# Applying dV/dT filters with AFDs

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## Introduction

A dV/dT filter is a device that controls the voltage spikes generated by adjustable frequency drives (AFDs) and long motor lead lengths. This voltage spike event is generally known as the reflected wave phenomenon [1]. This resulting reflected wave can cause very high voltages on the motor leads, which can lead to damage and premature failure of the motor winding insulation (even with inverter duty rated motors), particularly within the first few turns.

As a general rule, the reflected wave is twice the DC bus voltage, where the DC bus can be calculated at 1.41 (square root of 2) times the line voltage. Therefore, for a 480 V service, the maximum reflected wave will be 480 x 2 x 1.41, or 1353 V. Even though AFD rated motors and cables are designed to handle higher voltages, this voltage level can contribute to a reduced service life for the motor. Likewise, the lower the service voltage, the lower the peak value for the reflected wave. For a 240 V motor, the reflected wave would be closer to 680 V, so a dV/dT filter would not be required; however, a load reactor is always recommended. The motor hp is also a factor when determining reflective wave because a smaller hp motor appears more like a capacitor, while a larger hp motor appears more like an inductor. To illustrate this idea, think of a wave as it crashes into shore; if the shore is a brick wall, the wave splashes high into the air, which simulates the reflected wave of a smaller hp motor. When the wave comes onto the beach, it slowly dies out, simulating a larger hp motor. For this reason, a dV/dT filter may need to be applied on a shorter lead length motor when the hp is smaller than when the hp is larger. Generally, for a 20 hp or lower motor, the maximum lead length is 60 feet, while for a greater than 25 hp motor, the threshold is 100 feet. Eaton motor control centers (MCCs) apply a standard 3% load reactor to add extra impedance, which helps to match the impedance of the motor and control the reflected wave voltage until these thresholds are met.

Another factor that affects the reflected wave is the carrier frequency of the AFD. In today's AFDs, the carrier frequency can be as high as 20 kHz, which helps to control audible noise at the motor. Typically, if the carrier frequency can be set between 3 kHz and 12 kHz, the short lead length applications will see a reflected wave that is less than the insulation rating of a standard inverter duty rated motor.

## IGBT switching time

The driving factor behind the voltage of the reflected wave is the speed at which the IGBT turns on (the dV/dT), which can be as high as 8000 V per microsecond for an IGBT. The system impedance and/or capacitance will affect the measured rise time of the IGBT. For smaller hp loads, the rise time may be 150 ns (more capacitance than inductance), and a larger hp load would be closer to 200 ns (more inductive). With the increased impedance in the load, time increases as the AFD becomes larger. **Figure 1** shows the representation of the service voltage and the reflected wave versus distance and the rise time of the IGBT.

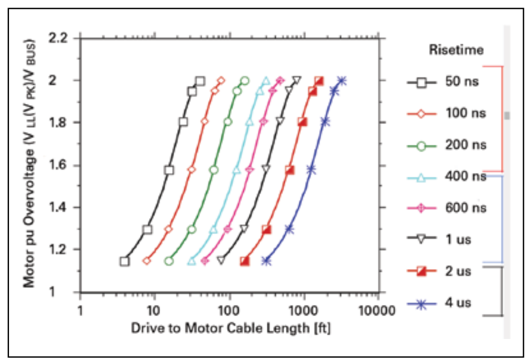


**Figure 1. Cable Length Versus Overvoltage [2]**

The switching speed for standard IGBT technology is in the range of 8000 V per microsecond, which puts the rise time of the IGBT of a 690 Vdc bus at 86 ns rise time (690 Vdc bus / [8000 V/µs] = 86 ns). Taking into account the impedance of the system, the measured rise time will be between 150 ns (smaller motors) and 200 ns (larger motors). From **Figure 1**, one can see that for a smaller motor the maximum lead length is closer to 60 feet, while for a larger motor it would be closer to 100 feet.

