Output Filters and Motor Lead Length

Introduction

When designing a VFD controlled system, it's critically important to consider the length of the cable run between the Drive and the motor, as well as options for filtering at the output of the Drive. Variable frequency drives utilize Insulated Gate Bi-polar Transistors (IGBTs) which supply a pulsed DC Voltage to a motor, not a smooth AC waveform. These pulses, determined by their switching frequency, in combination with cable transmission distance between a VFD and a motor can create premature high voltage-induced insulation breakdown. It is possible that voltage peaks reach as high as 2x the nominal DC Bus voltage corresponding to nearly 1400V peak for a 480VAC rated VFD. All harmonic distortion that is not filtered generates heat in the motor's windings, causing excessive stress and efficiency losses.

System Design Considerations

Primary system design considerations:

- Motor type (Inverter or non-inverter duty rated)
- Cable type (Inverter or standard duty rated)
- Distance between motor and VFD (cable length)
- Motor voltage
- VFD switching frequency
- Motor size

Reflected Wave and Corona

- Motor cables have inductance and capacitance directly proportional to their length and thus impedance. Similarly, motor windings have their own characteristic inductance, capacitance and impedance. Impedance mismatches can result in voltage 'ringing' at the point of connection to the motor. As conductor length increases, the overshoot peak voltage also increases. An increase in the switching frequency will increase the amount of times the overvoltage is applied to the motor.
- Drive Overcurrent or other current faults can be the result of motor damage caused by corona discharge. Normally reflected wave failures occur in the first winding of the motor. Below shows the voltage pulse to the motor and voltage ringing due to this impedance mismatch.

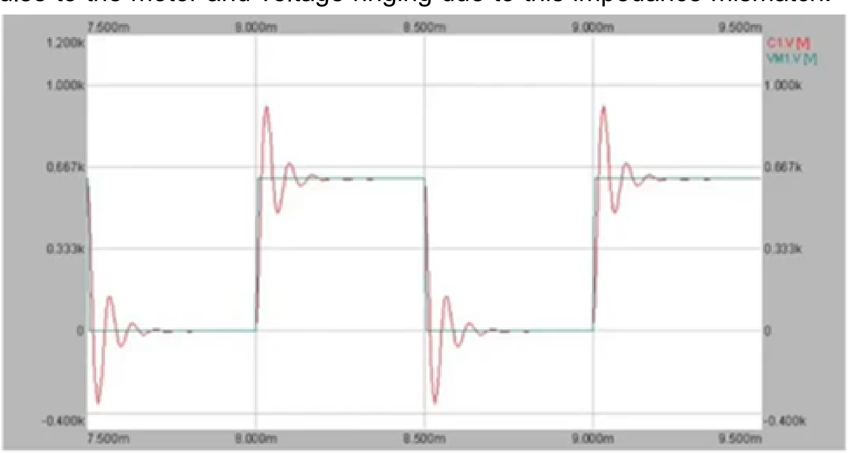

Figure 1 - voltage pulse to the motor and voltage ringing due to impedance mismatch.

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- An insulation tester, such as a “Megger”, can apply a high voltage to the motor’s stator windings to con-firm if insulation break-down is a problem.
- Refer to Application paper ‘The Reflective Wave Phenomena’, AP040013EN for more detail about this phenomenon.

Solutions to Reduce Reflected Wave

1. **Output Load Reactor**
   The output reactor is a three-phase series inductance on the load side of a VFD. It is used to reduce transient voltage (dV/dt) and peak voltages at the motor terminals. Coils (an inductor) oppose fast changes in the current passing through them therefore will increase the rise time of the pulses at the motor. A 3% output filter is recommended for motor cable lengths up to 300 ft.
2. **dV/dT Filter**
   Used to reduce the transient voltage (dV/dt) overshoot at the motor terminals. 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 VFD while resisting the urge to oversize the cable. Recommended for motor cable lengths over 300 ft and up to 1000 ft. When applying a dV/dt filter, one may have to set the switching frequency of the VFD to a specific frequency. Refer to Application paper ‘Applying dV/dt filters with AFDs’, AP043001EN for more detail.
3. **Sine Filter**
   Sine wave filters (LC filters) are low pass frequency filters and have the longest range of motor protection. Designed to reduce voltage peaks and ‘clean-up’ the PWM pulses to a near sinusoidal AC waveform. Recommended for motor cable lengths exceeding 1000 ft. Note that sine wave filters cannot be used in Sensorless Vector control due to capacitance in the filter. The drive is prone to trip on overcurrent faults.

