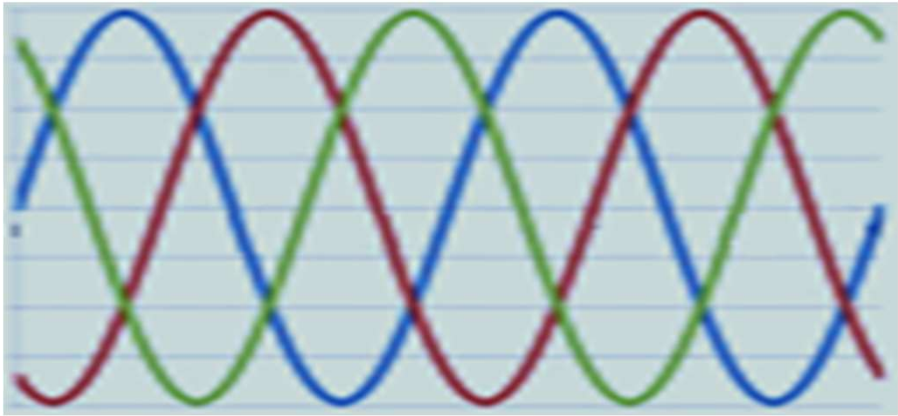
VFD: PWM TO MOTOR

VFD to Motor issues from PWM Output

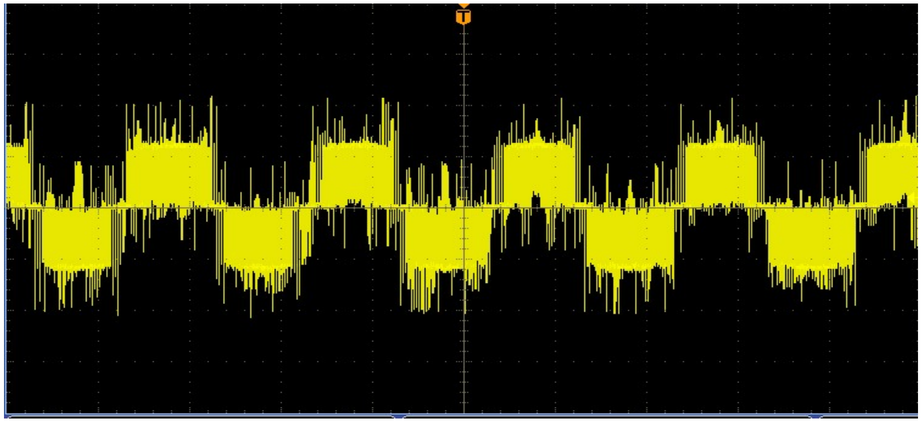
VFD Output

VFDs **do not** produce sinusoidal output to the motor
VFDs produce Pulse Width Modulation (PWM)
PWM: Short pulses of DC power with alternating polarity
PWM is the output from VFD to motor

3 Phase AC Power



PWM Output from VFD

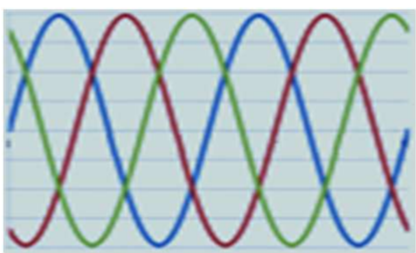


VFD Output
PWM

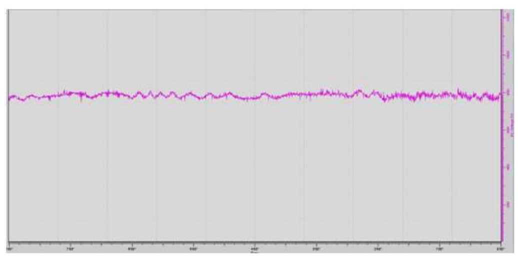
VFDs Convert AC to DC power and Invert DC to PWM

- VFDs store DC power in capacitors (DC Bus)
- DC power Voltage in capacitors is 1.414xUtility Voltage
- 480V Utility power system: 480V(1.414) = 678V
- PWM is bursts of DC Bus voltage i.e. 678V

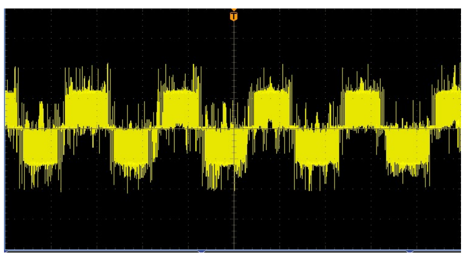
3 Phase AC



DC



PWM
Pulse Width Modulation



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VFD Output
PWM—Unique Issues

- PWM, non-sinusoidal, power output to motors causes phenomena that sinusoidal power doesn't.
  - Bearing Fluting
  - dV/dT
  - Reflected Wave
  - Capacitive Coupling
  - Common mode current
  - Common mode voltage

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VFD Output
PWM - *Motor Issues*

- PWM, non-sinusoidal, power output to motor causes phenomena that sinusoidal power doesn't.
  - These phenomena cause
    - Motor Winding damage/failure
    - Shaft bearing damage/failure
    - Electrical noise: high frequency signals which interfere with electrical equipment.

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VFD Output
Capacitive Coupling

Capacitive Coupling: 2 or more conductors in close proximity develop capacitance when energized

- The capacitance of the conductors is affected by:
  - Conductor length
  - Conductor insulation material and thickness
  - Conductor construction (size and number of strands)
  - Frequency of incoming power
  - The longer the conductors the greater the capacitance

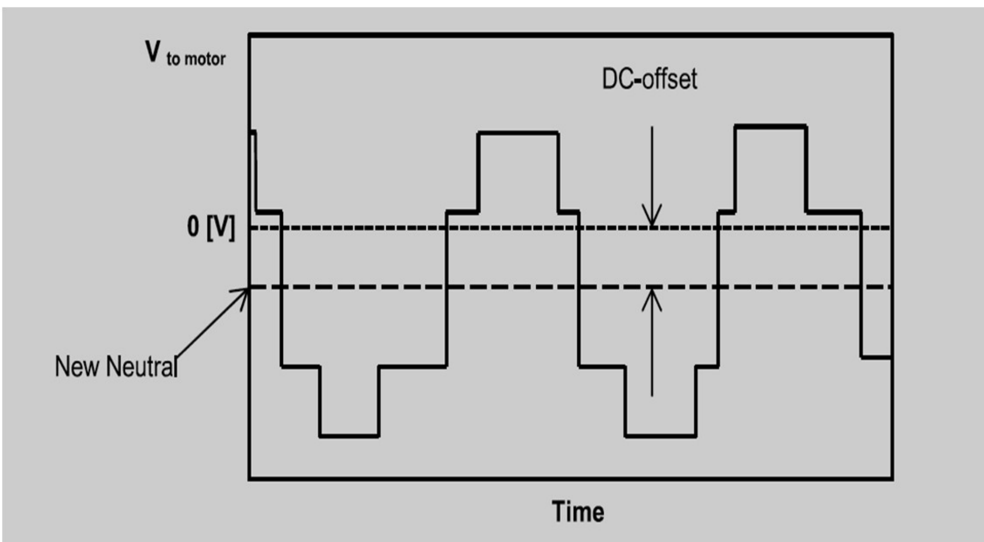
VFD Output
Inductance of conductors

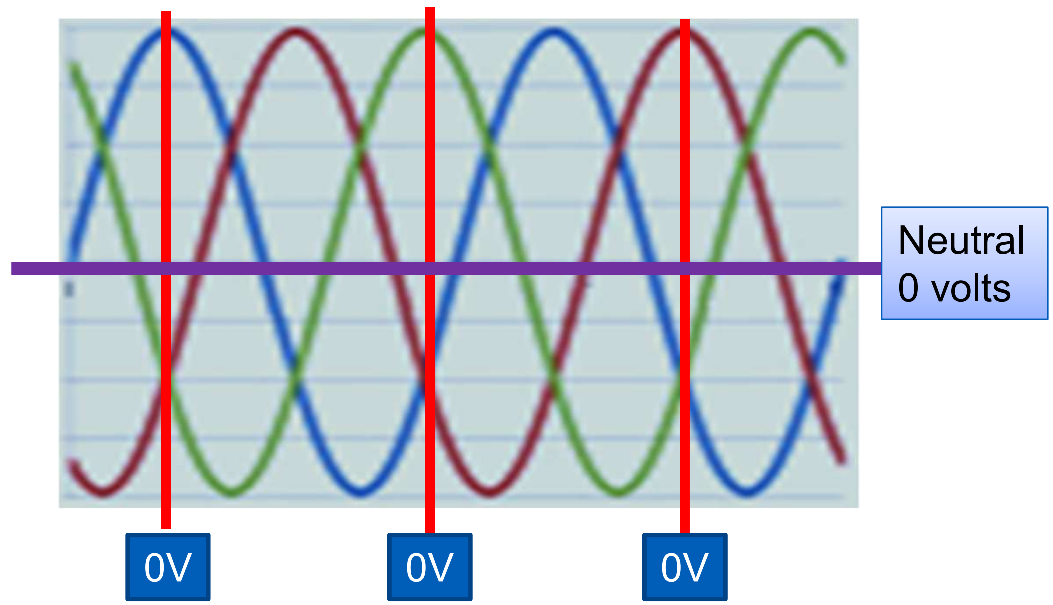
Conductor Inductance:

- Wires from VFD to motor have inductance, which is much lower than motor inductance
  - Conductor length determines inductance
  - Conductor insulation material and thickness
  - Conductor construction (size and number of strands)
  - Frequency of incoming power
  - The longer the conductors the greater the inductance

DG1
Common mode voltage

- PWM: can cause voltage in the rotor shaft produced from common mode voltage.
  - Common mode voltage is created when motor outputs do not sum to 0V
  - Common mode voltage accumulate and sum to large voltage

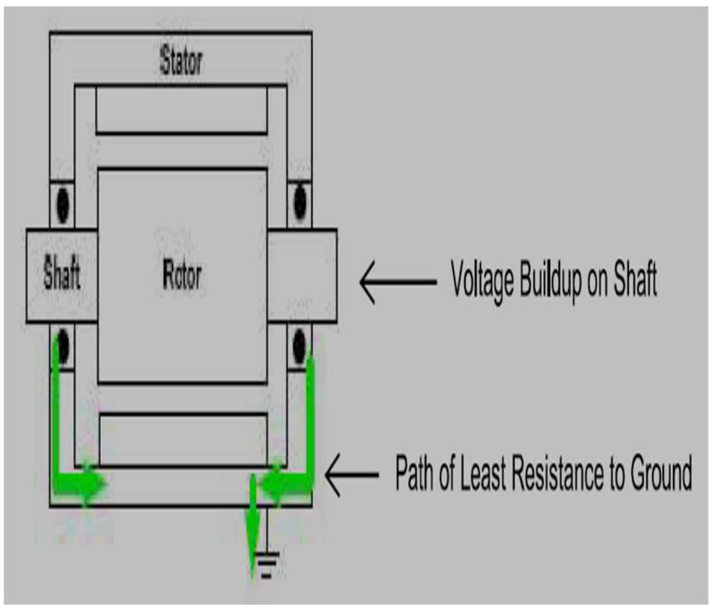


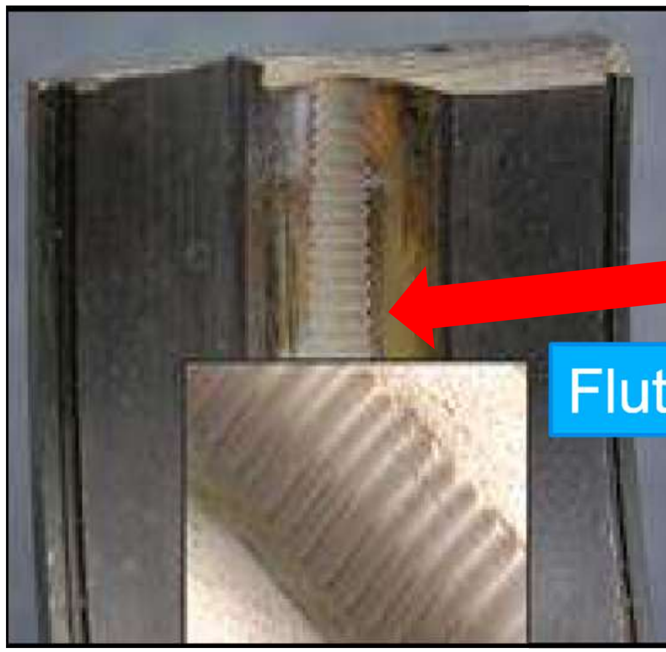


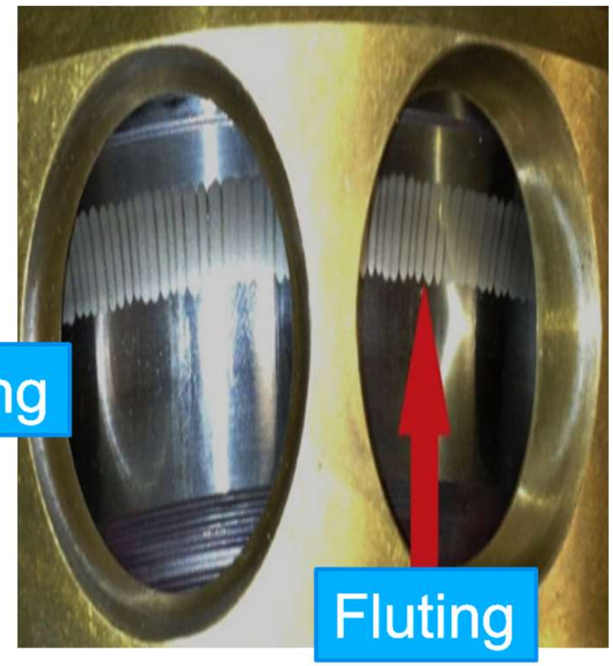
VFD Output
Bearing Fluting

Bearing Currents: occur when an induced voltage on the motor rotor, from common mode voltage, is great enough to discharge from the motor shaft through the rotor bearings (>50V) to the motor housing.

- Voltage discharge through the bearings causes arcing to the bearing raceway
- Arcing at the bearings damages the bearing housing causing "fluting"







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VFD Output
Bearing Fluting

Common Mode voltage and current will be present with VFDs. Can be controlled by various hardware/installation techniques.

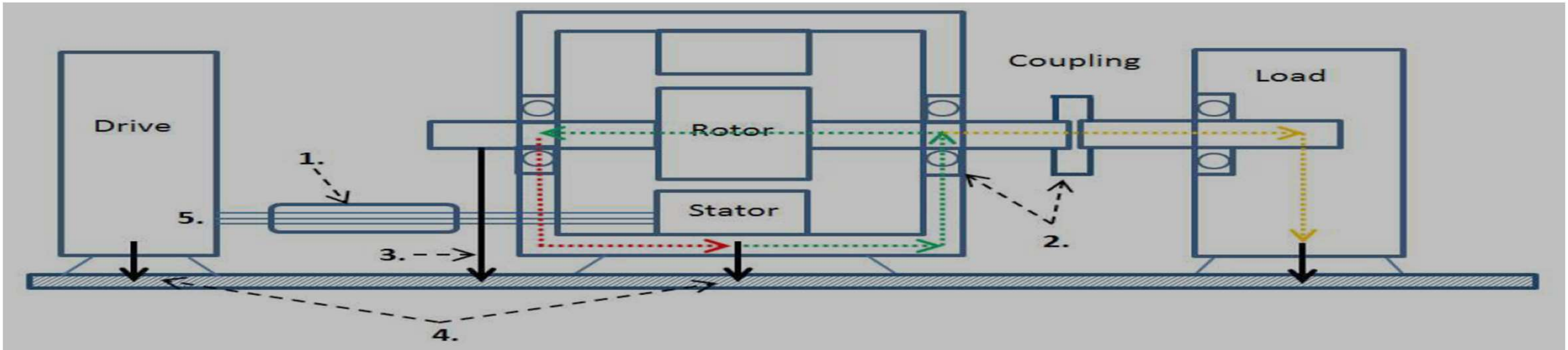


Figure 5. Three Phase Voltage Source Inverter Driving Voltage with Common Mode Other than 0 [V]

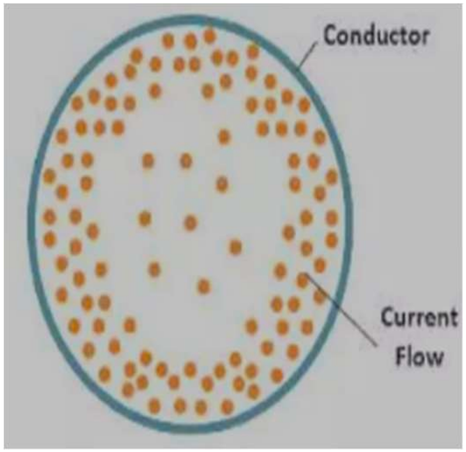
1.) Shielded motor cables
2.) Insulated bearings
3.) Shaft grounding brushes
4.) Fine stranded grounding cables
5.) Filtering

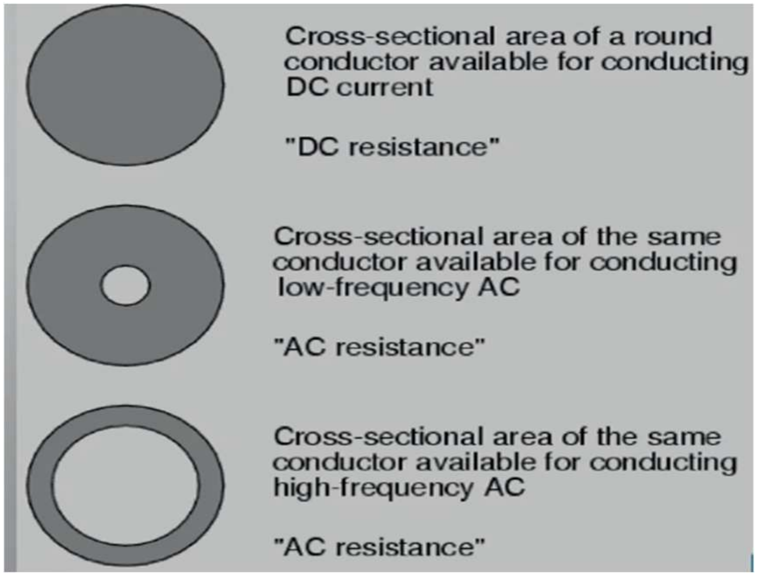
VFD Output

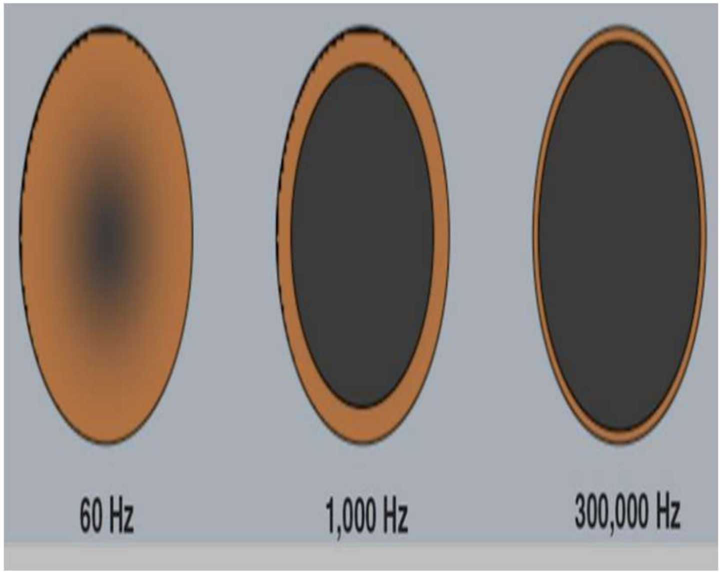
Conductor Skin Effect

Skin Effect: In a conductor electricity flow is concentrated in the outer cross-sectional area – electricity flows near the surface of the wire and not in the center.

