Protecting Submersible Motors from the Effects of PWM Voltage

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Abstract—**When induction motors with long cables are controlled by PWM variable frequency drives, they can be subjected to harsh voltage conditions such as fast rising pulses (dv/dt) and excessive peak voltage. Additionally, PWM voltage produced can increase the voltage stress on motor windings causing increased heating and shortened motor life. Submersible motors are a special case where the problems can be more severe and may appear at shorter cable lengths. This paper explains the effects of PWM voltage on motors, addresses the unique characteristics of submersible pumping applications using VFDs, and compares alternative methods for motor protection.**

Index Terms-- dv/dt, filters, IGBT, insulation breakdown, over-voltage, Pulse Width Modulation (PWM), sine wave filter, variable frequency drive (VFD), voltage reflection.

I. INTRODUCTION

It is a popular practice to operate submersible motors with variable frequency drives (VFDs) because the drive can substantially improve the system energy efficiency. Submersible pumping applications however, have the tendency to cause stress of the motor windings and insulation system, at distances much shorter than for applications where the motor leads are in air. The typical effects of PWM voltage include:

- Increased peak voltage,
- High dv/dt rate,
- Increased motor watts loss and temperature rise.

A. *Typical Motor Capabilities*

To explore the effects that PWM voltage can have on motors, it is useful to review some specific characteristics of standard motors. Most commercially available motors have been designed to NEMA standards for operation on sine wave power.[1] A good reference for this is Nema standard MG-1. Nema MG-1, part 30 addresses standard Non-inverter duty motors, while part 31 addresses inverter duty motors. Each part of the standard suggests voltage stress levels that can typically be endured by standard induction motors.

Nema standard MG-1, part 30 states that although “exact quantitative effects of peak voltage and rise time on motor insulations are not fully understood, it can be assumed that when the motor is operated under usual service conditions there will be no significant reduction in service life due to voltage stress, if the following voltage limits at the motor terminals are observed.”[5]

Nema std MG-1, part 30 states the voltage limits to be observed for non-inverter duty motors. The standard covers both low voltage (≤ 600V) and medium voltage (> 600V) motors. Low voltage 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 calculates to a dv/dt of 500V/u-sec. A 230 volt motor has the same voltage limits as a 600 volt motor.

TABLE 1 – NEMA STD MG-1, PART 30 VOLTAGE LIMITS [5]

Motor Parameter	$V_{rated} \leq 600$ volts	$V_{rated} > 600$ volts
Peak voltage	≤ 1000 volts	≤ 2.04 x V_{rated}
Rise time	≥ 2 usec	≥ 1 usec

Nema std MG-1, part 31 states the voltage limits to be observed for inverter duty motors in either the low voltage or medium voltage classes.

TABLE 2 – NEMA STD MG-1, PART 31 VOLTAGE LIMITS [5]

Motor Parameter	$V_{rated} \leq 600$ volts	$V_{rated} > 600$ volts
Peak voltage	≤ 3.10 x V_{rated}	≤ 2.04 x V_{rated}
Rise time	≥ 0.1 usec	≥ 1 usec

B. *VFD PWM Output Voltage*

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

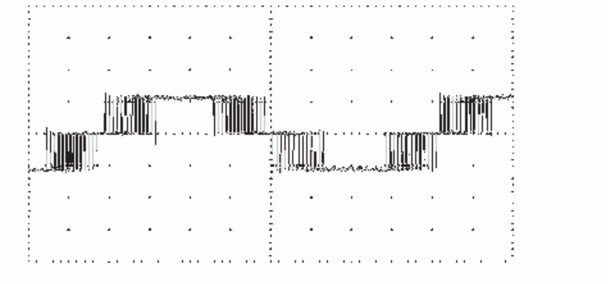


Fig. 1. PWM voltage measured at VFD output terminals [3,4]

For a 480 volt system, the DC bus voltage would normally about 1.35 times the AC line to line input voltage (650VDC). Under normal conditions, the DC bus voltage establishes the peak voltage available for the motor.

Although this magnitude of peak voltage is suitable for standard motors, the PWM voltage waveform can increase motor losses and temperature rise. Most commercially available motors have been designed to NEMA standards for operation on sine-wave power [1]. 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 can result in a 50% reduction of motor insulation life.

