LOW COST MOTOR PROTECTION FILTERS FOR PWM DRIVE APPLICATIONS STOPS MOTOR DAMAGE

Karl M. Hink, Executive Vice President

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ABSTRACT

Motor protection filters are proven economical devices to improve inverter-fed motor reliability, increase motor life, and solve long lead over voltage problems. This paper demonstrates the benefits and applications of a number of different types of motor protection filters, including sine wave and single element low-pass filters. Output voltage waveforms are presented along with relative cost data.

1. INTRODUCTION

Contemporary pulse width modulated (PWM) inverters provide motors with a nearly sinusoidal current waveform, but their output voltage waveform can cause over voltage failures and fatigue failures in motor electrical insulation systems.

Figure 1, for example, shows the typical motor voltage waveform for a drive operating from an inverter with a switching frequency of 6 KHz and a fundamental frequency of 60 Hz. The distance between the inverter and the motor is 750 ft. with 480V input voltage. Peak motor terminal voltage is 1460V.

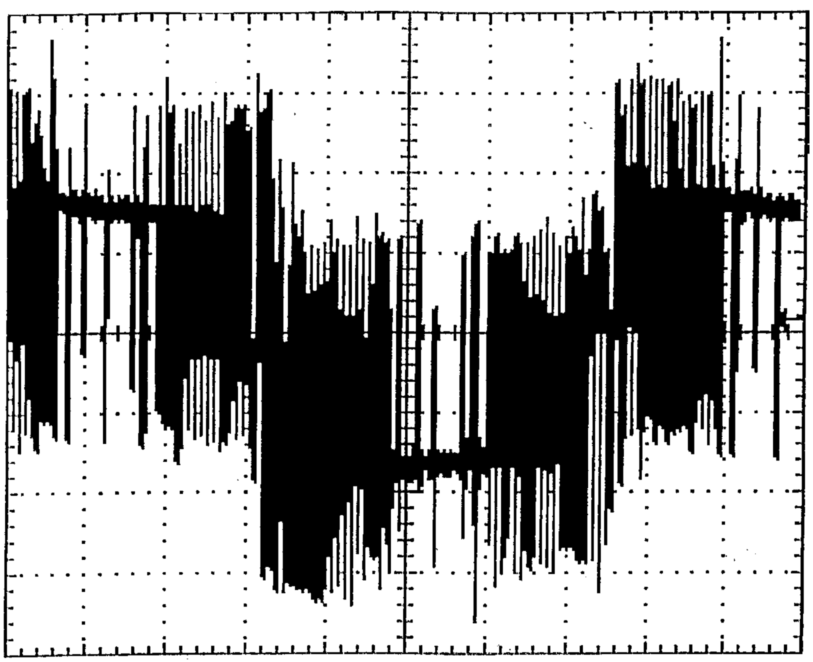


Figure 1. Typical Motor Voltage Waveform

In this example, the conductors connecting the motor to the inverter act as a transmission line, and a voltage doubling is occurring at the motor because of a reflected wave. In addition to over voltage, notice that the motor is being subjected to fast dv/dt pulses. The number of these pulses the motor sees is determined by the switching frequency of the inverter. The faster the switching frequency, the more repetitive pulses the motor will see. It is these pulses which, accumulated over time, can lead to motor insulation system fatigue failures.

2. MOTOR RATINGS

Many inverters are applied to existing 460 volt NEMA Design “B” motors. These motors are specified to operate at a peak voltage of 1000 volts and with wave front rise time not less than 2 microseconds, or a dv/dt less than 500 volts per microsecond. Experience has shown that these installations require the use of a motor protection filter to mitigate the high dv/dt of the inverter and promote long motor life.

