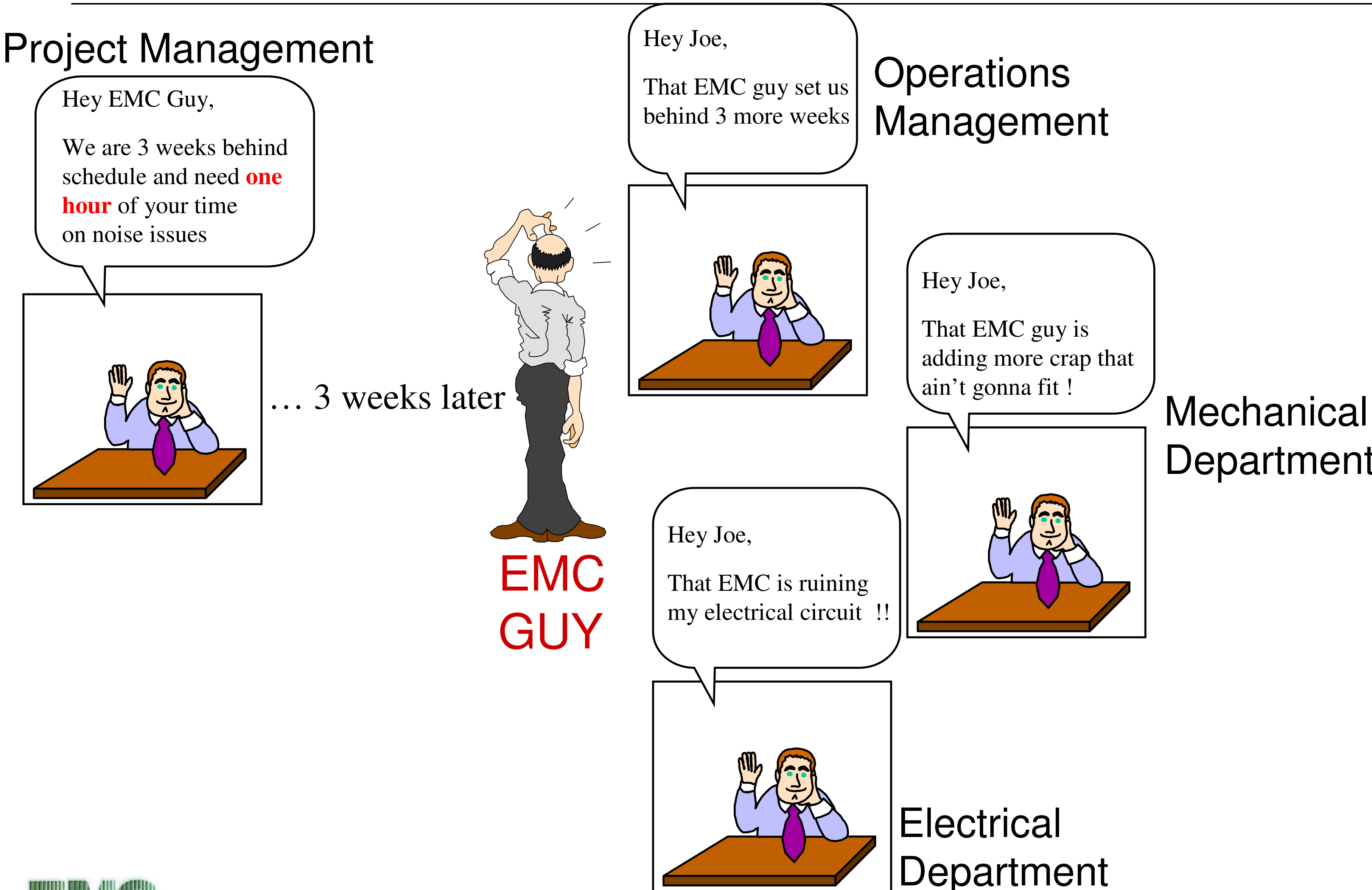
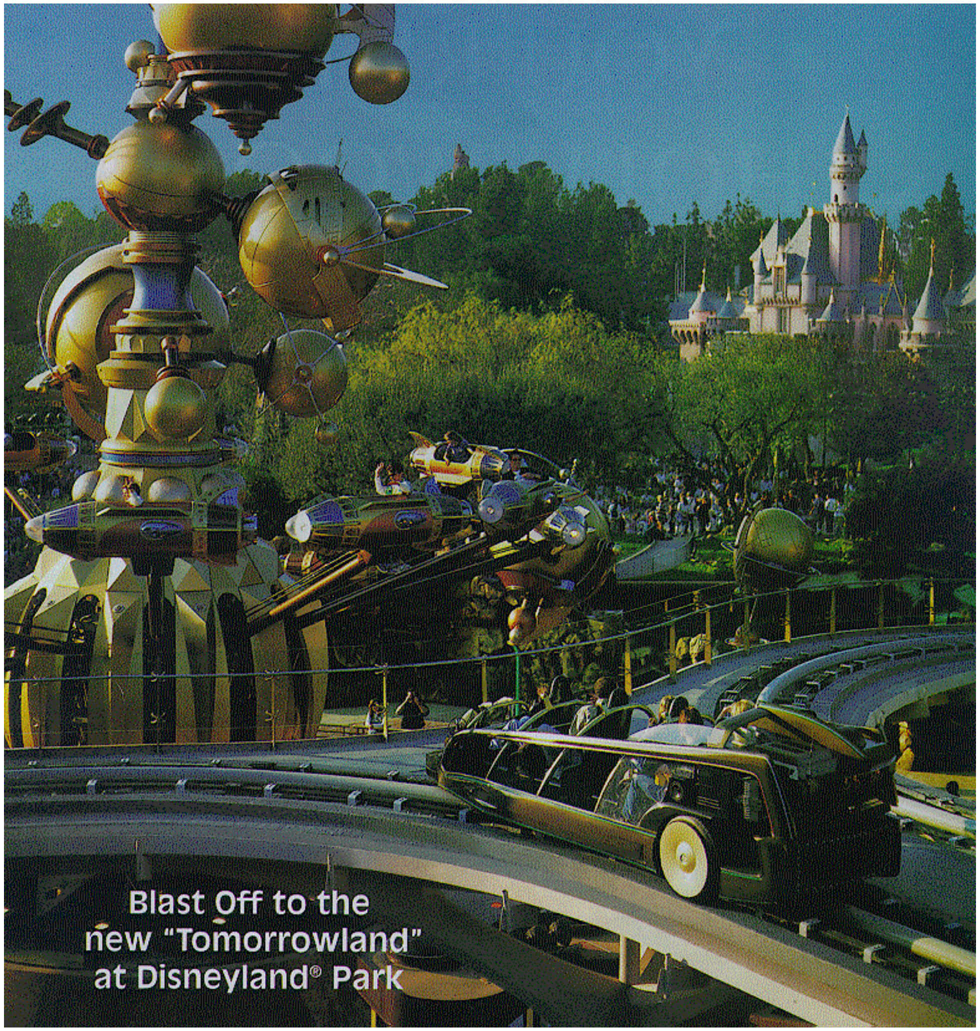
Mobile EMC Adventures

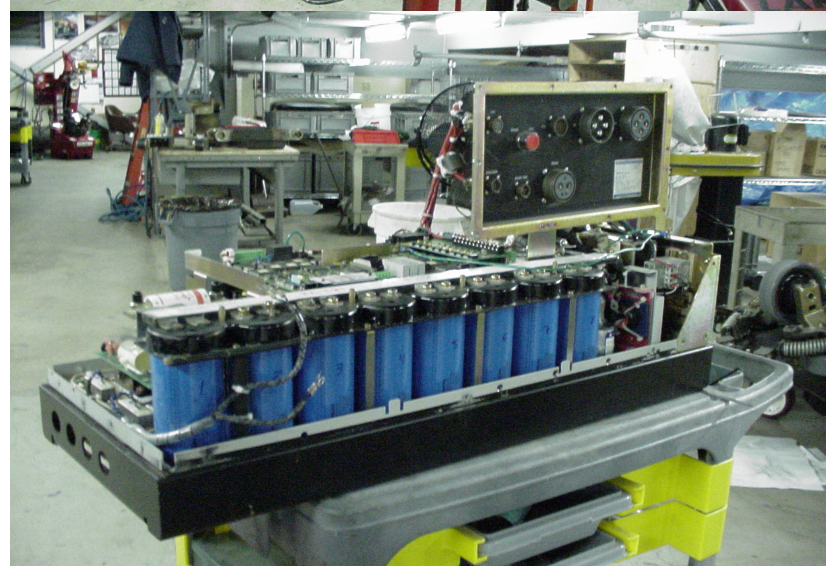
by
G. L. Skibinski

Most EMC Problems follow this path



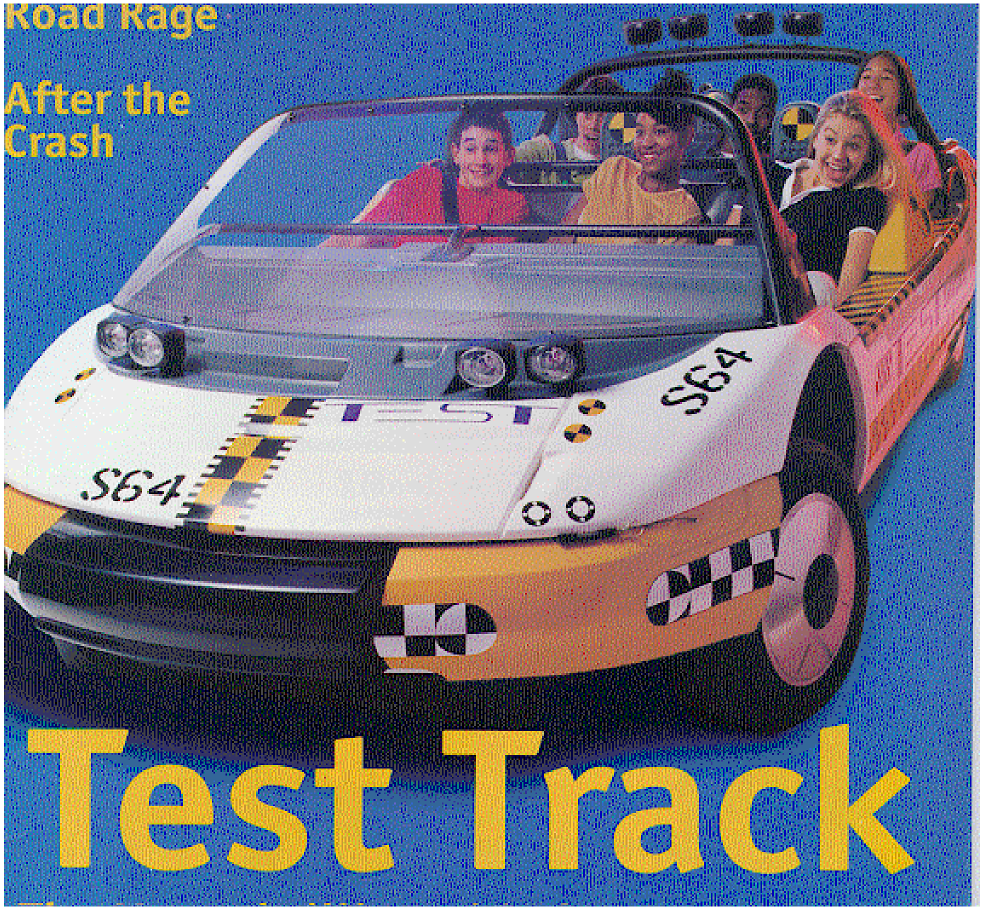
Rocket Rod sled 125 hp Disneyland





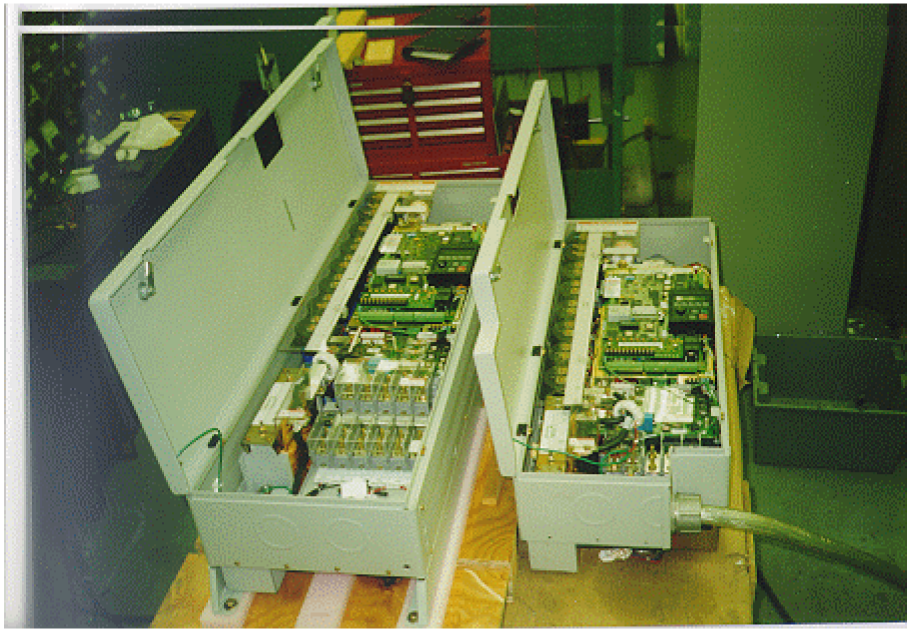
Shoe rail pick up
Steel frame used as ground

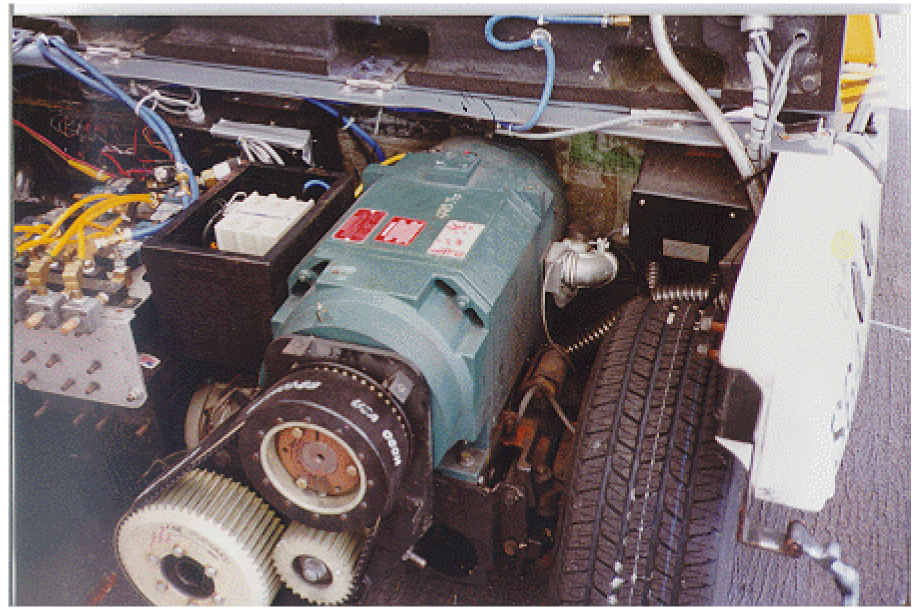
GM Test Track 125 hp Disney World



Shoe rail pick up
Carbon graphite frame

GM Test Track 125 hp Disney World





Standard drive

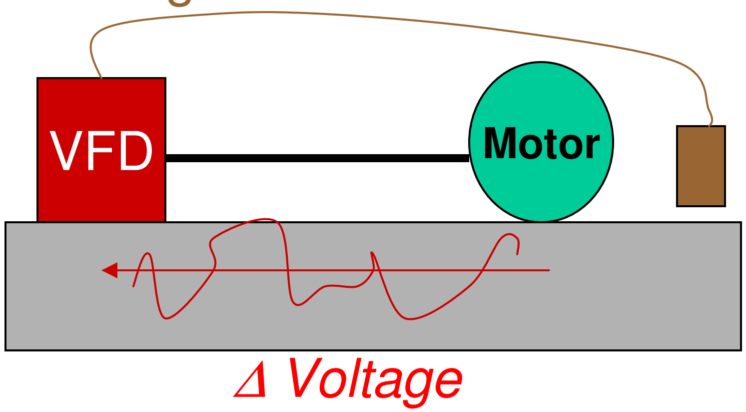
Modified drive

Drive motor

Effect of Noise Conduction thru ground plane

Rocket Rod

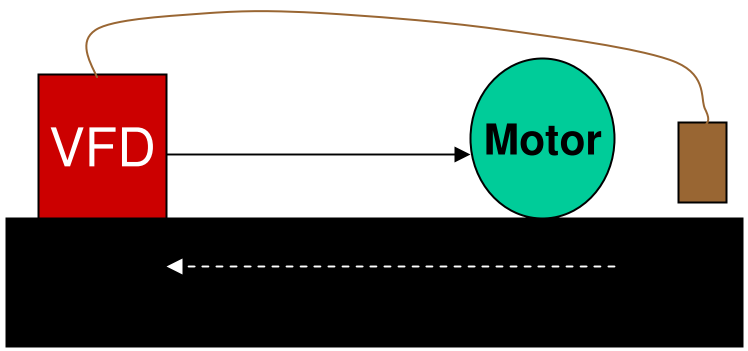
Single ended sensors



Large Ground noise thru
Steel frame

Test Track

Twisted Shielded Pair differential sensors



Little Ground noise thru
Carbon graphite frame

Heavy Expanded Mobility Tactical Truck

- Diesel-electric drive technology 20% fuel efficiency improvement
- 100 kW onboard generator
- Climbs 60 percent grade   65 mph on secondary roads

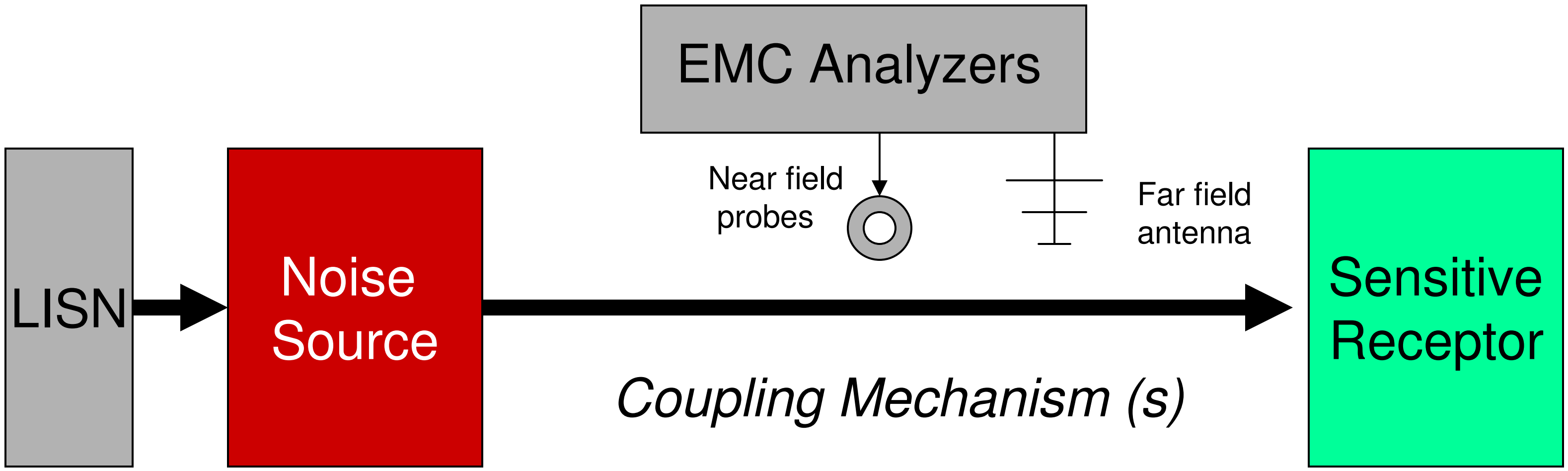
Discuss during Radiated section !!!

EMC Philosophy

by
G. L. Skibinski

EMI Emissions of Modern PWM AC Drives,
IEEE Industry Applications Magazine, Vol. 5, No. 6, November / December 1999,

EMC Philosophy: only Conducted & Radiated Emissions



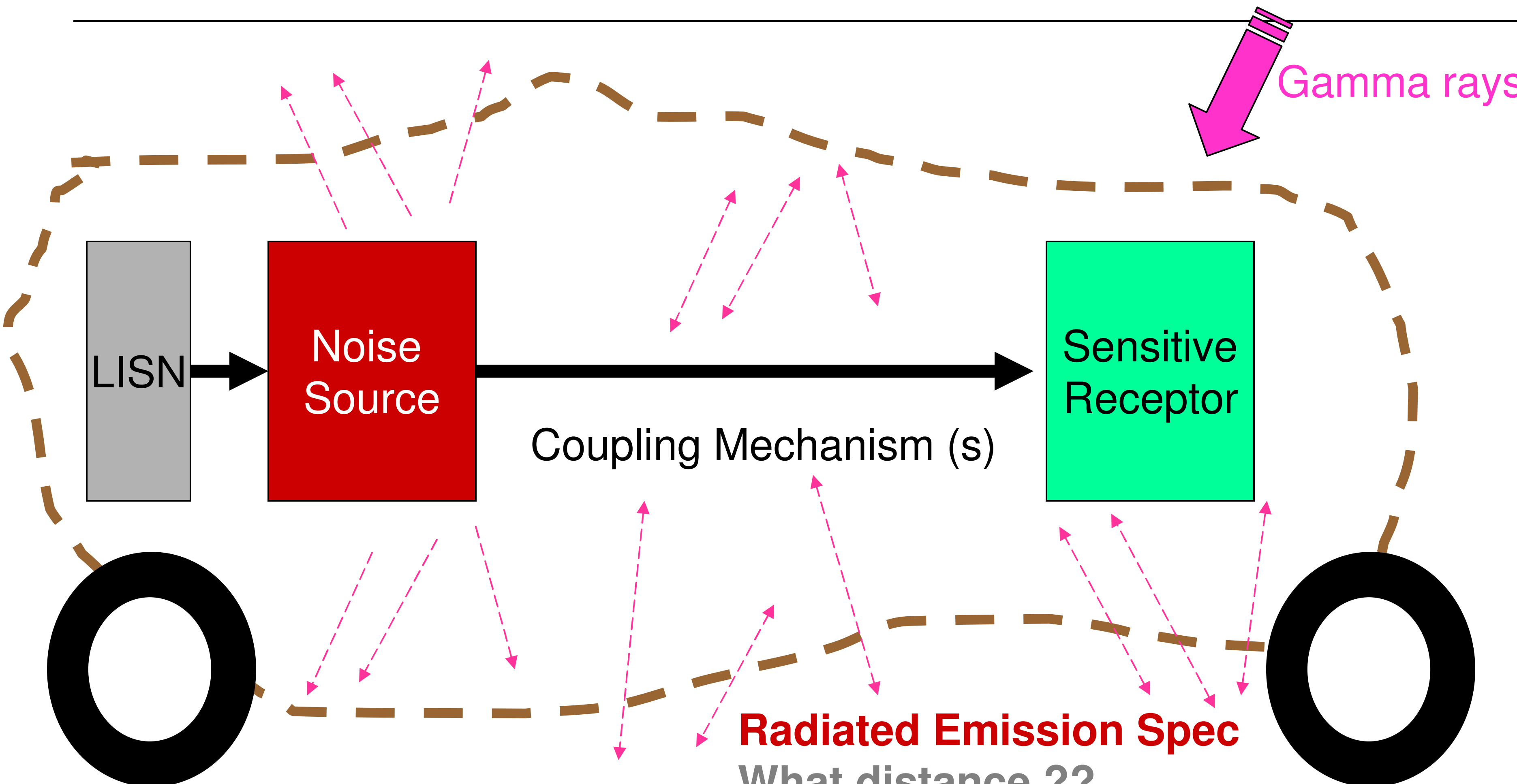
Conducted

	Magnetic Field ?	**Current inductive**
	Electric Field ?	**Voltage capacitive**
Radiated	**?**	**High frequency > 1 MHz**

Line Impedance Stabilization Network:
Measures Conducted Emission Spec

Radiated Emission Spec
EMC spectrum analyzers

Automotive Application: Conducted & Radiated Emissions



Radiated Emission Spec

What distance ??

how many HEV nearby ?

Susceptibility to what ? Blackberry?

Conducted Emissions

- **Compatible internal operation**
- **Guide to minimize radiated**

EMC Philosophy : "How TO " from the Start

Identify all Switching Noise Sources and Frequencies

clock edges, clock frequencies, PWM risetime, SMPS risetime, SMPS frequency, diode recoveries (5Mhz), find antenna's like heatsink edge or component leads or PCB traces
Slower risetimes and frequencies makes it easier if possible

Identify the Coupling Paths

Conductive
Capacitive coupling Electric field
or inductive coupling from current
Radiated at higher frequencies

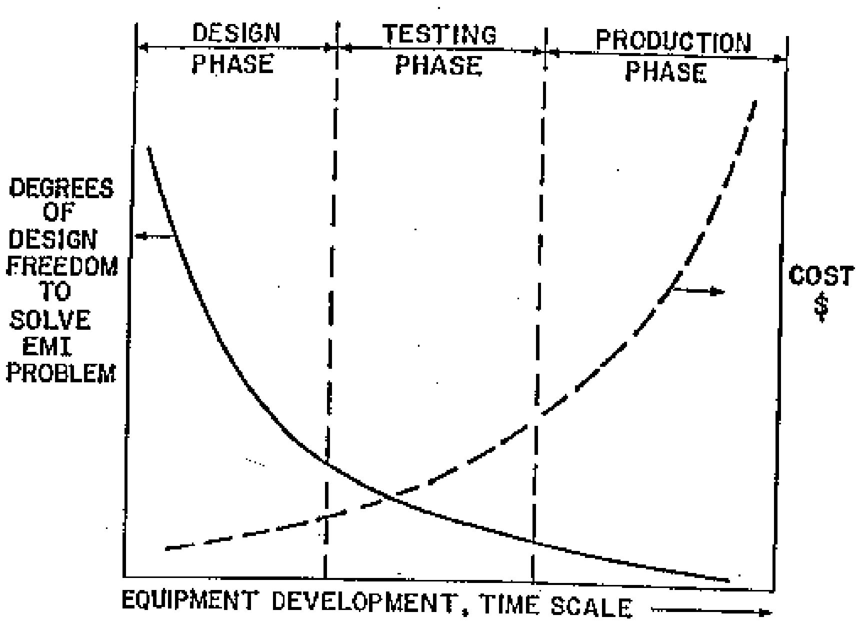
Attenuate the Noise

Find ways to kill it or block it by Integrating additional EMC filter components around existing drive components

Capture the Noise

Better layouts , bonding & shielding

EMC Philosophy : "Fix-ins" from the Start

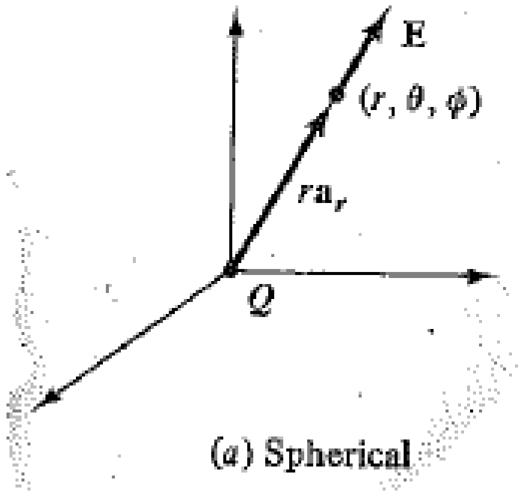


DESIGN GOAL

- **Learn from past**
- **Integrate EMC components around existing drive components to meet emission limits**
- **Make final unit smaller in size & lower cost than present**

EMC Rule: Electric and Magnetic Field Summaries

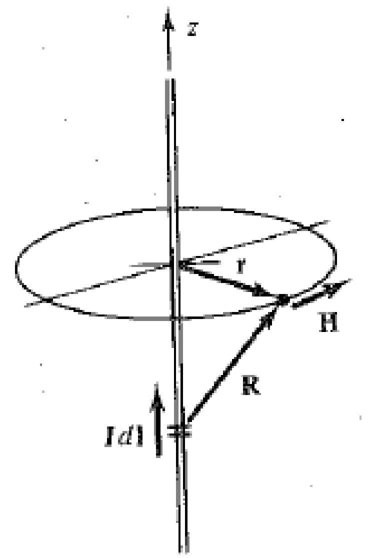
Electric Field



$$\mathbf{E} = \frac{1}{Q_T}\mathbf{F}_T = \frac{Q}{4\pi\epsilon_0 r^2}\mathbf{a}_r$$

E field varies inversely as [1 / Radius^2]

Magnetic Field



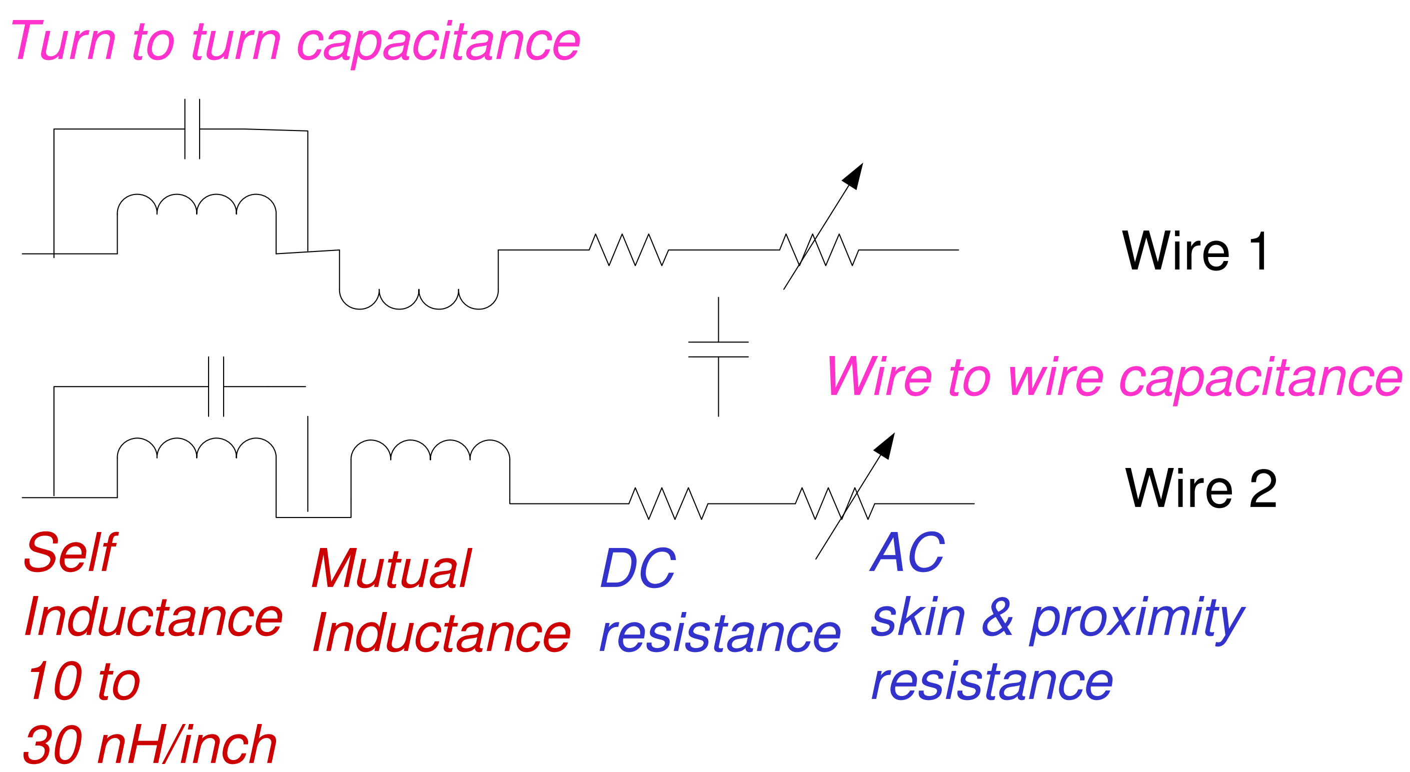
$$\mathbf{H} = \left[\int_{-\infty}^{\infty} \frac{Ir\,dz}{4\pi(r^2 + z^2)^{3/2}}\right]\mathbf{a}_\phi = \frac{I}{2\pi r}\mathbf{a}_\phi$$

H field varies inversely as [1 / Radius]

EMC Rule: Electric and Magnetic Field Summaries

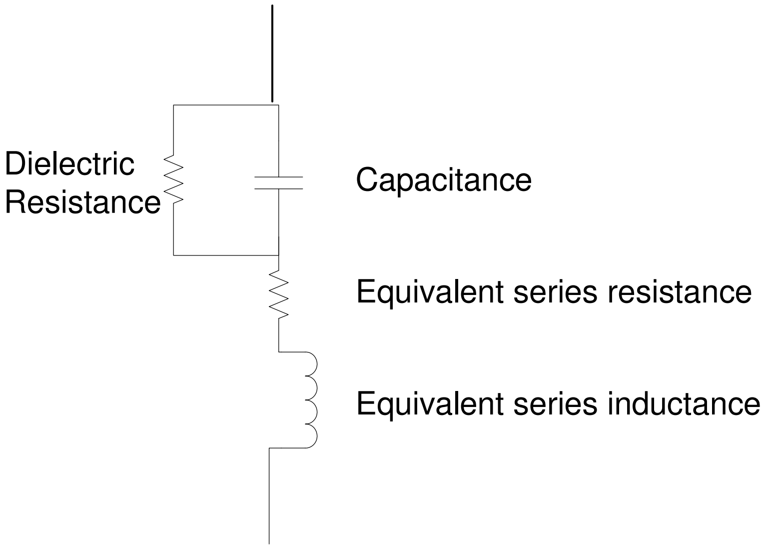
EMC Rule: Requires a Reset of Thinking

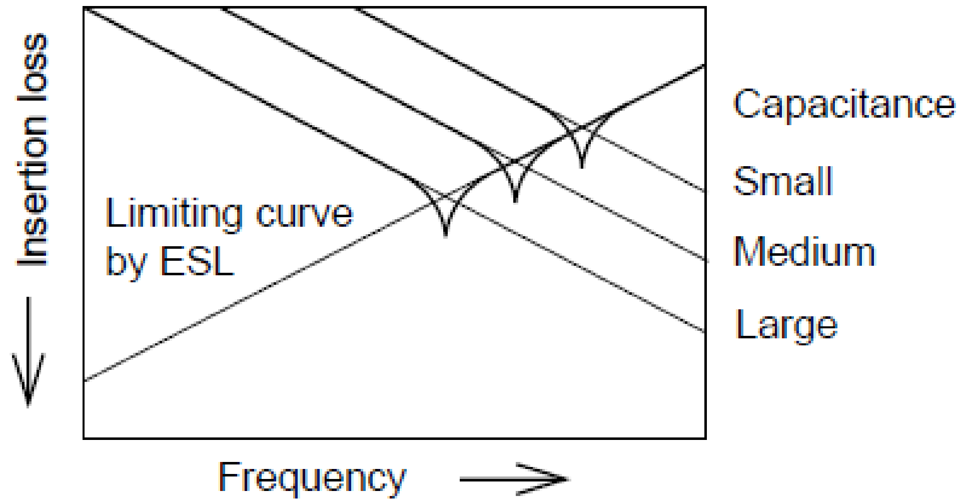
I'm sorry even a Wire = resistor , capacitor and inductor



