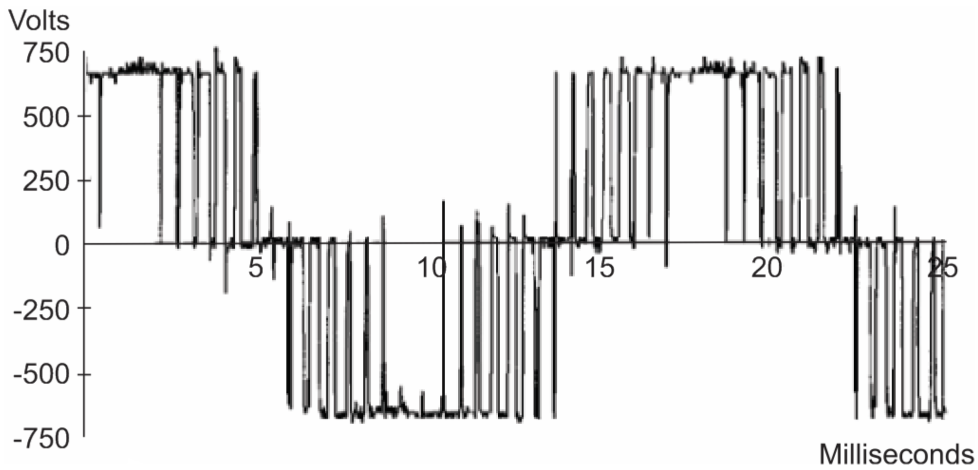

Figure 12: Typical output voltage of a 460V variable-frequency drive.

Figure 12 shows the typical output voltage of a 460V variable-frequency drive. As expected, the voltage reaches a level of approximately 650V which is the DC bus voltage. (AC line voltage x 1.414 (sqrt. of2))

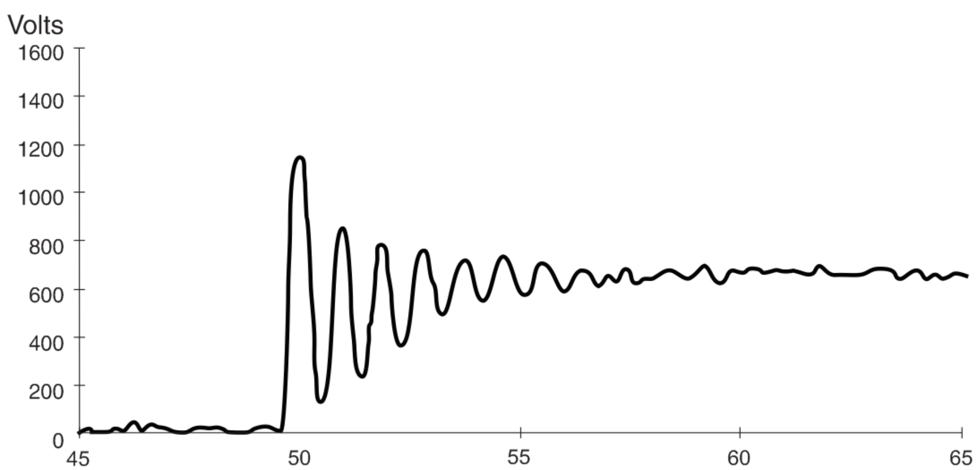

Figure 13: Magnification of one voltage pulse at the motor end

In Figure 13 the magnification of one voltage pulse is shown, as it appears at the motor end of the cable. It can be seen that the voltage not only reaches the 650V of the DC bus, but spikes up to almost twice that value. Thus, more than 1,200V would stress the cable.