NEMA Inverter Duty 460V motors are specified to operate at a peak voltage not exceeding 1600 volts and with a wave front rise time not less than .1 microseconds, or a dv/dt of less than 16,000 volts per microsecond. However, nothing is said about motor life as a function of the applied frequency of the voltage and dv/dt. Certainly an industry-wide testing procedure for inverter duty motor insulation systems would be useful, but what is clear is that motors are failing and there is a demand for motor protection filters that will protect electrical machines from the harsh voltage waveforms produced by PWM inverters.

3. LONG LEADS

When the motor is a long distance from the inverter, the conductors connecting the motor to the inverter act like a transmission line with the equivalent circuit shown in Figure 2. The inductance is the phase inductance per unit length, and the capacitance is the line-to-ground capacitance per unit length.

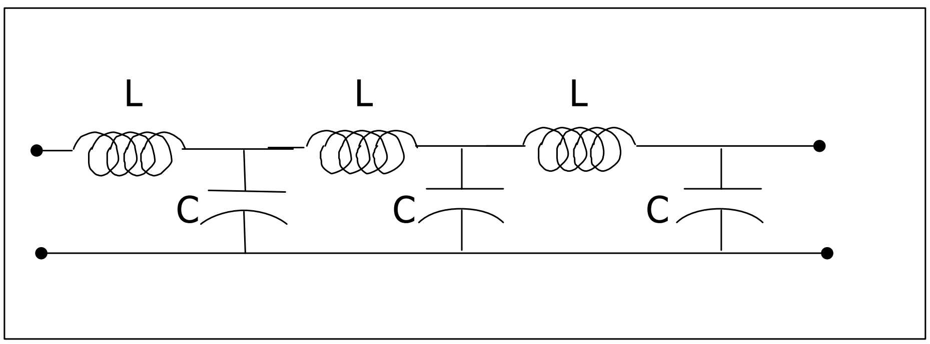


Figure 2. Equivalent Transmission Line Circuit

From transmission line theory, when the line impedance is less than the load impedance, voltage and current waves are reflected, and the voltage is largest at the load. This is the case for drive applications. Although the mismatch between cable and motor impedance is highest for small motors, in all cases, voltage is greatest at the motor.

Table 1 shows typical reflection coefficients for various size motors.

Table 1. Typical Reflection Coefficients

HP	p
25	0.90
50	0.83
100	0.76
200	0.65
400	0.52

The reflection coefficient is

$$p = \frac{Z_m - Z_c}{Z_m + Z_c}$$

Where Z_m is the motor impedance, and
Z_c is the characteristic impedance of the line which is equal to $\sqrt{L/C}$.

The voltage at the motor is the sum of the incident and reflected waves. For motors smaller than about 25 HP, the reflection coefficient is 1.0. For long leads, voltage doubling occurs at the motor terminals.

4. CRITICAL CABLE LENGTH

The critical cable length is the maximum cable length at which voltage amplification does not occur. It is the length at which the sum of the reflected and incident waves are equal to the peak value of the incident wave.

If the propagation speed (the voltage wave) is S and the rise time of the PWM wave front (defined as the time taken for the output to go from 10% to 90% of its peak value) is T, then the distance traveled by the wave front during its rise time is S x T. If the motor is at a position where the incident wave has just reached 50% of its full value and if the reflection coefficient is 1.0, then the sum of the reflected and incident waves will yield 100% of the peak value of the incident wave. Any distance greater than this critical lead length would result in a voltage greater than 1.00 per unit. So the critical lead length is given by:

$$D_{Critical} = \frac{S \times T}{2}$$

The propagation speed over a conductor depends on its inductance and capacitance per unit length and can be expressed as:

$$S = \frac{1}{\sqrt{LC}} \text{ m/sec}$$

Typical values for propagation speed range from 100 to 150 meters per microsecond.

Table 2 lists critical lead lengths with a propagation velocity of 100 meters per microsecond for rise times ranging from 2 microseconds to .05 microseconds. The rise time of the voltage wave is controlled by how quickly the power semiconductors in the inverter are turned on. Typical rise times for power semiconductors used in inverters range from .05 to .50 microseconds.

