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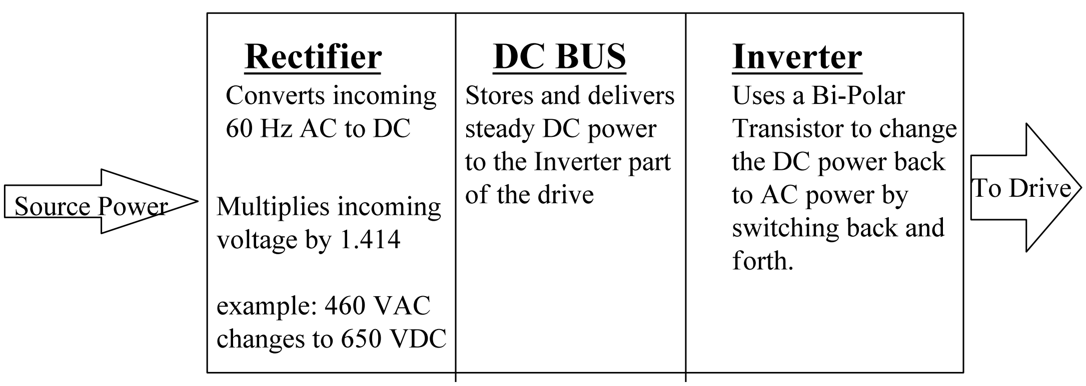
VFD Systems and Cable

Background

VFD is the acronym for Variable Frequency Drive, which has become a very popular method to adjust a motors speed. Frequency can be defined as an electrical term meaning power pulses of voltage and current. In the United States 60 Hertz, or 60-power pulse cycles per second, are conducted through most wires and cables throughout the country. As the power in the United States is alternating current (AC) each of these frequency cycles contain one positive and one negative power pulse of voltage and current. Increasing the number of power pulses per second will make the motor turn faster. Likewise, decreasing the number of power pulses per second will make the motor turn slower. Therefore by increasing and decreasing the frequency of the power pulses, the drive can adjust the speed of the motor.



The components of the drive system are broken into four major categories: Source power, VFD, Cable and the Motor. Other ancillary components exist such as resolver and encoder feedback devices, tachometers, sensors, relays and others that help supplement the system.

The local electrical company provides the source power for all electrical equipment and apparatus for operation. The source power may go through a transformer to either increase or lower the voltage but the frequency will remain constant at 60 Hertz.

The function of the drive is to send all power pulses that control the motor’s start-up, operating speed, and stopping. The three major tasks that a VFD drive has to accomplish prior to adjusting a motor’s speed are:

First, the source power must be converted from Alternating Current (AC) to Direct Current (DC). This conversion is accomplished by means of a rectifier, a diode is used for simple rectifying and a Silicone Controlled Rectifier (SCR) is used for more intelligent rectification. The power source that was 460 Volts AC, 60 Hertz now is converted to 650 Volts DC. This AC to DC conversion is necessary before the power can be changed back to AC at a variable frequency. In short the power goes from AC to DC then back to AC again so it can be used for VFD applications.

Second is a large capacitor, which is known as the DC bus. A capacitor can be simply defined as an electronic component that stores energy. The DC bus acts like a storage battery to supply DC power to the third part of the drive.

The third part of the drive is known as the inverter. An inverter converts DC back to AC by utilizing an electronic component known as a Bi-polar transistor. The inverter can be controlled to vary the frequency so that the motor receives the correct flow of power pulses. This is the advantage of utilizing a Variable Frequency Drive. The pulse width modulation (PWM) frequency is approximately 20,000 Hertz and offers finer control by only varying a few cycles. In contrast at the power source frequency of 60 Hertz, changing a few cycles only offers a much coarser change and will not allow for as close control.

The VFD drive output is basically a flow of AC power pulses at a certain frequency that provides or maintains the desired speed of a running motor. The motor through means of power supply cables receives these power pulses. Cables and their functions will be discussed later.

The motor consists of two major parts the armature (rotor) physically turns and the field (stator) that remains stationary. The cables are connected to the stator and upon the application of power cause an electromagnetic field to rotate. This rotating field causes the rotor to follow the moving electromagnetism and turn. The stator of the motor is constructed of insulated wire that is wound through slots a specific number of times in a required pattern. This is the defenseless part of the motor. The wire insulation is extremely thin and can get nicked during the winding process. These nicks are the bare spots in the wire that causes arcing and can lead to motor failure.

