Technical Note 176

Motor cable distance from drives

Satisfying the needs of the drive and motor

When designing a facility, what is considered a "long" motor cable distance between the drive and motor? What impacts and design factors need to be considered when a motor is connected to a drive using longer cable lengths? What solutions are available to make both the motor and the drive "happy" in this situation? This technical note is intended to educated on the various motor and drive concerns with long cable distance, including voltage overshoot (reflected wave), insulation ratings, output filtering, carrier/switching frequency, single/multiple motor scenarios, and bearing currents.

Voltage overshoot

A drive controls a motor's speed by supplying a pulse width modulated (PWM) voltage waveform with varying magnitude (voltage) and frequency (hertz). A PWM signal is made up of square voltage pulses created by the drive's output switches or IGBTs (insulated gate bipolar transistors). To create a more uniform sine wave to simulate an AC voltage signal, the IGBTs turn on and off very quickly. When an IGBT turns on the rising edge of the square voltage pulse can overshoot briefly creating a spike in voltage. The voltage spike eventually comes back down to a value equal to the drives DC bus voltage. Typically, the magnitude of the overshoot can equal up to twice the value of the DC bus voltage.

Figures 1 and 2 are oscilloscope images showing the individual rising edge voltage overshoot spikes at the motor. This example is of a 5 HP (4 kW) 460 VAC motor connected to 100 feet (30 meters) of wire from the drive. The peak voltage is approximately 1300 V, the rise time is 0.19 microseconds, and the drive DC bus voltage is approximately 672 V.

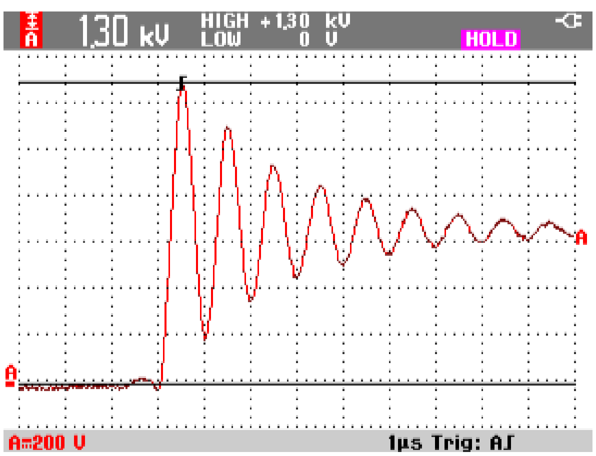

Figure 1: Voltage spike on 100 feet of VFD cable

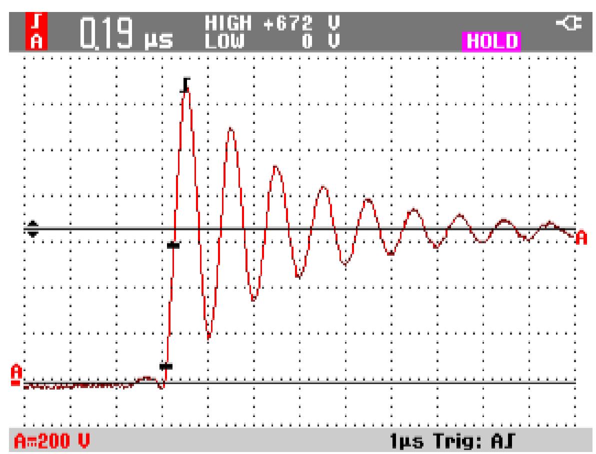

Figure 2: Rise time on 100 feet of VFD cable

What causes voltage overshoot?

There are a variety of variables that cause and impact the magnitude of the overshoot:

- Impedance of the motor
- Length and size of the motor cable
- IGBT rise time from the drive

The motor (stator) windings create the first impedance value of importance. A larger motor has a smaller impedance than a smaller motor. Likewise, smaller motors tend to have higher impedance than larger motors.

The cable length and size impact the cable's impedance and capacitance characteristics, creating a second impedance value of importance. The longer the cable is, the greater the impedance and capacitance the cable has, thus allowing the cable to store more energy.

When there is an impedance mismatch between the motor cable and the motor windings, reflected waves can be created in the motor cable. Essentially PWM voltage pulses can be reflected back from the motor, creating the voltage overshoot at the motor windings. The magnitude of that overshoot is dependent on the above-mentioned motor and cable variables, along with the rise time of the IGBT. A faster rise time on IGBTs will usually create a greater overshoot. A greater impedance mismatch, longer cable wires (more stored energy), and the fastest rise time will typically lead to the highest overshoot levels.

