Protecting Submersible Motors from Reflected Voltage Waves

It has become a very popular practice to operate submersible motors with variable frequency drives (VFDs) because the drive can substantially improve the system energy efficiency. This type of application has the tendency however, to induce more stress onto the motor windings and insulation system, due especially to the reflected voltage pulses that are impressed on the initial turns of the motor windings. When voltage reflection occurs, due to the mis-matched impedance of the motor cables versus the motor, the peak voltage measured at the motor terminals is equal to the initial pulse plus the reflected pulse. Factors that affect the magnitude of voltage reflection include motor cable length, voltage pulse rise time, pulse velocity, cable characteristic impedance and motor characteristic impedance.

VFD PWM output voltage

When voltage is measured at the VFD output terminals, although the voltage waveform is PWM, not sinusoidal, its peak voltage is equal to the DC bus voltage as shown in Fig. 1.

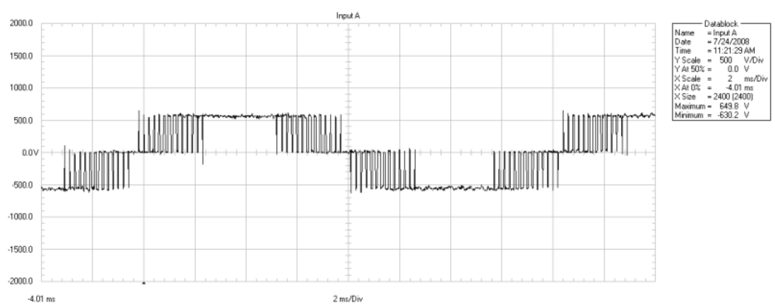


Fig. 1, PWM voltage measured at VFD output terminals

For a 480 volt system, the DC bus voltage would normally about 650-680VDC, which corresponds to the peak voltage associated with 480VAC. Although this magnitude of peak voltage is suitable for standard motors, the PWM voltage waveform can increase motor losses and temperature rise. Motor operation from PWM voltage increases the watts losses of electric motors and results in higher operating temperature. In general, a 10°C increase in temperature rise results in a 50% reduction of motor insulation life.

Reflected Voltage

Depending on the cable length between the VFD and motor, the dielectric medium surrounding the cable, and the relationship between motor and cable surge impedance values, the motor terminal voltage will typically be significantly higher than the VFD terminal voltage. It is important to note that shielded cables, underground cables, and cables submersed in water have significantly higher capacitance than cables in air. Since water has a dielectric constant that is approximately 80 times higher than for air, cables that are submersed in water experience higher capacitance and lower characteristic impedance than for air. Following EQ 1.01, we see that higher capacitance means lower surge impedance for these cables, which will result in higher reflected voltages at shorter cable lengths.

$$Z_c = \sqrt{\frac{L_c}{C_c}} \qquad \text{(EQ. 1.01)}$$

:

Theoretically, the reflected voltage can reach 1.0 p.u. of the incident voltage (originating pulse peak voltage), and in reality, often exceeds this.

How much of the PWM voltage pulse will be reflected?

This depends on the characteristic (surge) impedance of both the cable and motor. The magnitude of reflected voltage can be determined using equation EQ 1.02.

$$\rho = \frac{Z_m - Z_c}{Z_m + Z_c} \qquad \text{(EQ 1.02)}$$

Where *Zm* = motor characteristic impedance and *Zc* = cable characteristic impedance.

For typical motors, the characteristic impedance may range from a few hundred ohms (large power ratings) to several thousand ohms (small power ratings), and for cables it can range from 30ohms (large power ratings) to 100 ohms (small power ratings). It is clear to see there is typically a significant mis-match between these impedances is significant and the reflected voltage will be significant. Based on motor cables of sufficient length and conductors in air, some typical reflection coefficients are as follows:

Motor	*P*	Peak Voltage at motor	Peak Voltage (for 480V VFD)
1HP	1.00	2.00 x Vdc	1300 Vac
25HP	$\geq$ 0.90	1.90 x Vdc	1235 Vac
100HP	$\geq$ 0.75	1.75 x Vdc	1137 Vac
200HP	$\geq$ 0.65	1.65 x Vdc	1072 Vac
400HP	$\geq$ 0.50	1.50 x Vdc	975 Vac

Reflection coefficient for applications involving buried electrical or submersed electrical cable can be higher, due to increased capacitance. Motors conforming to Nema standard MG-1, Part 30 (for non-inverter duty motors) can handle up to 1000 volts peak and voltage rise times of 2micro-seconds or slower. This equates to a dv/dt of 500V/u-sec.

