VFD Installations and Applications

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Chicago IEEE Chapter

Part 3

Agenda

Part 1:

- Harmonic Mitigation
  - Methods to reduce Ithd, Vthd
  - Line reactors and DC link chokes
  - Multi-Pulse
- Active Rectifier Applications
  - Downhill conveyors
  - Centrifuges
  - Making Kevlar
  - ID fans
- Active Rectifier Operation

Part 2:

- Motor speed vs max load / cooling, use of motor RTDs
- Overspeed with fans / pumps and increase in torque and power (2.5%, 5% increases)
- Min speed with pumps
- SCCR for drives
- HRG vs solid ground

Part 3:

- Load reactors on the output (and reflected waves)
- Shaft grounding brushes / bearing currents
- Wiring on input / output
  - Insulation types
  - Conduit, tray
  - Type (VFD, individual wires)
  - Control wiring management

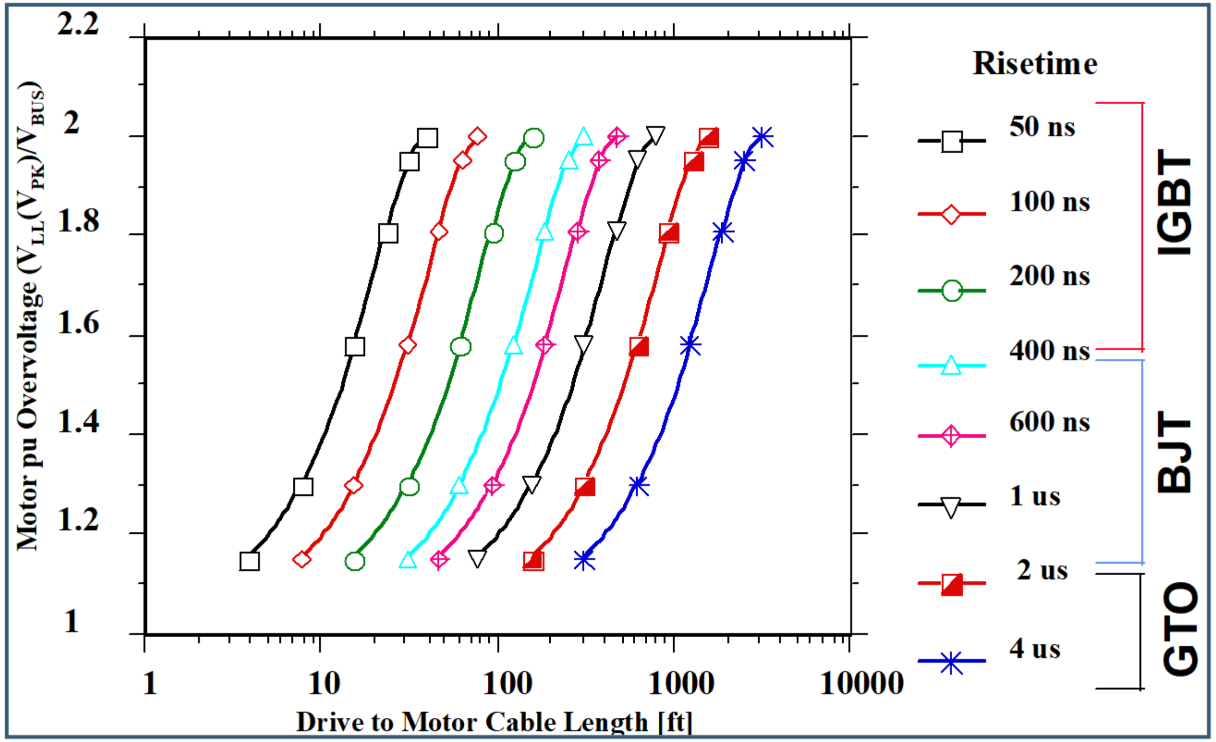
Load Reactors

Reflected Waves

- For many years, there was no real concern about the type of cable or the length of cable between the drive and motor.
- This was because the switching speed of the power semiconductors used in the drives were slow, and most of the AC drives were for 230V motors. Also, distances were usually less than 400ft.
- However, as the semiconductors became faster, and as the bus voltage increased, motors started to fail. Why?
- Peak voltage at the motor terminals was exceeding a value that caused premature motor insulation failure
- At the drive terminals, peak voltage is 1x the DC bus voltage
- At a critical cable length, the peak voltage at the motor would be 2x the DC bus voltage
- This is a problem

Motor Insulation System

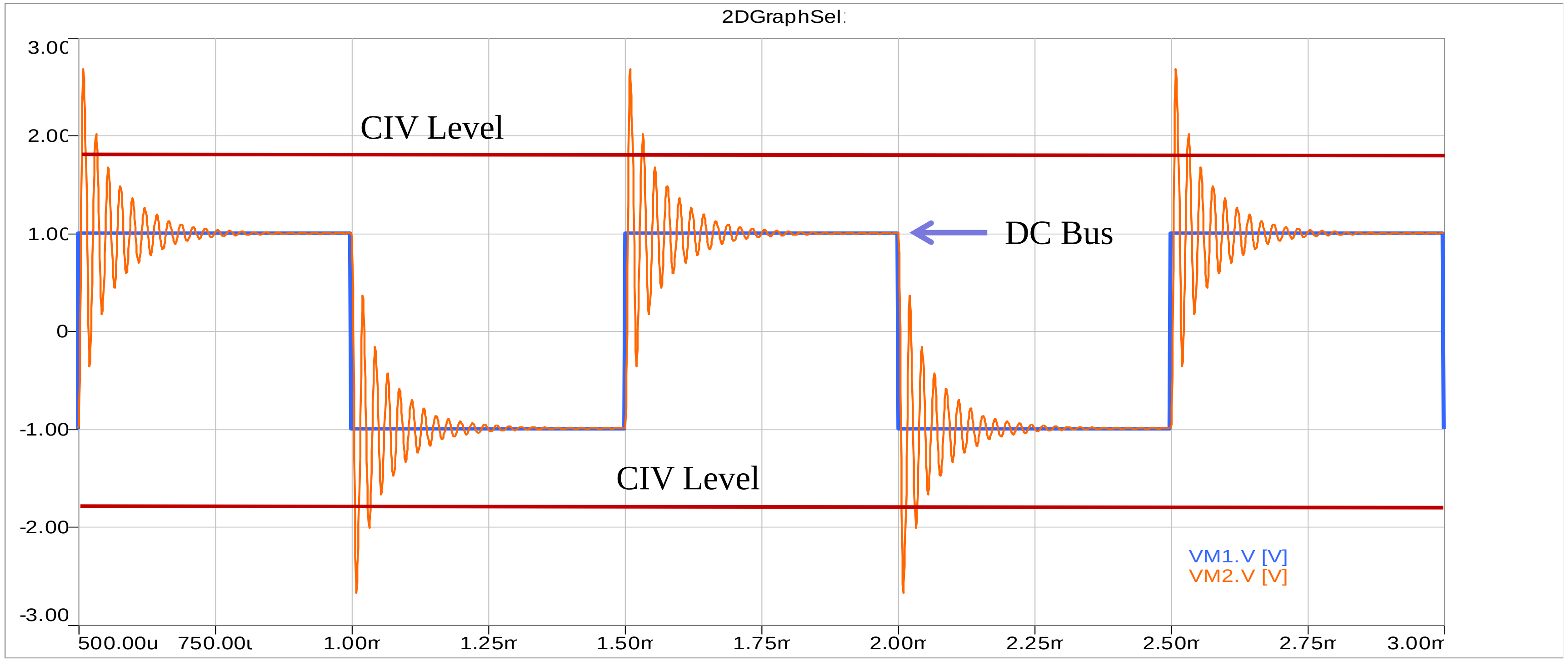
- Peak withstand voltage for slow risetimes (for example, > 6 us) was determined by the breakdown strength of the magnet wire insulation
- Peak withstand voltage for fast risetimes and higher carrier frequencies causes corona failure mechanism of the magnet wire insulation
- IGBT technology creates greater stresses on the motor's insulation system than previously seen with older style switching devices



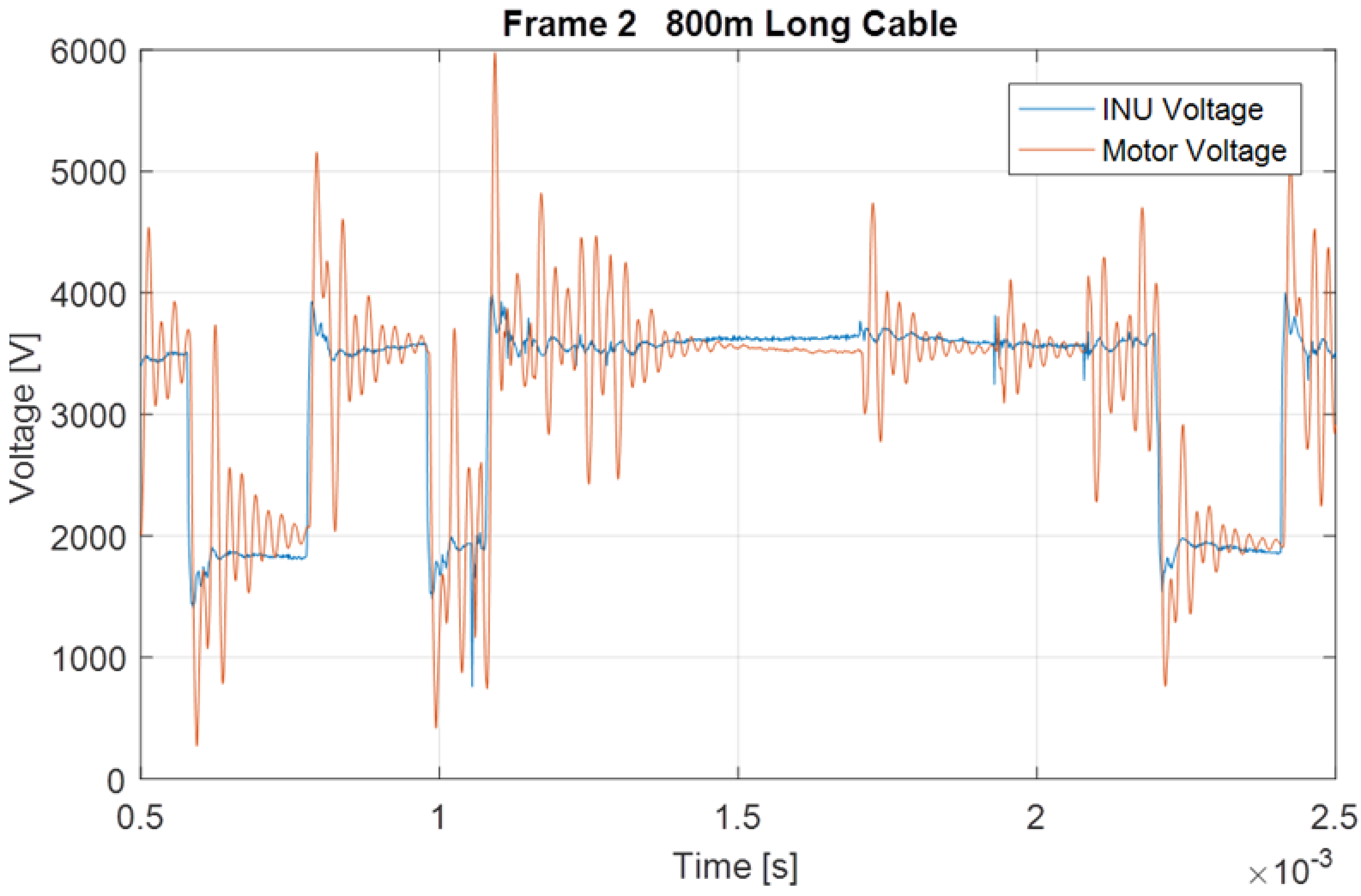
Z Liu, GL Skibinski, *Method to Reduce Overvoltage on AC Motor Insulation from Inverters with Ultra-Long Cable*, IEEE IEMDC Conference, 2017

When does PD (Corona) occur?

- Reflected wave produces voltage peaks at the motor terminals
- Terminal voltage in excess of the insulation system Corona Initiation Voltage (CIV) level will begin the Partial Discharge (PD) process
- Excessive voltage causes partial discharges / corona that attacks insulation materials

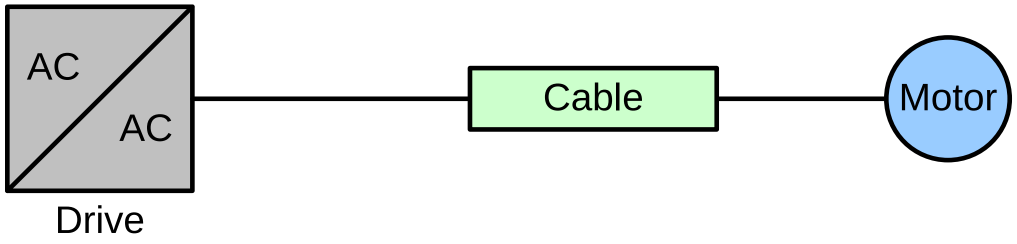


Example, Medium Voltage Drive and Motor



Reflected Waves

- Why can this be a problem?
  - Partial Discharge
  - First-Turn Failures



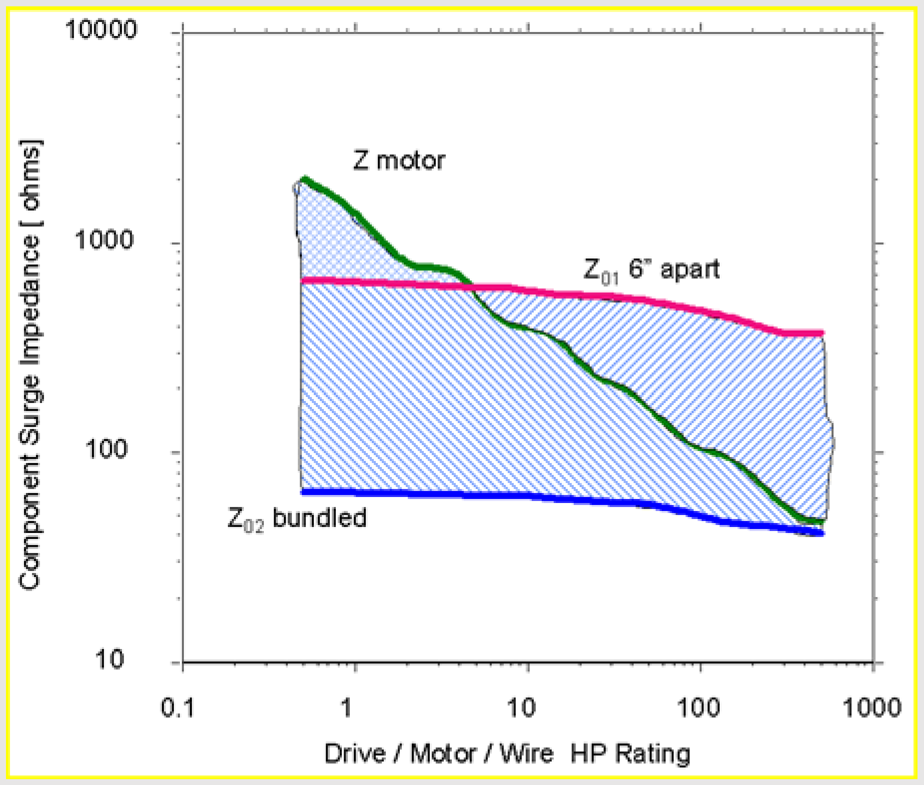
- Affected by:
  - Length of cable between drive and motor
  - Magnitude of PWM voltage pulses (DC bus voltage)
  - Rate of rise of PWM voltage pulses (dV/dt)
  - PWM minimum spacing between pulses
  - Motor and cable surge impedance mismatch
  - Motor load

L Saunders, G Skibinski, S Evon, D Kempkes, *Riding the reflected wave – IGBT drive technology demands new motor and cable considerations*, IEEE PCIC Conf, Sept 1996

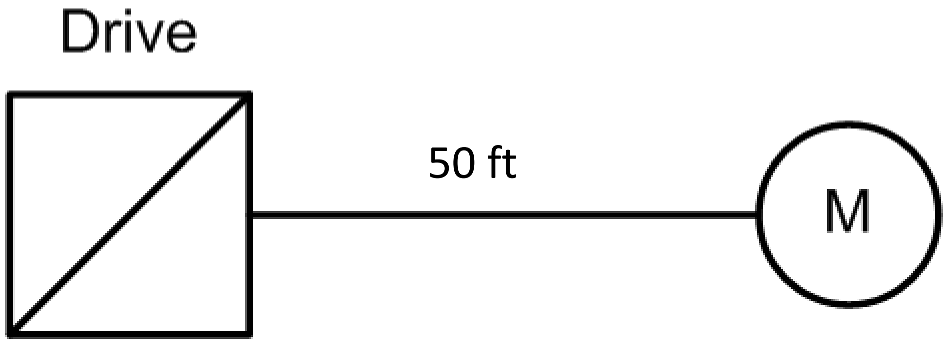
Why motor and cable surge impedance?

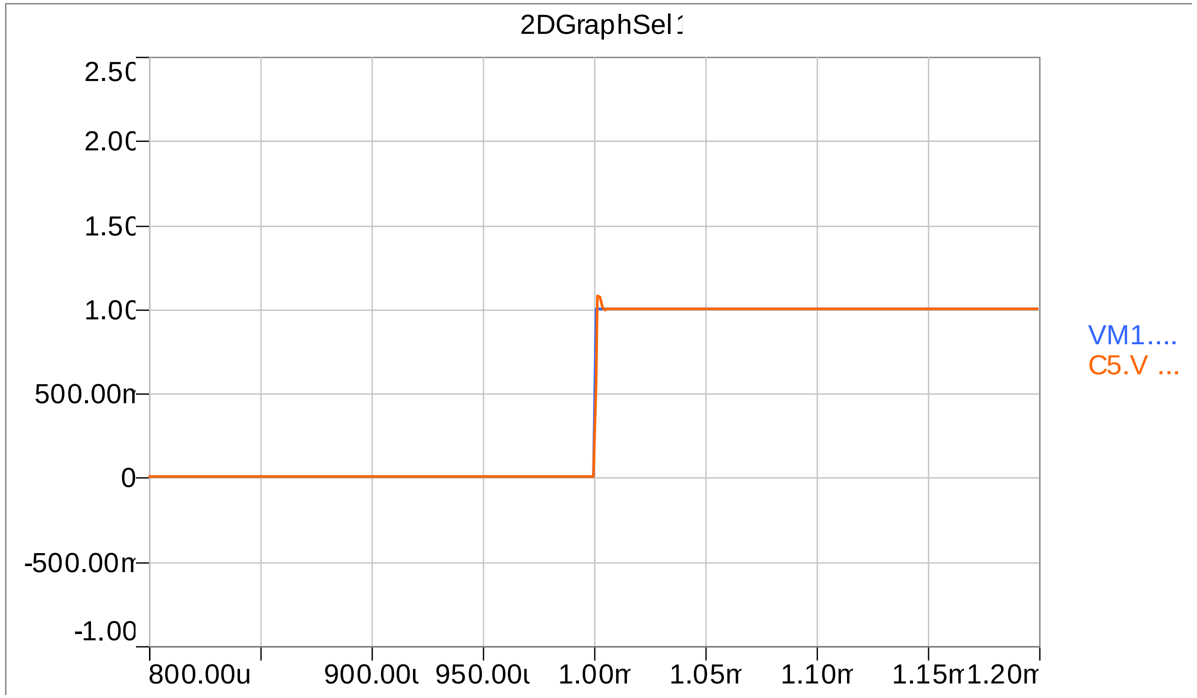
- A difference in surge impedance between the cable and motor causes voltage ring-up
- Reflection coefficient = Γ (gamma)
- Cable impedance about 80 to 180 Ohms
- Motor impedance about
  - <5hp = 2000 to 5000 Ohms
  - 125hp = 800 Ohms
  - 500hp = 400 Ohms
  - load affect is secondary

$$V_{\text{receiving end}} = (1+\Gamma)V_{\text{sending end}} \qquad \Gamma = \frac{Z_{load} - Z_0}{Z_{load} + Z_0}$$

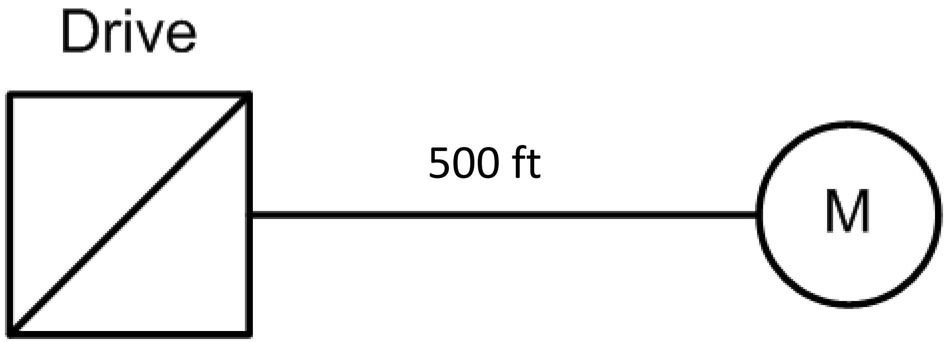


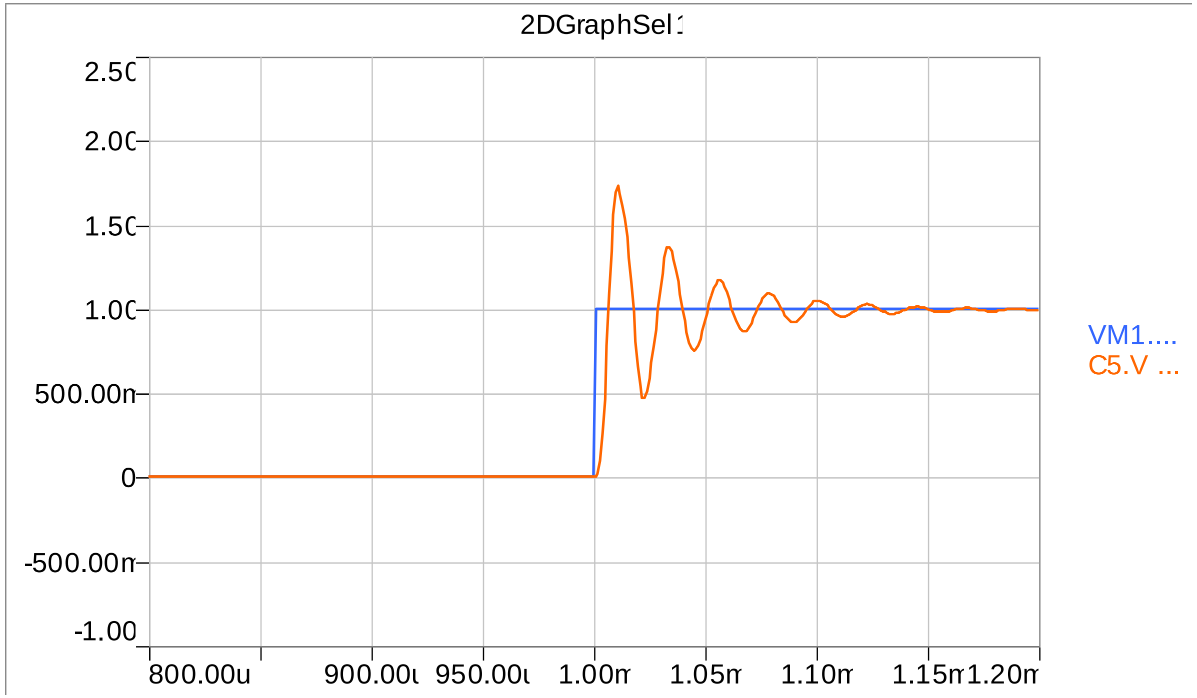
Short Cable


Drive
50 ft
M

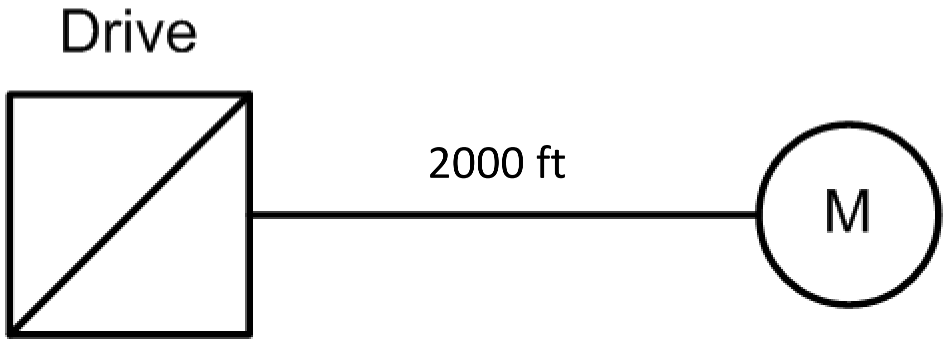

2DGraphSel1
2.50
2.00
1.50
1.00
500.00m
0
-500.00m
-1.00
800.00u
900.00u
950.00u
1.00m
1.05m
1.10m
1.15m
1.20m
VM1....
C5.V ...