- Increases in current density in outer area of the conductor increases the effective resistance of the conductor.
- The area of current density is affected by Frequency.
- Conductors designed with more surface area are able to conduct more high frequency current than conventional round wire.







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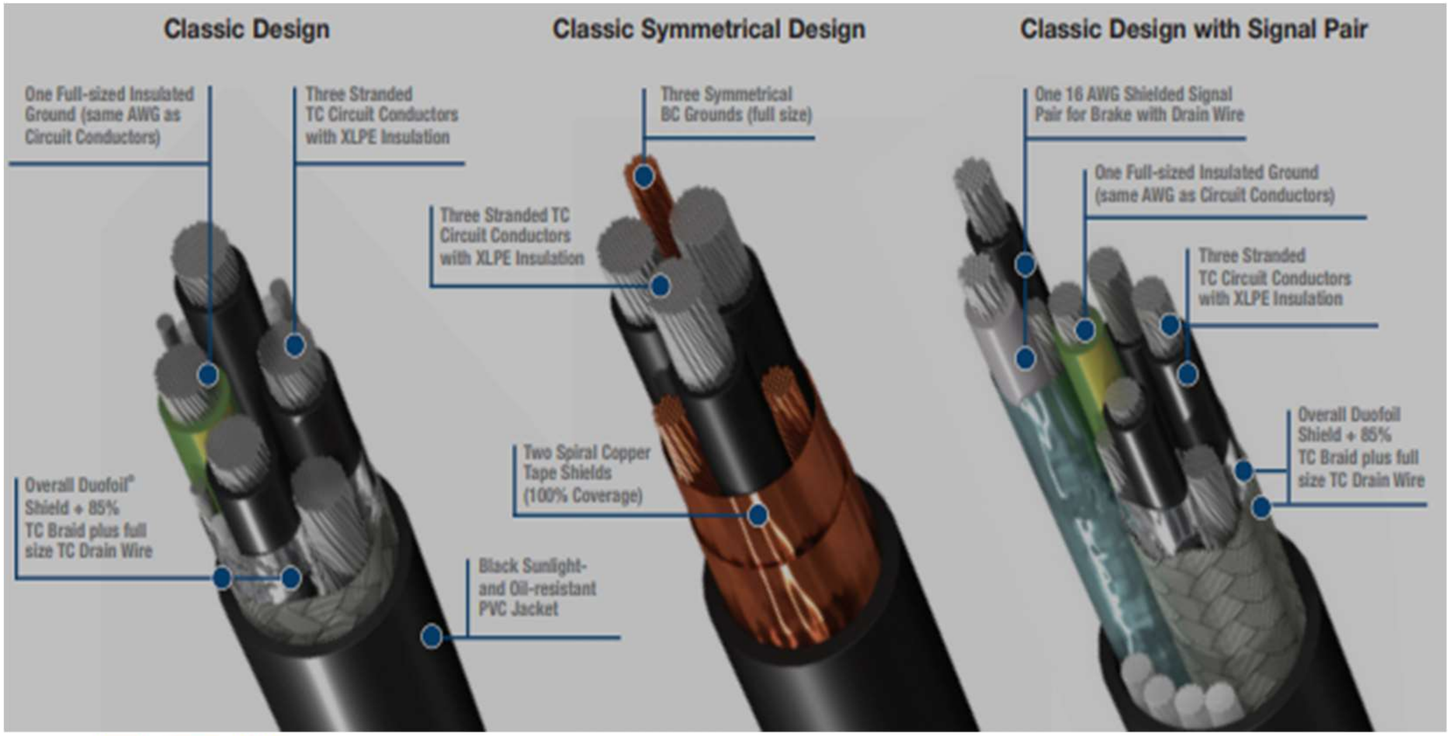
VFD Cable

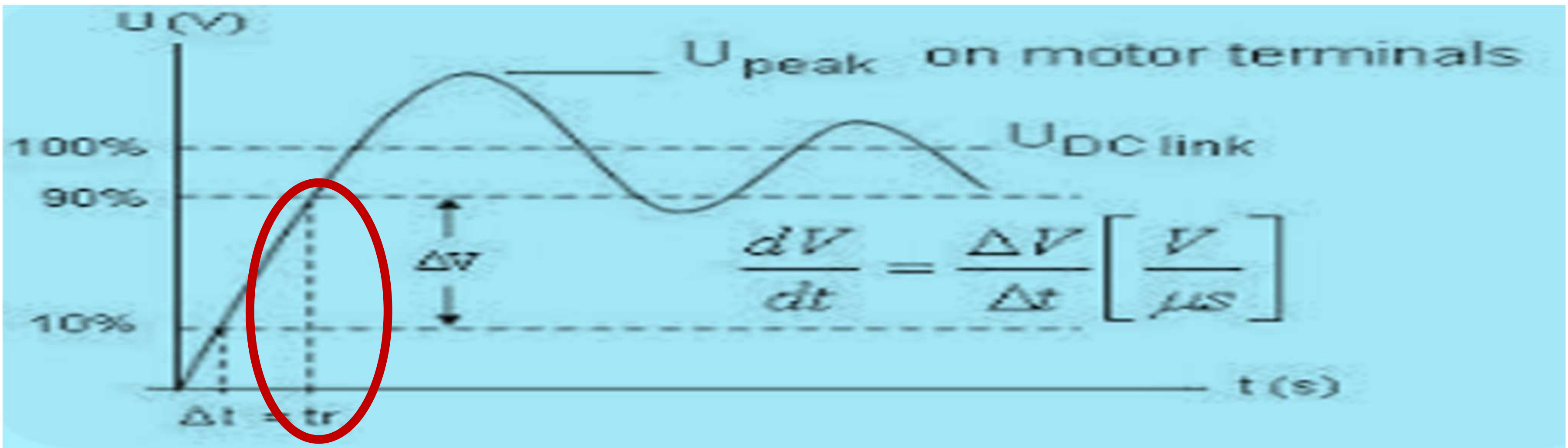
<u>Skin Effect:</u> VFD Cable shielding provides greater conductor surface area or "skin" for high frequency noise caused by common mode voltage/current.



VFD Output
Rise Time

<u>Rise Time</u>(t_r): time required for voltage to rise to 90% of peak voltage.

- IGBTs switch extremely fast: 2K switches/sec to 16K switches/sec in VFDs
- IGBT switching: Voltage increases from 0V to 650V in 0.1µs. Resulting in voltage rise times of 6500-7500 V/µs.