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## Sizing of a dV/dT filter

Depending on the frame size of the dV/dT filter, the terminals are designed to connect to a range of wire gauges. There is an urge to oversize the motor cables to minimize voltage losses, which may appear to be a positive action; however, this ends up increasing capacitive coupling, leading to an increased common mode current. A high common mode current can lead to higher motor bearing currents as well as heating of the dV/dT filter core, potentially leading to premature failure of the dV/dT filter. When it is necessary to use a wire that is too large for the dV/dT filter, see if it is possible to move to the next largest dV/dT filter that will accept that wire gauge. **Table 1** shows the minimum and maximum wire sizes for a given dV/dT filter/AFD combination, as well as a calculated voltage drop at 1000 feet for the maximum terminal size. Voltage drop is calculated using E=K*P*L*I/A, where K=12 (specific resistivity), P=1.73 (phase constant), L=wire length (feet), I=amperes, and A=circular mills of the wire.

The common mode current (stray current that leaks to ground from all phases at the same time) causes heating of the dV/dT filter core because the dV/dT filter is tuned for a specific system impedance. When oversized cables are used, it may also be necessary to oversize the dV/dT filter to accept the larger cables. At times, oversizing the dV/dT filter is the right choice, in that a larger core will have less impedance and is capable of handling larger amounts of common mode current, thereby dissipating the heat that the common mode current produces. However, oversizing the dV/dT filter decreases the effectiveness of the dV/dT filter because it is tuned for a specific current and motor impedance. There will be times that simply changing the switching frequency to 2 kHz will solve heating issues. Other times, an added inductor will be required in front of the dV/dT filter to tune the system so that the excess capacitance is tuned out. For extremely long runs, it is not unheard of to add another 3% or 5% inductance after the AFD and before the dV/dT filter, or to move to a sine wave filter instead of a dV/dT filter.

Upsizing the dV/dT filter can be beneficial in that the lugs typically get larger so that the filter can accept a larger gauge wire; the core is larger and can dissipate the heat generated from common mode currents. However, upsizing the filter can reduce the expected performance of the dV/dT filter, making it less effective in reducing the reflected wave. Very simply, the filter works by an inductor that is good at removing high frequency components and a resistor in parallel that is used to dampen the voltage spikes. As the dV/dT filter gets larger, the value for the inductor gets smaller, which will not remove as many of the high frequency components because the current is less than what the filter is designed for per V=L(dI/dT). The reflected wave will be reduced, but it may or may not be reduced as much as it would be for a filter rated for the exact motor operating current. When the filter is used this way, the application should be evaluated to verify that the desired filtering effect is achieved.