Figures 3 and 4 are oscilloscope images of the peak voltage and rise time for the same motor from Figures 1 and 2, but now wired only 50 feet (15 meters) away from the drive. Peak voltage has decreased from 1300 to 1020 V. Figures 1 and 3 show that cable distance is a key variable in impacting the magnitude of voltage overshoot.

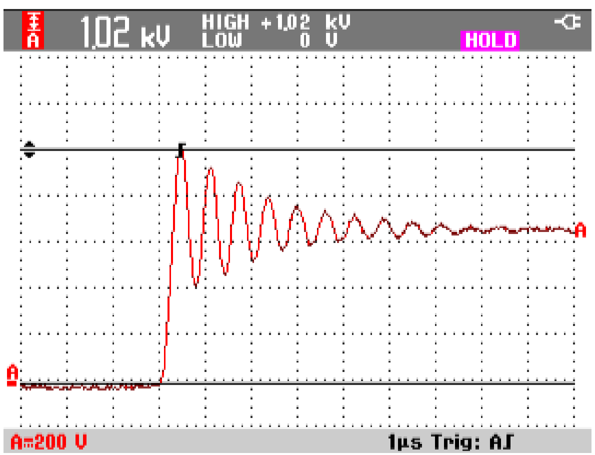

Figure 3: Voltage spike on 50 feet of VFD cable

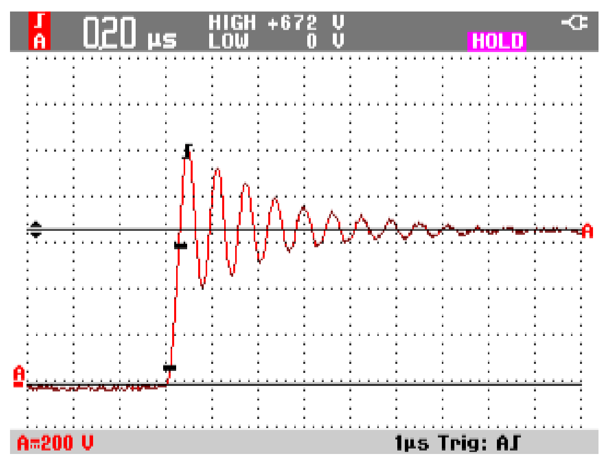

Figure 4: Rise time on 50 feet of VFD cable

Insulation ratings

If the voltage overshoot level is greater than the insulation rating of the motor winding, then the insulation starts to break down. The effects within the motor, corona discharge and partial discharge, will begin to break down the motor insulation. Eventually, a point of the insulation will fail causing a phase-to-phase short, often in the first turn within the stator windings. The drive will detect this short in the motor winding and will fault in an attempt to protect the drive, however the motor is permanently damaged and requires repair or replacement. This damage can be avoided by either reducing the magnitude of the voltage overshoot or by using a motor with insulation rating sufficient to be operated with a drive.

The NEMA MG1 Part 31 is the standard for inverter-fed motors. Section 31.4.4.2 provides guidance on the insulation rating for these types of motors. The standard states the insulation should be rated to handle approximately 3.1 times the rated voltage. This 3.1 value is derived from the below equation made up of a safety factor (1.1), considering the reflected wave (2), and the rectification of AC to the drive's DC bus voltage ($\sqrt{2}$). MG1 Part 31.4.4.2 also states the rise time should be greater than or equal to 0.1 microseconds.

$$V_{Peak} \leq 1.1\ x\ 2\ x\ \sqrt{2}\ x\ V_{rated}$$

Newer motors designed for use with drives are often referred to "inverter duty" or "inverter ready" motors. These motors have an insulation rating capable of withstanding at least 1431 V when operated at 460 V, per the above equation from NEMA MG1 Part 31. Inverter ready motors are designed knowing that this reflective wave phenomena is possible and thus the motor insulation is capable of handling the expected overshoot magnitudes. Note that 1600 V is another value often associated with inverter ready motors, as that was the value used before the 2006 update to NEMA MG 1 Part 31 standard.

Filter types (output reactor, dV/dt, sine filter)

A way to reduce the magnitude of the voltage overshoot is to add an output filtering device after the drive. Load reactors, dV/dt filters, and sine wave filters are (3) types of output filters. AC load reactors are the most basic and lowest cost solution and work by slowing down the PWM rise time, thus reducing overshoot. However, they are best for shorter distances. While not common, there have been instances where the added impedance of the load reactor essentially acts like a section of long motor cable, thus still creating issues. Another filter type, the sine wave filter can be used, but their cost can be prohibitive in many applications so consider their application when needed for greater cable lengths, such as over 1000 feet (300 m) or for specialty applications. The optimal solution, especially in HVACR applications, is typically an output dV/dt filter which is easy to install near a drive or even in the same enclosure.