Motor terminal voltage

Depending on the relationship between the characteristic impedance of the motor and cable the pulse rise time and cable length, the motor terminal voltage can be significantly higher than the DC bus voltage. Fig. 2 is an example of a measurement of the motor terminal voltage for a long cable length application. While the RMS voltage is only 466V, and the DC bus voltage is approximately 650 volts the peak–peak voltage reached as high as 2270V volts, and the peak voltage is clearly over 1000 volts.

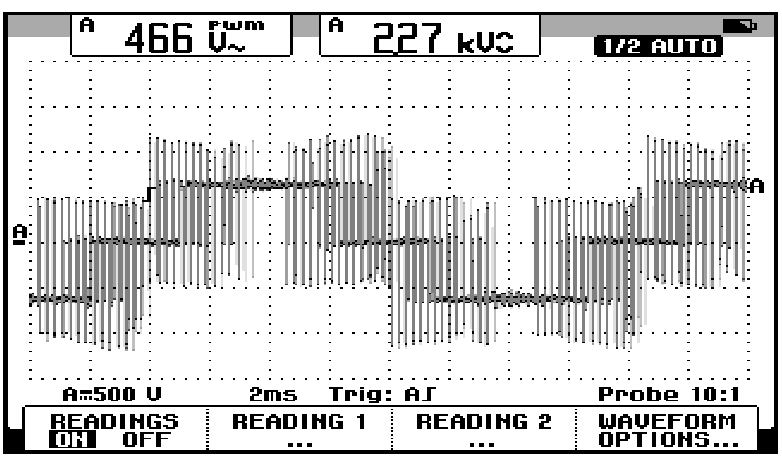


Fig. 2 Motor terminal voltage measurement

What is a safe motor cable length?

Regardless how long or short the cable length, PWM voltage will be reflected if the cable and motor impedances are mismatched. The critical cable length defines the cable length where over-voltage begins to occur and alerts one that exceeding this length could be detrimental to the motor. Critical cable length is a function of the pulse rise time and the velocity at which the pulse travels on the cable. The pulse rise time is primarily influenced by the switching technology (IGBT, BJT, GTO), and the pulse velocity is a function of the cable inductance and capacitance.

$$v = \frac{1}{\sqrt{L \cdot C}} (meters\ per\ second) \qquad \text{(EQ 1.03)}$$

Typical values for the pulse velocity range from about 100 to 150 meters per second. Higher values of cable capacitance (ie: buried or submersed cable) results in slower pulse velocity, which reduces the critical cable length.

$$\text{Critical Cable Length} = \frac{v \cdot t_r}{2} (meters) \qquad \text{(EQ 1.04)}$$

Where: t_r = pulse rise time in micro-seconds

Using an average pulse velocity rate (125m/sec) and some typical pulse rise times, one arrives at the critical cable lengths shown in Table 1.

