Eliminating Motor Failures Due to IGBT-Based Drives when Connected with Long Leads

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Abstract

The application of new generation Variable Frequency Drives, (VFD's), utilizing Insulated Gate Bipolar Transistors, (IGBT's), in the inverter section with motors connected by long leads has been a source for concern and expense. Motors controlled by VFD's installed some distance away often fail due to high voltage-induced insulation breakdown. This paper will offer a concise analysis of this phenomenon. It will also recommend some practical solutions for correcting existing problems and for protecting against future failure.

The Problem Described

Drives and motors often need to be separated by distance. Motors in wells must be controlled above ground: the deeper the well, the longer the leads between the drive and the motor. In some plants, motors can withstand the harsh surroundings. However, sensitive VFD electronics cannot tolerate such environments, forcing long distances between the motor control centers that house the drives and the motors that they control. Conveyors and presses often utilize single drives to operate multiple motors that are positioned along the length of the conveyor. The length of the conveyor often dictates the longest distance between a drive and a motor.

Most manufacturers of VFD's publish a maximum recommended distance between their equipment and the motor. The restriction of that maximum distance often makes application difficult, impractical, or unfeasible. Maximum tolerable distances vary by manufacturer, but might be 100 to 250 feet. Many users of VFD's have elected, or have been forced, to disregard the maximum recommended distance. These users are now replacing or rewinding motors after a 2-week, a 6-week, or a 6-month life span. In some cases, motor failure occurs even though the installation is within, but close to, the maximum recommended distance. Both the cost of these repairs and the downtimes that they demand are mounting quickly.

The PWM Voltage

VFD's generate the useful "fundamental" voltage and frequency via a modulation technique known as "Pulse Width Modulation (PWM)". For a 480V system, the typical fundamental voltage ranges from 0 to 460V and the fundamental frequency varies from 0 to 60Hz. The inverter circuit "switches" rapidly, producing a carrier upon which is contained the useful fundamental voltage and frequency. This switching is quite similar to an AM or FM radio where the useful information, music or talk, is transmitted to the radio receiver at some assigned radio frequency. The carrier, or switching frequency used for IGBT-based VFD, generally ranges between 3 to 15 kHz.

Switching time is the time required for the IGBT inverter to transition from the “off” (high impedance) state to the “on” (low impedance) state and visa-versa. For the latest generation of IGBT’s, the switching time varies from 100 to 200 nanoseconds, (ns). Because these devices are used in circuits fed by approximately 650 V DC, for a 480V system, the rate of change of voltage with respect to time, (dV/dT), can exceed 7500 volts per microsecond, (V/μs).

IGBT’s

The relatively recent availability of high voltage, high current IGBT’s has led to the wide use of these devices as the main switching element in the D-C to A-C inverter section of 1-phase and 3-phase AC Pulse Width Modulated VFD’s. Virtually all of the manufacturers of these types of power conversion circuits have developed, or are developing, product lines that utilize these relatively new devices. One of the main reasons for the widespread use of these devices is their extremely fast switching time. This switching time results in very low device transition losses and, therefore, results in highly efficient circuits. In addition, a fast switching time allows drive carrier frequencies to be increased above the audible range. (Slower switching topologies operating at a range of 1 to 2 kHz often induced irritating mechanical noise in a motor.)

The Reflected Wave Phenomenon

Voltage wave reflection is a function of the voltage rise time, (dV/dT), and of the length of the motor cables which behave as a transmission line. Because of the impedance mismatch at both ends of the cable, (cable-to-inverter and cable-to-motor), some portion of the waveform high frequency leading edge is reflected back in the direction from which it arrived. As these reflected leading edges encounter other waveform leading edges, their values add, causing voltage overshoots. As the carrier frequency increases, there are more leading edges present that “collide” into one another simultaneously, causing higher and higher voltage overshoots. If the voltage waveform was perfectly periodic, it might be possible to “tune” the length of the wire. However, since the width of the pulses varies throughout the PWM waveform, it is not possible to find any “null” points along the lead length where the motor may be connected without the fear of damage.

The Resonant Circuit Phenomenon

Another way to analyze the problem is with respect to system resonance. Because multiple conductor wire runs contain both distributed series inductance and distributed parallel capacitance, the conductors can be viewed as a resonant tank circuit. (See figure 1.)