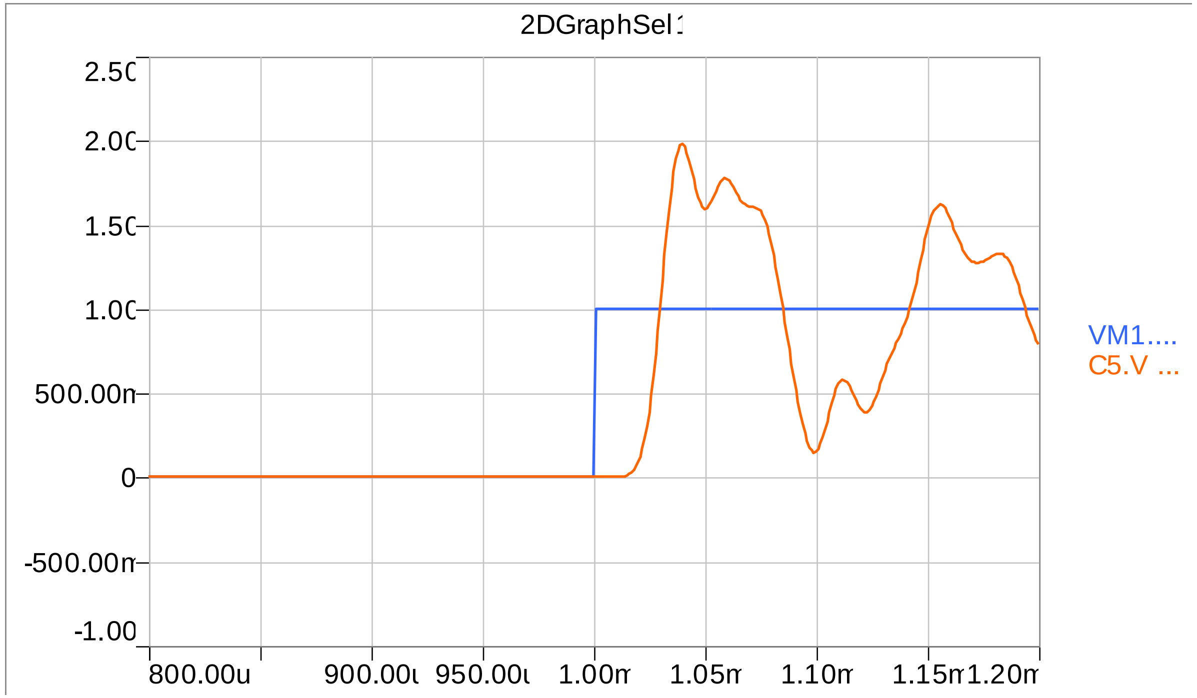
Longer Cable



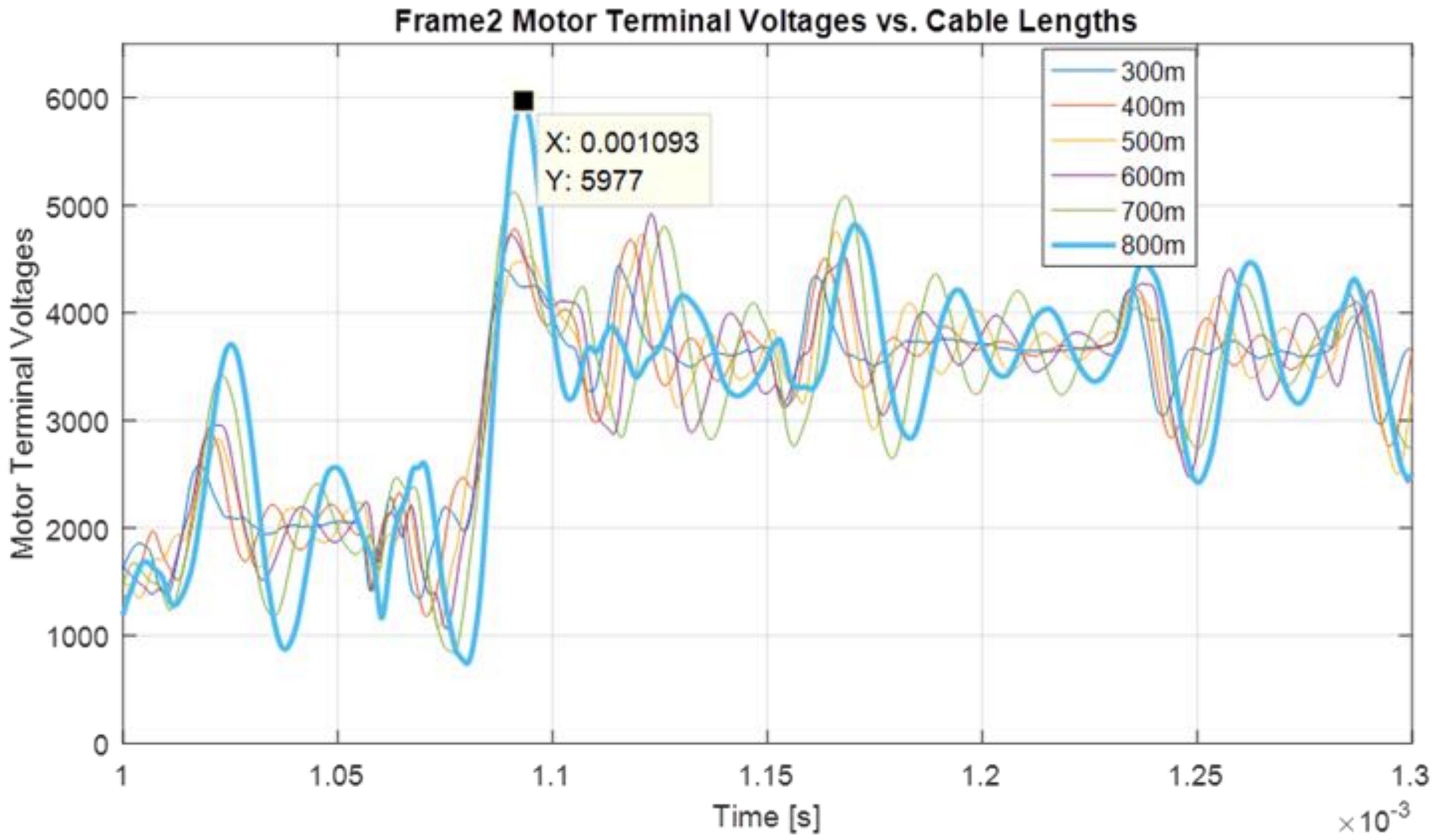


Longest Cable

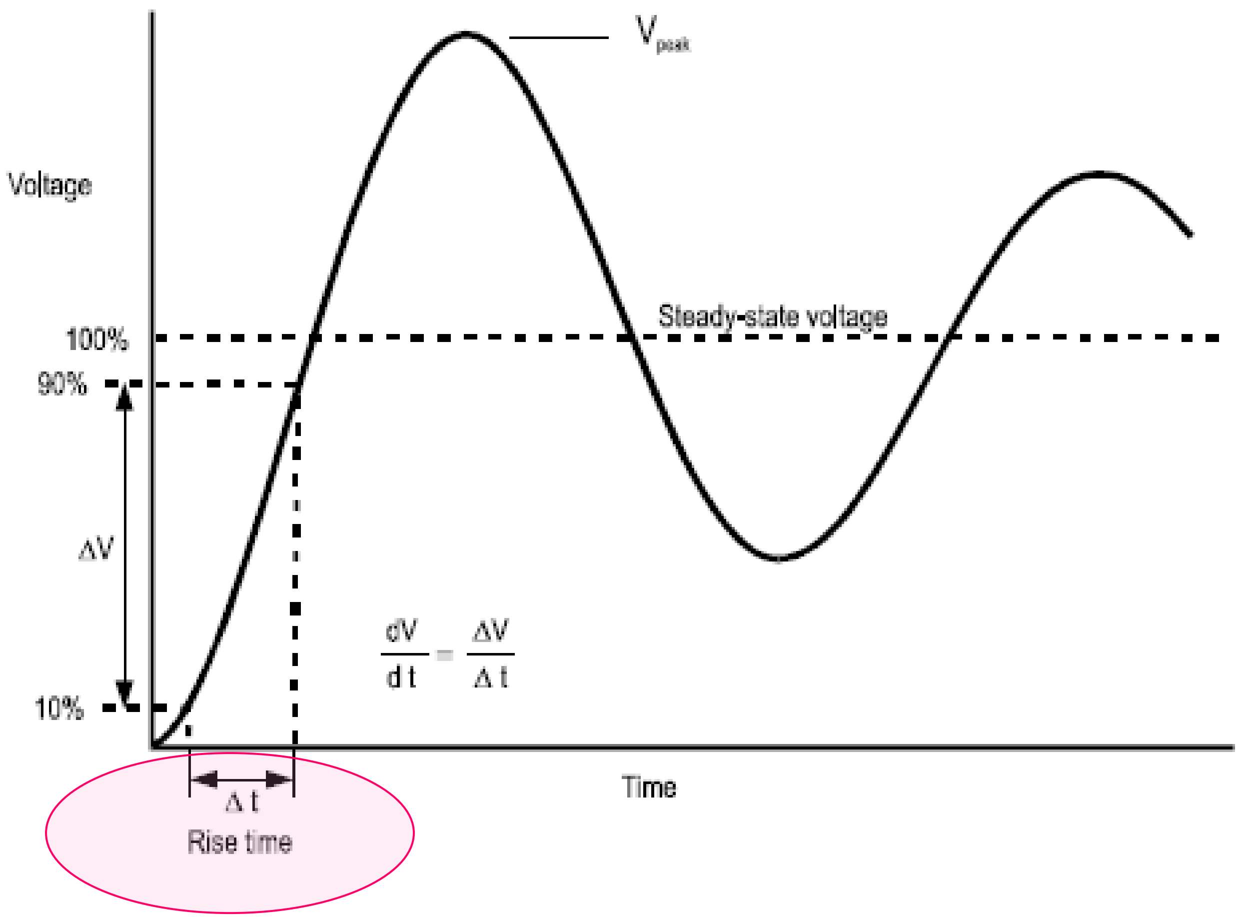




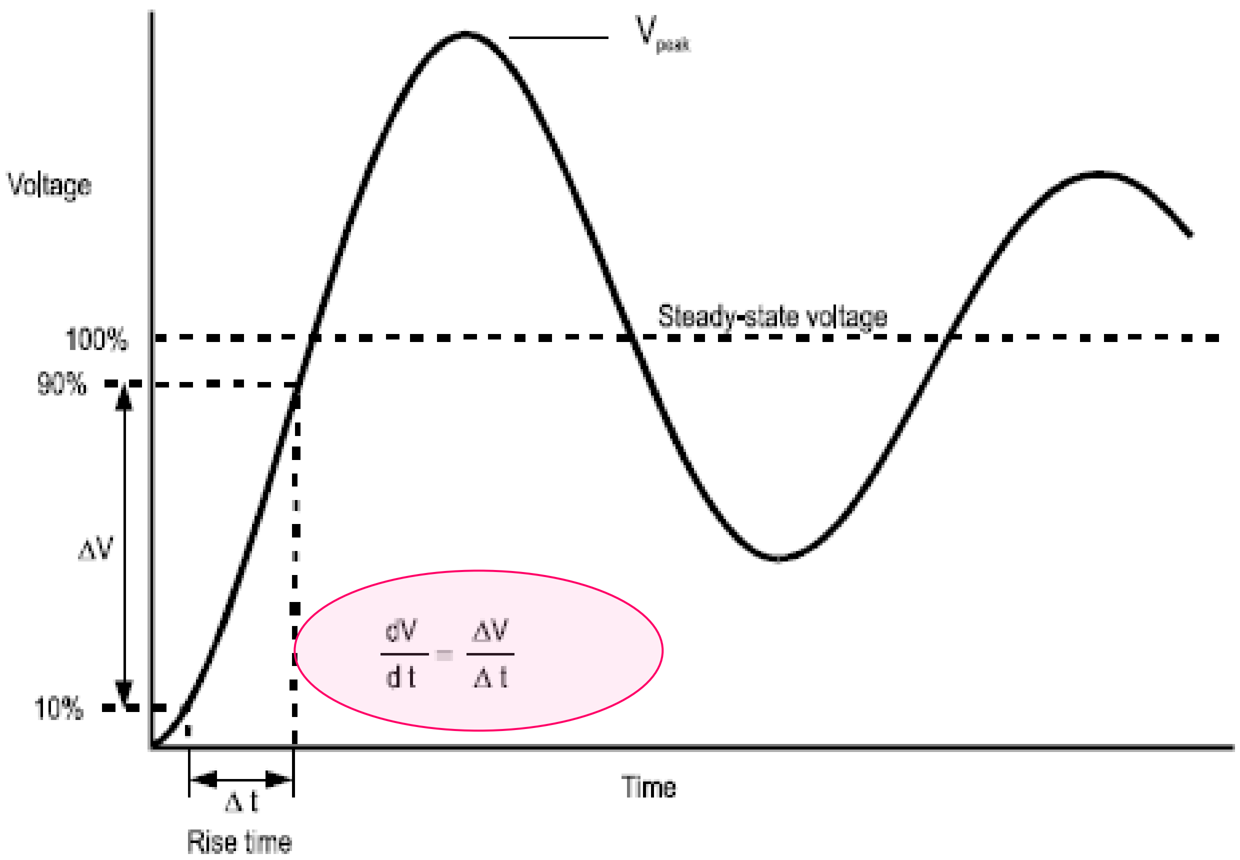
Example of Motor Terminal Voltages vs Cable Length



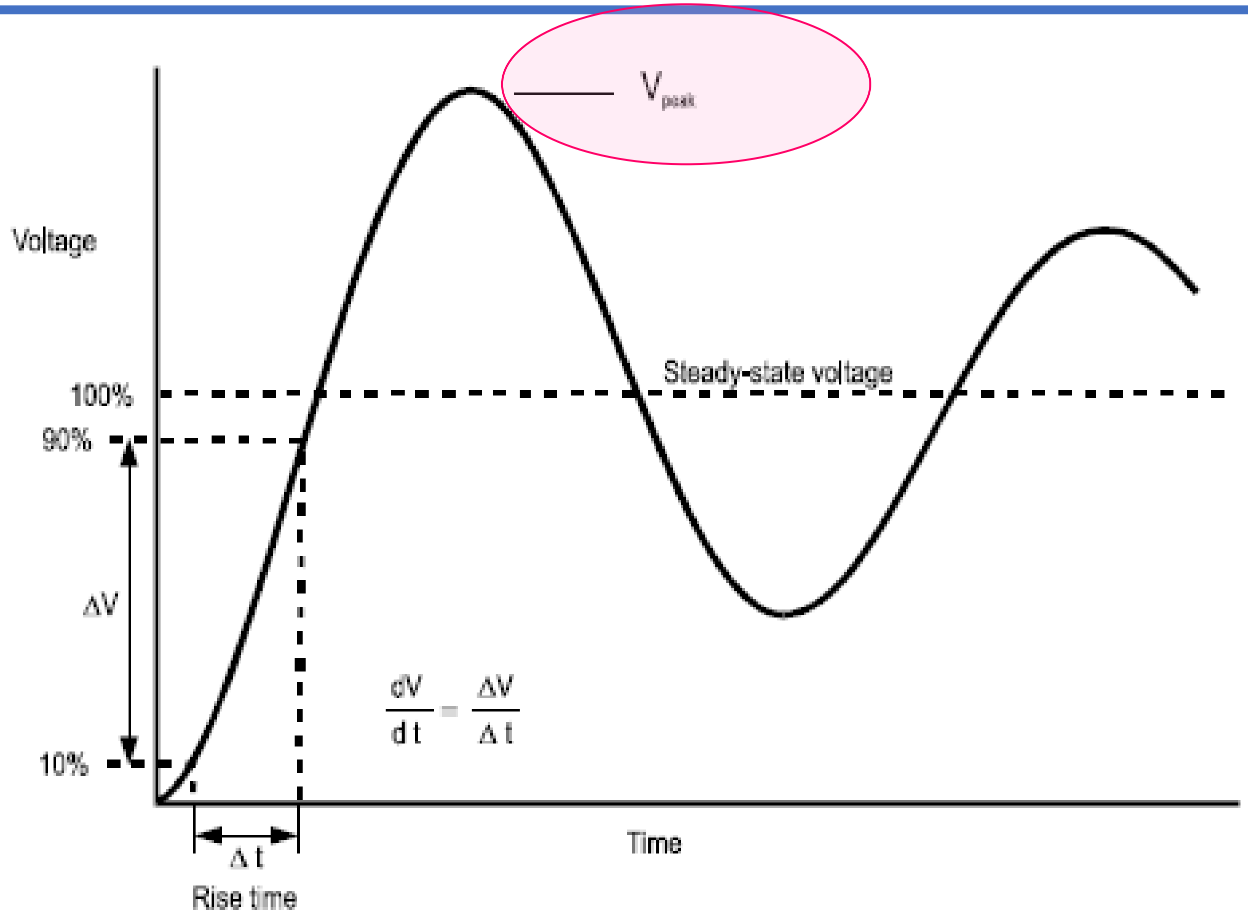
Risetime Definition (MG1)



dV/dt Definition (MG1)



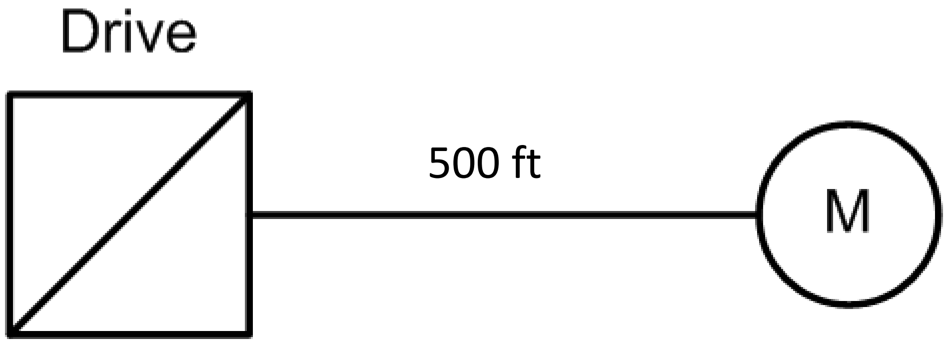
Vpk Definition (MG1)