What Happens

The VFD drive transition from AC to DC then back to variable AC is not done cleanly. Power distortions are created by the first part of the drive (rectifier) and then sent back through the source power system. Power distortions are also created by the third part of the drive (inverter) and sent on to the motor. Therefore, power distortions are created at both ends of the drive causing non-linear spikes, wave reflections and inrush currents. The following will explain these types of phenomena:

Harmonics, non-linear spikes, and reflections are common power distortions. In rush currents is an additional problem that the motor and cable are subjected to. Harmonics are multiples of a fundamental frequency. As an example if the fundamental frequency is 60 Hertz, the 5^{th} harmonic is 300 Hertz (5x60). Power distortions are caused by harmonic frequencies. Some harmonic frequencies are “in-phase” with the fundamental frequency and rotate in the same direction as the field, except more quickly due to the higher harmonic frequency. This condition causes the power, both voltage and current of each harmonic to add to the voltage and current of the fundamental frequency. Keep in mind that the power in the fundamental frequency is all that is needed or wanted. The additional power from the harmonic frequencies cause overheating, high voltage stress and also confuse electronic functions that depend on the fundamental frequency for clock or timing functions. The added harmonic power also affects the motor and power supply cables.

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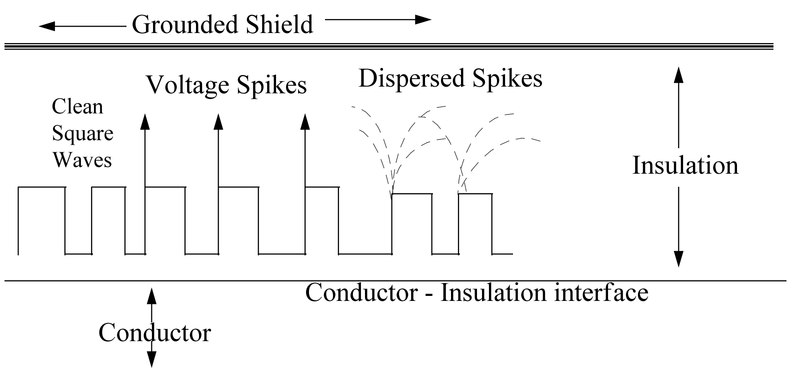
As previously mentioned, a higher flow of power pulses will cause a motor to run faster. Harmonic frequencies cause a motor to fine-tune its adjustments with braking and other heat generating reactions. The 7th and 13th harmonics rotate with the field, supply additional power pulses and require the brake to regulate motor speed. The 5th and 11th harmonics oppose the field's rotation and require additional current (heat) to regulate motor speed. The 3rd, 9th, & 15th are triple harmonics which do not rotate but are the most in-phase and additive to neutral current (heat). The harmonics that are commonly generated by a VFD drive are the 5th, 7th 11th, and 13th.

The definition of non-linear power is that a change in voltage does not generate the same change in current. The motor expects a power pulse to be regulated. When the frequency is increased, the motor expects the right amount of current to be included in the power pulse to sustain the increase in speed. In the case of non-linear power, the current does not properly support the motors requirements. This distorted current either fights or overdoes the change, resulting in high voltage stress and heat.



A spike is a very quick increase in voltage that occurs for a short time. The inverter in the drive which is a fast switching transistor must rise from zero to 650 volts (rectified 460 volt system) and then go back to zero 20000 times a second. This is a very fast rise time. Several things can happen as the inverter is switching and conducting the power pulses through the cable to the motor. The 650-volt normal voltage can overshoot higher to 2000 volts or more. The cable that connects the VFD drive to the motor looks electrically different to the power pulse as the length increases. The longer the cable length the greater the increase in inductance, which in turn affects the overshoot of the voltage spike. Therefore a long power supply cable will have greater and more intense voltage spikes than a shorter cable. Voltage spikes are very quick lasting for only a few millionths of a second. The inverter in the drive is called an Insulated Gate Bipolar Transistor (IGBT) and is one of the fastest switching inverters in the Pulse Width Modulation (PWM) type of variable frequency drives.

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Frequency waves that seem to be standing still are reflections and are often called standing waves. As a comparison this would be similar to seeing a spinning wheel that appears to be frozen but actually is in motion. At the cable attachment to the motor the standing wave sees a large difference in impedance and can be reflected back to the drive. A long power supply cable allows for more opportunity for a reflected standing wave to get in phase with itself at a certain point in the cable and double the voltage and current there. The 650-volt normal voltage now becomes 1300 volts and the current also doubles. At this spot the insulation is severely stressed and will in time overheat and puncture causing the cable to fail.