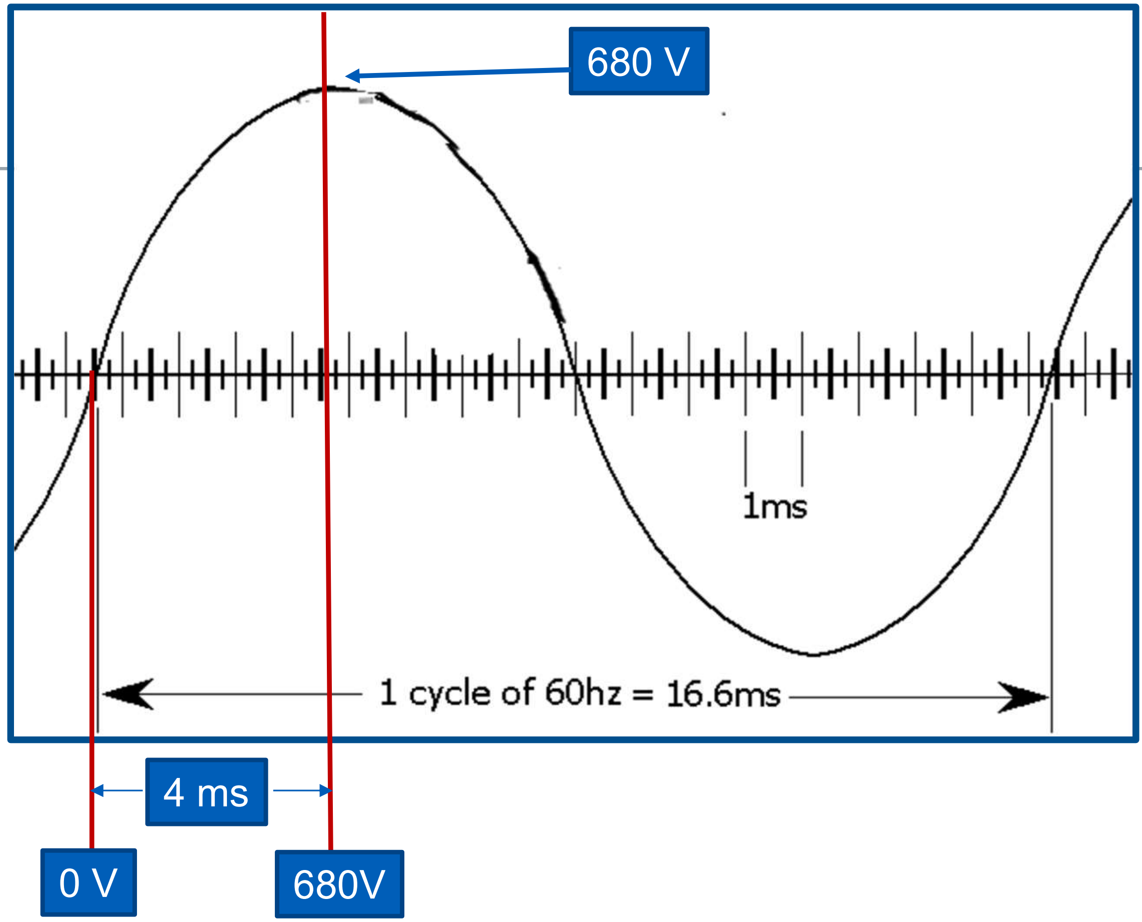
VFD Output
Sine Wave Rise Time

Sine Wave rise time and dv/dt is slow and steady (relative to PWM)

Slow rise time is why sinusoidal power doesn’t cause the same issues as PWM

<u>60 Hz Sine Wave rise time</u>
680V/4 ms = 170 V/ms = 0.17 V/µs

<u>PWM rise time</u>
6800 v/µs



VFD Output
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Slow rise time is why sinusoidal power doesn't cause the same issues as PWM

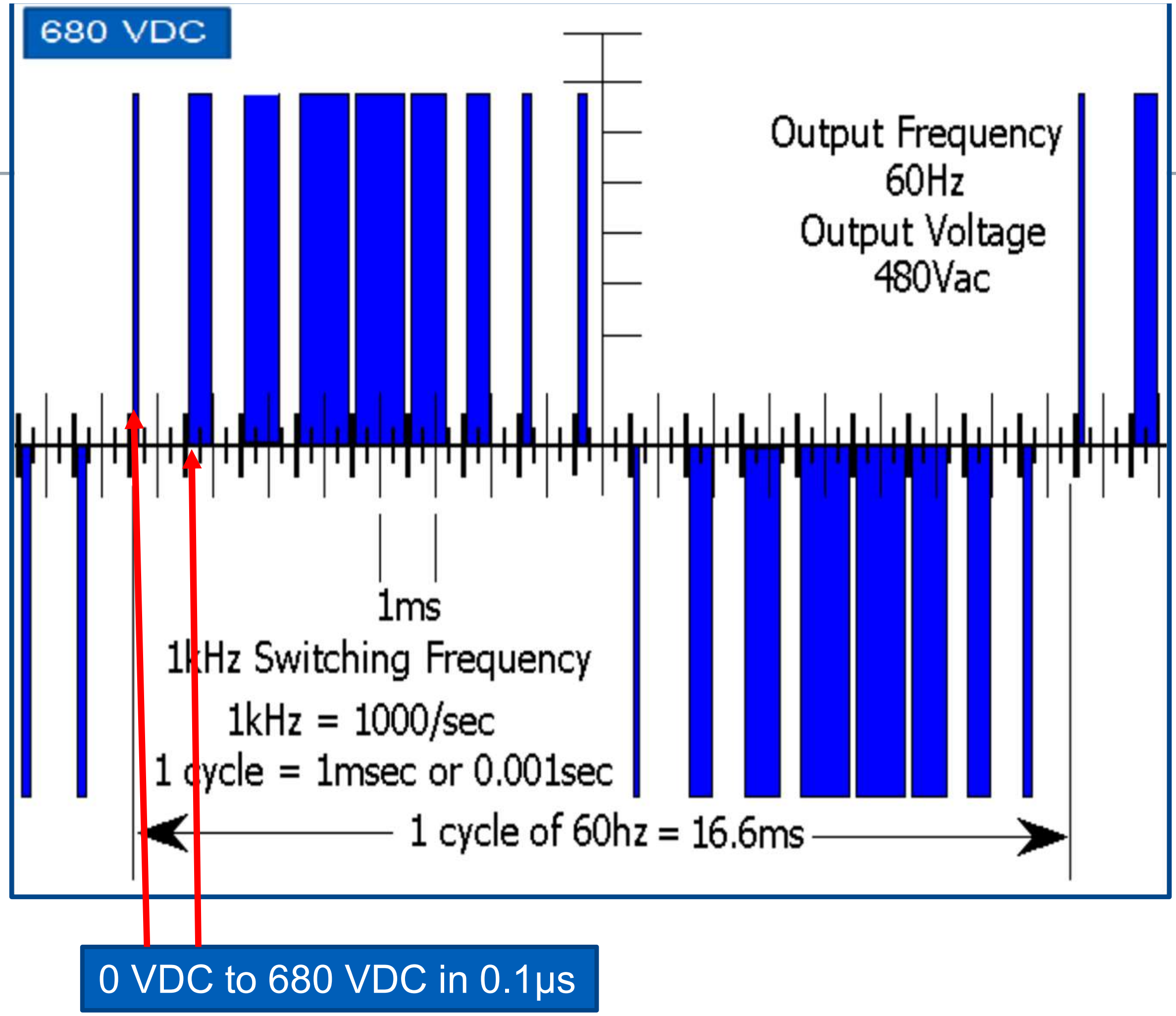
60 Hz Sine Wave rise time

680V/4 ms = 170 V/ms = 0.17 V/µs

PWM rise is extremely fast. The rapid voltage rise time causes issues sine wave power doesn't.

