Application Report
Long Drive/Motor Leads

The benefits of using Variable Frequency Drives (VFDs) include increased energy savings in HVAC applications, improved motor torque and speed control capability and improved motor protection. VFDs have evolved from output schemes that incorporated Darlington pair transistors to today's industry standard of Insulated Gate Bipolar Transistors (IGBTs). The unique characteristics of IGBTs, including reduced energy loses during switching, have significantly increased VFD drive performance and made possible the smaller packaging designs seen today.

However, the controls industry has seen motors that have operated for years error free, suddenly fail a few weeks after the installation of an VFD. The mode of failure is usually a winding failure caused by voltage overshoot. More specifically, the failure usually occurs in the first turn, as either a phase-to-phase short, or a phase-to-stator short. Research has indicated that the fast switching capability of the IGBT's, along with an excessive lead length between motor and VFD will contribute to reduced motor life.

To understand why an VFD may cause a motor to deteriorate more quickly, two phenomenon need to be understood. The first is the reflected wave or standing wave condition, and second is voltage overshoot, otherwise known as a tank circuit or resonant circuit condition. In theory these two phenomenon may be analyzed differently, but in practice the solutions are the same.

Reflected Wave. By viewing the lead length as a transmission line circuit, the following formulas may be applied to determine the critical length or lead length where a voltage reflection should take place.

Critical length is determined by the formula;

$$V = Co / e$$

$$t = L/v$$

v = velocity of the progressive wave (ms),
Co = 3x10E8 meters/sec (velocity of light)
e = 3.5 (approx. specific inductivity of the cable)
t = rise time of voltage pulse,
L = length of transmission line

The next equation relates the rise time of the IGBT (t) to the critical length (L) of the transmission line.

$$L = t/0.00624(ms)$$

When this length is exceeded, a standing wave may be generated. Since the rise time of the PWM Drive output is generally from .1 to .3 ms, the minimum distance required for a surge voltage to appear is 16.0 to 48.0 m. or 52.0 to 156 ft.

Voltage Overshoot. A more accurate description, of what is happening in the motor is as follows. The overshoot (ringing), is a function of the energy stored in the leads during the rise time of each output voltage pulse. The amount of inductance is a function of the lead length used between the motor and the VFD. Inductance increases the amount of time it takes to charge the capacitance of the motor, which increases the amount of energy in the leads. When the motor charges to the correct voltage potential, the remaining energy in the leads continues to charge the motor voltage, thus causing voltage overshoot.

In fact, if the lead lengths are long enough, the motor terminals may see twice the DC Voltage of the VFD. It can be stated that the greater the distance between motor and VFD, the more voltage overshoot. However, it would be inaccurate to say that the relationship of overshoot is proportional to lead length. Maximum voltage overshoot is calculated as follows:

Input Voltage (rms) x 110% = Maximum Input Voltage Due to High Line Condition

Vmax x 1.414 = Maximum DC Bus Voltage

Max. DC Bus Voltage x 2 = Max. Overshoot Voltage

On a typical 460 volt power system the maximum overshoot voltages measured at the motor terminals could be 1500 Volts peak. Almost 80% of this voltage is distributed across the first winding of the motor.

The inherent rise time of IGBTs used in VFD design do have an affect on voltage overshoot. If the turn on time of the output device is slow, the capacitance of the motor has an opportunity to charge and discharge in line with the IGBT. However, if the output device's turn on time is faster, the voltage applied across the leads increases, therefore more energy is stored, resulting in more overshoot voltage.

Drive Technology	Turn-on Time
3RD Generation IGBT's	0.1 ms
1ST Generation IGBT's	0.25 ms
Bi-polar Transistors	0.5 - 1.0 ms
GTO's	15.0 ms - 20.0 ms
SCR's	40.0 ms - 100.0 ms

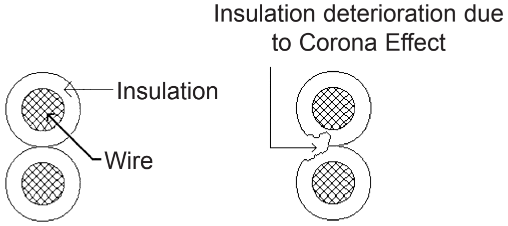


Diagram of "Corona Effect"

This explains why VVI 6-Step Drives using Darlington Pair Transistor technology rarely had this problem at equivalent lead lengths. It's also important to note that 230 volt 3 phase motors are adequately protected from failure due to voltage overshoot by present insulation standards.

Corona Effect

To understand why the motor deteriorates due to voltage overshoot, it is important to understand what corona is. It is generally understood that between current carrying conductors, a relative voltage potential exists; the result is an established electric field. It is possible that the electric field strength around the conductors can be high enough to cause the air to break down. The air breaks down because there is enough energy to ionize oxygen ($O2$) to ozone ($O3$). Ozone is highly reactive and attacks the organic compounds in the insulation system. The additional oxygen in the insulation causes it to deteriorate. The corona will start when the voltage potential in the conductors reaches a certain threshold called the corona inception voltage. Corona inception voltage (CIV) is a function of spacing, type of insulation, temperature, surface features, and humidity.

If the motor does not have the proper insulation system, it may fail prematurely. It is suggested that a motor controlled by an VFD be manufactured with class F insulation or higher, as well as having properly installed phase paper. Properly installed phase paper requires phase sheets and insulation to stay in place, or remain between the coils, during the insertion process. It has been observed that motors with unrefined manufacturing techniques, frequently have engineered the phase sheets into the design only to have the sheets slip out to the side of the stator slot during the insertion process.