During motor start-up inrush currents occur. The motor and power supply cable act as a large capacitor that must be charged up to the normal operating power level. When a motor is first energized, it can draw up to six times its full load running power requirements. The cable must be of adequate conductor AWG size so there will not be any significant voltage drop.

When the current in power pulses from a source circuit end up in the power pulses of another circuit, capacitive coupling takes place. This is caused from a changing electric field in the source circuit. The change in voltage, from zero to full and back to zero, causes the current to flow and couple from one copper conductor to another. In short, power pulses from one circuit are added to compatible pulses of another circuit that result in heat and stress.

Lapp VFD Cable

The Lapp VFD cable is different from ordinary motor power supply cable because it can disperse all of the spikes that the VFD drives generate. The cable construction starts with a unique semi-conductive composite insulation applied over the conductor. The use of a semi-conductive layer will be discussed in later in greater detail.

The color of the insulation on three conductors is black and each conductor is identified with white numbers, the fourth conductor is colored green/yellow for purposes of grounding. All conductors are rated for 1000 volts and 3000 volts peak. This enables the cable to withstand reflections, standing waves, and spike voltages that a VFD cable may experience under typical conditions of use. Lapp VFD cable is both UL and CSA approved and is available in conductor size range from 18 AWG up to 2 AWG. Other combination of conductors and different AWG sizes can also be made upon request.

Part of the standard VFD cable design incorporates an inner jacket to help provide an additional layer of protection between the insulation and braid shield and also lowers the capacitive interaction between the braid and power conductors. The inner jacket is also sized to fit an MS-SC type shielding connector for full circumferential 360^{o} grounding of the shield. The outer jacket is also flame resistant, has superior resistance to oils and helps provide overall optimum cable impact and crush resistance. A single jacketed version is also available for those applications requiring UL and CSA Tray cable approval.

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Why a semi conductive layer?

The application of a semi conductive compound over an electrical conductor is a process that has been in practice for years. Semi conductive compounds are available both in thermoplastic or thermosetting types to complement the type of insulation system that is being used in the cable. As Lapp VFD cables are primarily insulated with polyvinylchloride, the semi conductive compound is of a thermoplastic type.

About a half-century ago, engineers in the cable industry became aware that the simple cable design of conductor/insulation/shield was voltage limited in the aspects of safety and long-term trouble free operation. The problem arose from the where the conductor met the primary layer of insulation and the creation of voids that occurred where the insulation did not fully penetrate into the small spaces in outer layer of the stranded conductor. This resulted in unwanted corona discharge across these voids, which in turn led to the quick deterioration of the insulation. Another problem was the small diameter of the individual wires in the outer conductor layer and their surface irregularities, which produced points of high electrical stress, again attributing to rapid deterioration of the insulation.

In order to resolve these problems the use of semi conductive compounds as a stress-relieving layer between the conductor and primary insulation were introduced. The application of an extruded semi conductive compound provided a rounder and smoother continuous layer and also completely filled in all areas of the outer layer in the stranded conductor. In short the extruded semi conductive layer now provided complete and void free contact between the conductor and primary insulation. The use of extruded semi conducting compounds now alleviated many problems of the past and resulted in improved cable reliability, extended life, breakdown voltages and corona levels.

Semi-conductive material extruded over the conductor is a very common process used in the high voltage cable industry to help maintain the cables overall performance while under extreme conditions. Likewise the application of the semi-conductive layer over the conductor helps to relieve electrical stress that is experienced by the Lapp VFD cable during periods of high voltage spikes. The semi-conductive layer disperses the high voltage spike so that the primary insulation is not damaged. Therefore no degradation to the primary insulation begins and the cable remains in operation with no disruption in service. All Lapp PVC insulated VFD cables have an extruded thermoplastic semi conducting layer applied directly over the conductor which helps to insure long service life and trouble free operation.

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Other cable companies that use semi conductive insulation are involved with the manufacture of high voltage cables. These manufacturers provide cables to customers such as major utilities and power companies. Depending upon the manufacturer these companies offer cables that use semi conductive insulation in their designs for cables that are rated for 5,000 to 138,000 Volts. Some these High Voltage cable manufacturers include:

- The Okonite Company
- General Cable
- USA Wire & Cable, Inc.
- Nexans Energy
- Kerite

What is Corona?

Corona is the ionization of the nitrogen in the air caused by an intense electrical field. Corona can be detected as a crackling or hissing type of audible sound and it also produces light, which can be seen by the naked eye in darkness.