General Guidelines - Motor Lead Length

Table 1 represents cable length guidelines depending upon motor type and cable type used. Inverter duty rated motors typically have an insulation rating of 1488V which is why the motor run can be longer with standard cable. Non-inverter duty rated motors insulation rating is typically 1200V or if older motor, 1000V. The 1000V rating level is the minimum that should be considered for use with a PWM controlled adjustable frequency drive. Table 2 represents cable length guidelines depending upon switching frequency and motor voltage.

Table 1 - Cable lengths dependent upon motor and cable types

Configuration	Standard motor - Standard cable	Inverter-duty motor - Standard cable	Standard motor - Inverter-duty cabl	Inverter-duty motor - Inverter-duty cable
No output filter	< 100 ft	< 150 ft	< 300 ft	< 300 ft
3% output reactor	100 ~ 300 ft	150 ~ 350 ft	150 ~ 350 ft	300 ~ 650 ft
DV/Dt filter	300 ~ 1000 ft	350 ~ 1000 ft	350 ~ 1000 ft	650 ~ 1000 ft
Sine Wave filter [1]	> 1000 ft	> 1000 ft	> 1000 ft	> 1000 ft

Table 2 - Cable lengths dependent upon switching frequency and motor voltage rating

Carrier Frequency	Max Cable Length for 230V motors - no output filter	Max Cable Length for 460V motors - no output filter	Max Cable Length for 575V motors - no output filter
3	600 ft	125 ft	40 ft
6	600 ft	100 ft	25 ft
9	600 ft	85 ft	20 ft
12	600 ft	75 ft	15 ft

PWM Waveforms

PWM Waveform at motor with dV/dT filter

- Figure 2 is of a PWM waveform taken at a motor. System has a dV/dt filter.
- This image was captured using a Fluke 199C (color) ScopeMeter with 200MHz bandwidth and 2.5Gsamples/sec, measuring phase-to-phase.

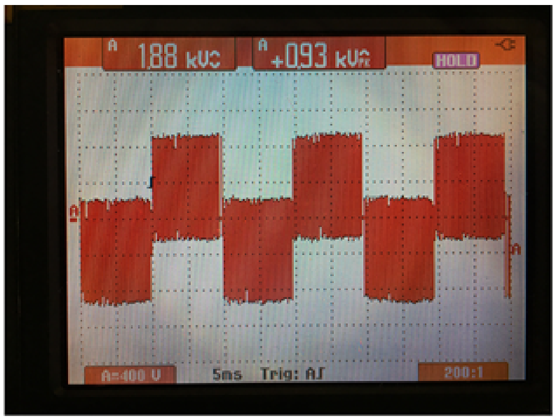

Figure 2 - PWM waveform taken at a motor with dV/dT filter

PWM Waveform at Motor with and without dV/dT filter

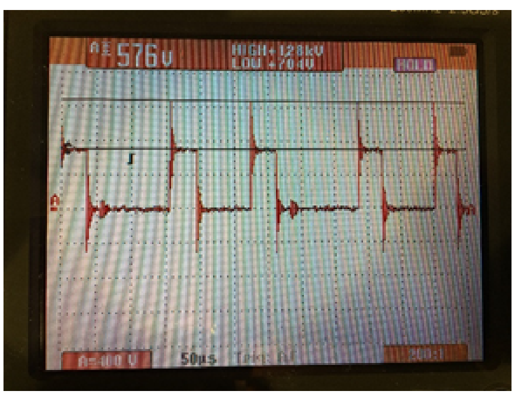

Figure 3: Without dV/dT filter

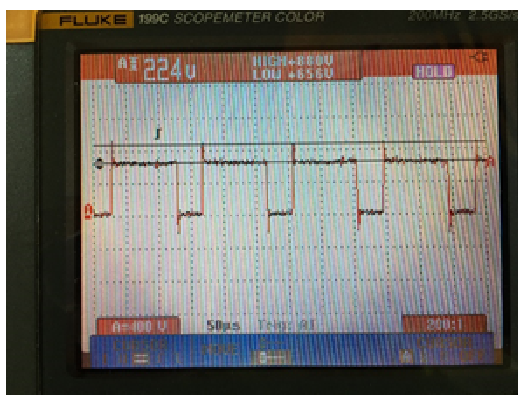

Figure 4: With dV/dT filter

PWM Waveform at Motor with and without Sine Filter

Figure 5: Without Sine Filter

Figure 6: With Sine Filter

Additional Factors When Considering Output Filters: Motor cable length & motor insulation stress

Switching frequency

- Lower switching frequency reduces the number of voltage pulses received by the motor, thus reducing the impact of pulses built up in the motor and the corona ozone effect.
- High switching frequencies has the opposite effect as when the switching frequency is low. The motor lead voltage can be as high as twice the line voltage.