Related Issues
Generated EMI/RFI. The amount of electrical noise produced by the output leads of the VFD is also a function of how much lead length is used. The solution is to properly shield cable in a new installation. If this is not an option, than filtering techniques can be used mitigate the effects of the generated EMI.

Protective tripping of the drive. In some situations, it is possible to create a condition where the VFD will protect itself on a "GF" (Ground Fault) or on a "OC" (Over Current) Fault. This occurs in situations where multiple cable runs are in close proximity to one another and are not properly shielded.

Using basic electronic physics, one can show that passing current down one wire lead induces a voltage as well as a current flow in the wire leads in close proximity to that wire. Having multiple leads in relatively close proximity to one another can set up a condition where unequal voltages and currents can be induced in separate phases per drive; the result could be a Ground Fault.

It is also known that the phase to ground and phase to phase capacitance increases with the amount of lead length used. Therefore, it is possible for an Over Current Fault to occur during the time that the inrush current is charging the line-to-line and line-to-ground capacitance.

While these types of trips are rare, they can be prevented by proper installation techniques. If these conditions already exist, it is possible to improve the situation by using the filtering techniques discussed.

Solutions
Minimize Conductor Length. To reduce the likelihood of possible excessive voltage overshoot at the motor terminals, the lead length distance between the motor and VFD should be less than 150 feet. It is also a good idea to lower the carrier frequency of the VFD to what is audibly acceptable. This will reduce the number of output voltage pulses to the motor per second, which translates into lower transition losses in the IGBTs and longer motor life.

Inverter Duty Motor. The simplest and most cost effective solution is to use an Inverter Duty Motor. NEMA Standard MG-1 (section 31.4) indicates that Inverter Duty Motors shall be designed to withstand 1600 volts peak and rise times of greater than or equal to .1 μs. on motors rated less than 600 VRMS. If a motor is properly constructed and meets this standard, the user can expect years of error free operation at any lead length.

Three Phase Output Reactor. A reactor located at the output of the VFD will lower the voltage stress applied to the motor windings. The rise time of the output pulse will be reduced to about 1.1 μs, therefore reducing the dV/dT to about 540 V/μs. This is equivalent to the rise times of the Darlington Pair Transistors used in the past, and is very effective at lengthening motor life. The output reactor solves approximately 75% of all premature motor failure problems associated with long lead lengths. Typically, 3% and 5% impedance reactors are used. At full load, approximately 3 to 5 % of the output voltage will be dropped across the reactor terminals. However, if motor torque is an issue, the application should be examined closely to insure adequate motor torque at full speed.

Method	Recommendations1
Base Line VFD	If possible, keep distance below 150 feet
Inverter Duty Motor	Operate at any distance, if manufacturers recommendations are followed
Reactor at VFD output	Operate motor to 300 feet
Reactor at Motor input	Operate motor to 650 feet
Output dV/dT Filter	Operate motor to approx. 2000 feet

Reactor at Input of Motor. It is possible to place the output reactor at the input terminals of the motor. This allows lead lengths in excess of 650 feet without affecting the application. In this configuration, the reactor may deteriorate, but at a significantly longer time period than that of a motor. However, this may be the most reasonable and economical solution, particularly in applications where the existing motor may not have proper insulation, such as deep well pumps.

Motor Protecting Output Filter. To ensure error free operation at distances up to 2000 feet, a specifically designed output filter should be used if the motor has insufficient motor insulation. These filters are designed to strip the high frequency component from the PWM output, as well as slow down the rise time to approximately 1.2 µs. This ensures that the motor windings will see a clean PWM signal.

Why IGBTs ?

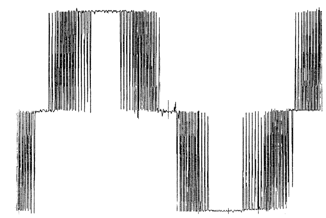
• The extremely fast turn on time correlates to lower energy losses in the device, allowing for smaller packaging, which translates into lower costs to the user.

• IGBTs allow the VFD to utilize a higher carrier frequency to transmit output voltage pulses to the motor. Carrier frequencies greater than 8 kHz significantly reduce audible motor noise and provide the motor with a current wave form with significantly reduced current harmonic, and lower peak currents.

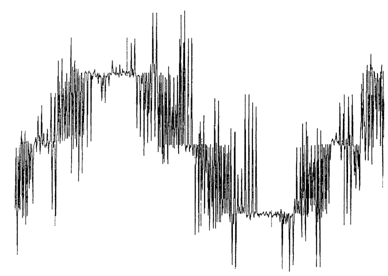
• Minimizing current harmonic, reduces wasteful higher frequency magnetization of stator laminations, which generate audible noise, hysteresis (iron) loss and copper (I2R) loss.

• The lower peak currents of the IGBT design means a cooler running motor, which translates into more torque-producing current throughout the speed range.

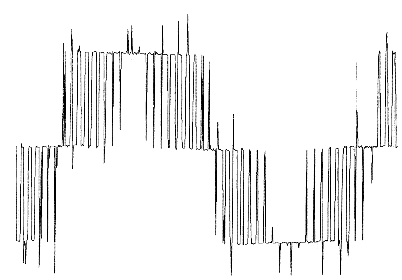
All of these benefits can be routinely realized with proper consideration of the lead lengths to be employed at time of installation.



Output PWM waveform at 30 ft



Output Waveform at 1000 ft



Output Waveform at 1000 ft with dV/dT Filter