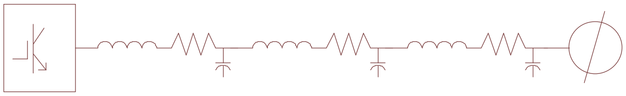

Figure 1

Knowledge of the Inductance, (L), and the Capacitance, (C), values of any circuit allows for the calculation of the circuit’s natural resonant frequency. As wire lengths grow, L and C will both increase, reducing the resonant frequency as described by the equation:

Equation 1

$$Fr = \frac{1}{2 * 3.14159 * \sqrt{L * C}}$$

In those applications where the physical length of conductors connecting the motor to the inverter exceeds 50 ft., L and C values combine to form a typical resonant frequency range between 2 to 5 MHz, depending on wire characteristics. If the length is longer than 250 ft., the resonant frequency will be lowered to the range of 500 kHz to 1.5 MHz. These self-resonant frequency ranges are at, or below, the high frequency components of the voltage waveform produced by the IGBT inverter. (A spectral analysis of the voltage waveform generated by inverters employing IGBT’s would reveal frequency components ranging in excess of 1 to 2 MHz). Furthermore, whenever the self-resonant frequency of the conductors approximates the frequency range of the IGBT voltage waveform, the conductors themselves go into resonance. The conductor resonance then creates a “Gain”, or an amplification of the voltage components at, or near, the conductor’s natural resonant frequency. This results in voltage spikes at the waveform transition points. These voltage spikes can readily reach levels in excess of 2 to 2.5 times the DC voltage feeding the inverter. (See figure 2.)

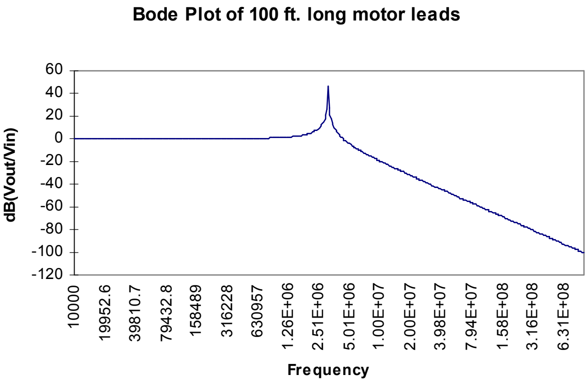

Figure 2

Voltage Overshoot

For a 480 V system, it is common to find voltage spikes at the motor terminals ranging between 1200 to 1550 V. (575/600V systems are even more vulnerable, as peak voltages are further amplified by the higher system voltage.)

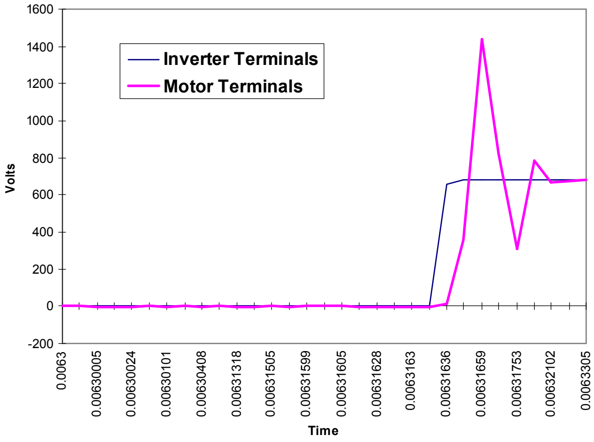

Figure 3

Also, recall that these voltage spikes can have a rise time, dV/dT, in excess of 7500 V/µs. This can have an extremely detrimental effect on the motor windings and on the insulation system, often causing premature motor failure. Most motor manufacturers believe that the life of the motor will be greatly extended by limiting both the magnitude of the voltage spikes to levels below 1000V and the dV/dT at the motor terminals to levels less than 1000 V/µs.

Motor Failures

Compare the Voltage Overshoot to a Mini-Dielectric Test

All manufacturers of motors and of other electromagnetic components, such as inductors, perform one or two dielectric tests on their equipment during the manufacturing stage in an attempt to detect any defects in the insulation system components. For 600V class equipment, these tests consist of applying a relatively high voltage, 2500 to 3000V, for a short period of time. These types of tests stress the insulation system components and, if applied too many times or for too long a period of time, damage the insulation system. When long motor leads create a voltage overshoot, each spike acts like a little dielectric test. If enough of them occur, the insulation system will fail and the motor will need to be repaired or replaced.

Insulation Punch-Through Failures

Seldom, if ever, do large motors fail due to insulation punch-through. This is because they are usually “perfect” wound, which means that the location of each turn of wire in the phase winding is precisely controlled. Therefore, the level of voltage from turn to adjacent turn is controlled. In smaller motors, however, the wire size is quite small and the number of turns is large. Usually, these motors are “random” wound and do not lend themselves to control over the proximity of adjacent turns. Therefore, it is quite possible to have two turns of wire next to each other with a high voltage potential that is close to the maximum allowable limit of the insulation system. Even in the absence of an overshoot voltage, when a high dV/dT is applied, the insulation components may experience punch-through, causing motor failure. Normally, these types of failures occur within hours or weeks of start-up.