EMC Rule: Requires a Reset of Thinking

A Capacitor = resistor , capacitor and inductor

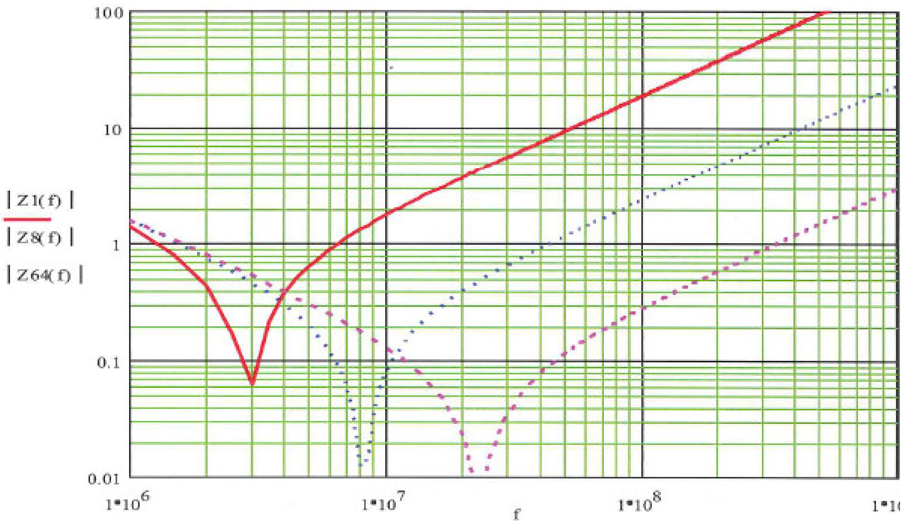


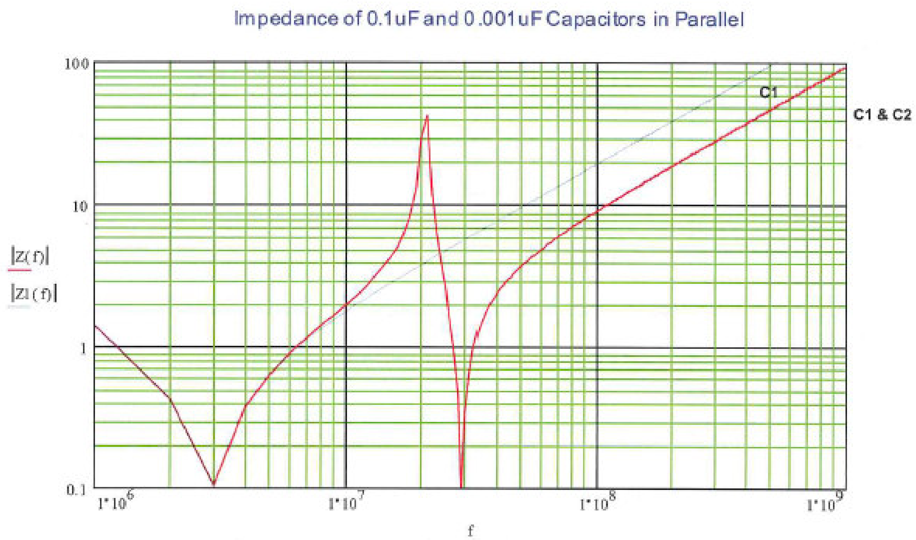


http://www.murata.com/emc

EMC Rule: Requires a Reset of Thinking

A Capacitor = resistor , capacitor and inductor



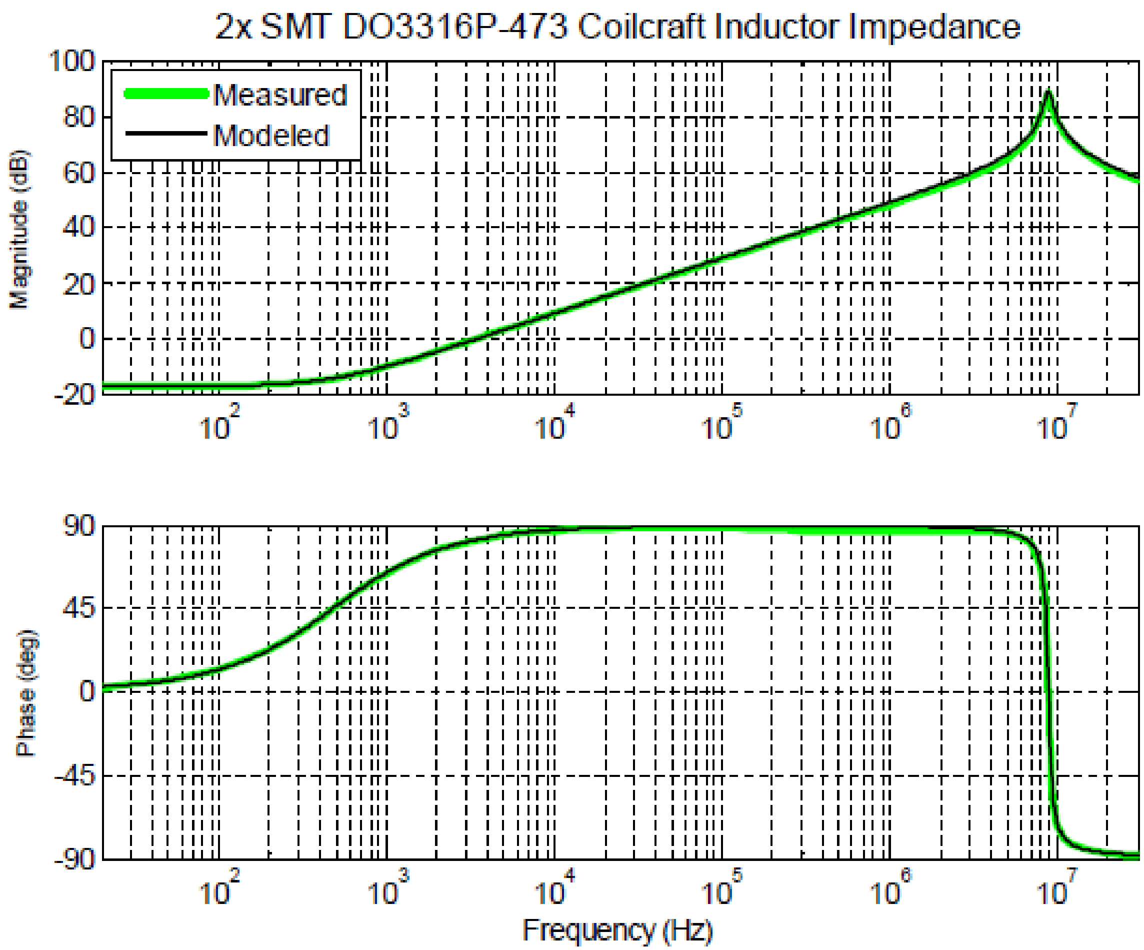


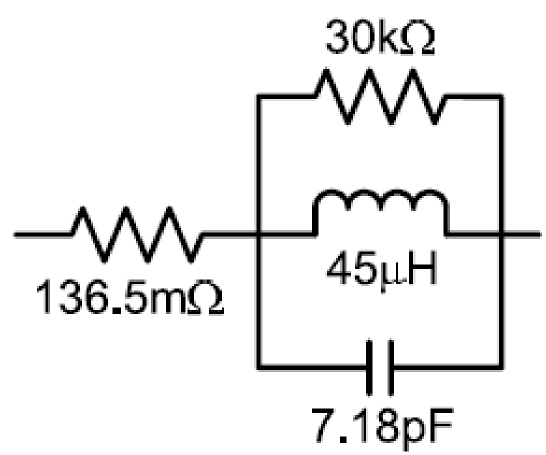
0.1 uf
and qty 2 parallel 0.1 uf
and qty 3 parallel 0.1 uf

0.1 uf and 0,001 uf in parallel

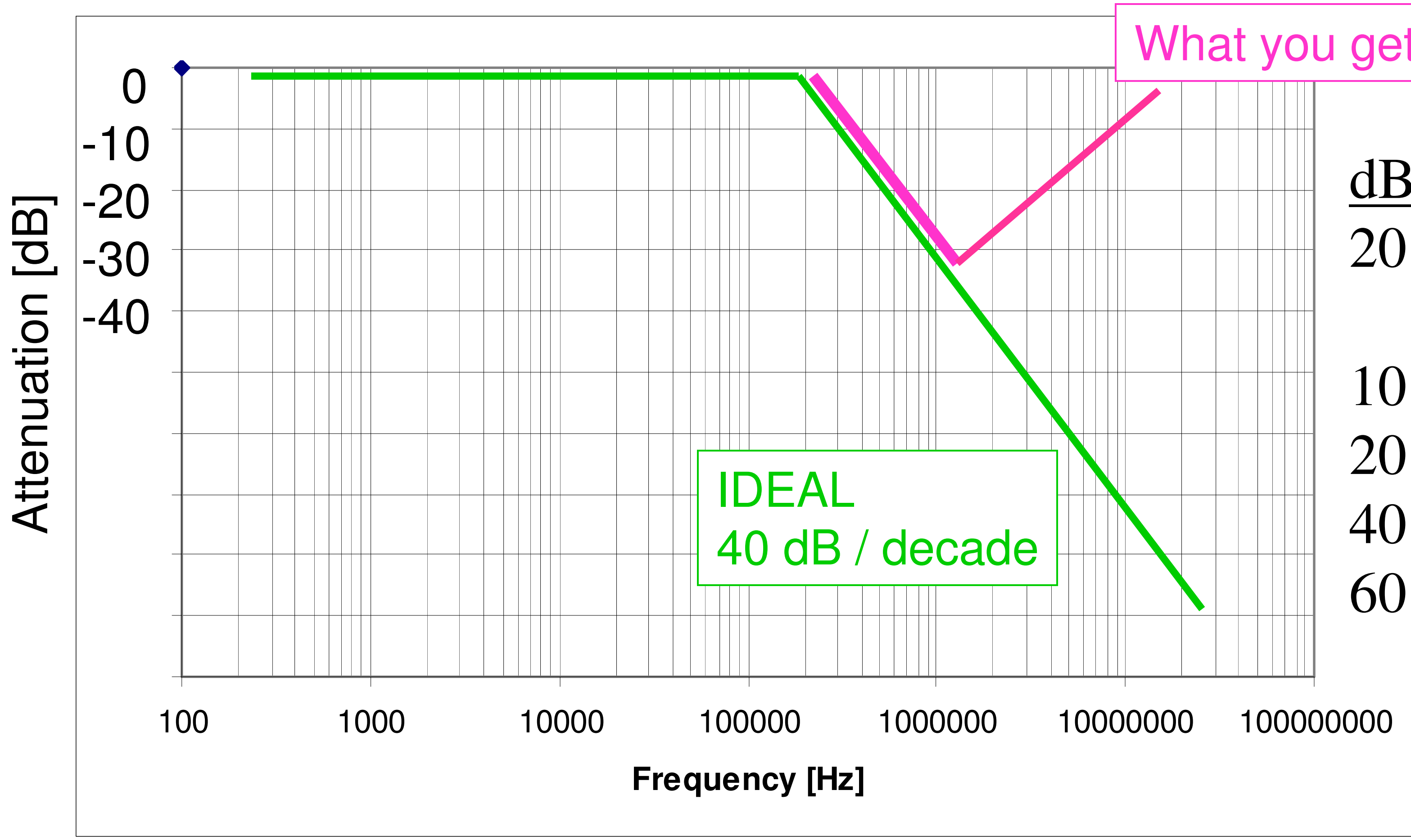
EMC Rule: Requires a Reset of Thinking

An Inductor = resistor , capacitor and inductor





EMC Basic Rule: Low Pass Inductor-Capacitor LC Filter



dB Attenuation

20 Log {V2/V1}

10 dB 3.5 :1

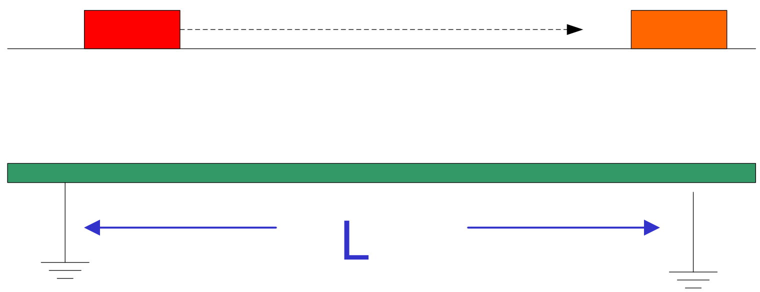
20 dB 10:1

40 dB 100:1

60 dB 1000:1

- ~ [- 30 dB / frequency decade] attenuation possible per LC stage
- Inductors are open circuits at high frequency eg $2\pi f L$
- Capacitors are short circuits at high frequency eg $[1/(2\pi f C)]$

EMC Basic Rule: Ground Plane analysis



Traveling pulse or sinewave source

Ground plane dimensions

Potential #1 Potential #2

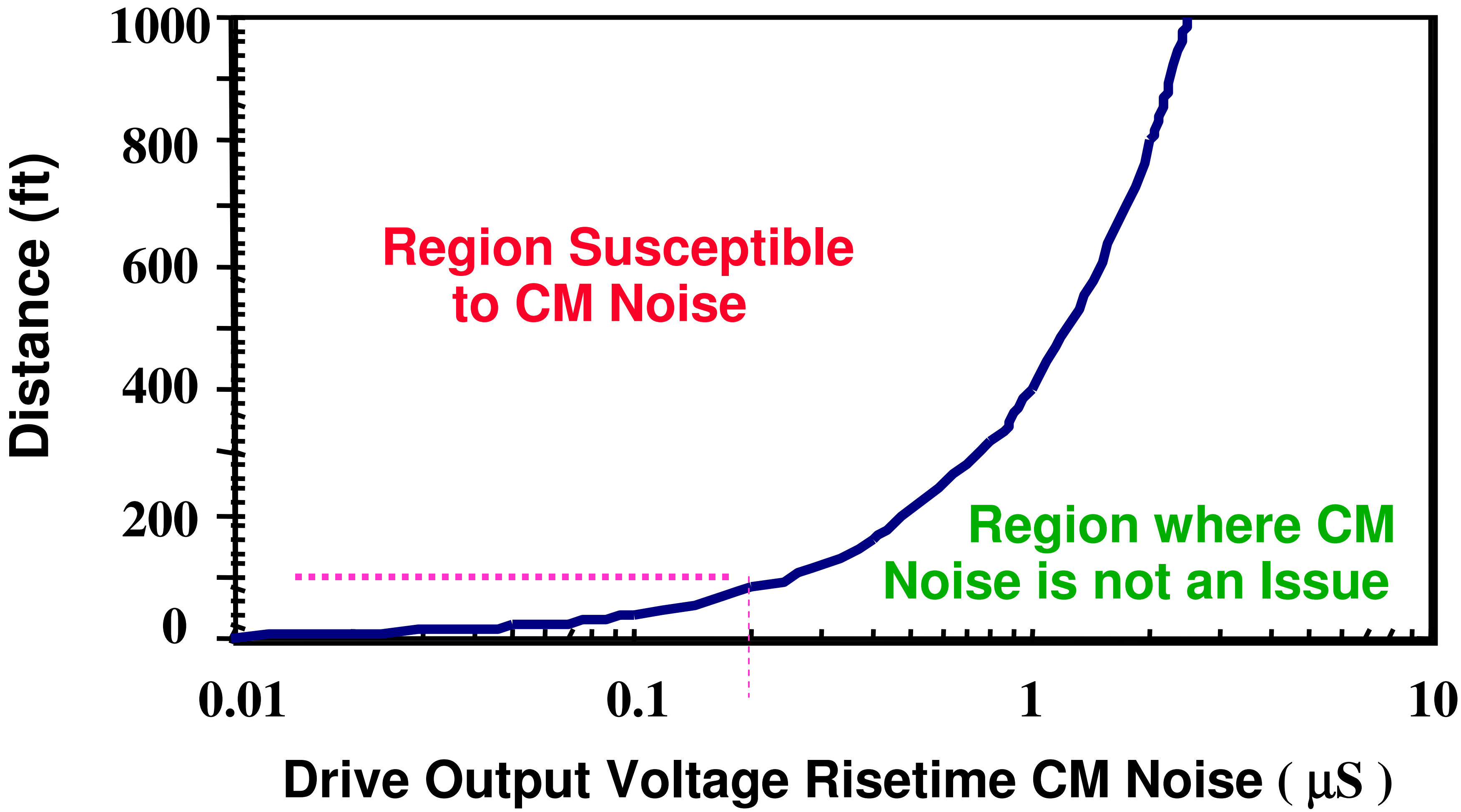
In order to have both potential #1 and Potential #2 at equal voltage
Or not have phase distortion , reflected wave spikes, noise …etc then ….

$$\text{Wavelength } \lambda = \frac{c \text{ speed of light (3 e8 m/s)}}{fu \text{ frequency Hz}}$$

fu = [1/ π trise] for pulse
fu = frequency for sinewave

L maximum length dimension must not exceed λ/10

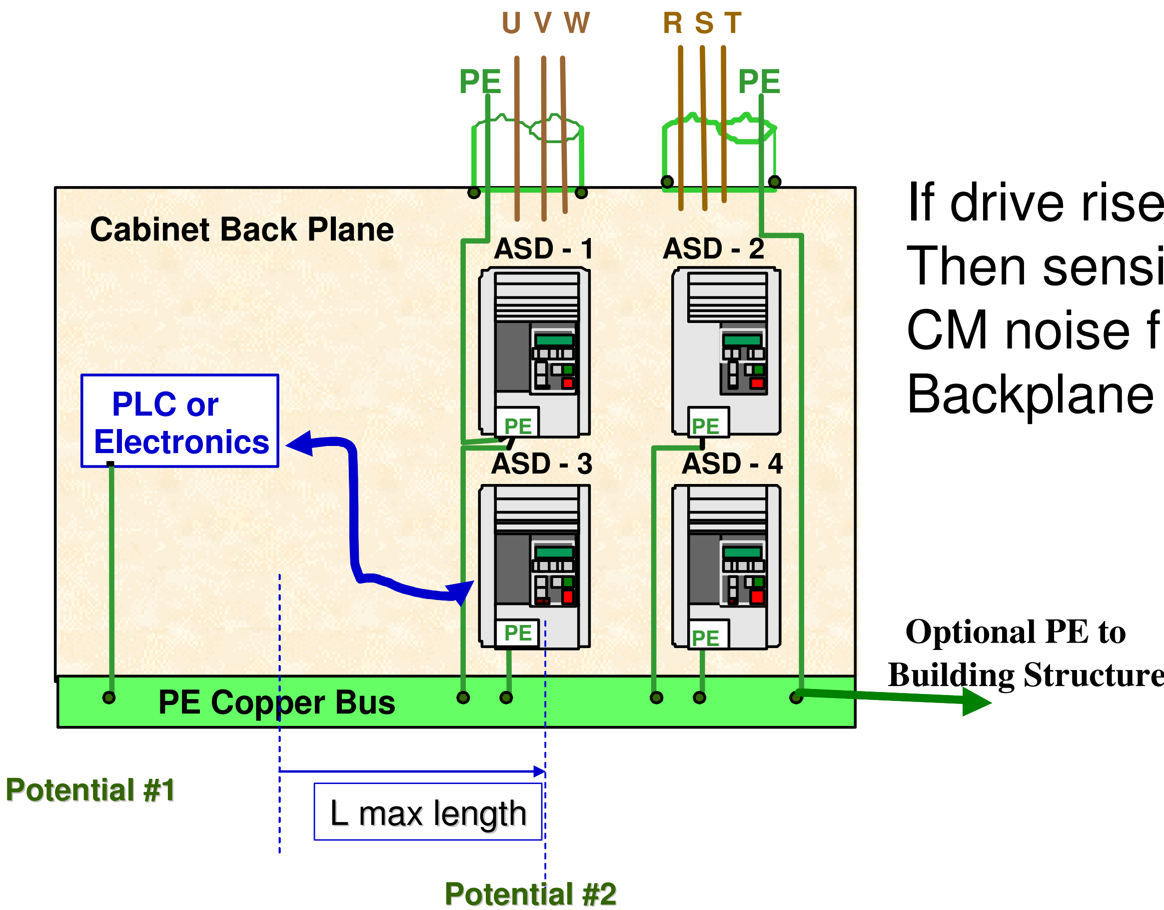
EMC Basic Rule: Ground Plane analysis



Risetime vs. distance separation allowed for NO CM problem with single ended systems.

- **Faster risetimes > higher spike voltage**
- **ok as long as high frequency impedance between nodes is "0" ohms**

EMC Basic Rule: Ground Plane analysis Example



If drive risetime trise = 0.2 us
Then sensitive signals see no CM noise from IGBT EMI if Backplane Lmax < 100 ft from chart

EMC Basic Rule: Other Ground Plane analysis Example

How long can a 30 MHz clock be safely routed before distortion ?

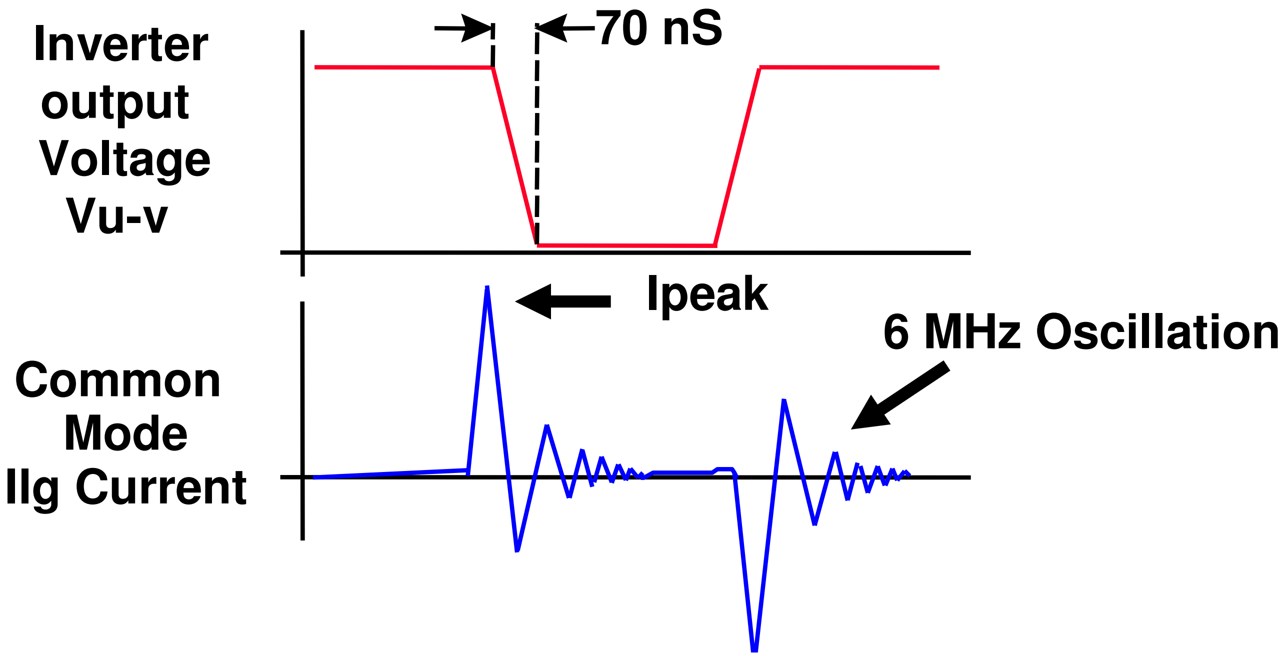
CAN chip risetime is 10ns, how long can it be routed before possible distortion ?

Identifying Common Mode Noise Coupling paths

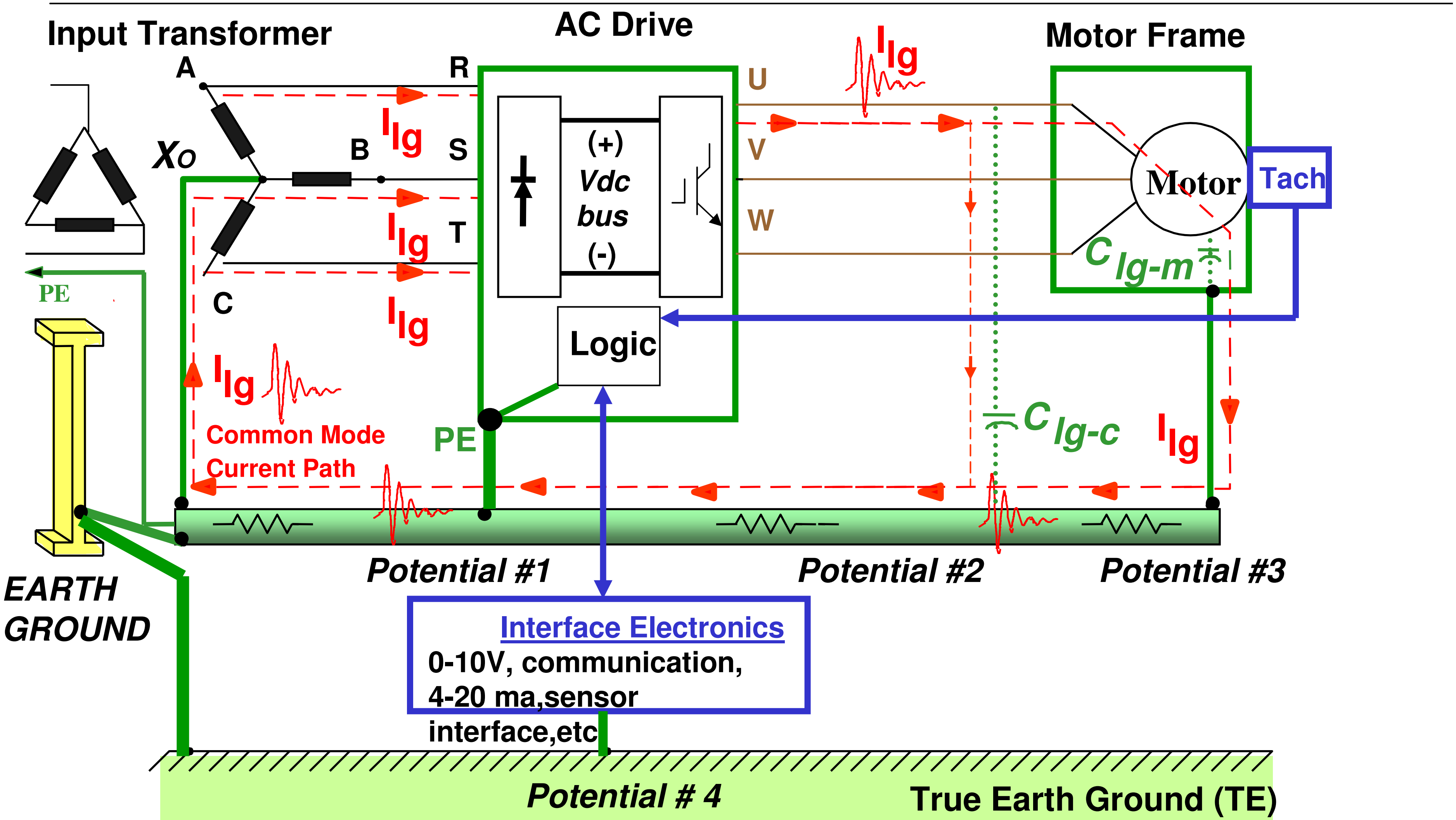
Conducted paths

Radiated paths

PWM EMI Noise Current Effect on coupling paths

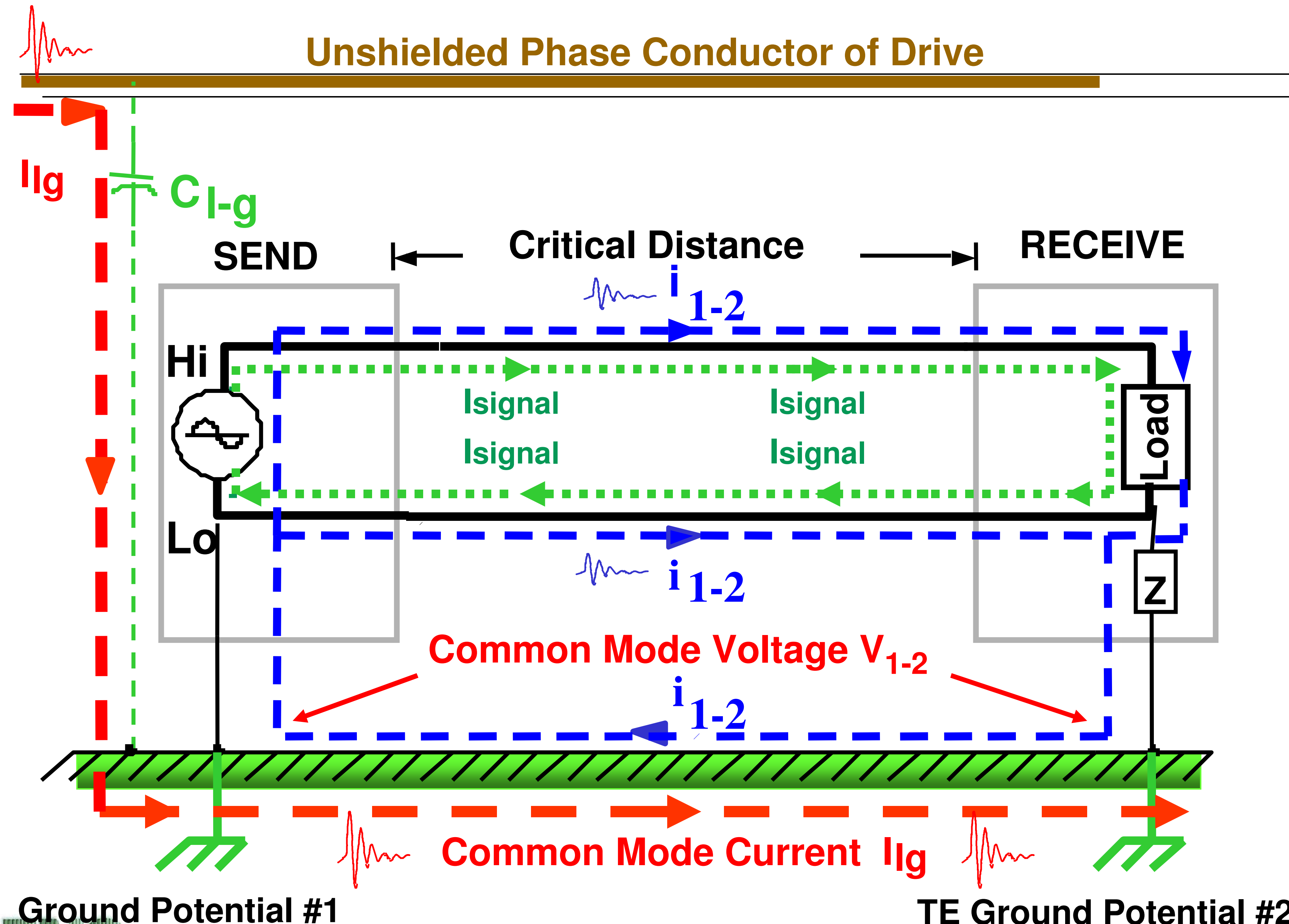


PWM Noise Source is Line-ground Stray Current Path

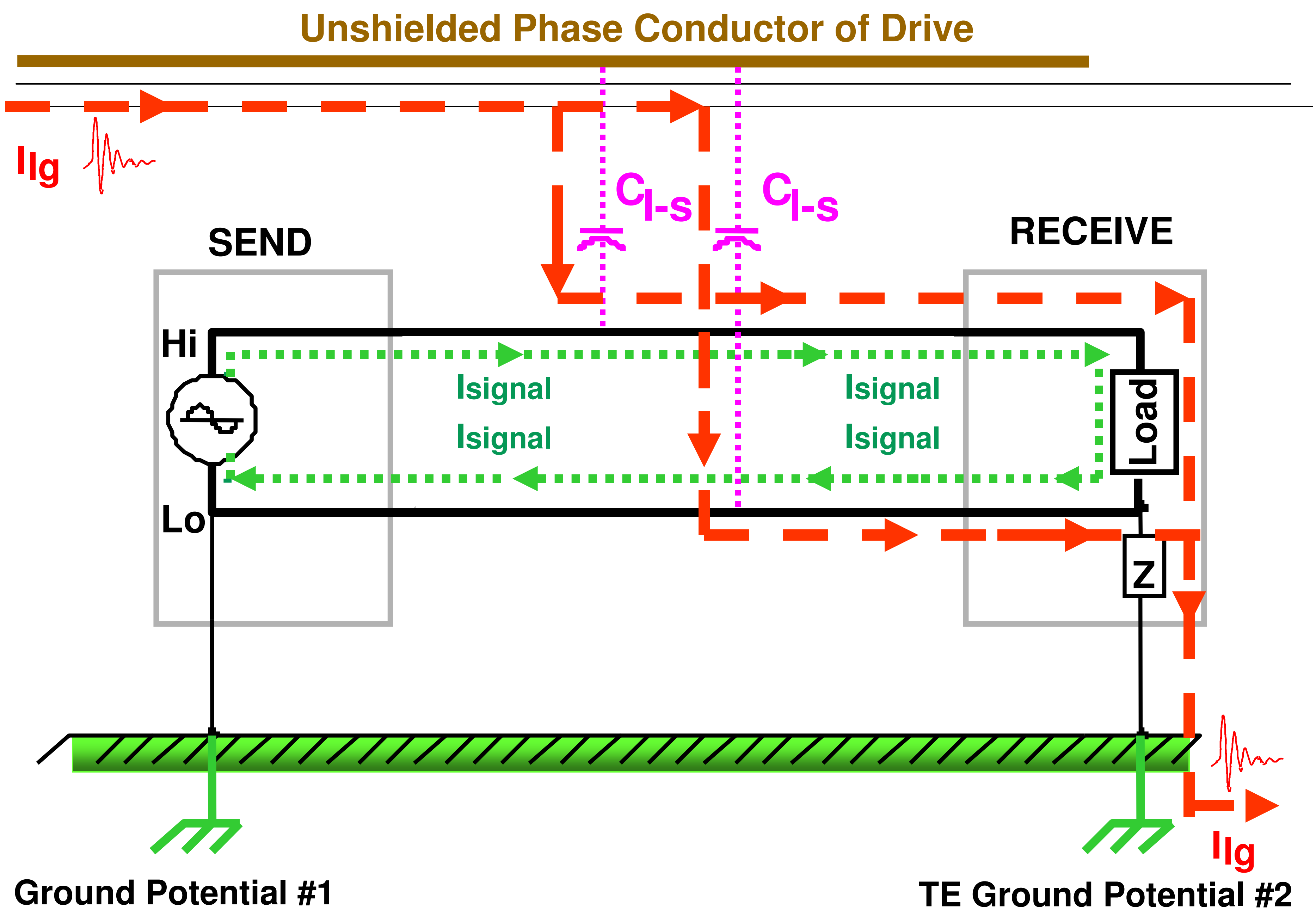


- **PWM lline-ground noise thru stray cable & motor capacitance screws up user grounds as well as any and all drive logic interface**

