Installation Considerations

In the last few years, Adjustable Speed AC Drive (ASD) manufacturers have migrated from Bipolar Junction Transistor (BJT) semiconductors to Insulated Gate Bipolar Transistors (IGBTs) as the preferred output switching device. The advantage of IGBTs over BJTs is that device rise and fall time switching capability is 5 - 10 times faster, resulting in lower device switching loss and a more efficient drive. However, for a similar motor cable length as the BJT drive, the faster output voltage risetime of the IGBT drive may increase the dielectric voltage stress on the motor and cable due to a phenomenon called reflected wave. Faster output *dv/dt* transitions of IGBT drives also increases the possibility for phenomenon such as increased Common Mode (CM) electrical noise, Electromagnetic Interference (EMI) problems and increased capacitive cable charging current problems. This paper is going to discuss these issues and give solutions for each phenomenon.

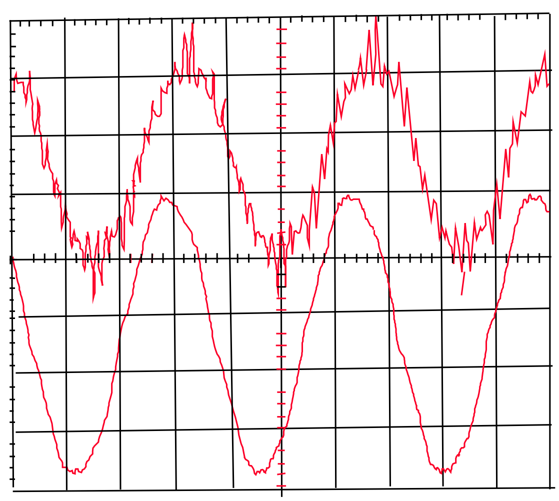
Why the Migration to IGBT devices?

The low switching loss feature of the IGBT is advantageous to both drive and motor. Reduced semiconductor switching loss results in smaller heat sinks and ultimately lower drive package cost. The IGBT being a voltage rather than current controlled gate device has a lower base drive circuit cost that also results in lower drive package cost. The low switching loss, along with fast transition times, may now allow higher carrier or switching frequencies in the 6 to 12 kHz region compared to a 1 to 2 kHz limitation for BJTs. As shown in Fig. 1, higher carrier frequencies of IGBT drives produce less peak current ripple, thus allowing rated motor torque with lower peak current than BJT drives. IGBT drives with high carrier frequencies have substantially reduced motor ripple current and have dramatically improved torque performance in the low speed region < 10 Hz. The higher carrier frequency also reduces motor lamination noise in the audible range. These system advantages have created a greater demand for IGBTs, thereby shifting semiconductor manufacturer cost reduction efforts toward the IGBT and making IGBTs the preferred switch for next generation drives.

Figure 1
Phase Current of BJT and IGBT Drive

Bipolar
Carrier Frequency
@ 1.26 khz

IGBT
Carrier Frequency
@ 9 khz



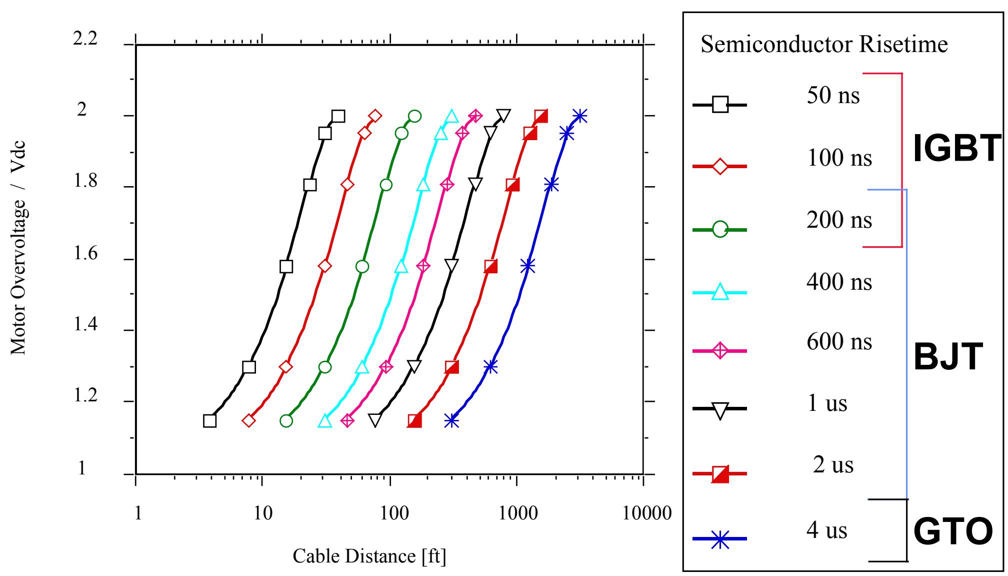
Reflected Wave Phenomenon

Background of Reflected Wave Problem

This overvoltage phenomenon, known as "Reflected Wave", "Transmission Line Effect" or "Standing Wave" may produce potentially destructive voltage stress on the motor insulation. From theory, whenever cable surge impedance does not match load (motor) surge impedance, a reflected wave may occur at the load terminals. Reflected wave magnitude is dependent on the extent of impedance mismatch occurring, with a maximum value equal to the incoming pulse voltage. Incoming pulse and reflected wave magnitudes add so that, in theory, up to twice bus voltage may exist on line to line motor terminals for an uncharged cable condition.

Drive pulse risetime is controlled by semiconductor device switching time and determines a critical cable distance where 2 pu (per unit) peak motor overvoltage is fully developed. Critical distances for various semiconductor risetimes are shown in Fig. 2. Reflected wave phenomenon has always been possible on AC motors with older BJT and GTO device technology. However, 2 pu voltage occurred outside the realm of normal application distances > 200 ft. Fig. 2 shows that, for a given motor cable length, as device technology has changed, the transient motor overvoltage magnitude has steadily increased along with faster risetimes. Thus, reflected wave is ***now*** an application issue to consider.