Partial Discharge (Corona Inception) Failures

As the voltage associated with the high dV/dT increases, the likelihood of partial discharge, or “corona”, also increases. When corona is present, highly unstable ozone, O_3, is generated. This very reactive by-product then attacks the organic compounds in the insulation system. Corona can easily develop whenever the dV/dT and the resulting voltage overshoot are not controlled. Even the larger motors, whose turn-to-turn voltage can be controlled with “perfect” winding techniques, are vulnerable to corona. Overall, this corona effect will lead to motor failure.

Some Techniques for Correction

The addition of a Line Reactor

Applying a line reactor at the drive terminals has been attempted. Unfortunately, adding inductance merely reduces the resonant frequency of the total circuit. (Refer to Equation 1, page 2, for calculating Fr.) Because there are additional losses associated with the inductor, both in the copper and in the core, overall circuit dampening increases. This dampening may reduce the overshoot slightly, but it will also increase the duration of the overshoot voltage, applying additional stress on the motor windings.

Applying a line reactor at the motor terminals has also been attempted. Since line reactors and motors share common construction materials, line reactors applied in front of motors simply become sacrificial lambs. They will eventually fail due to the same voltage-induced stresses.

Carrier-Stripping Filters

A tuned low-pass filter can be designed to remove all carrier frequency voltages. These application-specific, custom filters were originally designed to strip low frequency carrier energy from Bipolar and Darlington transistor-based drives to limit audible motor noise. While this approach removes all frequencies above the fundamental, and affords the ultimate in motor protection, it comes at a severe price. These filters are large, costly, and consume large amounts of power. In addition, they reduce the fundamental voltage due to high inductor insertion losses and force the motor to draw higher fundamental currents to produce rated horsepower. Finally, the specific tuning frequency of a carrier-stripping filter greatly restricts the ability to alter carrier frequencies after installation. This limits fine-tuning of the drive application.

Voltage Clippers, Snubbers, Etc.

These energy-consuming devices must be applied at the motor terminals, which is difficult in most industrial and commercial applications. They require the addition of extra junction boxes or equipment enclosures as well as alterations and additions to the conduit scheme.

The Dampened Low-Pass KLC Filter (Patent Pending)

A TCI KLC filter combines inductance, capacitance, and resistance, (see schematic—figure 4), to form a dampened low-pass filter with a break frequency in the range of 25 to 55 kHz.

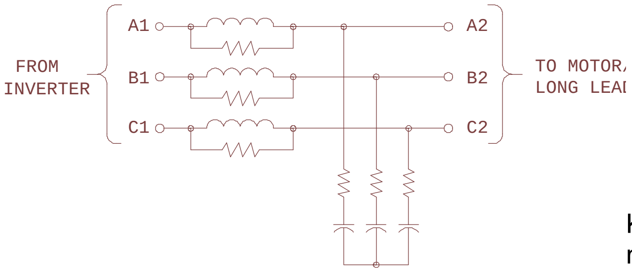

Figure 4

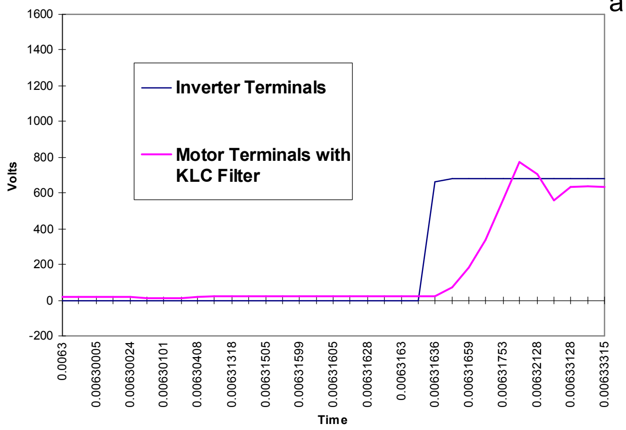

Figure 5

The KLC filter does not attempt to strip the entire carrier frequency. Instead, it is designed to simply slow down the steep edges of the PWM voltage waveform, (see figure 5). It is not the carrier itself that produces motor failures. Rather, it is the high dV/dT (steep edge) of the PWM waveform that induces a damaging voltage overshoot. The KLC filter is specifically designed to reduce voltage waveform dV/dT. By doing so, it will also lower the dV/dT's associated frequency to levels well below the expected natural resonant wire frequency for runs ranging from 50 to 3000 ft. Consequently, the wire will no longer be able to resonate because the higher frequency components are gone, as illustrated in figure 6.