A dV/dt filter is simply inductors on the three output phases to the motor with an additional resistive or resistive-capacitive network. Figures 5 and 6 show the addition of a dV/dt filter into the same system used in Figure 1 and 2. By adding the filter, the peak voltage was reduced from approximately 1300 down to 920 V. The rise time was increased from 0.19 microsecond to 2.4 microseconds. The ringing is also almost eliminated after the rising edge, allowing the voltage to settle around 656 V.

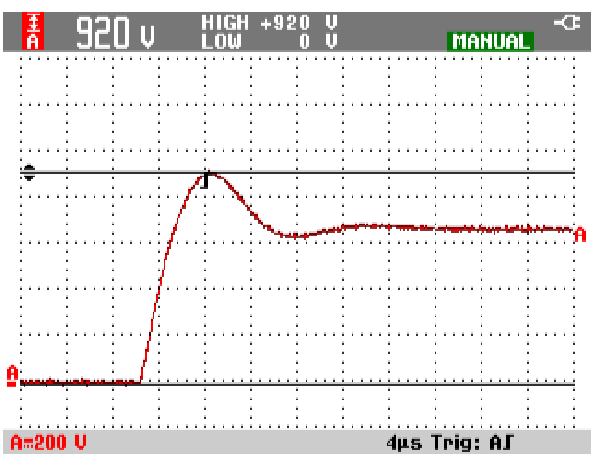

Figure 5: dV/dt filter reducing peak voltage

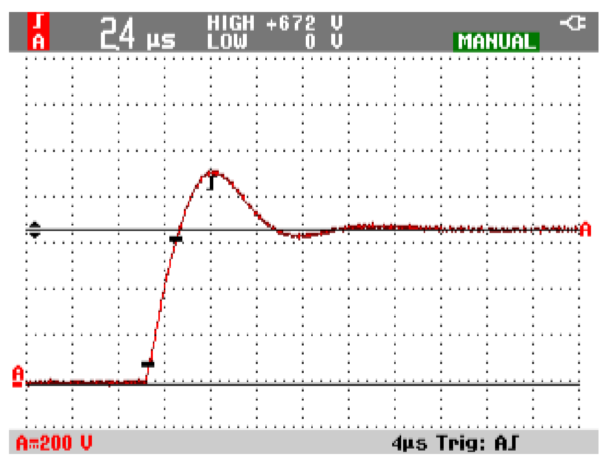

Figure 6: dV/dt filter increasing rise time

Carrier/switching frequency

The switching frequency refers to the number of PWM pulses per second. For example, a 4 kHz switching frequency results in 4000 pulses per second. Increasing the switching frequency is sometimes done to reduce the audible noise from the motor. However, when longer cable distances are involved, the recommendation is to keep the switching frequency lower to reduce the quantity of potential voltage overshoots per second.

If there is an output filtering device (i.e. dV/dt filter), these devices typically require a lower switching frequency. A maximum rating of 4 kHz is typical, although one should refer to the output filter manufacturer's specifications and guidelines for switching frequency limits.

Regarding Bearing currents

While longer motor cable lengths do increase the peak voltage to the motor, thus can increase the likelihood of bearing currents, discharges from the motor rotor shaft known as bearing currents can occur under any cable lengths. There are a variety of approaches used to reduce or prevent the effects of bearing currents.

- Proper cabling and earthing system with motor grounding back to the drive
- Provide a motor shaft grounding ring or brush, to reduce the potential voltage buildup and provide an alternative path for the discharges
- Use of a non-conductive bearing
- Damping the high frequency common mode current with filtering such as the output dv/dt filter

Drive considerations

Up until this point, this technical note has focused on items that impact the motor. Now, let's look at considerations needed to satisfy the drive. Combining long motor cables distances along with a PWM waveform (high frequency components) results in added capacitance of the wire itself plus a capacitive effect between the wires and ground, resulting in coupling of energy to ground. This capacitive effect (charging and discharging the wire) along with coupling of energy, can lead to nuisance faults from the drive, such as an earth fault. Table 1 is an example of the ACH580 series' maximum recommended motor cable lengths. Exceeding these values without the use of an appropriate output filter device, may result in issues like a nuisance earth fault on the drive.