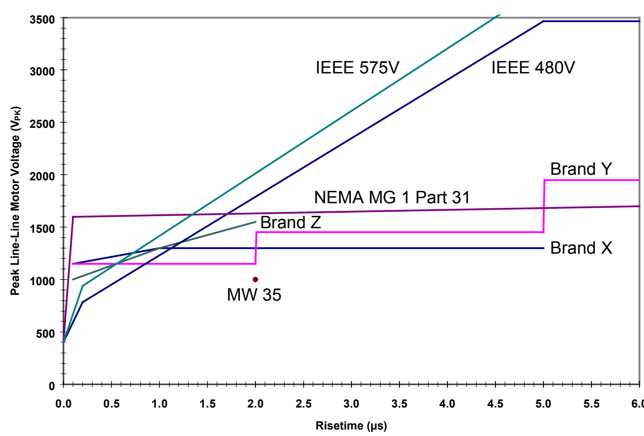
Figure 2
Motor pu Over-Voltage vs. Cable Length vs. Risetime



Effect of Transients on the Motor

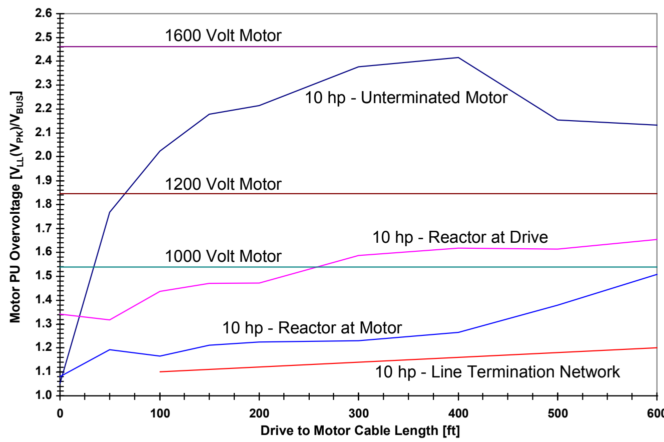
The magnitude and risetime of the reflected wave has a major influence on the dielectric withstand capability of the motor. Drive output risetime may be measured or obtained from drive vendors. Reflected wave voltage magnitude at a certain cable length may be estimated from Fig. 2. Fig. 3 shows various motor vendor insulation dielectric capability to withstand surge voltages with a given risetime. The high surge capability of the 480V IEEE curve at risetimes > 6 μs is limited by total dielectric breakdown of the magnet wire. Motor vendor curves for ASD operation in Fig. 3 have lower maximum values due to concern over partial discharges and corona within the motor. This is due to repetitive reflected wave voltage stress on every pulse edge that may exceed the Corona Inception Voltage (CIV) level of the motor and which occurs at the high carrier frequency selected (i.e.: 2,000 to 12,000 times a second). The downward derate slope of the motor vendor curves for fast surge voltage risetimes is due to a nonlinear distribution of the peak reflected wave voltage within the stator winding. High voltage stress within the winding turns may also contribute to corona induced dielectric failure.

Figure 3
Motor Dielectric Withstand Envelope vs. Surge Risetime



A 480 V BJT drive with dc bus of 650 Vdc, output risetime of 1 μs, and motor cable length of 100 ft will have a 1.2 pu overvoltage (780 Vpk) at the motor from Fig. 2. For the same 100 ft. cable length, a 480V IGBT drive, with output risetime at 0.1 μs will have ~ 2 pu or 1,300 Vpk at the motor. A plot of BJT operating point of 780 Vpk at 2 μs in Fig. 3 shows operation is well within motor maximum dielectric withstand capability and should expect no reflected wave issues. The IGBT operating point of 1,300 Vpk at 0.1 μs on Fig. 3 shows operation is outside motor maximum dielectric withstand capability of most vendors and may have reflected wave issues in the application. Of interest to IGBT drives is the region of Fig. 3 in the 0.1 μs range. Motor vendor *Z* has a 1,000 Vpk capability at 0.1 μs while vendors *X* and *Y* have ~1,200 Vpk capability at 0.1 μs. The classification of these two motor groups has been verified with corona testing. Some drive manufacturers have taken the 480 V pu overvoltage vs. cable distance information of Fig. 4 and for each hp frame size, state maximum allowable safe distances that insure motor voltage is < 1,000 Vpk or < 1,200 Vpk. This information allows easy determination if external protection devices are required for the cable length anticipated in the application. Customers may be relieved of coordinating peak applied voltage with motor dielectric withstand by choosing a vendor that supplies both drive and motor where drive/motor compatibility issues and options, have been investigated and tested.

Figure 4
Motor pu Over-Voltage vs. Cable Length vs. Solution



Customers should only specify "Inverter Rated" motors. These motors are designed to handle the extra harmonic heating. They may or may not have extra insulation such as phase paper between windings to handle the extra dielectric stress. Inverter Rated motor designs to NEMA MG1 part 30 standard have a 1,000 Vpk capability at 2 μs risetime. Thus, these motors are adequate for most BJT drives but not IGBT drives. Inverter rated motors designed to NEMA MG1 Part 31 para. 31.40.4.2 "Voltage Spikes" must be capable of 1,600 Vpk at 0.1 μs risetime in Fig. 3 and must be used with IGBT drives to insure dielectric survival at long cable distances. However, NEMA test standards are lacking on how to test a motor to see if it is indeed capable of repetitive 1,600 Vpk surges at 0. 1 μs risetime and also lacking on how long 1,600 Vpk inverter rated motors are expected to last in service.

Solutions to Reflected Wave Problem

(1) Select 240 V System Voltage: A 240 V IGBT drive has a 300 Vdc bus. Reflected wave motor voltages of 2 pu (600 Vpk) with a 100 ns output voltage risetime drive are within Fig. 3 dielectric withstand for standard 1,000 Vpk Inverter Duty motors. Field experience has also shown reflected wave is not an issue on 240 V systems.

(2)Specify NEMA MG1 Part 31 Inverter Duty Motors: 480 V systems have a 2 pu reflected wave voltage of 1,300 Vpk so that NEMA MG 1 Part 31 design of 1,600 Vpk insulation or higher is required. This motor eliminates the need for external motor protection on 480V systems as shown in Fig. 4.

(3) Limit Motor Cable Length: IGBT drives have output risetimes from 50 ns to 400 ns. Maximum cable distances that limit motor terminal voltages to 480 V motor vendor capabilities of NEMA MG1 Part 30 of 1,000 Vpk (1.55 pu) or typical 1,200 Vpk (1.85 pu) can be determined from Fig. 2 depending on drive output risetime. For example, a 400 ns IGBT drive with a 1,200 Vpk motor can have a 150 ft cable length before external protection is required. The intersection of the motor capability line and the drive pu overvoltage vs cable length curve in Fig. 4 gives a maximum allowable cable distance. Fig. 4 shows a typical 480 V drive output voltage vs. cable length intersecting a 1,000 Vpk and 1,200 Vpk motor

capability line. Some drive manufacturers have given maximum cable distances for each drive hp using 1,000 or 1,200 Vpk motors, since output risetimes and cable / motor surge impedance mismatch changes at each drive hp size.