Pulse Rise Time	Critical Cable Length for cables in air	
0.040 usec	2.5 meters	8 ft
0.050 usec	3.1 meters	10 ft
0.100 usec	6.25 m	20 ft
0.150 usec	9.37 m	30 ft
0.200 usec	12.5 m	41 ft
0.250 usec	15.6 m	51 ft
0.300 usec	18.75 m	61 ft
0.400 usec	25 m	82 ft
0.500 usec	31 m	101 ft
1 usec	62 m	203 ft
2 usec	125 m	410 ft
4 usec	250 m	820 ft
Sine Wave	No Limit	

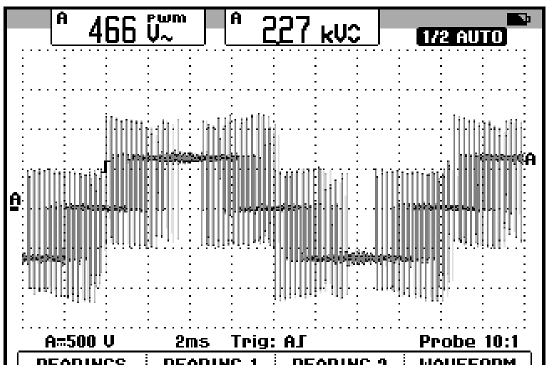
Table 1 – Critical cable Length

Critical cable length will be shorter for cables in water due to higher capacitance, lower characteristic impedance, and higher voltage reflection.

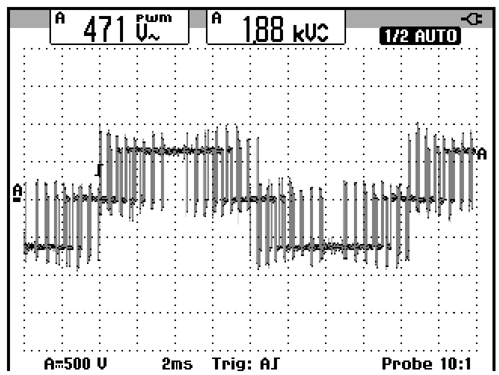
Alternative methods to Protect Submersible motors

dv/dt Filters

The typical dv/dt filter contains a reactor (L) (usually low impedance such as 1.5%), several resistors (R) and a few small capacitors (C). The L-R-C circuit basically forms a voltage snubber or clamp. Usually the dv/dt filter is designed to clamp the voltage at some magnitude below 1000 volts peak for 480 volt systems, but at higher voltage levels for 600 volt systems. One set of resistors (or capacitors) is typically connected in parallel with the reactor coils, creating a lower impedance path for the high frequencies to go around the reactor. The high frequencies therefore bypass the reactor instead of being attenuated by the reactor. Normally a reactor is used to slow down the rate of rise of current through a circuit, however in this case, the fast rising pulses (high frequencies) can actually bypass the reactor. The dv/dt filter typically reduces the peak voltage attained by the pulse and its corresponding reflected pulse but has little effect on the slope of the pulse. dv/dt reduction is primarily obtained through peak voltage reduction, not so much by wave shaping or changing the slope of the leading edge of the pulse.

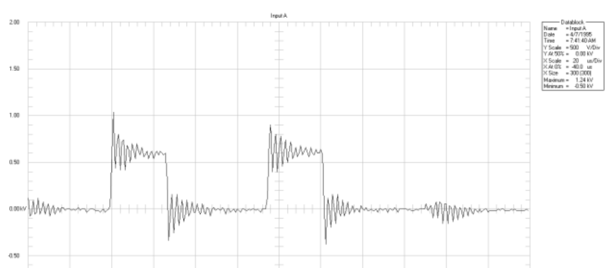


Motor terminal voltage – no filter 2.27kV pk-pk (1135 Vpk)



Motor terminal voltage – dv/dt filter 1.88kV pk-pk (940 Vpk)

Typical specifications for dv/dt filters indicate that (at 1000 feet maximum) the peak voltage will not exceed 1.5 x dc bus voltage. In a 480 volt inverter application, the normal dc bus voltage is about 650 VDC (1.414 x V_{L-L}). Considering a 480 volts system, 650 Vdc x 1.5 = 975 volts, which is very close to the NEMA standard MG-1, part 30 standard (maximum 1000 volts peak) for non-inverter duty motors. If line voltage is 5% high, then the possible peak voltage can be nearly 1024 volts. This does not meet the requirements of NEMA MG-1 for non-inverter duty motors. Of course for 600 volts systems, the problem is worse and peak voltage, even with a dv/dt filter in place, can be well over 1200 volts.