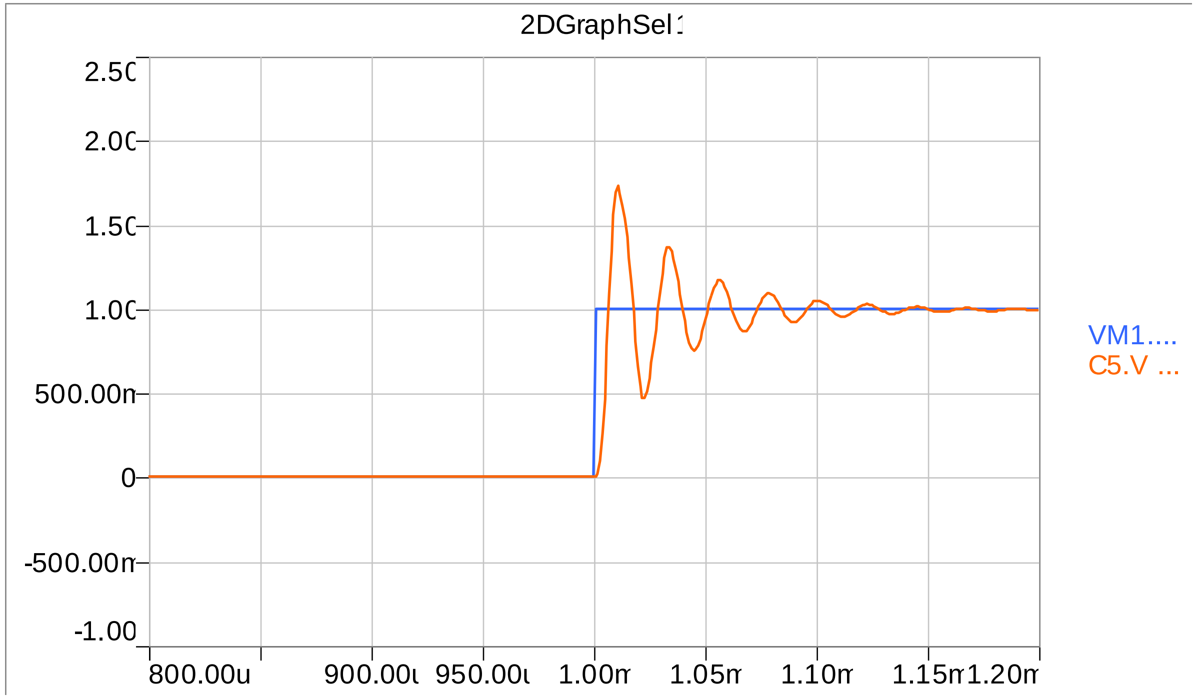


NEMA MG-1, Sect 30, 31: dt > 1us, Vpk < 2.04*Vrms rated

IEC uses 10-90% of Vpeak, not the steady-state DC bus voltage

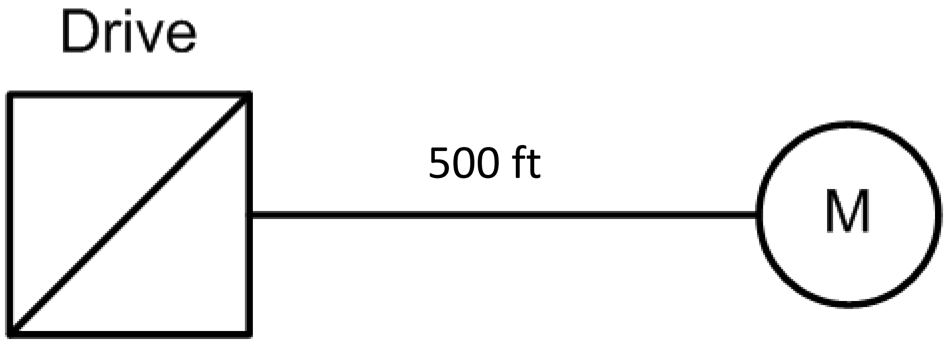
Step size of 100%

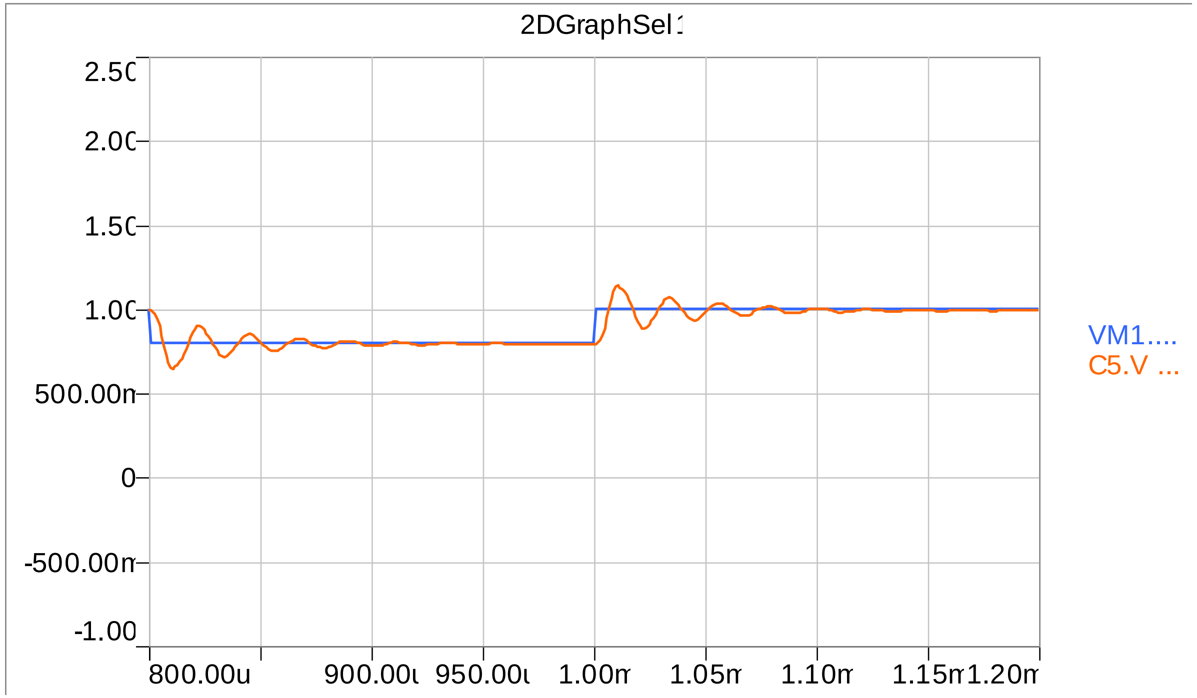




Vpk is about 1.7x the Voltage step size

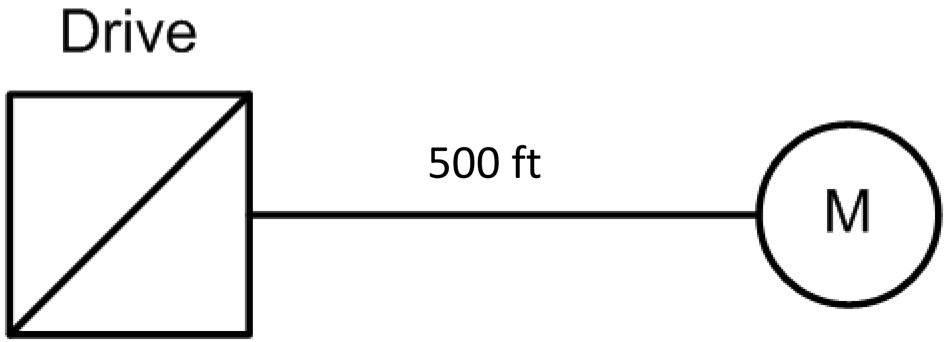
Step size of 20%

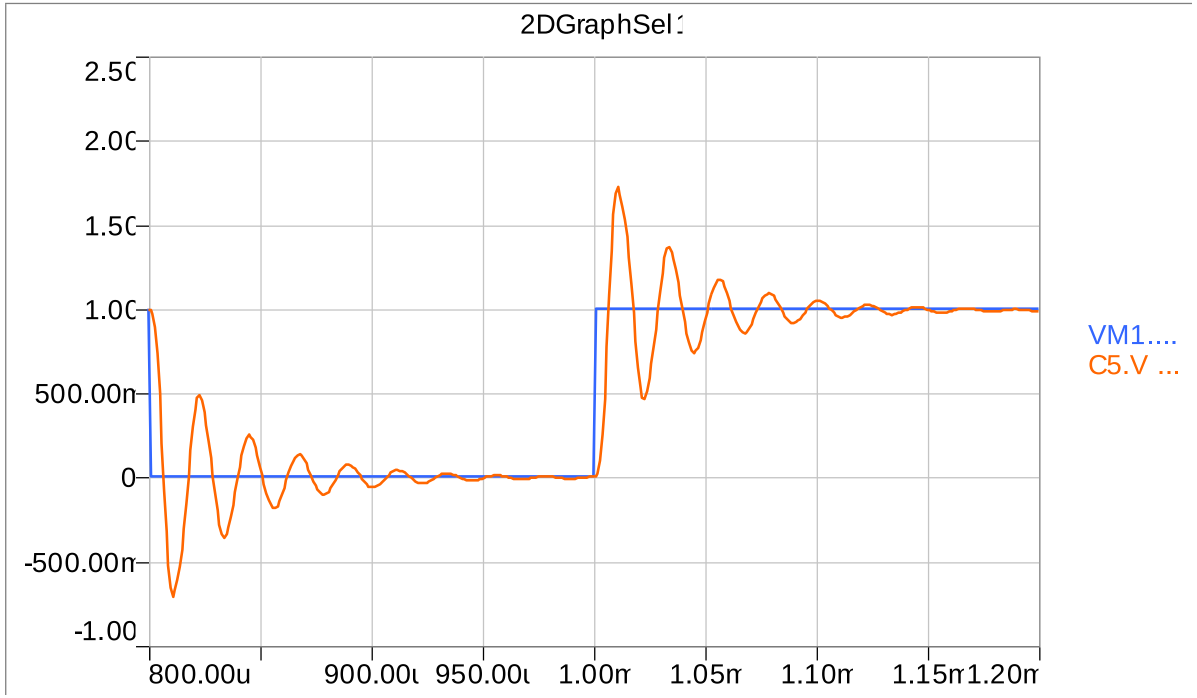




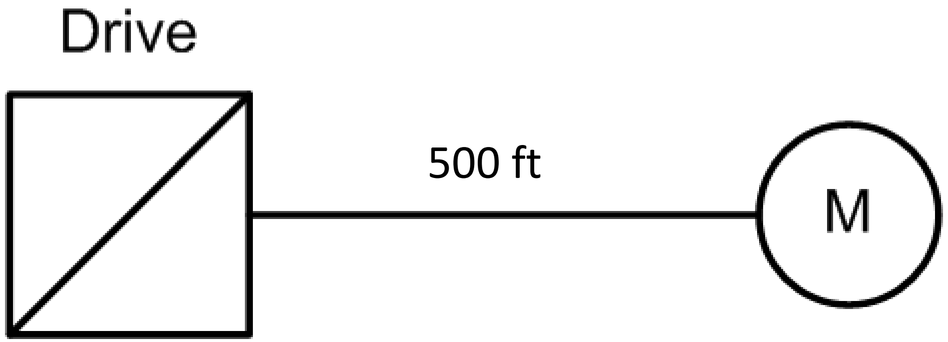
Small voltage steps helps

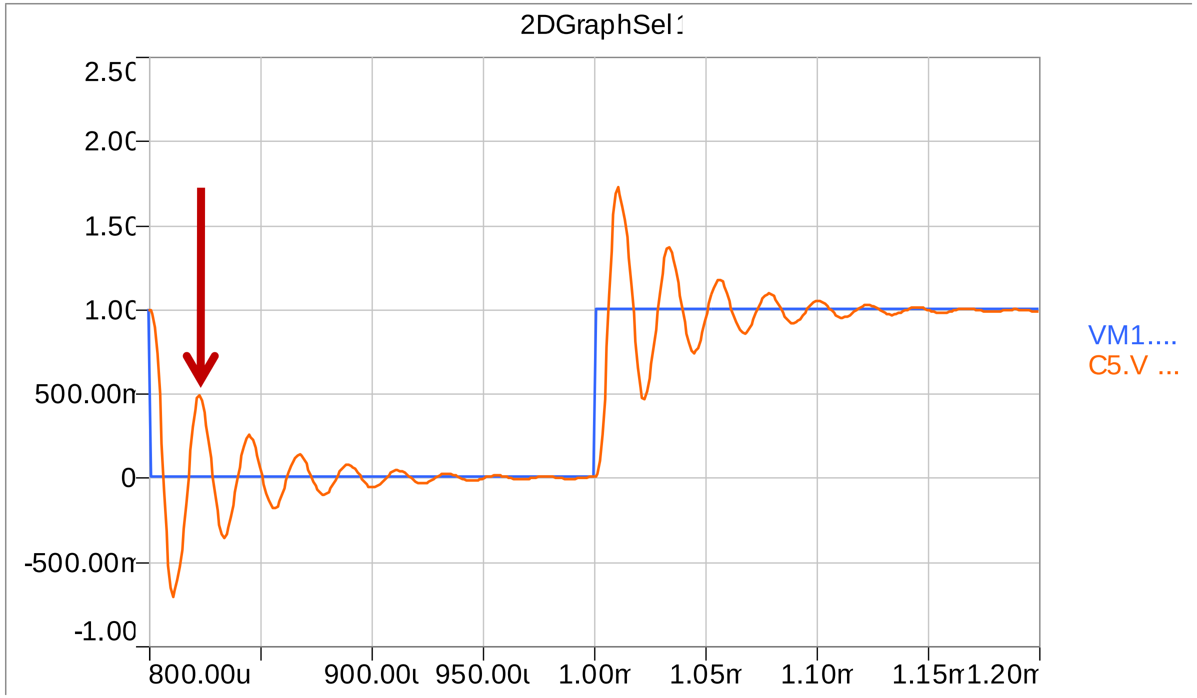
Pulse width 200 us



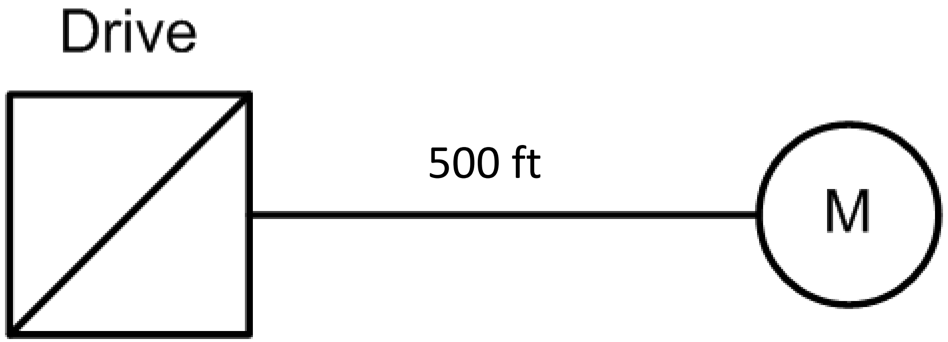


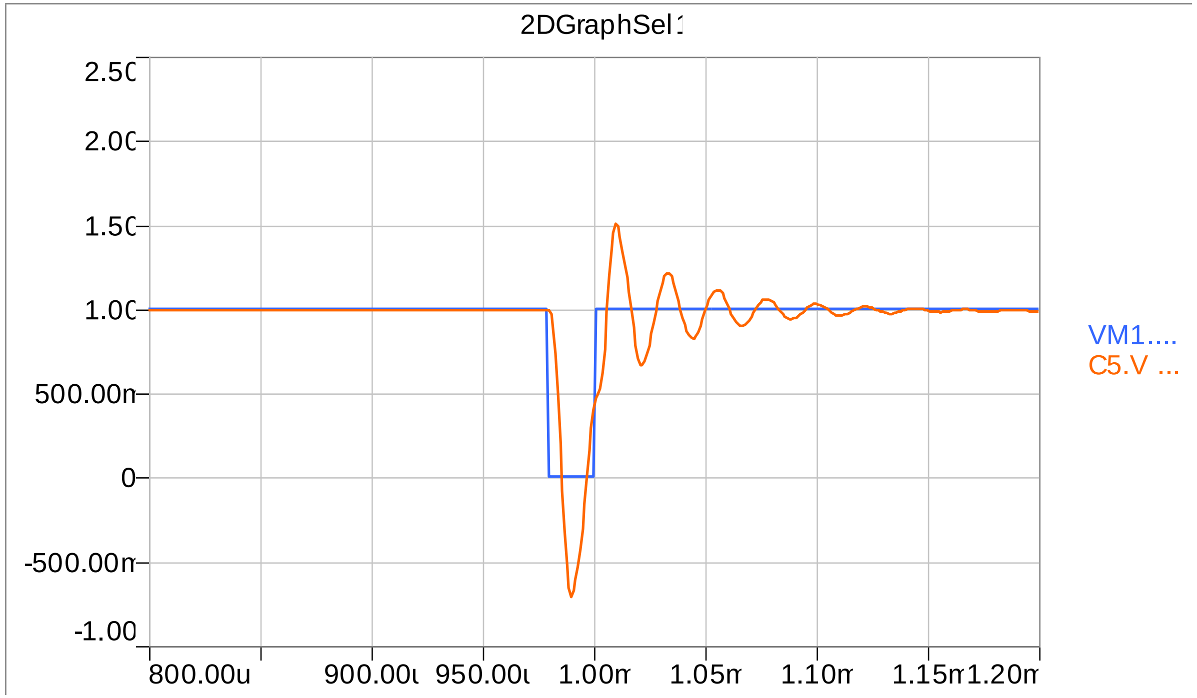
Pulse width 200 us



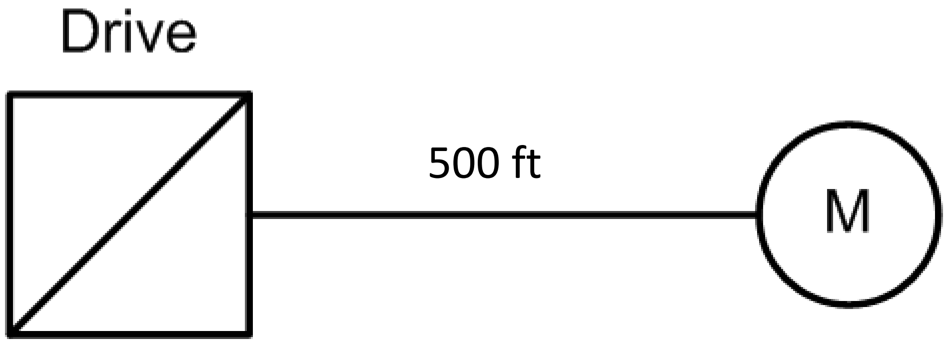


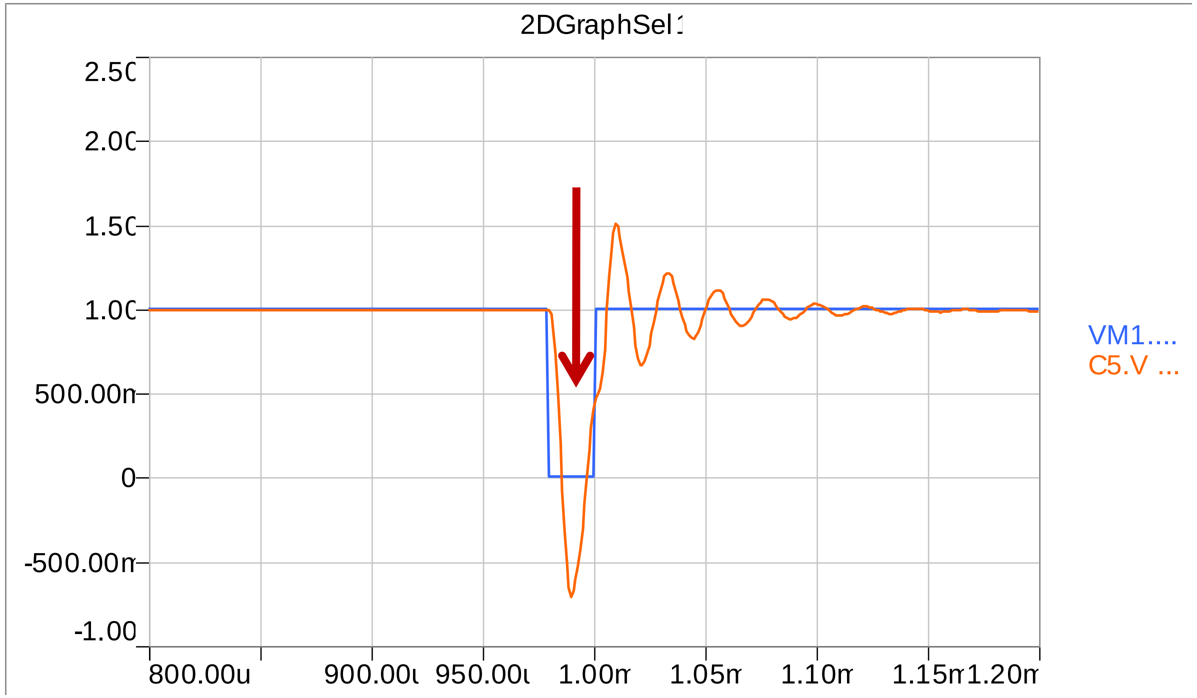
Pulse width 25 us



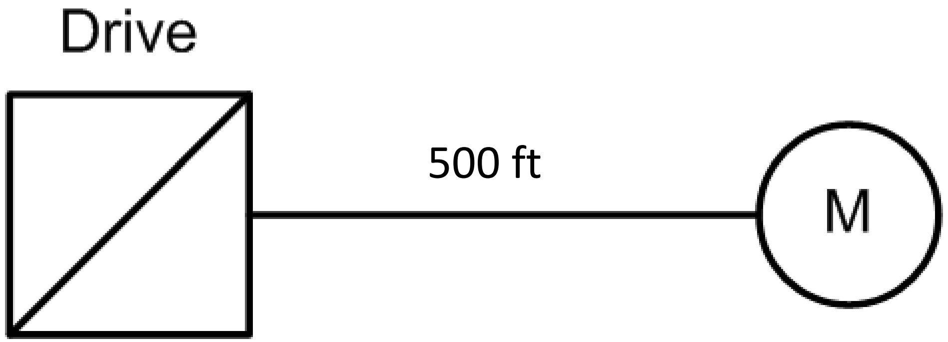


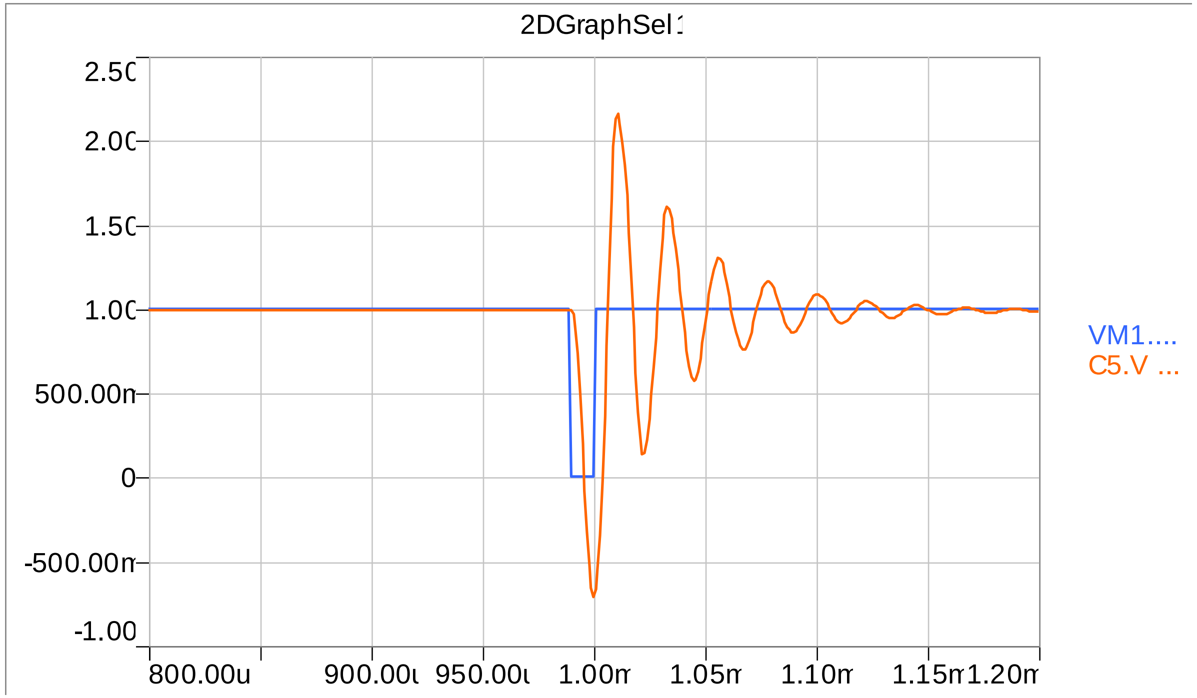
Pulse width 25 us





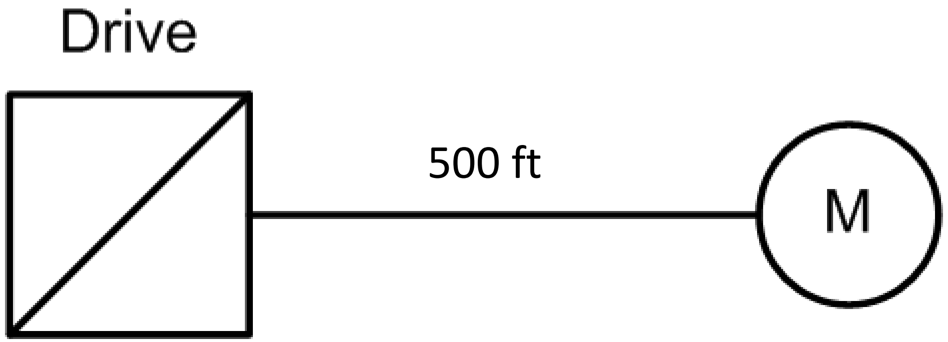
Pulse width 11 us

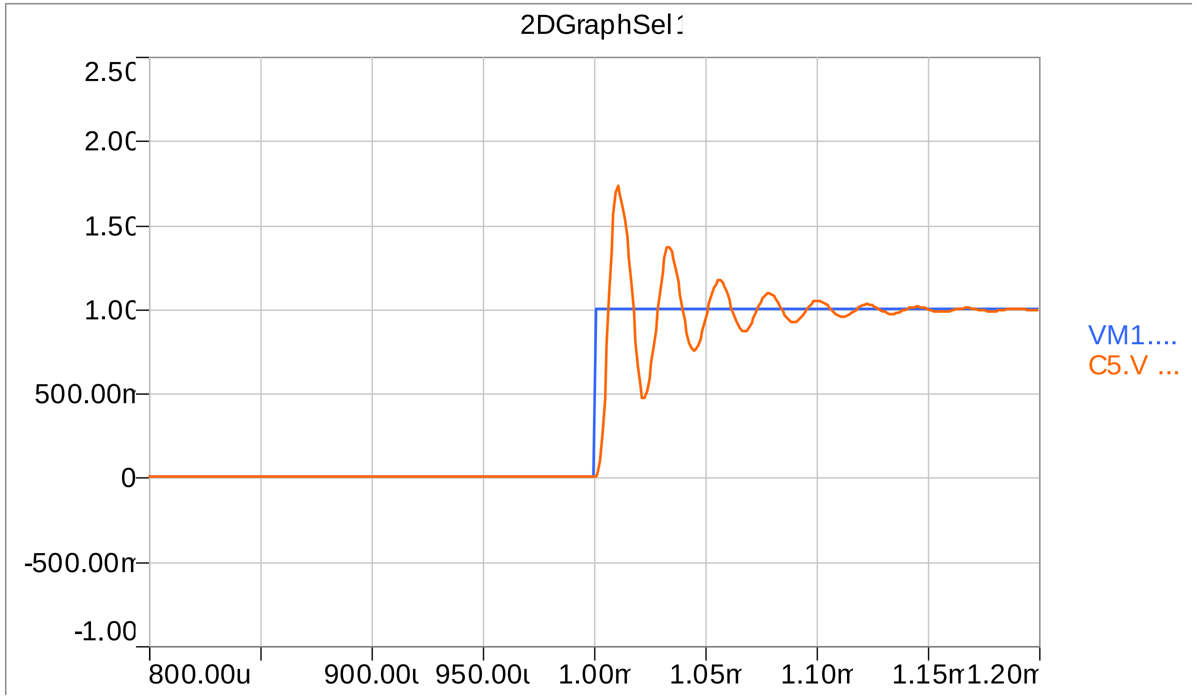




Need to eliminate very narrow pulses

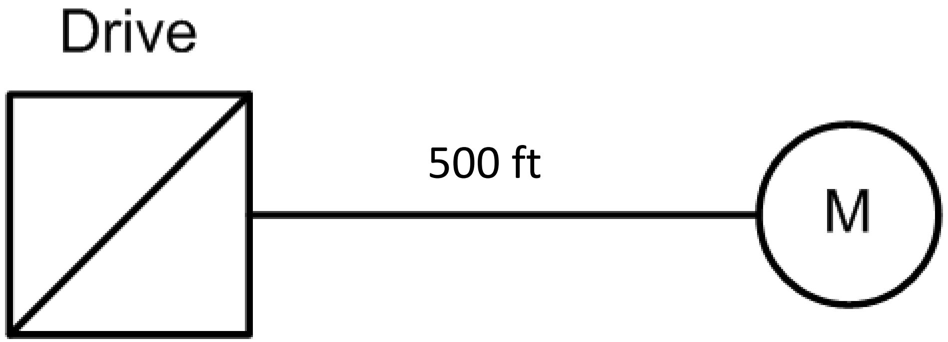
dV/dt = 10,000 V/us

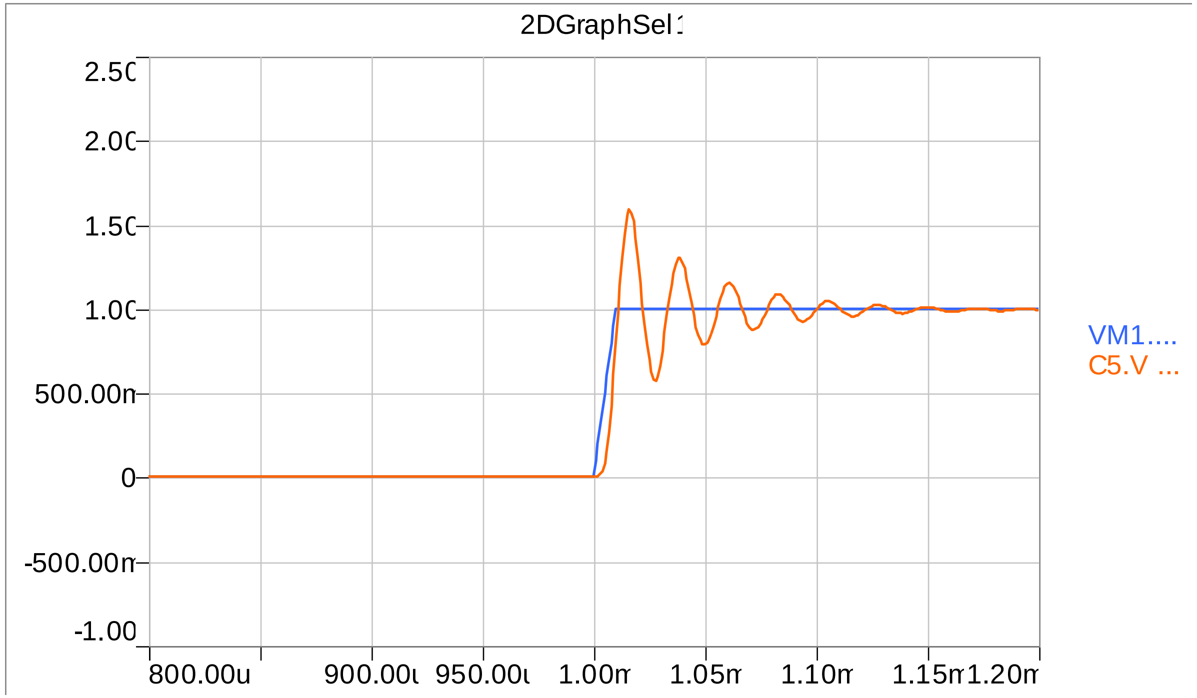




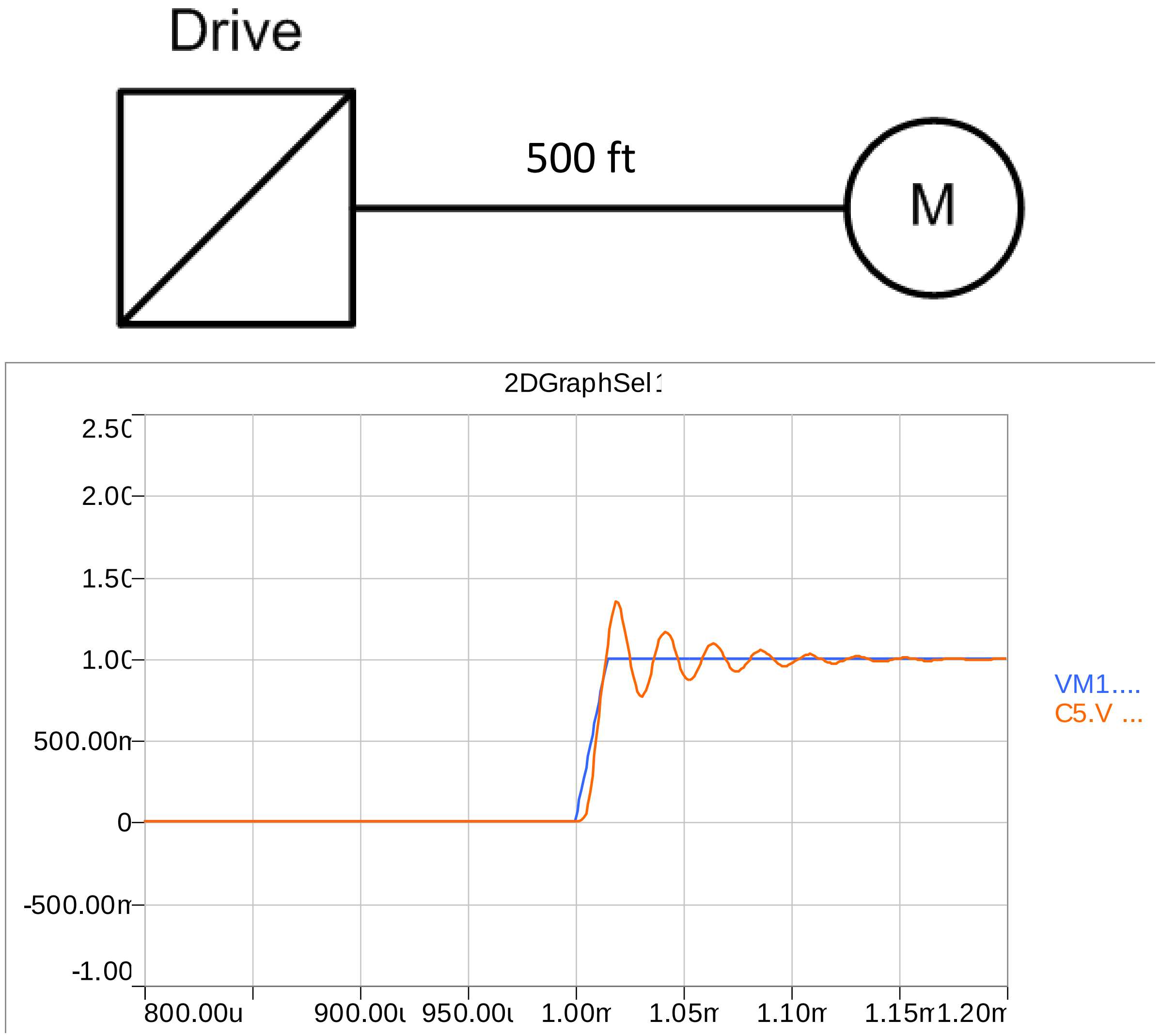
Small hp IGBTs have
dV/dt ~ 5000 V/us

dV/dt = 1000 V/us



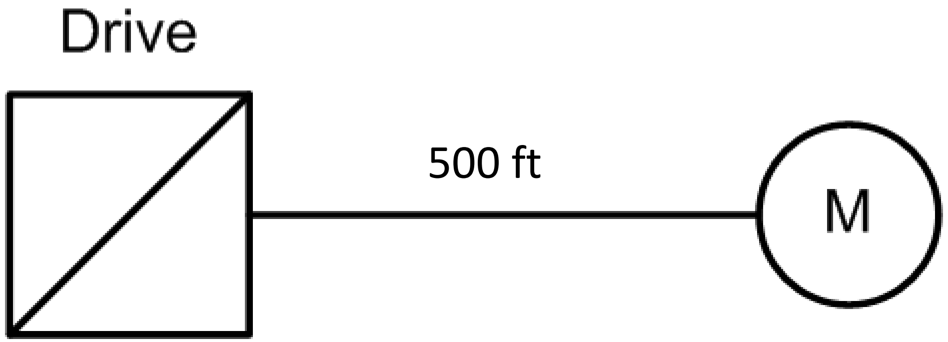


dV/dt = 700 V/us

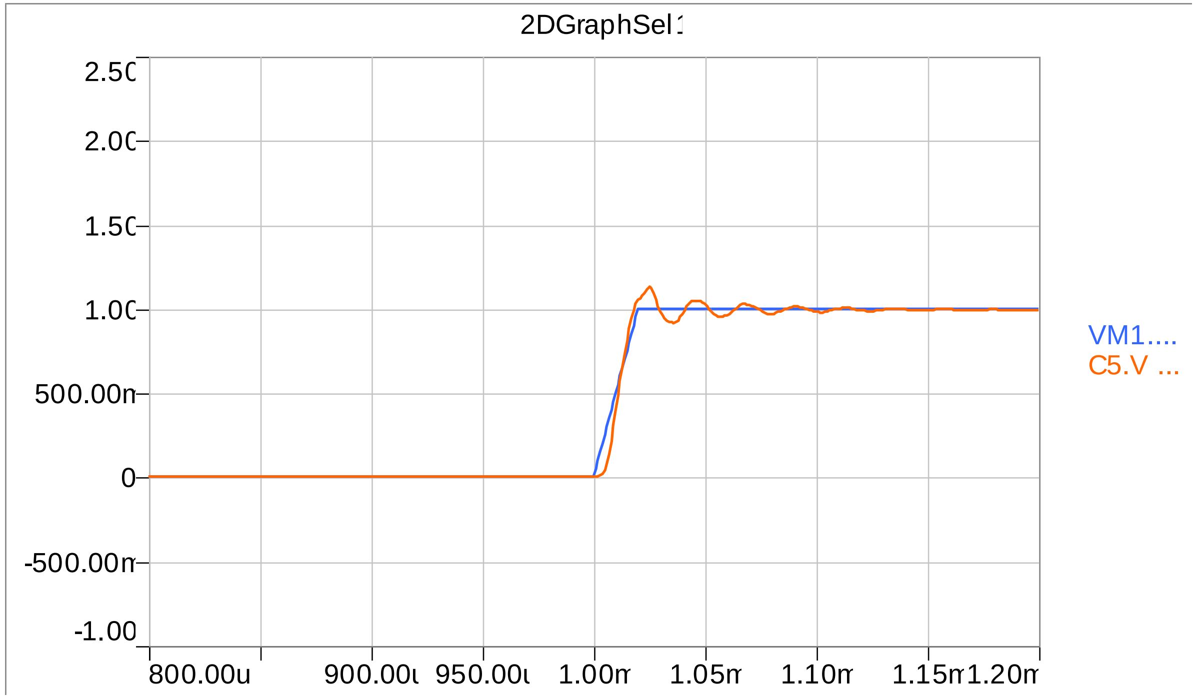


Drive
500 ft
M
2DGraphSel1
2.50
2.00
1.50
1.00
500.00m
0
-500.00m
-1.00
800.00u
900.00u
950.00u
1.00m
1.05m
1.10m
1.15m
1.20m
VM1....
C5.V ...

dV/dt = 500 V/us

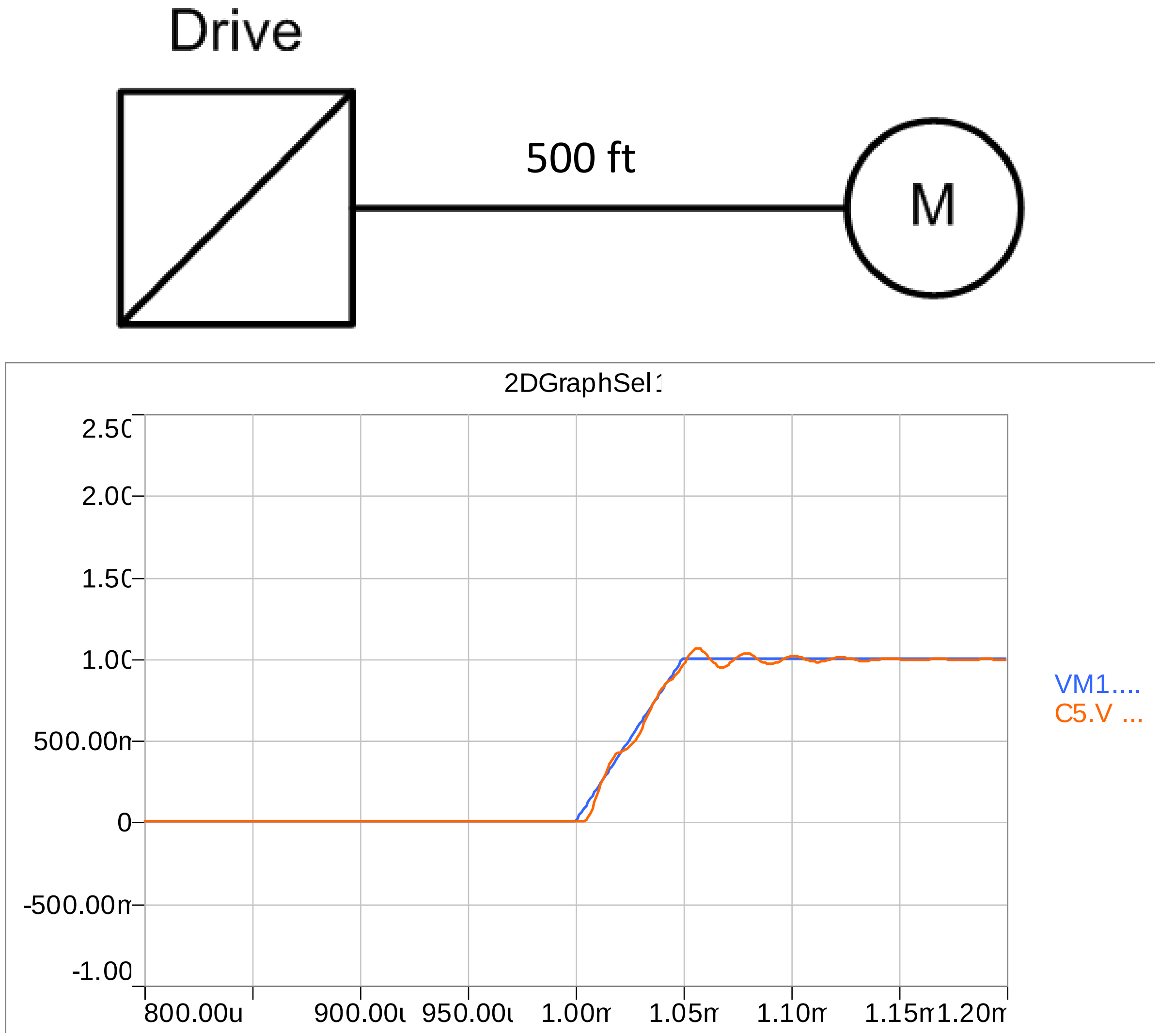


Drive
500 ft
M



2DGraphSel1
2.50
2.00
1.50
1.00
500.00m
0
-500.00m
-1.00
800.00u
900.00u
950.00u
1.00m
1.05m
1.10m
1.15m
1.20m
VM1....
C5.V ...

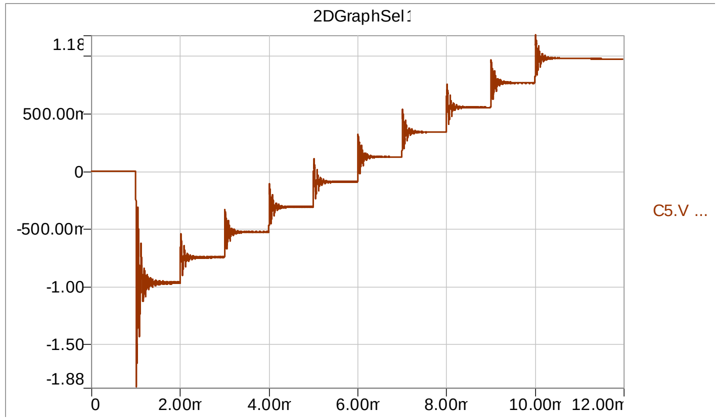
dV/dt = 200 V/us

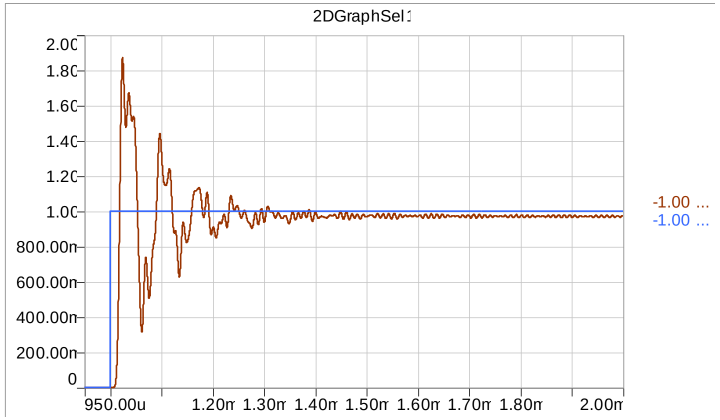


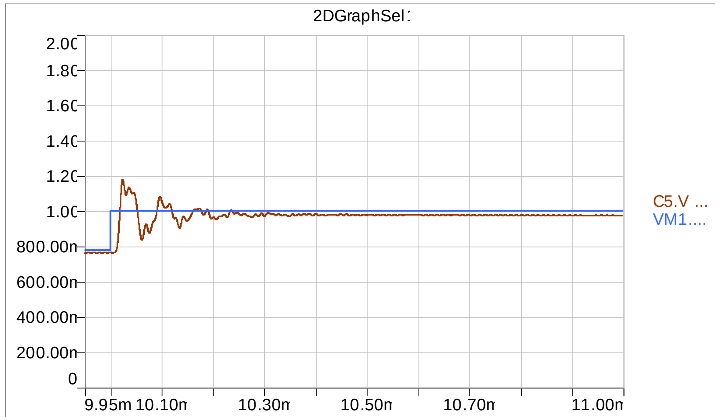
480V, 60Hz sinewave:
max dV/dt = 2*pi*f*V*10^{-6}
= 0.181 V/us
when voltage is crossing through zero

Slow down rate of rise

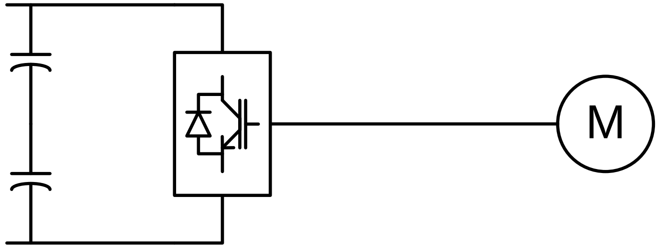
Multi-Step (5-Level) Approach, low dV/dt for MV Drives



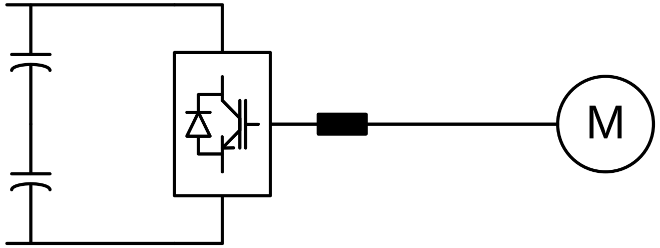




How else can we reduce the dV/dt? Filtering



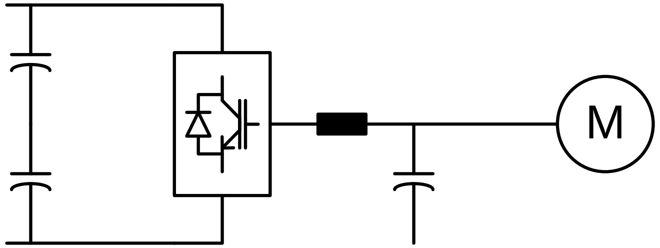
Basic Inverter and Motor



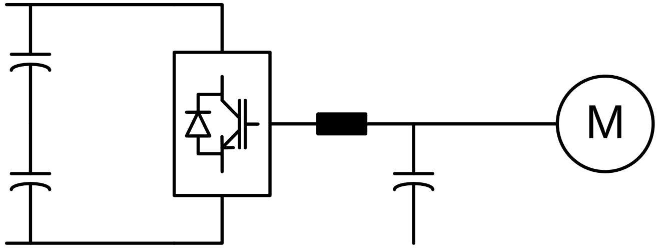
Output Load Reactor

Does help but may also cause more oscillations. Better to go with a dV/dt filter or SW filter.

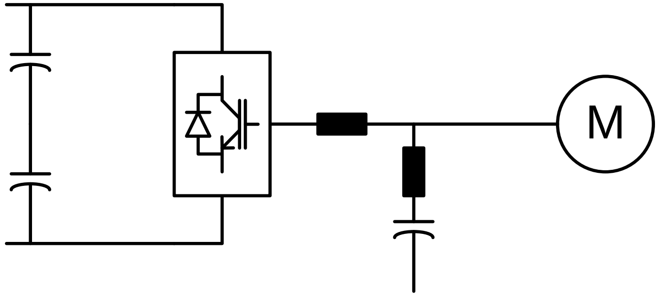
Its impedance will introduce a voltage drop to the motor. Keep it around 1.5%.
Cap reduces drive current!