(4) Pre and Post Installation Solutions: If the maximum allowable motor cable distance is exceeded for existing 1,000 and 1,200 Vpk motors or 1,600 Vpk motors are not obtainable, then external motor protection may be required. Solutions such as a line reactor or R-L-C filters mounted at the inverter output or a line termination network mounted near the motor are possible.

(a) Line Reactor at Drive Output: The fast inverter output risetime interacts with the inductance of the reactor and cable/motor capacitance, so that motor terminal voltage is sloped off to a slower risetime and voltage magnitude is also reduced. Fig. 5 shows motor voltage risetime is ~10 μs with a 1,000 Vpk magnitude on the PWM pulse edge vs. the 1,264 Vpk at 100 ns unterminated drive pulse with no external protection. The 1,000 Vpk at 10 μs risetime pulse should be within the safe dielectric envelope of Fig. 3 for most motors. A typical peak voltage vs. cable length for this solution is shown in Fig. 4. Maximum cable lengths for coordination with 1,000 Vpk motors are extended from 30 ft with no protection to 275 ft with a reactor at the drive. The reactor extends maximum cable length to 600 ft. when used with 1,200 Volt motors as shown in Fig. 4. Reactor designs should be recommended by the drive manufacturer, since low loss reactors may actually resonant the voltage to 2 pu. Commercially available *dv/dt* filters consisting of reactors, capacitors and damping resistors are also a possibility to limit motor magnitude and risetime to < 1,000 Volt peak with a risetime of 2 μs when long cable lengths are required.

(b) Line Termination Network (LTN) near Motor: The LTN is a NEMA 4X device mounted near the motor. The LTN theory of operation is based on transmission line analysis. The LTN passive network elements closely match the cable surge impedance so that voltage reflection is eliminated. A single LTN is possible for the entire hp range from 2 to 500 hp since bundled cable surge impedance only marginally changes from #18 awg to 500 MCM and motor surge impedance is always much greater than cable impedance. Motor terminal voltage is not sloped off but has the same risetime to the Vbus level as the drive output risetime. However, peak motor terminal voltage is usually less than 1.2 pu as shown in Fig. 4. Terminator waveform plots in Fig. 5 and 6 show the reflected wave peak voltage minimized for a single PWM pulse sent from the drive. The LTN will limit peak voltage at 600 ft of cable to 780 Vpk on a 480 V system and 960 Vpk on a 575 V system. Both values are safe values within the motor 1,000 Vpk at 0.1 us capability shown in Fig. 3.

Figure 5
Motor Reflected Wave Pulse Amplitude [5us/div:200v/div]
(A) Unterminated (B) Reactor at Drive (C) Terminator

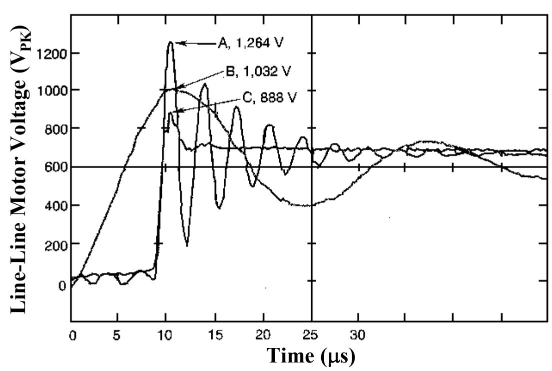
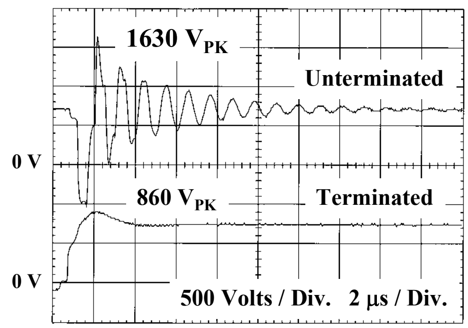


Figure 6
Motor Voltage With and Without Termination Network



Common Mode Noise Phenomenon

There is a possibility for electrical noise from drive operation to cause EMI interference with adjacent sensitive electronic equipment. This condition can be especially true when large quantities of drives are assembled in a concentrated area. This section discusses the basic noise problem common to ***all*** AC drives and what solutions are available to mitigate its effect.

What is Common Mode (CM) Noise?

Electro Magnetic Interference (EMI) noise is defined as an unwanted electrical signal that produces undesirable effects in a control system, such as communication errors, degraded equipment performance and equipment malfunction or non-operation. Common Mode Noise is a type of electrical noise induced on signals with respect to a reference ground. CM Noise problems imply a source of noise, a means of coupling noise by conduction or radiation and circuits/sensitive equipment susceptible to the magnitude, frequency and repetition rate of the noise impressed. Each aspect of the noise problem is covered in detail, starting with effects of CM noise on susceptible circuits.

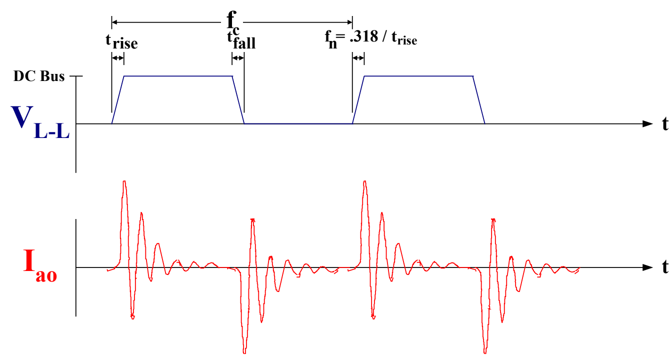
Susceptible Circuits

CM noise can affect an installation in a number of areas. Control interface examples are encoder feedback, 0-10V I/O and 4-20 ma current loop sense. PLC communication links including RS-232, RS 484, Remote I/O, Data Highway Plus, Scanport and Device Net. Susceptible equipment examples are ultrasonic sensors, weighing and temperature sensors, bar code/vision systems, capacitive proximity or photoelectric sensors, and computers.

Noise Source: VFD Common Mode Output Current

All drive manufacturer's have abrupt voltage transitions on the drive output as in Fig. 7 that are an inherent source of radiated and conducted noise. The majority of drive related noise interference with PLC's, controllers and instrumentation is conducted noise currents. The magnitude of these currents is determined by the amount of stray capacitive coupling phase to ground during the fast switching voltage transitions on the drive output. Voltage transition times are essentially controlled by rise and fall times of the semiconductor technology used. IGBT drive output voltage has abrupt .05 to .1 µs transitions to and from the DC bus level, which minimizes power loss, while BJT drives are less efficient having 1 to 2 µs transition times. IGBT's have maximized drive efficiency, reduced motor current harmonics with higher carrier frequencies and reduced drive heatsink size. This is a result of low switching losses associated with fast rise times.