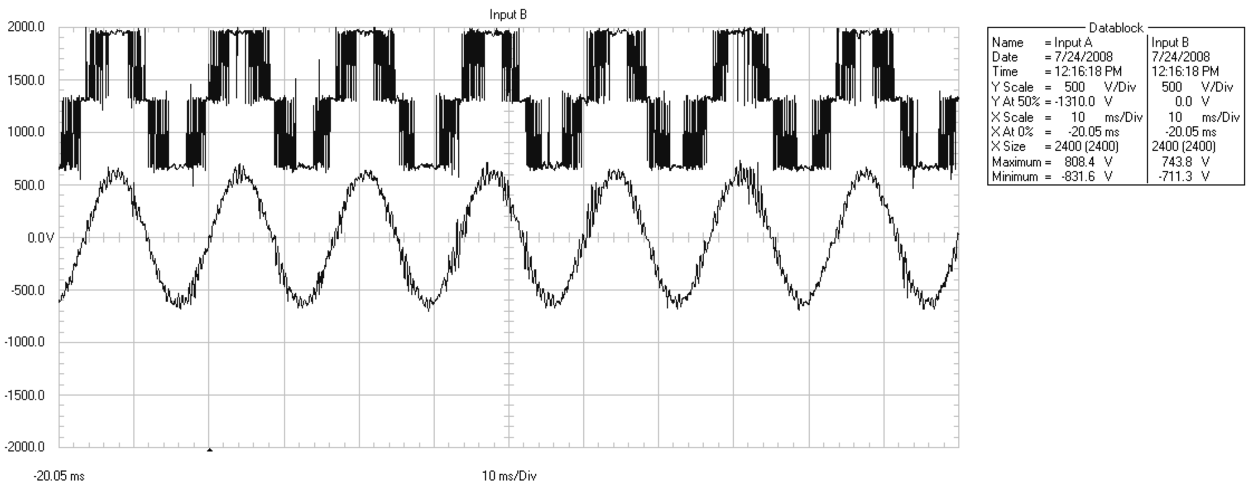


Reflection still occurs with dv/dt filters. Especially in submersible pump applications, the protection offered by this type of filter is considered marginal. dv/dt filters result in motor voltage that is still PWM, not a sine wave. Pulse rise time is considerably faster than for a Sine Wave filter. Voltage distortion is much higher than with a Sine Wave Filter, and motor heating is higher than with a Sine Wave Filter.

SINE WAVE FILTER

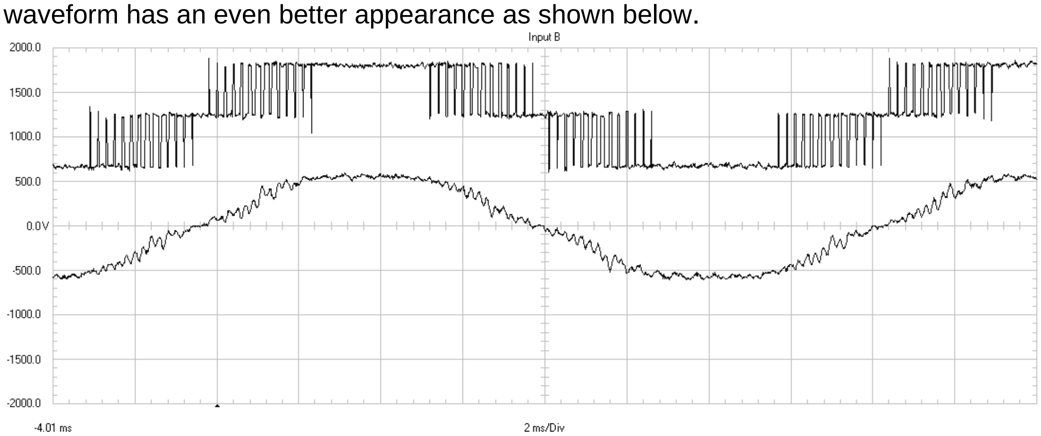
The Sine Wave Filter offered by PQC, Inc. is a low pass filter that actually converts the PWM voltage to a sine wave, with a small amount of ripple voltage at the carrier frequency. A PWM rated reactor is combined with a capacitor to form a filter with a resonant frequency well below the inverter switching frequency. This network removes most of the high frequency content (pulses) from the waveform. The result is nearly a sinewave typically with five percent of distortion or less, and with normal peak voltage (approximately equal to the DC bus voltage). Since the output voltage is practically a sine wave, virtually infinite lead lengths are possible (excepting for voltage drop). The waveform resulting from proper application of our sine wave filter complies with the requirements of NEMA standard MG-1 for non-inverter duty motors. This filter makes it possible to use either a standard non-inverter duty motor or inverter duty motor in a VFD application.