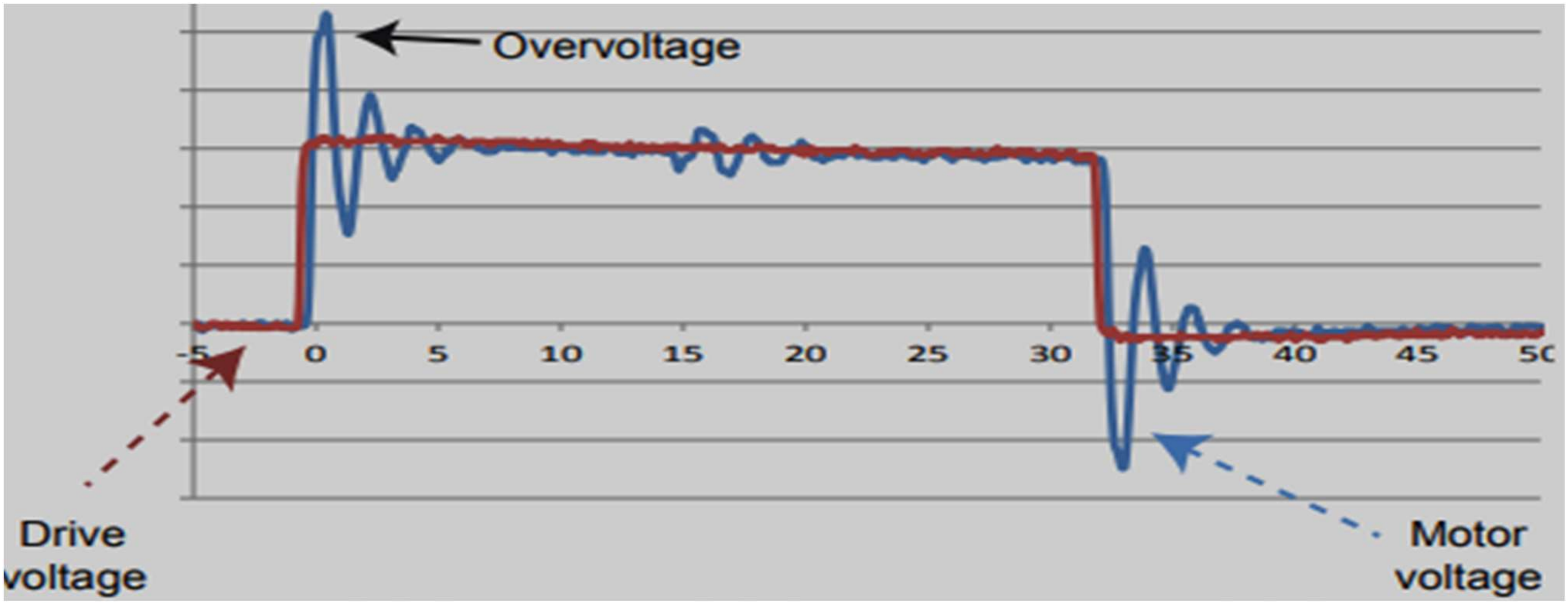
PWM rise time

680 VDC/0.1 µs = 6800 v/µs



VFD Output
Voltage Overshoot

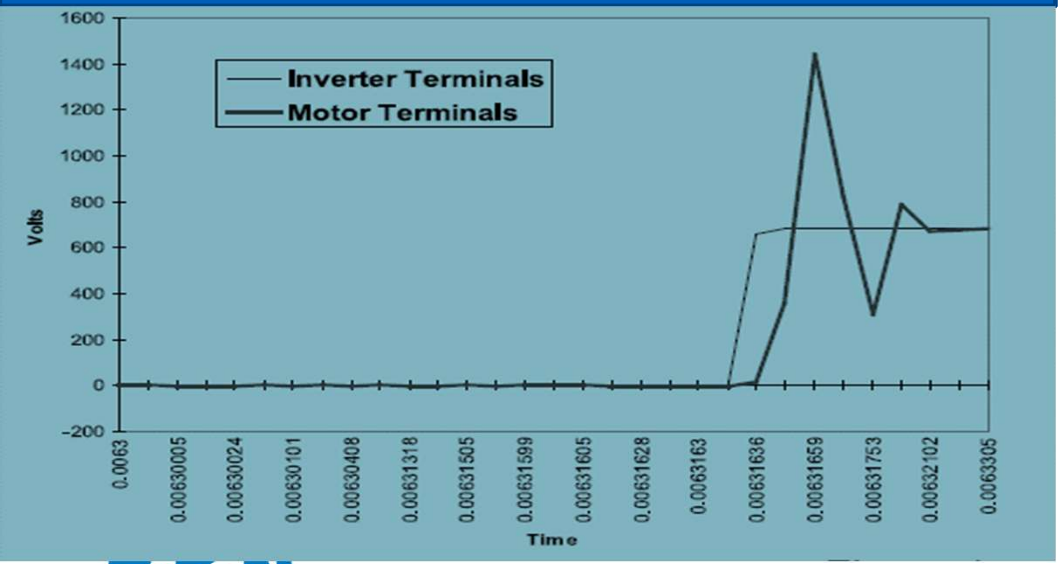
Voltage Overshoot: PWM pulse reaches the motor coil, high dV/dT and impedance difference of motor conductors and motor coils causes voltage to increase beyond DC bus voltage.



VFD Output
Reflected Wave

Reflected Wave: PWM pulse reaches the motor coil, Impedance difference causes Voltage to increase beyond DC bus voltage level (voltage overshoot).

- Voltage of PWM doubles at motor terminals.
- Doubled voltage pulse reflects back in direction of VFD.
- The nearest motor coils experience this high voltage.
- Reflected wave develops when motor conductors meet or exceed Critical Length

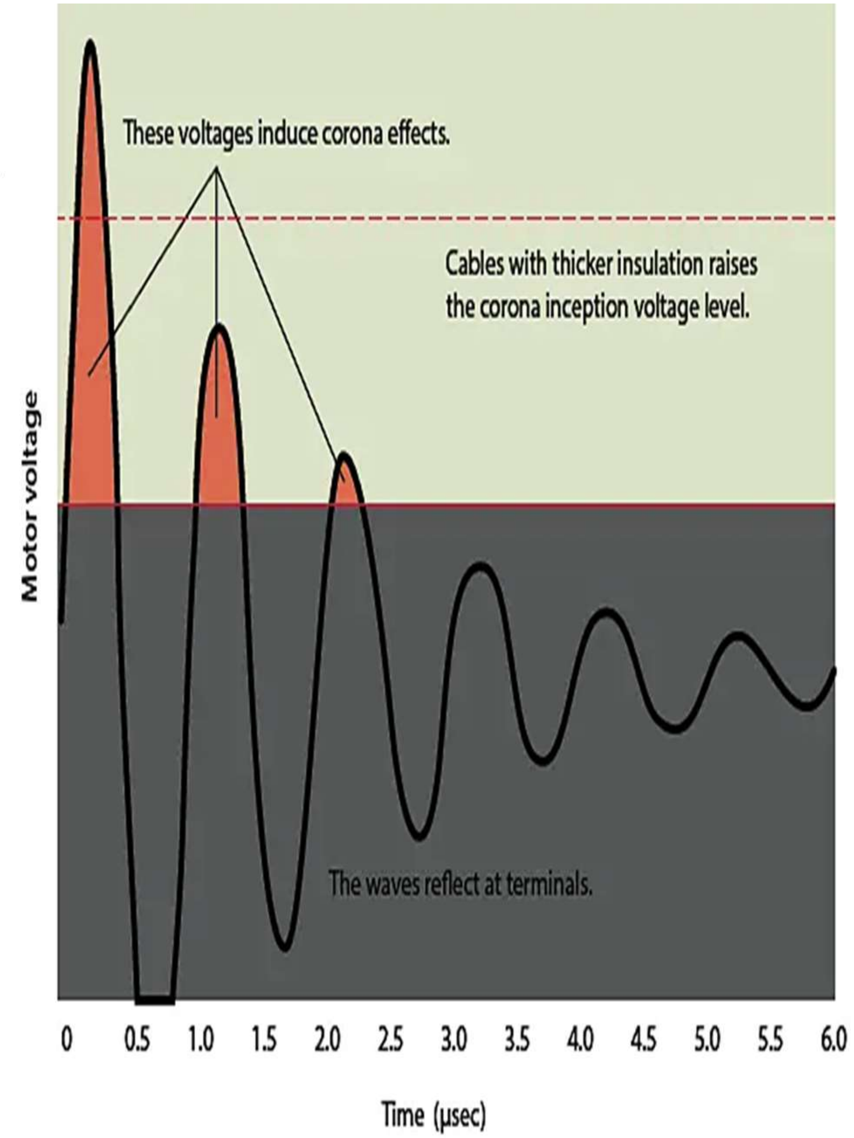


VFD Output
dV/dT and Reflected wave

<u>dV/dT</u>: Change in voltage over time.

- IGBTs switch extremely fast: 2K switches/sec to 16K switches/sec in VFDs
- IGBT switching: Voltage increases from 0V to 650V in nanoseconds. Resulting in voltage rise times of 6500-7500 V/µs.
- Motor coils have impedance mismatch with VFD terminals. Causes incoming voltage to increase 2-3x and reflect to VFD.
- The reflected wave can persist as a standing wave reflecting between the VFD and motor at 1000-1600V.

$$dv/dt = \frac{Peak\ Voltage \times .8}{t_r}$$



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VFD Output

dV/dT

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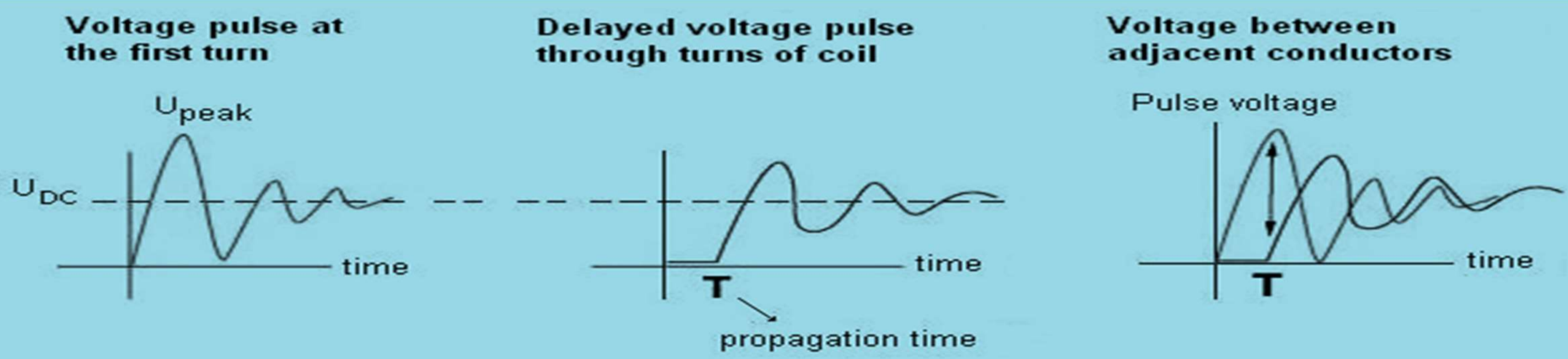
- IGBTs switch extremely fast: 2K switches/sec to 16K switches/sec in VFDs
- IGBT switching: Voltage increases from 0V to 650V in 0.1µs. Resulting in voltage rise times of 6500-7500 V/µs.
- Extremely fast voltage rise (dV/dT) causes uneven voltage distribution in the coils of the motor windings.
- First turns of stator coils experience higher voltage than subsequent turns due to capacitive dampening effect of adjacent coil conductors.