Figure 7
Noise Source: Drive Induced Common Mode Current



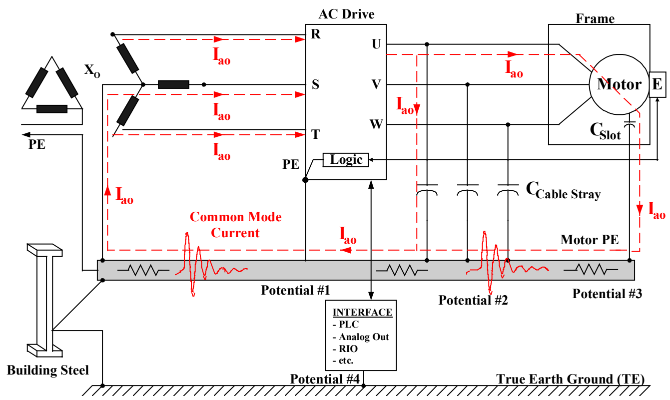
However, IGBT output *dv/dt* (change in voltage/change in time) is now 10 to 40 times greater than with BJTs. Both cable and motor line to ground capacitance interact during this high *dv/dt* transition to generate transient phase to ground currents referred to as common mode (CM), zero sequence or ground currents. These CM currents do not go to the motor and return on another phase. The common mode current may reach 20 Amp peak. Measurements have shown the peak current is similar in magnitude for low hp as well as high hp IGBT drives.

Faster drive risetimes and higher bus voltages cause higher *dv/dt* resulting in larger CM noise current magnitudes that have a greater chance of affecting sensitive equipment. A CM ground current with a 50 ns risetime equates out to approximately a 6 MHz noise spectrum. The higher the equivalent noise coupling frequency, the easier it is to couple into susceptible circuits. Drive carrier frequency in Fig. 7 determines the repetition rate of noise currents coupled to ground. A higher carrier frequency will create more electrical noise. Increasing the number of drives also generates additional CM current in an installation.

Noise Coupling: Conducted CM Current in Ground

An overview of a standard system installation is shown in Fig. 8. This example shows a common system configuration using poor wiring practice, having unshielded phase output wires randomly laid in a cable tray and a ground wire termination connected at the motor. A transient CM current is sourced out of the drive during an output voltage transition. Part of this current flows thru the cable capacitance to the grounded cable tray at *Potential #2* and the rest flows thru the motor stator winding capacitance to ground at *Potential #3* via the grounded wire at the motor. These CM currents flow thru the ground grid, bypassing drive PE, until they find the feeder transformer secondary grounded neutral. It is at this grounded connection where the CM currents find a path back to the drive source via either phase R, S or T. Once inside the drive, the CM current path selects the bridge rectifier diode that is conducting to get back to the + DC bus source.

Figure 8
Poor Wiring Practice: Random Unshielded Cable w/o Ground



The ground grid is high impedance to high frequency ground current so that an instantaneous voltage difference between the PE ground grid and the TE ground grid is created. Noise voltage between the ground grids is referred to as Common Mode (CM) voltage. Common Mode voltage is impressed on the susceptible interface equipment between the drive logic ground *Potential #1* (which is noisy compared to structure steel) and a remote interface ground *Potential # 4* (which is referenced to a low noise zero voltage TE potential). Common Mode voltage is also impressed between the encoder case at *Potential #3* and drive PE logic ground at *Potential #1*. Successful encoder operation depends on how much CM noise voltage is capacitively coupled from the noisy encoder case into encoder circuitry thru stray capacitance. Any additional equipment users referencing the PE ground grid may also experience CM voltage problems. The ability of external interface equipment to properly function in the presence of high frequency noise depends on it's common mode noise rejection ratio threshold tested at the frequency the common mode noise is ringing at.

Poor Wiring practice in Fig. 8 also exemplifies a radiated emissions problem due to a loop antenna formed between drive output wires to return ground and drive input wires to return ground grid. Thus, a better wiring practice is desired prior to drive installation.

Noise Abatement Solutions:

There are three basic steps to drive noise mitigation: grounding, attenuating the noise source and shielding the noise current away from sensitive equipment.

Grounding: The selection of a low impedance single point grounding node, drive/equipment panel grounds and selection of a ground system philosophy are important to CM noise mitigation. Noise mitigation involves a discussion of safety PE equipment ground and signal TE grounds.

TE Ground: Building structure steel is usually the best connection for zero voltage True Earth (TE) potential since girders are connected together in a low impedance grid pattern that have multiple column paths into ground. Ground resistance measurements of 1 to 2 ohms between columns is typical. Ground resistance is affected by soil resistivity which is also a function of moisture content. There have been instances where TE was low impedance until the summer months when the ground water table dries up. Ground rods driven into a plant floor have exhibited 1,000 - 5,000 ohms impedance between them and building structure steel due to stones and dry rocky soil under the concrete floor. However, ground rods in low resistivity soil may be adequate.

PE Ground: A Power Equipment (PE) terminal usually serves as safety equipment ground for AC & DC drives. Ungrounded drive metal accumulates electrical charge thru leakage current resulting in voltages greater than the recognized safe touch potential of 50 V. Thus, all drive metallic parts (internal & chassis) are bonded together and a wire is brought to drive PE terminal. Drive PE is wired to a cabinet PE bus bar that is scraped and bonded to the cabinet metal. The panel mounting the multiple drives and other panel mounted equipment should also be bonded to the PE bus. Insure armor, conduit and cable trays for drive input and output wires are bonded to the drive cabinet and PE bus, since as shown later, the PE ground also conducts drive high frequency noise currents. An appropriate sized single ground conductor leaving the cabinet (based on upstream fuse/breaker rating per NEC code) is then bonded to True Earth (TE) zero voltage ground. This insures safe touch voltage potentials exist under ground fault conditions.

(c) System Grounding Practice: Ungrounded, High Resistance or Solid Ground. The philosophy of the ground system for drive input power is usually specified by the user and based on user concerns other than electrical noise.

A solid grounded wye secondary system is a low impedance to the transient CM noise current and completes the return path back to the drive input leads from the ground grid. Highest CM current magnitude occurs with this system but very little CM noise goes out into the PE grid beyond the transformer neutral connection in Fig. 8, so that CM noise is contained. An advantage of grounded secondary systems is that primary side line to ground high voltage transients are attenuated by typically 20 dB on the secondary side, thus reducing the amount of transient energy the drive's Metal Oxide Varistor(MOV) transient protectors must handle.