TABLE 3 – MOTOR TEMPERATURE RISE COMPARISON [1]

HP	Voltage	Hz	% Speed	% Torque	Amps	Temp Rise
10HP	Sine	60	100	100	12	51
10HP	PWM	60	100	100	12.5	55
10HP	PWM	15	25	87	12	79
10HP	PWM	6	10	89	12.5	109
50HP	Sine	60	100	100	59.1	62
50HP	PWM	60	100	100	61.4	73
50HP	PWM	30	50	82	56.8	72
50HP	PWM	6	10	70	51.3	94

C. *Cable Capacitance*

Shielded 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 much higher capacitance and thus lower characteristic impedance than for cables in air.

TABLE 4 - DIELECTRIC CONSTANTS [2]

Medium	Dielectric Constant
Air	1.0
Methane	1.7
Petroleum	2.1
Water	80

Considering the basic equation (EQ.1.01) for capacitance between two parallel plates (conductors) the impact of the dielectric constant becomes obvious. Capacitance is directly proportional to the dielectric constant (*k*), therefore a higher dielectric constant will result in higher capacitance.

$$C=\left(\frac{k}{4\pi}\right)\frac{A}{l} \qquad (2)$$

where C = Capacitance in Farads, k = dielectric constant, A = area of one plate (cm), and l = the distance between the two plates (cm).

By using EQ 1.02, we see that higher capacitance means lower characteristic (surge) impedance (Z_c) for these cables, which will ultimately result in higher reflected voltages and motor terminal peak voltage at shorter cable lengths.

$$Z_c=\sqrt{\frac{L_c}{C_c}} \qquad (1)$$

D. *PWM Voltage Pulse reflection*

VFD applications with long motor cable lengths can experience a phenomenon called voltage reflection which increases the motor terminal peak voltage and dv/dt. The typical factors that influence the magnitude of reflected voltage and dv/dt include

- Cable length
- IGBT rise time
- PWM pulse velocity on the cable
- Dielectric medium surrounding the cable
- Characteristic impedance of motor and cable

Since the characteristic impedance of motors is typically considerably higher than for cables, the motor terminal peak voltage will typically be higher than the VFD terminal voltage. When voltage reflection occurs, the peak voltage measured at the motor terminals consists of both the peak voltage of the initial PWM pulses, plus the peak voltage of the reflected pulses. The magnitude of reflected voltage (*ρ)* can be determined using equation EQ 1.03.

$$\rho=\frac{Z_m-Z_c}{Z_m+Z_c} \qquad (3)$$

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 30 ohms (large power ratings) to 100 ohms (small power ratings). It is clear to see there is typically a mis-match between these impedances and the reflected voltage can be significant. Based on motor cables of sufficient length and conductors in air, some typical reflection coefficients (*P)* are as follows:

Motor	*P*	Vpk at motor
1HP	1.00	2.00 x Vdc = 1300 Vac
25HP	≥ 0.90	1.90 x Vdc = 1235 Vac
100HP	≥ 0.75	1.75 x Vdc = 1137 Vac
200HP	≥ 0.65	1.65 x Vdc = 1072 Vac
400HP	≥ 0.50	1.50 x Vdc = 975 Vac

The reflection coefficient for applications involving submersed electrical cable can be higher, due to increased capacitance.

Theoretically, the magnitude of the reflected voltage can reach the DC bus voltage and in some cases, actually exceeds this. The motor terminals see the sum of both the initial pulse voltage plus the reflected pulse voltage. Since pulse reflection can be 100% of the initial pulse, it is possible for doubling of the peak voltage to occur. This means that the motor terminals may see voltage as high as two times the DC bus voltage (about 2.7 times rated motor voltage).

TABLE 5 – POTENTIAL MOTOR TERMINAL VOLTAGE

AC Input Voltage	DC Bus Voltage	Motor Terminal Voltage
200	270 – 282	564
240	325 – 340	680
380	513 - 537	1074
415	560 - 587	1174
480	650 - 680	1360
600	810 - 850	1700

E. Motor Terminal Voltage

The sum of the initial pulse and the reflected voltage pulse will determine the peak voltage at the motor terminals. 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. As seen in this one cycle of PWM voltage, the motor is subjected to repetitive over voltage pulses.