VFD Output

dV/dT and Reflected wave

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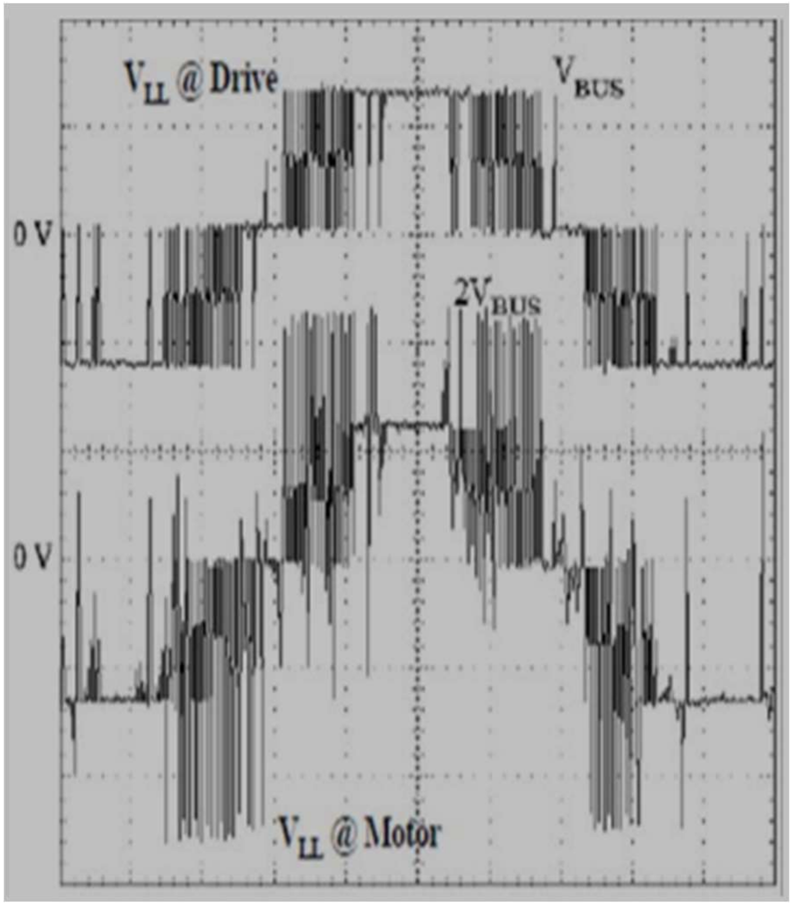
- Motor coils have impedance mismatch with VFD terminals. Causes incoming voltage to increase 2-3x and reflect to VFD.
- The reflected wave can persist as a standing wave reflecting between the VFD and motor at 1000-1600V.
- Standing wave persistence increases as cable length increases



VFD Output

Long Cable Length

Reflected wave can develop when conductor length between motor and VFD increases

$$\mathbf{L = V_{cable} \times t_r(\mu s)/2}$$

L = Critical Length

V_{cable} = Propagation Factor: speed that the PWM pulse travels from VFD to motor in fts/ µs (this value is dependent on the cable type and installation). Generally estimated at 500 ft/ µs.

t_r = pulse rise time

When conductor length ≥ L: a reflected pulse can combine with incoming pulses to create a reflected wave with V ≥ 1200V

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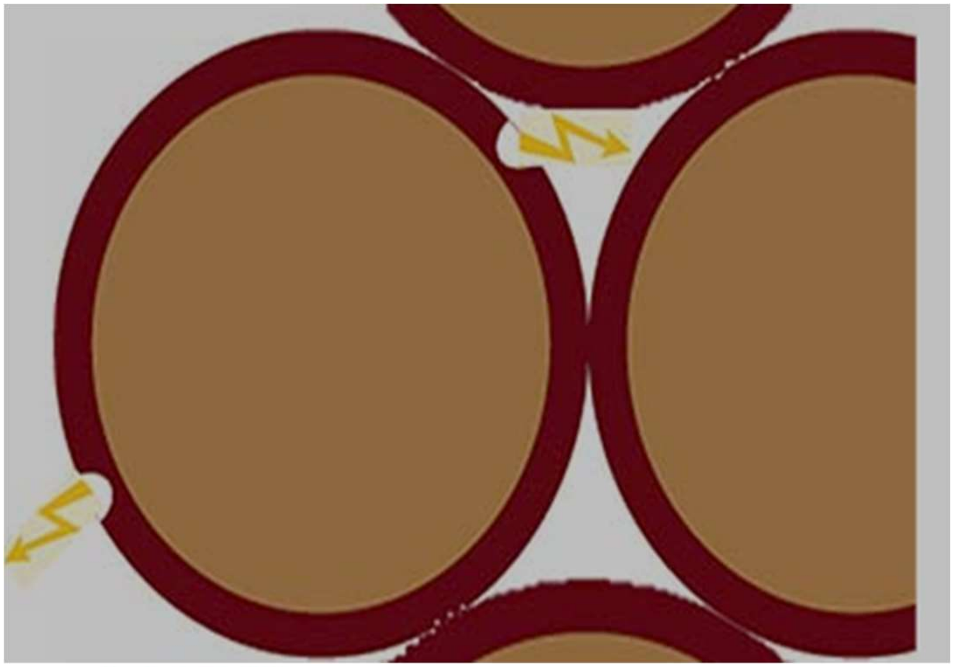
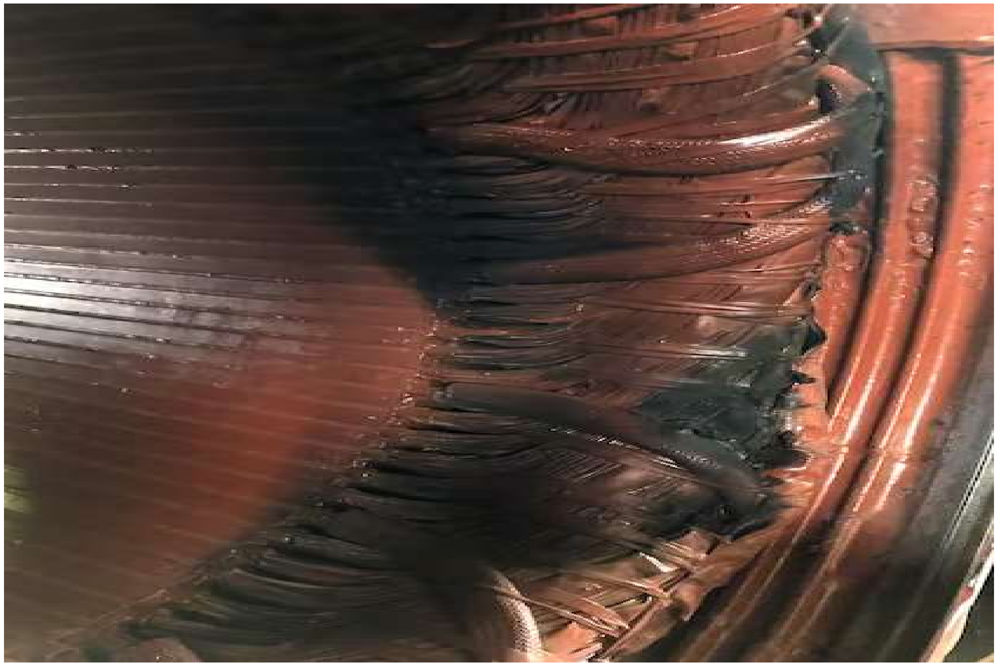
VFD Output
dV/dT, Reflected wave and motor issues

- **Partial discharge:** high dv/dt can cause localized electrical discharges “shorts” between adjacent coil wires damaging coil wire insulation.
- **Corona effect:** arcing from partial discharge creates heat. Heat causes formation of Ozone which degrades insulation and increasing the probability of stronger arcing events leading to permanent motor coil damage.





VFD Output
dV/dT, Reflected wave and motor issues

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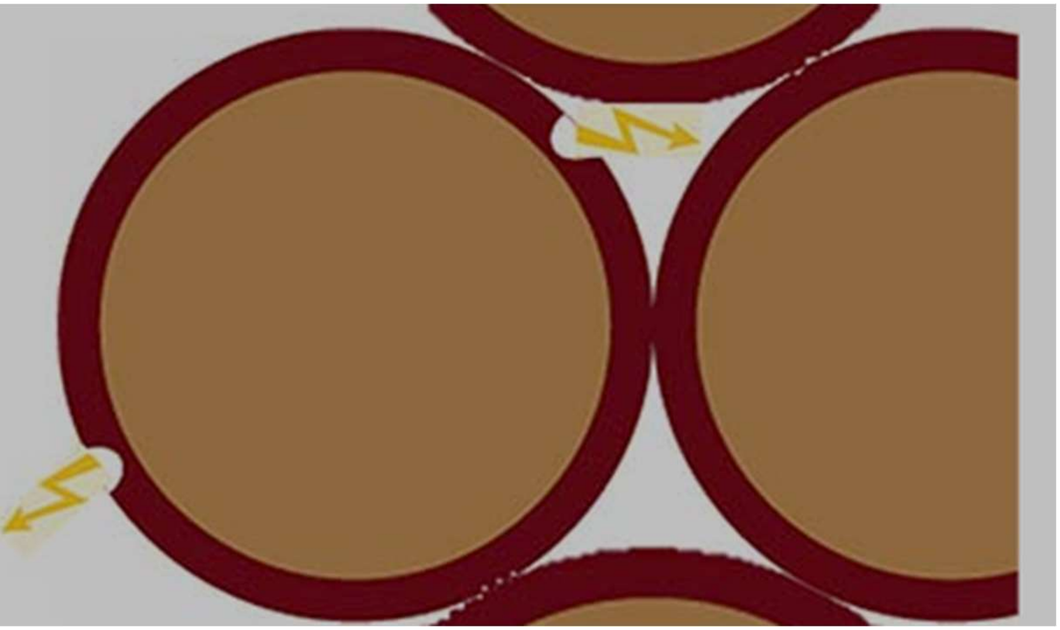