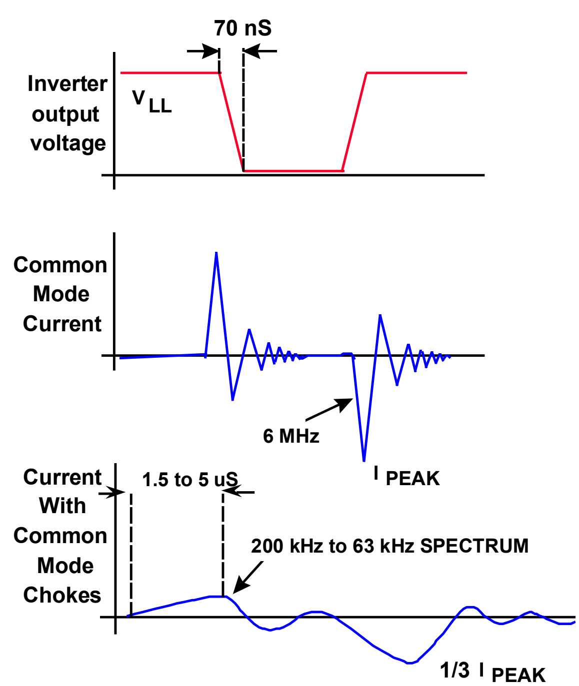
A high resistance ground system would add typically 150-200 Ω's to the Fig. 8 T1 secondary neutral circuit that is grounded. This resistor is in the series path of the CM noise current return and significantly reduces peak CM current magnitude to small levels such that potential differences in the plant ground grid caused by CM noise is minimal. Surge testing has shown acceptable primary to secondary line to ground transient voltage reduction.

An ungrounded secondary system breaks the CM return current path back to the drive input so very little CM current in the ground grid exists. Thus, CM noise is reduced. However, a disadvantage is that surge test results show primary to secondary line to ground high voltage transients are passed directly to the secondary side without attenuation. Also, safety concerns must be addressed with this system.

(2) Attenuate the Noise Source: The best way to eliminate system noise is to attenuate it at the source (the drive) before it gets out into the system grid and takes multiple high frequency sneak paths which are hard to track down in an installation. Past experience has shown Common Mode chokes on the drive output and CM cores on the interface equipment are highly effective in ensuring fully operational tripless systems in medium to high risk installations. A Common Mode Choke (CMC) is an inductor with output Phase A, B and C conductors all wound in the same direction thru a common magnetic core. The CMC provides a high inductance and high impedance to any line to ground based capacitive noise current generated during the drive's fast switching output voltage edges. Thus, the magnitude and rise times of these noise currents are substantially reduced below noise thresholds of affected equipment. The CMC is an optimal noise reduction technique since it does not affect the line to line power circuit while "choking" or high impedance blocking the ground based noise currents. As such, it takes up less physical space than an output line reactor. CMC's should be considered in installations with susceptible electronics. They may be used on retrofit situations, older systems with 3 wires in a conduit or preferably with the recommended shielded wiring practice to obtain maximum noise reduction benefit.

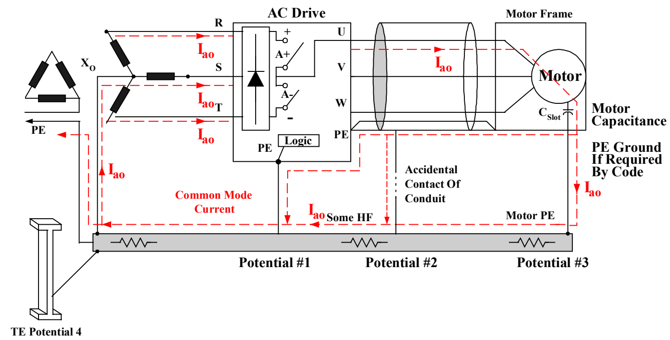
Drive PWM voltage transitions of 50-100 ns do not change when a CMC is added to the output. However, CM high frequency line to ground current magnitude is substantially reduced from 20 Amp peak to less than 5 Amp peak, as well as the rate of rise (*di/dt*) which is limited by the CMC inductance. Peak ground current now occurs at 5 μs instead of 100 ns and at a *di/dt* rate of 1 A/μs versus 200 A/μs without a CMC as in Fig. 9. The reduced ground current magnitude and low *di/dt* rate maintains ground potential difference fluctuations close to zero voltage or true earth ground. As a result, common mode voltages are reduced and error free operation of PLC, interface electronics and sensitive equipment is possible.

Figure 9
Attenuation of Drive Noise with Common Mode Chokes



(3) Shield Noise Away From Equipment: The third step is to predictably control the path of the attenuated high frequency CM noise away from any sensitive equipment referenced to ground by using 4 conductors in a conduit or better yet 4 conductor shielded/armor cable with insulated PVC jacket.

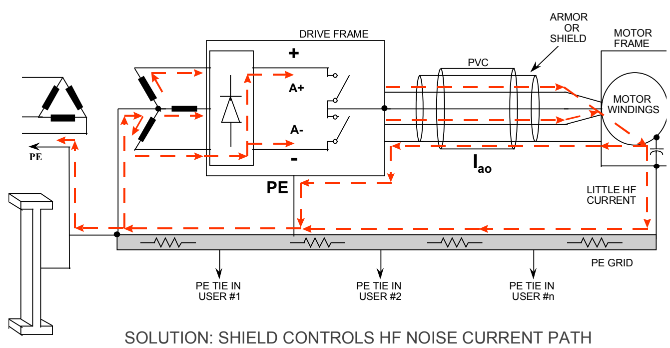
Figure 10
Better Wiring Practice: 3 Conductor & Ground in Conduit



(a) Shielding Noise with 3 wire plus ground Conductor in Conduit: The system CM current path taken with 3 phase output wires plus ground wire enclosed in a conduit is shown in Fig. 10. The conduit is bonded to drive cabinet and motor junction box and the green ground PE wire is connected to ground stud in the motor junction box and drive cabinet PE bus. A transient CM current is sourced from the drive as before. Part of the CM current flows thru cable capacitance to the grounded conduit wall and part thru motor stator winding capacitance to frame ground. Both green wire and conduit absorb most motor capacitive current and return it back to the drive out of the ground grid, thereby reducing "ground noise" for the length of the run as shown. A conduit may have accidental contact with grid ground structure due to straps, support, etc. The AC resistance characteristics of earth are generally variable and unpredictable. Thus, it is difficult to predict how noise current divides between wire, conduit or back to the ground grid inducing CM voltages. Drive PE cabinet wire, if grounded to building structure steel, sends CM currents back into the ground grid, thru the feeder transformer secondary grounded neutral, back to the drive input conductors and returning to the inverter noise source thru a drive input rectifier diode. Radiated electric fields from output wires are greatly attenuated by the conduit wall. However, CM voltage problems may still exist on susceptible interface equipment between the drive logic ground *Potential #1* (which is noisy compared to structure steel) and interface TE zero voltage ground *Potential #4*. Thus, a 4 wire conduit back to the transformer source is recommended with conduit & green wire bonded to the secondary *Xo* neutral terminal and another wire from *Xo* to the ground grid structure. This gives the CM noise a predictable metallic return path out of the ground grid. If possible, it is desirable to bring the drive isolation transformer closer to the drive cabinet to reduce noise current paths into ground. Use of a CM core in high risk applications will eliminate any concern over noise leakage to ground thru accidental conduit contact.