The cable between drive and motor is a contributiing factor to the strength of occurring reflected waves. The impedance of the cable can help in reducing its negative effect

Additionally, these high voltage levels result in a high electric field, which may be strong enough to ionize the air between the conductor insulation and the cable jacket. If the voltage level is high enough, the ionized air can initiate a partial discharge mechanism known as a corona. The voltage level that causes a corona discharge is referred to as the corona inception voltage (CIV). Corona discharges produce ultraviolet light and large amounts of ozone which degrades the insulation. As the insulation degrades, gases are released, creating new voids and cracks in the insulation. This accelerates the degradation and leads to premature cable failure eventually. A hissing sound and micro arches can occur during a corona discharge.
Mechanical stress caused by tight bends can also add stress to the insulation

The biggest possible bending radius should be chosen, especially for bends of 90º or more.

The material of the insulation and its thickness can also affect the CIV of the cable. A thicker insulation results in a higher CIV, and thus reduces the probability of a corona discharge.

For example the CIV of polyvinyl chloride (PVC) insulation reaches only 70-80 % of the CIV level of a cross-linked polyethylene (XLPE). The CIV level of PVC can be improved by adding an insulation stress relief such a semi-conductive layer.

It should be noted that the CIV declines over the lifetime of the cable due to natural aging. The presence of moisture will cause the CIV to decrease. While the presence of moisture will affect the CIV of XLPE cables by only a few percent, it can lower the CIV of a PVC cable to drop to half of its level than it would have in dry conditions.

In order to assure that a VFD cable reaches its expected life span, the insulation material and thickness are factors that have to be considered.

Furthermore, the type of insulation material that is used in a VFD cable affects the heat generation. The insulation is a so called dielectric material, a non-conductive material within the electric field of the live conductor. How much the insulation material is affected can be expressed by the dielectric constant. Since the cable acts like a capacitor, this dielectric constant is the ratio of the amount of stored electrical energy. For time-varying electrical fields which are the case in VFD applications, the dielectric constant becomes frequency dependent (generally called permittivity). The electric field polarizes the dielectric material and due to the high frequency this results in heat generation (dielectric losses within the material). As insulation materials have different dielectric constants, the intensity of cable heating depends on the insulation material used. PVC, for example, has a higher dielectric constant than XLPE. As a result, PVC cable will get hotter than XLPE cable under the same operation conditions.

> **The type of insulation affects the thermal stress of the cable. The insulation material will affect how much heat the cable is able to generate at a given amperage.**

As mentioned above, current variable-frequency drives use fast rise times and high switching frequencies. This can cause high electromagnetic interference (EMI) noise radiated and conducted through the reference ground. The conducted part of EMI noise is called common mode (CM) noise and contains frequencies from one kHz up to several MHz. CM noise is an unwanted electrical signal that is sourced at the drive, coming through the cable to the motor, and is conducted back to the drive through the protective earth (PE/GROUND) wire or the shielding.

If three separate THHN wires or an unshielded cable are used, the CM current will take unpredictable ways back to the drive, e.g. via sensor, interface, or communication cables which may be connected to the motor. This may cause errors, performance loss, or even failure of the connected systems, such as personal computers, logic controllers, or sensor measuring devices. Furthermore, the current may return to the drive via the ground grid. High levels of CM noise on the ground grid often cause equipment problems and failures since the device is designed to operate at a zero potential ground reference.

As mentioned above, CM noise occurs in a wide range of frequencies. Therefore, an appropriate VFD cable must contain an internal ground wire for low frequency current, a braided shield, which is most effective against low frequencies, and a foil shield against high frequencies.

> **Appropriate shielding and grounding of the cable is required in order to achieve proper functionality of the VFD system.**

However, a cable conduit should not be used to carry common mode currents since it may or may not have the required electrical characteristics due to aging or corroding. Cable conduits may also have unintended contact with the ground grid when metal straps are used. A VFD cable, on the other hand, isolates its shielding from ground grid contact by the non conducting outer jacket.

