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MTE Corporation P: 262-253-8200  
N83 W13330 Leon Road F: 262-253-8222  
Menomonee Falls WI 53051 E: sales@mtecorp.com

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## Understanding Adjustable Speed Drive Common Mode Problems and Effective Filter Solutions

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Todd Shudarek, Principal Engineer  
MTE Corporation

### Abstract

Pulse width modulation (PWM) AC drives can generate elevated differential mode voltages due to the reflected wave phenomenon, fast rise times and peak voltages. While many users are familiar with differential mode voltages, common mode voltages created by PWM inverters are less familiar. Problems associated with common mode voltages can include erratic behavior of the controller resulting in time out errors, ground faults, and in the most extreme cases, premature failure of the motor bearings, motor windings, and cables.

Many solutions to protect motors are present in the market. This paper presents data showing how three filters: a typical  $dV/dt$  filter, a  $dV/dt$  filter utilizing a triple defense core, and a common mode choke, perform in providing both common mode and differential mode filtering. The data shows that a typical  $dV/dt$  filter does not provide common mode filtering and a common mode choke does not provide differential mode filtering. Only the filter containing the triple defense core provides both common mode and differential mode filtering to protect the motor. This paper will also discuss how the various topologies lend themselves to providing the required protection.

### Introduction

Most users of pulse width modulation (PWM) AC drives are familiar with the elevated differential mode motor voltages due to the reflected wave phenomenon, fast rise times and peak voltages they can produce. However, many users are less familiar with common mode voltages produced by a PWM inverter that can also result in high voltages and peak currents to ground. Many of the problems associated with common mode voltages and currents are by nature not easy to locate. The common mode effects are associated with

difficult to define parasitic parameters of cables and motors. Since these values do not in any way contribute to the normal operation of a drive, they are unpublished. They can cause erratic behavior of a controller board that can give a time-out error. Sometimes a ground fault error will occur and prevent the drive from starting. At the most catastrophic level, ringing of the common mode voltages and currents can cause premature failure of the motor bearings, motor windings, and cables.

Many solutions to these common mode voltages and currents have been proposed.

A properly designed  $dV/dt$  filter or common mode choke can reduce the effects of these currents. Another possible solution is a shaft grounding kit which provides protection for the bearings, but all common mode currents throughout the system are not reduced.

This paper provides the reader with information about how to understand a common mode circuit and the suitability of various inductor topologies for common mode filtering. There is also a discussion of the origin of common mode signals within a PWM AC drive. Experimental data is also presented to demonstrate the effectiveness of various filtering options. Some topologies are very effective at reducing problems associated with elevated differential mode voltages, but completely ineffective at reducing common mode problems at even the most basic theoretical level. A filter that provides both common mode and differential mode filtering is an optimal solution.

### Origin of PWM Drive Common Mode Signals

Common mode voltages and currents that exist on the output of a typical PWM drive are inherent to the switching topology. Figure 1 shows the summation of each of the three phase voltage waveforms on a typical PWM drive. There are three phases and the dc bus voltage can only be switched on or off by the IGBTs. Ideally, all the phases could sum together like three phase sinusoidal waveforms and result in no common mode voltage. This is not the case with three PWM signals. Inherently, they can never sum to zero during operation because the only time an odd number of switched waveforms can sum to zero is if all of them are turned off. This only occurs when the drive is not operating.