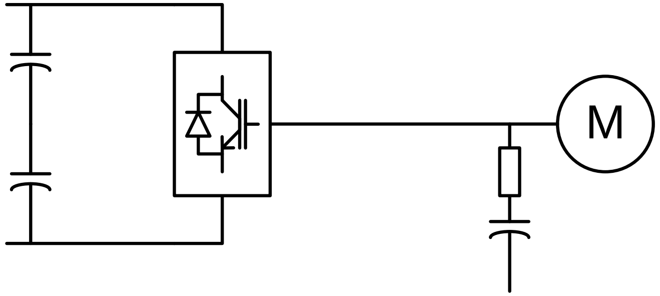
*dV/dt Filter



*Broadband Sinewave Filter



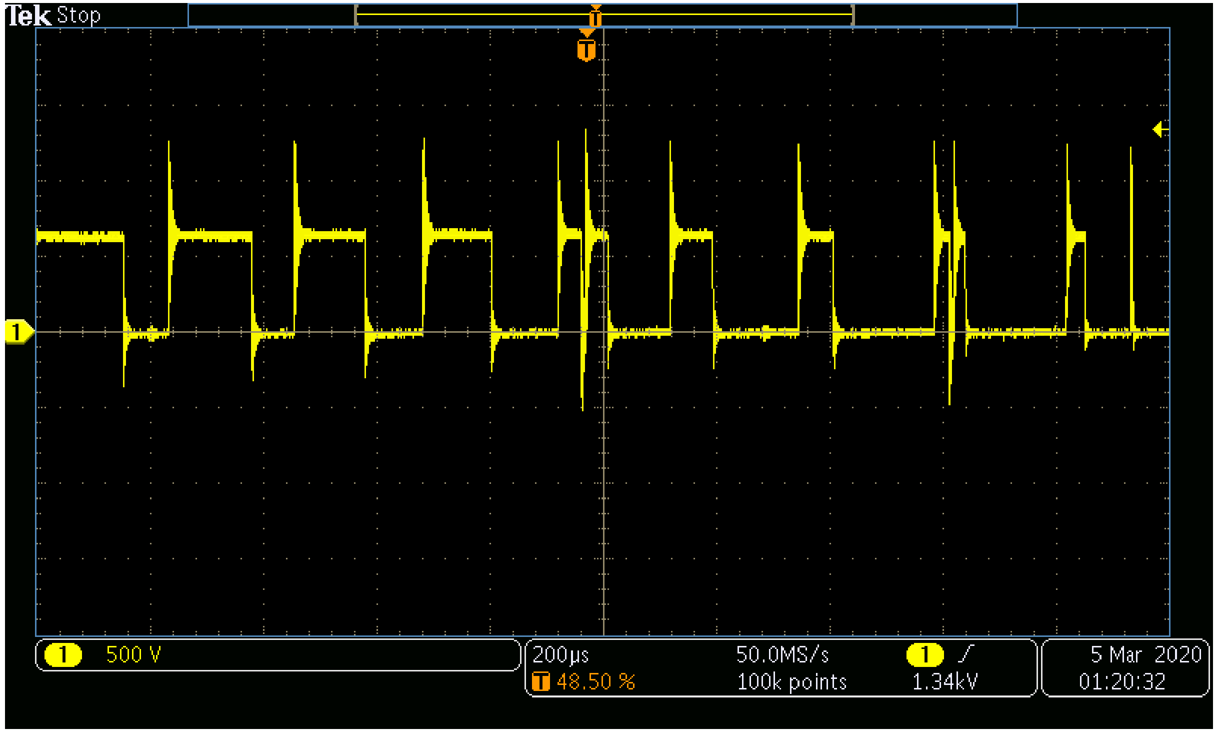
Sinewave Filter



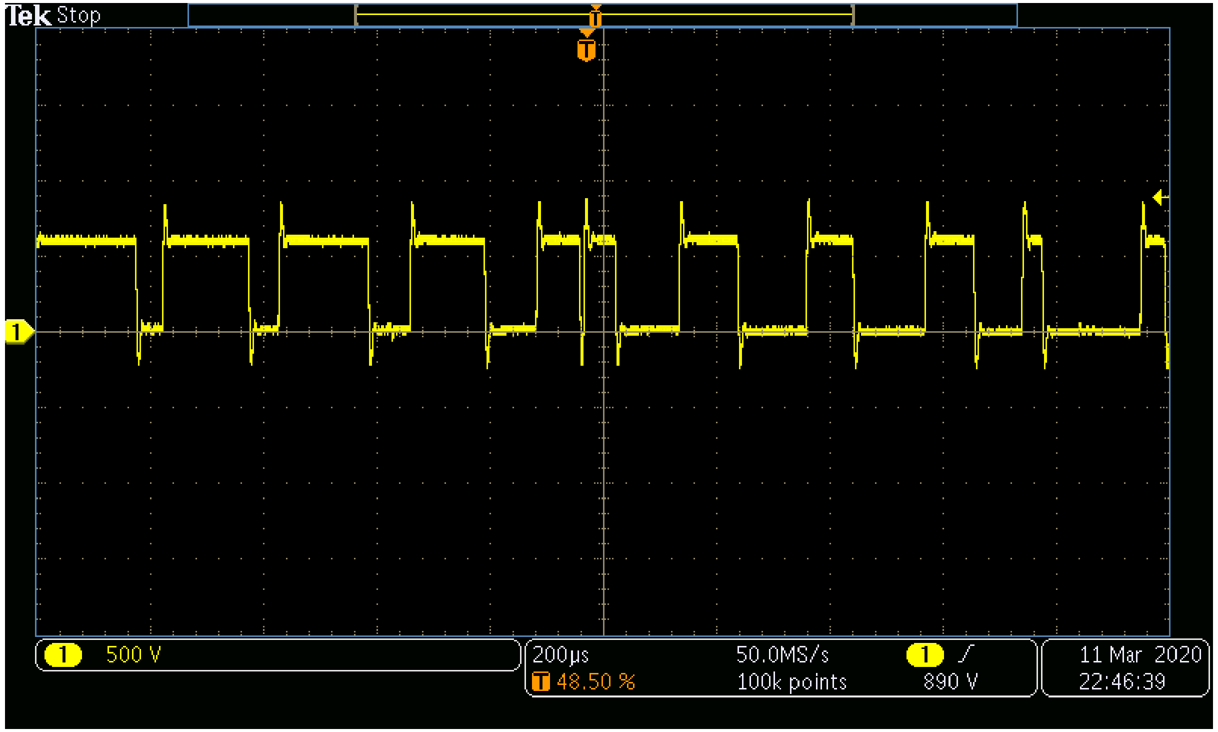
RC Terminator

* Used in MV drives

Vmotor without and with Load Reactor (1.5%)

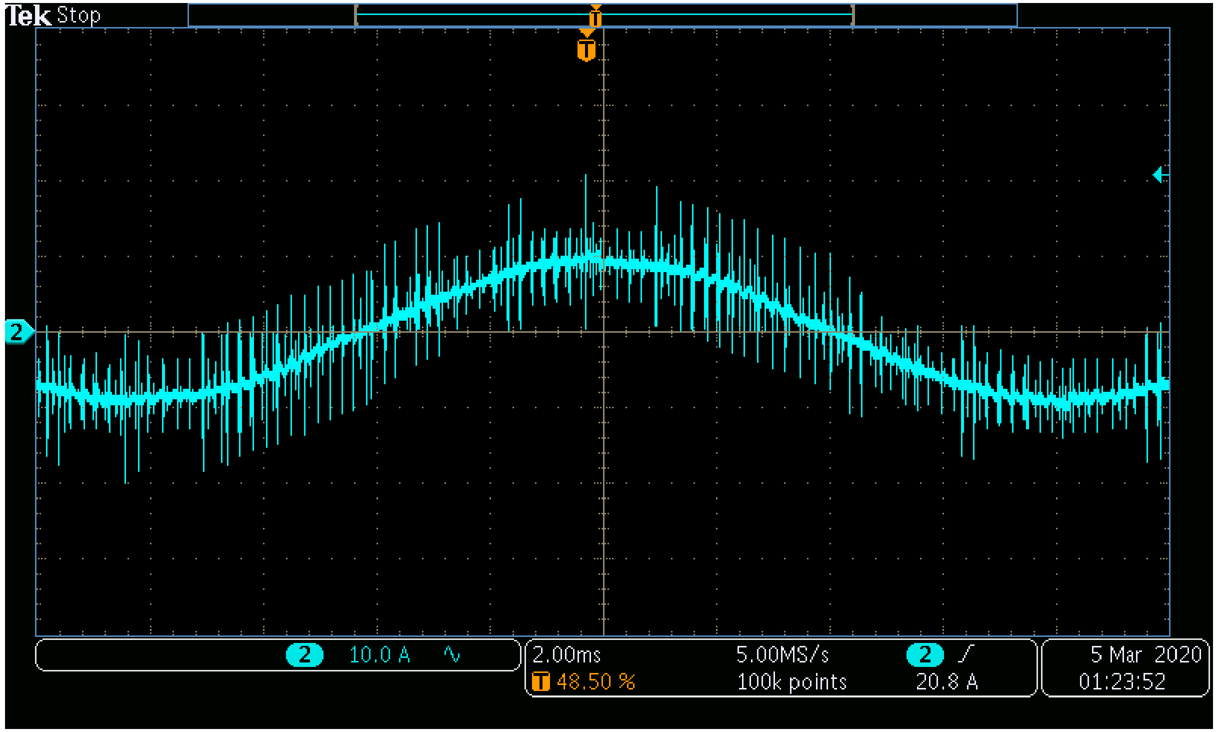


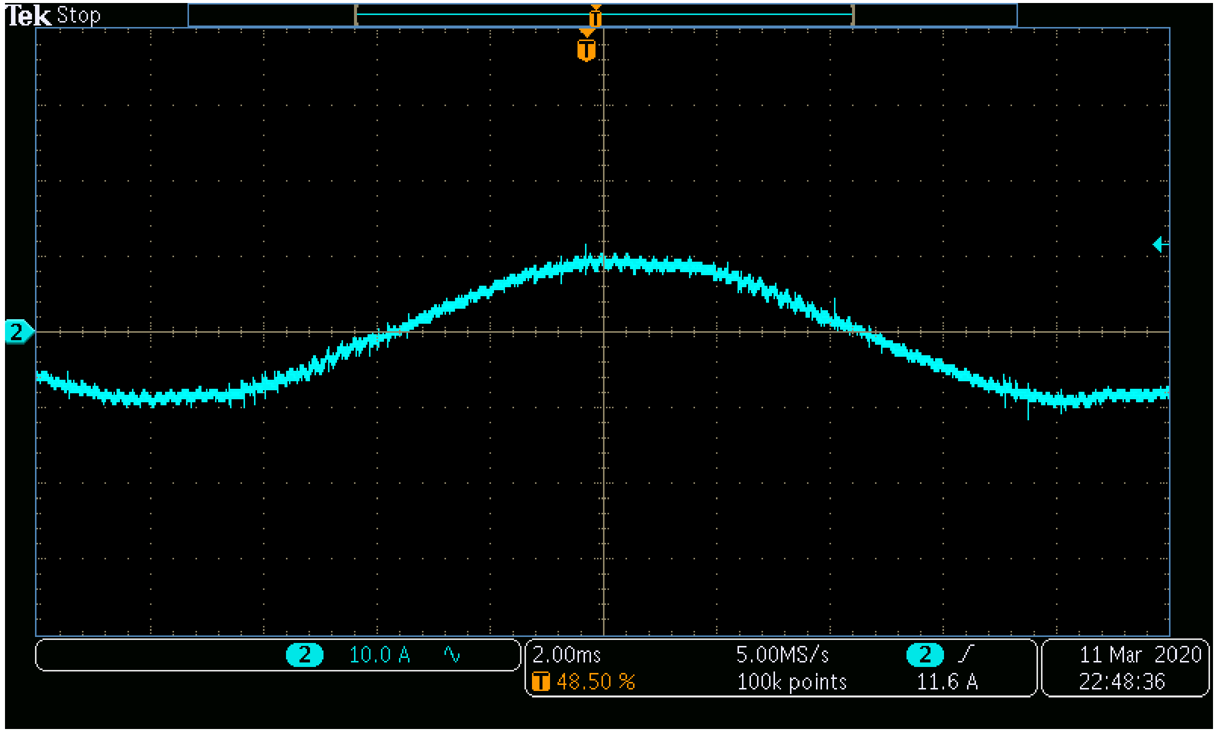
Cable length ~ 500 ft. Vpk ~ 1.9 x DC bus voltage



Vpk greatly reduced to 1.2 x DC bus voltage

Imotor without and with Load Reactor (1.5%)

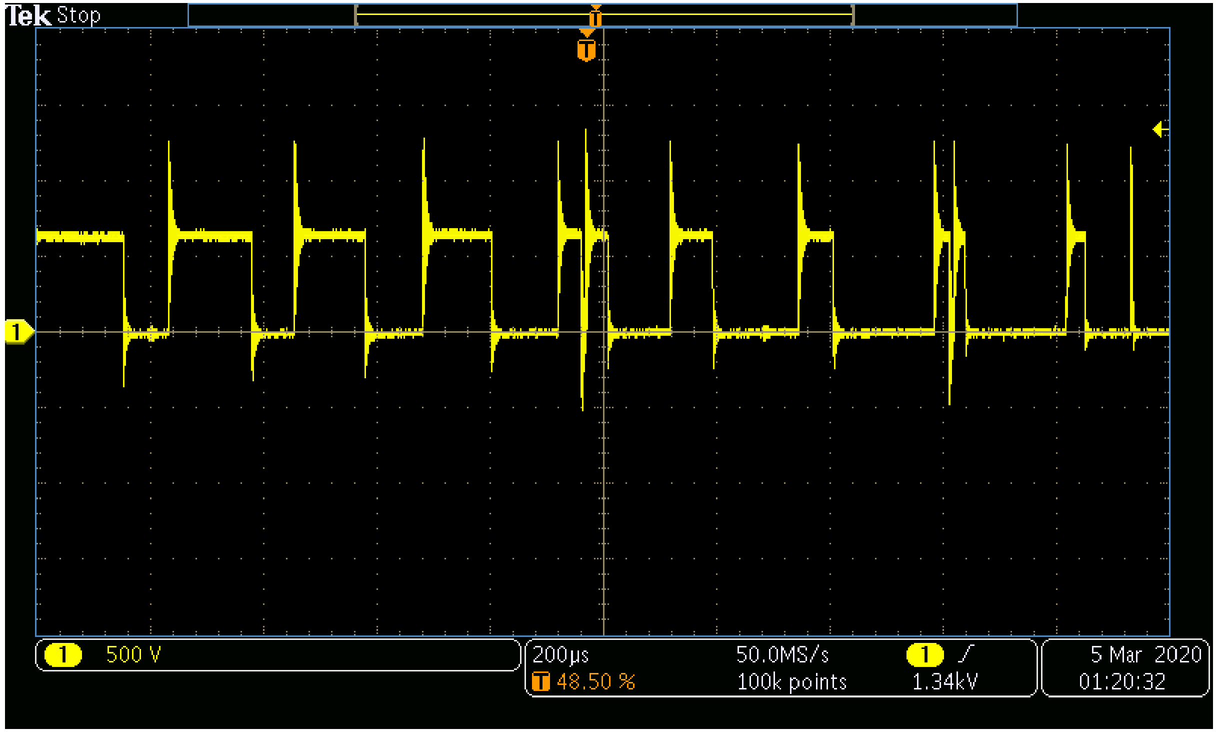


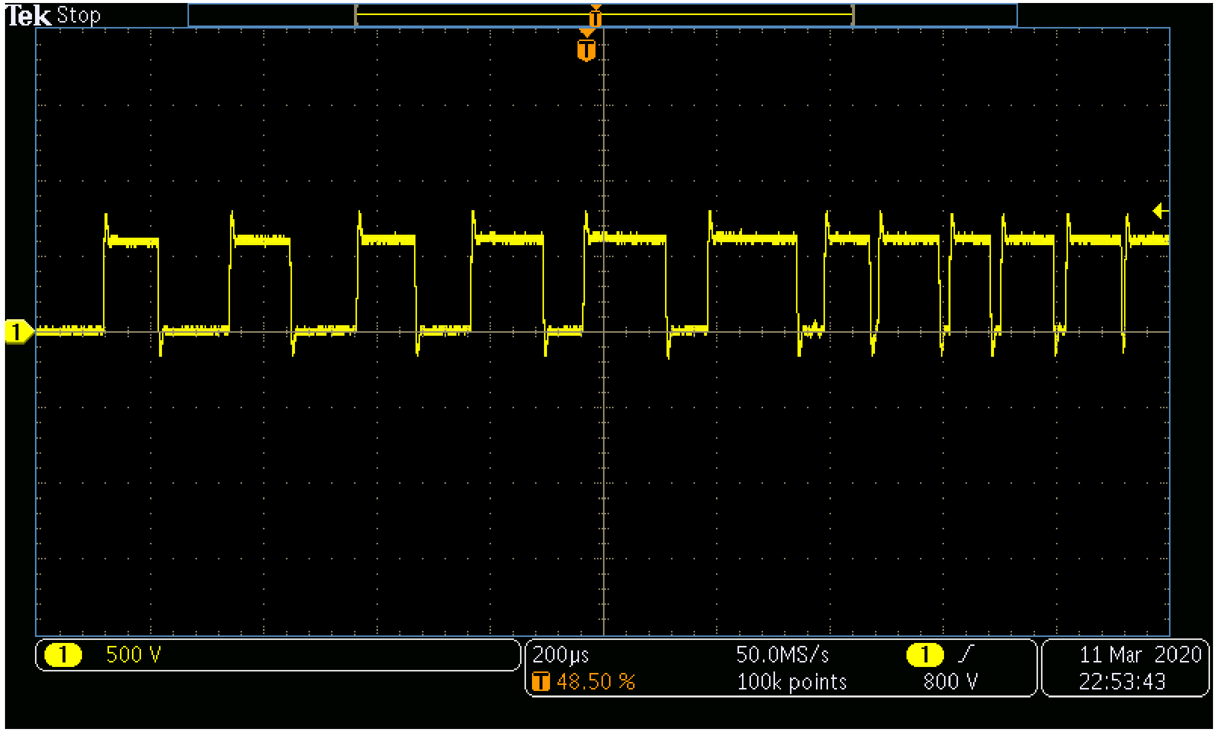


Cable charging current can cause small drives to trip on overcurrent the instant they start modulating.

Cable charging current greatly reduced

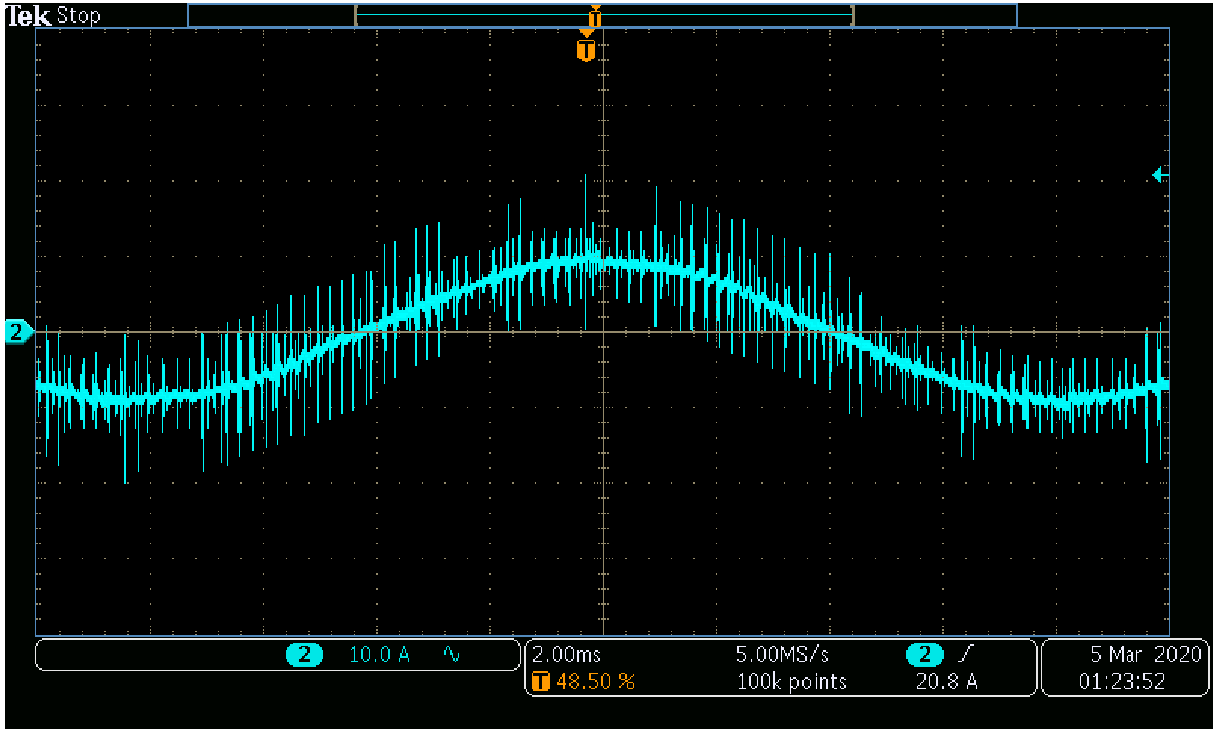
Vmotor without and with dV/dt Filter

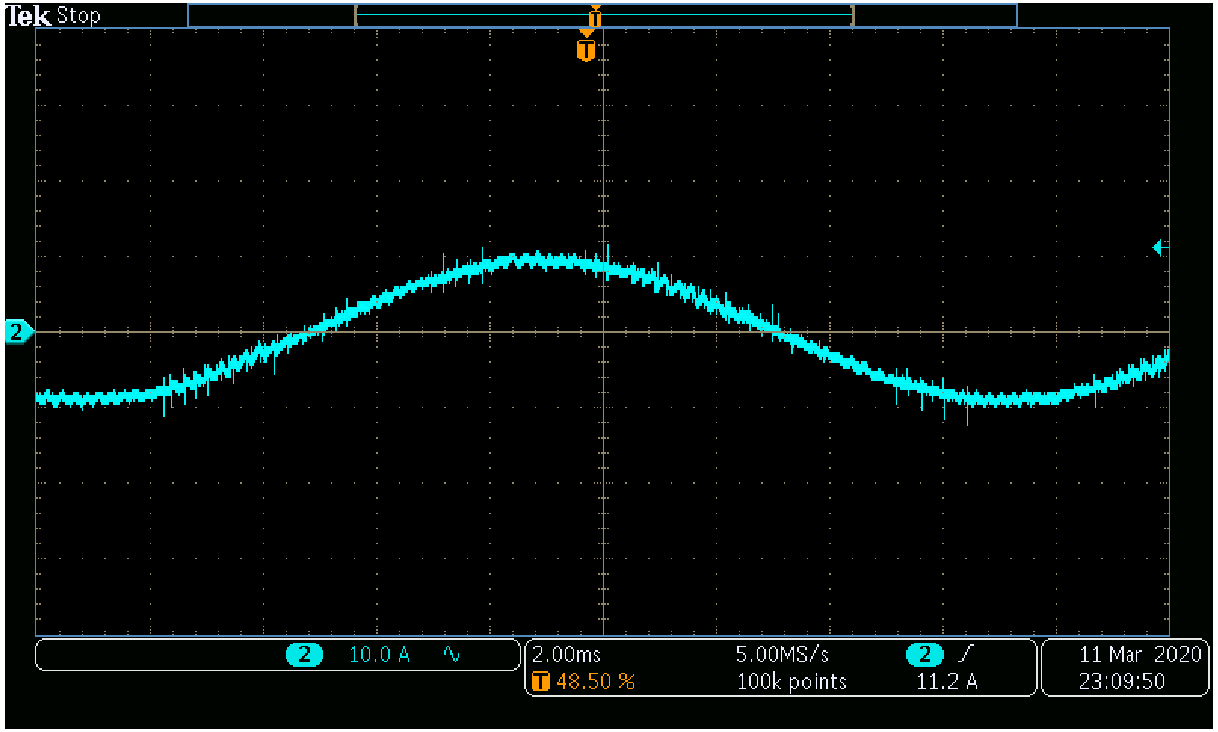




Vpk greatly reduced. ~ 1.15 x DC bus voltage

Imotor without and with dV/dt filter





Cable charging current greatly reduced

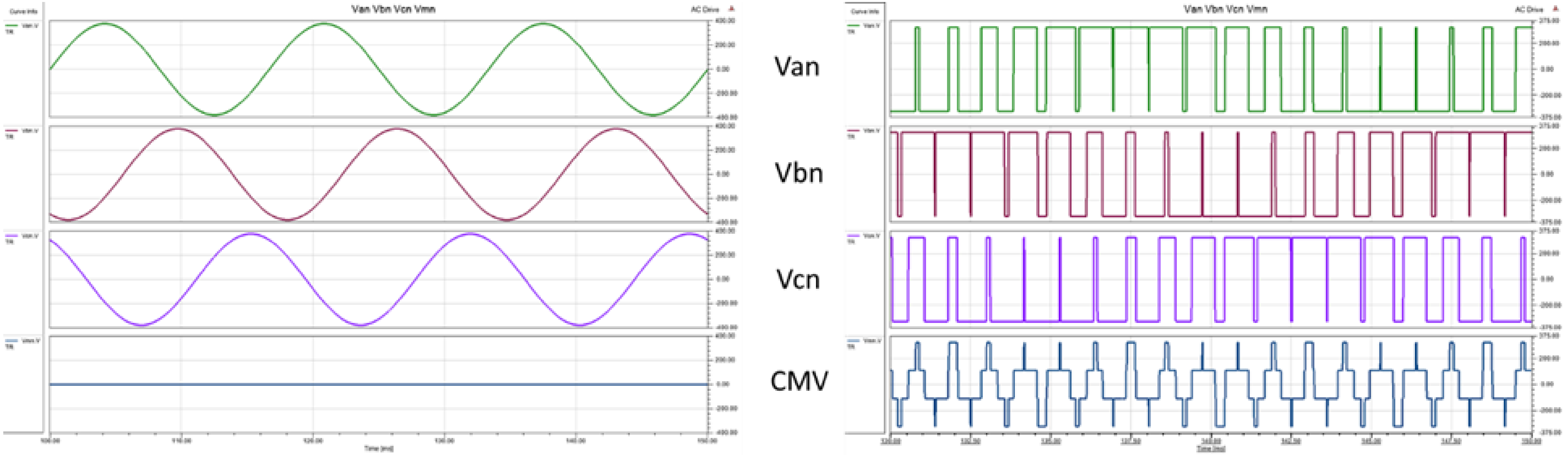
Shaft Grounding Brushes and Bearing Currents

What is Common Mode Voltage (CMV)?

CMV = (Van + Vbn + Vcn) / 3

3ph Sinusoidal Voltages

3ph PWM Voltages



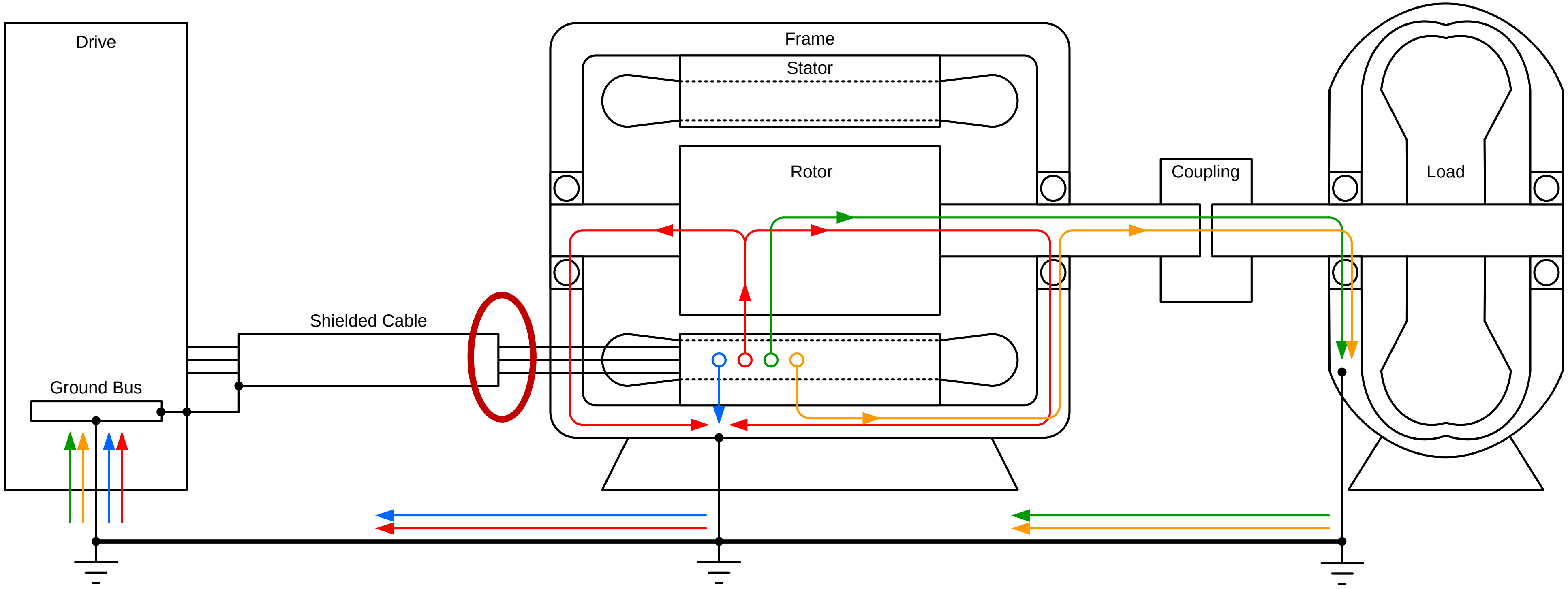
CMV = (Van + Vbn + Vcn) / 3 = 0

CMV = (Van + Vbn + Vcn) / 3 ≠ 0

High dV/dt = high common mode current

Icm = C x dV/dt

Currents within a motor and load

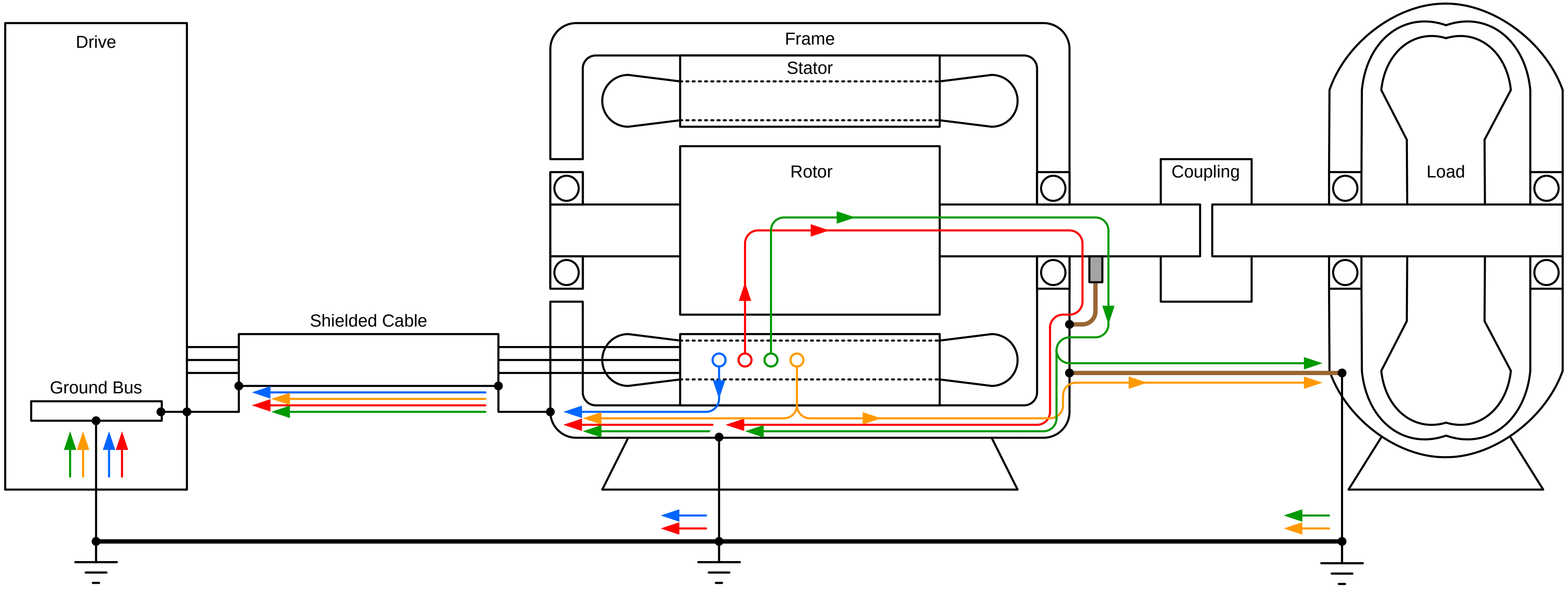


Cable shield not connected to motor frame

Paths of common mode currents from stator to ground back to drive

Load bearings may fail before motor bearings!