5 Examples of VFD manufacturer statements on requirements of VFD cables

5.1 ABB (Asea Brown Boveri)

- VFD cables must provide a very good high frequency return path. Typically this is done with either a continuous corrugated aluminum corrugated armored cable or a power shielded cable.
- ABB promotes a symmetrical ground design (triple ground) to minimize the inducted voltage in the ground circuit.
- Voltage ratings are always 600VAC or higher.
- The insulation type is primarily determined by the application.
- The maximum cable length varies from 100 to 1500 feet depending on the power level of the drive involved.
- Cable shielding must be continuously bonded on a 360 degree mechanical basis on both ends of the motor cable.

Source: ABB Grounding and cabling of the Drive System

5.2 Rockwell Automation – Allen-Bradley

- Four tinned copper conductors with XLPE insulation.
- Copper braided shielding with 85 % coverage and foil shielding with 100 % coverage.
- Tinned copper drain wire
- PVC jacket
- Typical motor lead length recommendation is 100 ft max, longer length are possible

Source: DRIVES-IN001

6 Demands on VFD cables

6.1 Technical demands

Listed below are technical requirements of cables summarized from the VFD issues discussed above, the VFD manufacturer statements on VFD cables, and additional demands:

- Voltage rating sufficient to withstand occurring reflected waves
- Low cable capacitance for low charging current
- Oil, water, and dirt resistance
- Robust jacket for industrial environments
- Good shielding for low and high frequencies preferred, e.g:
    - Foil shielding, 100 % coverage & drain wire
    - Braided shielding typically with 70% or more coverage
- Tinned copper conductors to prevent oxidation
- 4 conductor design including full size ground for smaller Motors
- 3 conductors with 3 symmetrical grounds design for larger motors

6.2 Installation demands

The following cable characteristics are commonly demanded in order to deploy the cable in the field.

- National Recognized Testing Lab (e.g. UL) verified or listed
- TC–ER rated for installation in cable trays per NEC 336.10
- Rugged jacket with sunlight and oil resistance
- Easy strip jacket for installation in the field
- Good flexibility for cable routing purposes

6.3 Review of the demands

Because of the electrical issues described in the leading chapters the cable insulation type is probably the most important factor in choosing a drive cable. The capacitance level should be as low as possible, the voltage breakthrough resistance or dielectric strength should be as high as possible.
The next important factor is the overall construction such as effective shielding and a durable jacket followed by additional features such as flexibility. And for the proper deployment in the field, the cable must have the appropriate ratings to satisfy electrical code requirements.

7 Comparison of insulation materials

There is a great variety of insulation materials available. For industrial applications, especially in conjunction with the use of electrical motors, the most commonly used conductor insulation materials are polyvinyl chloride (PVC), PVC/Nylon aka THHN, cross-linked polyethylene (XLPE) and thermoplastic elastomer (TPE). Each of these materials has specific advantages and disadvantages as listed below:

7.1 Polyvinyl chloride (PVC)

PVC is commonly used in multi-conductor control cables. The material comes in many different formulations, for example with improved oil – or improved heat resistance.

Advantages:

- Inexpensive
- Flame retardant properties
- Flexible
- Easy to strip/process

Disadvantages:

- Humid environments greatly decrease the CIV
- No TC–ER rating available due to brittleness and insufficient crush resistance.
- Disadvantageous electrical characteristics for high-frequency applications
- Not halogen-free. In case of a fire, gaseous hydrogen chloride (HCl) is formed. This acidic gas is highly toxic, poses health hazards and can damage machinery
- Poor weather and cold resistance

7.2 Polyvinyl chloride with nylon coating (THHN)

In order to improve the mechanical strength of PVC insulation it is possible to coat it with a thin layer of nylon. This type of insulation is called THHN (Thermoplastic High Heat-Resistant Nylon-Coated). This type of wire is build per UL 1063 construction B. While this construction offers reduced cable diameters it also has some drawbacks in particular in VFD applications.