(b) Shielded Power Cable Controls Conducted Noise Current Path: The drive generates perfectly balanced phase voltages so that fundamental frequency phase currents are also a balanced set. During the switching transition of phase voltages, high frequency line to ground capacitive CM noise currents are generated from cable phase conductor to the cable green ground wire, from phase to cable shield and from motor winding to ground. These CM currents sourced from the drive are also called zero sequence currents. These currents have 3 return path options back to the drive; the 60 Hz green Safety wire, the cable shield/armor or the customer ground grid. The predominant return path is the shield/armor since it has the lowest impedance to the high frequency noise. The shield/armor is isolated from accidental contact with grounds by a PVC outer coating so that the majority of noise current flows in the controlled path of the cable and very little high frequency noise goes into the customer PE ground grid. Ground potential differences will be minimized between true building structure earth ground and the customer's grounding at the PE grid.

Figure 11
Shielded Power Cable Controls Conducted Noise Path



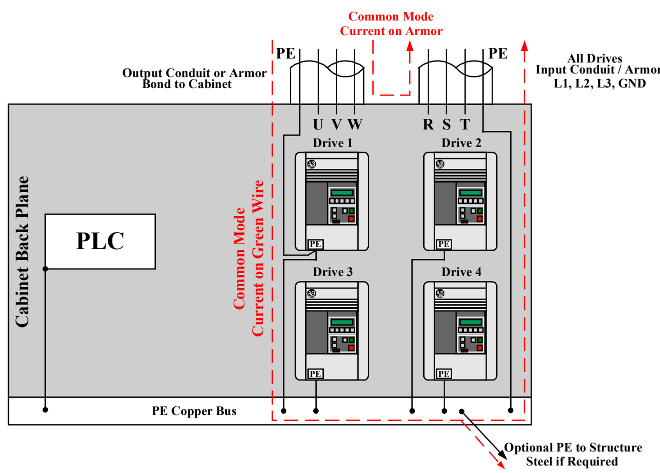
SOLUTION: SHIELD CONTROLS HF NOISE CURRENT PATH

Noise current returning on the shield or safety ground wire is routed to drive PE terminal, down to the cabinet PE ground bus, out the cabinet PE ground wire, to the customer ground grid and then to the grounded neutral of the drive source transformer. The noise completes a return path back to the DC bus source via drive input phase A, B or C depending on which drive input bridge diode is conducting. If the drive input transformer is far away, then the ground grid pollution at *User #1* may exist and the use of drive input shielded power cables back to the main supply may also be desirable.

Radiated emissions in this cable are minimal since the armor completely covers the noisy power wires. Also, the armor prevents EMI coupling to other signal cables that might be routed in the same cable tray. Thus, the use of CMC to attenuate the noise combined with drive input and output shielded/armor cables to control the noise path are effective noise reduction mitigation methods.

(c) Diverting Noise from Susceptible Equipment with Proper Cabinet Layout: Grouping the input and output conduit/armor to one side of the cabinet as shown in Fig. 12 and separating the Programmable Logic Controller (PLC) and susceptible equipment to the opposite side will eliminate many effects of CM noise currents on PLC operation. CM noise current returning on the output conduit or armor will flow into the cabinet bond and most likely exit out the adjacent input conduit/armor bond near the cabinet top, well away from sensitive equipment. CM current on the return ground wire from the motor will flow to the copper PE bus and back up the input PE ground wire, also away from sensitive equipment. If cabinet PE ground wire to the closest building structure steel is deemed necessary, then if this wire is taken from the right side under the conduits and drives, the CM noise is still shunted away from the PLC backplane.

Figure 12
Proper Cabinet Ground - Drives & Susceptible Equipment



Use of EMI/RFI Filters

The use of proper grounding, proper cabinet layout, proper shield termination of control wire, shielded power cables on input and output, and using CM cores on drive power leads and drive interface leads will solve the majority of any EMI noise problem that might arise. However, there are installations where the above solutions may not reduce EMI emissions low enough with respect to surrounding ultra-susceptible equipment requirements.

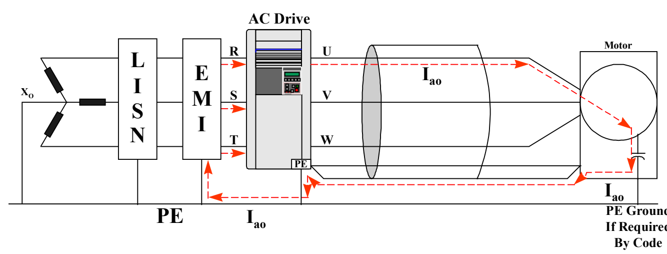
IGBT drive installations in heavily residential areas are examples of where consideration to an EMI filter might be given to solve possible AM radio and TV interference problems. Other examples are hospitals that use CAT scanners or NMR machines off the same power source. Drive based equipment that must meet European CE conformity standards must also use an EMI/RFI filter connected to the drive input.

How Does the EMI Filter Work?

It was previously shown how common mode line to ground noise current is transiently sourced from the drive output during the drive semiconductor risetime. It also was shown that CM current returns via the ground grid to the supply transformer *Xo* connection and back to the drive via the 3 phase input lines. It was also shown that a CM core on the drive output significantly reduced the peak current and slowed the effective risetime to ground. Further, shielded cables on both drive input leads to the transformer supply *Xo* and output power leads to the motor were shown to collect most of CM current and keep it out of the ground grid where CM voltages may be developed.

The EMI filter of Fig. 13, that is used with output shielded cables, works on the same series noise path described. However, instead of placing a high impedance CM core to limit ground current at the drive output leads, the EMI filter on the drive input contains a high impedance CM core inductance, as well as individual phase inductors, to limit the series ground return current to extremely low values.