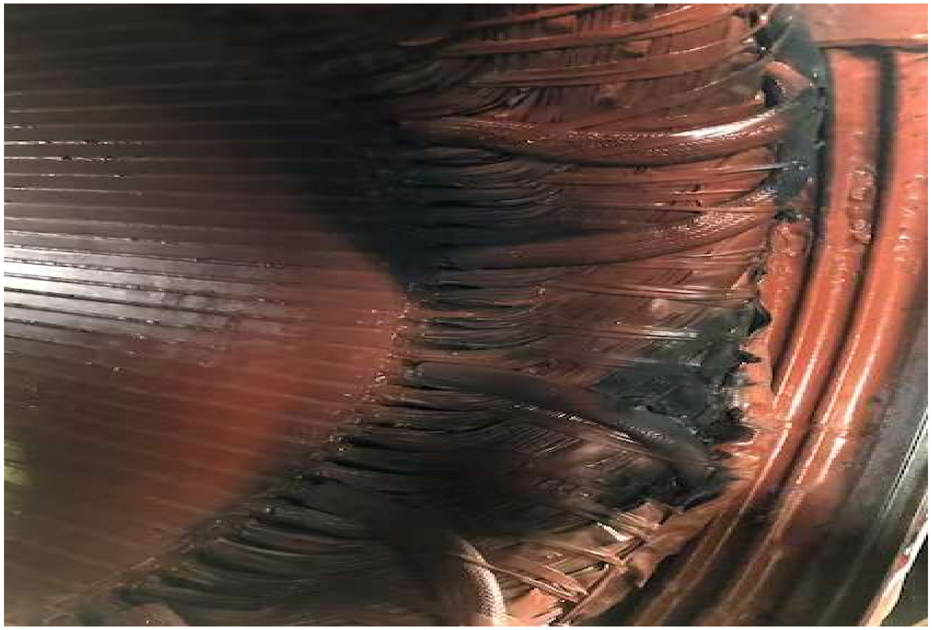

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VFD Output
Remedies for PWM Output issues

Hardware Techniques to overcome PWM issues:

NEMA Inverter Duty rated motors

VFD Cable

Output Filters

1) Output reactor
2) dV/dT Filter
3) Sine Wave Filter

VFD Output
Inverter Rated Motors

NEMA MG 1-2021: Standard for Electric Motors

- Defines the specifications for NEMA rated motors
- Definite Purpose Inverter (VFD) rated: Section IV, Part 31
- Coil Wire insulation higher grade than standard motor to withstand PWM voltage
- Insulation rating allows for diminished cooling caused by running motor at less than 60 Hz

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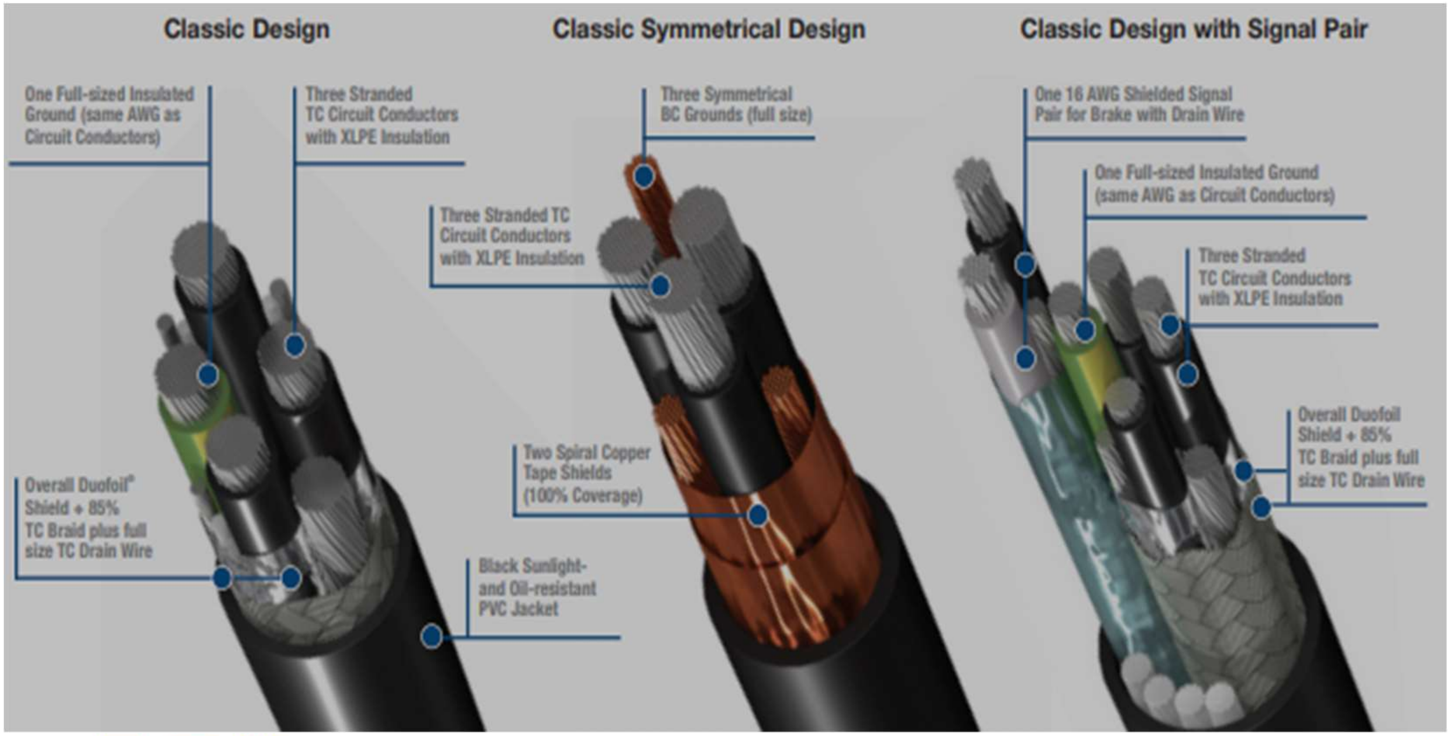
VFD Cable

<u>**Skin Effect:**</u> VFD Cable shielding provides greater conductor surface area or "skin" for high frequency noise caused by common mode voltage/current.



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DG1
Output Filters – Load Reactors

Filters can reduce or eliminate the problems associated with PWM output

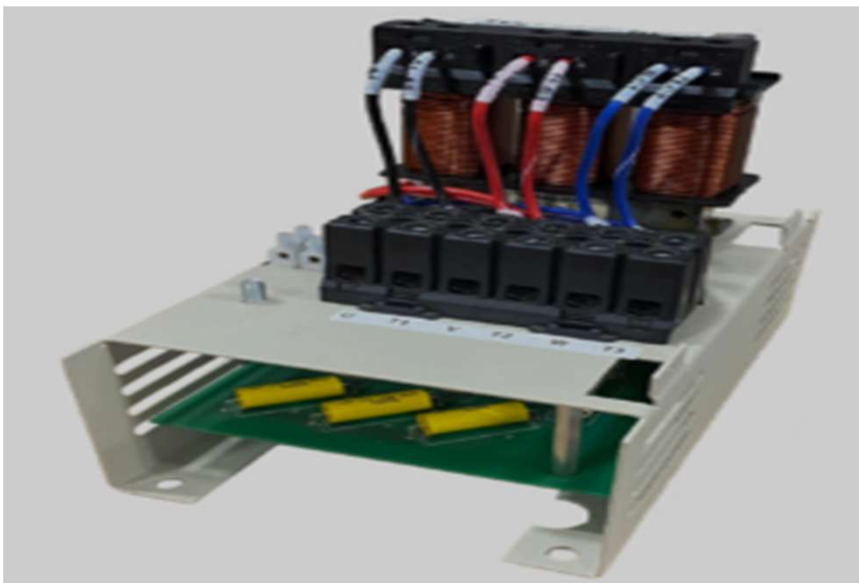
- Load Reactor: 3 coil Inductor installed in series with motor. Adds Impedance between VFD and Motor (usually 3% or 5% Impedance).
- Use when conductor length is 100’ – 300’
  - Impedance increase voltage rise time (dv/dt) which reduces peak voltage at motor coils.
  - Impedance causes voltage drop, which may reduce efficiency of motor and increase motor temperature because of current rise (typically this is not a problem)

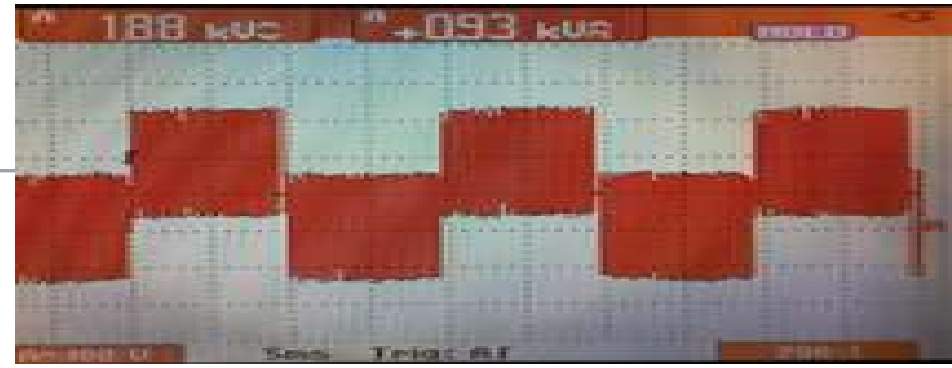
VFD Output
Output Filters – dV/dt filters

dV/dt Filters: Reduces transient voltage overshoot at the motor terminals. Low pass filter - consisting of inductor, capacitor and resistor.

Reduces dv/dt.