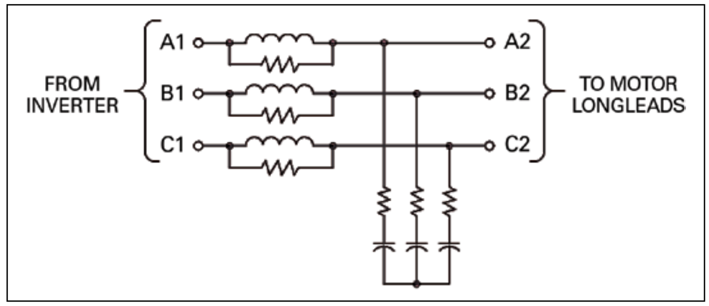


**Figure 2. dV/dT Filter Schematic [3]**

**Table 1. AFD to dV/dT Filter Cross [3]**

| SVX High OL | DG1 High OL | Frame Amperes | dV/dT Filter Terminal Ranges | Maximum Wire Size of dV/dT Filter | Voltage Drop at 1000 Feet | Wire Size at 1000 Feet at 4% Voltage Drop |
|---|---|---|---|---|---|---|
| FR4 | FR1 | 2.2 | 12–14 AWG | 12 | 1.5% | 16 |
| FR4 | FR1 | 3.3 | 12–14 AWG | 12 | 2.3% | 14 |
| FR4 | FR1 | 4.3 | 12–14 AWG | 12 | 3.0% | 12 |
| FR4 | FR1 | 5.6 | 12–14 AWG | 12 | 3.9% | 12 |
| FR4 | FR1 | 7.6 | 12–14 AWG | 12 | 5.3% | 10 |
| | FR1 | 9.0 | 12–14 AWG | 12 | 6.2% | 10 |
| FR5 | FR2 | 12 | 12–14 AWG | 12 | 8.3% | 8 |
| FR5 | FR2 | 16 | 4–12 AWG | 4 | 1.7% | 8 |
| FR5 | FR2 | 23 | 4–8 AWG | 4 | 2.5% | 6 |
| FR6 | FR3 | 31 | 1–6 AWG | 2 | 2.1% | 4 |
| FR6 | FR3 | 38 | 1–6 AWG | 2 | 2.6% | 4 |
| FR6 | FR3 | 46 | 1–4 AWG | 1 | 2.5% | 2 |
| FR7 | FR4 | 72 | 1–3 AWG | 1 | 3.9% | 1 |
| FR7 | FR4 | 87 | 2/0–1/0 AWG | 2/0 | 2.3% | 0 |
| FR8 | FR5 | 105 | 2/0–1/0 AWG | 2/0 | 2.8% | 1/0 |
| FR8 | FR5 | 140 | 250 kcmil–3/0 AWG | 250 | 2.5% | 2/0 |
| FR8 | FR5 | 170 | 2 by 2/0 | 2/0 | 2.3% | 3/0 |
| FR8 | FR6 | 205 | 2 by 2/0 | 2/0 | 2.8% | 3/0 |
| FR9 | — | 245 | 2 by 2/0 | 2/0 | 5.2% | 350 |
| FR9 | FR6 | 261 | 600 kcmil or 2 by 500 kcmil or 3/0 | 600 | 1.0% | 350 |
| FR10 | — | 330 | 2 by 350 kcmil or 4/0 | 2 x 350 | 2.1% | 2 x 200 |
| FR10 | — | 385 | 2 by 600 kcmil–2 by 300 | 2 x 600 | 1.4% | 400 |
| FR10 | — | 460 | 2 by 600 kcmil–2 by 350 | 2 x 600 | 1.7% | 500 |
| FR11 | — | 520 | 2 by 600 kcmil–2 by 500 kcmil | 2 x 600 | 2.0% | 600 |

## Six application tuning factors

There are six factors that come into play when tuning a system. These factors will provide positive and negative effects in many cases, and must be balanced to achieve the desired outcome.

1. Common mode current
2. Carrier frequency
3. System voltage
4. Load size
5. Lead length
6. Cable diameter

**Common mode current** is created mostly by capacitance due to oversized cables combined with increased lead length. One way to control this effect is to take care not to oversize the cables to the AFD. Depending on the lead length, a dV/dT filter may not be the best choice, and a sine wave filter may need to be used. An effect of lead length is that as the cable becomes longer, common mode current is bled off across the length of the wire, making the common mode current at the motor less than a shorter cable. Shorter cables will have less common mode current; however, the current at both ends of the cable will be very similar because less current is bled off, which will lead to higher common mode currents at the motor and increased current across the bearings. When the current across the bearings is high it can lead to premature bearing failure, which is why some motors are designed with insulated bearings.

**Carrier frequency**, as well, controls dV/dT filter heating, because dV/dT filters are designed to operate between 2 kHz and 4 kHz. Most AFDs come out of the box at 12 kHz, so it is important that the carrier frequency is set to the recommendation of the dV/dT filter for the given size.

**System voltage** greatly affects the reflected wave, because the reflected wave can reach about twice the system voltage. Due to this effect, a 480 V or 575 V system will be much more susceptible to the effects of the reflected wave, while a 230–380 V system will have maximum reflected waves far below the insulation rating of the wire and motor windings.