Table 2. Critical Lead Length for Various Rise Times

Rise Time (microseconds)	Critical Lead Length (meters)	Critical Lead Length (feet)
2.00	100	328
1.0	50	164
0.50	25	82
0.10	5	16
0.05	2.5	8

5. LONG LEAD FILTER OPTIONS

Four options are generally used for protecting inverter feed motors that operate from long leads.

The first is known as a terminator. From transmission line theory, we know that if the load impedance matches the line impedance, then there is no reflected wave. The concept of the terminator is to place an impedance in parallel with the motor where the parallel combination is designed to match the line impedance. The difficulty with this approach is that the terminator must be located at the motor. In many applications, the environment and available space at the motor location make it difficult to accommodate a second piece of equipment at this location. In addition, designers prefer to locate motor protection filters in the same cabinet as the inverter.

Another option is a dual element, low pass sine wave filter consisting of an output reactor and capacitor located at the output of the inverter. The circuit is shown in Figure 3. The inverter's output voltage waveform is then converted to a nearly sinusoidal waveform. Figure 4 shows the output of filter with a 5% load reactor tuned to 2.5 KHz. The minimum switching frequency of the inverter must be set at twice the tuned frequency of the filter. Cable length with this type of filter is unlimited.

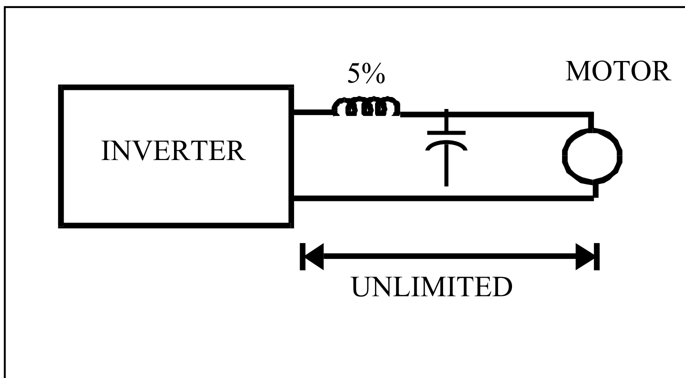


Figure 3. Sine Wave Filter Circuit

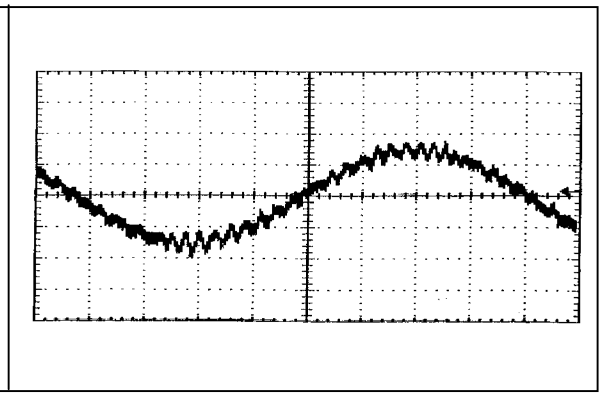
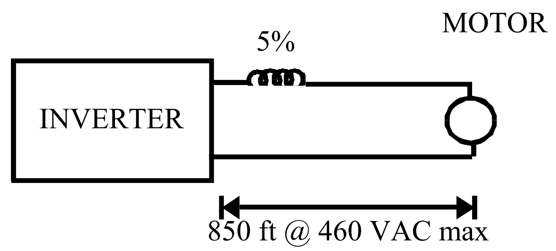


Figure 4. Sine Wave Filter Output Voltage Waveform

A third option is the use of a single element low-pass filter consisting of a 5% load reactor in series with the output of the inverter. The reactor is located at the inverter. Tests on 460 volt applications show that motor peak voltage is under 1000 volts for lead lengths up to 850 feet. The motor voltage waveform appears in Figure 6. Notice that with the addition of the output reactor, the sine wave begins to emerge from the PWM signal. There are no constraints on minimum switching frequency with this approach. Rise times are greater than 4 microseconds.