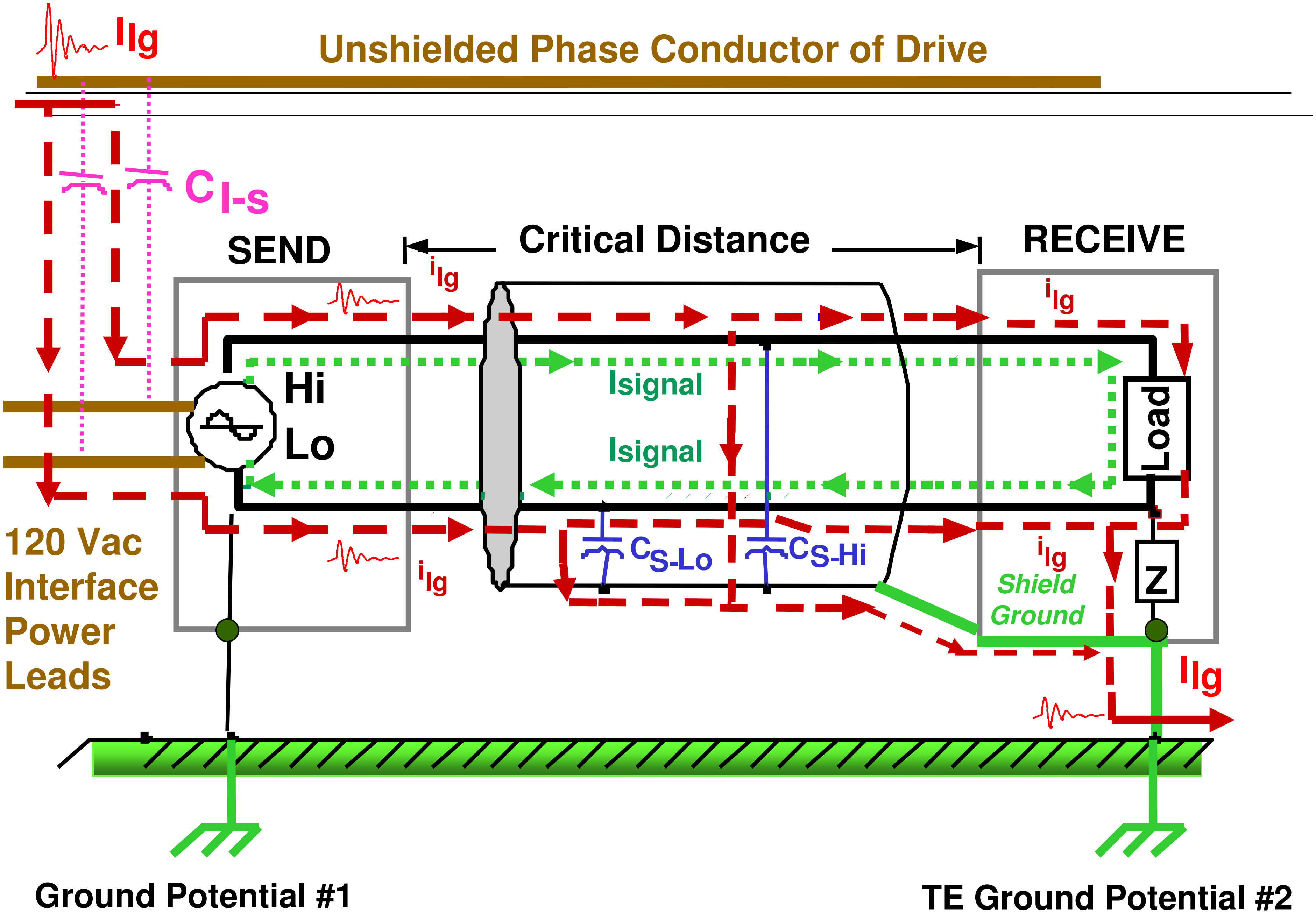
Unshielded Phase Conductor of Drive



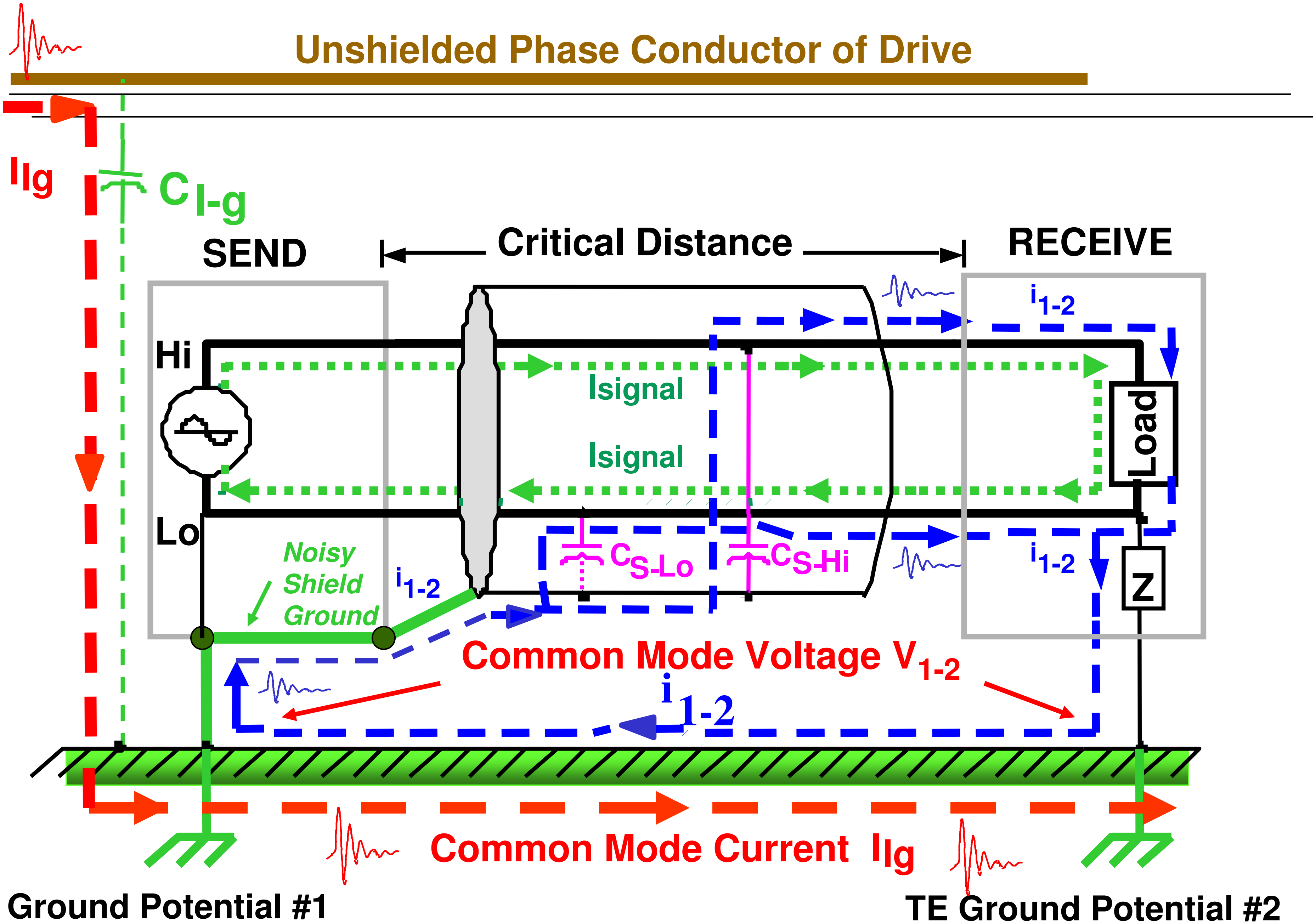
Conducted EMI Noise Problem for I/O



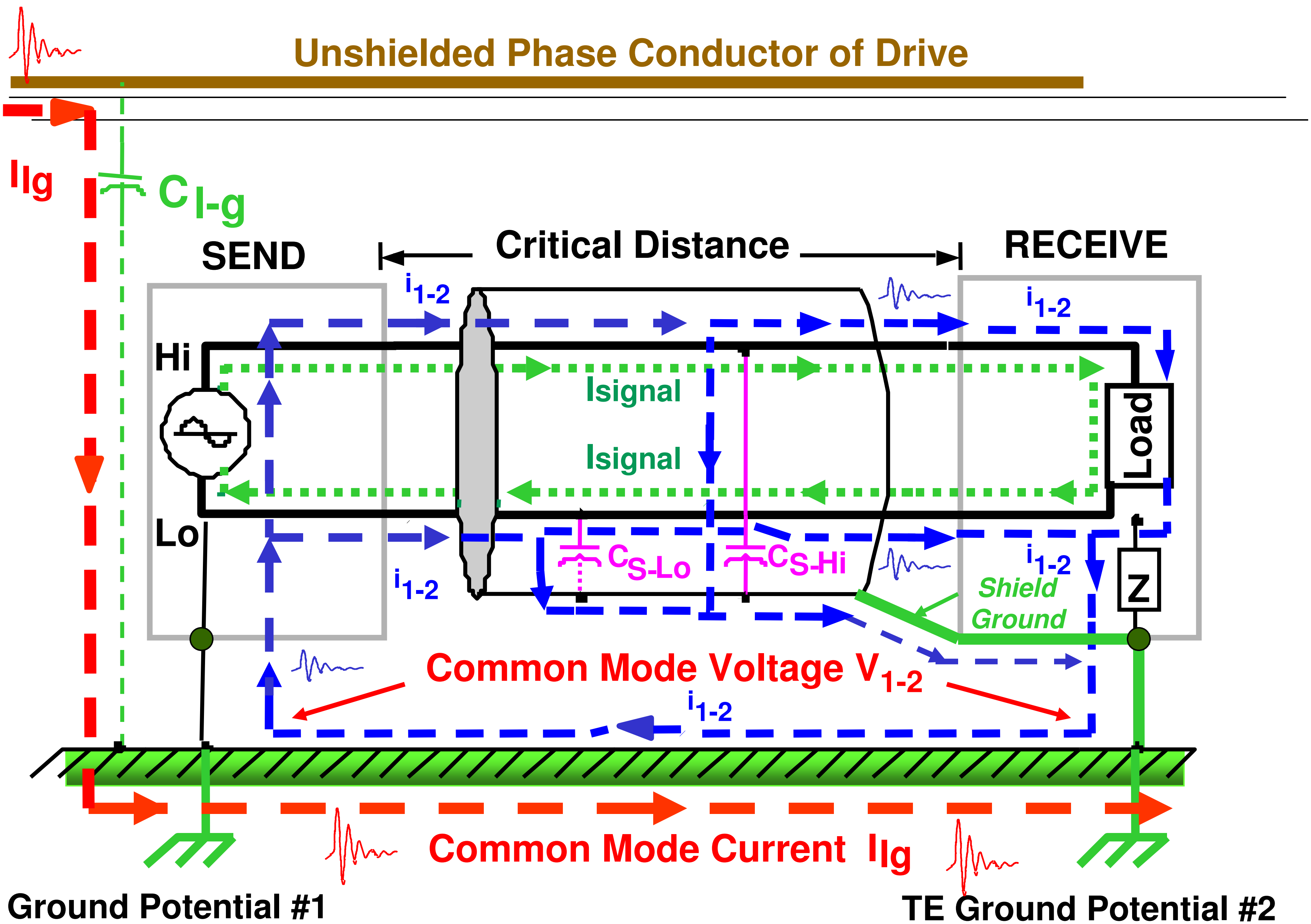
Unshielded Power coupling to Unshielded control



Unshielded Power coupling to Unshielded control Power

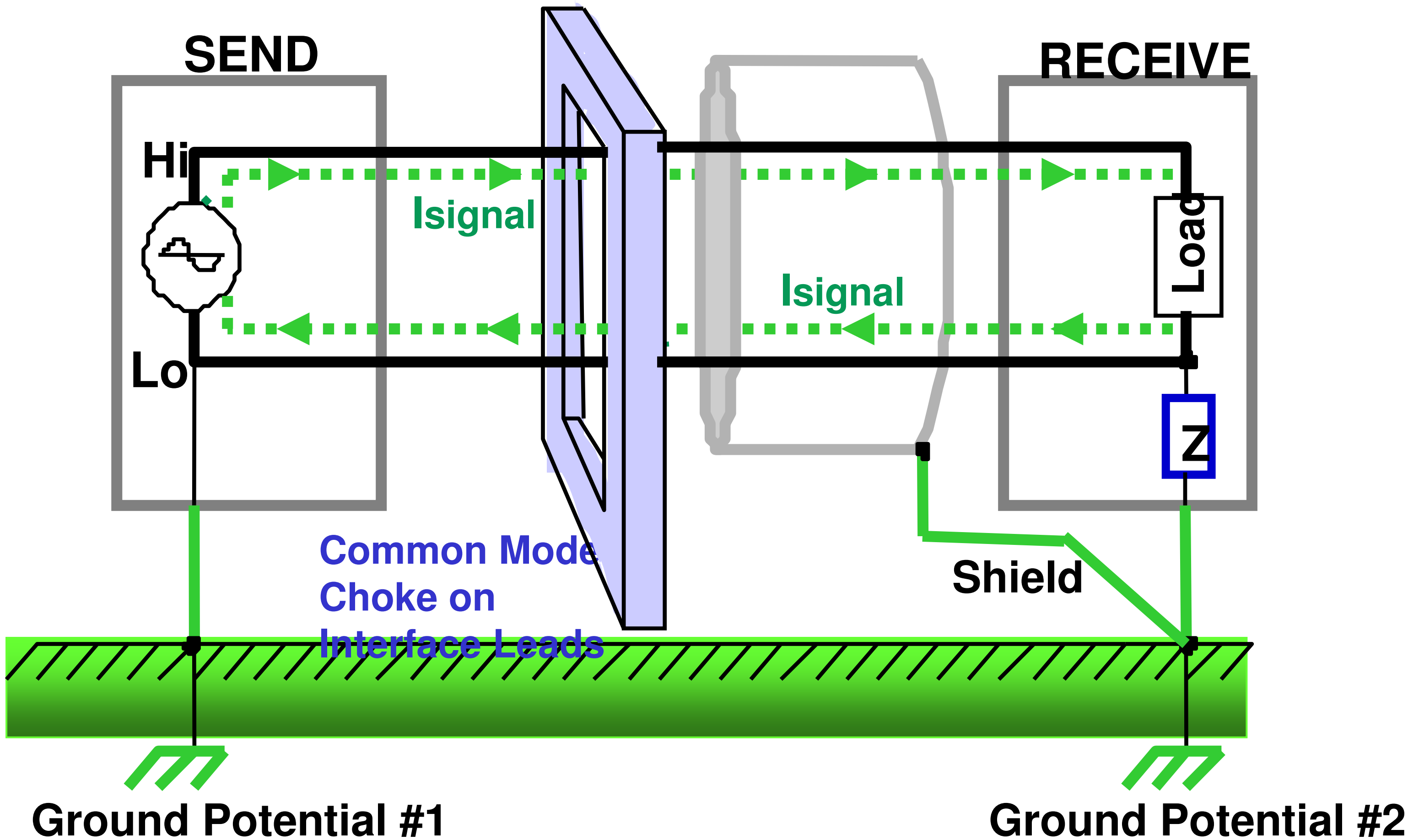


Unshielded Power coupling to Noisy Shield Ground @ drive end

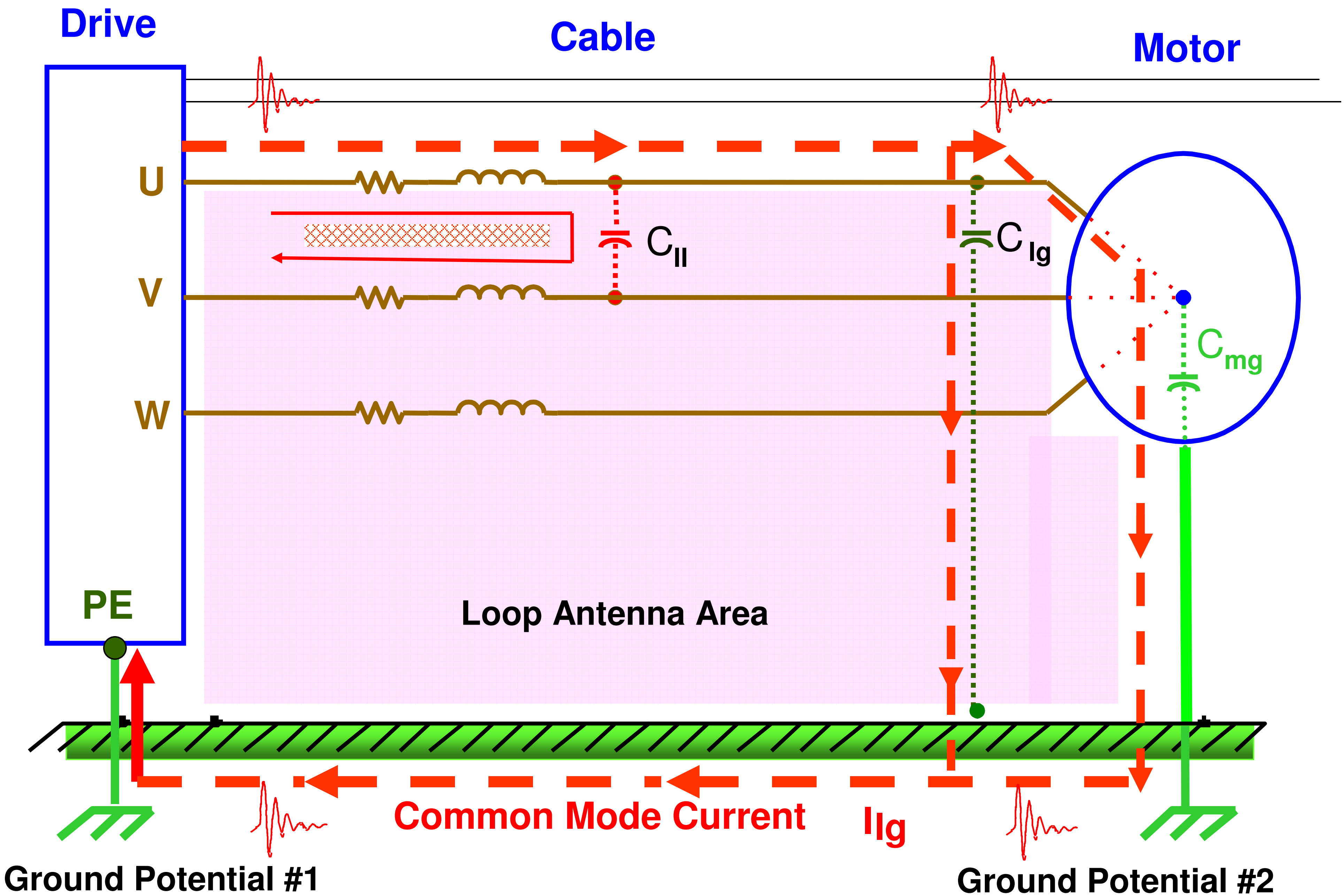


Unshielded Power w/reduced coupling to Control shield gnd @ receive end

CM core solution to signal line noise issues



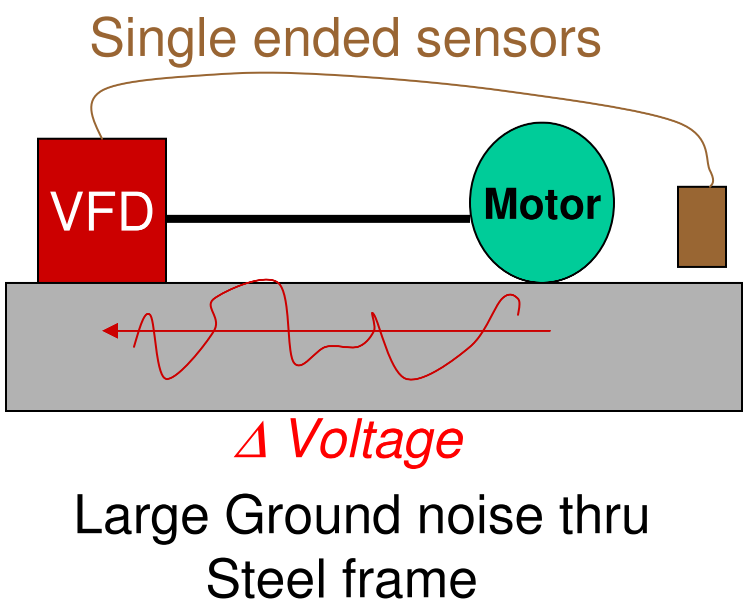
Implementation of CM core in signal lines between noisy grounds works



EMC SOCIETY

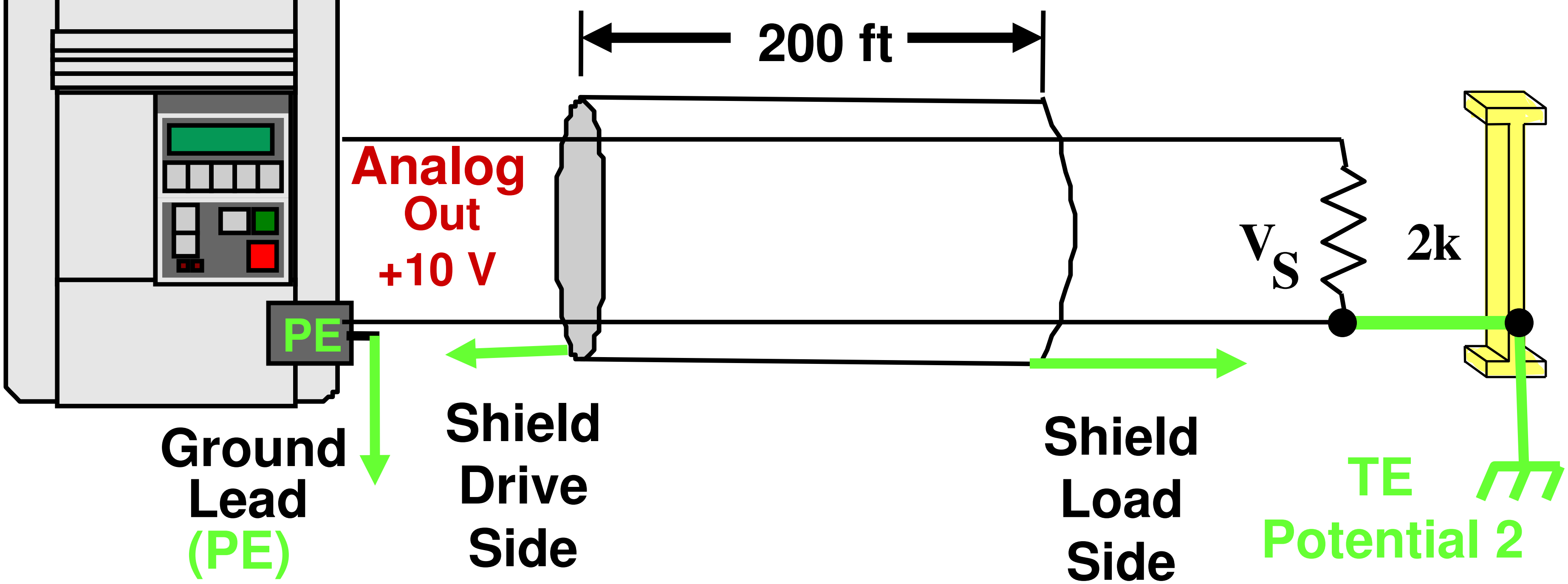
Unshielded Power line-line and line-ground radiated emissions

Shielding Solution to Single ended signal line noise issues



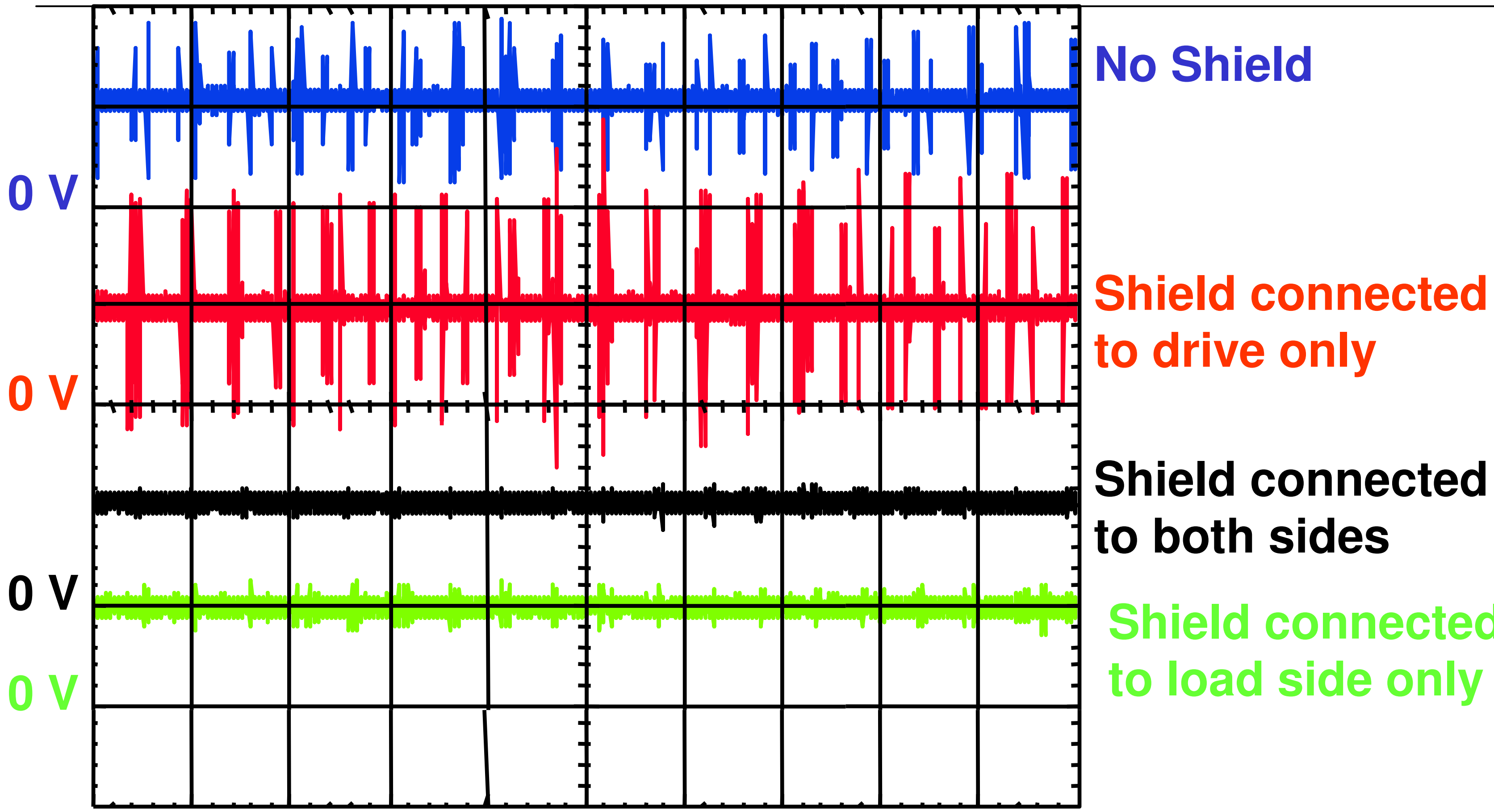
CM noise test CASE EXAMPLE

Shielding Solution to Single ended signal line noise issues



CM noise test CASE EXAMPLE

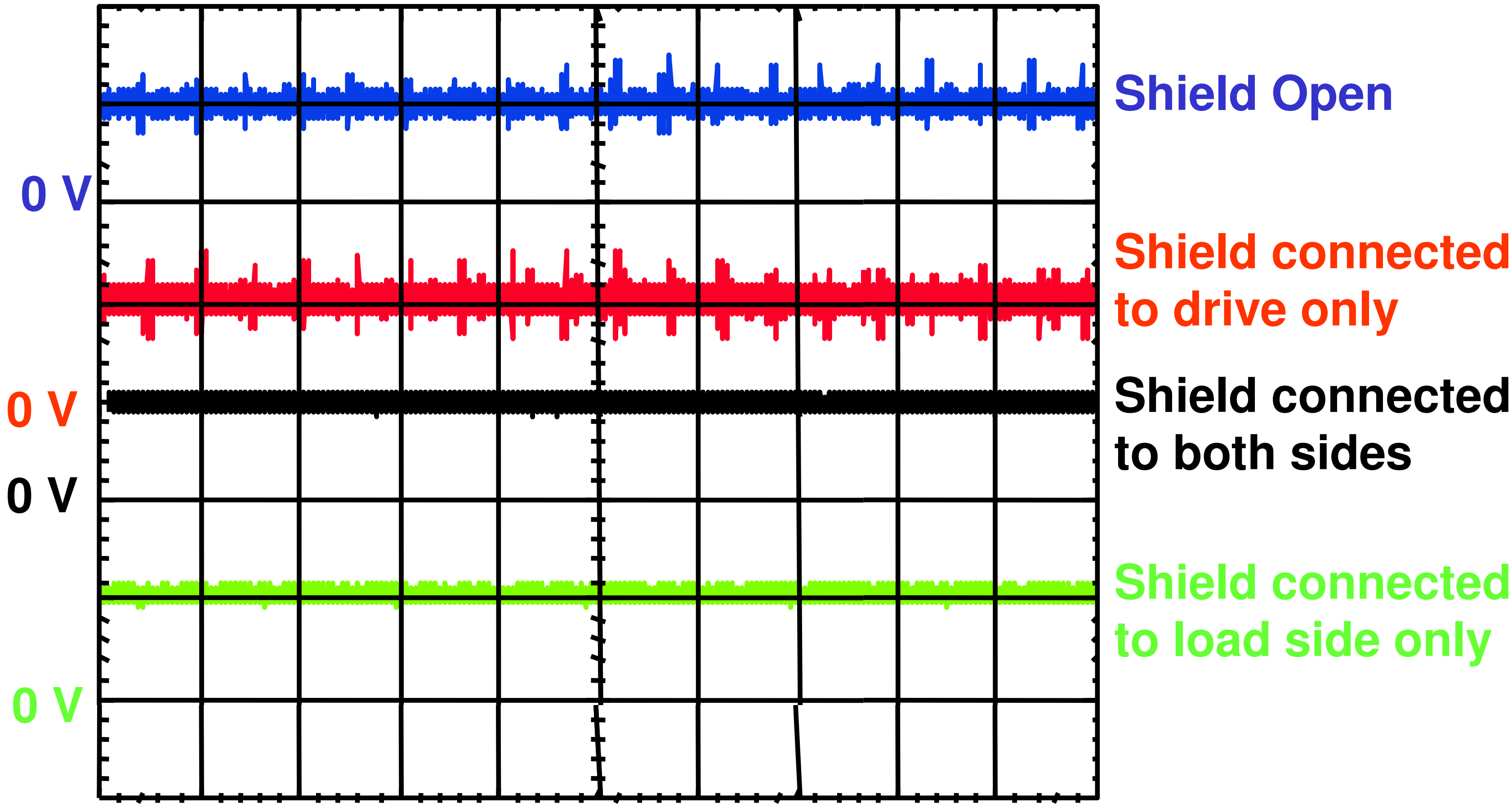
Shielding Solution to Single ended signal line noise issues



10 V / Div.   500 μs / Div.

CM Noise with NO CM cores in drive output and various shield grounds

Shielding Solution to Single ended signal line noise issues



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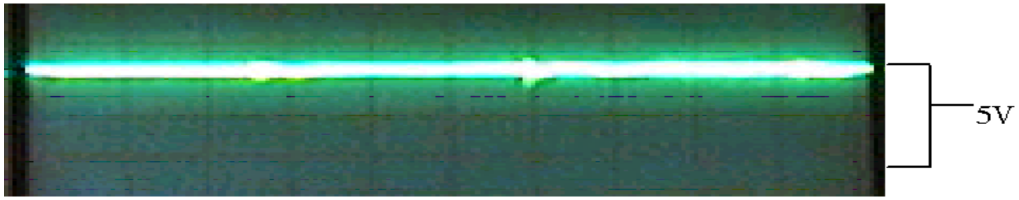
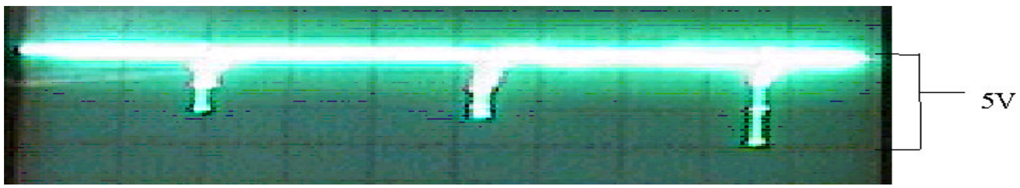


2 Volts / Div

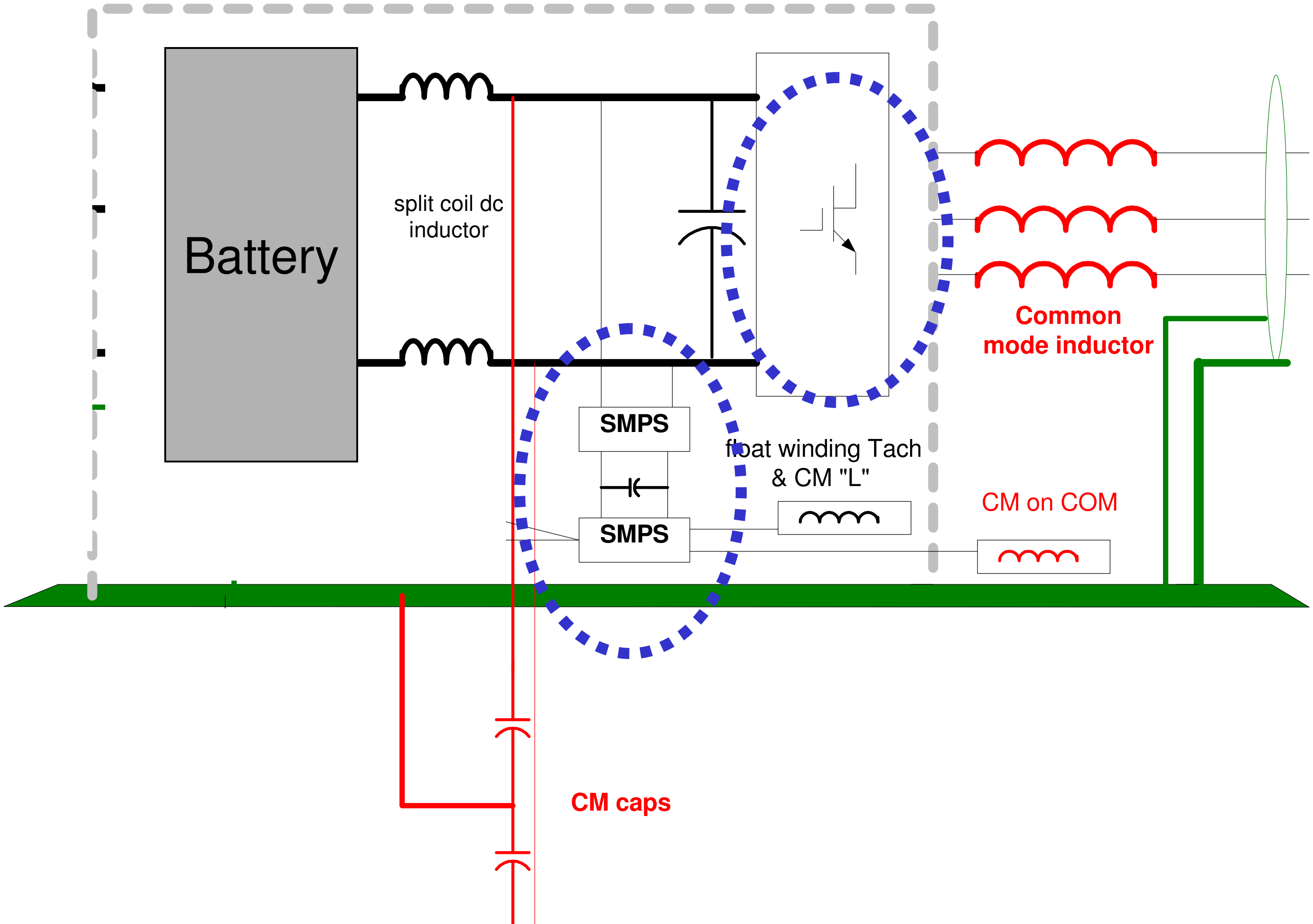


2 Volts / Div

- **CM Noise on Tachometer before with SO type drive output cable and after with braided shielded drive output cable installed.**
- **Low impedance braid@ high frequency makes encoder case ground follow logic ground so no noise is induced**