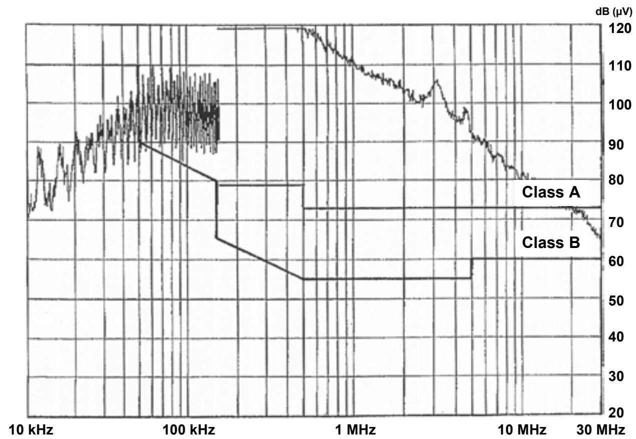
Figure 13
Noise Current Paths Controlled with an Input EMI Filter



In addition, the EMI filter contains high frequency common mode *line to ground* bypass capacitors that short circuit any high frequency ground noise current returning on the output shielded cable, right back to the drive's R,S,& T terminals. In a simplified explanation, the EMI filter low impedance bypass capacitors return most of the noise current to the drive input from the PE ground grid. Also, the EMI filter CM and phase inductors are high impedance blockers to insure that little high frequency noise current is allowed to flow in the plant power lines or ground grid that is ahead of the EMI filter.

The LISN connected to the EMI filter input is the equipment that detects just how much noise voltage is developed in the plant power lines. The LISN measures Common Mode noise voltage on the line. The reason being past EMI experience has shown this type of noise is greater than normal mode noise and appears to be the predominant problem in the field. Fig. 14 shows that a typical PWM drive operating without shielded cables exceeds the conducted emission Class A and B limits regulated by European Norm EN 50008-1 & 2 between 150 kHz and 30 MHz (similar to FCC Class A and B limits). This implies that drive operation will interfere with TV, radio and other communication in this frequency band.

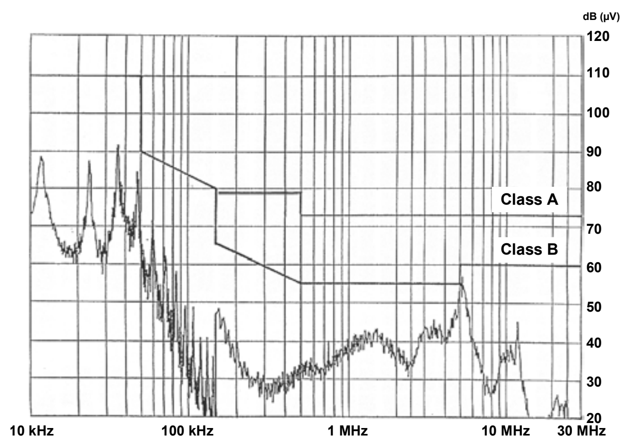
Figure 14
Measurement of Conducted Drive Noise without Filter



EMI Filter and Shielded Cable Solution

Fig. 15 shows that with a specially designed input EMI filter matched to the drive, shielded armor cable on both drive input and output cables and a metal cover on the drive, that class B limits are met.

Figure 15
Class B Conducted Emissions with Filter/Shielded Cables

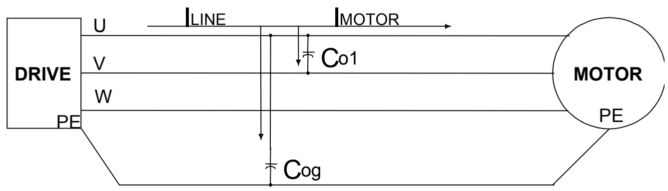


Cable Charging Current Phenomenon

A drive to motor 3 wire plus ground cable consists of C_{o1} line to line stray distributed capacitance and C_{og} distributed line to ground cable capacitance. There also exists a motor line to ground capacitance, defined by the stator winding capacitance to the motor PE frame ground, which may be added to C_{og} . During each *dv/dt* transition on the drive output line to line pulse, a capacitive coupled cable charging current is sourced from the drive, flows through C_{o1} and

returns through another phase. The drive switching transition in a given phase output also sources another cable charging current path from line to ground through C_{og}. Fig. 16 shows the additional drive capacitive coupled current paths taken during a *dv/dt* transition. These additional currents may still exist whether the motor is connected or not. Fig. 17 shows the capacitive coupled current spikes could exceed the normal drive rated current for a given motor load.

Figure 16
Cable Charging Current Paths

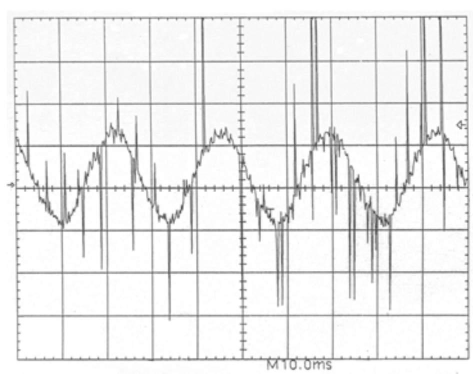


Capacitively coupled currents could exceed the drive rating.

C_{o1} = Line to line capacitance path

C_{og} = Capacitance path line to ground

Figure 17
Cable Charging Current Exceeding Rated Phase Current



This phenomenon exists for all drives. However, drives < 2 hp are more susceptible to overload and overcurrent trips due the additional charging currents. This phenomenon is exhibited to a greater degree on 460 V drives than on 230 V drives due to the higher output transition voltage. This phenomenon is made worse by having long leads on small hp drives or multiple cable loads from a single small drive. The rms current value of this charging current is made higher and may approach the drive rms overload limit by increasing the carrier frequency (the number of device switchings per second). Shielded motor cable has higher capacitance line to line and line to ground than wires in a conduit and may increase the charging current magnitude. Capacitively coupled currents can also exist between the output wires of different drives that are routed in the same conduit. It is recommended that no more than 3 drive output wires be routed in the same conduit to prevent additional drive to drive capacitive currents resulting from tightly bundled output wires in a conduit.

General methods to mitigate this effect are by reducing carrier frequency to 2 kHz, reducing cable lengths to manufacturer recommended values, and using 230 V drives when possible. Over-sizing the drive hp for a smaller motor hp load is also effective to insure cable charging limits are not met. Some drive manufacturers have recommended maximum allowable cable distances for various drive and motor hp combinations in the < 2 hp applications to mitigate the cable charge effect at the installation planning stage. Another mitigation technique is to add a 3 phase inductor on the drive output to reduce the cable charge current magnitude.