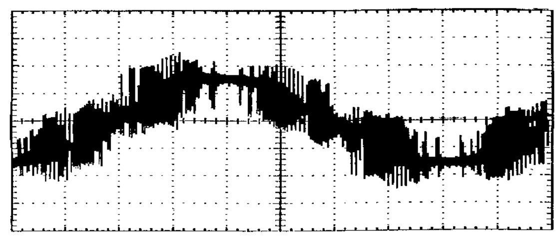
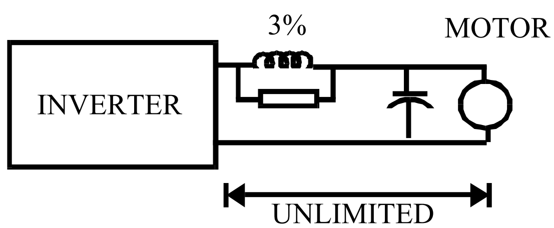


Figure 5. Single Element Low-Pass Filter Circuit

Figure 6. Single Element Low-Pass Filter Output Voltage Waveform

The fourth approach is a high-frequency snubber. The circuit, shown in Figure 7, consists of a parallel combination of a 3% reactor and bypass resistor. The motor voltage waveform appears in Figure 8. Rise times are still fairly steep with this approach but are greater than 2 microseconds. The filter is located at the inverter. Switching frequency is limited to 3.75 KHz; lead lengths are unlimited.



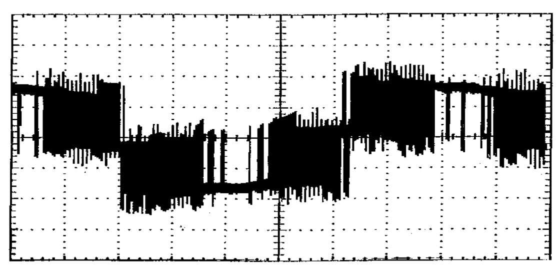
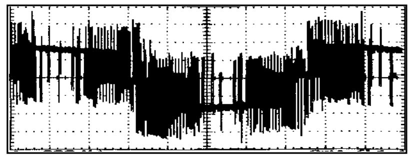
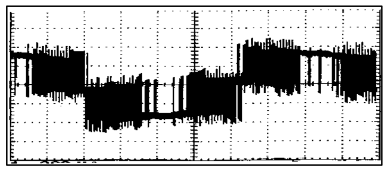
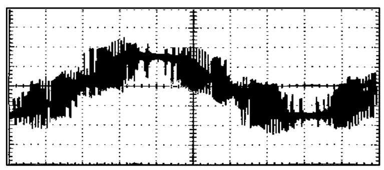
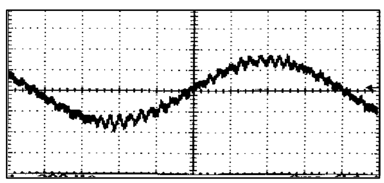


Figure 7. High Frequency Snubber Circuit

Figure 8. High Frequency Snubber Output Voltage Waveform

Table 3 provides a visual comparison of the relative costs and performance of output reactors, snubbers and sine wave filters. Sine wave filters greatly mitigate the output voltage waveform produced by PWM inverters, eliminating over voltage problems caused by long lead lengths and reducing the potential for motor insulation system failures. Output reactors also play an important role in motor protection by increasing voltage rise times to four microseconds or more and reducing peak motor voltage.

Table 3. Long Lead Filters Performance and Cost Comparison

Option	Waveform	Relative Cost (5HP/460V)
Do Nothing		0
Snubber		1.48
5% Reactor		0.65
Sine Wave Filter		1.00