Identifying the Noise Sources in Automotive Application

Drive Power Structure Platform Issues

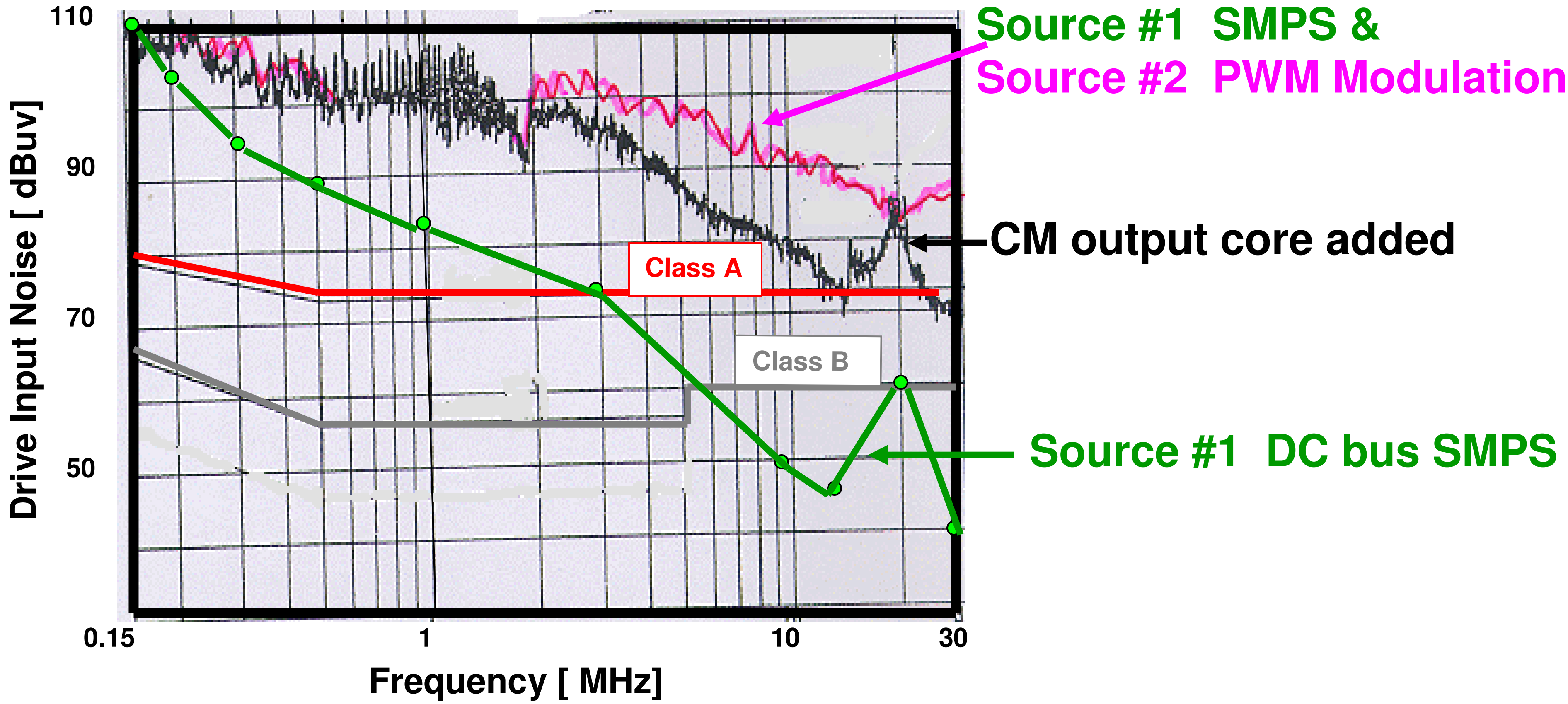


- **Two sources of Switching noise emitting from drive**

  Source #1:   SMPS switchmode power supply off the DC bus

  Source #2:   PWM modulation of IGBT inverter to drive Output

Two Sources of Switching Noise Exceeding EMC Limits



- **Conditions: 1336 10 hp with 80m output cable**

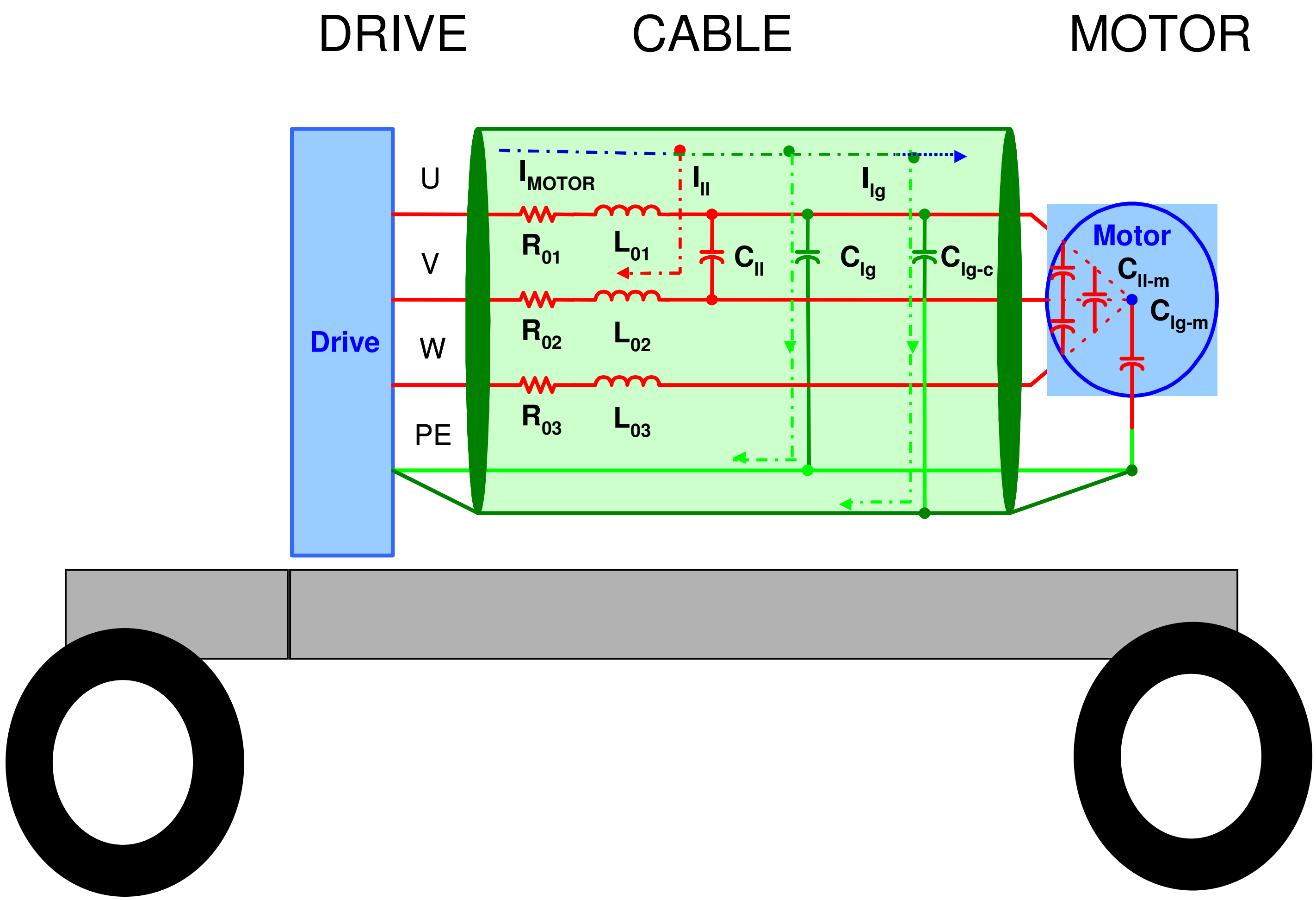
- ***Conclusion: SMPS dominant noise producer 150 kHz to 3 MHz range***
- ***Conclusion: PWM is dominant noise producer 3 MHz to 30 MHz range***

Noise Source Generator: ***PWM modulation IGBT inverter to Output***

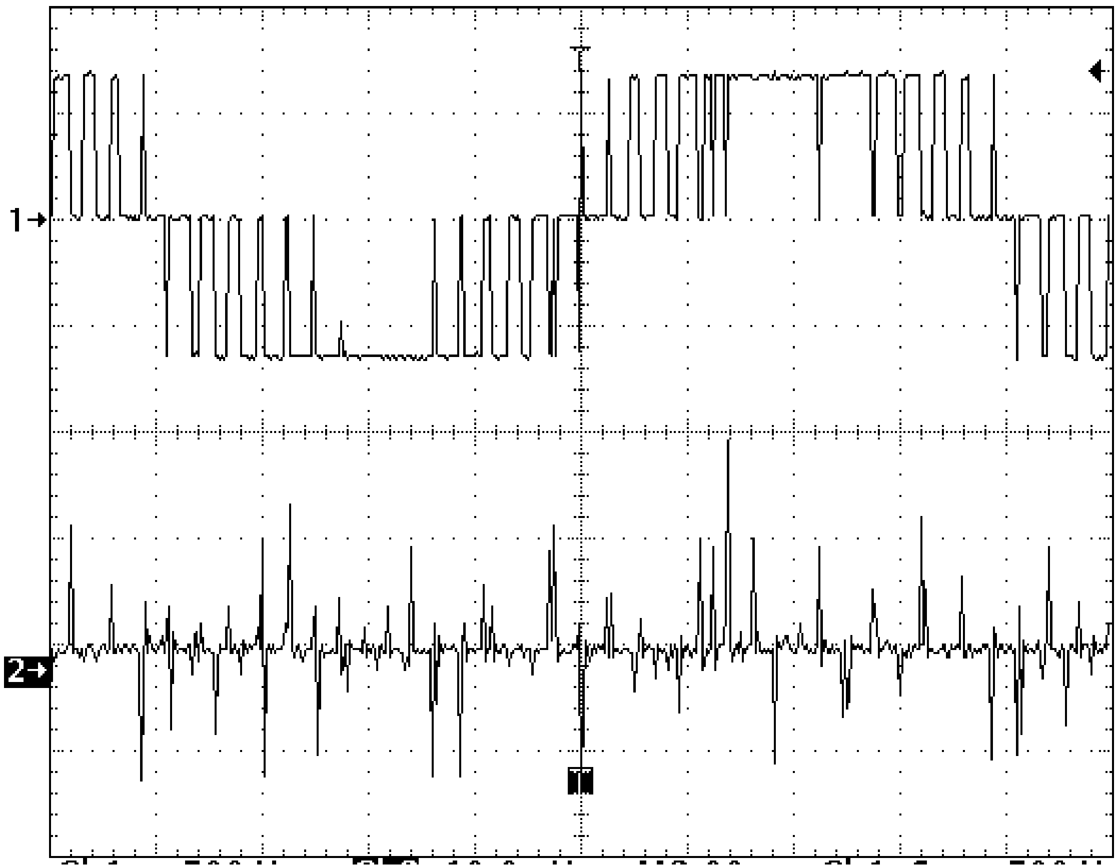
GENERATION of DIFFERENTIAL MODE or Line-Line ELECTRICAL NOISE

GENERATION of COMMON MODE or Line-Ground ELECTRICAL NOISE

PWM Noise Source: Line-Ground & Line –Line Stray Currents



PWM Noise Source: Line-Ground & Line –Line Stray Currents

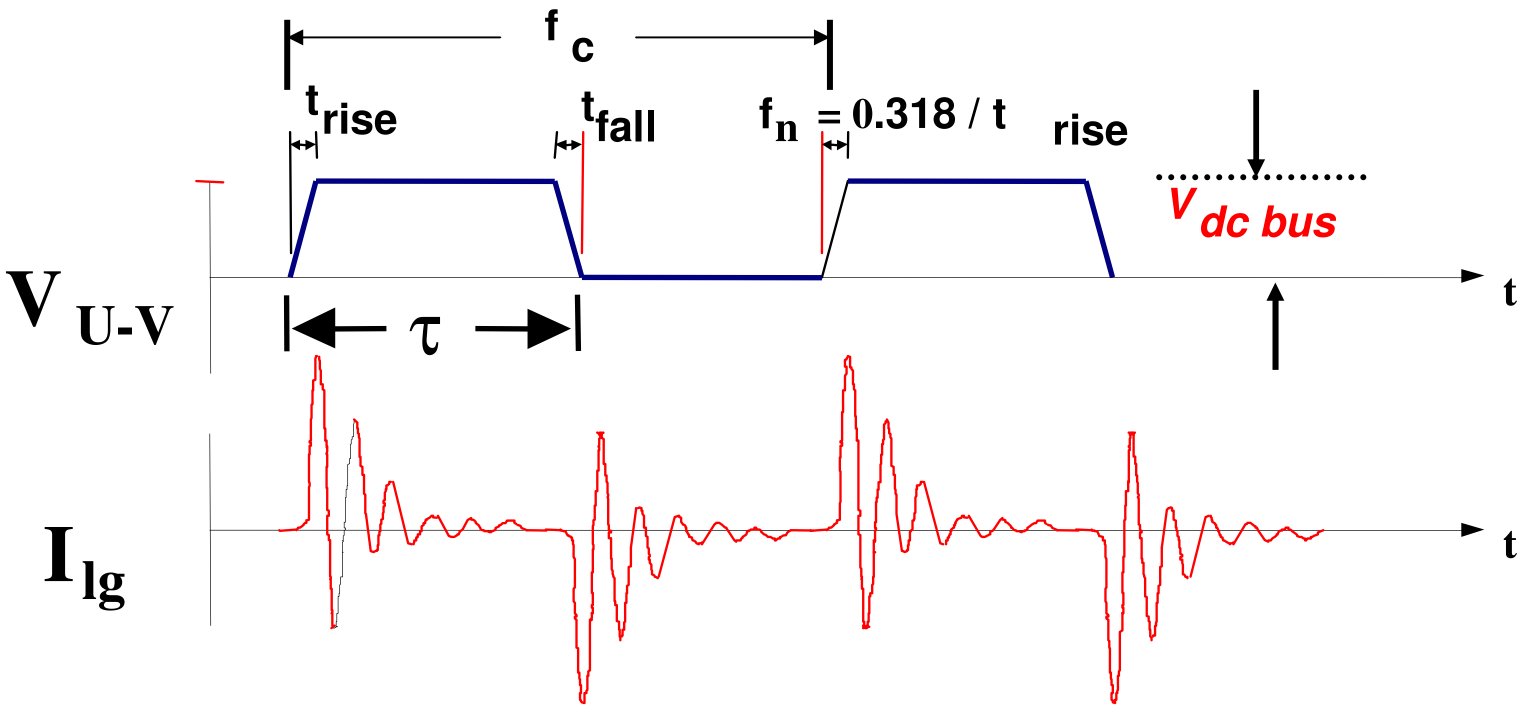


line to line voltage

line to ground current

- During every PWM transition from DC Bus
- stray current line-to-ground is sourced outward to Cable & motor ground

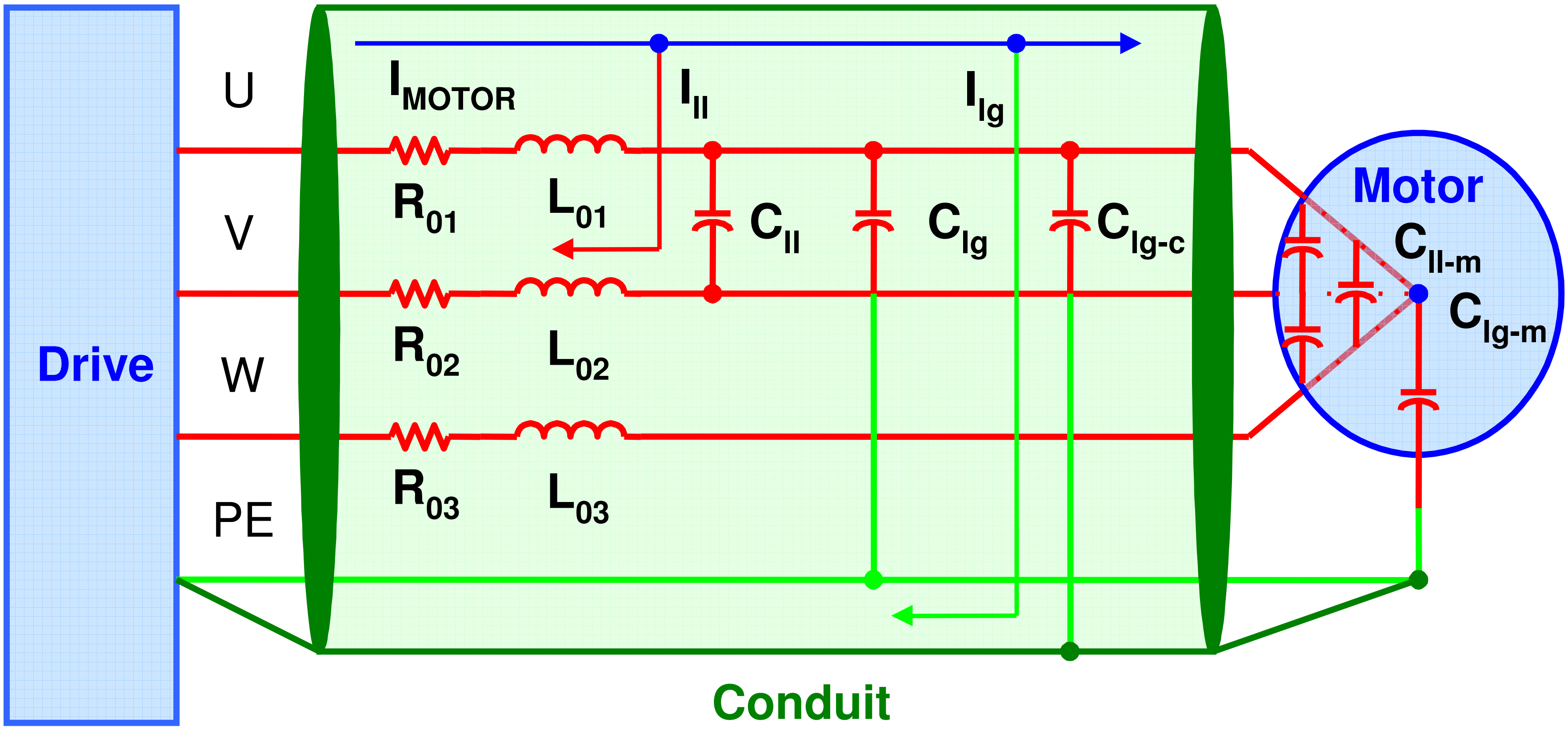
PWM Noise Source: Line-Ground & Line –Line Stray Currents



- **Time expansion of previous slide**
  - **EMI Risk is ~ Cstray [dv/dt] and Application Specific Factors**

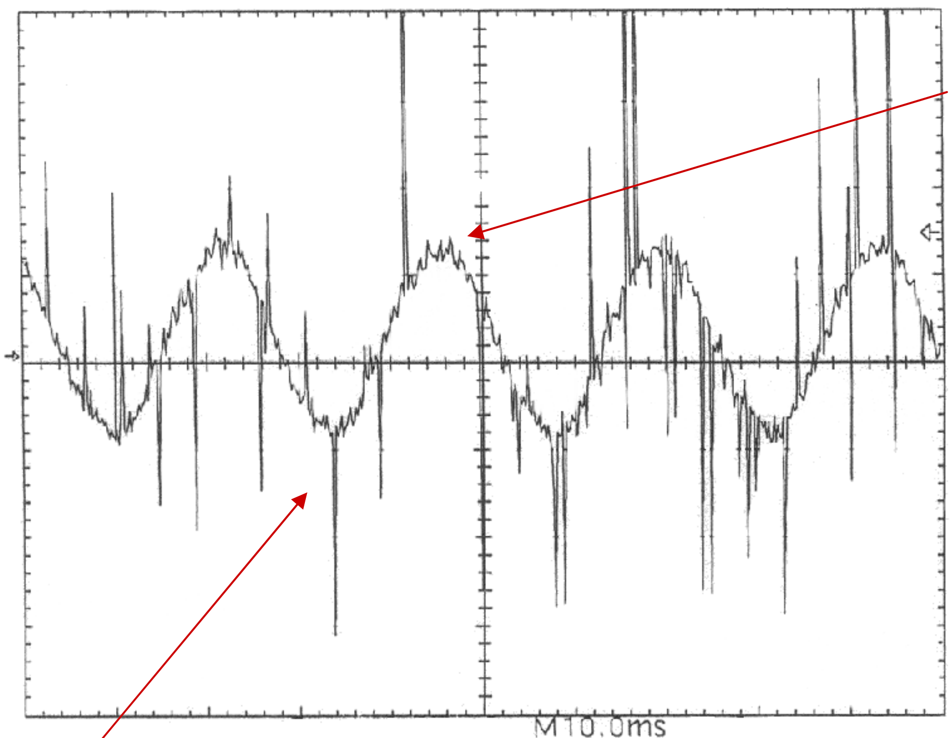
higher voltage > dv/dt
faster risetime > dv/dt
higher fc > greater rms noise
more drives > greater noise

PWM Noise Source: Line-Ground & Line – Line Stray Currents



Line-to-line & line-to-ground simplified capacitive charging current path into cable /conduit / armor and/or motor

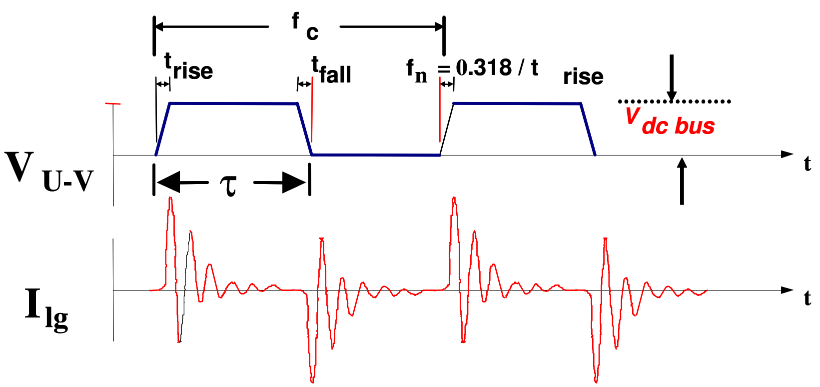
PWM Noise Source: Line-Ground & Line – Line Stray Currents

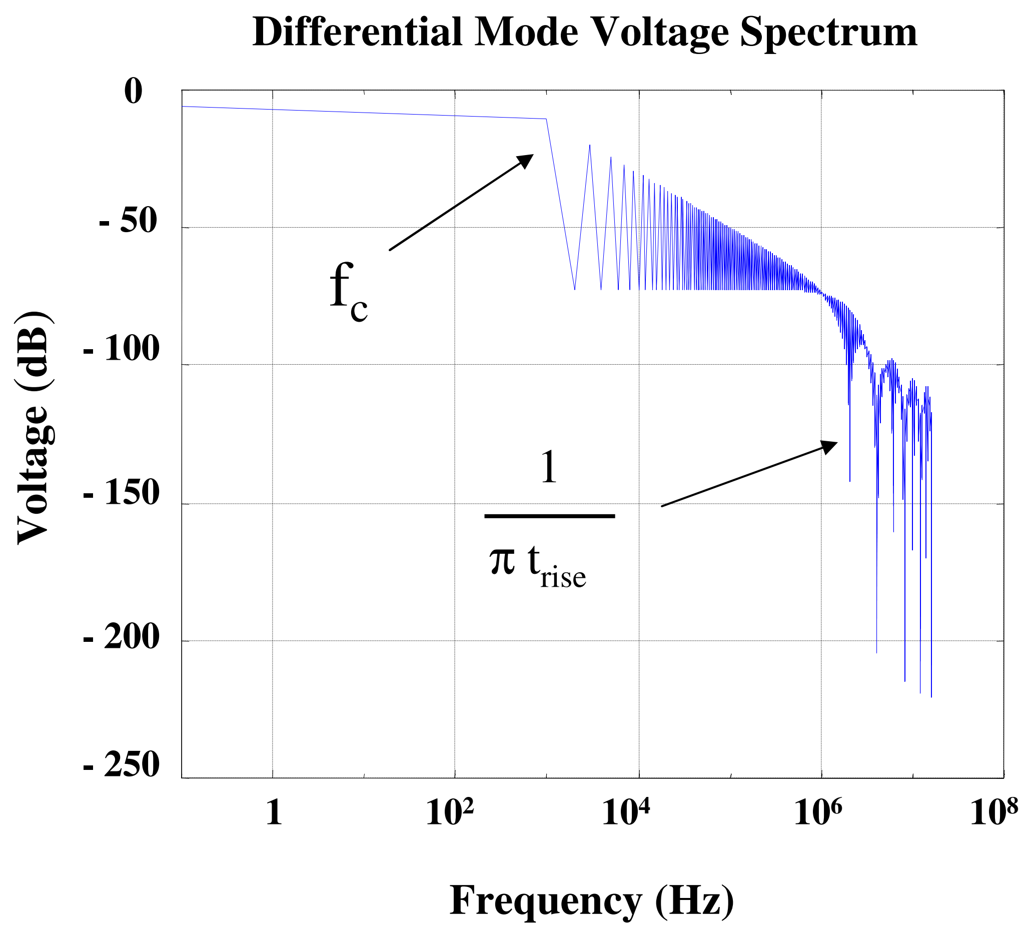


IGBT semiconductor switching fc
Carrier frequency is typically 4 khz to minimize motor ripple current and motor overheating

Line-line and line-ground current spikes ride on top of fundamental current

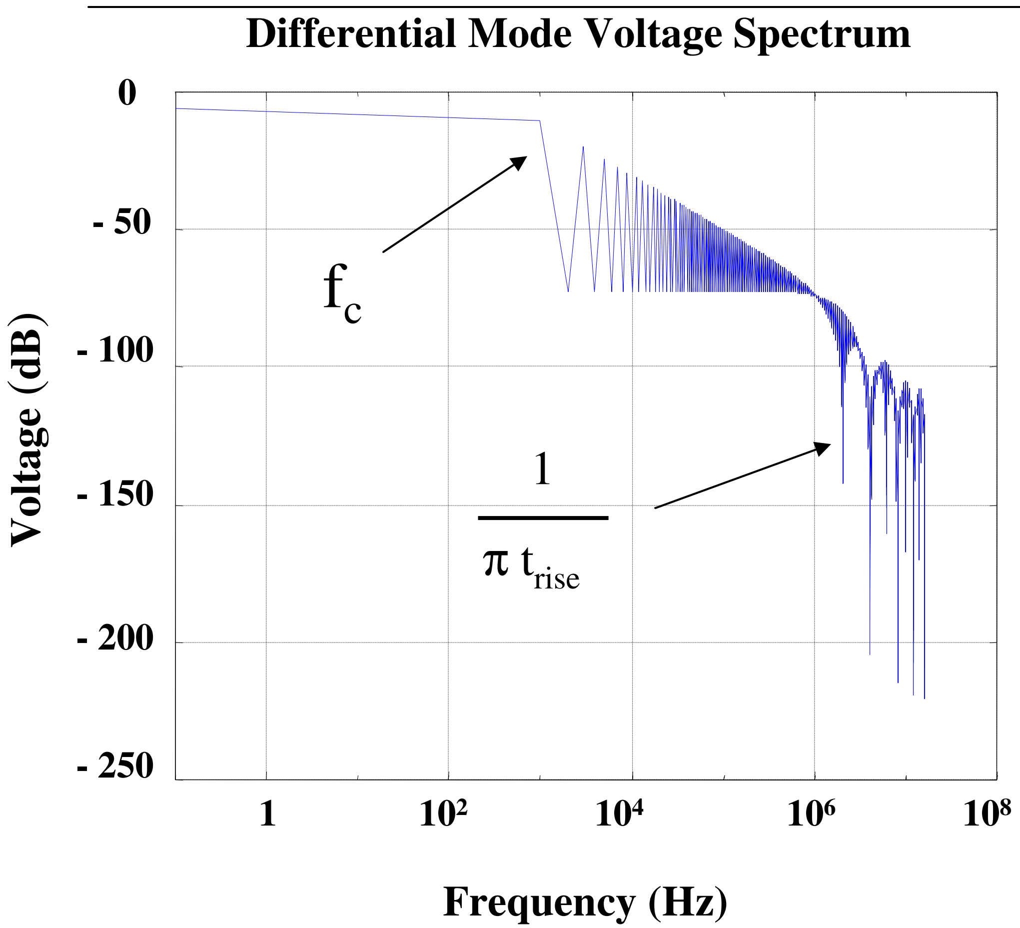
PWM Noise Source: Differential Mode Line–Line Stray Current





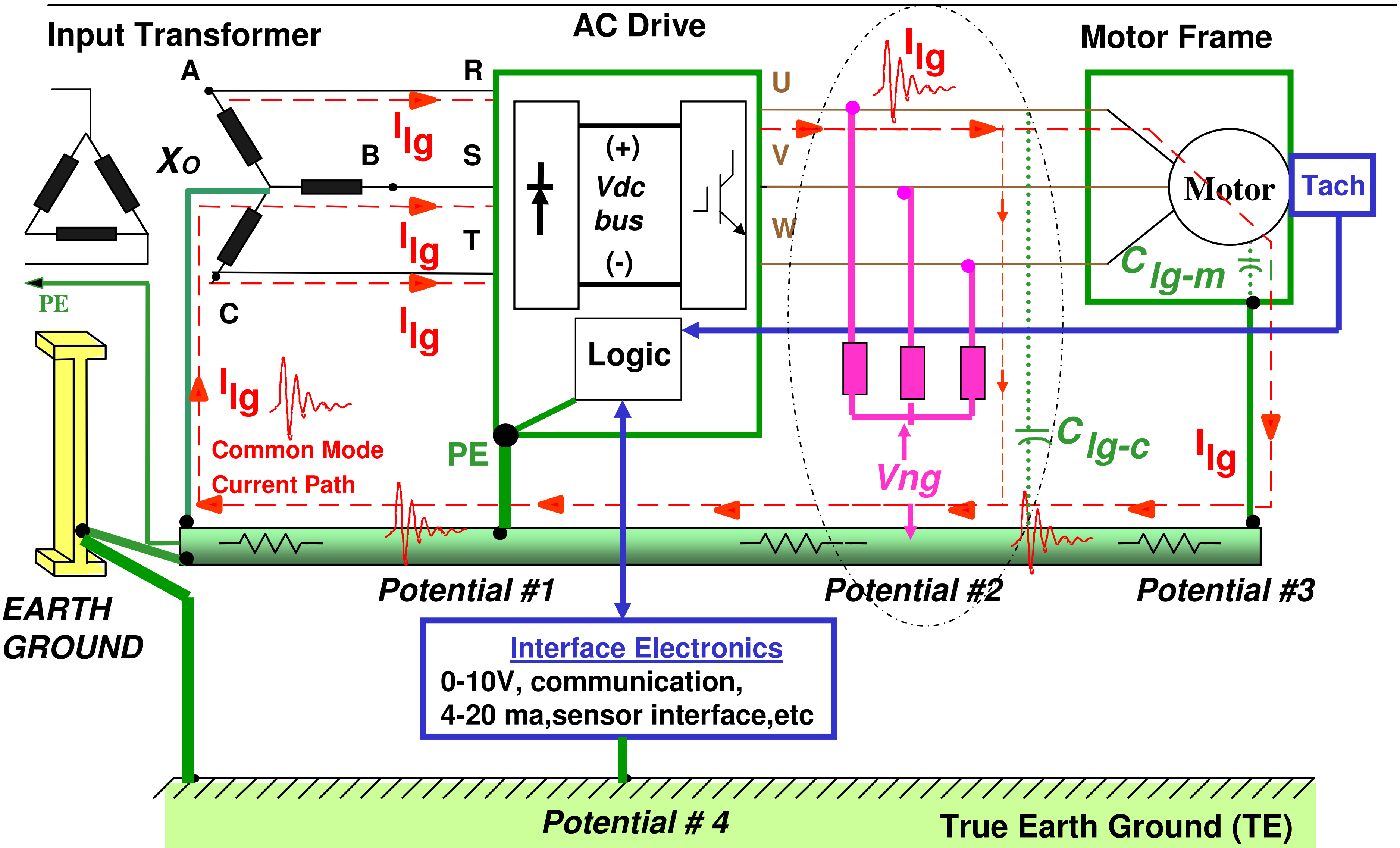
spectrum will cause an equivalent EMI differential mode spectrum through Cstray line to line

PWM Noise Source: Differential Mode Line–Line Stray Current



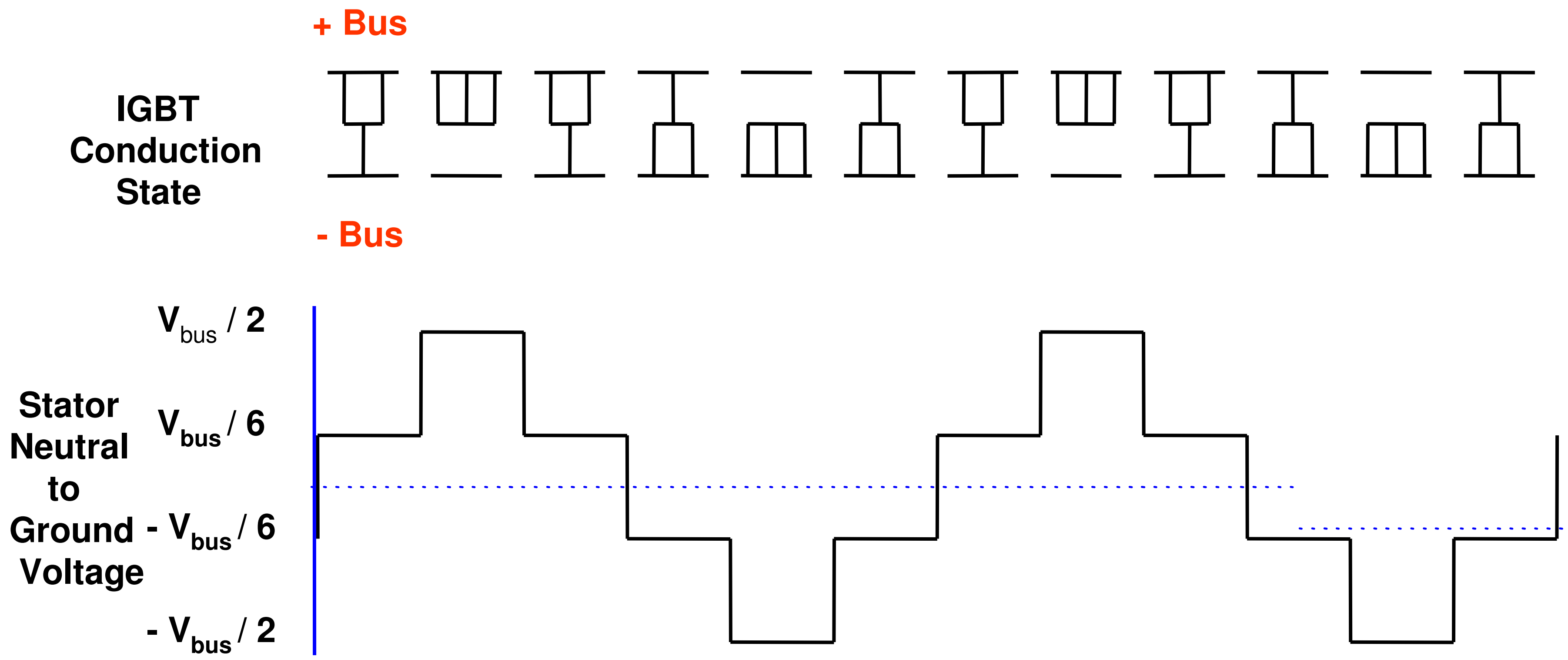
- fc spectrum smears due to variable pulse width
- IGBT risetime is next breakpoint frequency

PWM Noise Source: Common Mode Line–Gnd Stray Current



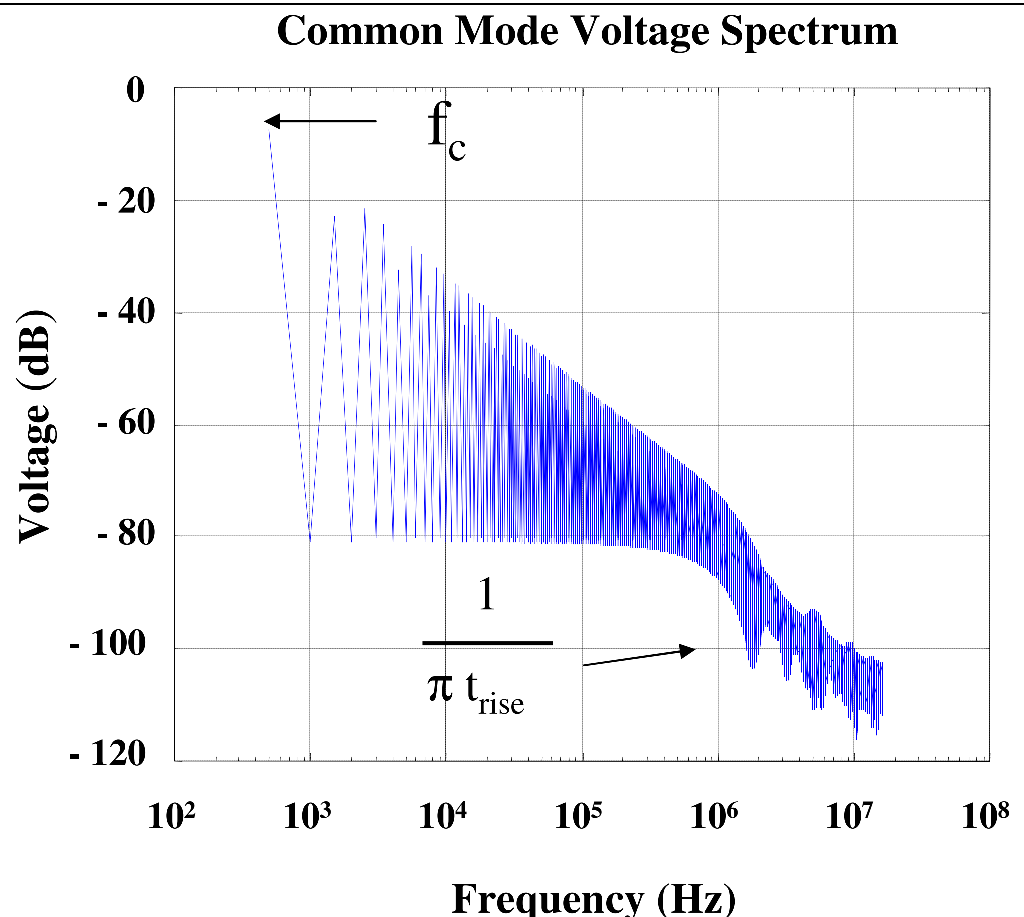
Common Mode Noise Current Path causing ground EMI Interference