Advantages:

- TC–ER rating available due to good crush resistance of the Nylon
- Good resistance to petroleum by-products and chemical agents
- Better resistance against abrasion due to nylon coating

Disadvantages:

- Difficult to strip and/or process due to the nylon coating
- Disadvantageous electrical characteristics for high-frequency applications
- Total insulation wall thickness not adequate for voltage spikes

7.3 Cross-linked polyethylene (XLPE)

Cross-linking alters the molecular structure of the insulation material to achieve better mechanical characteristics. This can be done by a chemical or radiation treatment.

Advantages:

- High CIV due to very good dielectric properties
- Provides very good protection against corona discharges in humid environments
- Good impact and abrasion resistance
- TC–ER rating available
- Lower cable capacitance than PVC, reducing cable charging currents and allowing longer cable runs
- Halogen-free
- Higher temperature rating than PVC

Disadvantages:

- More rigid than PVC, not as flexible
- Longer processing time due to cross linking

7.4 Thermoplastic Polyester elastomer (TPE)

Advantages:

- Halogen-free
- Very good for continuous motion applications due to very good impact and abrasion resistance
- Very good weather and oil resistance
- Excellent heat and cold resistance
- High abrasion resistance
- Good electrical values

Disadvantages:

- Expensive
- No TC–ER rating available

7.5 Semi-conductive layer

A semi-conductive layer is only used to improve insulation and can be applied around the conductor and under the actual insulation. The semi-conductive layer is also referred to as “Insulation stress relief”. The semi-conductive layer is often times found in combination with PVC or nylon-coated PVC to improve the weaknesses of PVC for Drive applications. The TC–ER rating of the cable is not affected by the use of semi-conductive layers.

Advantages:

- Reduces the probability of corona and partial discharges
- Disperses voltage spikes
- Extends life span of the cable

Disadvantages:

- More expensive than cable without a semi-conductive layer
- Increases size of conductor and adds cost

8 Comparison of cable jacket materials

The jacket is another important part of the cable. It holds the conductors together and protects them against mechanical and environmental stress. Similarly to conductor insulations, there is also a great variety of materials available for the cable jacket. The three most commonly used materials for industrial cable jackets are PVC, TPE and Polyurethane (PUR). To prevent premature cable failure the jacket material has to be carefully chosen for its designated application. That is why the jacket is often the most significant selection criterion for cables.
Some selection criteria may be:

- Mechanical requirements, e.g. flexural strength
- Chemical requirements, e.g. resistance to acids
- Operating temperatures and environments
- Electrical requirements
- Safety issues, e.g. fire behavior

8.1 Polyvinyl chloride (PVC)

- Cost effective
- Good water and chemical resistance
- Flame retardant properties (achieves FT4 per CSA)
- Flexible for routing and bending
- Medium performance continuous motion flexing

8.2 TPE Thermoplastic Elastomer

- Rubber like feel and tear resistance
- Very good impact and abrasion resistance
- Flexible for bending and continuous motion flexing

8.3 Polyurethane (PUR)

- High flexibility even at low temperatures
- High performance continuous motion flexing
- Excellent abrasion resistance
- Halogen-free
- Resistant to radiation
- Resistant to oil, weak acidic solutions, gasoline, microbes
- Very good weather resistance
- Recyclable

9 Requirements for VFD cables in factory automation applications

Demands on the cable vary with different applications. Depending on the location of electrical motors within the machinery the cable can be routed in a variety of ways. It can be routed through a metal conduit, placed in a cable tray, attached to moving or flexing parts, or placed in a continuously moving cable track. Depending on the application, the design engineer will have to decide which part is more important, to satisfy the electrical requirement or the mechanical requirement, or both equally.

There are two main applications from a mechanical standpoint in regards to industrial machinery.

9.1 Fixed installation

Used in industrial enclosures, cable conduits, cable trays or anywhere cable is permanently routed and does not experience moving or flexing afterwards. Nevertheless, a stiff cable would be disadvantageous.