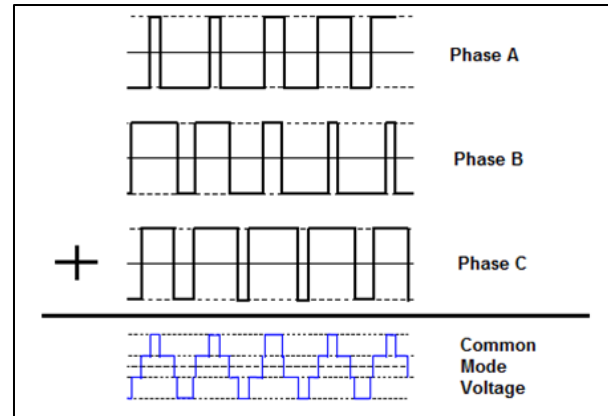


Figure 1 Summed PWM phase voltages

### Common Mode Filter Characteristics

There are many misconceptions about what a filter with common mode characteristics look like. Common mode signals are identical on all three phases. A very effective means to understand the common mode filtering characteristics of a three phase filter topology is to short the three input terminals together and then short the three output terminals together. The circuit and/or equivalent circuit remaining provides an understanding of the common mode filtering characteristics. For example, the common mode filter characteristics for a typical LC filter shown in Figure 2, constructed with three separate inductors and capacitors, can be determined by shorting the input terminals and output terminals. Figure 3 shows the circuit after applying the shorted connections, the capacitors are shorted across and therefore are no longer in the equivalent circuit. The equivalent inductance of three paralleled inductors is  $L$  divided by 3. The final common mode equivalent circuit of Figure 2 is shown in Figure 4, a single inductor with a value of  $L/3$ .

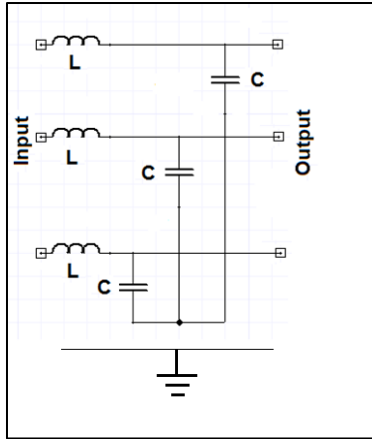


Figure 2 Typical LC filter

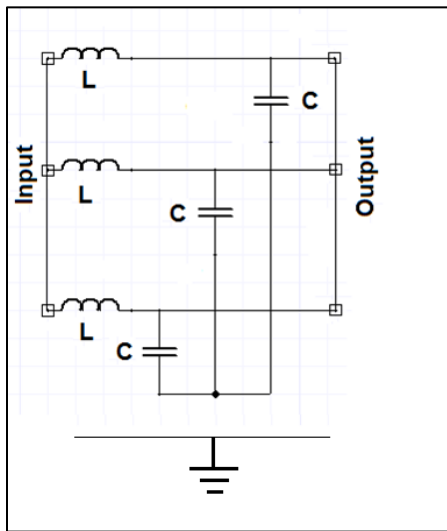


Figure 3 Typical LC filter with inputs and outputs shorted

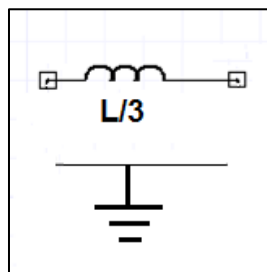


Figure 4 Typical LC filter common mode equivalent circuit

### Common Mode Current Paths

The common mode voltage produced by the typical PWM drive induces common mode currents that travel through parasitic capacitances located in the cable and motor. Figure 5 illustrates the locations of common mode parasitic capacitances in the cable from each line to ground through the shield and ground wire. Figure 5 also illustrates the locations of the common mode parasitic capacitances throughout the motor from the stator to the frame through the motor bearings to ground. The red arrows illustrate just some of the paths of the common mode current. Common mode currents can travel through any of the capacitors shown.

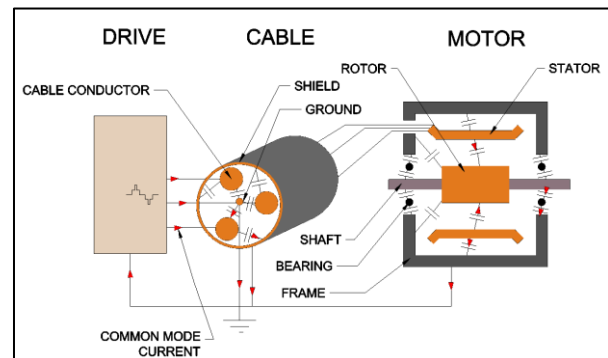


Figure 5 Locations of common mode parasitic capacitances

### Inductor Core Topologies

It is important to understand the coefficient of magnetic coupling and self-inductance when evaluating the effectiveness of a three phase inductor for use in a filter that has common mode characteristics. The self-inductance is the inductance of single coil without the other coils being energized. The coefficient of magnetic coupling is the ratio of the magnetic flux that interacts with another coil to the total magnetic flux generated by a single coil. The self-inductance  $L_s$  and coefficient of magnetic coupling  $k$  in terms of line inductance  $L_L$  and common mode inductance  $L_C$  are defined as follows:

$$L_S = \frac{2}{3}L_L + L_C \quad (1)$$

and

$$k = \frac{3 \times L_C - L_L}{3 \times L_C + 2 \times L_L} \quad (2)$$

where  $k$  = magnetic coupling coefficient

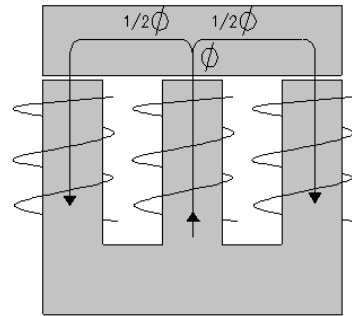
$L_C$  = common mode inductance

$L_L$  = line inductance

*Equations (1) and (2) are valid when the self-inductances are equal and the magnetic coefficients of coupling are equal.*

#### *Typical three phase reactor*

Figure 6 shows a typical negatively coupled three phase reactor construction. The flux generated from each of the coils is defined as traveling upward due to three phase symmetry. The flux generated going upward from each of the coils have a return path going downward through each of the remaining coils. The magnitude of the flux traversing downward through the remaining coils is about half of the flux density magnitude of the coil that generated it since it is shared between two paths, therefore the magnetic coefficients of coupling will be approximately -0.5. The solution to equation (2), with magnetic coefficients of coupling of -0.5, is  $L_C$  equal to zero. A typical three phase reactor provides negligible common mode inductive reactance.



*Figure 6 Typical negatively coupled three phase reactor*

#### *Common Mode Inductor*

Another type of three phase inductor is a common mode inductor. A common mode inductor is a positively coupled three phase reactor construction. Figure 7 shows a three phase common mode inductor implemented on a toroid. The magnetic flux generated from each of the coils is defined as traveling clockwise due to three phase symmetry. When the permeability of the core is high, almost all of the flux generated from one coil interacts with the other two so the coefficient of magnetic coupling is practically unity. Equation (2) has a solution of  $k$  equal to 1 when the line inductance  $L_L$  is equal to zero. This inductor construction typically has all common mode inductive reactance and negligible line inductive reactance.

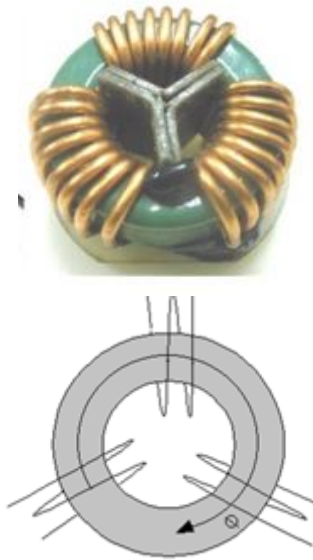


Figure 7 Three phase common mode inductor

#### Triple Defense Core

Figure 8 shows the recently developed triple defense core reactor, a positively coupled three phase reactor construction that has both line inductance and a common mode inductance [1]. The flux generated by a single coil splits between a path that includes the remaining coils and a path that bypasses the other coils. The magnetic coefficient of coupling can be set between zero and one by adjusting the reluctance ratio of the two paths. The reluctances along each path can be changed by use of various core materials, adjusting the core

cross sectional area along the magnetic path or by placing gaps of non-magnetic material along the magnetic paths, or combination of both.

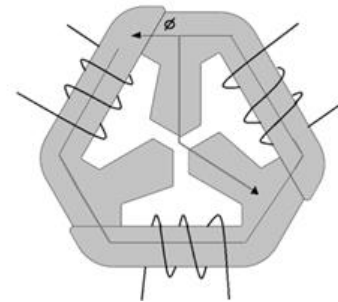


Figure 8 Triple defense core inductor

Table 1 shows a convenient reference to the effect of various  $k$  values to the ratio of the common mode inductance to the line inductance.