Output Power Cables for Motor Load

Commonly Used Cable Types and Insulation

Typical cable constructions used in industrial applications are:

- Tray Cable (TC) or shielded TC laid in a 12" – 24" tray
- PVC, galvanized steel or box type conduit with individual phase and ground conductors
- Metal Clad (MC) armor cables

Common cable insulations used are cross-linked polyethylene (XLPE) and Poly Vinyl Chloride (PVC). Many reasons exist for selecting a specific cable construction and insulation type. Final selection may be based on important non-electrical characteristics such as mechanical rigidity, fire retardency, chemical resistance, moisture resistance, UL and agency approval listing, as well as past historical experience. Users expect PVC and XLPE to have a cable service life of 20 – 50 years under sine wave voltage and inverter operation, so initial capital investment cost is amortized over its life.

Effect of Reflected Wave on Cable Life

Standard insulation voltage ratings are 600 Vrms, 2 kVrms and 5 kVrms. Reflected wave stress of 2 – 2.4 pu on 480v systems is 1300 to 1560 Vpk while 575v systems result in 1620 to 1945 Vpk stress. Although peak reflected wave duration is short, less than a few microseconds, it occurs at the carrier frequency rate, which is 12 khz for small drives and 2 khz for large drives. Thus, a concern is whether a 20 year service life of 600v rated cable is achievable with 2 to 2.4 pu peak reflected wave stress. A final answer is difficult without long term testing. The dielectric failure mechanism most likely to reduce cable life is if the insulation is susceptible to corona at the 2 to 2.4 pu peak transient voltage. Corona Inception Voltage (CIV) is the minimum applied voltage at which partial discharges occur, that is, the lowest applied voltage that caused electrical breakdown of the air around the cable or in air voids.

Corona Testing of XLPE and PVC Cable

CIV testing was done on XLPE and PVC 600v rated insulation under wet and dry conditions. No degradation in sinewave rated cable life is expected if the measured CIV peak voltage is higher than the 2 to 2.4 pu reflected wave peak voltage. A corona tester measured the CIV level bundled wire samples for XLPE and PVC. The results show that both perform within specified dielectric UL levels in a dry environment. The CIV levels ranged from 4,942 – 6,749v for XLPE and

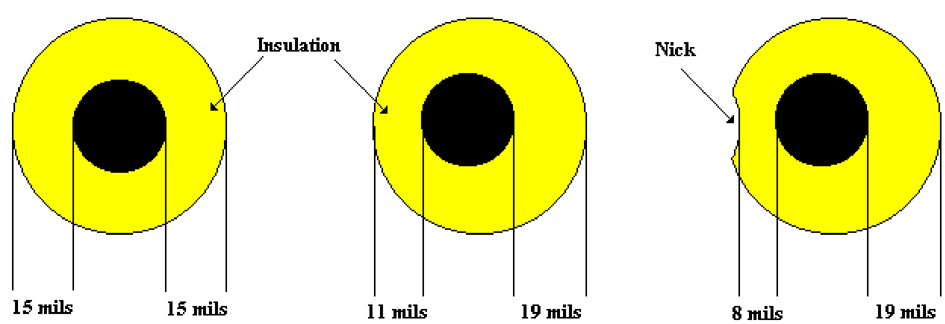
from 2,723 – 4,793v for PVC. The results were somewhat different under wet conditions. The XLPE CIV level decreased only 5% while PVC had a 50% reduction in the CIV. Thus, XLPE will retain higher CIV levels than PVC in the presence of moisture. There is concern for 15 mils thickness PVC wire (2,723v CIV level) used in moisture laden applications and which contain nicks in the insulation by the wire pulling process. This combination may drop this type of wire into the peak reflected wave voltage range. All 600v rated XLPE cables are adequate to handle the 2 pu reflected wave transient per our test results. 600v PVC cables will be suspect based on insulation thickness and environment conditions. Applications where moisture is prevalent in the environment should refrain from using THHN (PVC insulation) wire with IGBT based drives.

Manufacturing Inconsistencies and Their Effect on Cable Life

Due to inconsistencies in manufacturing processes or wire pulling, air voids can occur in THHN wire between the nylon jacket and PVC insulation. Because the dielectric constant of air is much lower than the dielectric of the insulation, the transient reflected wave voltage may appear across the small air void capacitance. The CIV for the air void may be reached, which attacks the PVC insulation and produces carbon tracking, leading to the susceptibility of insulation breakdown as in the above case.

Asymmetrical construction of the insulation has also been observed for some manufacturers of PVC wire. A wire with 15 mil specification was observed to have an insulation thickness of 11 mil at some points. The smaller the insulation thickness, the less voltage the wire can withstand.

Wire Insulation Inconsistencies



Installation Considerations

THHN jacket material has a relatively brittle nylon coating that lends itself to damage (i.e. nicks, cuts) when pulled through conduit on long wire runs. This issue is of even greater concern when the wire is pulled through multiple 90 degree bends in the conduit. Nicks reduce the thickness of the installation. It is these nicks that may be a starting point for corona that leads to insulation degradation.

XLPE & PVC Cable Life with Reflected Wave Solutions

Reactors at the drive, output filters and terminator networks will beneficially reduce the reflected wave amplitude seen on the cable, increase cable life and eliminate wire voltage concerns. Terminators limit peak applied cable voltage to less than the 850 Vpk sinewave rating, insuring cable service life similar to sinewave operation.

Cable Recommendations

Belden YR41709 cable is a PVC jacketed, shielded type TC with XLPE conductor insulation designed to meet NEC code designation XHHW-2 (wet locations). Based on Rockwell Automation research, tests have determined the Belden YR41709 is notably superior to loose wires in dry, damp and wet applications and can significantly reduce capactive coupling and common mode noise.

Conclusion

This paper has showed the significant advantages of going to IGBTs as the preferred semiconductor of choice in new VFD designs. The advantages again are relative to reducing drive size, reducing drive cost and increasing drive performance. The next generation of new IGBT drives have the same old motor heating and derating issues as the BJT predecessor. However, the faster switching IGBT has also introduced additional drive system issues in terms of increased motor dielectric stress and increased EMI system noise.

A review of the reflected wave phenomenon was presented so that system users may understand the limitations of the new technology prior to installation. Knowing motor cable length, drive risetime and motor dielectric capability guarantees a successful installation by co-ordinating applied stress with motor dielectric withstand capability. Some drive manufacturers have performed this coordination by giving maximum safe cable distances before external protection devices must be used and extended safe cable distances with external motor voltage protection added. Various solutions to the voltage stress problem were also given. The motor industry is rapidly improving its dielectric capability with new magnet wire and varnish so that the external solutions may only be temporarily needed over the next few years.

Even though the motors may ultimately be dielectrically compatible with fast switching IGBT drives with no external protection, the system EMI noise may still be an issue. Proper grounding, shielding and panel layout techniques prior to installation are shown to solve most EMI problems encountered. The Common Mode Choke was shown to be an external noise solution that virtually eliminates any concern for system EMI problems.