The cable has to be flexible that it can be routed at small bending radii within the machinery without damage. Often times VFD cable will be laid in cable tray systems in industrial buildings and therefore a TC-ER rating is very important.

This rating is in accordance to NEC article 336.10 and allows the cable to be installed in tray and exit the tray without the use of conduit if in accordance with NEC 336.10(7). However the cable will have to be supported every 6 ft outside the cable tray.

Demands:

- Good shielding capability
- Easy to route
- Jacket easy to strip
- TC–ER rating required for tray installations
- UV stability and weather resistance
- Cable roundness for installation with connectors

9.2 Continuous motion installation

This type of installation is required in cable tracks (aka drag chains), multiple-axis machining, robotics pick and place systems, assembly or material handling systems, or any other application in which cable is in continuous motion. The cable may experience high speeds, fast accelerations, and long travel distances.

Contrary to common expectation, the high flexible cable needed in these applications may feel somewhat more rigid due to the highly abrasion resistant PUR jackets. However, it is designed to withstand millions of flexing cycles without damage.

Demands:

- Mechanical requirements often more important than electrical requirements: foil shielding and drain wire omitted to improve flexing characteristics
- High abrasion resistance
- Superfine conductor stranding
- Core layout for continuous motion
- UV stability and weather resistance
- Cable roundness for continuous motion

10 Lutze VFD cables

Lutze offers three types of cables covering fixed install and continuous motion applications:

10.1 Lutze DRIVEFLEX™ VFD and Servo Cable

The premium solution for VFD and Servo applications

DRIVEFLEX™ is a family of cables designed to meet the unique electrical challenges in VFD and Servo applications. All DRIVEFLEX™ cables use a special formulation of cross linked polyethylene insulation (XLPE), providing excellent electrical characteristic while maintaining the utmost flexibility for a Drive Cable.

- For VFD, Servo and Motor applications
- For harsh environments
- For operating conditions with high interference and noise levels
- Specially formulated jacket for oil resistance and easy strip design for field installation
- XLPE thick wall insulation with low capacitance
- Designed for longer cable runs
- NFPA 79 compliant for wiring of industrial machinery
- TC-ER for use with cable trays and exposed run without conduit
- WTTC for use in Wind Turbines
- cUL listed

XLPE is a very low capacitance insulation offering superior electrical characteristics for use as a VFD cable, especially in long cable runs. The XLPE insulation is a thermo-set material with a very high voltage breakdown level, thus inherently addressing the corona discharge effect and making it the premium insulation for any type of Drive application.

XLPE insulation is recommended by most Drive manufacturers, and Lutze DRIVEFLEX™ exceeds the VFD cable requirements by Rockwell™. The extra thick insulation offers a 1000V rating per UL. A foil and braid shield combination with drain wire assures compliance with EMC requirements. Lutze DRIVEFLEX™ XLPE is the most flexible XLPE cable in its class - offering easy stripping & installation, thus saving time and money.

DRIVEFLEX™ is available in three configurations:

1. Lutze DRIVEFLEX™ XLPE (C) PVC 0.6/1kV, Shielded A216 series Flexible VFD & Motor Supply Cable with 4 conductors including one full

size ground. Suitable for all generic Drive Applications with classic three phase wiring.

2. Lutze DRIVEFLEX™ N (C) Servo I PVC 0.6/1kV, Shielded A217 series Flexible VFD & Motor Supply Cable with 4 Conductors including one full size ground, plus one twisted shielded pair for feedback. Suitable for servo systems such as Rockwell, Siemens etc., which require one control pair.

3. Lutze DRIVEFLEX™ N (C) Servo II PVC 0.6/1kV, Shielded A218 series Flexible VFD & Motor Supply Cable with 4 Conductors including one full size ground, plus two twisted shielded pairs for feedback. Suitable for servo systems such as Rockwell, Indramat etc., which require two control pairs.