**Load size** affects the length as well. Small hp loads are more susceptible to common mode current, because the motor itself has more capacitance. Therefore, small hp loads will have to move to a dV/dT filter or a sine wave filter before larger hp loads will.

**Lead length** affects filter performance. The shorter the lead, less common mode current is generated, and less core heating occurs.

**Cable diameter** has an effect on the amount of capacitance and resistance that the cable produces. A larger diameter cable will have more surface area and more capacitance, leading to higher common mode currents, and less resistance, leading to reduced dampening of the reflected wave.

## Cable types

There are many types of cables that can be used to connect to the motor. The most common are AFD cables and standard stranded cables. When a standard stranded cable is used (such as THWN or THHN), all of the cables are loose (not bundled or twisted) and there is a significant amount of cross talk due to EMI/RFI. In essence, each wire is an antenna that broadcasts all switching frequencies to adjacent wires. To solve the issue of cross talk, AFD rated cables were created. AFD rated cable twists the leads and then inserts a ground per lead to space out the cables from one another to control EMI/RFI. With this type of cable, the cross talk is eliminated or at least greatly reduced. However, all of the added ground wires can add more capacitance, and this will add some common additional mode current.

In today's applications, most motors that are connected to AFDs are inverter duty rated, as are the motor cables. An inverter rated motor is designed with higher voltage insulation on the windings to counter the reflected wave, and is also designed to operate at lower frequencies without overheating.

## Cable splices

If at all possible, splicing of the cable between the dV/dT filter and the motor should be avoided. If a large cable is used going to the motor, first look at upsizing the dV/dT filter to accept the cable if that is the reason for the splice. A splice in the cable will introduce an impedance change, causing an impedance bump that is an additional reflection point for the reflected wave. Also, even though the shield may be carried through, it is not protecting the conductors and intrudes a place where EMI and RFI can be both induced and radiated. When a splice cannot be avoided, place that splice as close to the dV/dT filer as possible to keep the leads to that splice short.

## Shielding and grounding

A typical AFD cable has three conductors, three grounds, and a shield that runs the length of the cable. The cable ground should be tied to the motor ground lug, then tied to the ground lug of the AFD unit or MCC structure on the other end. Placing the ground as close as possible to the AFD helps reduce the impedance of the ground path, thereby reducing system common mode voltages. The shield should only be tied to the ground at one location to eliminate ground loops, either at the motor or at the AFD.

## Summary

To control the effects of the reflected wave created by IGBTs in certain applications, a dV/dT filter will need to be applied as noted in this paper. The design of a dV/dT filter is based on a number of factors, including IGBT switching time, load ampacity, cable length, and cable diameter. It is always best to use a dV/dT filter with an ampacity matched to the motor, and cable sizes (AWG) that are appropriate for the distance between the motor and the AFD while resisting the urge to oversize the cable. When an oversized cable must be used, upsizing the filter is an option if the lugs are not large enough for the cable. However, there is a risk when upsizing the filter too much; this is because the performance of the filter is reduced when the amperage of the filter is too large for the load. In these situations, it is advisable to add a terminal block at the dV/dT filter to step the cable down to the filter lug size. When applying a dV/dT filter, always remember to reduce the AFD carrier frequency to 2–4 kHz. Taking these factors into account will assist in the performance of the dV/dT filter in the application and the protection of the motor from dangerous reflected wave voltages up to 1000 feet from the AFD.

## References

[1] For more on reflected waves, search the Eaton.com website for "Reflective Wave Phenomenon."

[2] "Riding the Reflected Wave—IGBT Drive Technology Demands New Motor and Cable Considerations." Presented at IEEE IAS Petroleum and Chemical Industry Conference 1996.

[3] Information based upon Eaton standard dV/dT filters. Non-standard dV/dT filters may have different physical features.

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Printed in USA
Publication No. AP043001EN / Z15630
September 2014

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