PWM Noise Source: Common Mode Line–Gnd Stray Current



Generation of Drive Common Mode Voltage Waveform

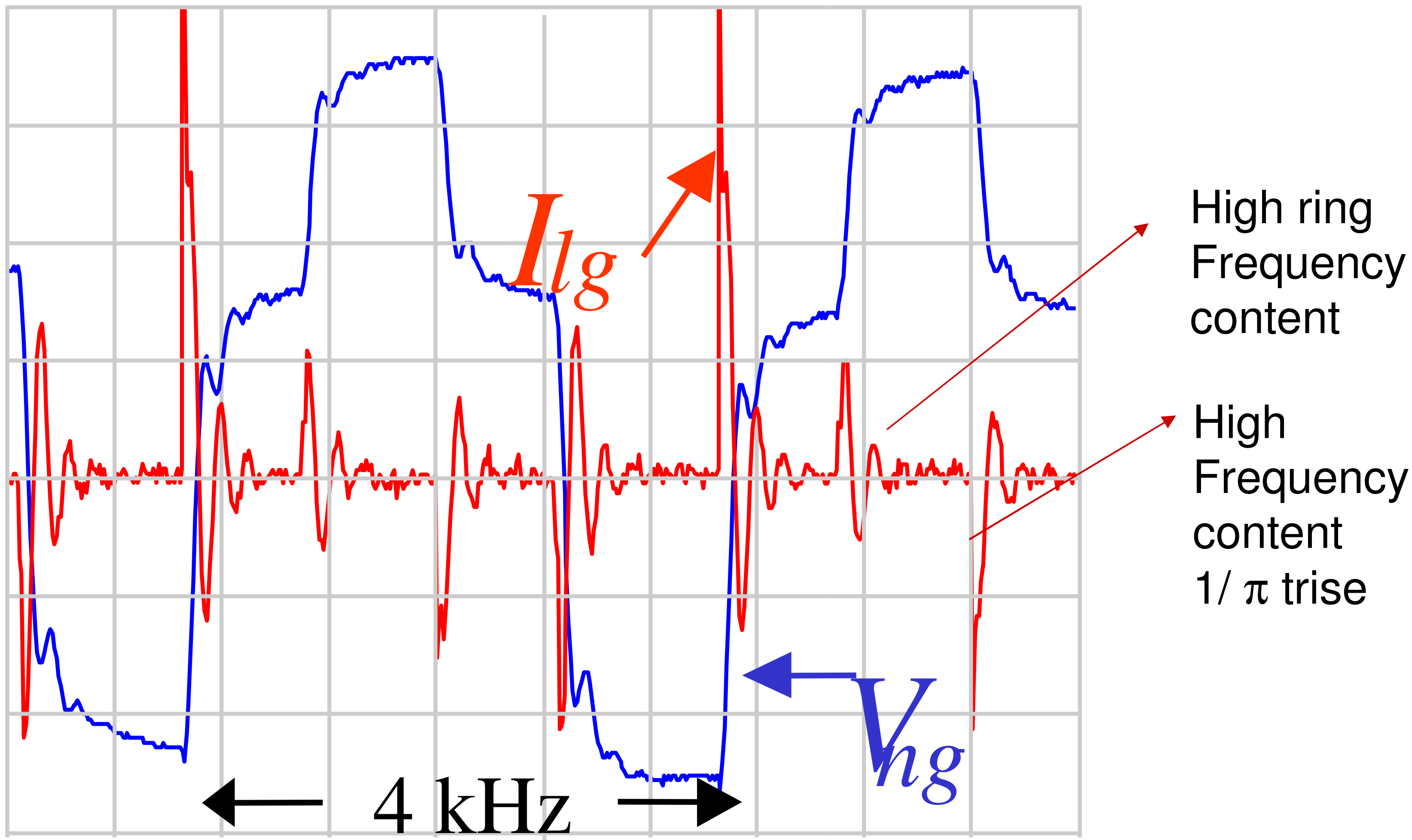
PWM Noise Source: Common Mode Line–Gnd Stray Current



V_{CM} spectrum causes equivalent EMI mode spectrum thru Cstray line-to-ground

- **higher the Vbus > noise content amplitude**
- **fc greater > higher content to fc breakpoint,**
- **Semicoductor trise affects 40 dB /decade breakpoint**

PWM Noise Source: Common Mode Line–Gnd Stray Current



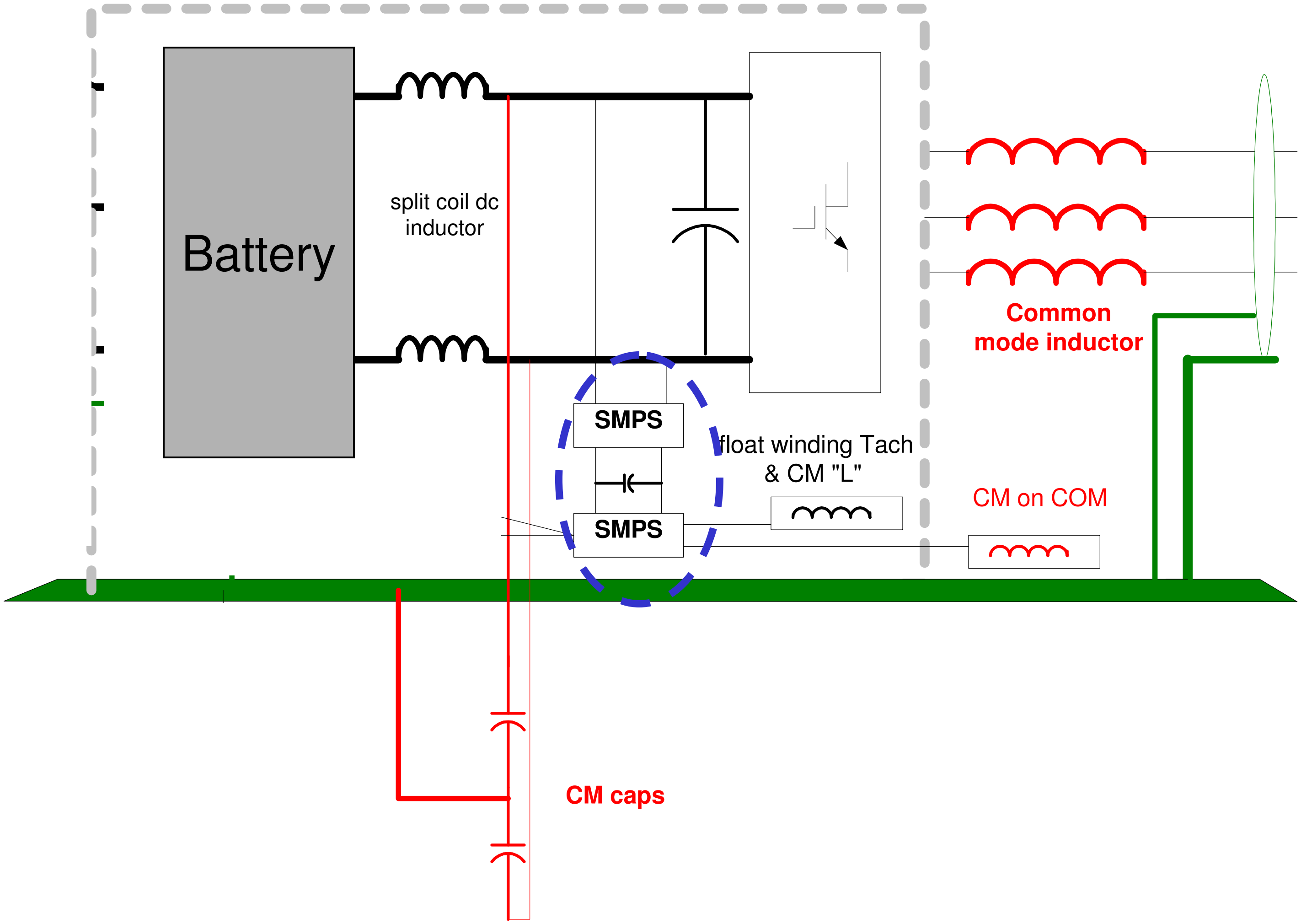
Expanded CM drive output voltage and resulting CM current

Noise Source Generator: SMPS FET modulation to DC bus & Output

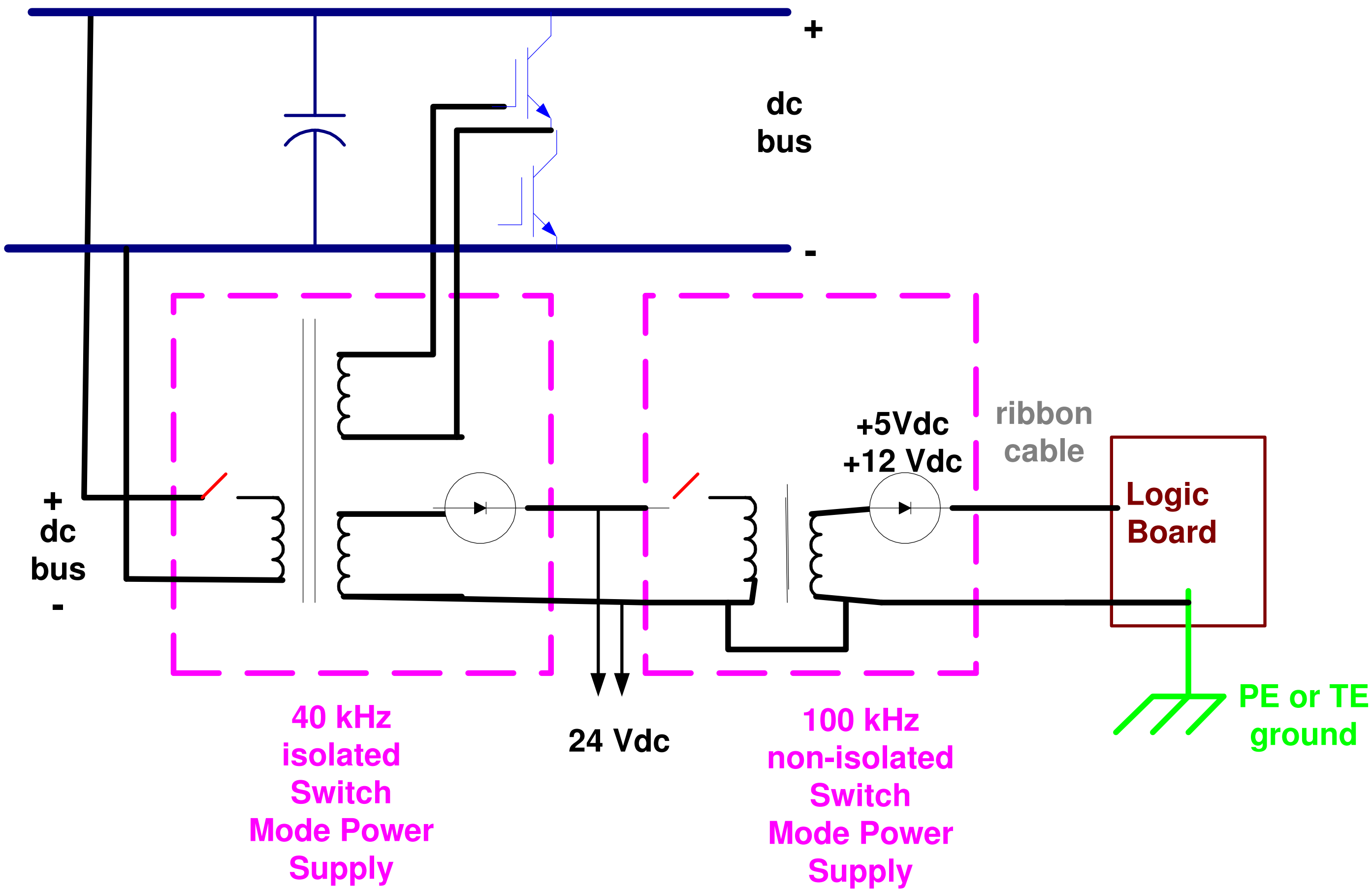
GENERATION OF DIFFERENTIAL MODE or Line-Line ELECTRICAL NOISE

GENERATION OF COMMON MODE or Line-Ground ELECTRICAL NOISE

Drive Power Structure Platform Issues

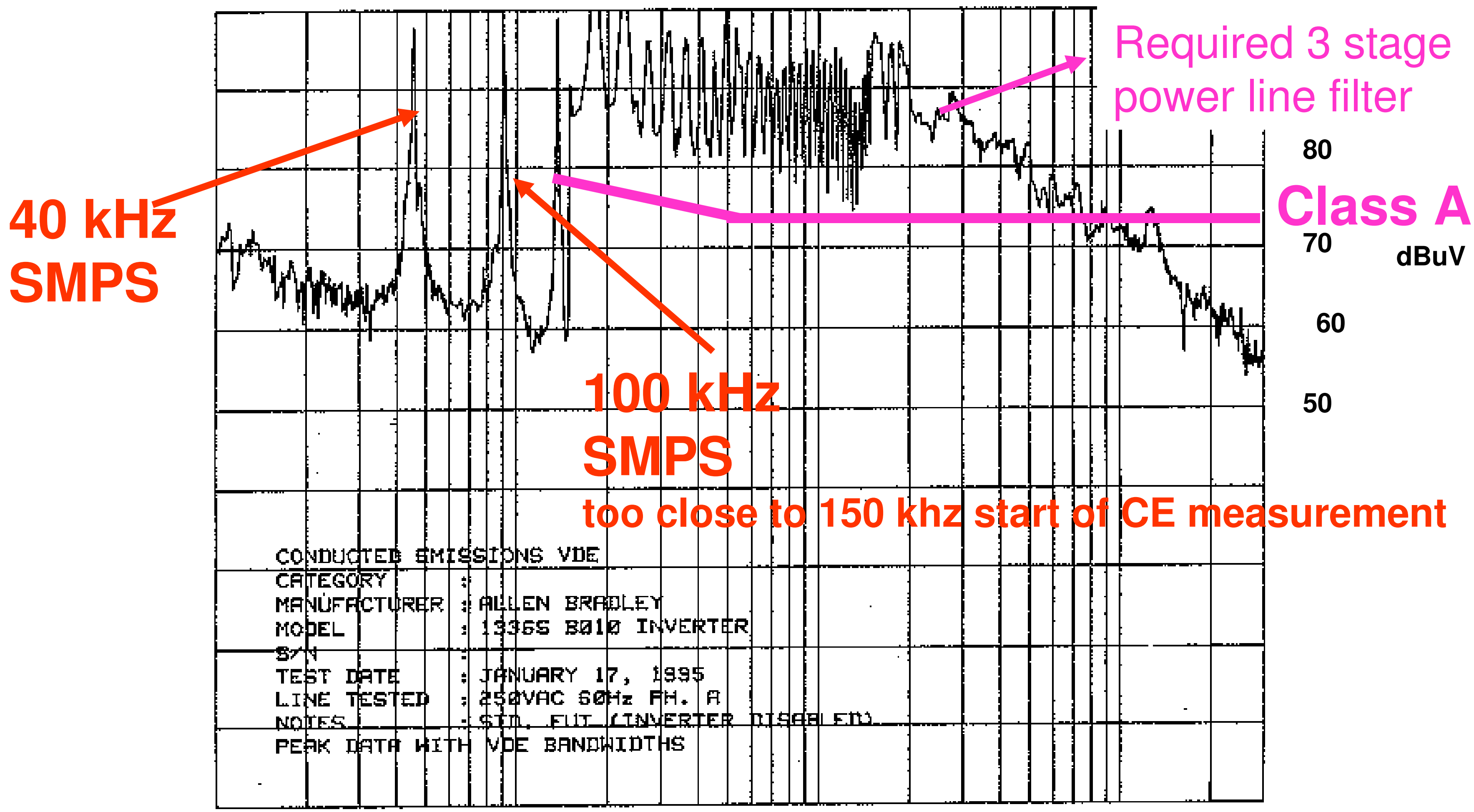


Problem 1: SMPS's in old VFD 40 KHz bulk & 100 kHz control



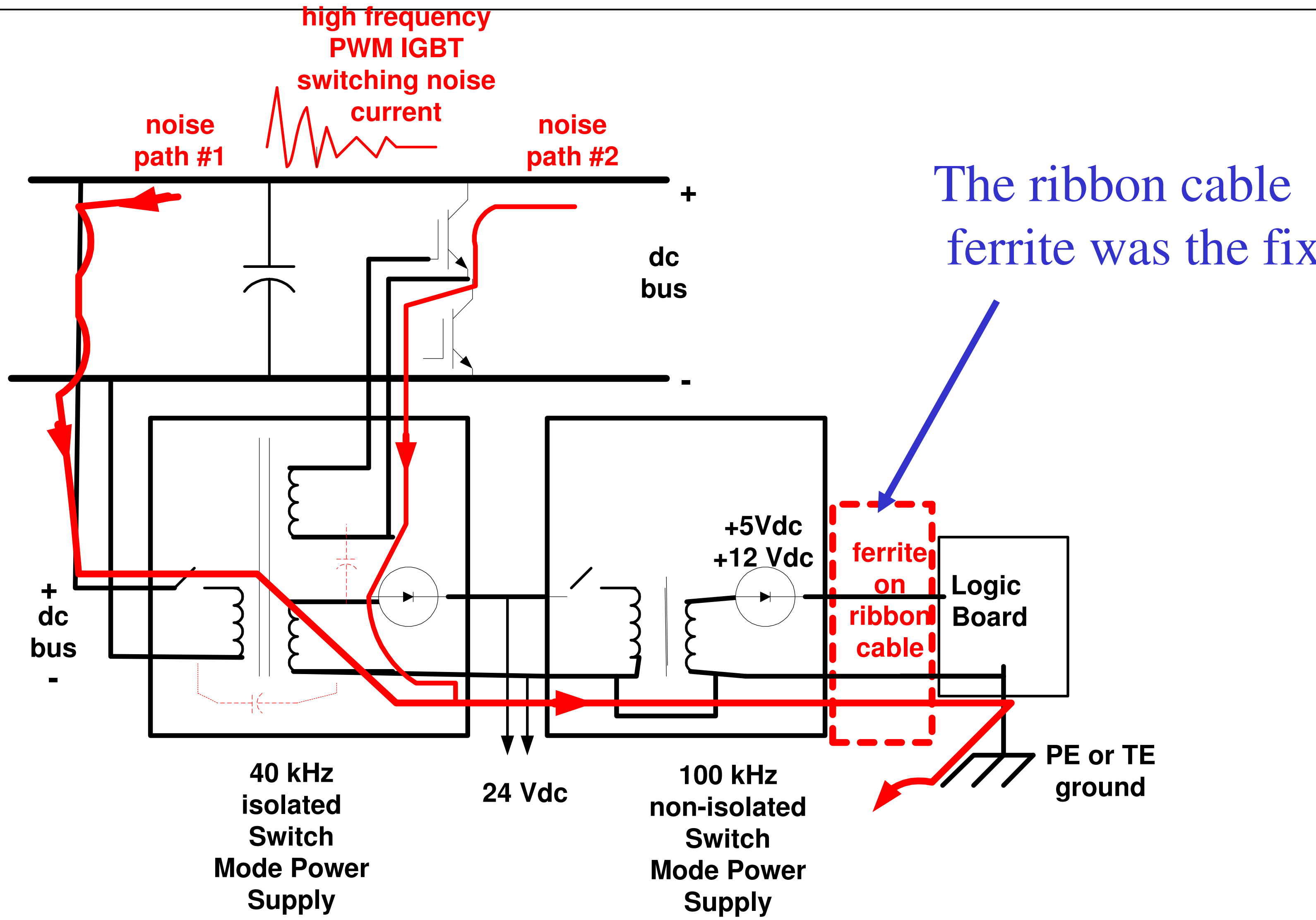
- **Increased noise generation from 2 SMPS's but allowed 24 Vdc auctioning to hold logic up.**
- **Different 24 Vdc auctioning in PowerFlex**

Problem 1: SMPS's in old VFD 40 KHz bulk & 100 kHz control



- **EMI spectrum plot clearly shows the two SMPS operation (w/o PWM on) are by themselves adding to be above Class A limits**

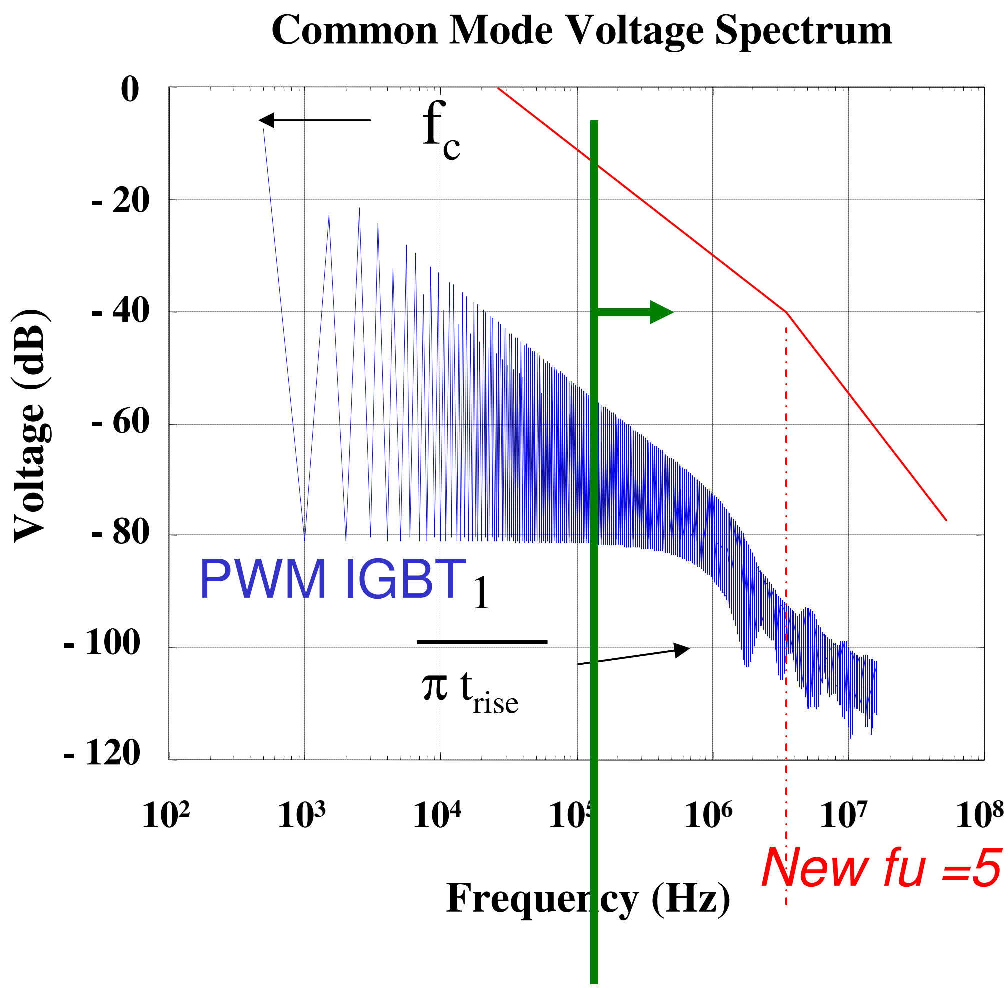
Problem 2: PWM IGBT EMI switching noise into 100 kHz SMPS



IGBT switching noise finds its way thru SMPS to logic ground plane

GENERATION OF SMPS COMMON MODE VOLTAGE SPECTRUM

New SMPS fc =30 kHz

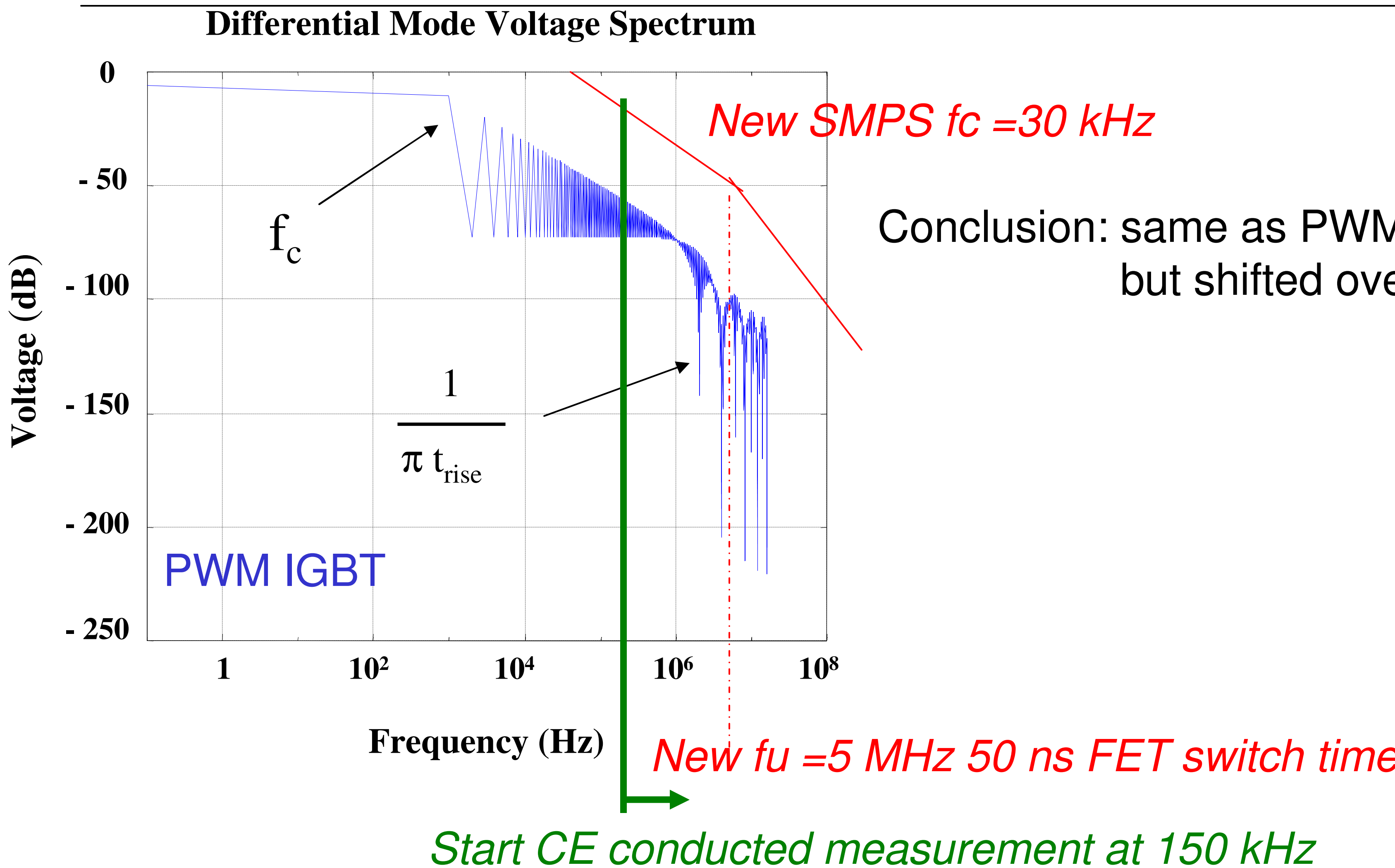


Conclusion: same as PWM IGBT
but shifted over

New fu =5 MHz 50 ns FET switch time

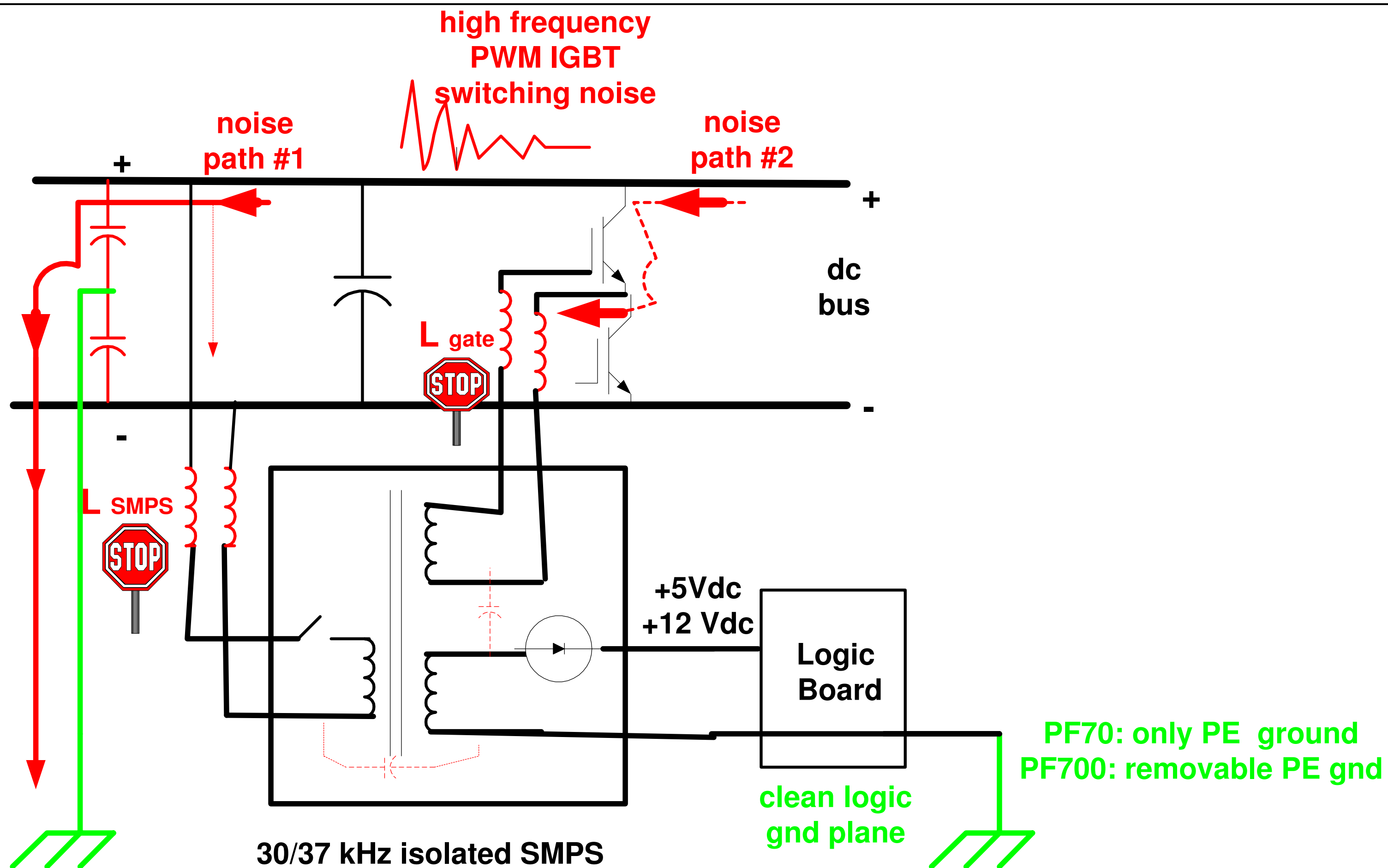
Start CE conducted measurement at 150 kHz

GENERATION OF SMPS DIFFERENTIAL MODE VOLTAGE SPECTRUM



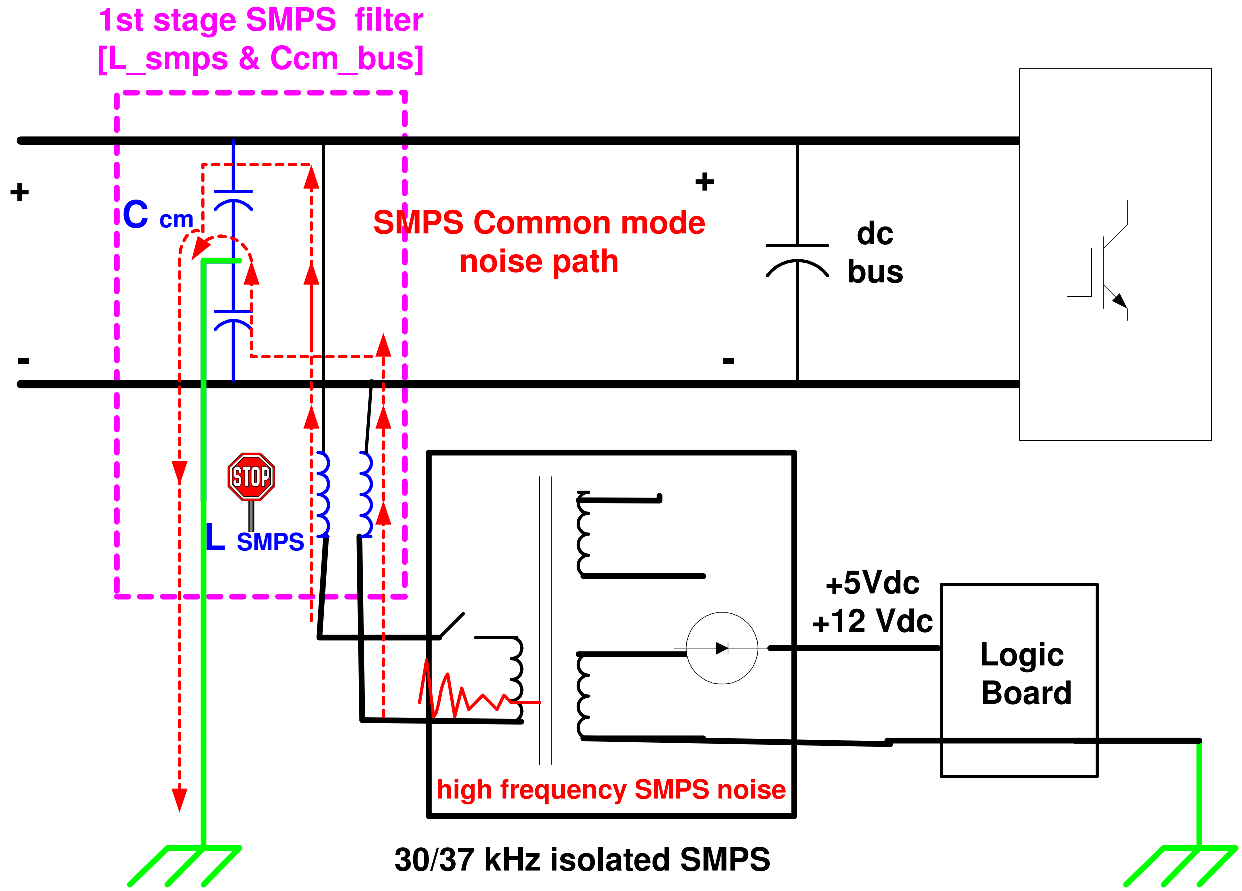
Conclusion: same as PWM IGBT but shifted over

Problem 2: PWM IGBT EMI switching noise into new SMPS



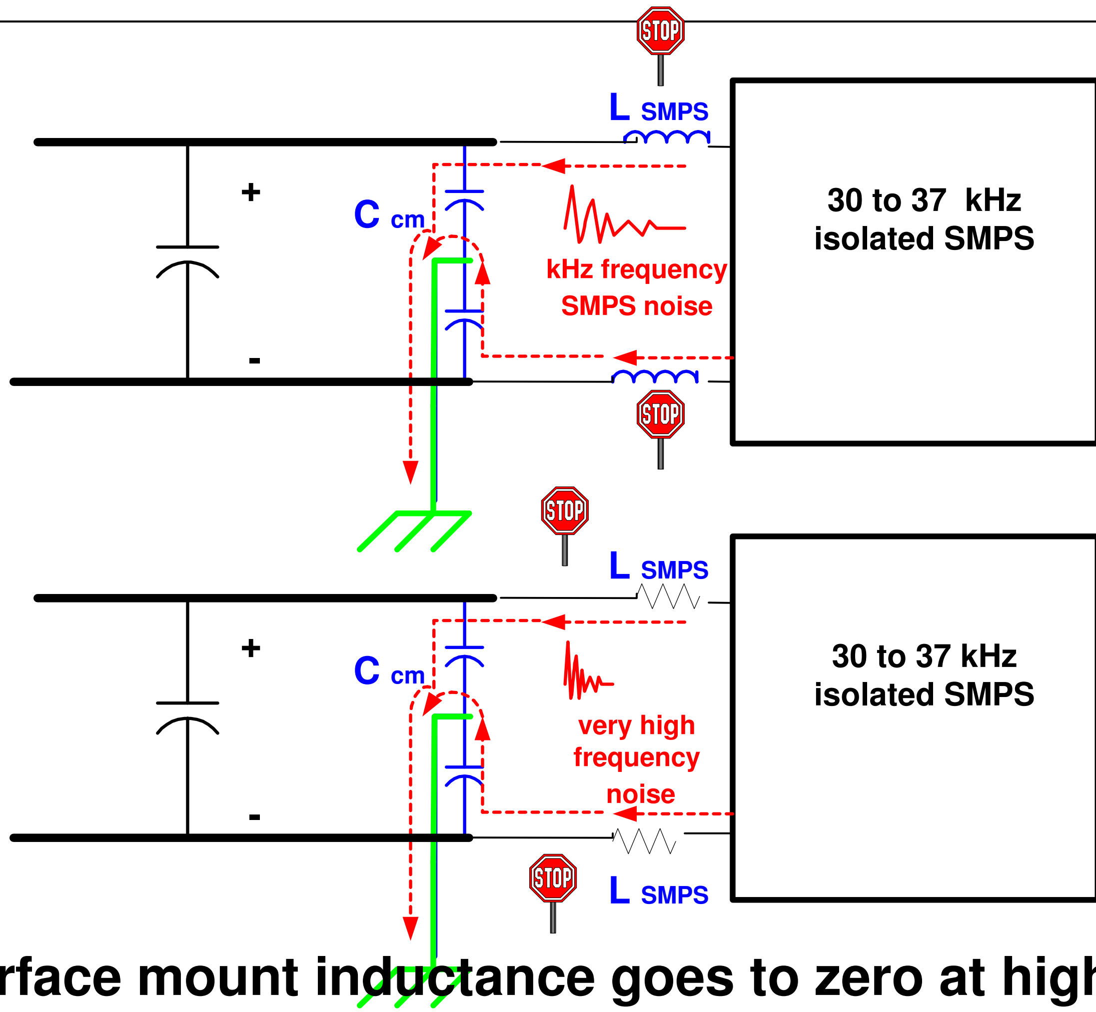
- now only one SMPS @ reduced 30 kHz operation
- IGBT switch noise blocked by surface mount gate supply (Lgate) ferrite inductors
- IGBT switch noise also blocked by surface mount (Lsmps)ferrite button inductors
- CM dc bus caps also shunt IGBT noise from SMPS & Logic ground