10.2 Lutze Superflex Plus M (C) PUR 0.6/1kV

Low capacitance high flexing Servo, Motor and VFD Cable for continuous motion in C-tracks. This cable is designed to withstand the most demanding applications with extremely rough operating conditions and oil exposure. Compatible with all major brand C-tracks. This cable can be used in long C-tracks with over 40m traverse distance. Also available in composite Versions with 1 or 2 control pairs.

Characteristics
- Superfine stranding per Class 6 for continuous moving applications
- TPE conductor insulation
- Highly abrasion resistant PUR jacket
- Highest level of resistance against cooling fluids, greases and oils
- Abrasion and hydrolysis resistant, low water absorption
- UV resistant
- Non-wicking fillers
- Silicone/Talc free

11 Methods to improve operation reliability

Some variable-frequency installations may cause problems during operation. These problems are more likely to occur in areas of high electrical noise, e.g. due to multiple VFDs or high current applications. Similar problems may be encountered if long cable runs are used between the drive and the motor. Drive malfunctions or failures may occur, even if the drive and the motor function correctly when tested separately. It is often falsely concluded that there is a problem with the VFD cable. In many cases, the cable is actually not faulty, but some marginal installation details have not been considered. To ensure proper operation, it might be necessary to install external devices to ensure proper operation, e.g.:

- Output reactors
- Output filters
- EMI/RFI filters
- Motor filters
- Ferrite rings

Output reactors and filters reduce the PWM waveform effects, e.g. the fast rise times of the output voltage that can negatively affect materials. They also reduce motor peak voltages and high surge currents, which extends the life of cable and motor. The proper selection and installation of these devices include:

- Proper selection of the desired voltage rating
- Proper selection of the impedance value
- Proper selection of the device’s size regarding the maximal occurring continuous current
- Installation of the device on the output side of the VFD, located as close to the VFD as possible

EMI/RFI filters reduce the noise that is generated by the VFD on the power lines. In this manner they are input filters that protect electronic devices in front of the drive.

The drive’s manual will state the necessary actions that have to been taken to ensure proper drive functionality.

As a general rule we advise to always upsize to the next cable size if unsure which size to choose from.

12 Installation guidelines for VFD cables

- The length of the VFD cable has to be kept within the limits set by the drive manufacturer. Always avoid unnecessarily long cable runs.
- Cable shielding (foil and braided shields) must be connected at both the drive and the motor end unless the Drive manufacturer provides different guidelines.
- The shielding must be connected at a 360° contact. Connecting only the drain wire to be used for grounding and cutting off the shielding does not provide sufficient EMC noise protection.

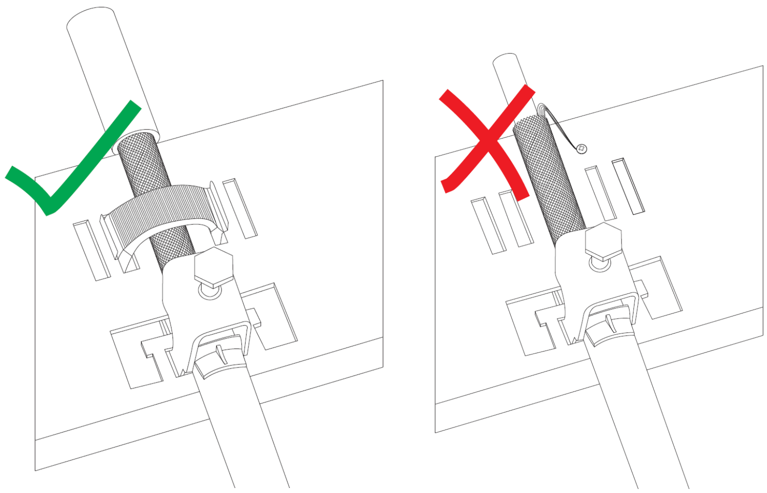

Figure 14: Correct (left side) and wrong (right side) connection of VFD cable; correct 360° connection of shielded cable requires cable clamps or metal fittings