Table 1: ACH580-01 maximum recommended motor cable length, 480 V

Frame size	Max motor cable length, 4 kHz feet	Max motor cable length, 4 kHz meters
R1	330	100
R2	660	200
R3-R9	990	300

For applications, such as fan arrays, with multiple motors being operated from a single drive, it is important to add all the motor cable lengths together to determine the total cable length from the drive's perspective. For example, a 2x2 fan array with approximately 100 ft (30 m) of distance from a single 7.5 HP (R1) drive to each motor, looks like 400 ft (120 m) of total distance. In that example, 400 ft (120 m) would be checked against Table 1. From the motor's perspective, the motor only sees 100 ft (30 m) of distance.

Note that motor cable distance can also impact EMC ratings and electrical noise. These topics are outside the scope of this technical note.

Rules of thumb

Human nature will look for "rules of thumb" or "quick answers" regarding motor cable distance. There is no one single rule of thumb that applies to all motors. However, individual situations can be analyzed to provide recommendations that are based on a combination of physics and field experience. Most situations fall into one of two categories. One category is a new or existing motor with insulation designed to NEMA MG1 Part 31.4.4.2. The other category is an existing motor with an unknown insulation rating, that did not have a drive in the past. In both of these situations, the strategy is to determine the "weakest link" in the drive and motor combination. Are we concerned about the motor or the drive? Note that the following rules of thumb are assuming 400 V or 480 V variable torque pump or fan applications.

The simplest situation is a motor designed with insulation that meets 31.4.4.2. In this case, the motor has been designed to handle the typical level of voltage overshoot. Thus, the drive would be that weakest link. Table 1 (or an equivalent table for the drive being used) is the answer. If the distance meets the Table 1 requirements, then the drive and motor should be compatible together at that cable distance. If the distance exceeds the Table 1 requirements, then an output filtering device, such as a dV/dt filter or sine wave filter, should be used.

The more complicated situation is when a drive is used on a motor with an unknown insulation rating, or it has a known but poor (i.e. 1000 V) insulation rating. As previously discussed, the drive itself (IGBT rise time), the cable distance, cable size, and motor impedance are all variables that impact the magnitude of a voltage overshoot. As a result, there can't be a single rule of thumb distance that guarantees everything will work correctly.

How does the industry typically handle these situations with existing motors that did not have a drive in the past? One answer is to simply replace the motor to one that meets 31.4.4.2. But when trying to re-use the existing motor, for a high degree of confidence solution, add a dV/dt filter after the drive. As seen in Figure 5, a dV/dt filter limits the peak voltage to a level that the motor should be able to tolerate. Upgrading directly to a dV/dt filter, and skipping over a load reactor, is a best practice.

For the cost-conscious situation where the dV/dt filter won't be used, or where they want to "try" using the existing motor before replacing it, then 50 ft (15 m) is a starting point value used by many experienced drive technicians. If the motor is smaller (i.e. 5 HP, 4 kW), then 50 ft (15 m) of cable distance may be a little too long. If the motor is larger (i.e. 100 HP, 75 kW), then going a little past 50 ft (15 m) may be possible.

With any retrofit situation, the entire picture must be evaluated. How old is the motor and how much life expectancy can be practically left in that motor? How efficient is that motor? Older motors are less efficient, thus there can be a return on investment by installing a new motor. When factoring in the efficiency-based payback, upgrading to a new motor can be more economical in the long run than keeping the old motor and purchasing a dV/dt filter. Another consideration is ease of motor replacement. If this motor is difficult to replace, perhaps due to size, weight, and where in the facility the motor is located, then erring on the side of caution and adding a dV/dt filter may be the best approach.

All of the rule of thumb guidance up to this point have been based on 400 V and 480 V networks. In the case of 208-240 V networks and motors, the voltage overshoot is often not an issue. This depends entirely on the motor manufacturer. For example, a motor manufacturer may use the same insulation on a 230 V motor as they do on a 480 V motor. Even if that motor has an insulation rating of only 1000 V, the voltage overshoot will not reach 1000 V on a 240 V network. Another consideration is if the motor is a 230/460 V rated, the 230 V wiring uses the same insulation rating as the 460 V wiring, thus again the insulation will be high enough to protect the motor in the case of a 240 V based reflected wave voltage overshoot.

All rules of thumb information provided is intended as a reference point only. Each application is unique. ABB and our partners have application experts that review each installation on a case-by-case basis and provide guidance.

Summary

Inverter duty/ready motors are designed with wire insulation rated for the peak voltages well above the rated voltage when operated with VFDs. When using long motor cable lengths, output dv/dt filters can reduce the magnitude of these voltage spikes extending the life of a motor. For motors not rated to meet NEMA MG1 part 31, adding a dv/dt filter may be needed on cable lengths approximately 50 feet or greater to limit the voltage spikes the motor was never intended to be exposed to. Understanding the limits of the motor insulation and the potential for high peak voltages can help avoid premature failures or nuisance faults.