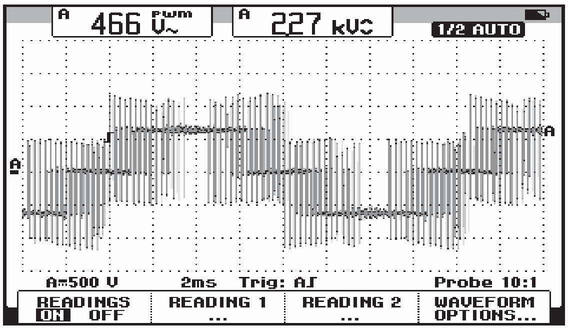


Fig. 2. Motor terminal voltage measurement

F. Safe Motor Cable Length

The critical cable length identifies 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.

$$v = \frac{1}{\sqrt{L \cdot C}} (meters\ per\ second) \quad (4)$$

Typical values for pulse velocity thru air, range from about 100 to 150 meters per second. The higher values of capacitance for submersed cables cause slower pulse velocity, and reduces the critical cable length. Critical cable length is shorter for cables in water due to higher capacitance, lower characteristic impedance and higher voltage reflection.

$$\text{Critical Cable Length} = \frac{v \cdot t_r}{2} (meters) \quad (5)$$

Where: t_r = pulse rise time in micro-seconds

Table 5 shows critical cable length for various pulse rise times using an average pulse velocity rate (125m/sec).

TABLE 6 – CRITICAL CABLE LENGTH

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
Sine Wave	No Limit	

G. Alternative Methods to Protect Submersible Motors

Do nothing (No filter used)

If one chooses to use the motor without any protection, the motor will be best served with a low PWM carrier frequency. In these cases, the PWM carrier frequency of the VFD should be set as low as possible (1.0 – 2.0kHz).

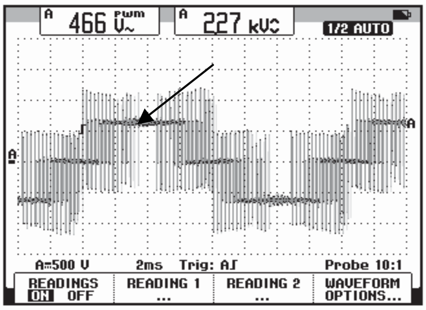


Fig.3. Motor terminal voltage – no filter 2.27kVp-p

From the graph in Fig 3, it is easy to see the DC bus voltage which is represented by the nearly solid horizontal line (and arrow points to it). The voltage pulses above this are the reflected pulses. In this case, the voltage measured at the motor terminals is 2270Vpk-pk, or about about 1135Vpk. This is high enough to damage a non-inverter duty motor.

dv/dt Filters

Traditional dv/dt filters contain a reactor (L) (usually low impedance such as 1.5%), several resistors (R) and several 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. For most manufacturers of dv/dt filters, voltage clamping is specified to be at 150% of DC bus voltage (at 1000 feet).

TABLE 7 – TYPICAL VOLTAGE CLAMPING FOR DV/DT FILTERS

AC Input Voltage	DC Bus Voltage	150% of V_{dc} Bus
200	270 – 282	405-423 Vpk
240	325 – 340	487-510Vpk
380	513 - 537	770-808 Vpk
415	560 - 587	840-880 Vpk
480	650 - 680	**975-1020 Vpk**
600	810 - 850	**1215-1275 Vpk**

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.

Table 6, above, demonstrates that for motors rated 460 volts and higher, traditional dv/dt filters provide marginal motor protection at best. 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 (clamping), not so much by wave shaping or changing the slope of the leading edge of the pulse. As illustrated in Fig 4 below, the appearance of the waveform after the dv/dt filter is still PWM, except that the peaks have been reduced slightly.

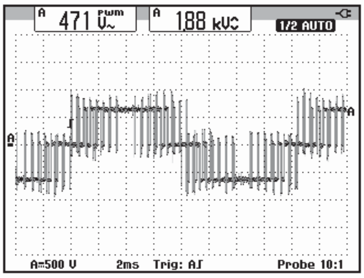


Fig. 4. Motor terminal voltage – with dv/dt filter 1.88kVp-p

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 (1.35 x V_{L-L}). Considering a 480 volts system, 650 Vdc x 1.5 = 975 volts, which is marginally 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.

Voltage reflection still occurs with traditional dv/dt filters as seen in Fig 4. The waveshape is still PWM. 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.

Submersible motor applications are susceptible to higher voltage levels and faster dv/dt rates than typical applications with cable sin air. Traditional dv/dt filters are considered inadequate for protecting motors in these environments. There are a number of 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.

Sine Wave dv/dt Filters

The Sine Wave dv/dt Filter is a low pass filter that actually converts PWM voltage to a sine wave, with only a small amount of ripple voltage at the carrier frequency. The Sine Wave dv/dt Filter virtually eliminates reflected voltage and minimizes the dv/dt of the motor voltage waveform. 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 with relatively low voltage distortion (often about five percent, and with normal peak voltage (approximately 1.00 - 1.10 times the DC bus voltage).