Table 1  $k$  values required for various values of  $L_C/L_L$

Three Phase Inductor Construction	$L_C/L_L$	$k$
Common negatively coupled three phase core (Negligible common mode inductance) Figure 6	$\approx 0$	$\approx -0.5$
Three separate inductors, (non-coupled) Figure 2	$\approx 0.33$	$\approx 0$
MTE Triple defense core construction, Figure 8	$> 0.33$	$0 < k < 1$
Common mode inductor (Negligible line inductance) Figure 7	Very High	$\approx 1$

## Shaft Grounding Brush

Although a shaft grounding brush is not a filter, it is a common method of protecting motor bearings. A typical shaft grounding brush is shown in Figure 9. A properly installed shaft grounding brush can protect the motor bearings by providing an alternate current path, bypassing the motor bearing [4].

Figure 10 illustrates how a shaft grounding brush can bypass the motor bearings. This bearing protection, although quite effective at protecting the motor bearing, can exasperate other problems. Since it creates a low impedance path to ground, ground currents can increase thereby making other problems such as the issues of erratic controller board behaviors and ground faults worse. The shaft ground brush solution also does not offer any protection against the elevated differential mode voltages and rise times that even the most typical dv/dt filter provides.



Figure 9 Shaft grounding brush

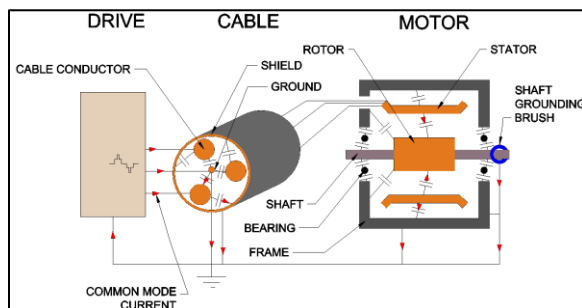


Figure 10 Drive system illustration with shaft grounding brush

## Testing and Data

Three filter topologies were selected to be tested: a typical dv/dt filter, a filter with the triple defense core, and a common mode choke. Each filter was tested using a 480V, 50hp drive system with 1,000 feet of cable, 8kHz switching frequency, and at full load. The line to line peak voltage was measured with an oscilloscope. The common mode currents were measure by placing a Rogowski coil around the three phases of the cable near the drive output as shown in Figure 11. Note that the Rogowski coil must only surround the three phases of the drive and not the ground or shield since the ground and cable shield are return paths for some of the common mode current. To understand the common mode filtering characteristics, the input terminals and output terminals were shorted together and a frequency response was performed with a precision LC meter.

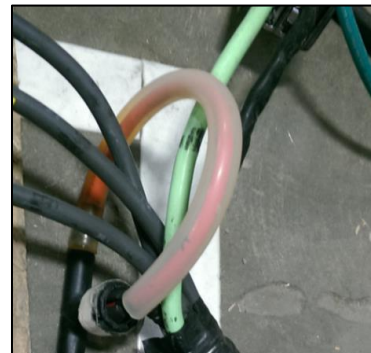


Figure 11 Common mode current measurement with a Rogowski coil

### Typical dv/dt Filter Test Data

Figure 12 shows a typical dv/dt filter that the manufacturer claims to have common mode filtering. The differential mode filtering capability of the filter in Figure 12 kept the voltage under maximum requirement of NEMA MG1-1998 Section 31 standard of  $3.1 \times V_{\text{rated}}$  for inverter duty motors [2]. The peak voltage was 1200V. This level of voltage also did not meet the manufacturer's claim of limiting to 150% of the DC bus voltage.



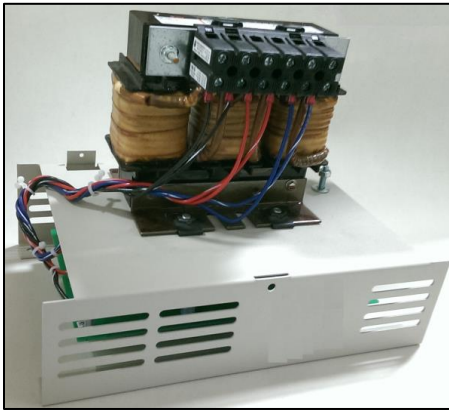
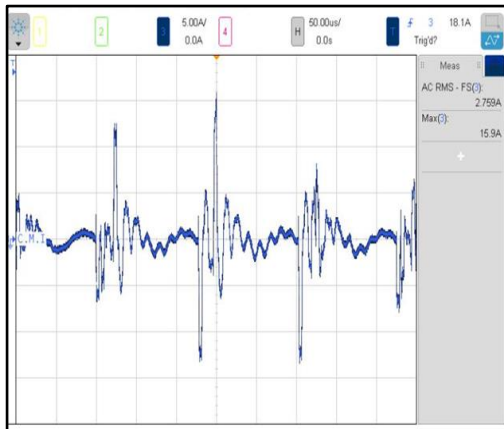