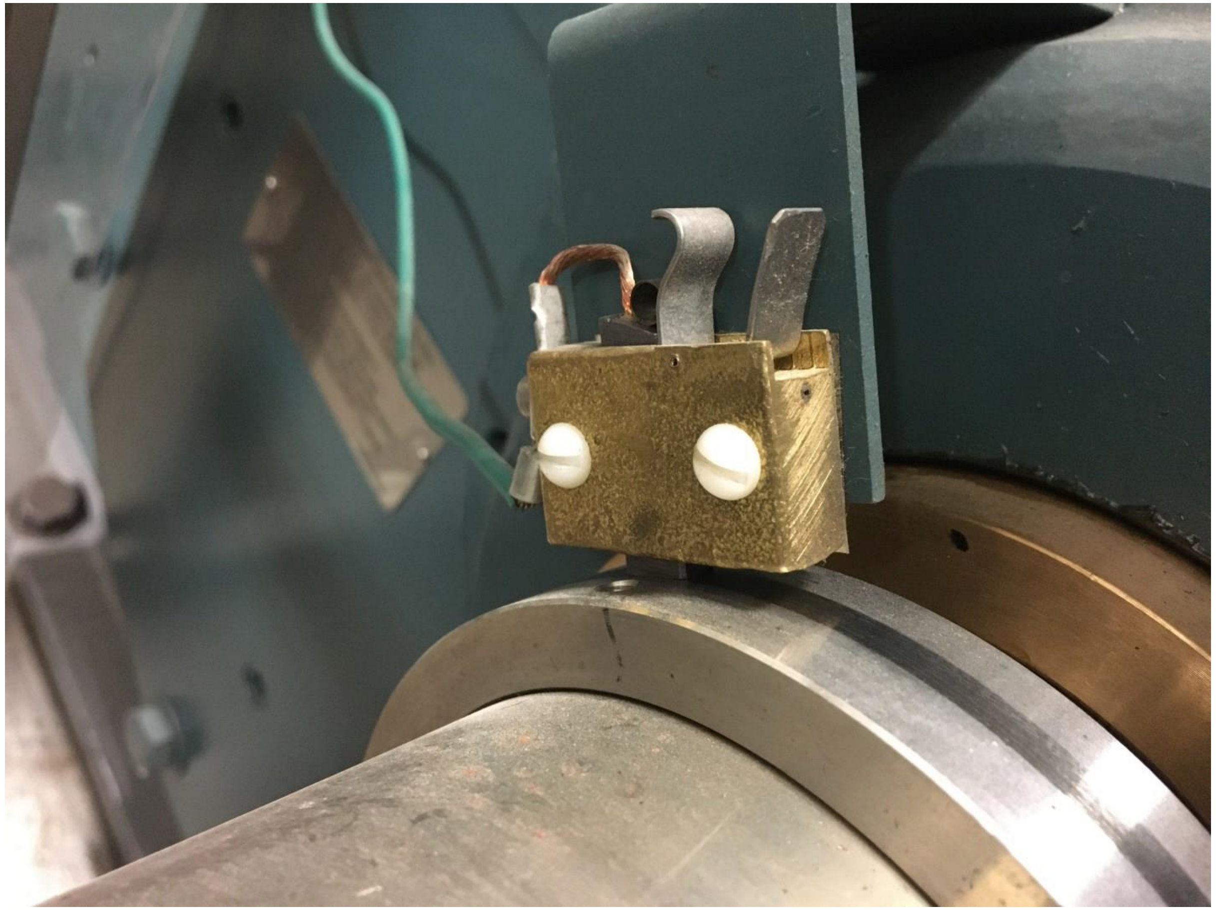
Currents within a motor and load

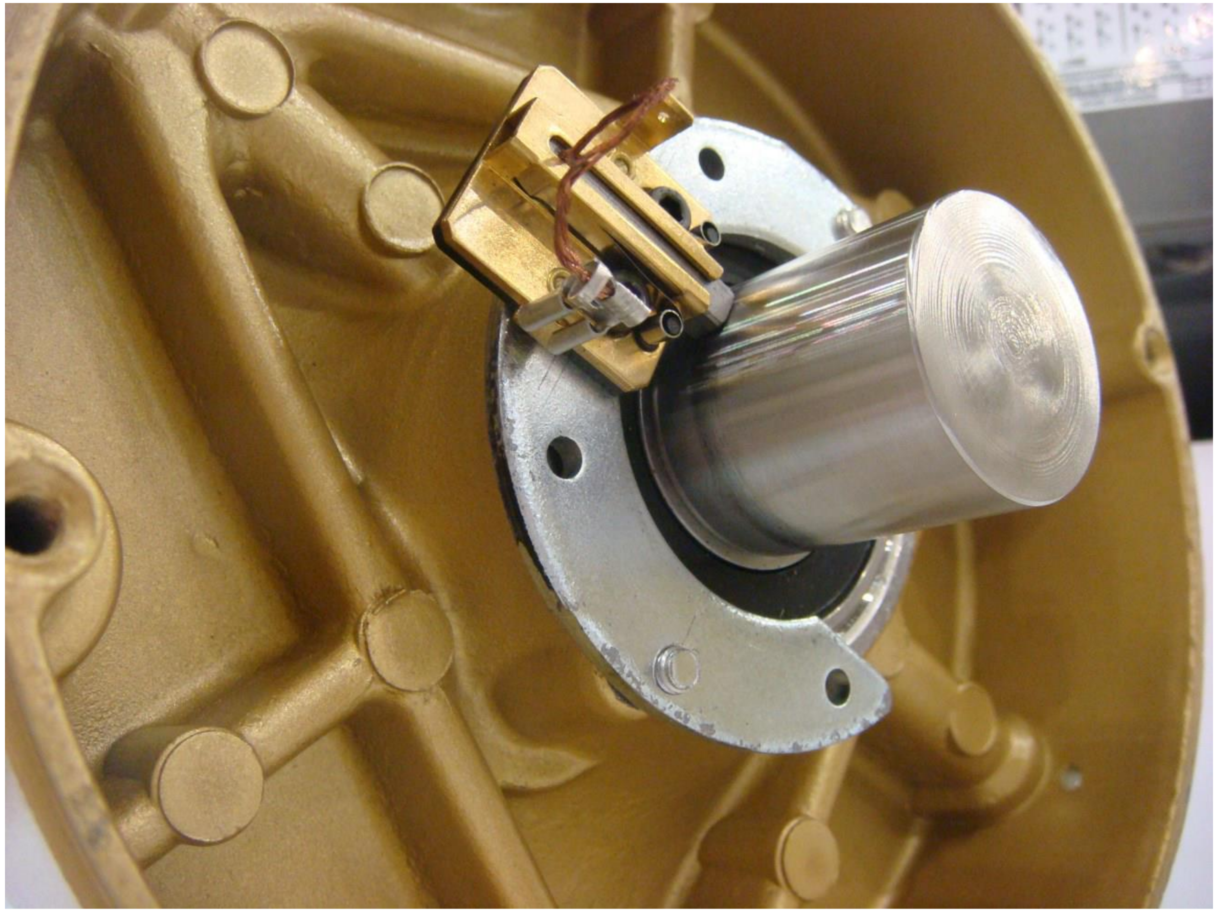


Cable shield is connected to motor frame

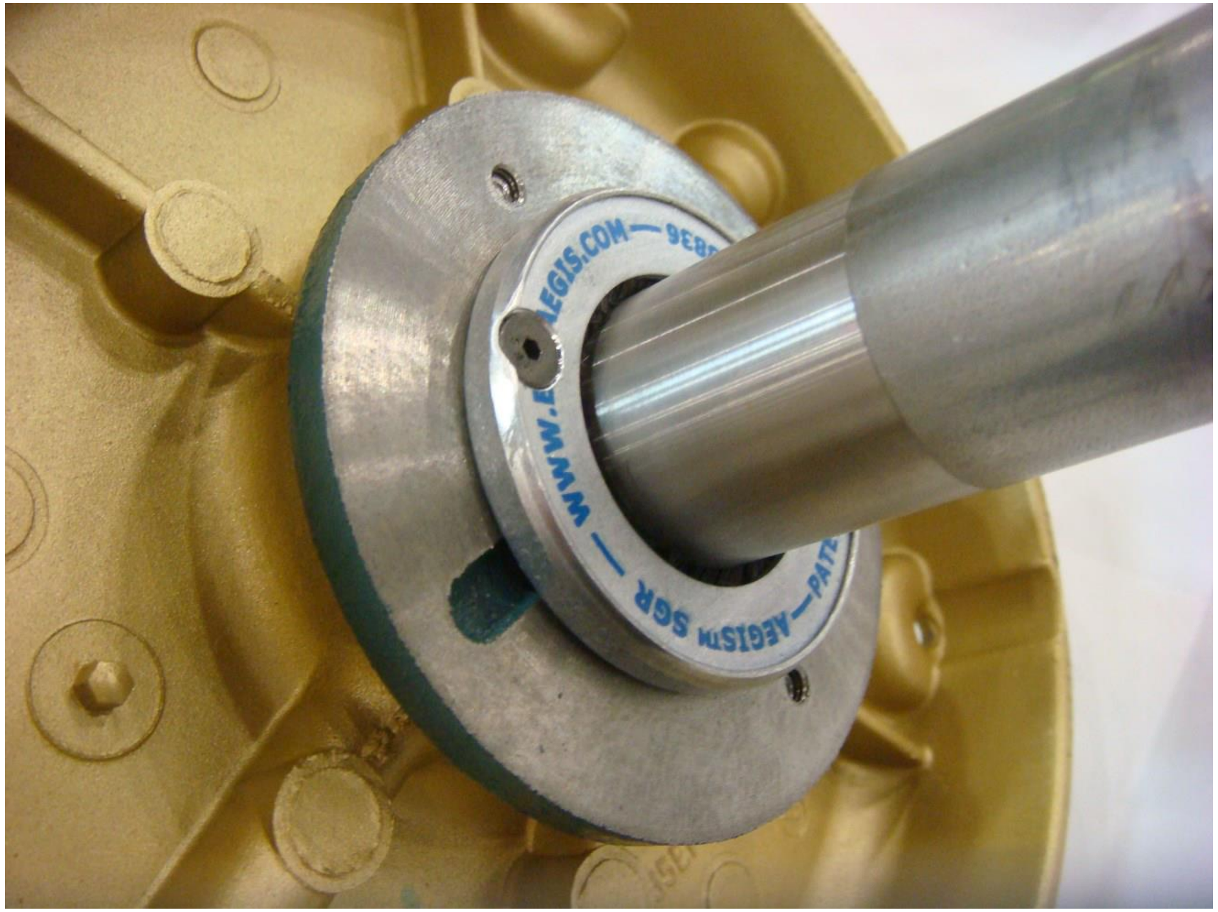
Paths of common mode currents from stator to ground back to drive through the cable shield which is a low impedance path for high frequencies (shallow skin depth, large surface area). Also, ground strap between motor frame and load frame to bypass load bearings.

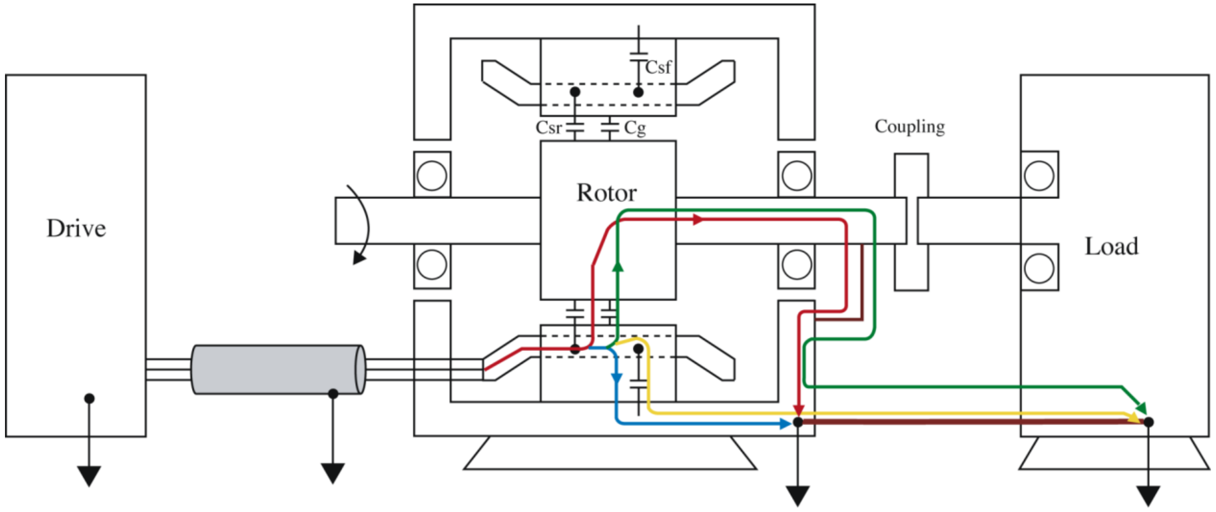
Shaft Ground Brush





Shaft Ground Brush





Bearing Current Remediation

- Proven results include:
  - Improving the high-frequency ground connection from the motor to the drive and from the motor to the driven equipment
  - Insulate the bearing on the opposite drive end of motor
  - Two insulated motor bearings
  - Shaft grounding brush across the drive end motor bearing which could be mounted inside the motor housing or outside
  - An important ground path is the connection between the motor and inverter. Cables should be used that provide continuous, low resistivity shielding around the three phase conductors. The termination of the cable shield should be made by landing these connections on a ground surface free of paint at both the drive ground bus and at the motor frame.

R.F. Shiferl, M.J. Melfi, "Bearing Current Remediation Options", *IEEE Industry Applications Magazine,* August 2004
R. McElveen, F. Hoadley, "Best Practices for Mitigating Bearing Currents", *Pumps & Systems*, June 2019, pp 51-55
M. Laufik, "The Need for Shaft Grounding on VFD-Driven Motors", *Pumps & Systems*, June 2019, pp 44-45

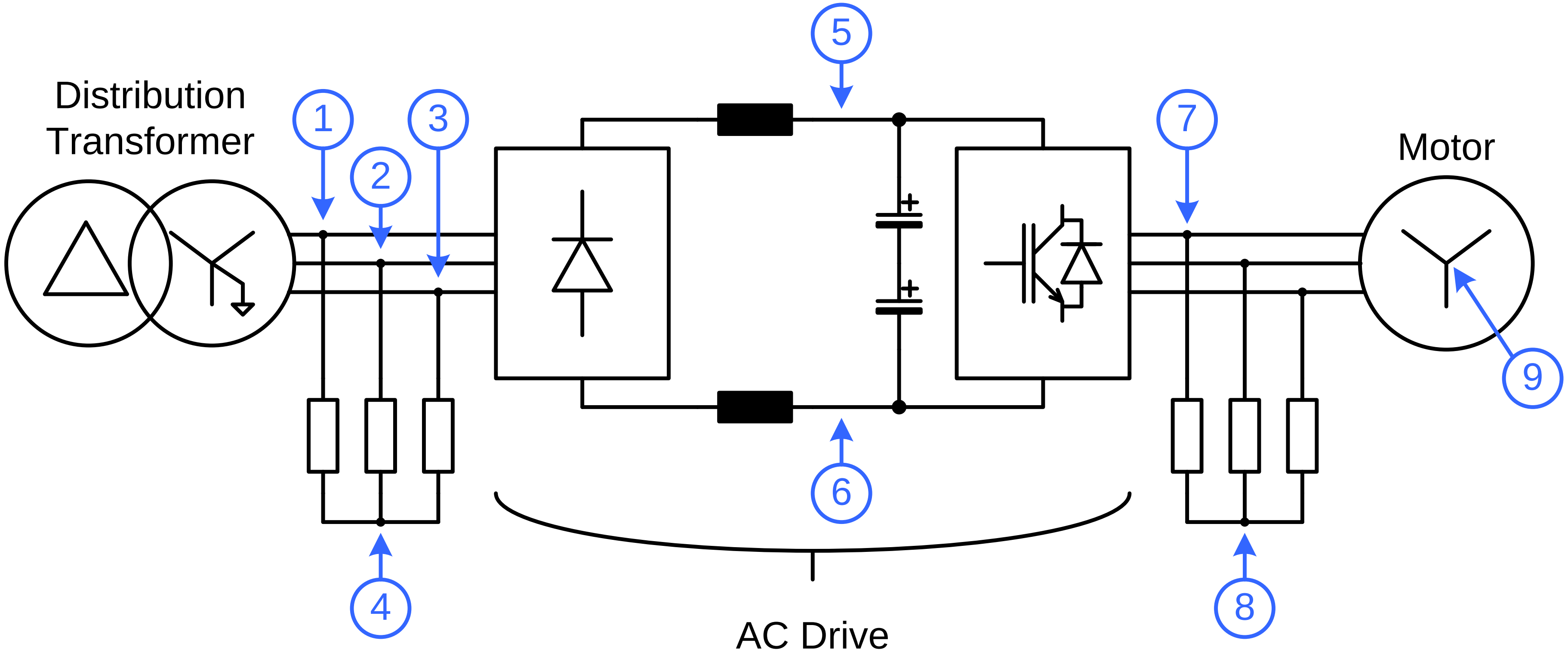
VFD Wiring, Common Mode

Common Mode Voltage / Current

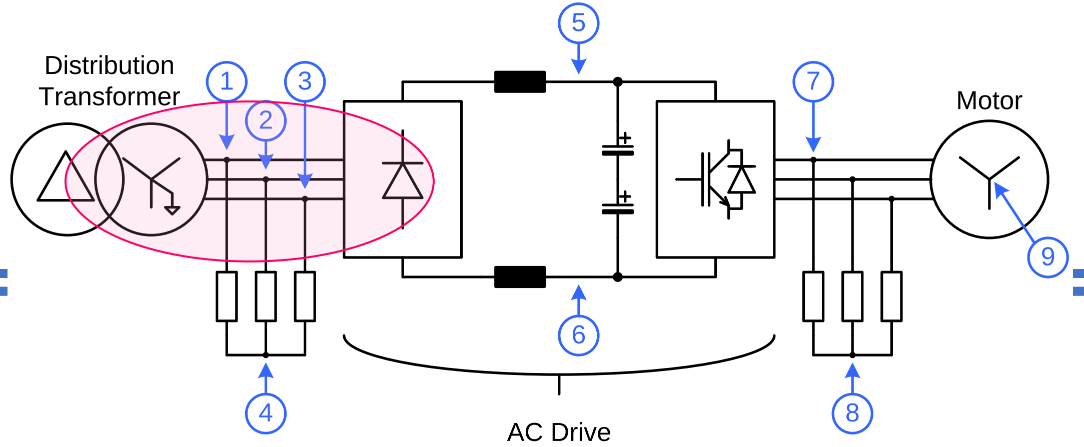
- Modern PWM drives create switching patterns where instantaneous average voltage to ground is not zero.
- Voltage has a rapid change of magnitude with respect to time (dV/dt)
- High dV/dt results in capacitively coupled currents from motor windings to ground through several paths

$$I = C \times dV/dt$$

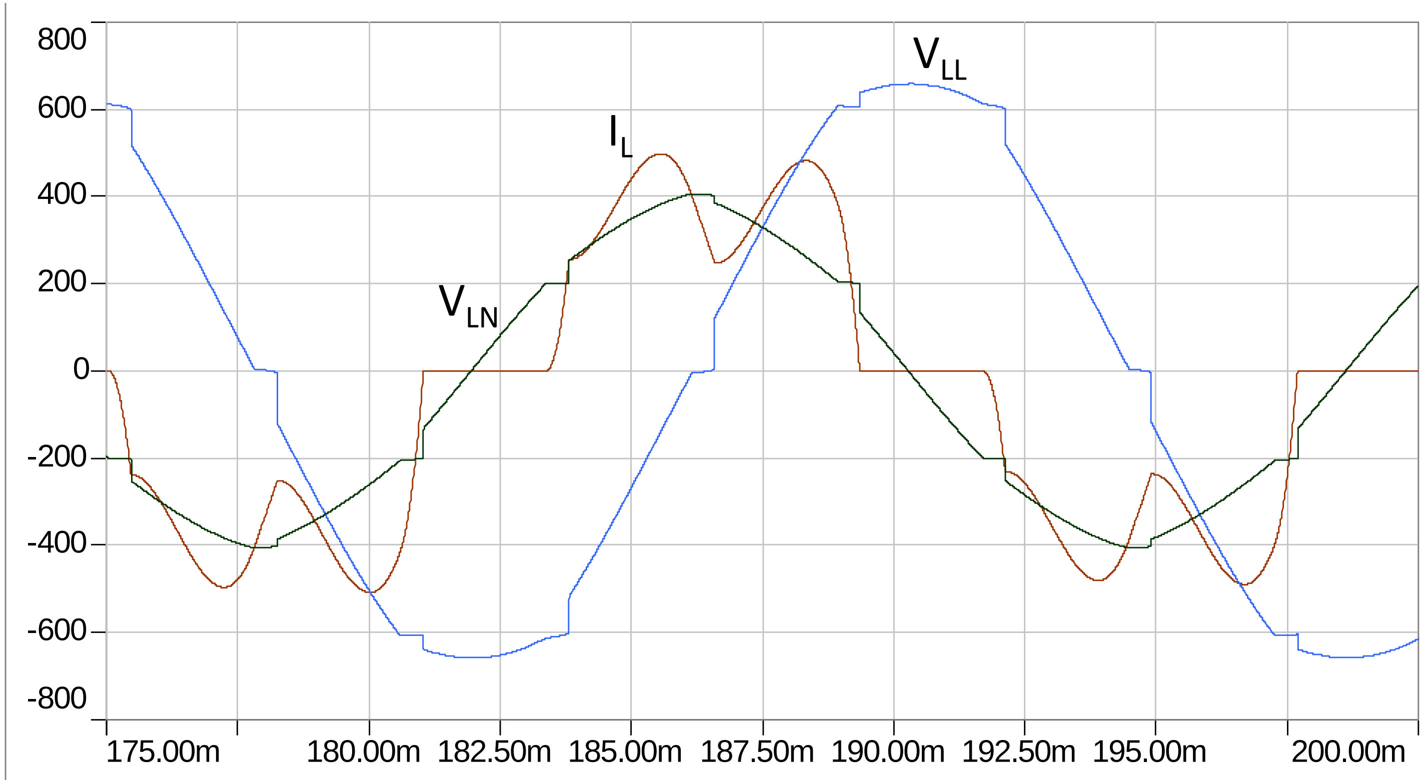
Voltage Probe Sites (Voltages with respect to ground)



Vin and I in

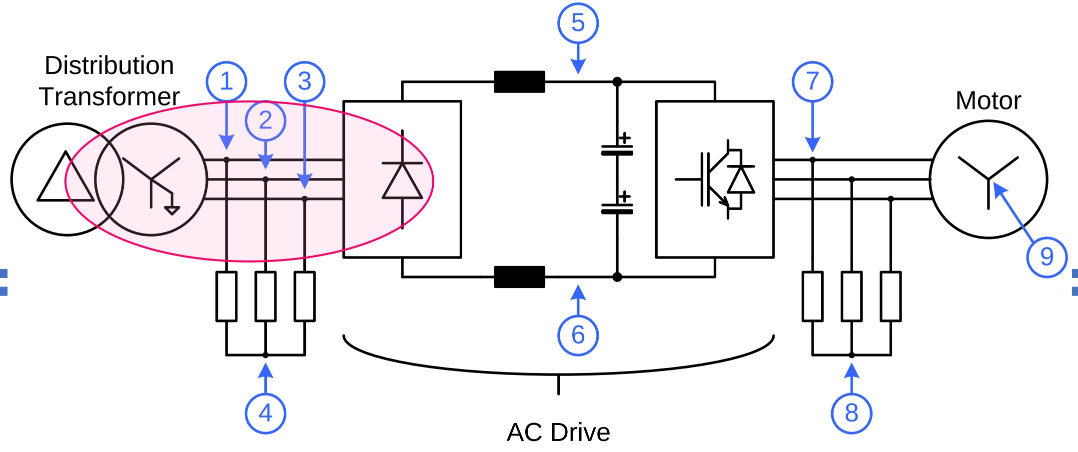


Distribution Transformer
1
2
3
4
5
6
7
8
9
AC Drive
Motor



800
600
400
200
0
-200
-400
-600
-800
175.00m
180.00m
182.50m
185.00m
187.50m
190.00m
192.50m
195.00m
200.00m
V_{LL}
I_L
V_{LN}

Iin – a,b,c


Distribution
Transformer
1
2
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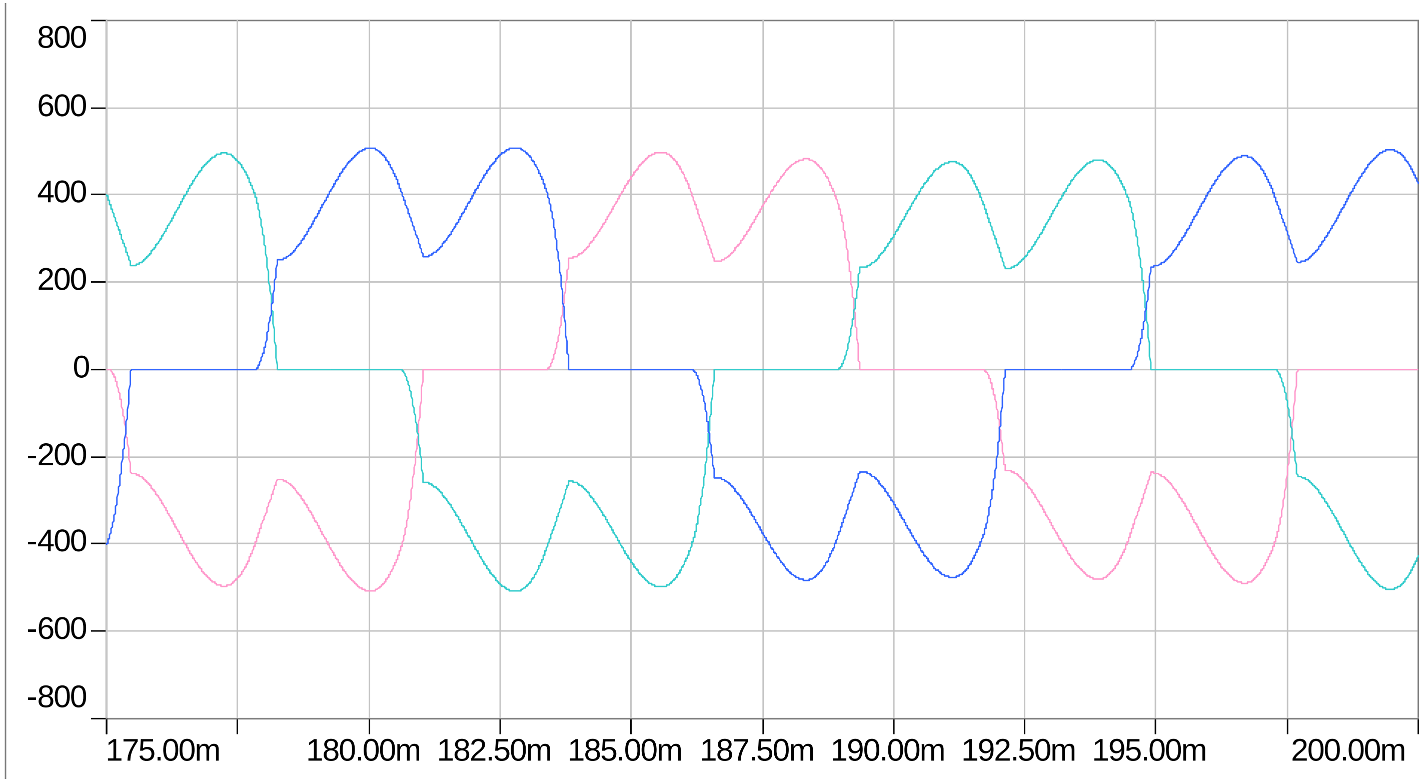
Motor
AC Drive