Problem 3: Containing new SMPS EMI switching noise



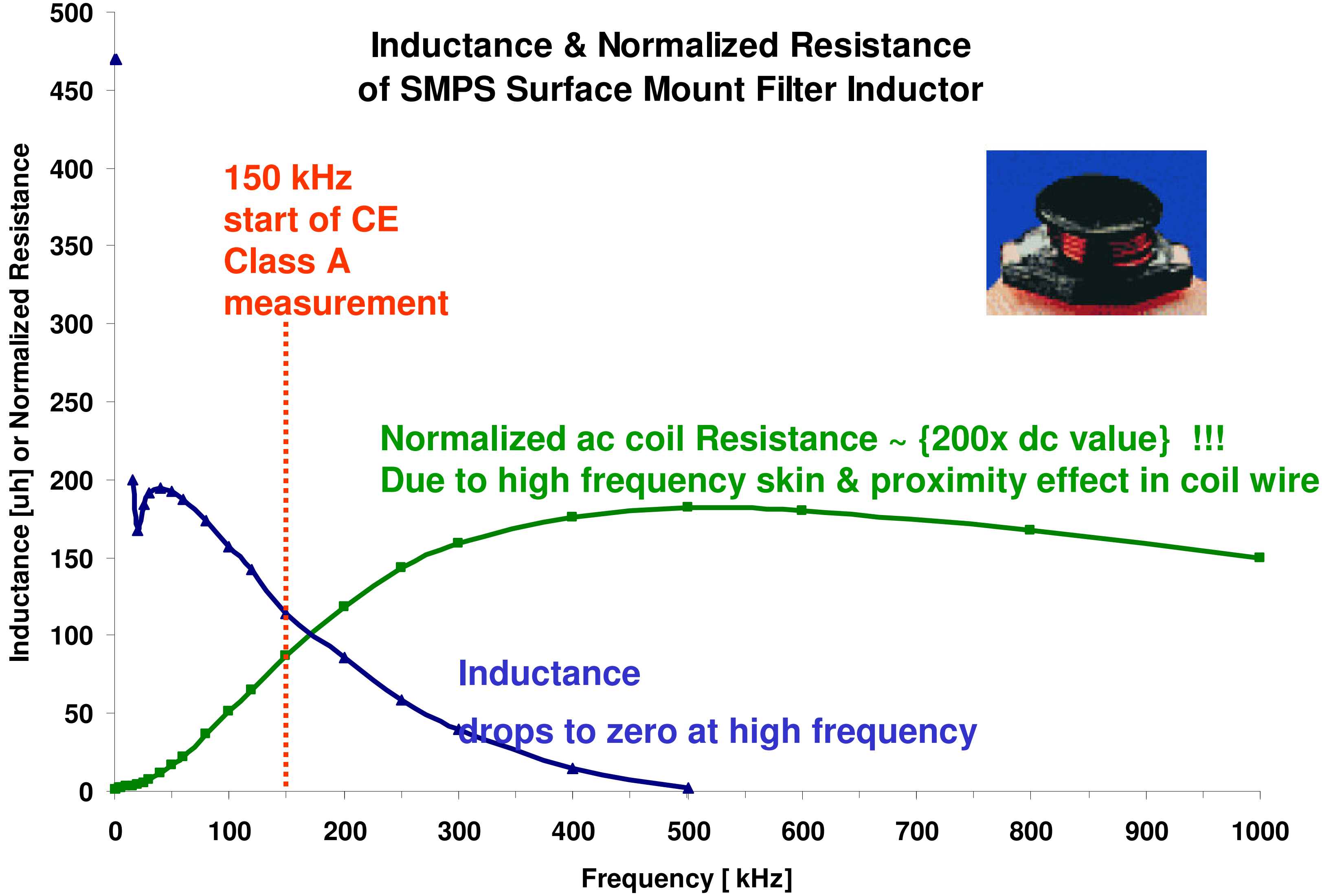
- **now only one SMPS @ reduced 30 kHz operation with slower FET risetimes**
- **SMPS noise filtered by surface mount (Lsmps) ferrite inductors & Ccm _bus forming LC filter attenuation**

Problem 3: Containing new SMPS EMI switching noise

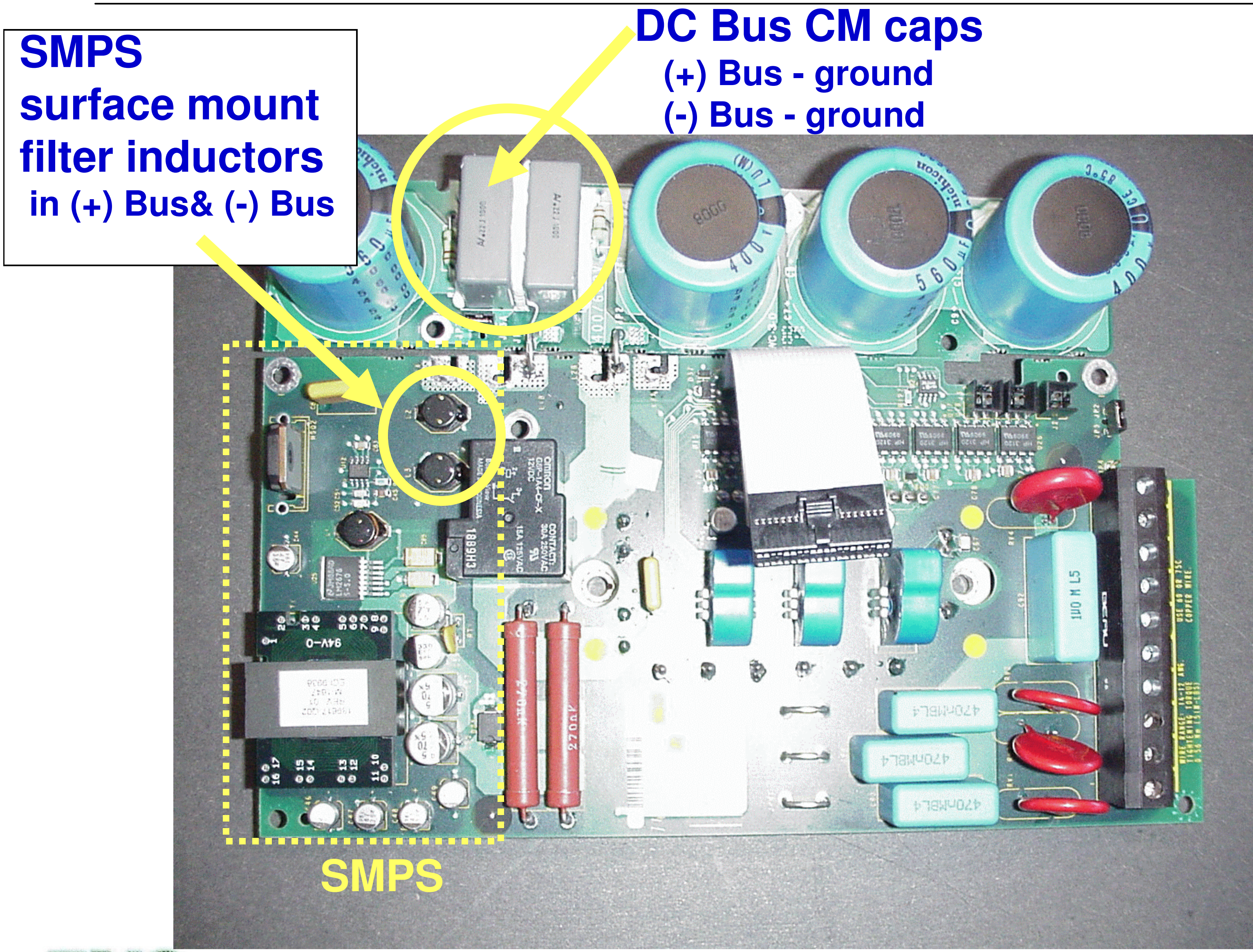


- **Lsmps surface mount inductance goes to zero at high frequency , but actually looks like an AC resistance 200X normal coil dc resistance**
- **Thus, the Lsmps inductor is replaced by RC filtering, and helping reduce and dampen high frequency noise**

SMPS Noise attenuation from Clever usage of wire Physics



SMPS built in 1st Filter fixes to meet Class A Limits

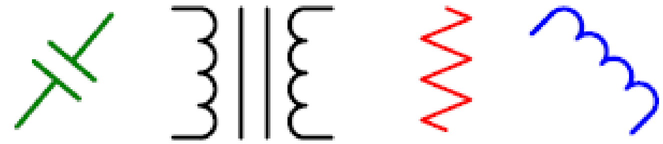


SMPS Modeling to meet Conducted Emission Limits

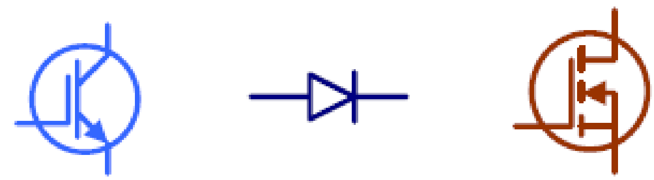
- Goal: Characterize and reduce EMI emissions from Flyback SMPS
  - Model SMPS
  - Determine critical components in system
  - Determine noise attenuating techniques
- Procedure
  - Model: Actives and Passives (discrete components and interconnects)
  - Use simulations to find critical paths
  - Focus attention on these paths to mitigate noise

SMPS Modeling Process

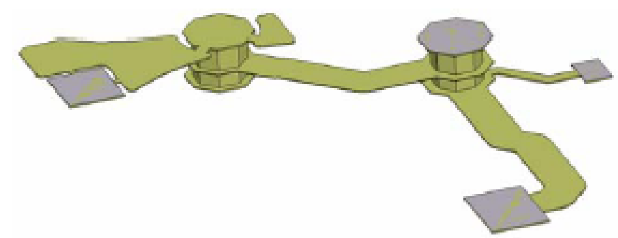
- Model all passive components using impedance analyzer



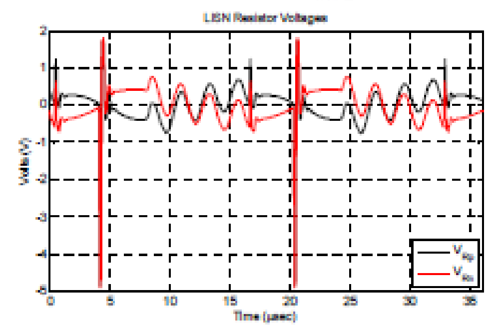
- Model active components from datasheet



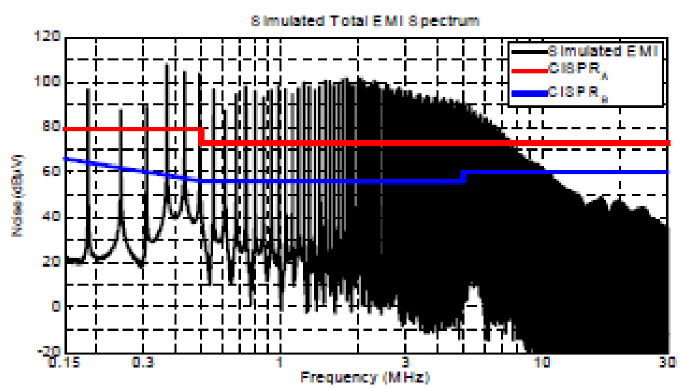
- Create geometric model in Q3D and solve



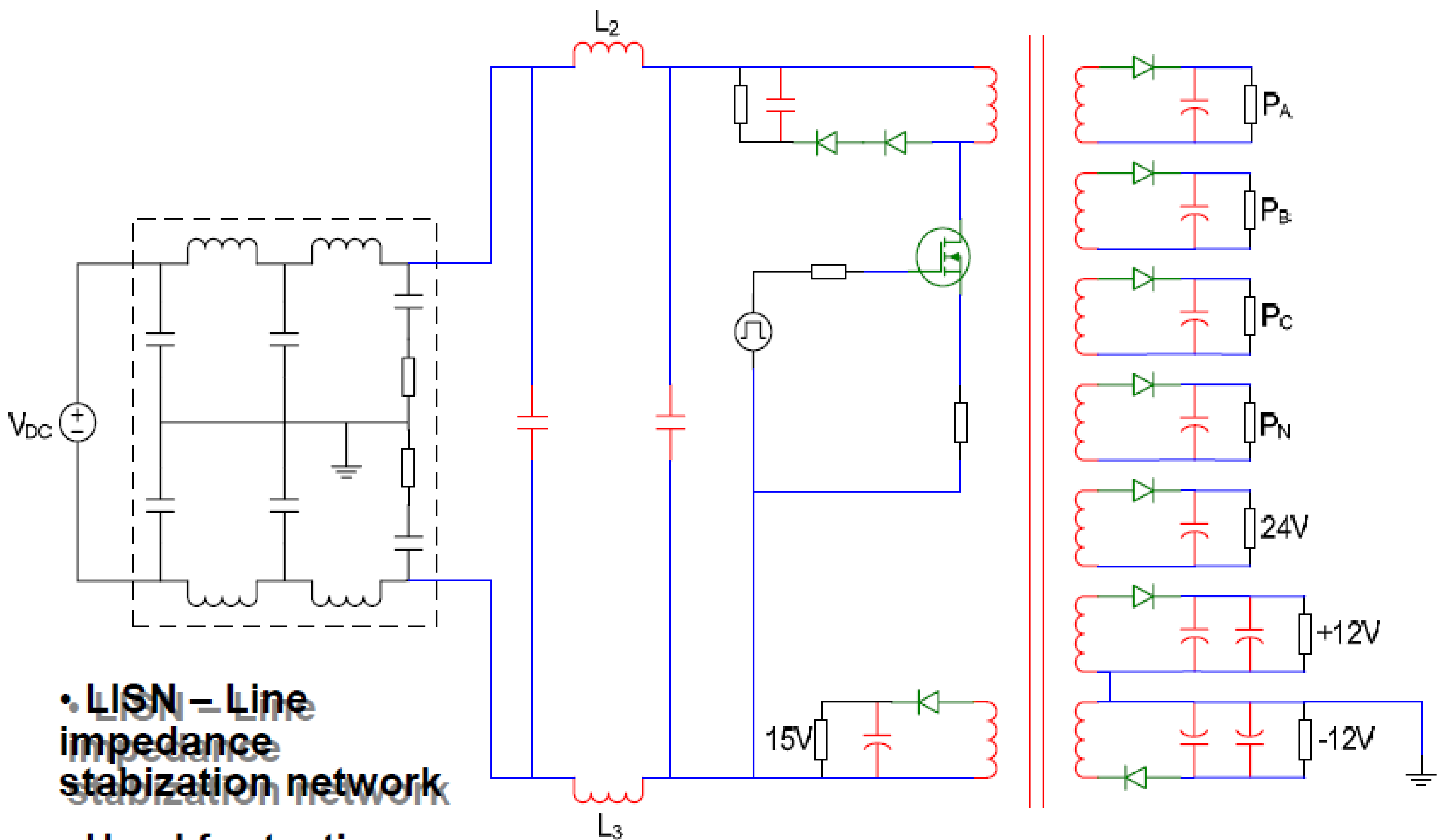
- Create and solve transient model in Simplorer



- Perform FFT in Matlab



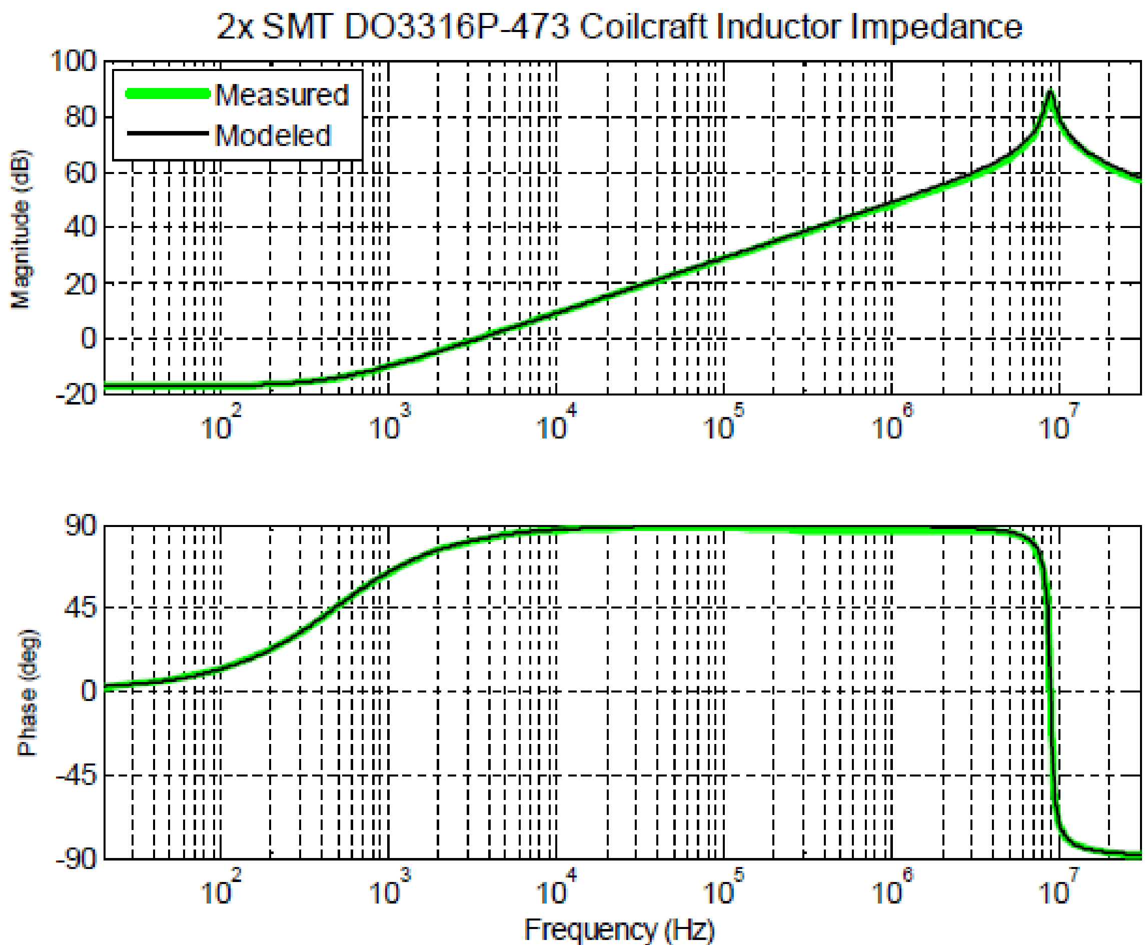
SMPS Modeling Schematic & LISN

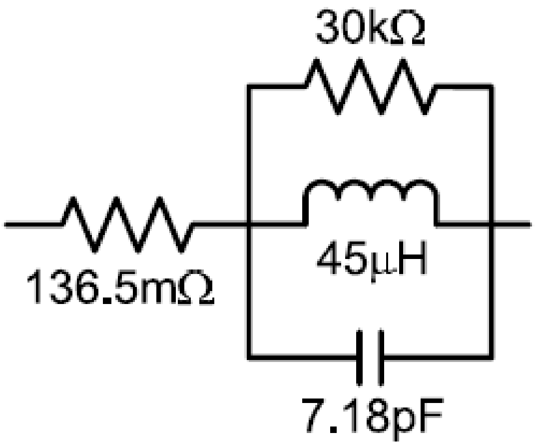


- LISN – Line impedance stabization network
- Used for testing

SMPS Passive Models

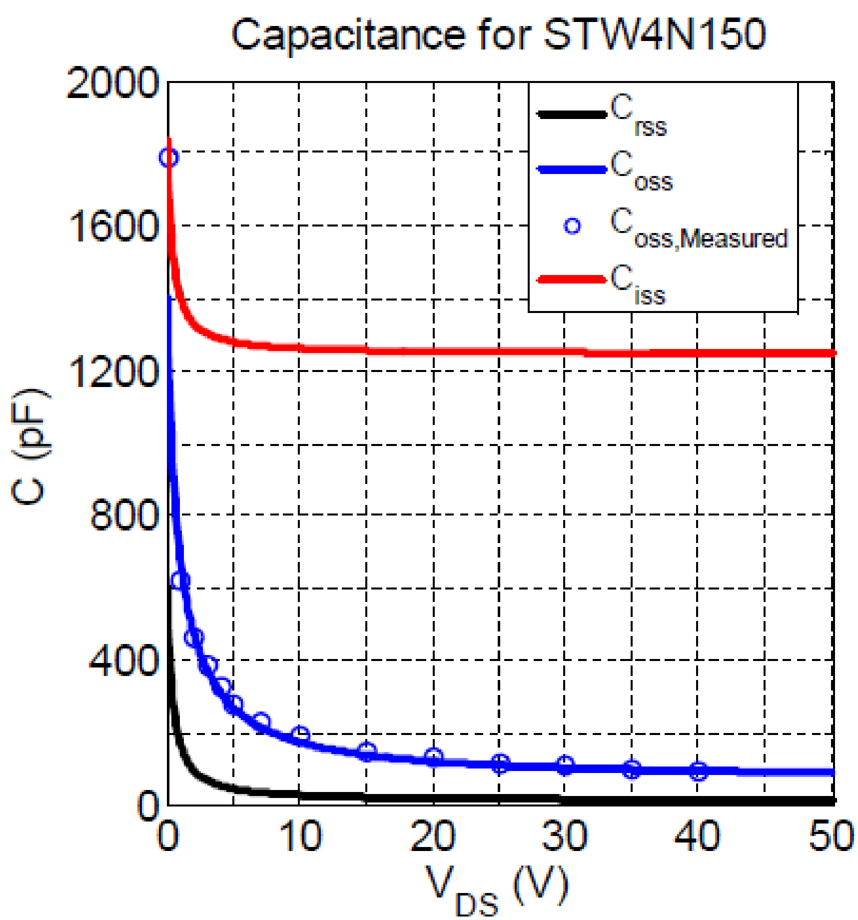
- Model all passive components with impedance analyzer
- To create frequency dependent equivalent network for device



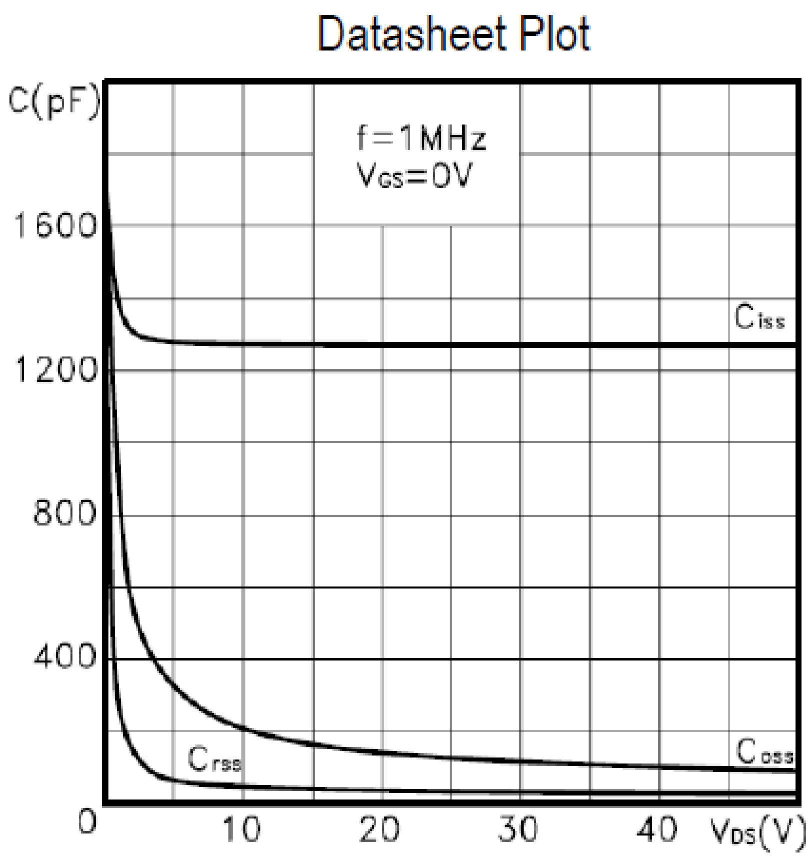


SMPS Active Models

Simplorer Model

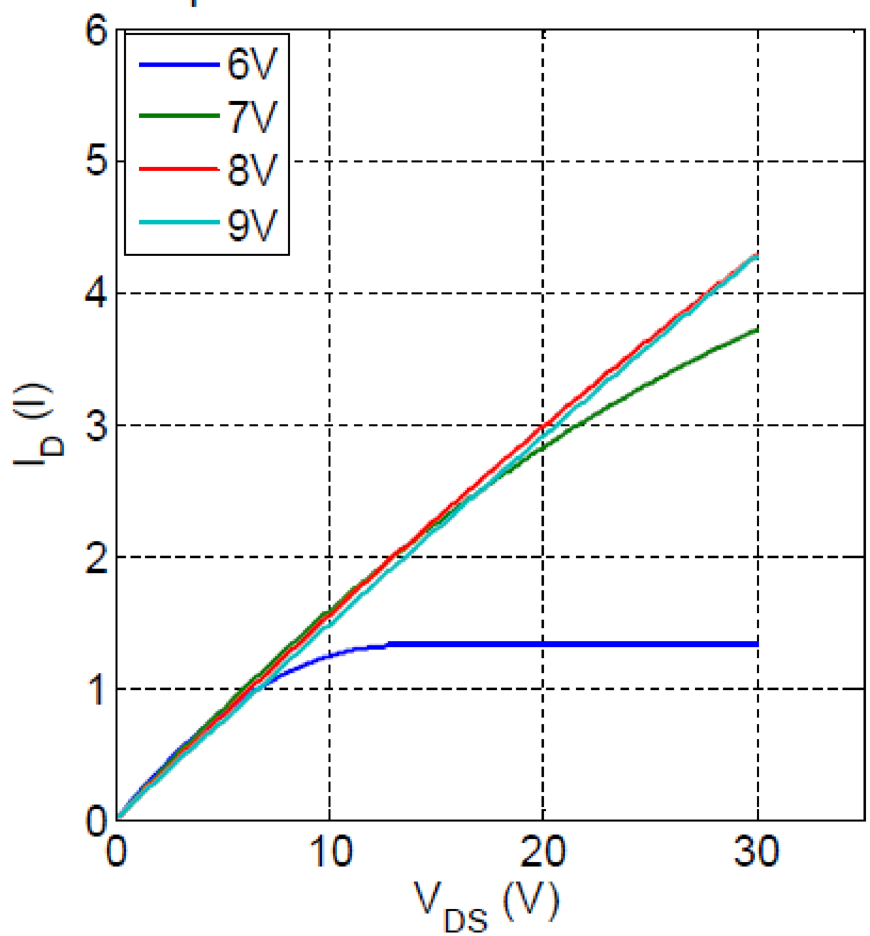


Datasheet

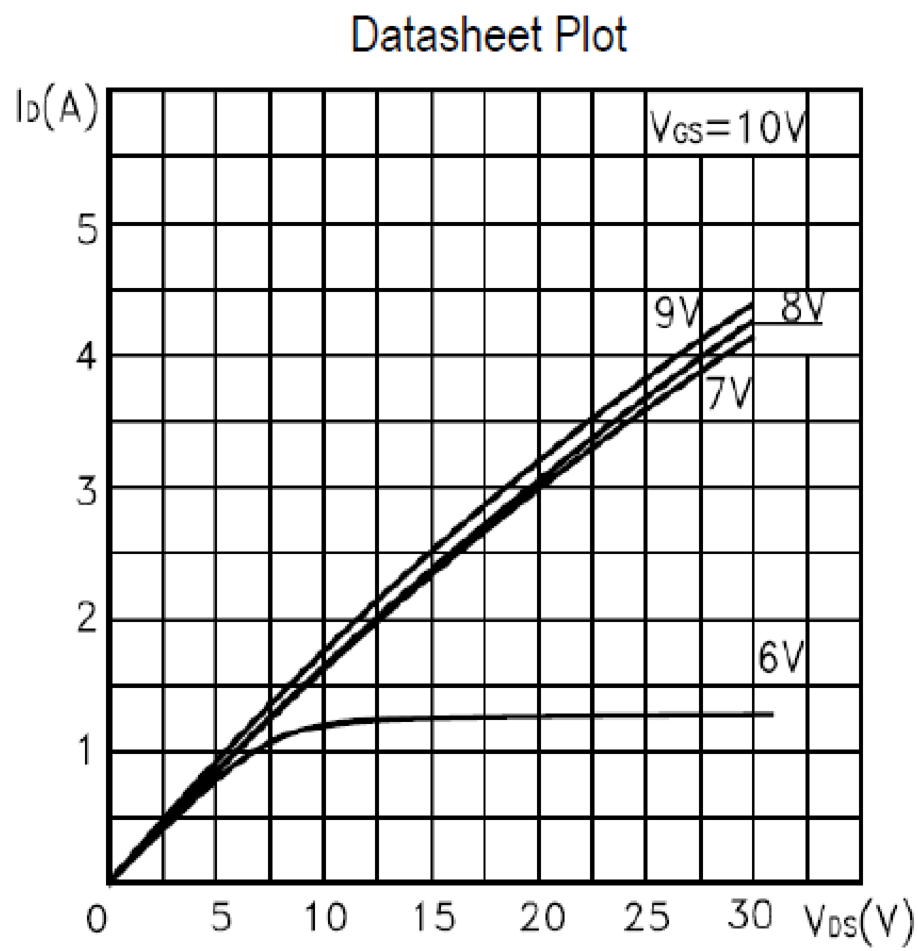


SMPS Active Models

Simplorer Model

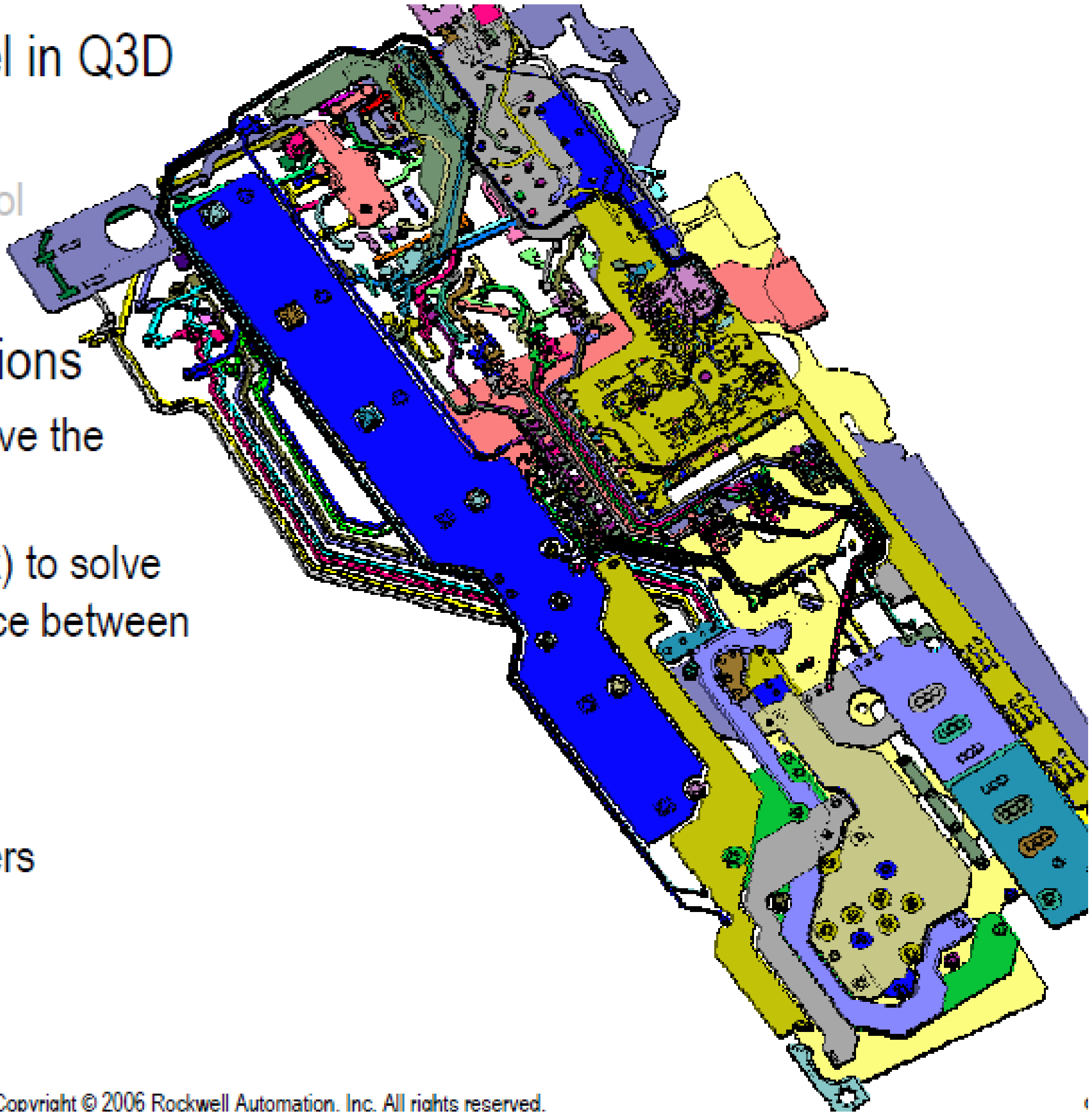


Datasheet

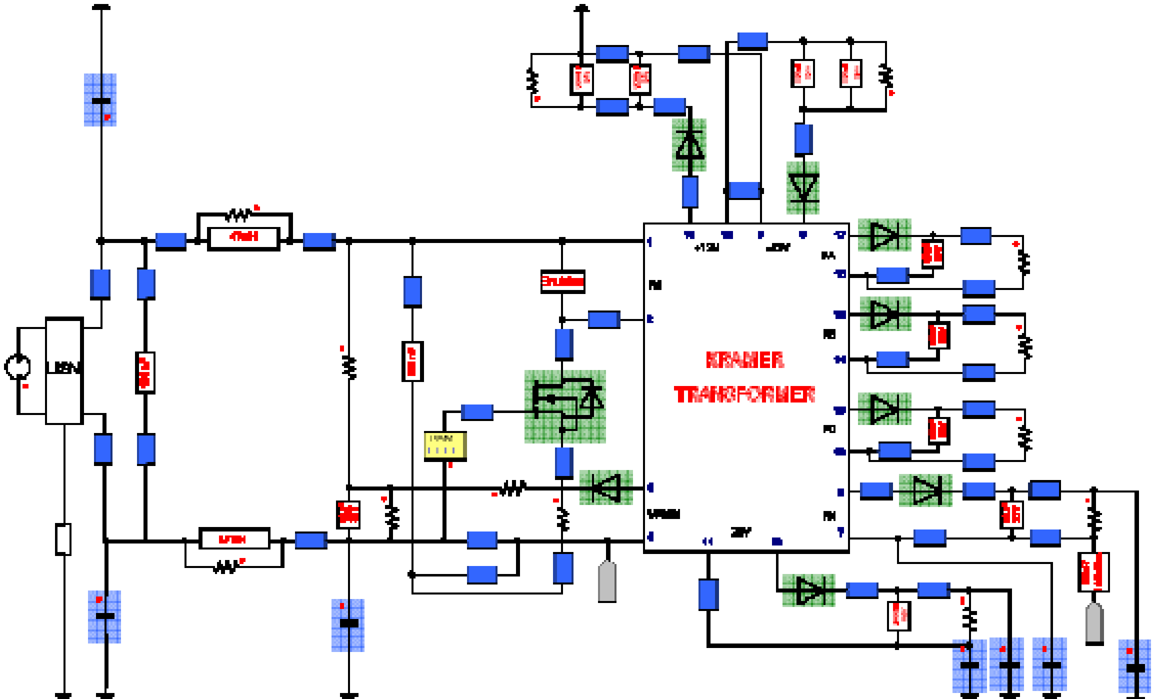


Q3D PC board R & L Models

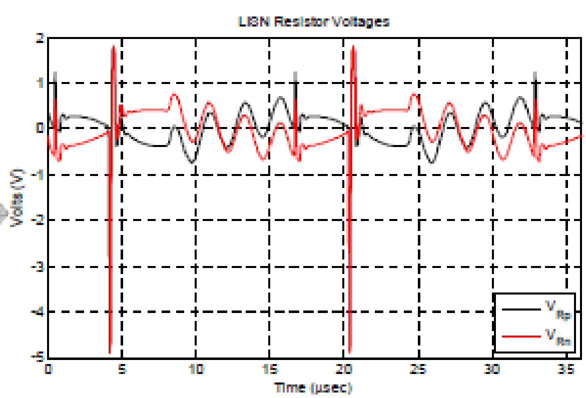
- Create geometric model in Q3D
  - Draw using layout
  - Import using interface tool
- Define materials
- Define boundary conditions
  - Conductors (Nets) to solve the capacitance between
  - Terminals (Sources/Sink) to solve resistance and inductance between
- Solve (C, R, L)
- Post Processing
  - Export lumped parameters
  - Matrix Reductions
  - Field plots