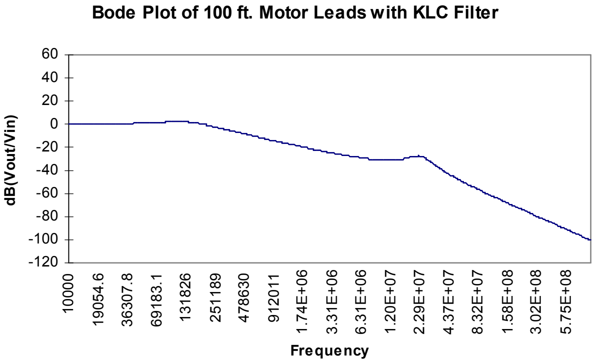

Figure 6

KLC's high coefficient of dampening ensures minimal overshoot on even the longest leads. Figures 7 and 8 offer a full cycle view of the PWM voltage measured before and after the application of KLC.

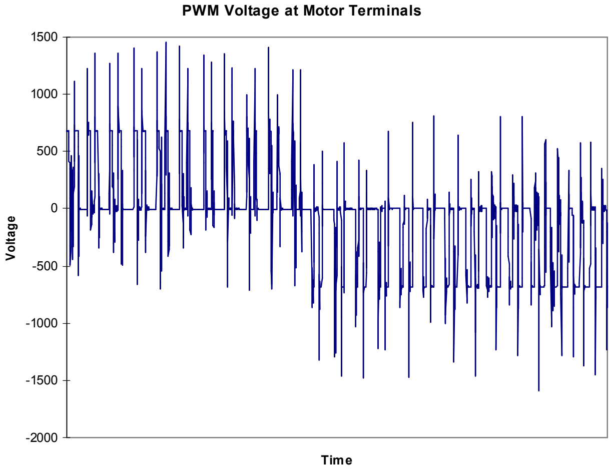

Figure 7

Careful consideration was given to the selection of series inductance to minimize the insertion loss and, therefore, the voltage drop. System losses are held to well below 1% of the drive/motor rating.

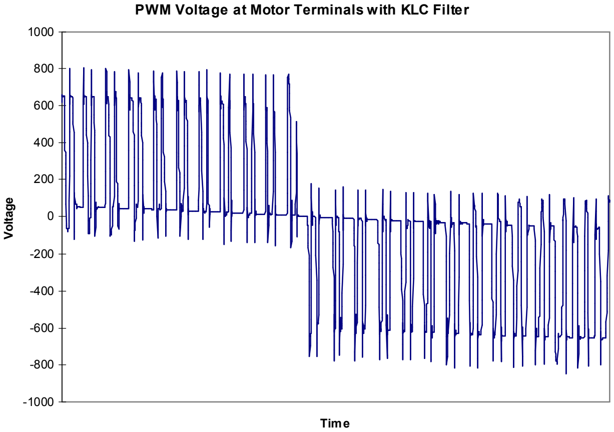

Figure 8

Both the break frequency and the high level of dampening ensure that *KLC can be confidently applied with any drive and motor.*

Summary

TCI recommends that a dampened low-pass filter be applied at the terminals of an inverter any time there is a risk of motor damage due to voltage overshoot. Refer to your drive's manufacturer's operation manual for recommended maximum installation lengths and apply KLC when you either approach or exceed them.

KLC should also be considered as an after-market correction in VFD/motor installations where the motor fails prior to its anticipated life cycle and where long wire lengths exist.

Finally, KLC creates an opportunity to continue to apply cost-saving variable frequency drives in environments and applications that were previously considered inappropriate.

Recommended Reading:

[1] A. von Jouanne, P. Enjeti, W. Gray, The Effect of Long Motor Leads on PWM Inverter Fed AC Motor Drive Systems, IEEE, 1995.

The Authors

John Hibbard was the Vice President of Engineering and Product Development for TCI. He joined TCI in 1989 and brought over 13 years of experience in the solid state adjustable speed motor controls industry. He has worked in sales, marketing, systems engineering, development engineering, and project management. Mr. Hibbard received his BS degree in Electrical Engineering from the Milwaukee School of Engineering in 1976. He also held an AAS from MSOE in digital technology. He was a member of the IEEE Industrial Applications and Power Engineering Societies and has published and lectured on the non-linear characteristics of adjustable speed motor drives.

Nicholas Hayes was the Vice President of Marketing and Sales for TCI. He attended the Universities of Wisconsin-Madison and LaCrosse and has been involved in the electronic, electrical, and magnetic industries since 1983. Before joining TCI in early 1993, he was the National Sales Manager for an industry-leading designer and manufacturer of components for switch-mode power supplies. He is a frequent lecturer on drive application and performance. Mr. Hayes is the author of TCI's popular CAM software.

The Company

TCI (Trans-Coil, Inc.) has conducted and continues to conduct extensive research into the application of VFD's from 208 to 600V and from fractional to 1000's of horsepower. Products from TCI include the industry standard SineGuard™ KLR series three phase input line reactors, HarmonicGuard™ load-applied harmonic trap filters, InverterGuard Air-Core Reactors, and many other protective and performance-enhancing products for variable frequency drives.