800
600
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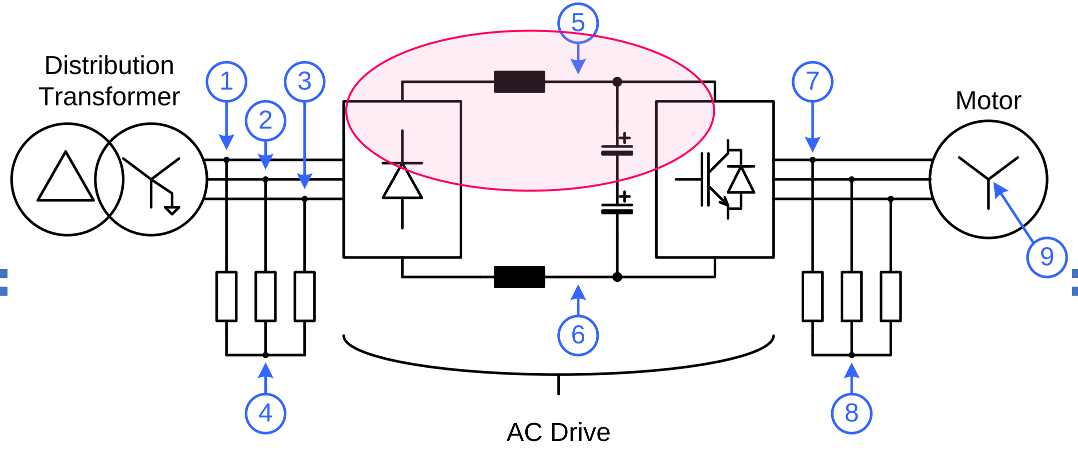
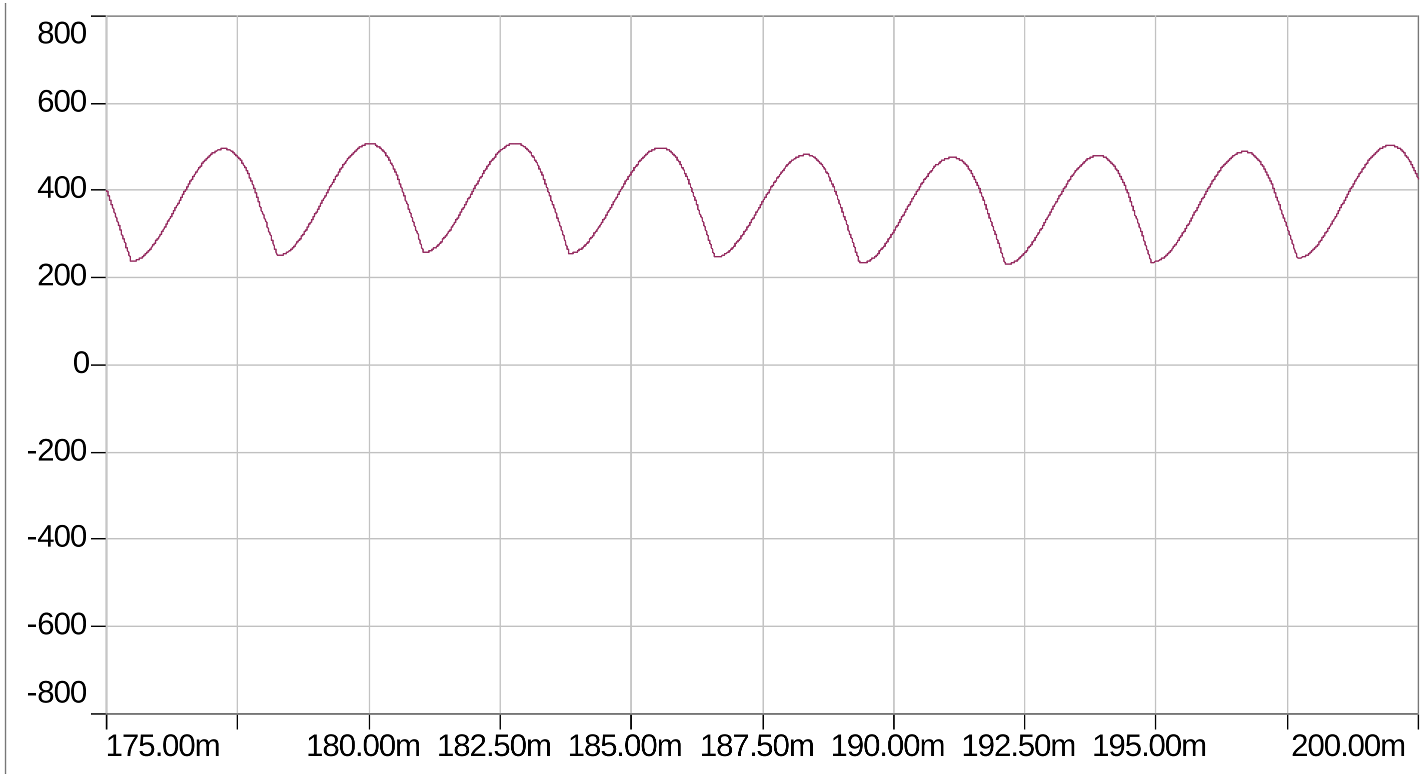
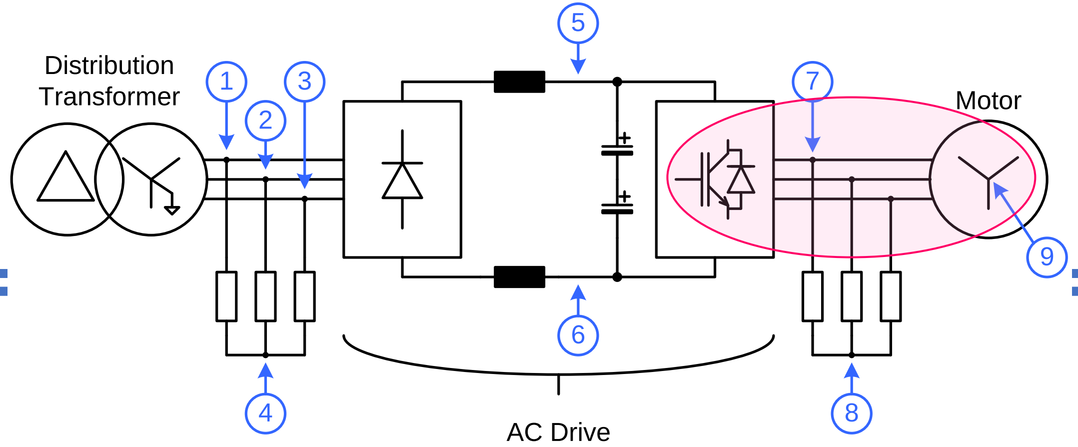
200
0
-200
-400
-600
-800
175.00m
180.00m
182.50m
185.00m
187.50m
190.00m
192.50m
195.00m
200.00m