- Where the cable has been stripped and the wires are exposed, a conductive tape should be used to improve EMC noise protection.
- The VFD cable should not be routed in the same tray/conduit as signal, networking, or communications cables. Always use separate trays or tray dividers for power and data cables.
- The cable should be stripped as little as possible. It has to be assured that the shielding is not damaged or interrupted.
- If the VFD cable has to cross signal or data cables, this has to be done at a 90° degree angle.
- The PE ground wire has to be connected at both cable ends.
- Cable bends must be reduced to a minimum. The biggest possible bending radius should be chosen, especially for bends of 90° or more.

13 Glossary

PWM:

Pulse Width Modulation is used to generate a variable AC voltage out of a DC supply voltage. PWM continually switches between two states, 0V and DC Bus voltage, with a constant frequency but with variable pulse widths. The widths of the pulses determine the effective output voltage. Smaller pulse widths result in lower effective voltage and larger pulse widths result in higher effective voltage.

IGBT:

These Insulated Gate Bipolar Transistors were designed to reduce component losses and to provide extremely short switching times. They combine the robustness and low power losses of bipolar junction transistors (BJT) and advantageous low signal level input characteristics of metal-oxide semiconductor field-effect transistors (MOSFET). The use of IGBTs in VFD devices reduces costs since smaller heat sinks can be used making the device more compact and efficient.

Fixed installation:

The cable used in this installation is still flexible but only moved or flexed during routing.

Flexible application:

The cable experiences infrequent flexing at low speed and short distances.

Continuous motion application:

The cable continuously flexes, often for millions of cycles. High flexing speeds and accelerations may occur, even with long cable runs.

Halogen-free:

Materials that are halogen-free do not form toxic or corrosive fumes in case of burning.

Reflected wave:

VFDs are known to have “reflected wave phenomena” resulting in Voltages at the motor end up to 2 times the nominal voltage. The reflected wave potential grows with the length of cable from Drive to the motor

Common Mode:

Electrical noise of high frequencies that is conducted on the PE GROUND wire, the cable shielding, or the ground grid. It may cause problems or failures of other devices in vicinity to the VFD application.

Corona discharge:

Audible and visible electrical discharge due to ionization of the air surrounding the conductor that causes ozone.

Corona Inception Voltage (CIV):

The voltage level that has to be exceeded so that corona can discharges initiate.

Corona Extinction Voltage (CEV):

The voltage has to fall below this level in order to cease Corona discharges.

Rise time:

The rise time refers to the time required for a signal to change from a specified low value to a specified high value or vice versa.

RoHS:

The Restriction of the use of certain hazardous substances in electrical and electronic equipment directive was adopted by the European Union. This directive restricts the use of six hazardous materials in the manufacture of electric equipment. The six substances are: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, and polybrominated diphenyl ether.

Desina:

Desina (Distributed and Standardized Installation Technology, http://www.desina.eu) is a specification for standardizing electric, pneumatic, and hydraulic components and their interconnection. Some standardized characteristics are: cable jacket colors, connectors, pin assignments.

CSA:

Canadian Standards Association develops standards and provides testing as well as certification services.

UL:

Underwriters Laboratories Inc. is a U.S. organization that develops standards and test procedures chiefly dealing with product safety. Also it evaluates materials, products, components and systems for compliance to specific requirements, and permits acceptable products to carry a UL certification mark.

Dielectric:

A dielectric is an electric insulator within an electric field.

Dielectric constant:

Also known as relative permittivity and describes the amount of electrical energy stored in any material

XLPE

Cross linked Polyethylene. The molecular structure of Polyethylene can be altered to achieve better mechanical characteristics.

THHN

PVC/Nylon insulated wire

14 Table of figures

15 List of references

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