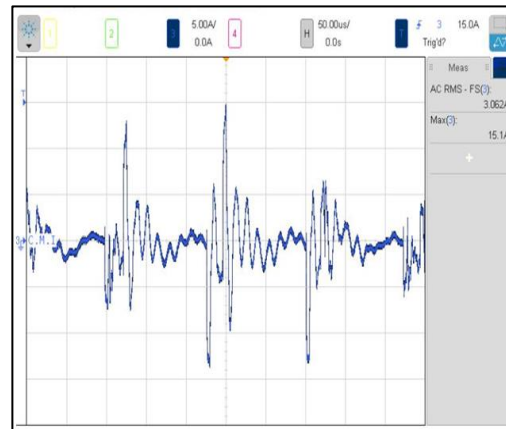
Figure 12 Typical dV/dt filter

Figure 13 shows that the common mode current waveforms were almost identical before and after the use of the filter. The peak to peak common mode current was 15.9A without a filter and 15.1A with this typical dV/dt filter. This is only a 5% reduction.

Figure 14 shows the impedance measured through a frequency range from 400Hz to 400kHz. As seen in Figure 13, the cables ring at about 70kHz. The filter only offers 1.5 Ohms of impedance at 70kHz.



No Filter



Typical dV/dt filter

Figure 13 Peak-peak common mode current without and with the typical dV/dt filter

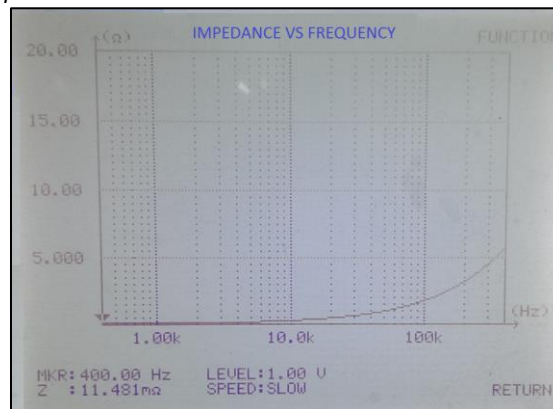


Figure 14 Common mode frequency response of typical dV/dt filter

## MTE dV Sentry dV/dt Filter Test Data

Figure 15 shows the MTE dV Sentry dV/dt filter that has the triple defense reactor core construction.

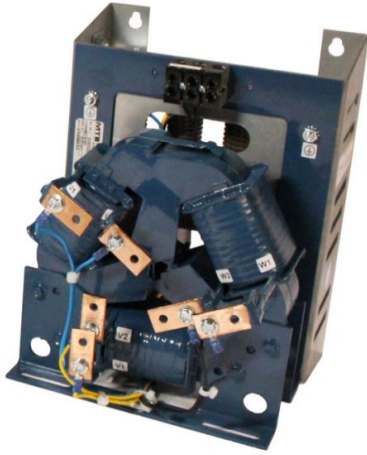
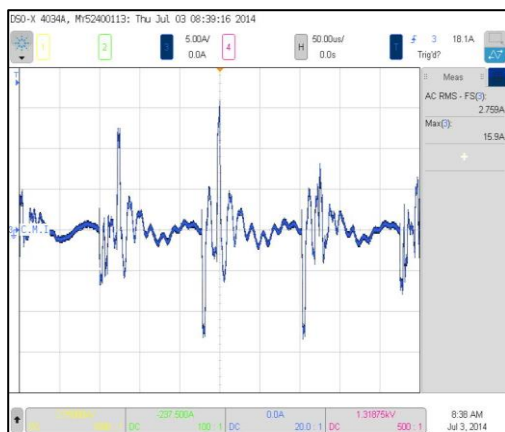