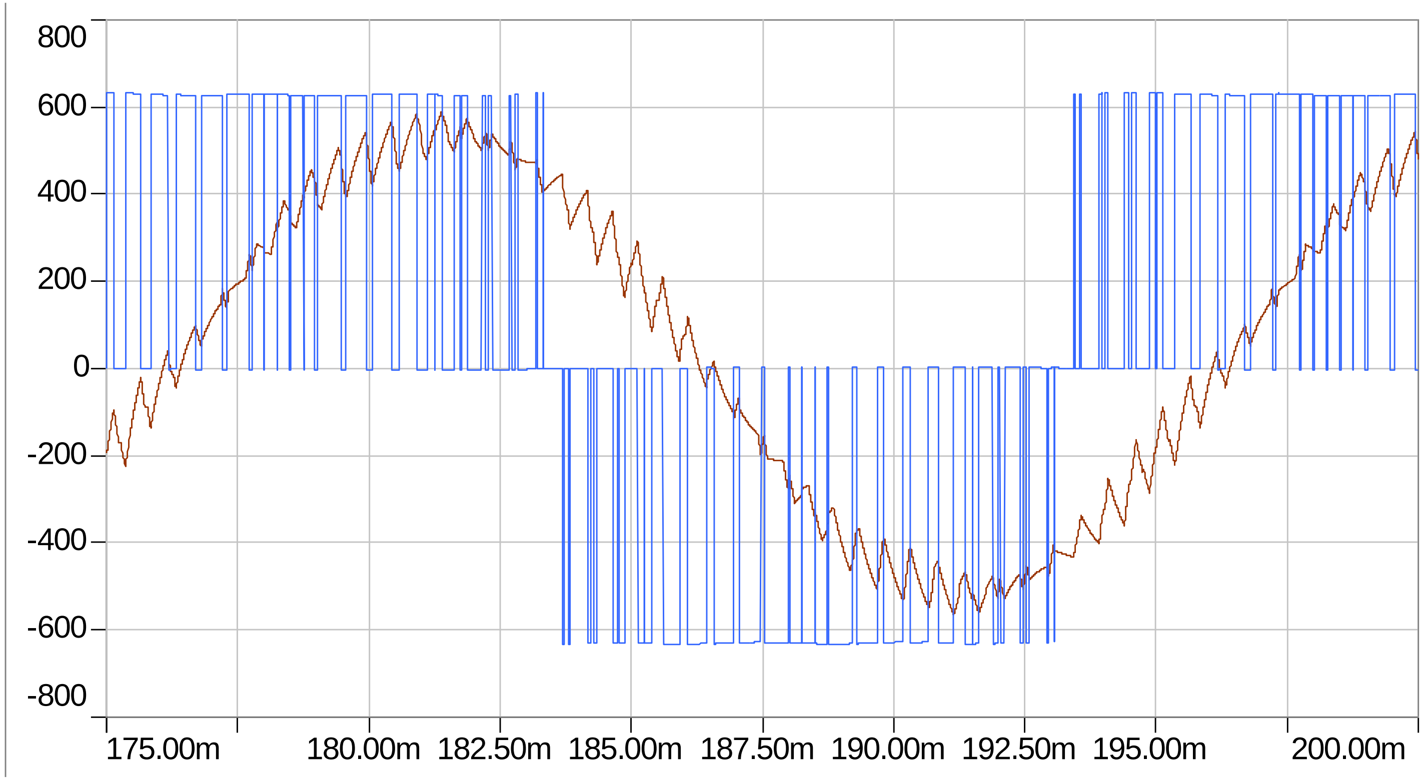
I dc link choke



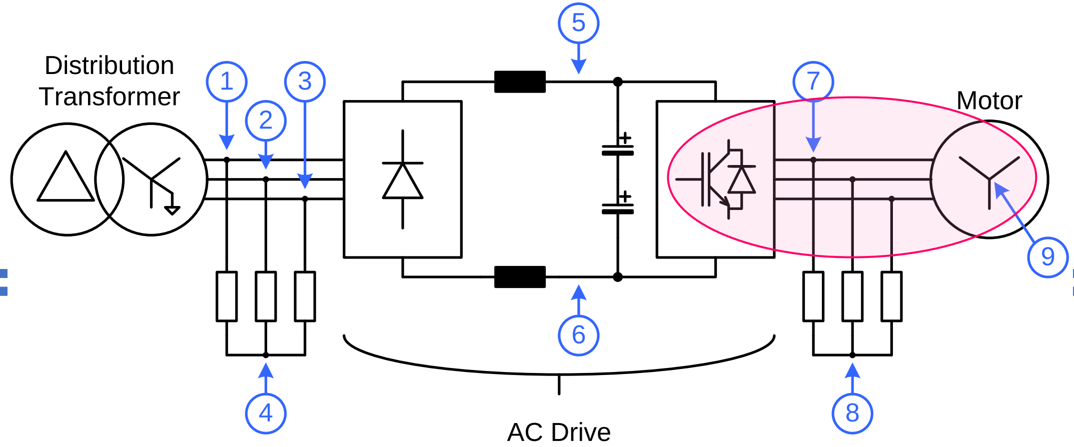


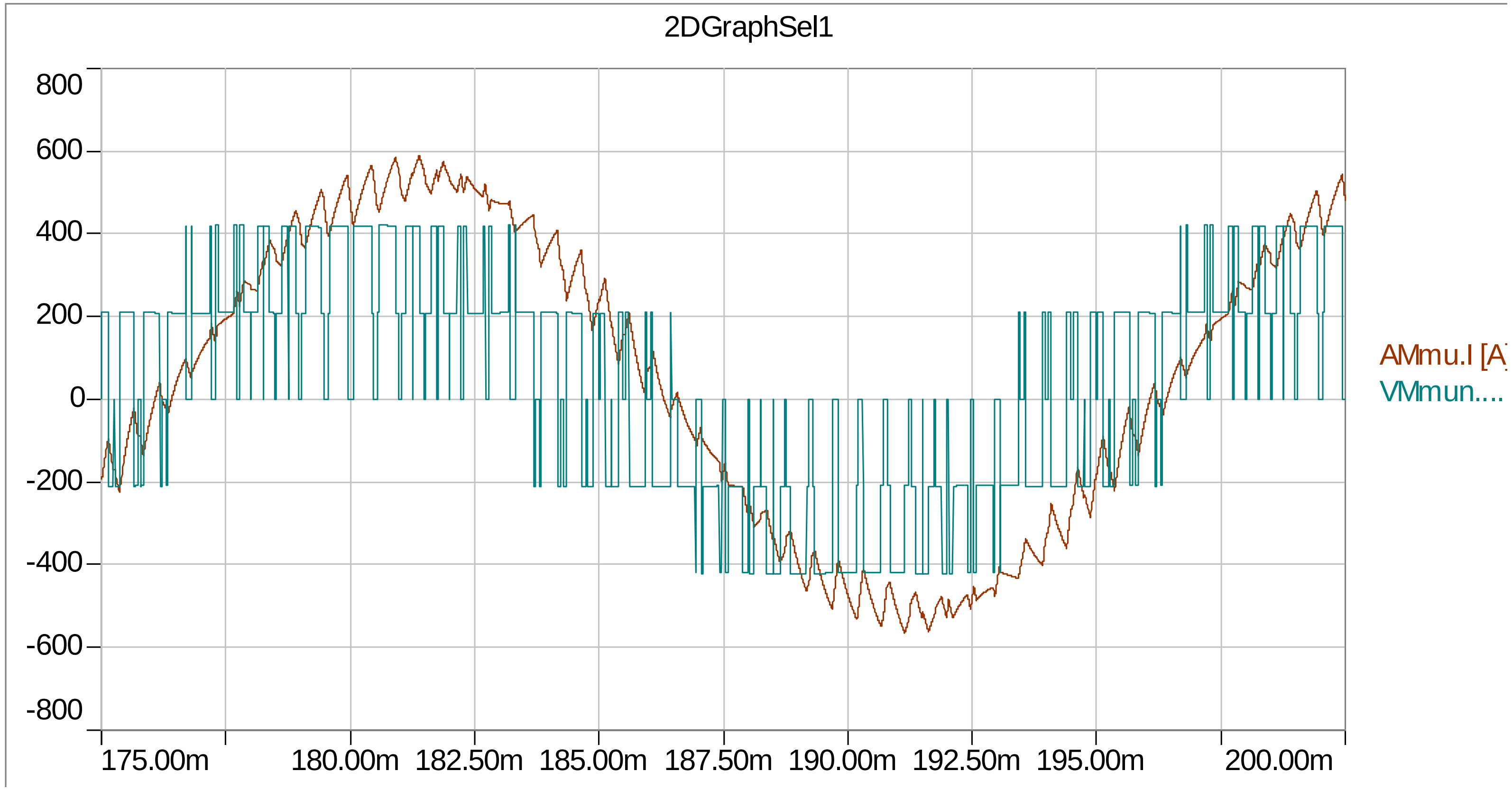
Vph-ph and I out



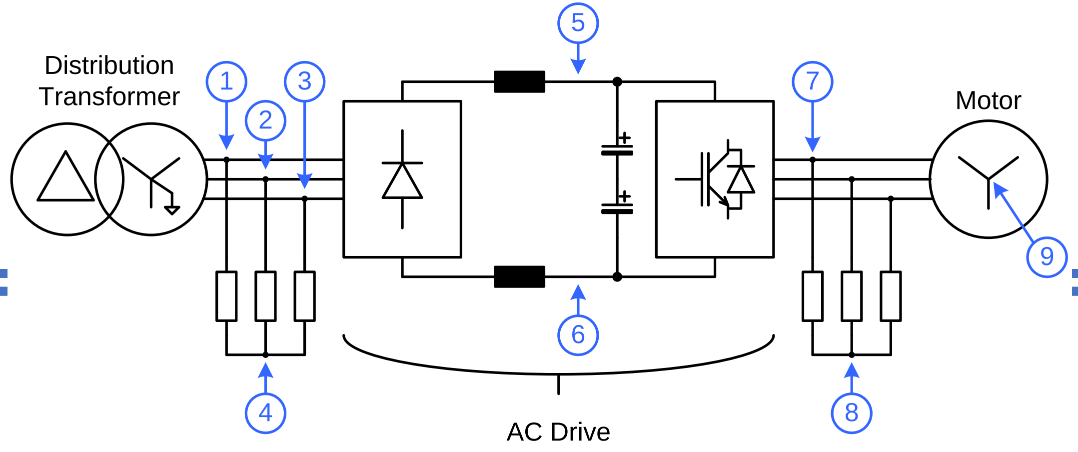


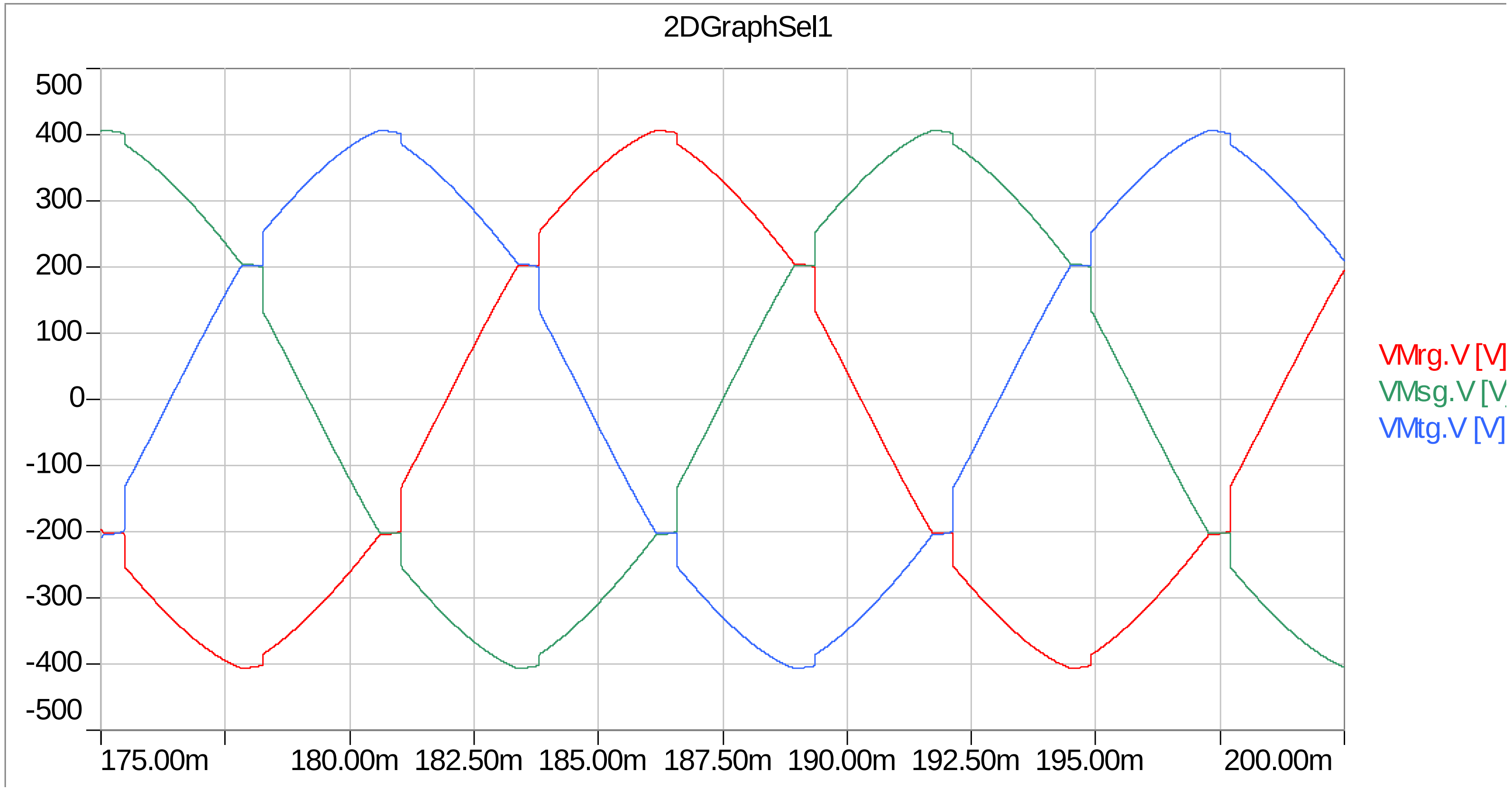
Vph-n and I out



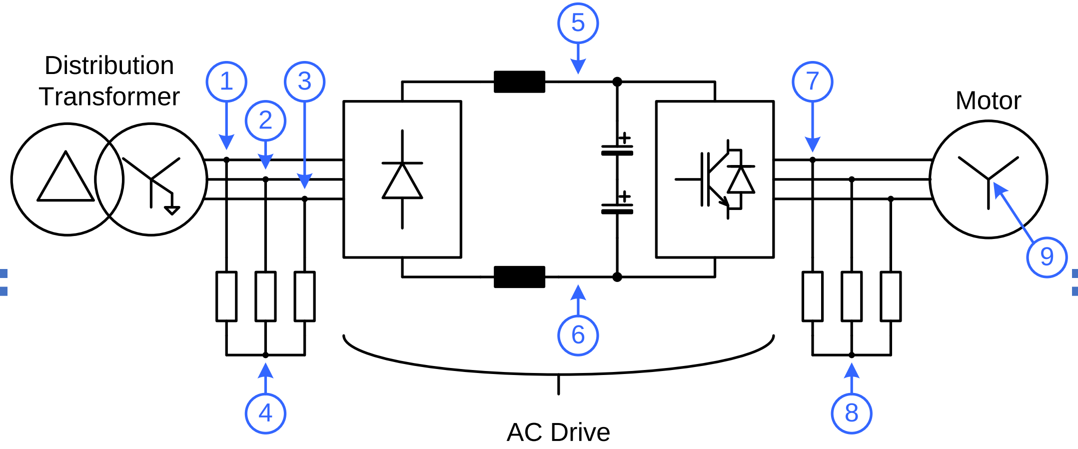


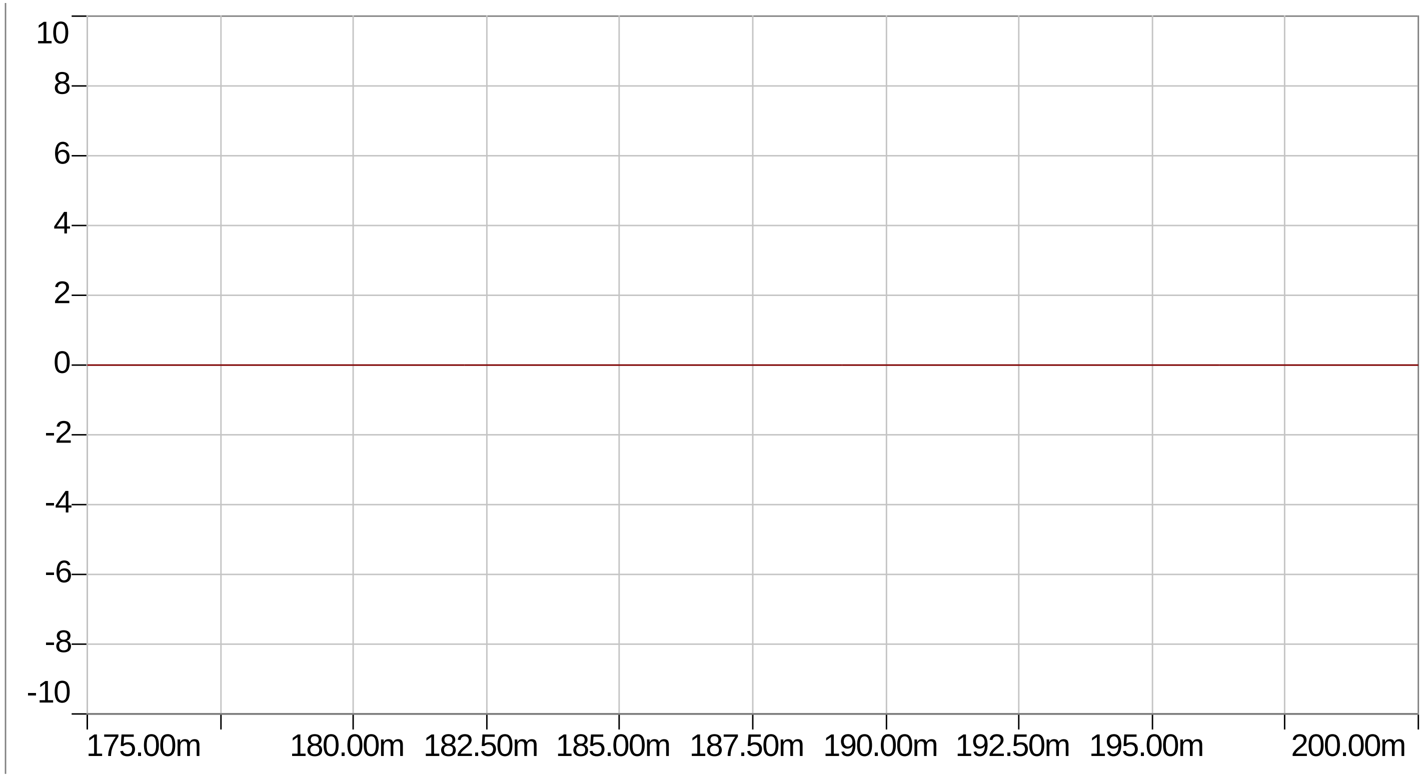
Probes 1,2,3 to gnd



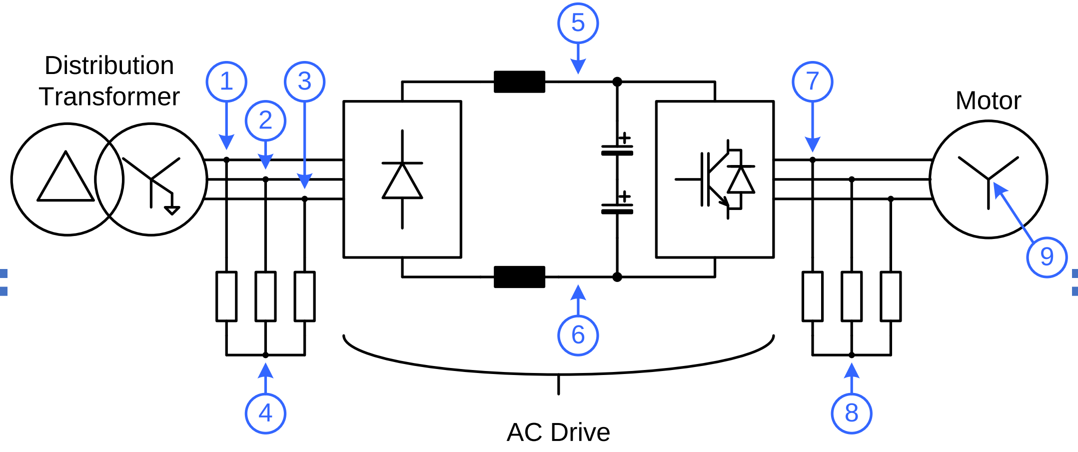


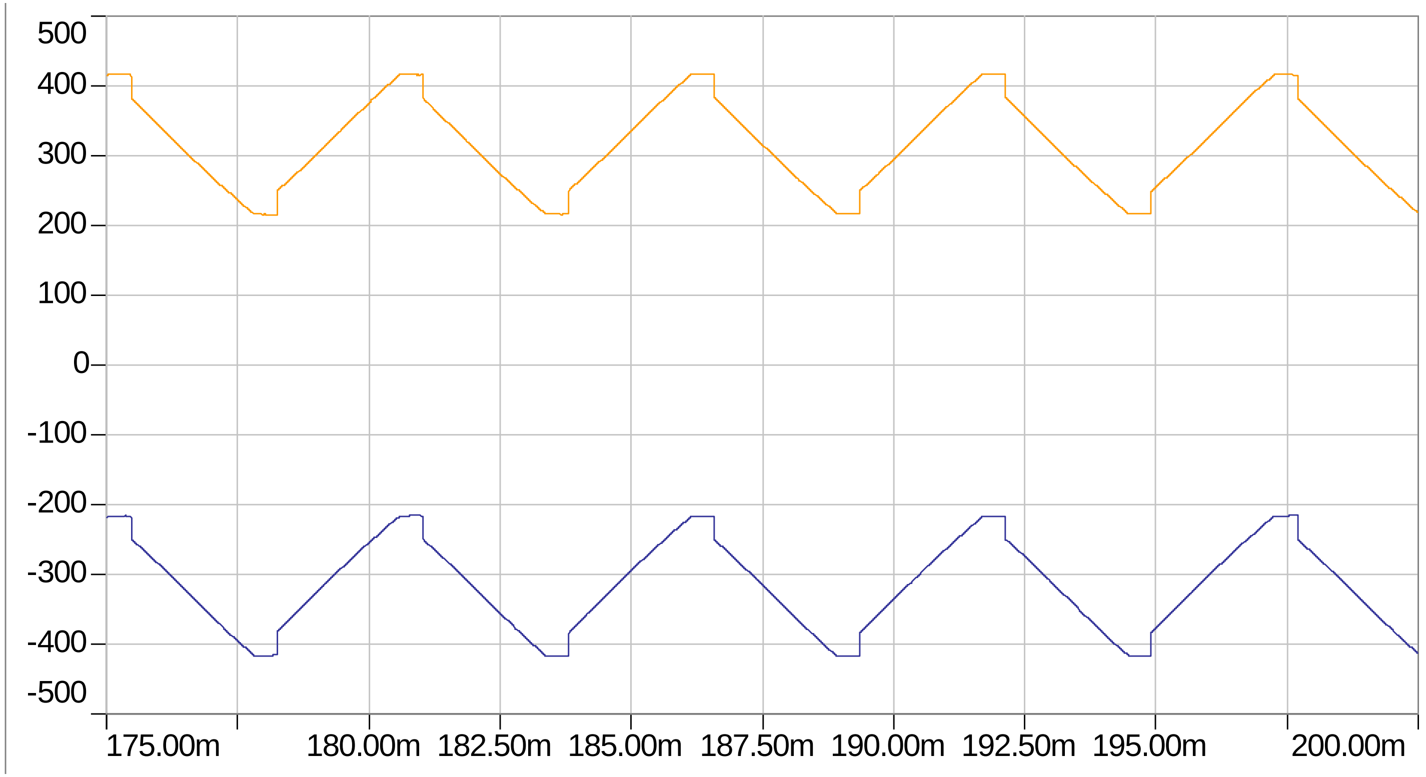
Probe 4 to gnd



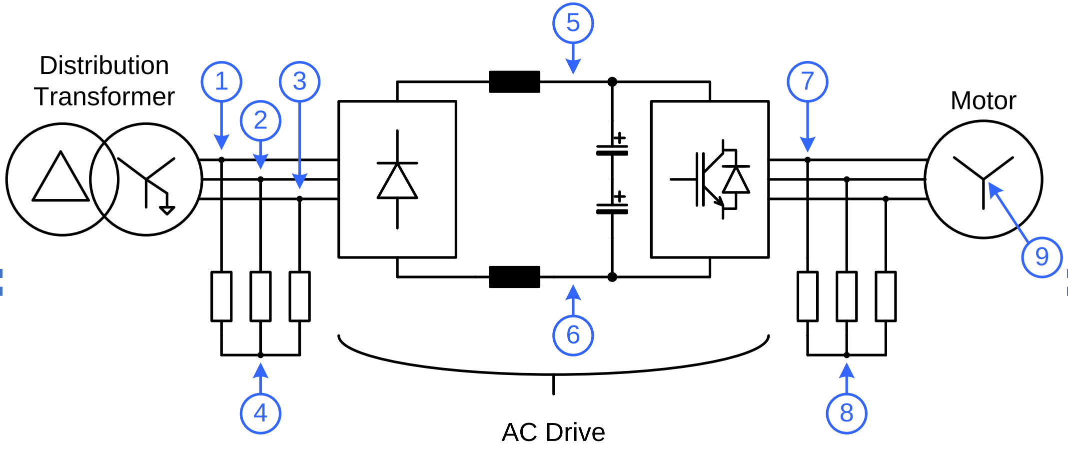


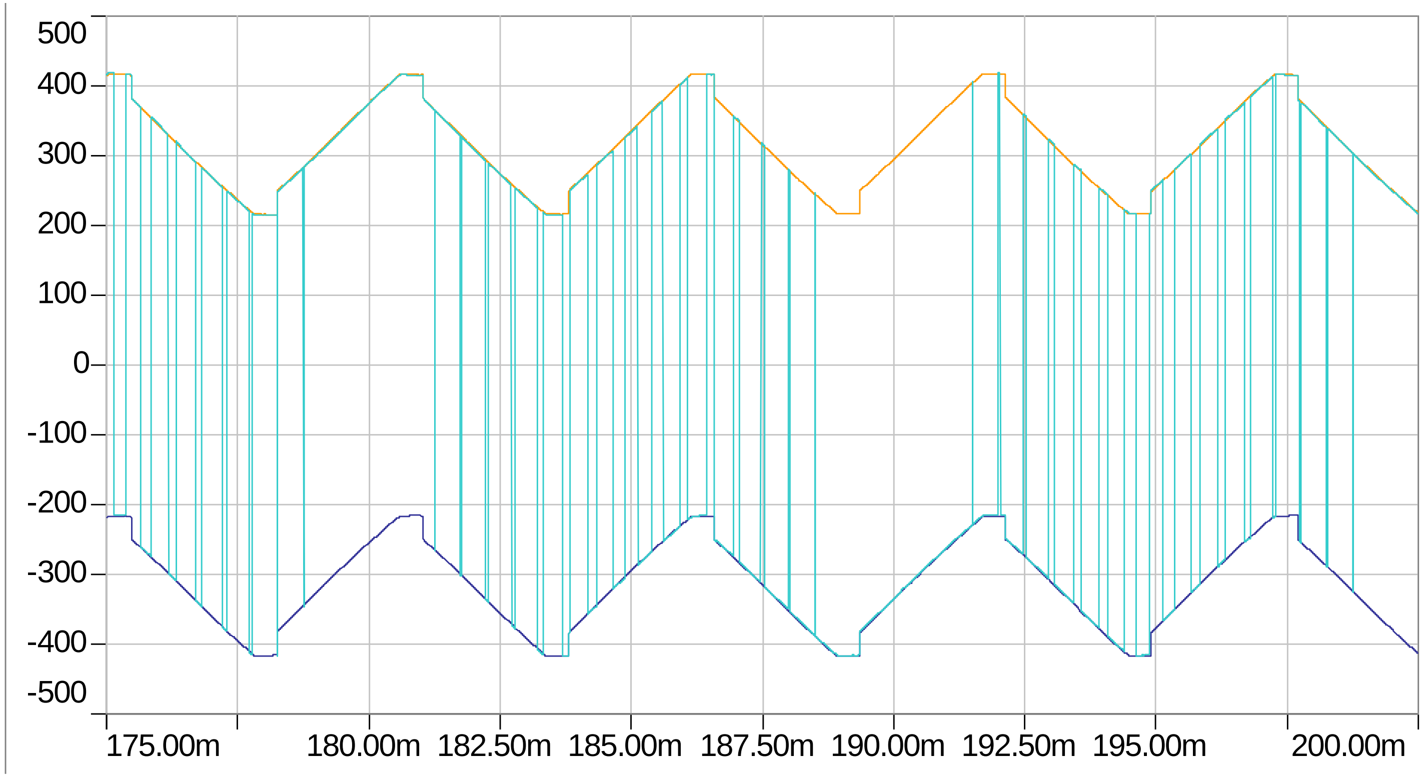
Probes 5,6 to gnd



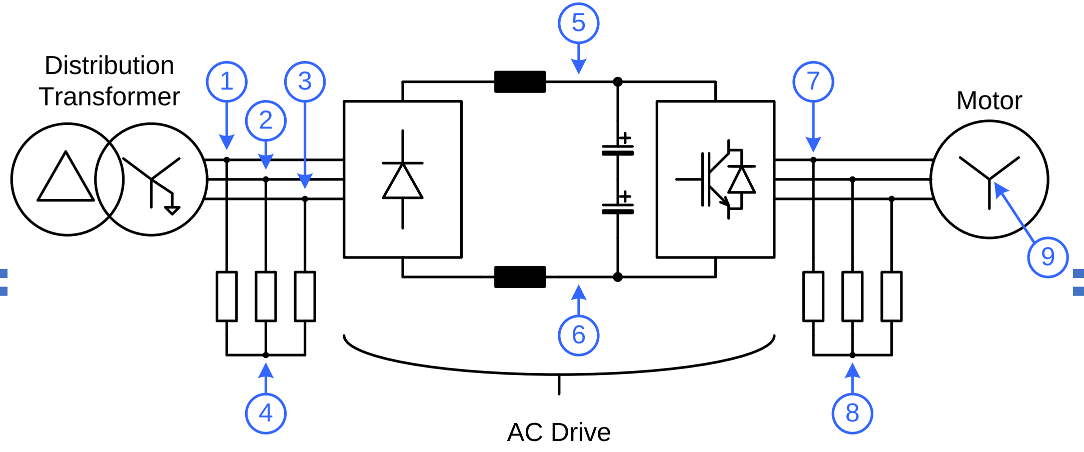


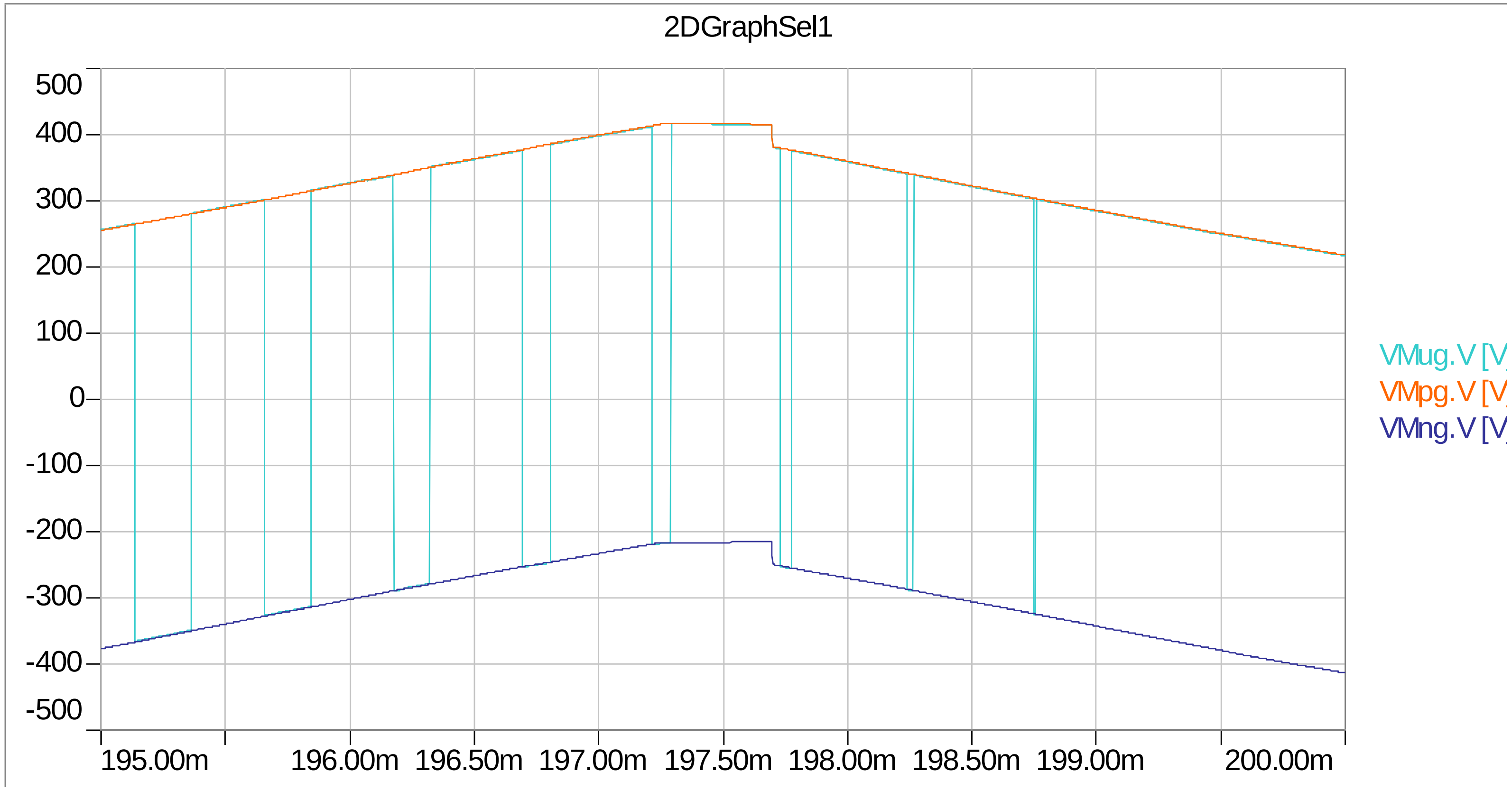
Probes 5,6,7 to gnd



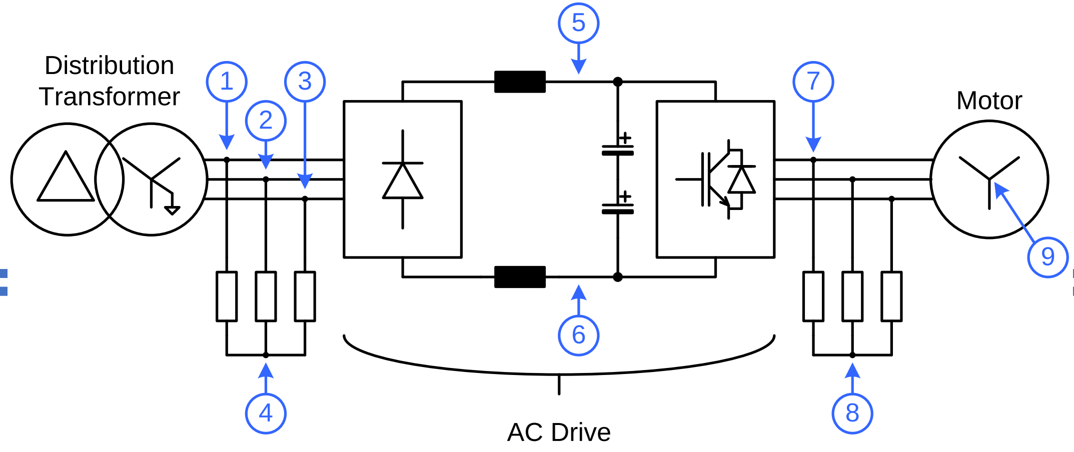


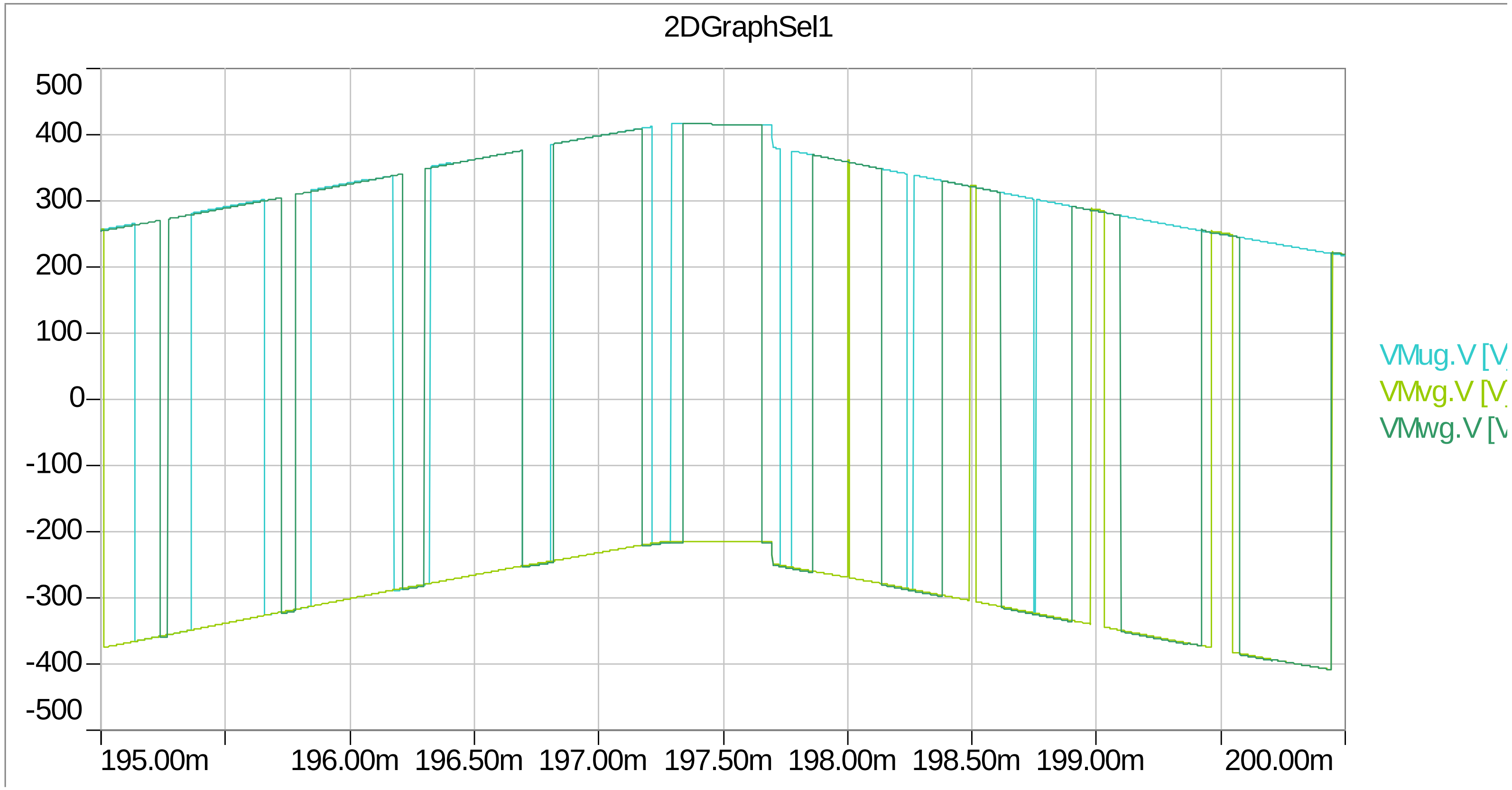
Probes 5,6,7 to gnd



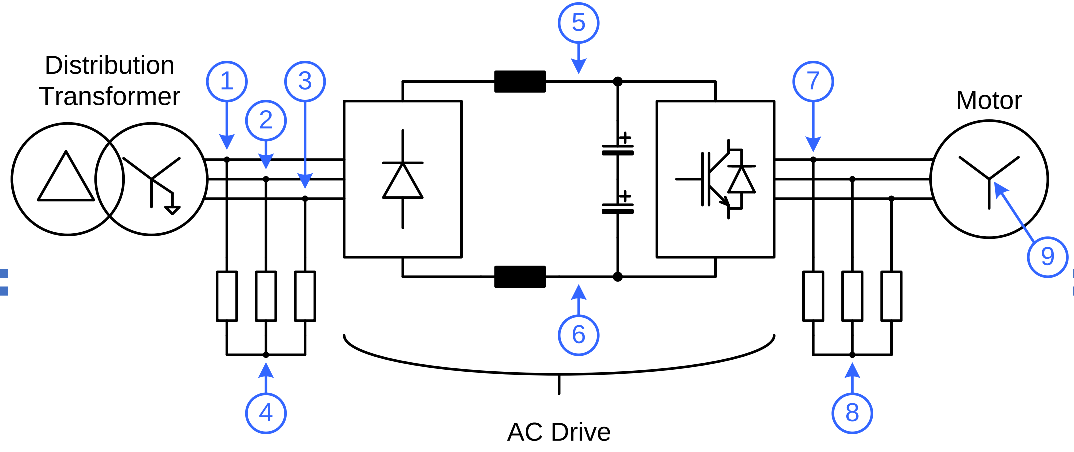


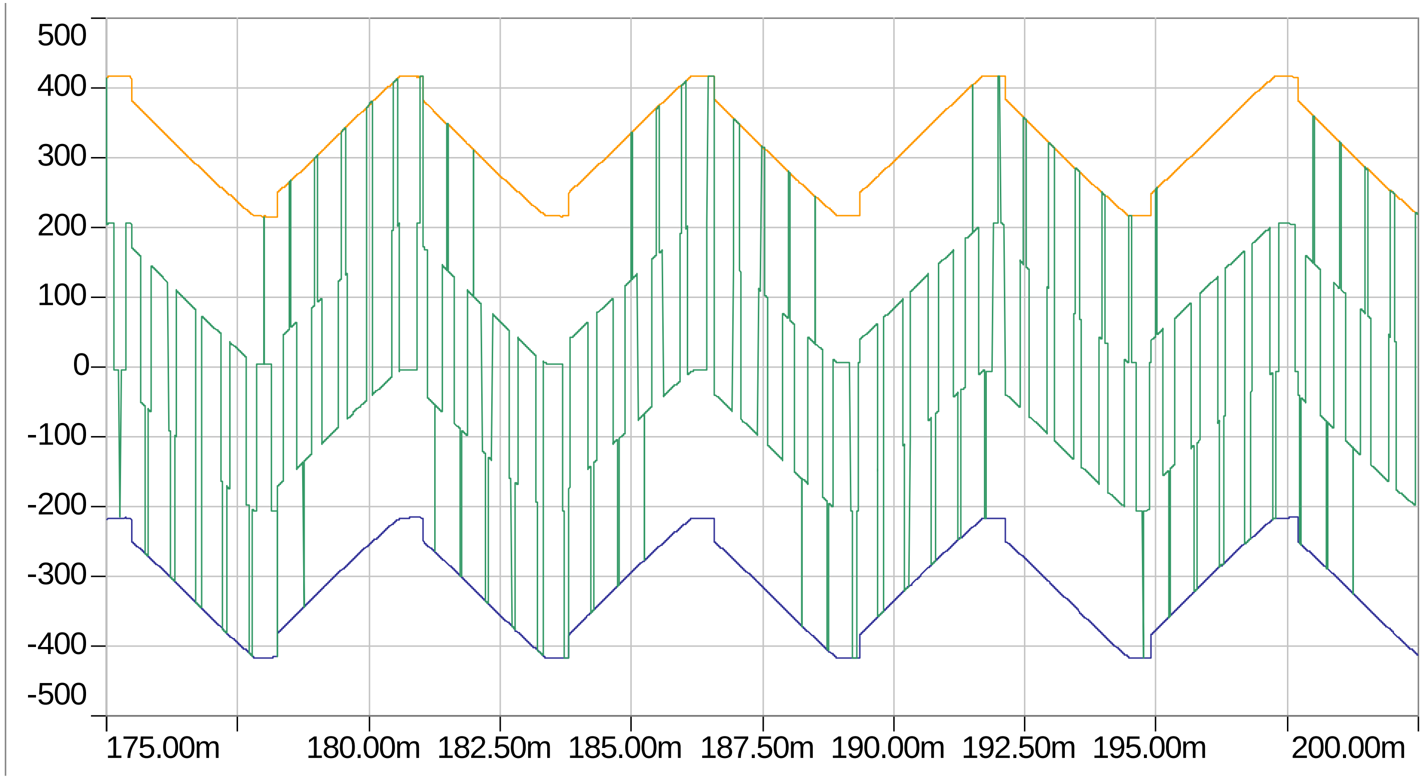
Probes 7u,v,w to gnd





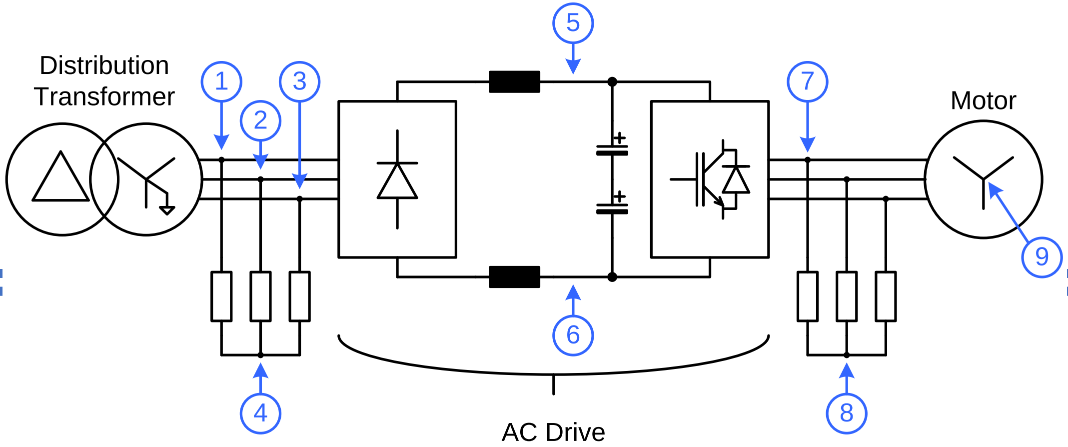
Probes 5,6,8 and 9 to gnd



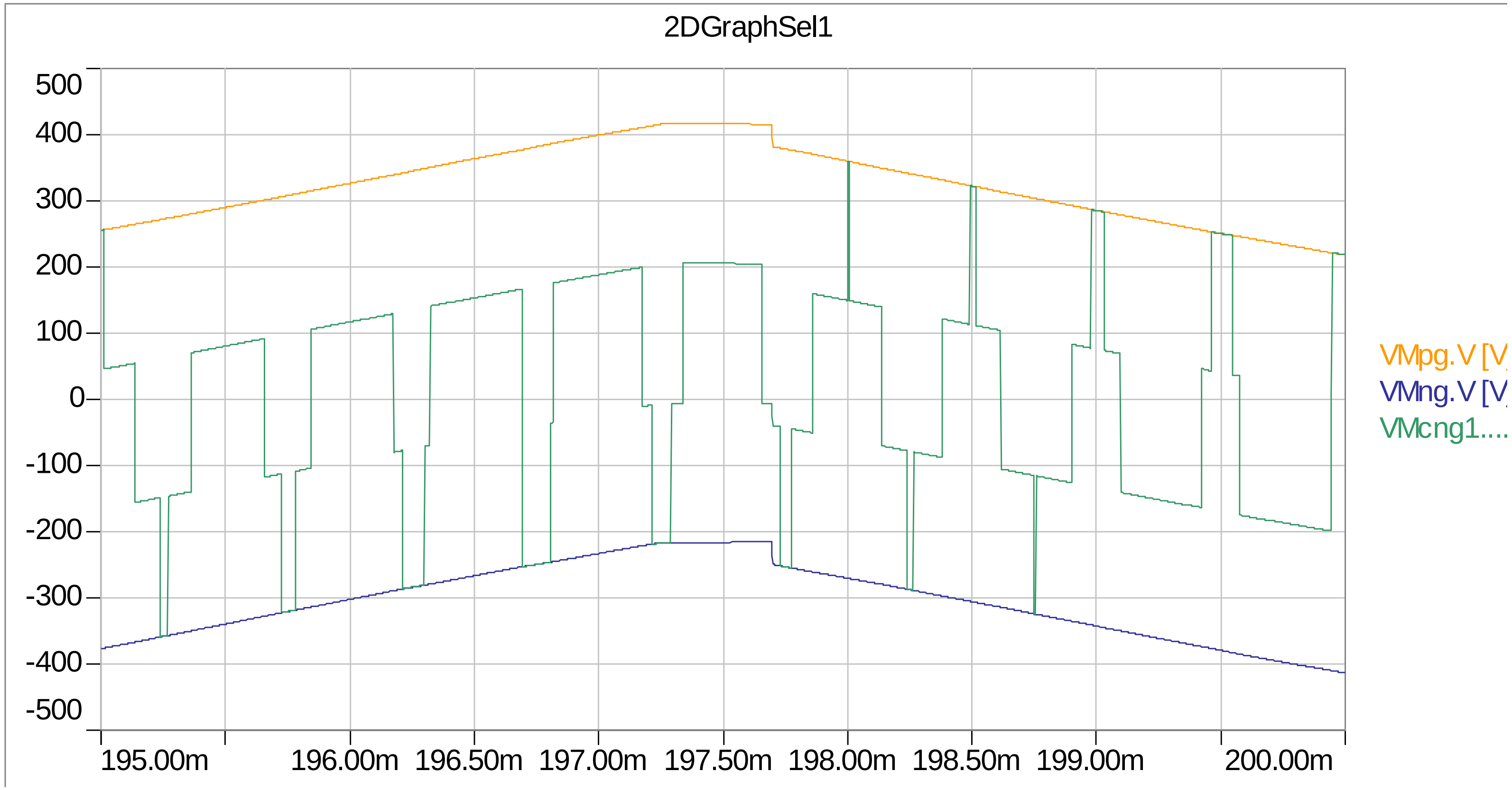


Green = CM voltage on output

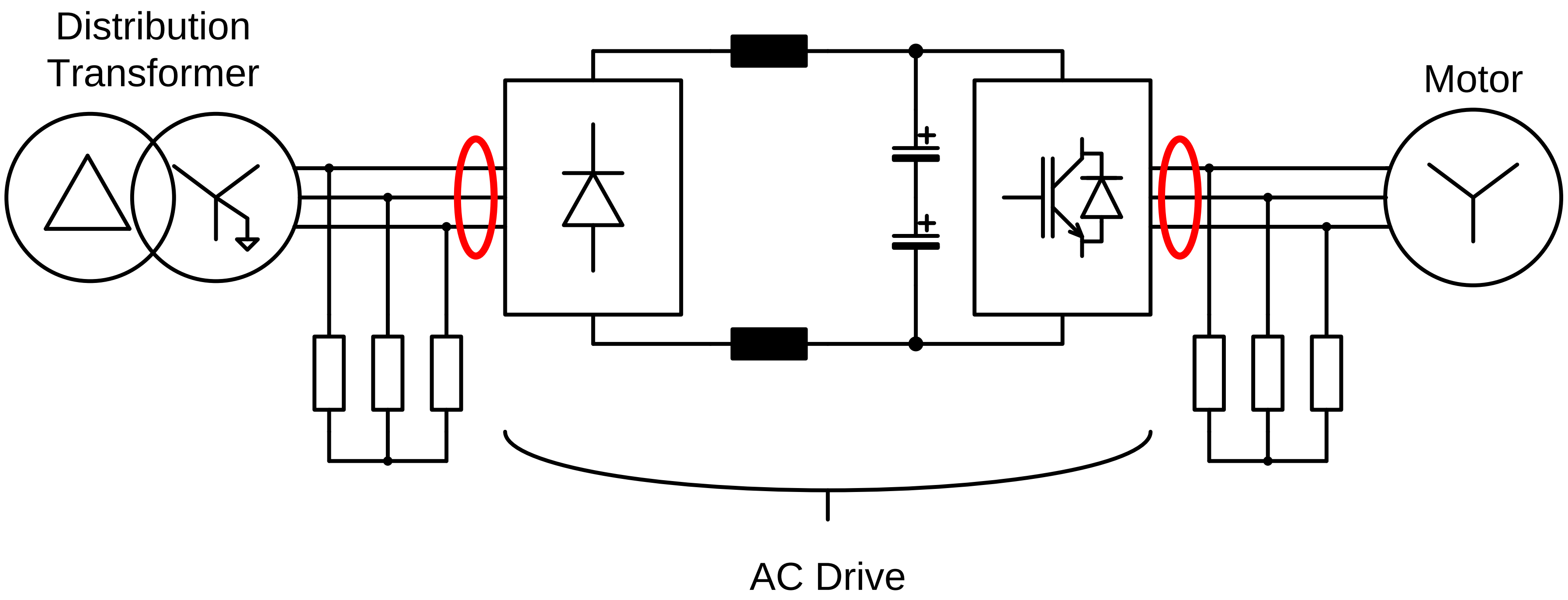
Probes 5,6,8 and 9 to gnd



8 and 9 are the CMV

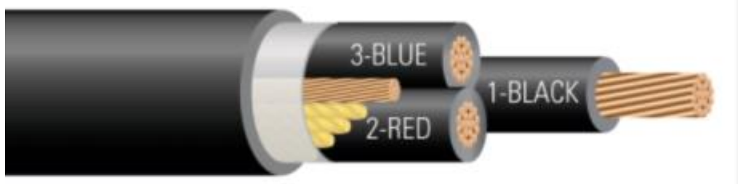


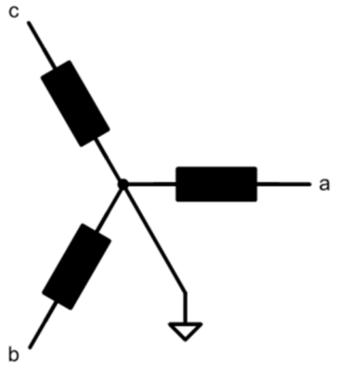
Common Mode Currents Measurement Locations



Drive Installation – Power Input

- Conventional cable type
  - Note: EMC (Electro Magnetic Compatibility) requires power input cable similar to output motor cable
- Cables sized in accordance with NEC (sections 430.6, 430.21, 430.25)
- Ampacity = 125% of drive input current normal duty rating
- If long distances, size should be increased to reduce voltage drop (Avoid voltage drop of >3% at rated load)
- Increased cable size may be needed due to quantity of cables in conduit (NEC Table 310.15(B)(2)(a))
- Increased cable size may also be needed due to ambient temperature or parallel conductor de-rates (NEC Table 310.16)
- 3-phase, grounded power network, with ground conductor

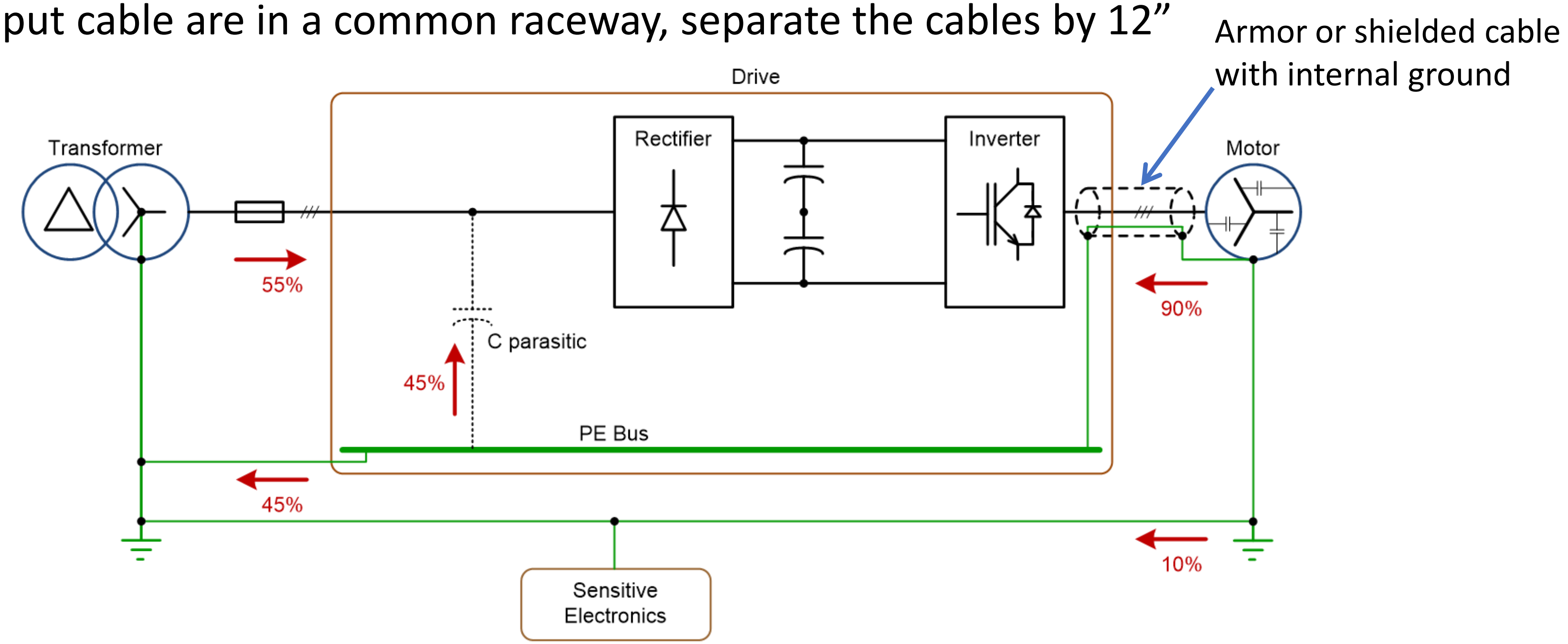




Drive Installation – Power Output

Motor cable must handle current & voltage output

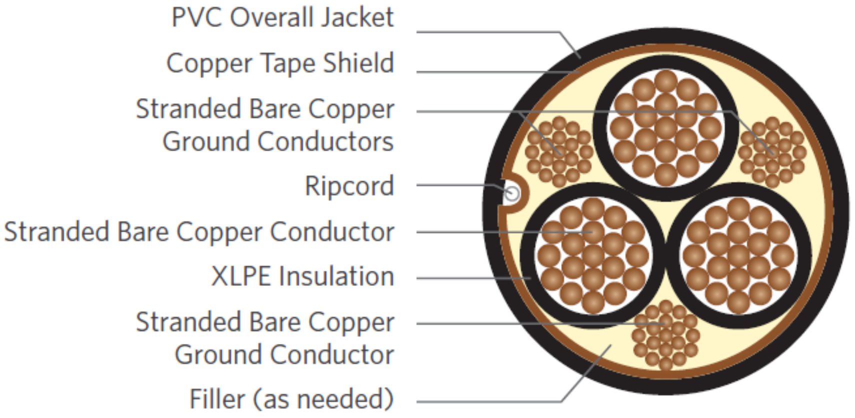
- Provide low impedance, high frequency return path to drive
  - Employ Single Point Grounding
- Provide high frequency shielding quality connections
- Each drive output run in separate conduit
- If output and input cable are in a common raceway, separate the cables by 12”