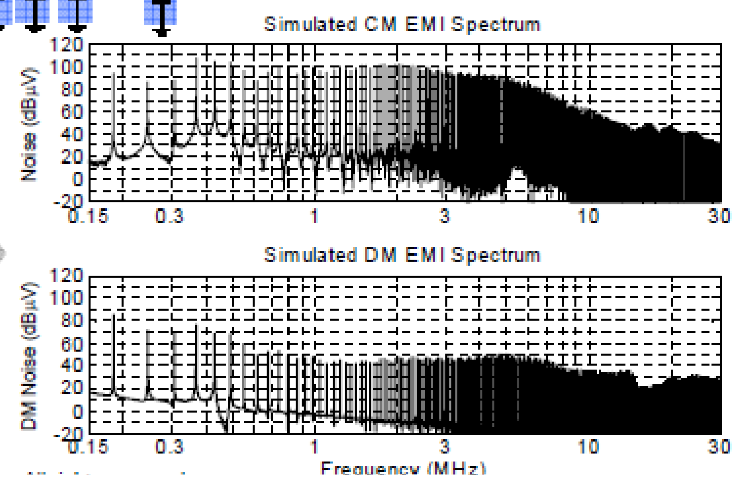


Simplorer circuit simulation Models



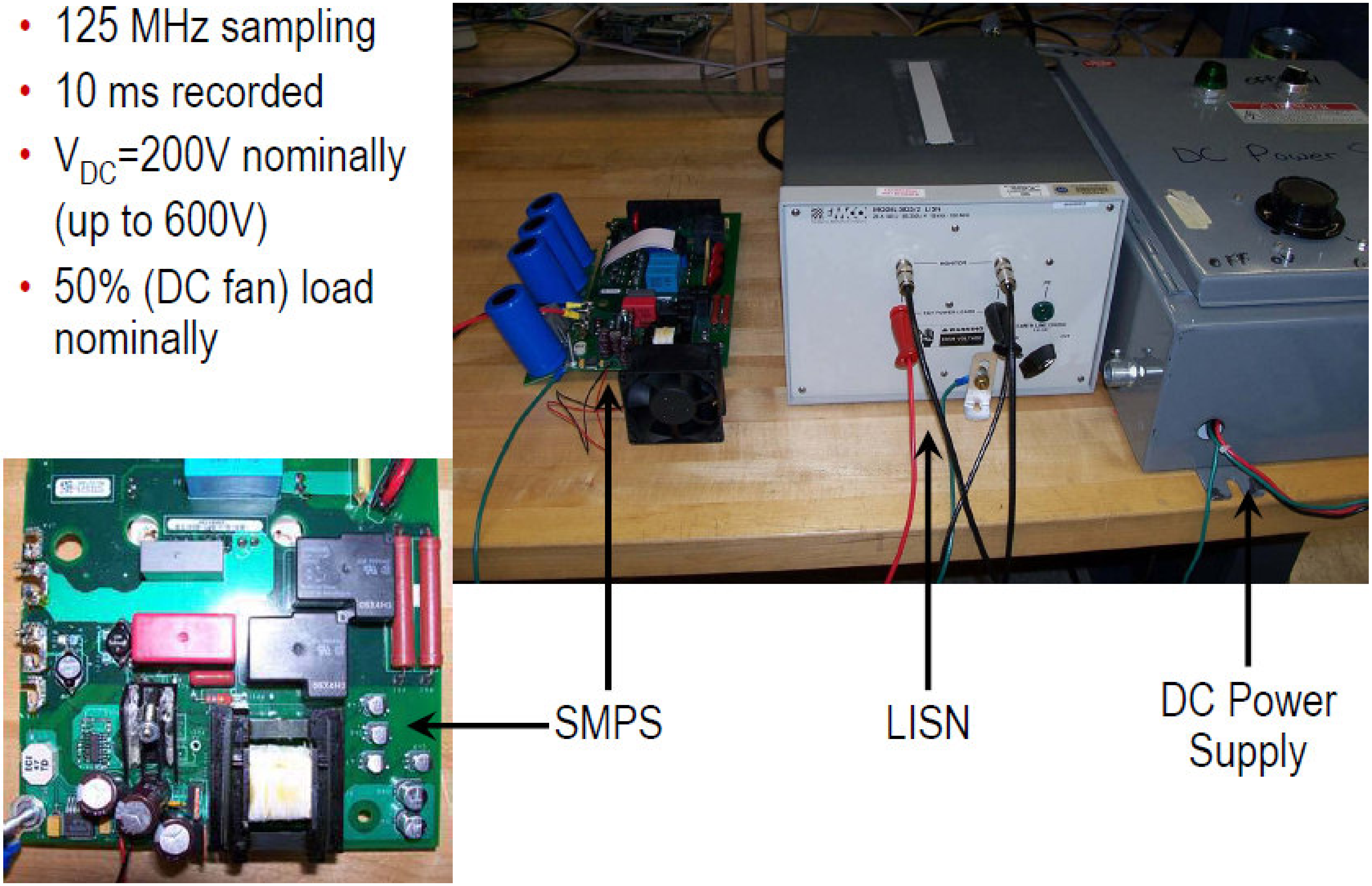
- Blue elements are manually input from Q3D and are turned on/off
- 2 ns step size
- 4 ms total time
- 30-60 min Simulation time
- V_{DC}=200V nominally
- 50% (resistive) load nominally



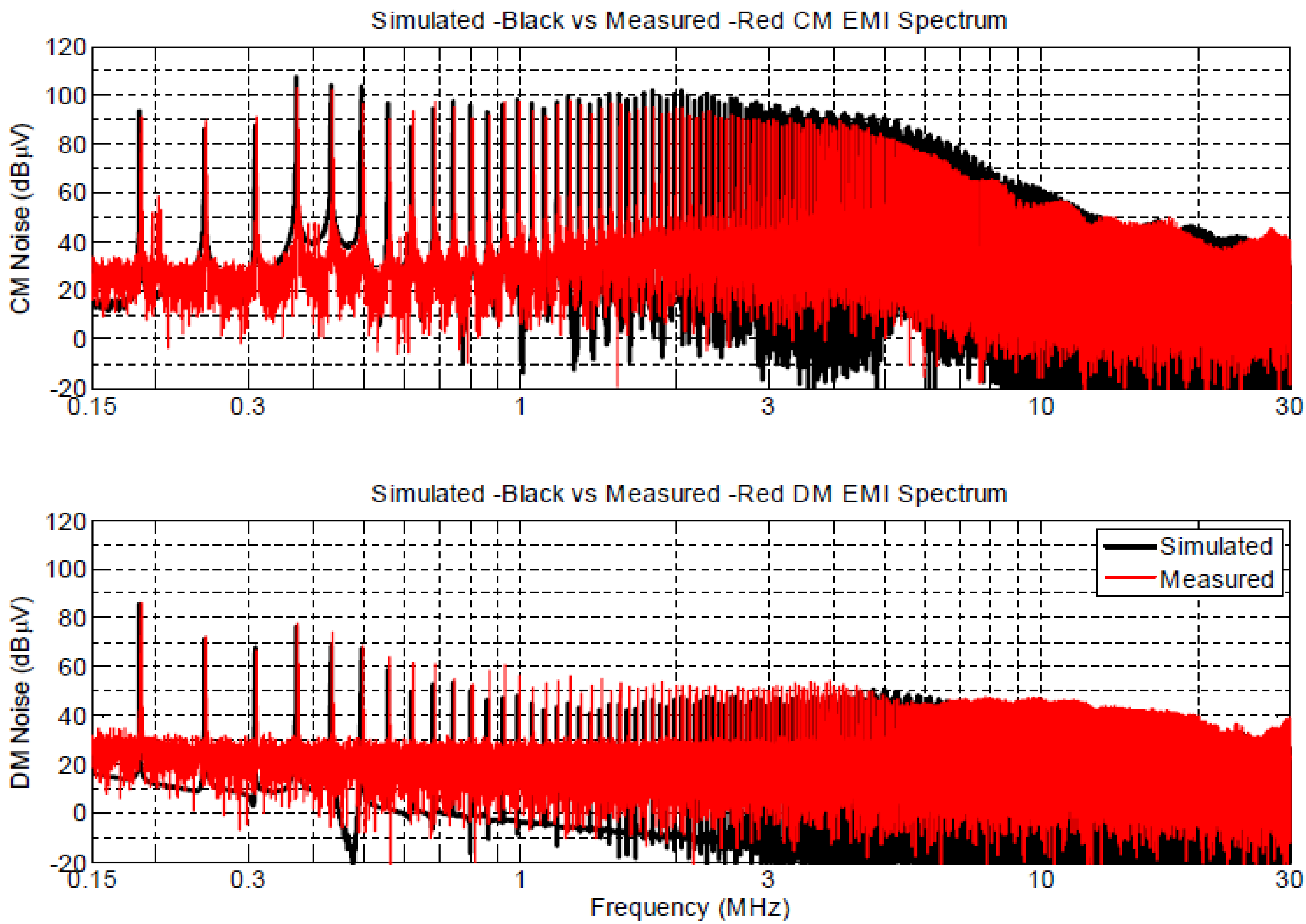


Lab Measurement

- 125 MHz sampling
- 10 ms recorded
- V_{DC}=200V nominally (up to 600V)
- 50% (DC fan) load nominally



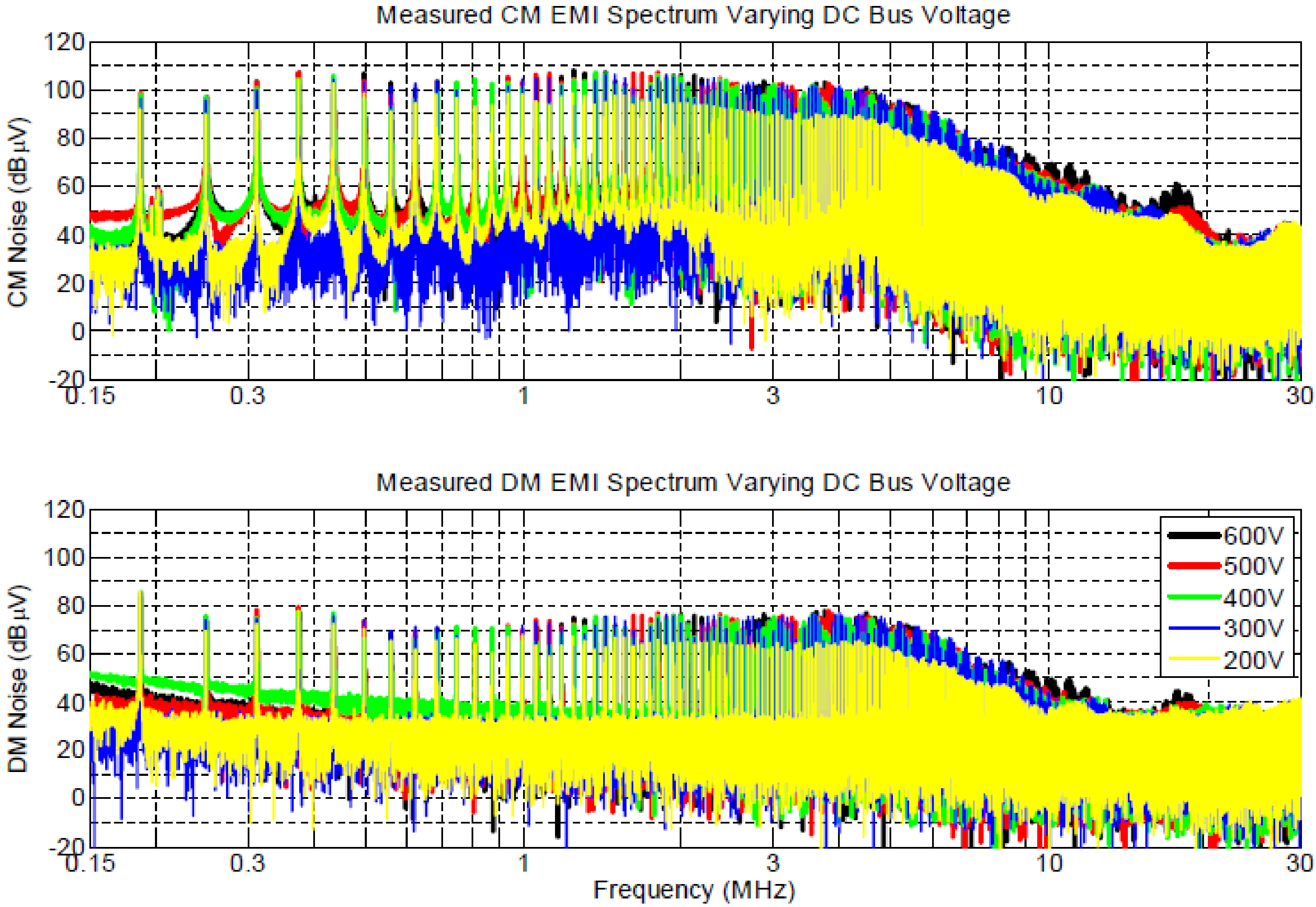
SMPS Model Results



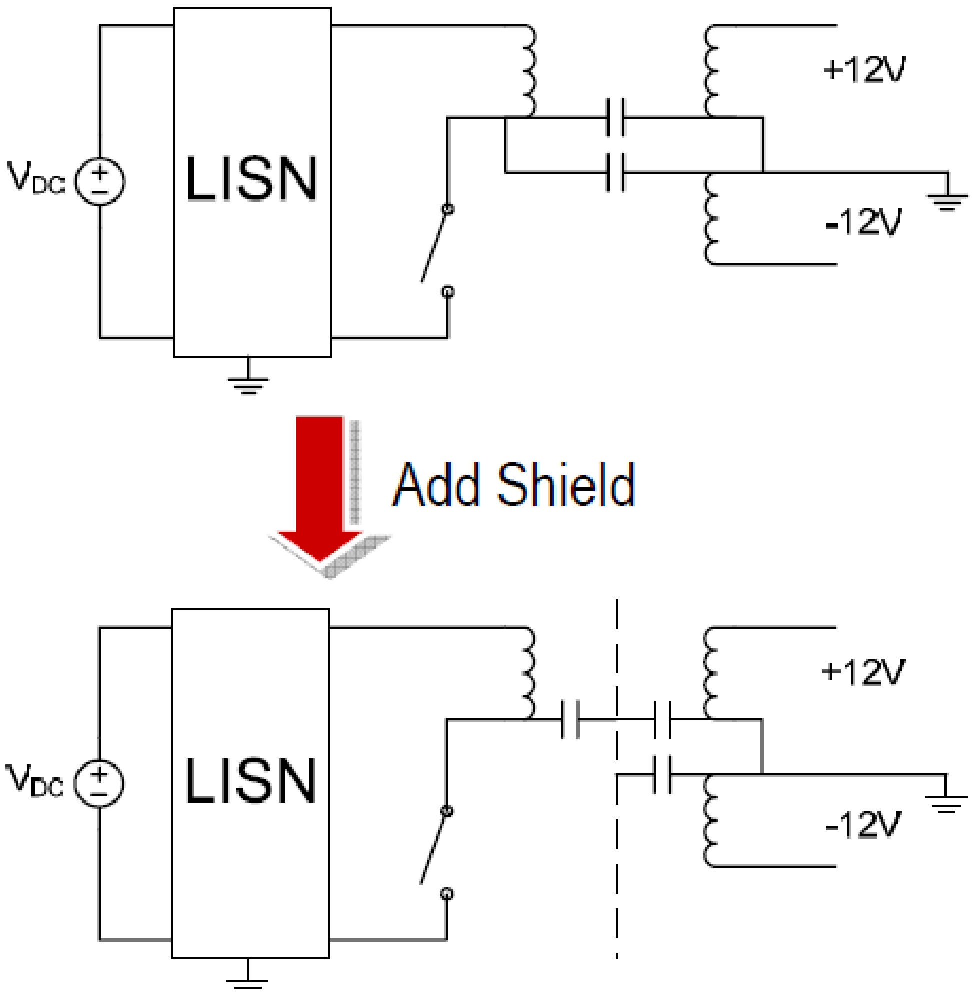
SMPS Model Benefits

- Show the importance of various aspect within the circuit
  - Trace impedances
  - Active components
  - Passive components: values and type
  - Critical paths
- Simple demonstrations of attenuations techniques
  - Adding filters into the circuit
  - Re-arrange the components
  - Shielding the Transformer

SMPS Model Benefits: dc bus variation

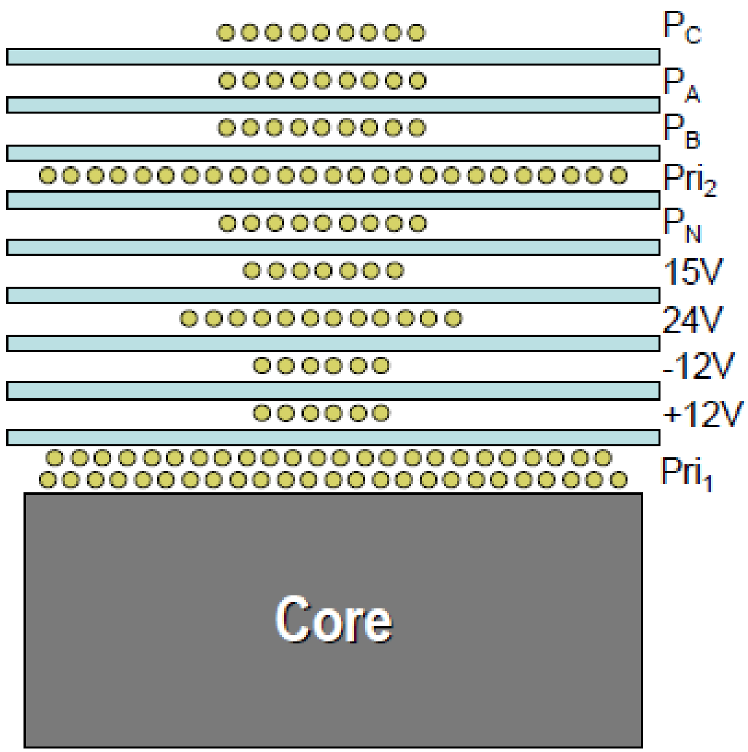


Simulation: Best SMPS xfmr Shielding technique ?

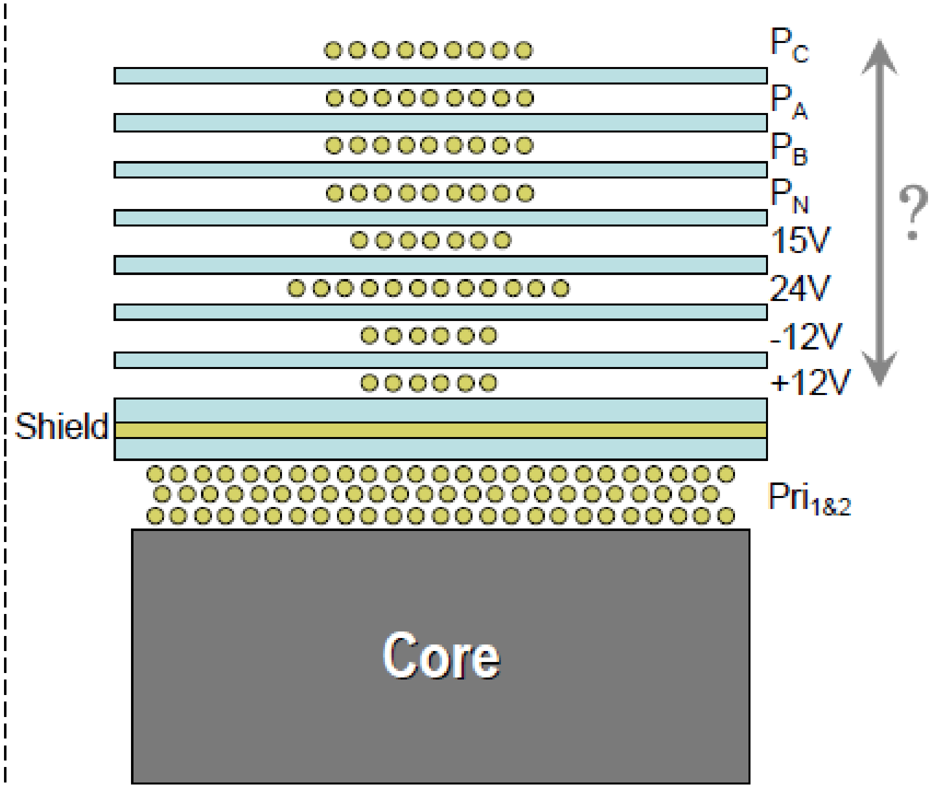


- Where/how to physically place shield
- Where to electrically connect shield
- Size and cost of shield
- Is it all worth it?

Simulation: Best SMPS xfmr Shielding technique ?

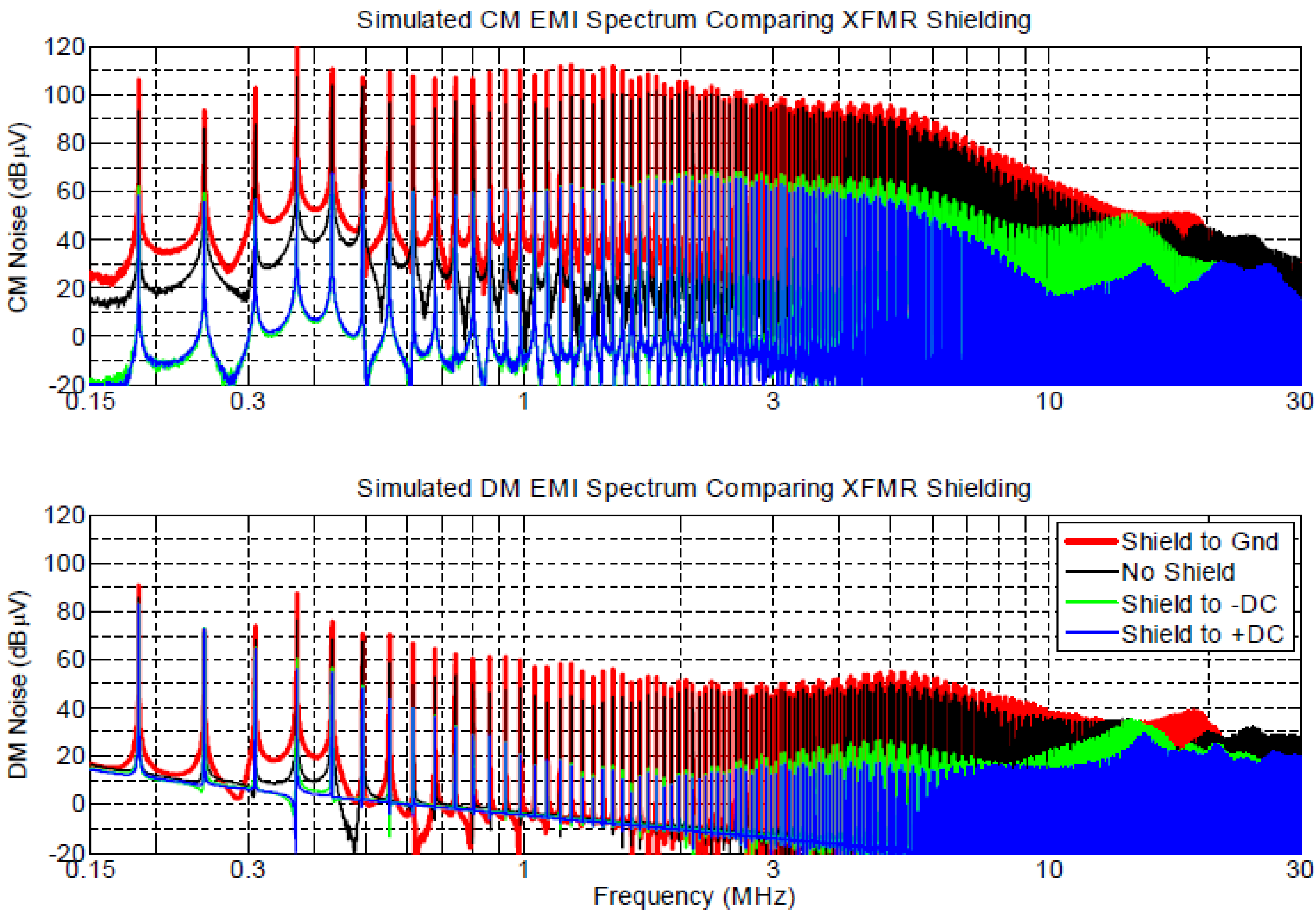


Present
Winding Cross-Section

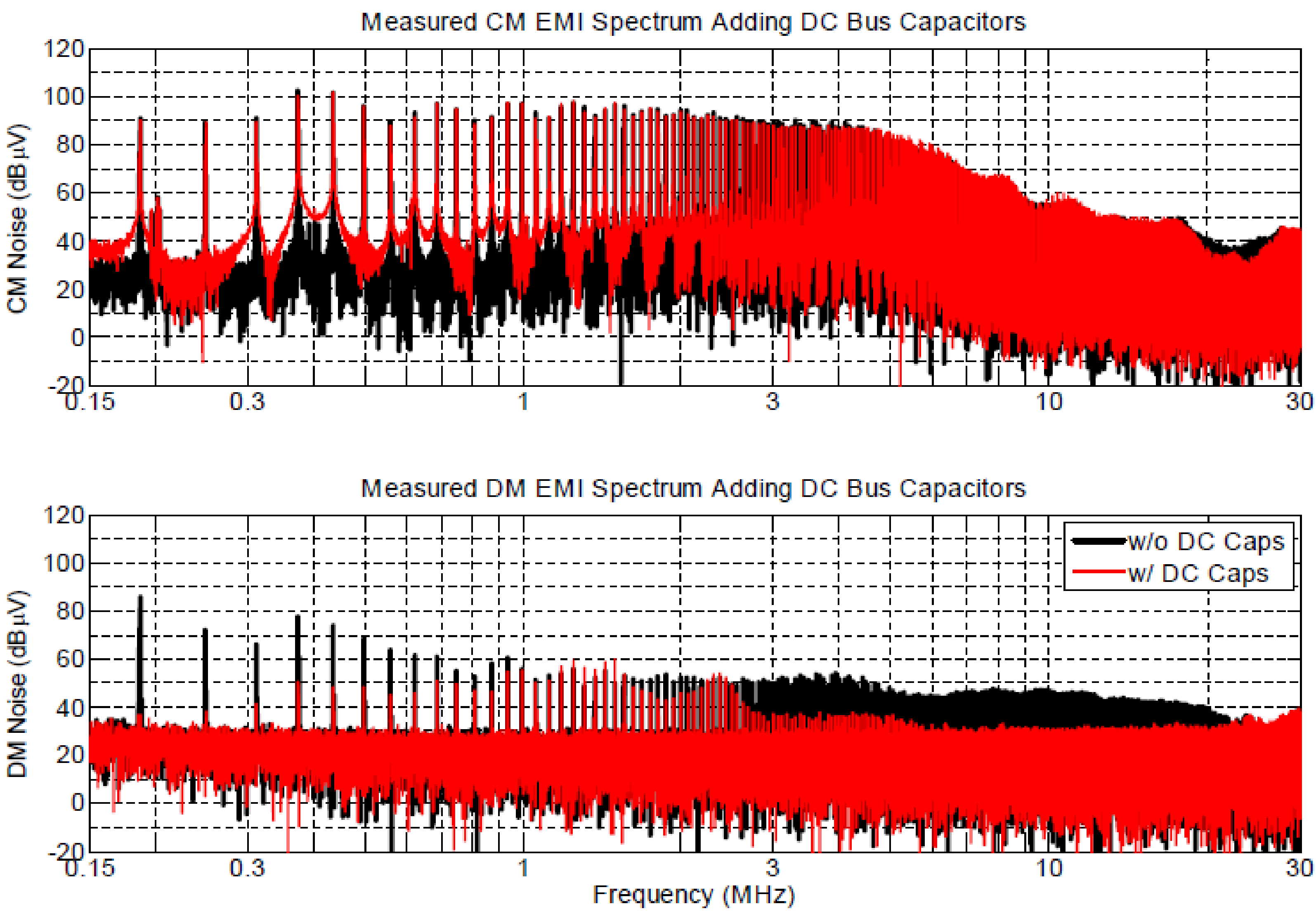


Proposed (Shielded)
Winding Cross-Section

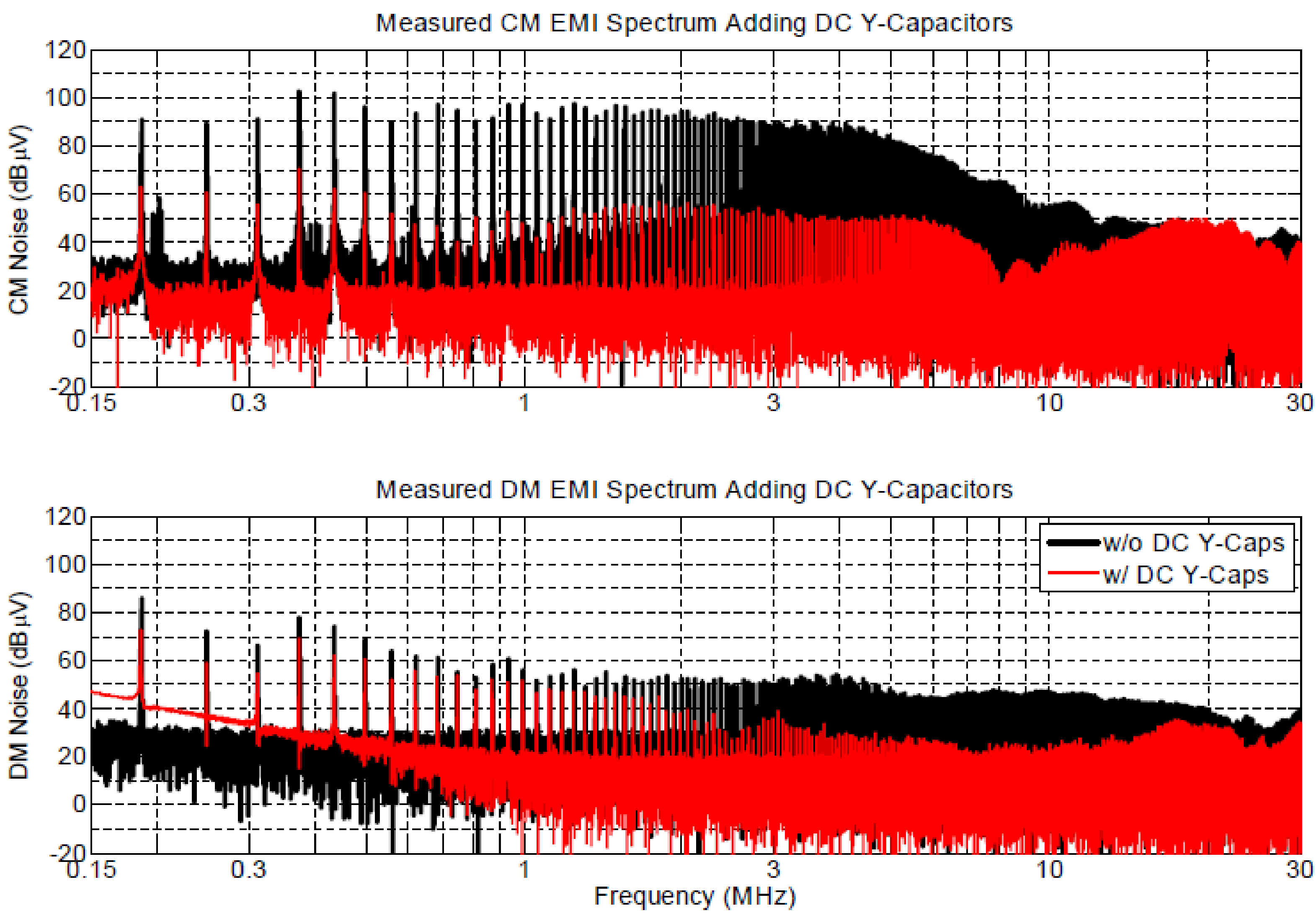
Simulation: Best SMPS xfmr Shielding technique ?