Cable length

- Peak voltage at the motor is a combination of the dV/dt of the PWM pulse and the motor cable length.

Cable diameter

- A larger diameter cable will have more surface area and thus more capacitance, leading to higher common mode currents and less resistance. Larger diameter cable will help with dampening of the reflected wave. However, oversizing motor cables increases capacitive coupling, leading to an increase in common mode current. Refer to Application paper 'Applying dV/dt filters with AFDs', AP043001EN for more detail.

Line Voltage

- 208/230V installations
    - Peak DC voltages generally stay within the rating of the motor's insulation. 230V motor installations typically use the same rated insulation as a 480V motor, so dV/dt filters or output reactors are typically not needed.
- 460V Installations
    - Peak DC voltages can be in excess of 1000V on the motor cable, given nominal 480V RMS (680V peak) voltage.
- 600V installations
    - Peak voltage is 25% higher than a 480V line, additional care must be taken to avoid motor insulation problems.

Insulation rating on the windings in the motor

- Inverter-duty-rated motors is typically 1488V
    - To verify, ask the motor manufacturer if the motor meets NEMA spec MG1par 31 1992.
- Non-inverter-duty-rated motors is typically 1200V or if older motor, 1000V
    - The insulation rating of the motor windings come from the motor manufacturer.

Motor size

- Smaller motors have less space for insulating the stator windings and wire bends at the ends of the coils are sharper causing more susceptibility to insulation damage.
- Smaller motors also have a higher impedance (AC current flow resistance). This can create impedance mismatch between the motor and the lower impedance of the motor cables and the VFD' inverter section.

Cabling methods

- Conduit, cable tray, buried, gauge, etc.

Screened vs. unscreened cabling

- Screened cables have a copper braid around the conductors. Its purpose is to keep external electromagnetic energy (EMI) from getting into the cable. It also prevents the cable from being a source of interference. Screened cabling needs to be correctly bonded to earth ground.

Motor Load

- Load on the motor has a relatively minor impact on the peak voltage at the motor terminals but there is a tendency for peak voltage to drop as more current is drawn through the motor.

Temperature and altitude

- As either increase, the dielectric strength of the air surrounding the insulation decreases. For a given corona level, as winding temperature increases from 25C to 130 C for class F insulation, the insulation life is reduced to 17% of the life at 25C. If the corona in a given motor is 1000V at sea level, it may be only 700V at 5000 feet of altitude.

VFD Cable

- VFD cable has many benefits and is the recommended cable on the drive output.
    - VFD cable has symmetrical grounds which helps reduce common mode currents.
    - VFD cable has a shield to reduce EMI to other equipment and induced voltages into the cable. The best shield is braided, should be grounded on both ends and should be grounded with a circular connection like a gland connector.
    - VFD cable insures sufficient ground between the drive and the motor.

Contaminants

- Any contamination on the surface of the motor windings (grease, oil, carbon, detergents, metal dust, salts, etc.) will create conductive paths along the surface of the windings and subsequently reduce the corona level.

Cable Size Selection and Motor Horsepower

Please refer to the cable size selection tables in the respective VFD Installation/User Manual.

Output Filter Product Offerings

Please refer to Eaton's Adjustable Frequency Drives catalog or your local Eaton sales engineer for appropriate recommendations.

References

- Applying dV/dt filters with AFDs - Application Paper AP043001EN
  Author: Gerry Feldmeier, Eaton Corporation, plc
  Author: Dan Kupersmith, Eaton Corporation, plc
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  Author: Shawn Lamp, Eaton Corporation, plc
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  Author: Nicholas Hayes; Vice President of Marketing and Sales, TCI, LLC
- Vacon 100 Industrial AC Drives – DU / DT Filter Technical Guide-DPD01929A
  Author: Vacon Drives
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Additional Help

In the US or Canada: please contact the Technical Resource Center at 1-877-ETN-CARE
or 1-877-386-2273 option 2, option 6.

All other supporting documentation is located on the Eaton web site at www.eaton.com/Drives

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