Drive Installation – Power Output

Achieve a solid return path via cable:

- Use continuous corrugated aluminum armored MC cable (symmetrical grounds recommended) OR
- Shielded power cable OR
- Fully bonded steel or metallic conduit (360^0 electrical contact joints)
  - Cables must be symmetrical and concentric
  - Use stranded cable instead of solid core cable



Drive Installation – Power Output

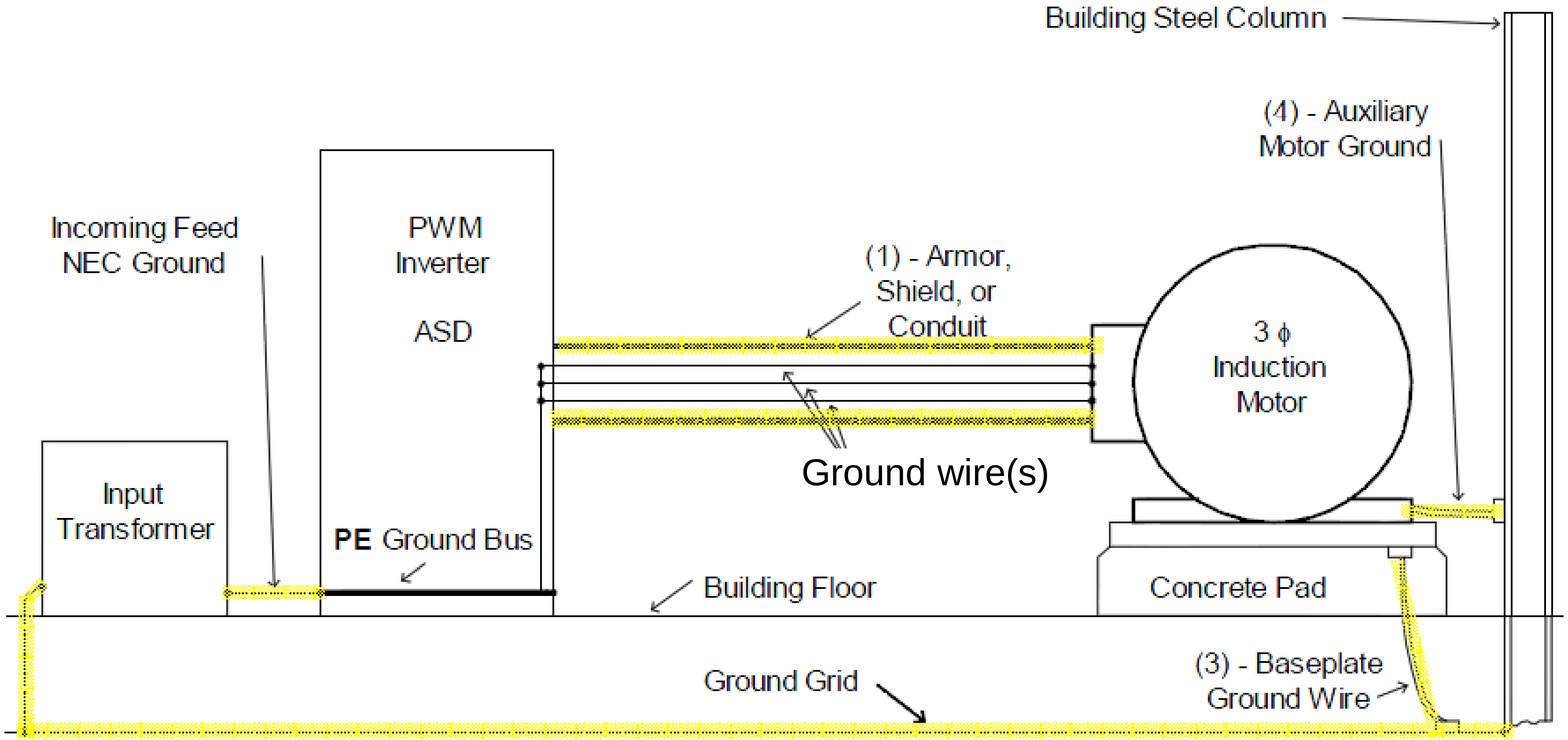
Cable	Insulation			NFPA 79 Compliant?
Type	Thickness[1]	Type	Compound	–
THHN	15 mils	Thermoplastic	PVC	NO
XHH, XHHW, XHHW-2	30 mils	Thermoset	XLPE or EPR	YES
RHH, RHW, RHW-2	45 mils	Thermoset	XLPE or EPR	YES

[1] for size #14 and #12 AWG cables

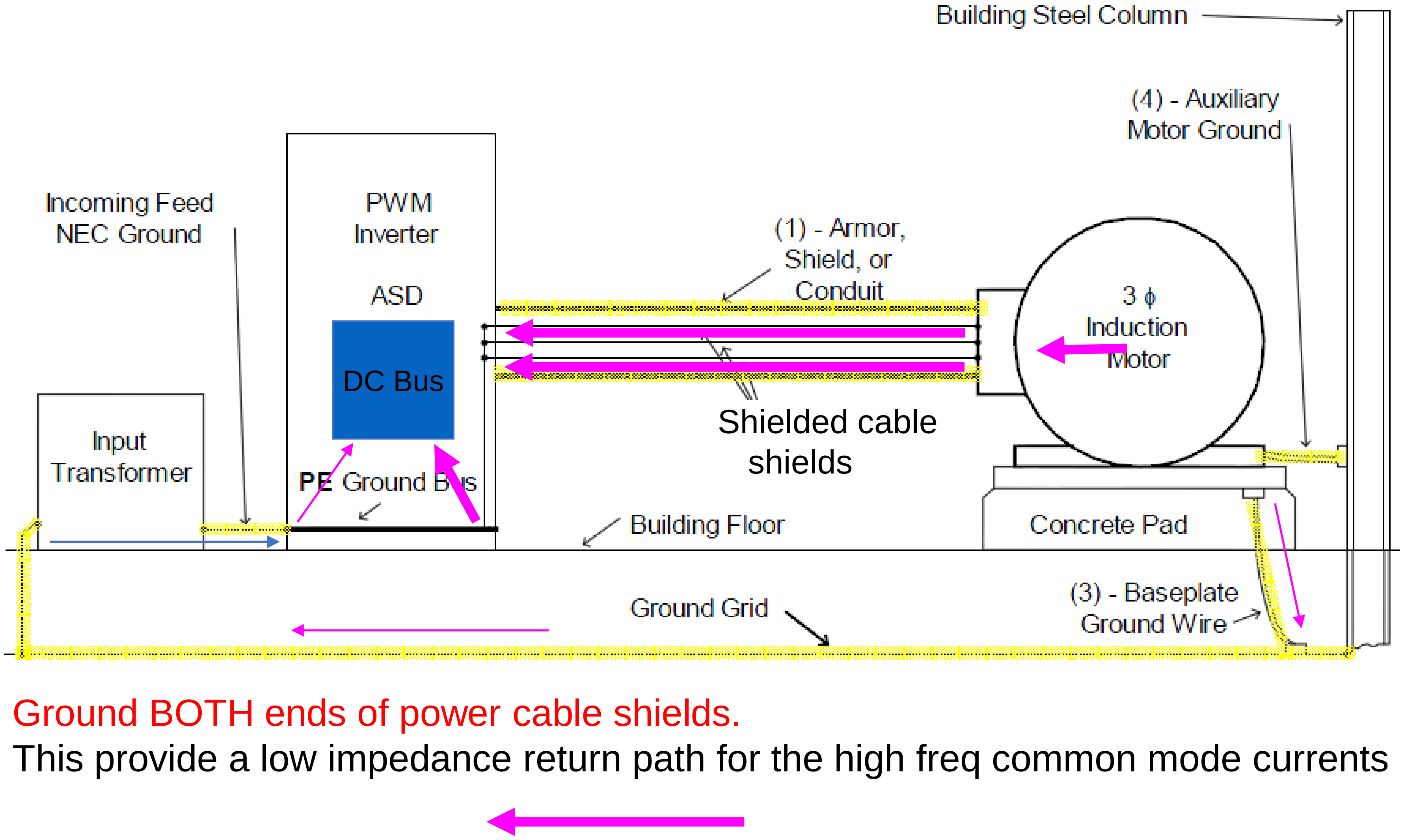
- THHN is not recommended for VFDs (OK for building wire and jackets)
    1. It will cold flow when subjected to heat and pressure
    2. Corona Inception Voltage (CIV) is low
    3. Its voltage withstand is significantly lower when wet (high humidity)
    4. Its capacitance is higher which leads to more common mode current in the shield and ground
    5. NFPA 79 does not allow the use of that for drives
- Shielded Cable is needed
    1. Provides low impedance path for high frequency common mode currents back to the drive
    2. Reduces crosstalk (coupling) between adjacent wires in a common raceway, tray, conduit, etc

S Wetzel, VFD Cable: Essential or Overkill?, Southwire presentation

Safety Grounding



Common Mode Grounding

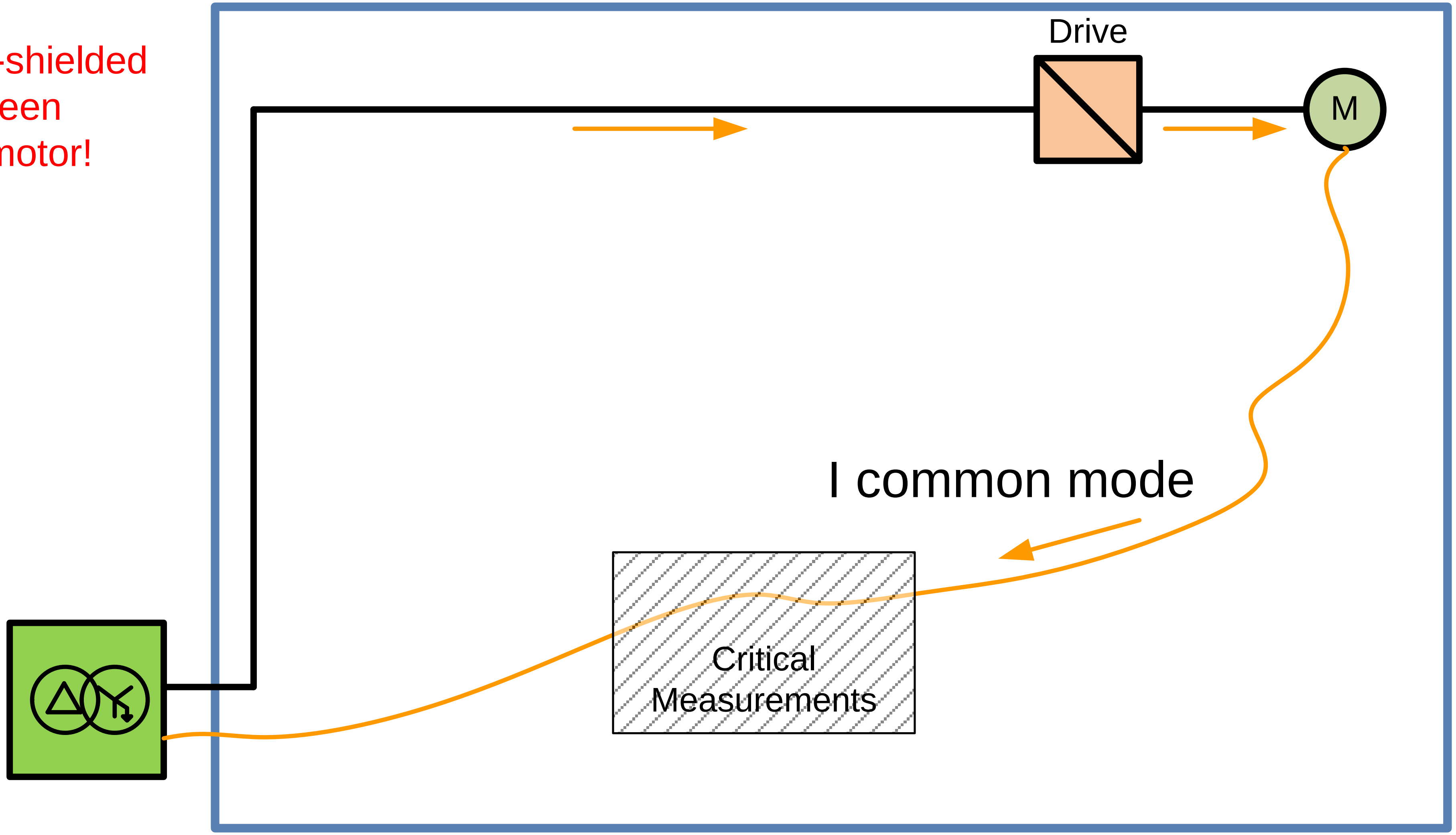


Ground BOTH ends of power cable shields.

This provide a low impedance return path for the high freq common mode currents

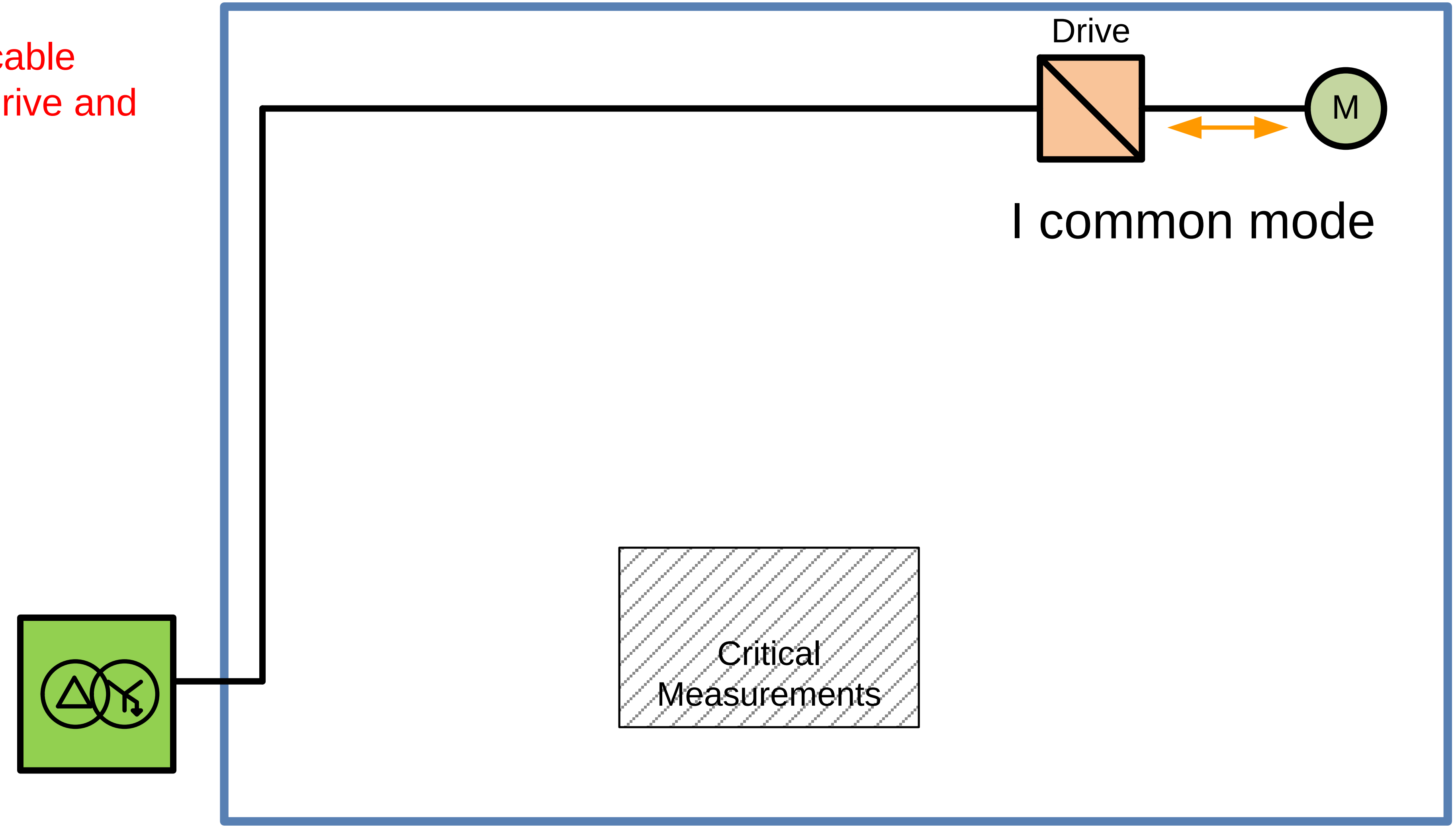
Possible Path for Common Mode Currents

Cheap, un-shielded cable between drive and motor!



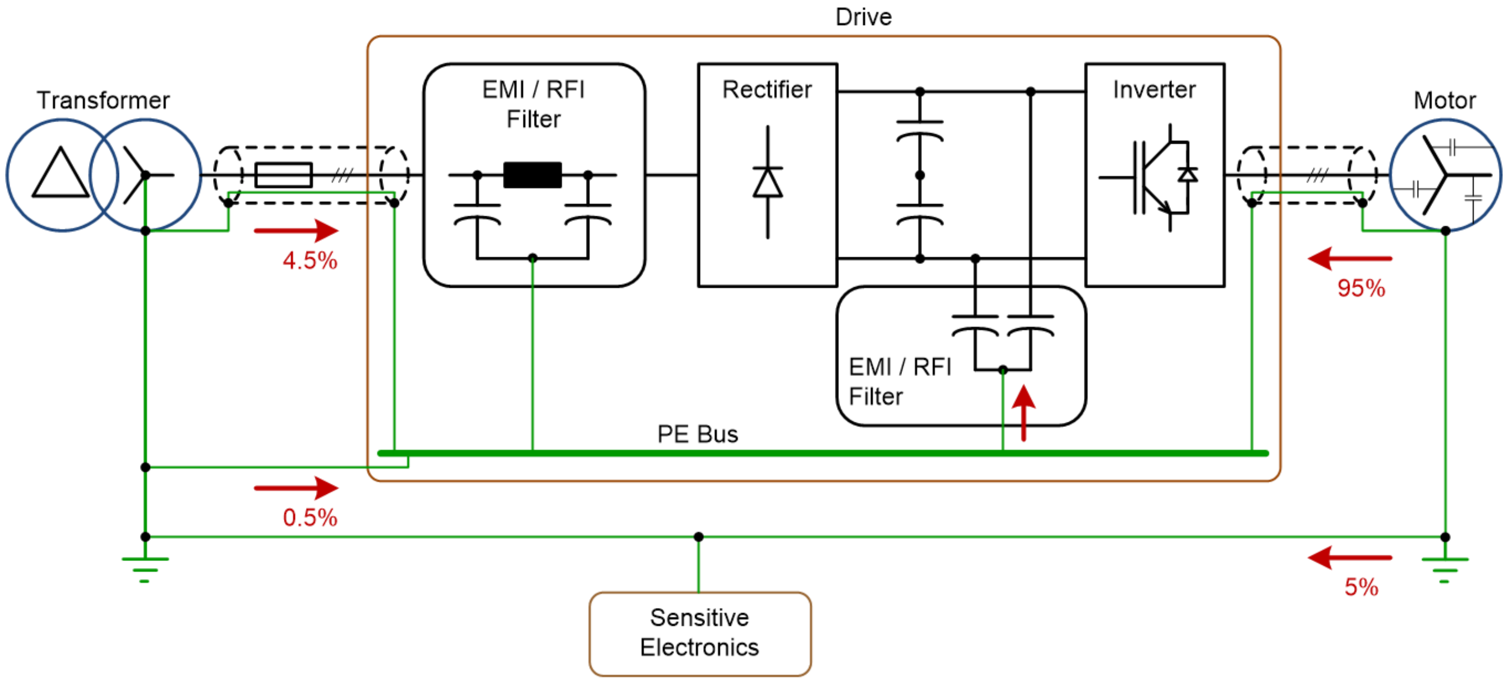
Preferred Path / Containment

Shielded cable between drive and motor!



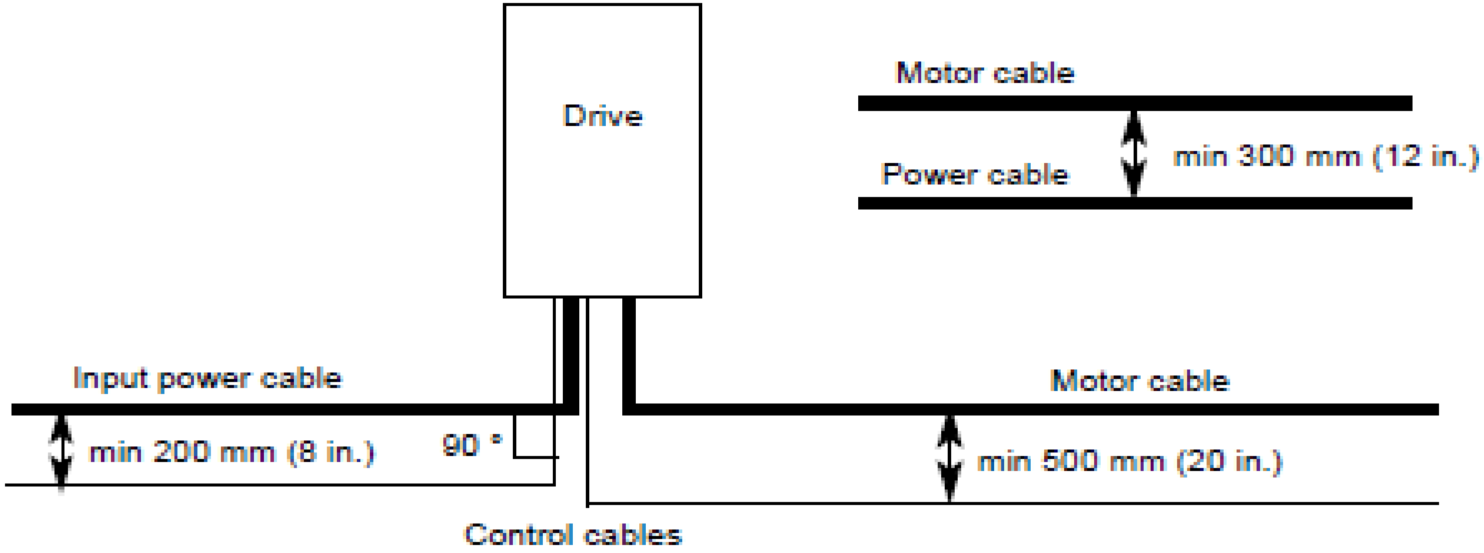
Drive Installation – Power & EMC Requirements

- Operation of a drive in a "CE" compliant country requires EMC compatibility
- To be compliant, both power input & output cables need to be shielded
  - 1st Environment Filter (may require an external filter)
  - 2nd Environment Filter (included in ABB Drives)
  - EMI / RFI filters minimize conducted & radiated noise



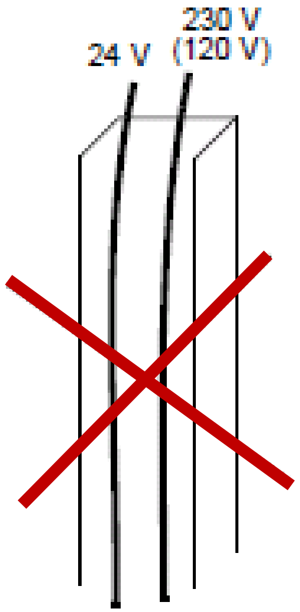
Drive Installation – Power & Control

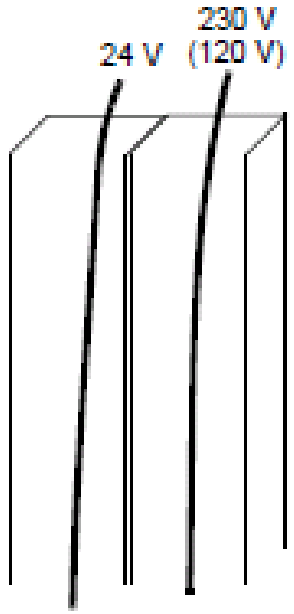
- Separate power and control wiring – use separate grounded metallic conduits for input, power & control
- If common raceways are used, separate drive input power and Control by 8” or output power and control by 20”
- Inside the drive enclosure, control wires must be permanently affixed to maintain a minimum of 2” spacing from power wiring



Drive Installation – Control Wire Routing

- Routing and Separation
  - **<u>Never</u>** run control in a conduit or raceway with power wiring
  - 120VAC control should be run in a separate conduit from power or other control (24VDC, analog, encoder or fieldbus)
  - Recommendation is one conduit each for:
    - Power Input
    - Power Output
    - 120VAC Control (if applicable)
    - All other control (24VDC, Communications, Encoder, etc)



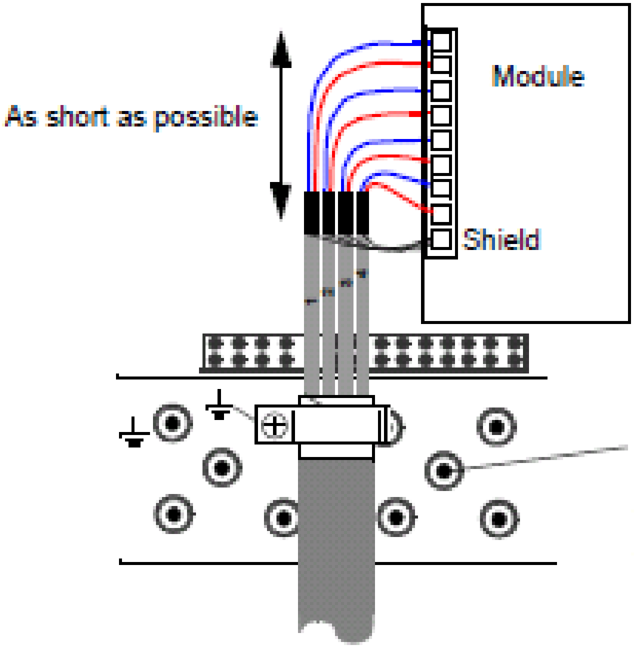


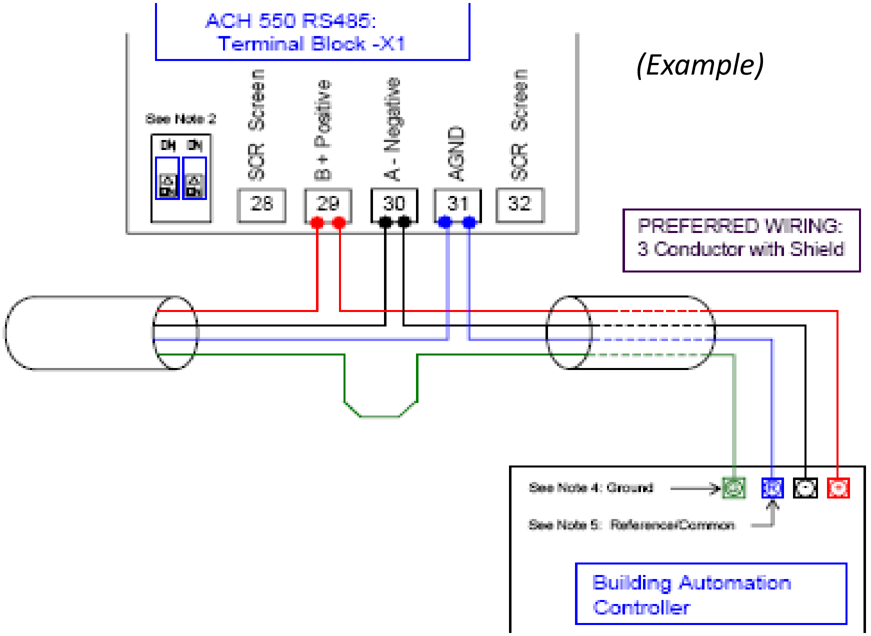
Drive Installation – Control Cables

- 120VAC control should use 600VAC rated, single conductor (e.g. THHN/THWN) or multi-conductor tray cable
- 24VDC (or 12VDC) control should be multi-conductor twisted cable (300 or 600V rating)
- Overall shield is recommended
  Belden type 9318, 9552, 9553, etc. with twisted pair, or equivalent)
- Analog Signals (0-10VDC or 0-20ma)
  - Use individually shielded multi-conductor twisted pair cable (Belden type 9318, 9369, 9369, etc. or equivalent)
  - Shield cut back and taped at the signal source – grounded at the drive end only
  - If signal device manufacturer requires grounding shield at the device, do not ground also at the drive

Drive Installation – Fieldbus Control

- Fieldbus signals should use the cable as recommended in the fieldbus manual for the specific protocol
  - Follow manufacturer's recommendation for cable type
  - Terminate shield at the location recommended by the manufacturer
  - Embedded fieldbus connections (A, B, Signal Gnd, Shield)





(Example)

Motor Installation

- Distance between drive and motor affects:
  - Cable capacitance (cable acts like a capacitor)
    - Small drives – limited to about 100ft.
    - Large drives – may support up to 1000ft
  - Switch Frequency
    - Lower switch frequency - longer cable length
    - Load reactor or dv/dt filter allows longer cable distance

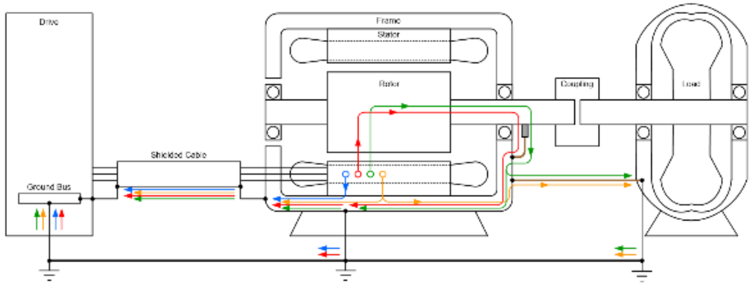
      and will help protect windings at short/long distances
  - EMC standards
    - Cable lengths are limited
    - Cable acts like an antenna to propagate EMC noise
  - Motor Winding & dv/dt (V reflection) – below 5ft, above 30ft
    - Inverter Duty Motors handle this issue
      (NEMA MG1, Part 31, sec. 31.4.4.2)
    - Load reactor or dv/dt filter will help protect windings at short/long distances

Best thing to do is:

Follow the manufacturer's recommendations!

Call them with questions!

End of Part 3


Drive
Frame
Stator
Rotor
Coupling
Load
Shielded Cable
Ground Bus