Fig. 5. Sine Wave dv/dt Filter: photo compliments of Arteche.

Since the output voltage is practically a sine wave, virtually infinite motor cable lengths are possible (except for voltage drop). The waveform resulting from proper application of a sine wave dv/dt 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. If using an inverter duty motor, the Sine Wave dv/dt Filter will reduce motor losses and temperature rise while increasing motor life.

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

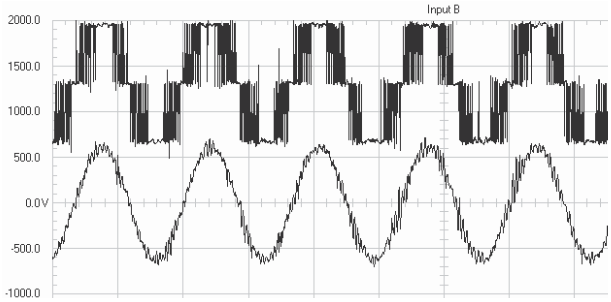


Fig. 6. Voltage; motor at 60hz. [3,4]
Top waveform = VFD output voltage
Bottom waveform = Sine Wave dv/dt Filter output voltage

When the Sine Wave dv/dt Filter is applied on a VFD/ motor system where the cables are in air, the voltage waveform will have an even better appearance as shown below. The waveform can also be further improved by raising the PWM carrier frequency, as illustrated in Fig. 6.

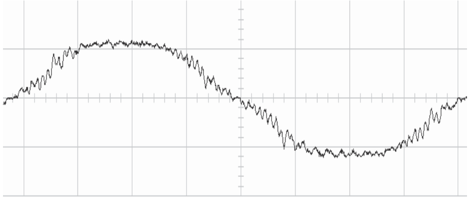


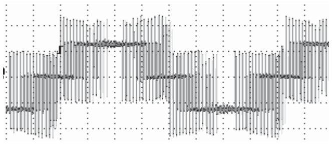
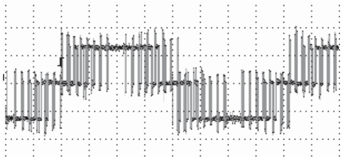
Fig. 7. Sine Wave dv/dt Filter output voltage
Motor cables in air, cable length = 300m/1000ft [3,4]

H. Conclusion

Submersible motor applications increase the voltage stress on motor windings and insulations systems, at shorter distances than normally experienced when motor cables are in air. The cost of removing, repairing and reinstalling a submersible motor can be very high, so this type of application demands absolute protection from dv/dt and excessive peak over-voltage. A Sine Wave dv/dt Filter can provide. This level of protection while increasing system efficiency and extending motor life.

When it comes to protecting submersible motors from the effects of PWM voltage, there are only a few choices. By re-establishing sine wave voltage for the motor, the motor windings are protected, the motor operates with lower temperature rise, motor power losses are reduced and motor lead length restrictions can be removed. Table 7 illustrates the basic choices available for submersible motor protection.

TABLE 8 – COMPARISON OF ALTERNATIVE TECHNIQUES FOR PROTECTING SUBMERSIBLE MOTORS AGAINST THE EFFECTS OF PWM VOLTAGE

Do Nothing Motor subjected to high peak voltage and dv/dt	
Traditional dv/dt Filter Marginal protection	
Sine Wave dv/dt Filter Good and adequate motor protection	

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BIOGRAPHIES:

Mateus Duarte Teixeira is manager of the Power Quality Unit of Arteche EDC. He earned his BSc in electric engineering at the Federal University of São João del Rei and his MSc in the Federal University of Uberlândia, both in Minas Gerais state.

Prior to joining the Arteche team, Mateus worked as researcher of the LACTEC and has published more than thirty papers in international transactions and conferences related to power quality. Currently, Mateus is responsible for application studies of power quality solutions at both industrial and utility facilities.

John Houdek (M'1985) graduated (1981) from the Milwaukee School of Engineering (MSOE), with a Bachelors Degree in Electrical Engineering Technology, and from Keller Graduate of Management (1989) with a Masters Degree in Business Administration (MBA).

His employment experience included the Square D Company, Eaton Cutler Hammer, Trans-Coil, Inc. and MTE Corporation. Houdek presently serves as a power quality consultant for the power quality group of Arteche, a world leader in electrical system power quality. His special field of interest is in power quality related areas including inverter power quality and motor power factor.

Houdek has authored many technical papers on various aspects of electrical power quality and has delivered power quality seminars throughout the world. Houdek is also an assistant professor at MSOE, where he teaches a course in electrical power quality.