Why is Corona not good for insulation?

Corona causes ozone and also nitric acid that occurs in the presence of moisture in the air and then accumulates as a white or dirty powder on the insulator. When the nitric acid accumulates micro arcing occurs creating carbon tracks across the insulating material. This can lead to defects in the insulating material over time eventually causing cable failure.

What is Corona Inception Voltage?

The voltage level at which corona initiates or begins.

What is Corona Extinction Voltage?

The voltage level at which corona ceases or stops.

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How is cable tested for Corona?

One method of testing cable for corona levels is indicated by the equipment and procedure indicated below:

Apparatus Required:
1. AC Power Supply
2. Voltage measuring device
3. Discharge measuring device
4. Cable sample

Proper connections are made so that when voltage is applied to the cable sample, both voltage and discharge levels can be measured. The cable samples tested were 50 ft. in length and the threshold used for inception and extinction was 5 Pico coulombs. The discharge-measuring device will display corona inception and extinction levels occur by means of an oscilloscope. The voltage-measuring device will display the corona inception and extinction voltage levels. Voltage is applied gradually to the cable sample until the corona inception has been reached, then the voltage is gradually reduced until the corona extinction has been reached.

Lapp VFD testing

Several cables were tested at an independent third party facility using ICEA T-24-380 as the reference test specification. Three12 AWG four conductor samples were tested as shown below:

Sample Number	Shielded Sample Description	Corona Inception Voltage	Corona Extinction Voltage
1	Insulation: PVC Jacket: PVC	2200	1800
2	Insulation: XLPE Jacket: PVC	2400	1900
3	Insulation: SC/PVC Jacket: PVC	2900	2500

Both corona inception and extinction voltage levels were significantly higher for sample 3 when compared to both samples 1 & 2. Sample 3 used Lapps unique primary insulation construction of a semi conductive thermoplastic layer applied directly over the conductor with a PVC insulating covering. In short the higher the corona inception and extinction levels the better long-term protection a cable has to offer when exposed to high voltage conditions that are experienced with VFD cables.

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The problem with cable

Basically with VFD systems the cable itself is the hardest component to check out. A drive has a self-diagnosis program and a shorted motor can be easily detected. A voltage spike only lasts a few millionth's of a second and is seldom actually recognized at the time of cable failure. The equipment just drops off line. A restart is usually possible if the cable damage is not severe enough to prevent system operation. When a cable's insulation is punctured from high voltage stress, the current then travels through the hole in the insulation to the nearest ground path, which is usually the braid shield. When the current from a hot phase conductor touches a grounded braid, an extreme amount of current is created. This is too much current for the shield to carry away fast enough, so the braid quickly heats up and burns. The braid will burn as long as the current can arc to it. Once the hole in the braid is burned big enough, the cable will self heal until the next high voltage stress puncture occurs at a different spot.

Eventually, the arcing that occurs will burn through the conductor and the cable damage will be detected by ordinary testing. But significant time has been lost from checking the motor and the drive. Up until the final failure, the cable may not show any defect if it has burned clear and is tested without using special cable insulation test apparatus. Once a cable is found to have failed, it is another matter to remove, replace and put connectors on the cable. The Lapp VFD cable's ability to disperse the failure causing spikes will prevent downtime delays that are associated with other typical motor power supply cables.

The VFD Systems solution

All four parts of the VFD drive system meet some fairly rigorous requirements to help insure safety and uninterrupted operation. Since 1996 the National Electrical Code Article 430-22a has specified that source power conductors are required to be sized at 125% of the full load current of the drive. This requirement was established to protect the cables from power distortions generated by the rectifier.

Having the pulse rate changed or switching the drive inverter transistor to a slower frequency can eliminate the higher power low number harmonics. To clean off the harmonics and block the spikes filters, reactors and isolation transformers can be added to the drive. In an effort to lower the inrush currents, startups can be made more gradual. These add-ons could be cost prohibitive and cause further voltage drop from the power supplied to the motor.

VFD motors are double insulated so that any nicks in the windings insulation can be avoided. In order to withstand distorted power the windings insulation have been enhanced for greater performance. The motors that remain susceptible to breakdown are those that were not changed when the drive was upgraded to an adjustable VFD type.

This cable is now left as the weakest link in the VFD system. If a motor power supply cable can be made so that it will not fail due to power distortions, the whole system will have been upgraded to handle the type of power that a VFD drive generates. Now the Lapp VFD cable exists which will insure trouble free operation even under the most extreme operating conditions.