The following waveforms were measured using a Fluke 199C scope meter with VFD carrier frequency set at 5kHZ. When carrier frequency is set higher, then sine wave actually has less ripple voltage, lower peak voltage, and less harmonic distortion.



Voltage; motor at 60hz.   Top = VFD output,   Bottom = Sine wave Filter output.

When the Type PSF sine wave Filter is applied on a VFD/ motor system where the cables are in air, the voltage waveform has an even better appearance as shown below.



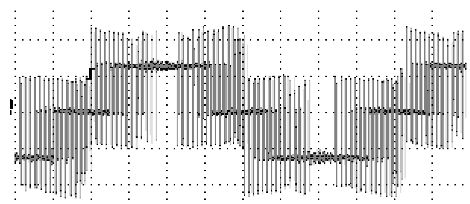
Conclusion

VFD applications involving long motor cable lengths, especially when cables are submersed in water, can increase the voltage stress on motor windings and insulations systems. Voltage stress can significantly reduce motor life, to as little as months or even weeks. Traditional dv/dt filters have proven to be only marginally effective at protecting motors in these environments. There are several cases where motor windings have failed due to peak overvoltage, even though a dv/dt filter had been used. In many of these cases, the motor cables were only 50 ft to 150 ft in length.

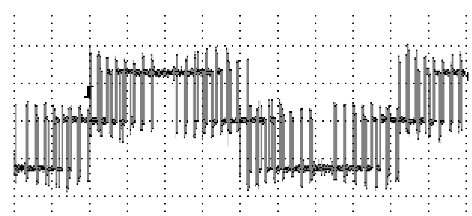
The cost of removing, repairing, and reinstalling a submersible motor can be very high, so this type of application demands the absolute protection, from excessive peak over-voltage caused by reflected voltage, that a sine wave filter can provide. By re-establishing a sine wave voltage for the motor, with a small amount of ripple voltage, the motor windings are protected, and the motor operates with lower temperature rise and with lower power losses.

There are only a few choices: do nothing, add marginal protection, or add complete protection.

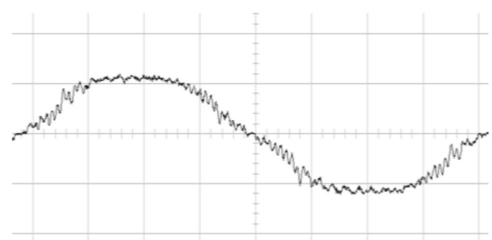
<u>Do nothing:</u>
Take your chances knowing that motor life will be reduced. This method can result in higher warranty costs for manufacturers or high life cycle costs as well as frustration for users and operators.



<u>Use marginal protection (dv/dt) filter:</u>
Often gives a false sense of security, especially in submersible applications where motor repair and replacement have the highest costs.



<u>Use Type PSF Sine Wave Filter:</u>
Have confidence in the installation, experience extended motor life and reduced motor losses. Has a direct impact on reducing motor warranty costs.



PQC Sine Wave Filters are optimized to convert PWM to sine wave voltage to protect motors, reduce motor losses and extend motor life, while keeping filter losses and voltage drop to minimums. Type PSF filters are available for low voltage (690V or less) and medium voltage motors in either standard or custom designs.