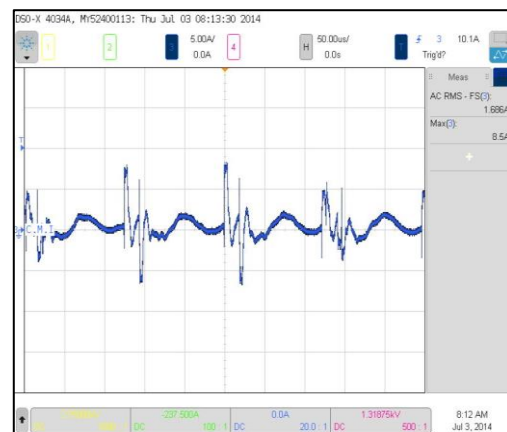
Figure 15 MTE dV Sentry dV/dt filter

The differential mode filtering performed well, keeping the peak line to line motor voltage to less than 1000V and the filter provided superior common mode filtering. Figure 16 shows that the peak to peak common mode current was reduced from 15.9A without a filter to 8.5A with the MTE dV Sentry filter. This is a 47% reduction in peak common mode currents.

Figure 17 shows the impedance measured through a frequency range from 400Hz to 400kHz. The filter has about 14 Ohms of impedance at the 70kHz where much of the ringing of the common mode current occurred. The 14 Ohms is ideally matched to the common mode characteristic impedance of the cable, therefore it is ideally damped [3].



No Filter



MTE dV Sentry Filter

Figure 16 Common mode current without and with the MTE dV Sentry filter

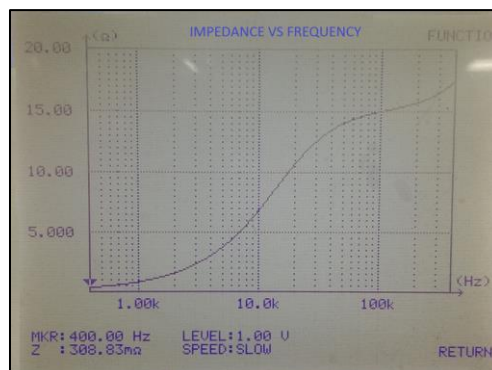


Figure 17 Common mode frequency response of MTE dV/dt dV Sentry Filter



### Common Mode Choke Core Filter Test Data

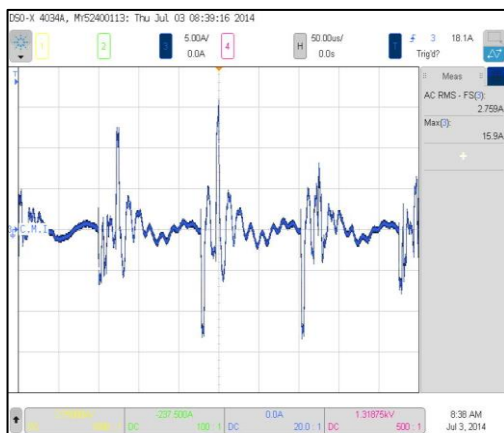
Figure 18 shows a typical common mode filter choke installed with the manufacturer's requirements for placing the three phase windings onto the core. Figure 19 shows that the peak to peak common mode current was increased from 15.9A to 18.7A. This is an 18% increase in peak common mode currents.

Figure 20 shows the impedance measured through a frequency range from 400Hz to 400kHz. The filter has about 60 Ohms of impedance around the 70kHz range that the cable resonates at. At 400kHz the impedance increases to over 400 Ohms, but this filter does

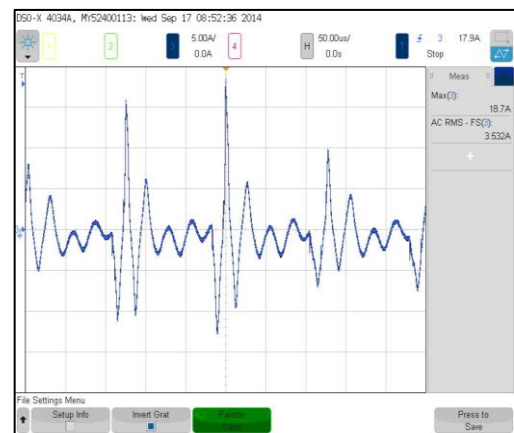
not provide any dampening so it always has the potential to resonate.