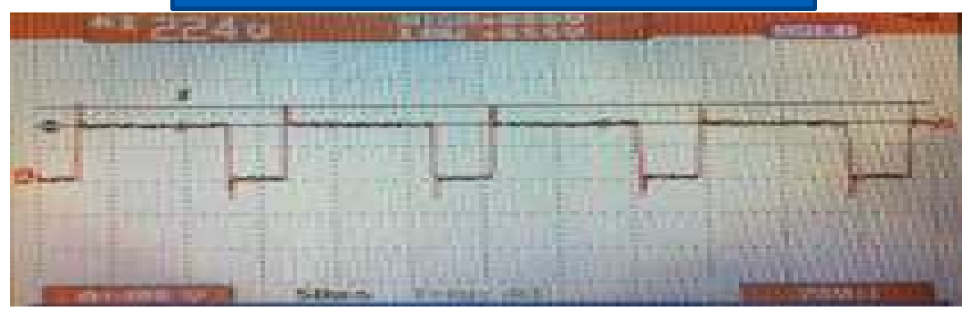
Conductor length 300’ – 1000’





PWM at motor with dV/dT Filter

PWM at motor without dV/dT Filter

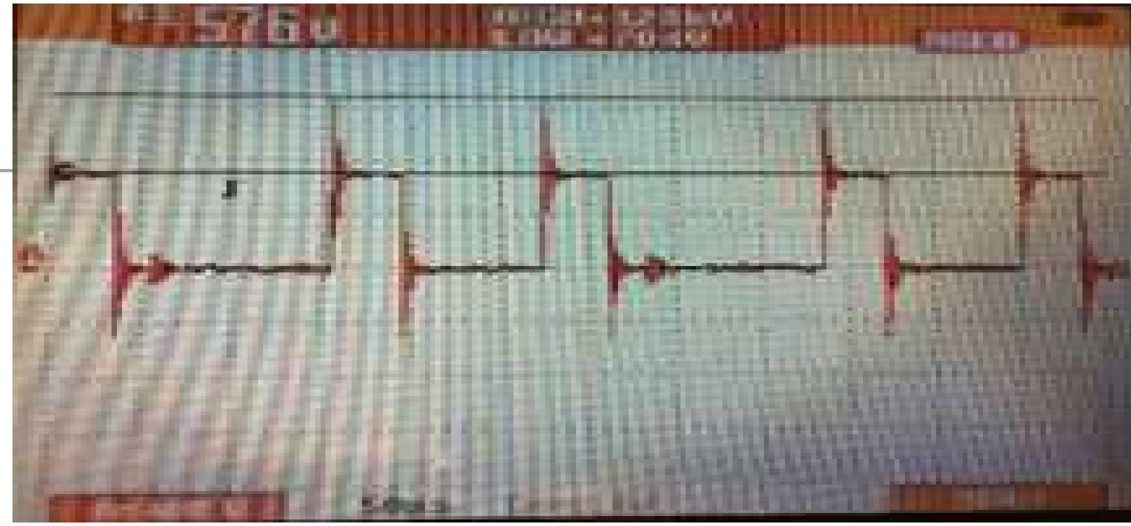


PWM at motor with dV/dT Filter

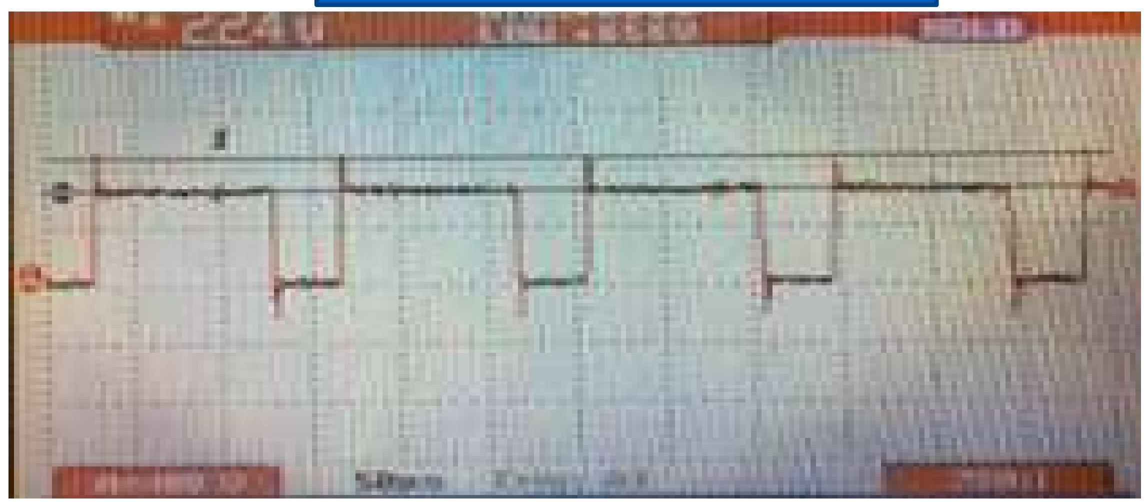
VFD Output
Output Filters – dV/dt filters

<u>dV/dt Filters</u>: Reduces transient voltage overshoot at the motor terminals. Low pass filter - consisting of inductor, capacitor and resistor (impedance). Slows down the steep rise of the PWM waveform.

- Reduces dv/dt.
- Conductor length 300' – 1000'
- Reduces voltage spikes to < 1,000V
- Protects conductors and conductor terminations
- Reduces Common Mode Currents and Voltage i.e. "Noise"
- Reduces heating in motor coils



Motor Output without dV/dT Filter



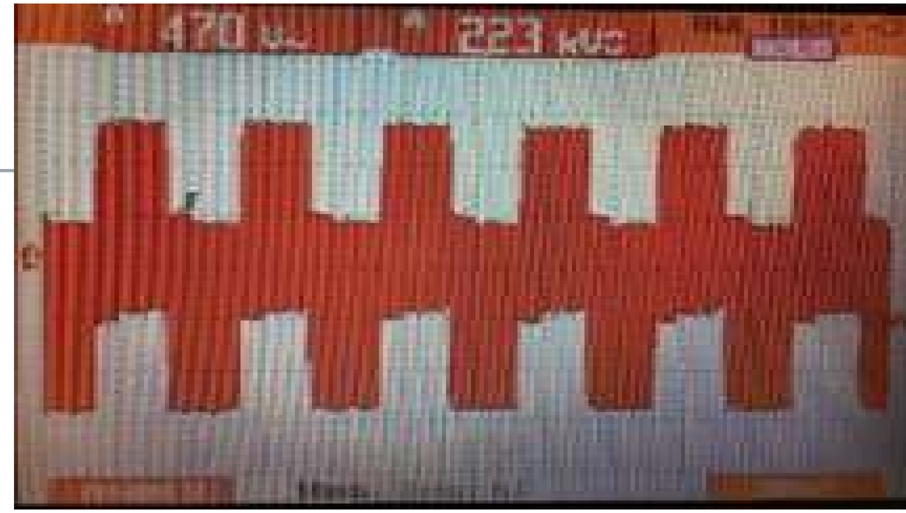
Motor Output with dV/dT Filter

VFD Output

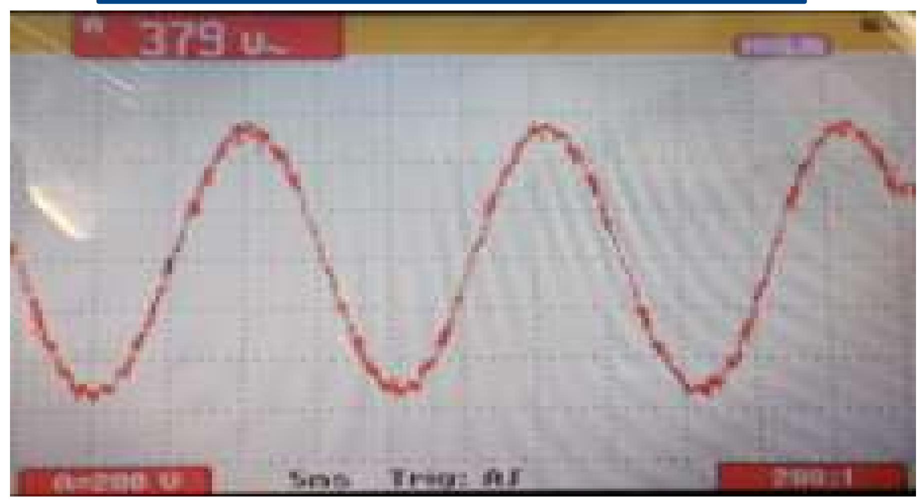
Output Filters – Sine Wave Filters

<u>Sine Wave Filters</u>: Low pass frequency filters

- Reduce voltage peaks
- Converts PWM to nearly sinusoidal output
- Conductor Length 1000’ – 15,000’
- Requires DG1: P8.11 – Sine Filter Enable – set to ENABLE



Motor Output without Sine Wave Filter



Motor Output with Sine Wave Filter

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DG1
VFD Cable

PowerXL Installation Manual MN040002EN

VFD Cable needs to be bonded at both VFD and Motor
- Tight, secure, 360º connection

DG1
Motor Lead Length and Output Filtering App Note

Application Note AP040213EN Effective May 2020

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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Application note available: eaton.com/dg1 AP040213EN

Eaton Resources

www.eaton.com/drives

dV/dT Filters Application Note: AP043001EN

Reflective Wave Phenomena Application Note: AP040013EN

Bearing Currents Application Note: AP040061E

Output Filters and Motor Lead Length Application Note: AP040213EN

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