Figure 18 Common mode choke wound per manufacturer's instructions



No Filter



Common Mode Choke

Figure 19 Common mode current without and with a typical common mode choke

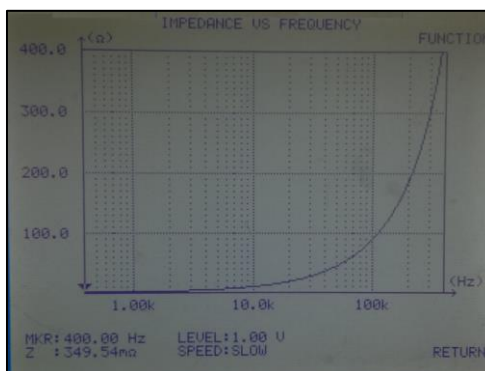


Figure 20 Common mode frequency response of a common mode choke

## Discussion

### *Typical $dV/dt$ Filter*

This filter topology erroneously relies on the typical negatively coupled three phase reactor for the common mode inductance. As discussed previously, a negatively coupled three phase reactor has negligible common mode inductance. Therefore, since there are no filter paths to ground and the inductor essentially performing like a wire, the filter has negligible common mode filtering by design. The filter did not provide the claimed common mode current reduction of 30%. In addition, this particular filter did not meet the manufacturer's claim of limiting to 150% of the DC bus voltage.

When it comes to common mode filtering, the low impedance further explains why the filter has negligible common mode filtering. The gradual impedance increase at higher frequencies is primarily due to the loss increase in the wire at higher frequencies and not the inductance of the reactor.

### *MTE $dV$ Sentry Filter*

This filter performed well in differential model, keeping the peak line to line voltage below the NEMA MG1-1998 Section 31 requirements. The peak common mode current reduction is also superior when compared to a typical  $dV/dt$  filter with a reduction of 47%. The common mode impedance is matched to that of the cable and therefore it is ideally damped.

### *Common Mode Choke*

A common mode choke provides no differential mode filtering so the voltages on the motor leads were about 1900V. This exceeds the requirements of MG1 Section 31 for inverter duty motors so typically the user would purchase another  $dV/dt$  filter with it.

The increase in common mode current can be explained by considering that the increase in common mode inductance lowered the resonant frequency between the inductance of the cable and choke, and the parasitic capacitances. The resonant frequency was reduced from about 70kHz to 40kHz. Since the PWM waveform of the drive contains many frequencies, the cable resonated at a different frequency with the addition of a common mode choke. There are instances where a common choke can be effective, it depends on what the resonant frequency is changed to and if the cable is being excited by the frequency with the PWM signal. Based on the common mode frequency response, the filter does not provide any dampening so it always has the potential to resonate.

## Conclusion

Common mode filtering with the suitability of various inductor constructions was explained. The origins of common mode voltages within a PWM AC drive were described. Experimental data was presented to demonstrate the effectiveness of various filtering options. Some are very effective at reducing problems associated with elevated differential mode voltages, but completely ineffective at reducing common mode problems at even the most basic theoretical level. A filter that provides both true common mode and differential mode filtering was shown to be an optimal solution.

The typical dV/dt filter does not filter common mode currents. Adding a shaft grounding brush can help protect the bearings, but again does not reduce common mode currents. A common mode choke can sometimes help but is unreliable at reducing common mode currents because it is typically undamped. The MTE dV Sentry is the best overall filter because it provides reliable common and differential mode filtering to protect the motor. Table 2 summarizes the tests results on a 50 hp system.

Table 2 Test data summary

<b>Filtering</b>	<b>Filter Common Mode Dampening</b>	<b>Change in Common Mode Current</b>	<b>Note</b>
Typical dV/dt Filter	NA	-5%	Negligible Common Mode Filtering
Common Mode Choke	None	18%	Unreliable Common Mode Filtering
Shaft Grounding Brush	NA	0%	Can Protect Bearings
MTE dV Sentry Filter	Optimal	-47%	Reliable Common Mode Filtering

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[2] "ANSI/NEMA MG 1-2011 Motors and Generators." American National Standard Institute, Inc. 2012

[3] Tallam, Rangarajan M., Gary L. Skibinski, Todd A. Shudarek, and Richard A. Lukaszewski. "Integrated Differential-Mode and Common-Mode Filter to Mitigate the Effects of Long Motor Leads on AC Drives." IEEE Transactions on Industry Applications: 2075-083. Print.

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