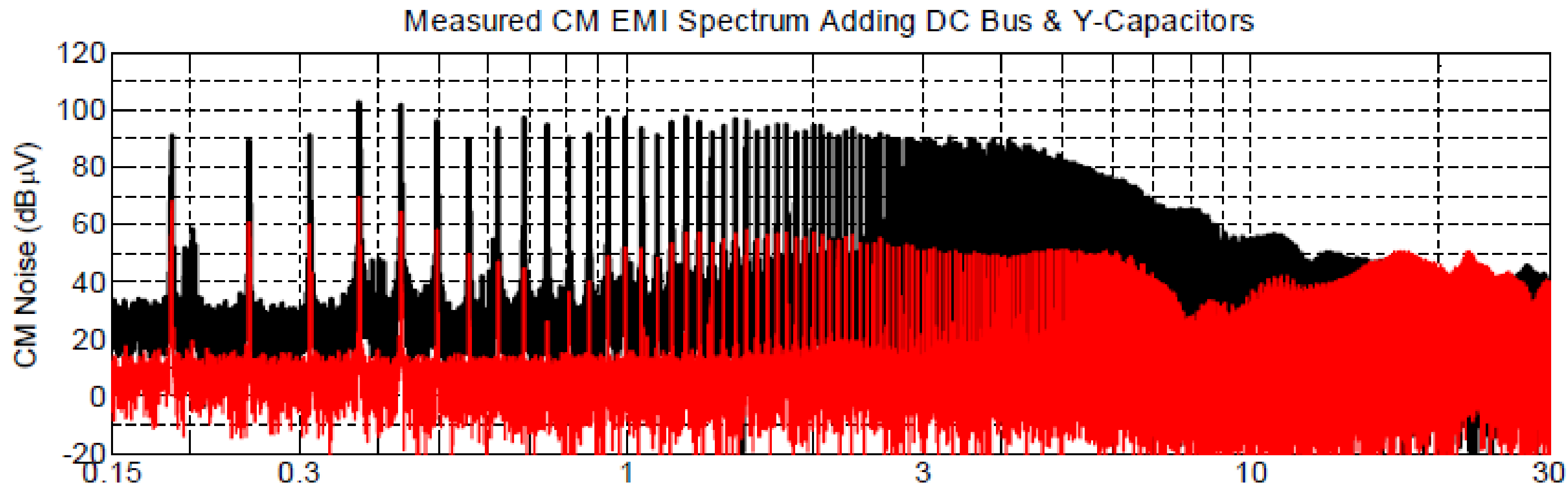
SMPS Model Benefits: DC bus Cap addition

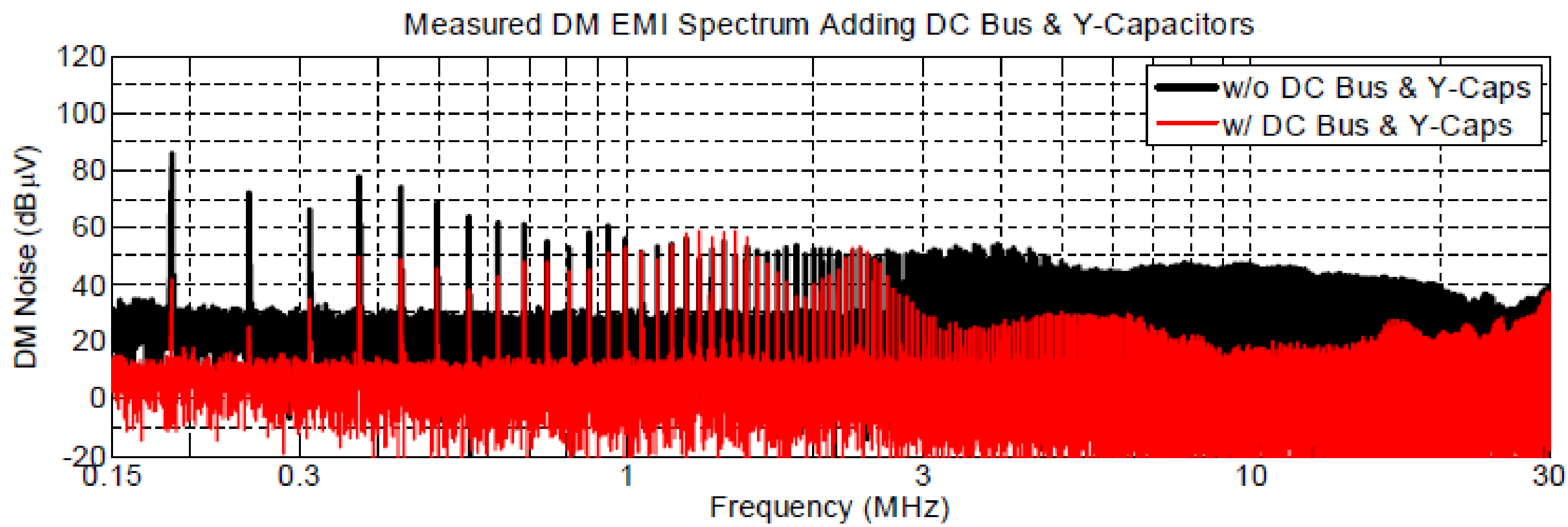


SMPS Model Benefits: Y type CM Cap addition

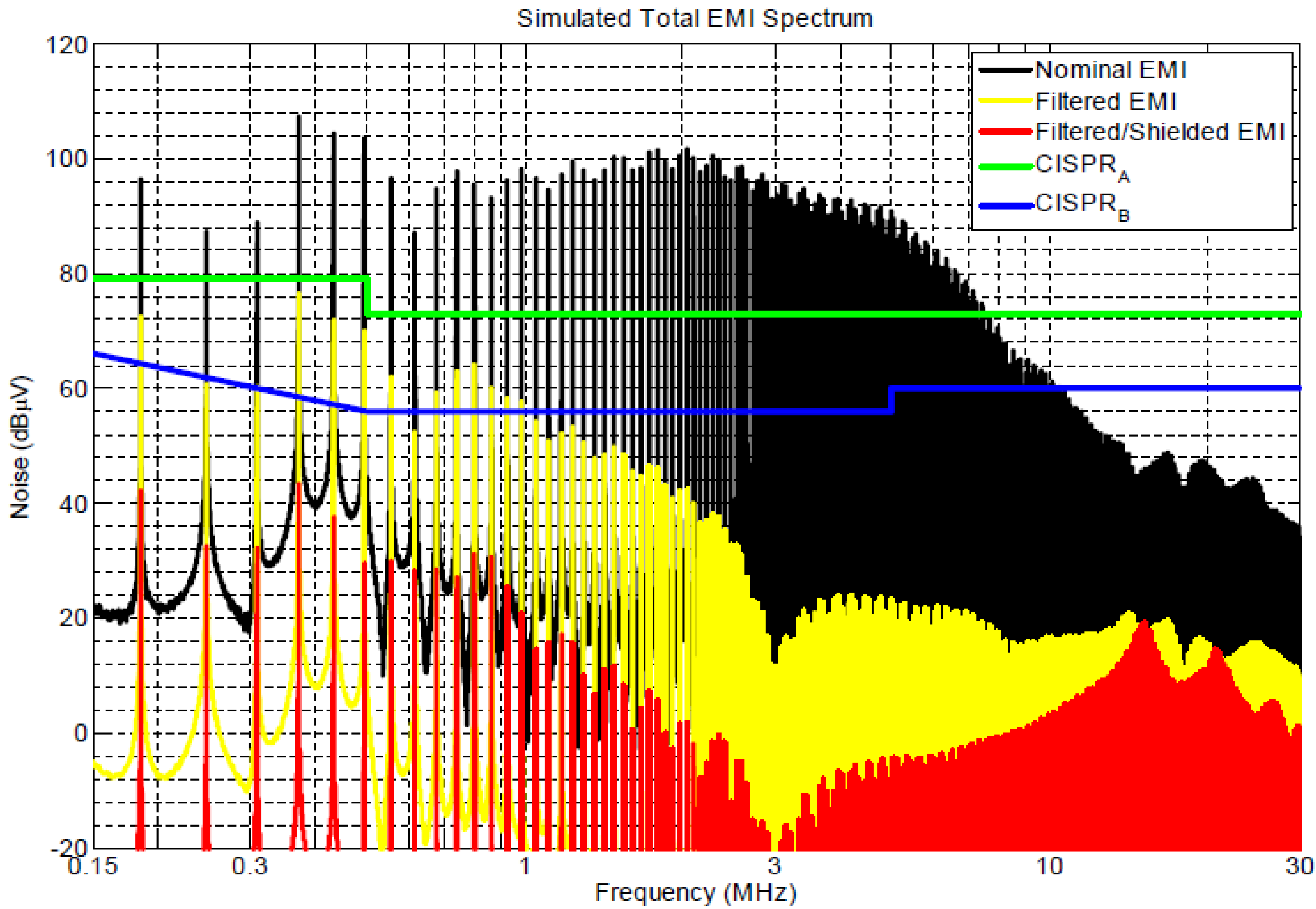


SMPS Model Benefits: DC Bus & Y type CM Cap Addition





SMPS Model Benefits: Potential EMI Reduction thru Addition



SMPS Model Conclusion:

- Modeling process that predicts EMI noise within 10 dB
  - Passive
  - Active
  - Interconnects
- Demonstrated the benefits of the modeling and characterized key parameters that affect the noise level
  - Primary loop is dominant
  - XFMR inter-winding capacitance
- Applied various attenuation techniques: simulated and measured
  - Filtering
  - Shielding

Radiated Emission Philosophy

by
G. L. Skibinski

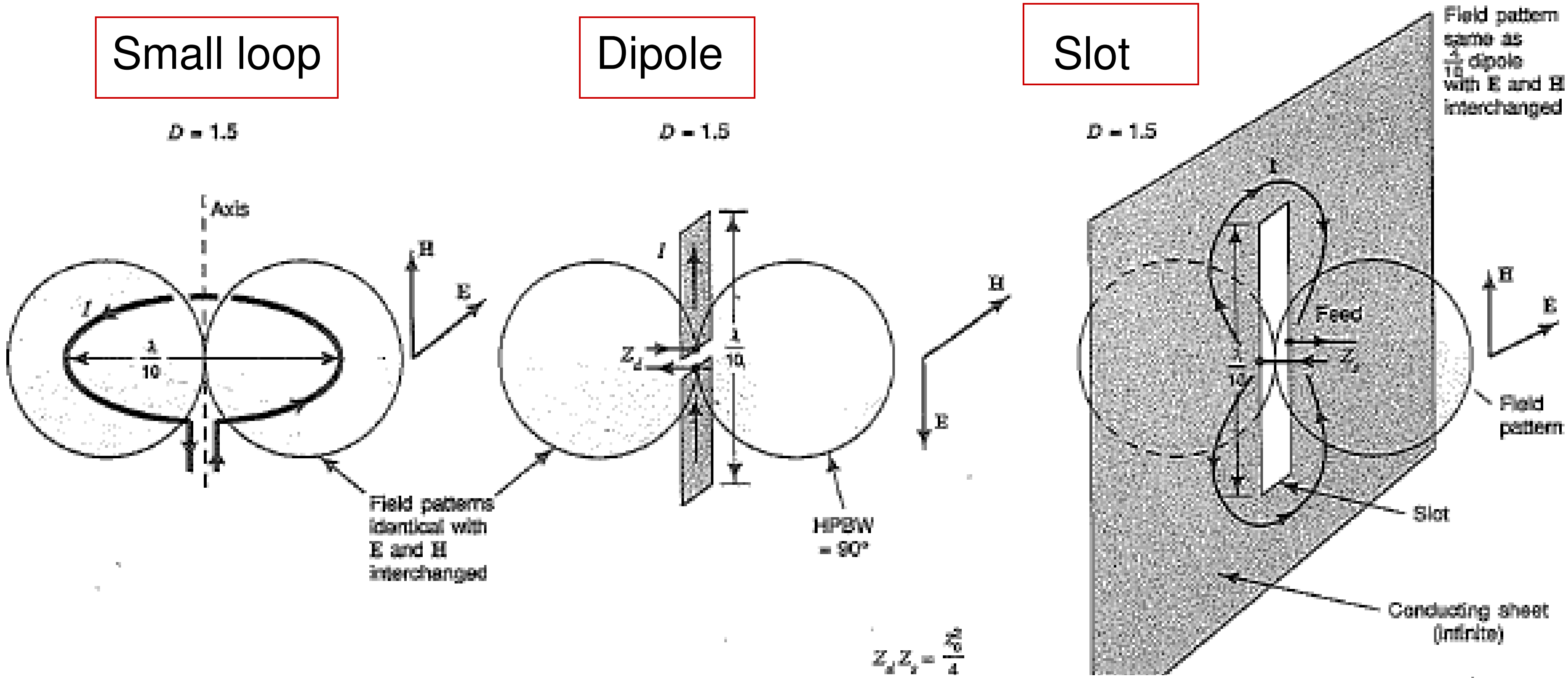
Basic Types of Radiated Emission Antenna

Basic Antenna

Small loop

Dipole

Slot



Electromagnetics,
J. Krause Mcgraw hill

Basic Types of Radiated Emission Antenna

Loop Antenna Radiation	Dipole antenna radiation
Differential Mode Loop Area Radiation Magnetic fields	Common mode Dipole Radiation Electric fields
$E = K_d f^2 A I_d$	$E = K_c f L I_c$
Less efficient ma required	Very Efficient uA required

Basic Law of LOOP AREA Radiated Emission Testing

Loop Area Law:

Reduction of Radiated Emissions [in dBuV / Mhz] is

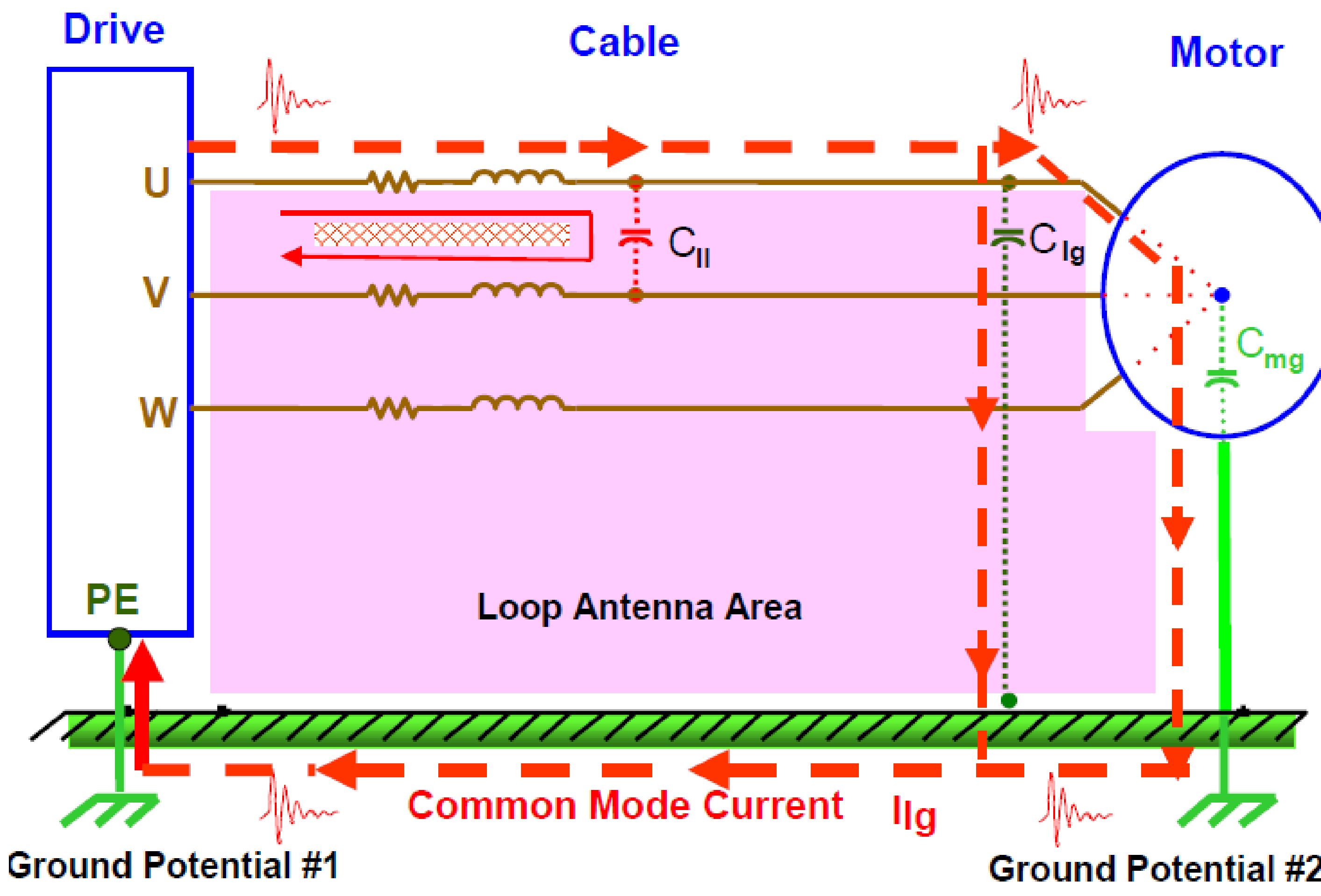
$$\alpha \quad \mathrm{LOG}\,[\,A_{new} / A_{old}\,]$$

for same Bus Voltage and Pulse risetimes

Solutions:

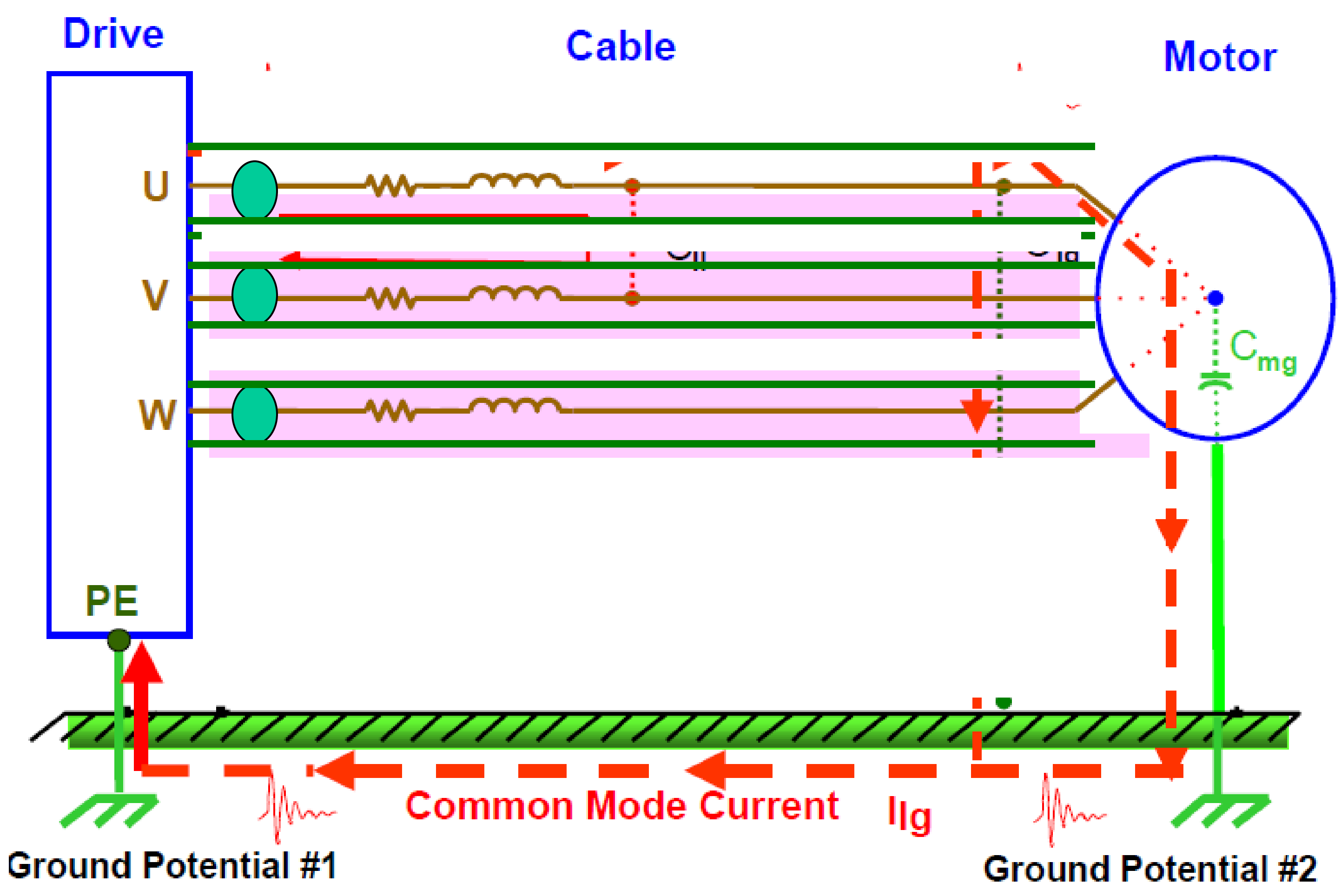
- **High Frequency Metallic Bonding**
- **High frequency Shielding**
- **Better ground plane layout**
- **Reduction of noise emitting area to External**

Basic Law of LOOP AREA Radiated Emission Testing



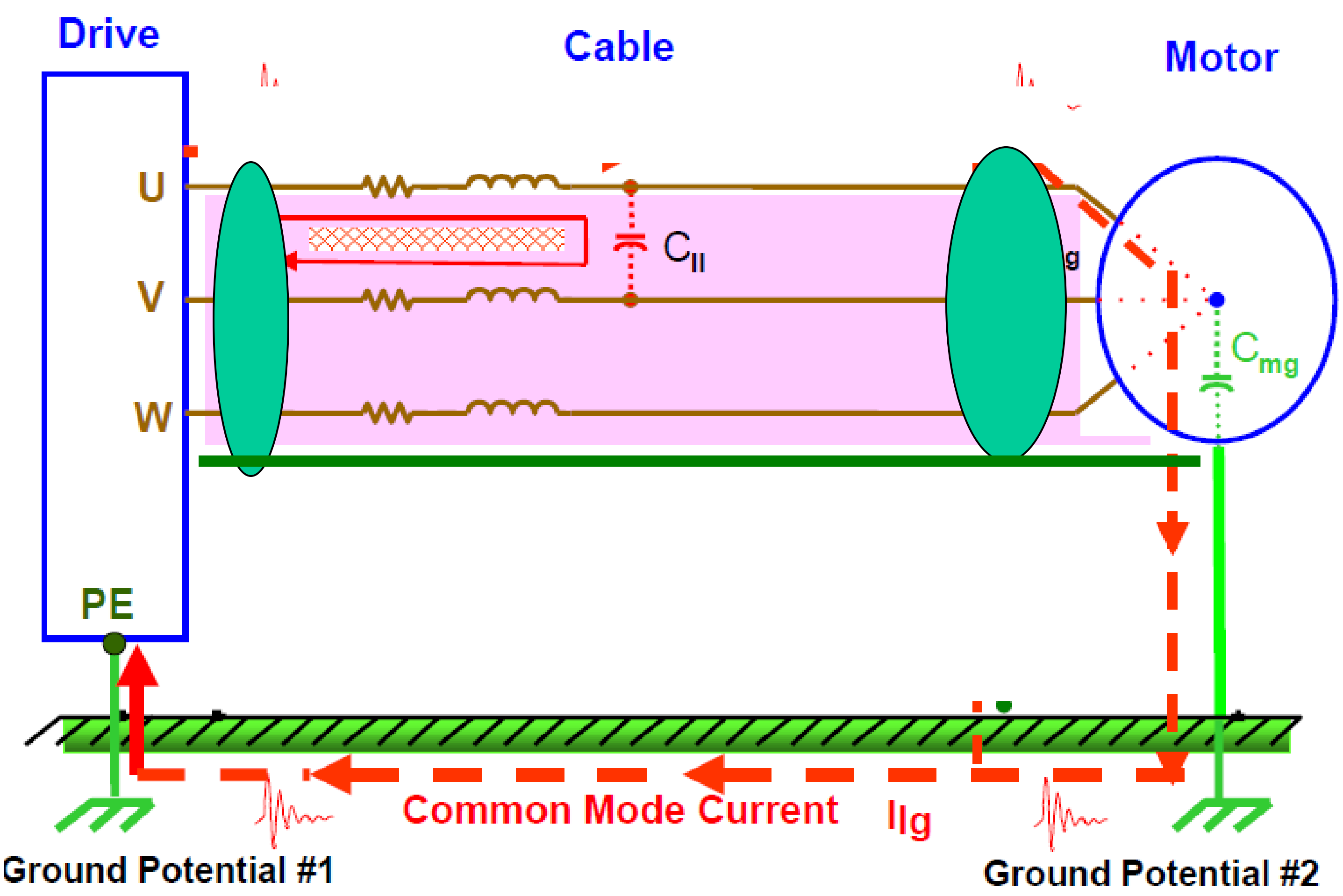
Why Shield Motor Wires ?? To reduce LOOP area if any high frequency in it

Basic Law of LOOP AREA Radiated Emission Testing



Why Shield Motor Wires ?? Individual Braid Tied at one end or both ??

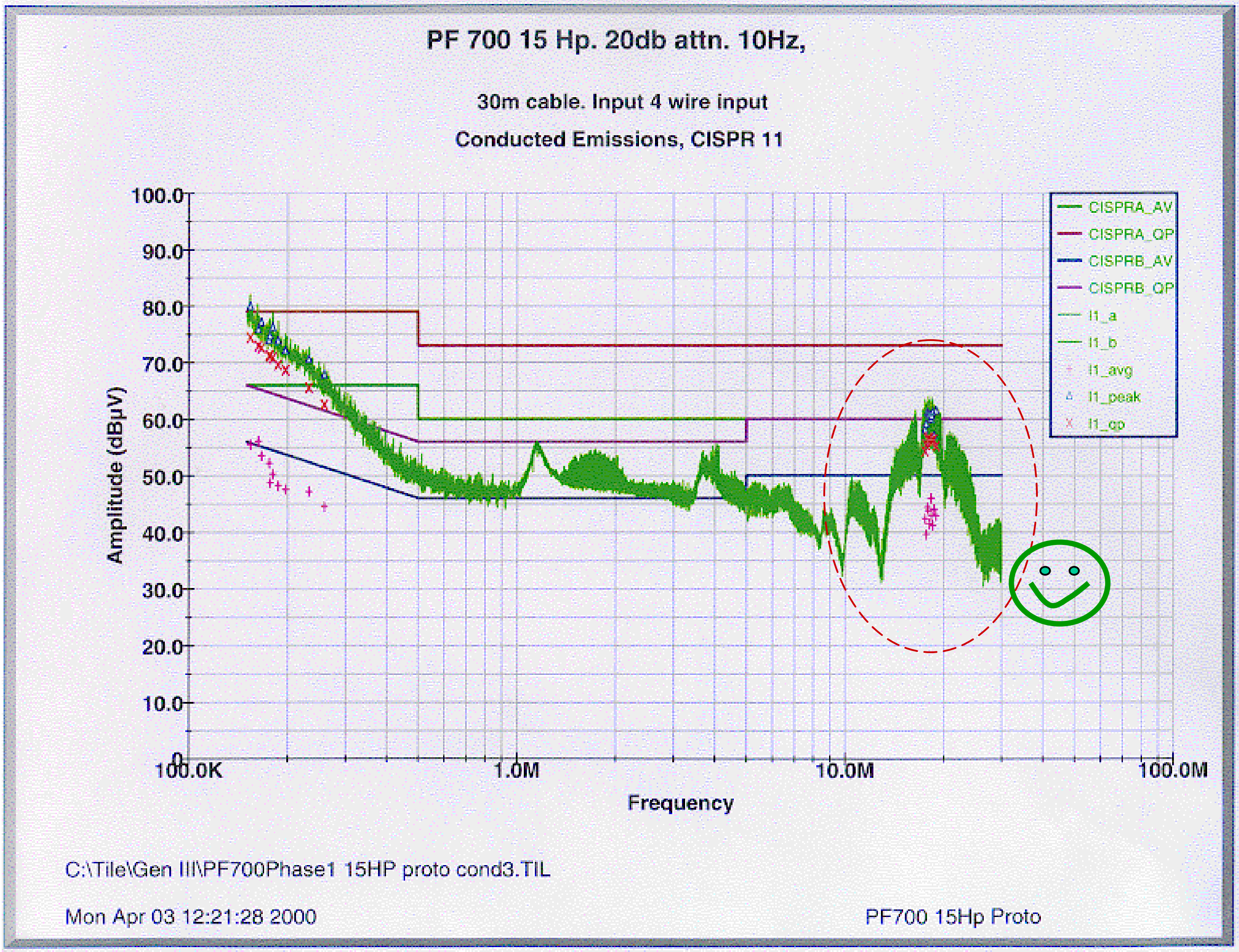
Basic Law of LOOP AREA Radiated Emission Testing



Why Shield Motor Wires ?? Overall Braid Tied at one end or both ??

Conducted Emissions lead to Radiated Emission

Typical VFD Conducted emissions with simple fixes 150 kHz to 30 MHz

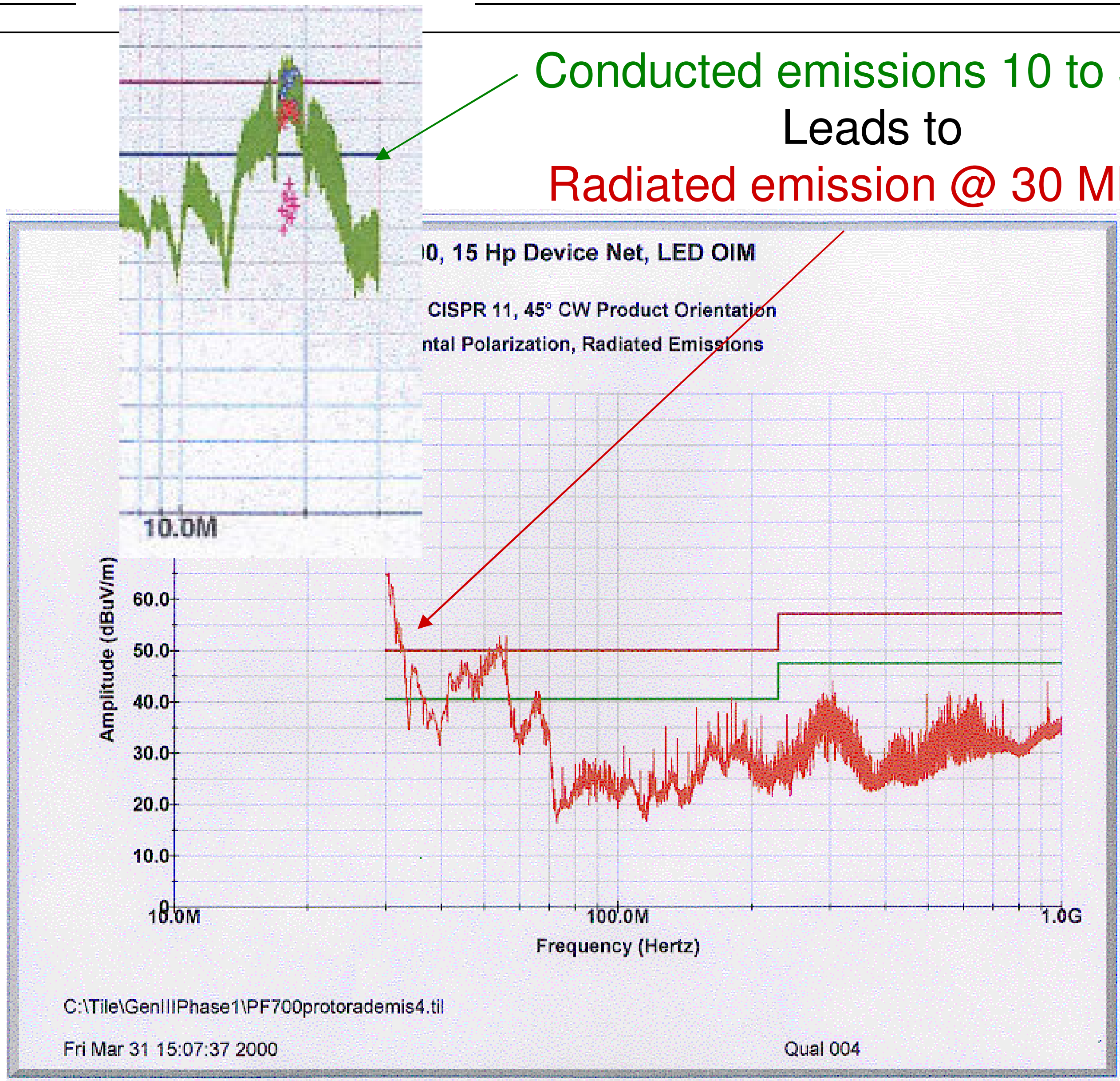


Conducted Emissions lead to Radiated Emission

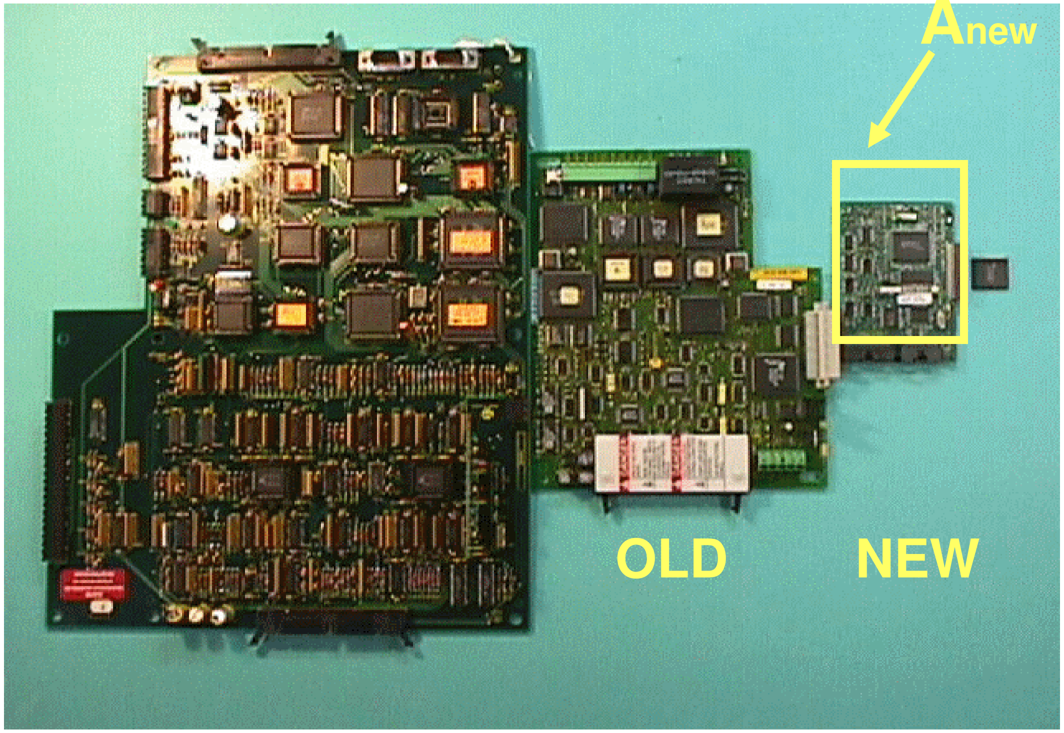
Conducted emissions 10 to 30 MHz (pass)

Leads to

Radiated emission @ 30 MHz (fail) !!!!



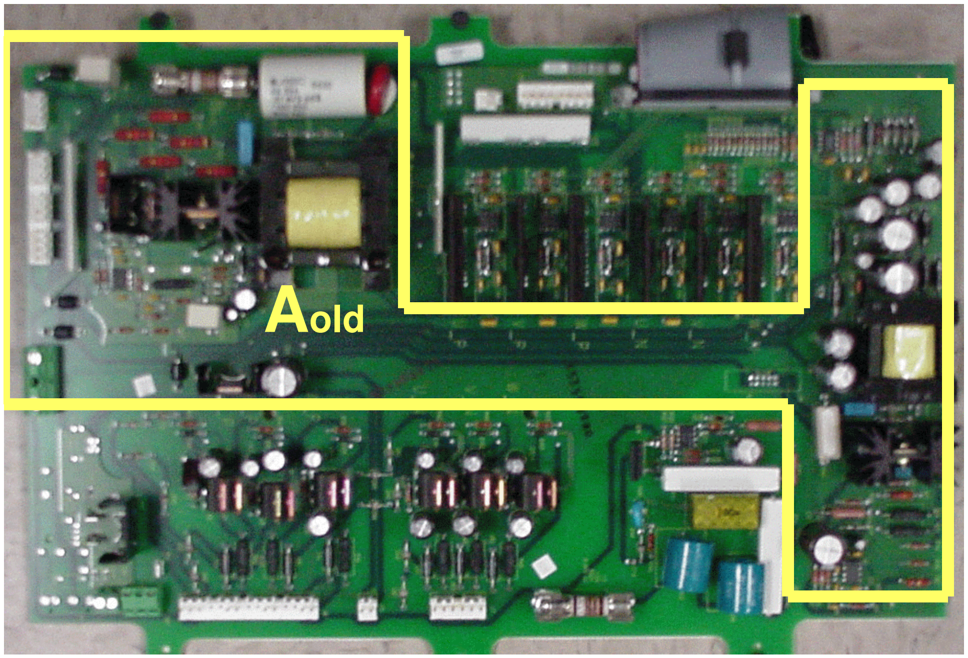
Control Board Radiated Emissions: OLD vs. NEW

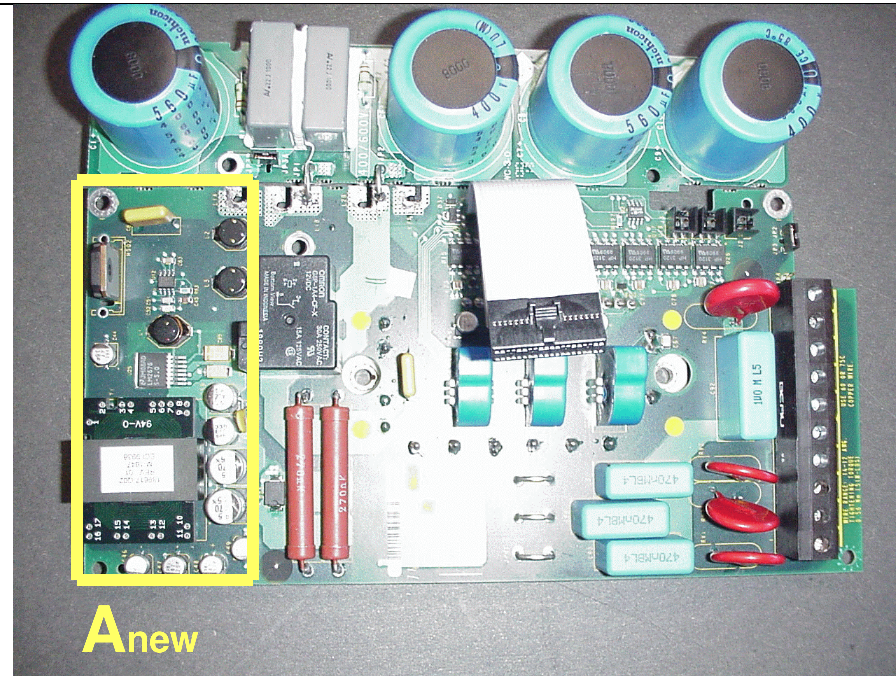


Radiated emission reduction [in dBuV / Mhz] is α LOG [A_{new} / A_{old}]

- **Conclusion: high speed clocks/data lines have less surface area exposed**
- **Conclusion: smaller board ⇨ substantial reduction in radiated emissions**

SMPS Radiated Emissions: OLD vs. NEW



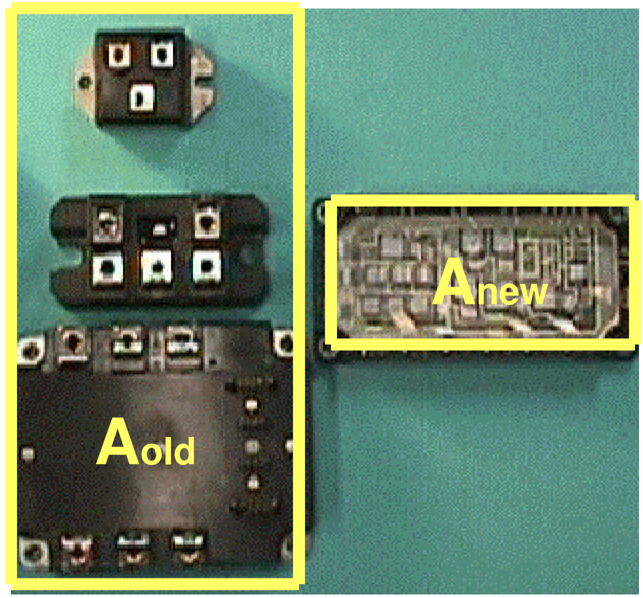


Radiated emission reduction [in dBuV/Mhz] is α LOG [A_{new} / A_{old}]

- **Conclusion OLD:**
  - **Layout connection from 100 kHz to 40 kHz SMPS's emits noise**
  - **Very high emissions at the DC bus connected 40 kHz FET heatsink with its multiple sharp points**

•**Conclusion: smaller board ➡ substantial radiated emission reduction lower SMPS frequency and slower FET risetime also helps, no heatsink**

Power Circuit Radiated Emissions: OLD vs. NEW



Rectifier Diodes, IGBT's, brake IGBT

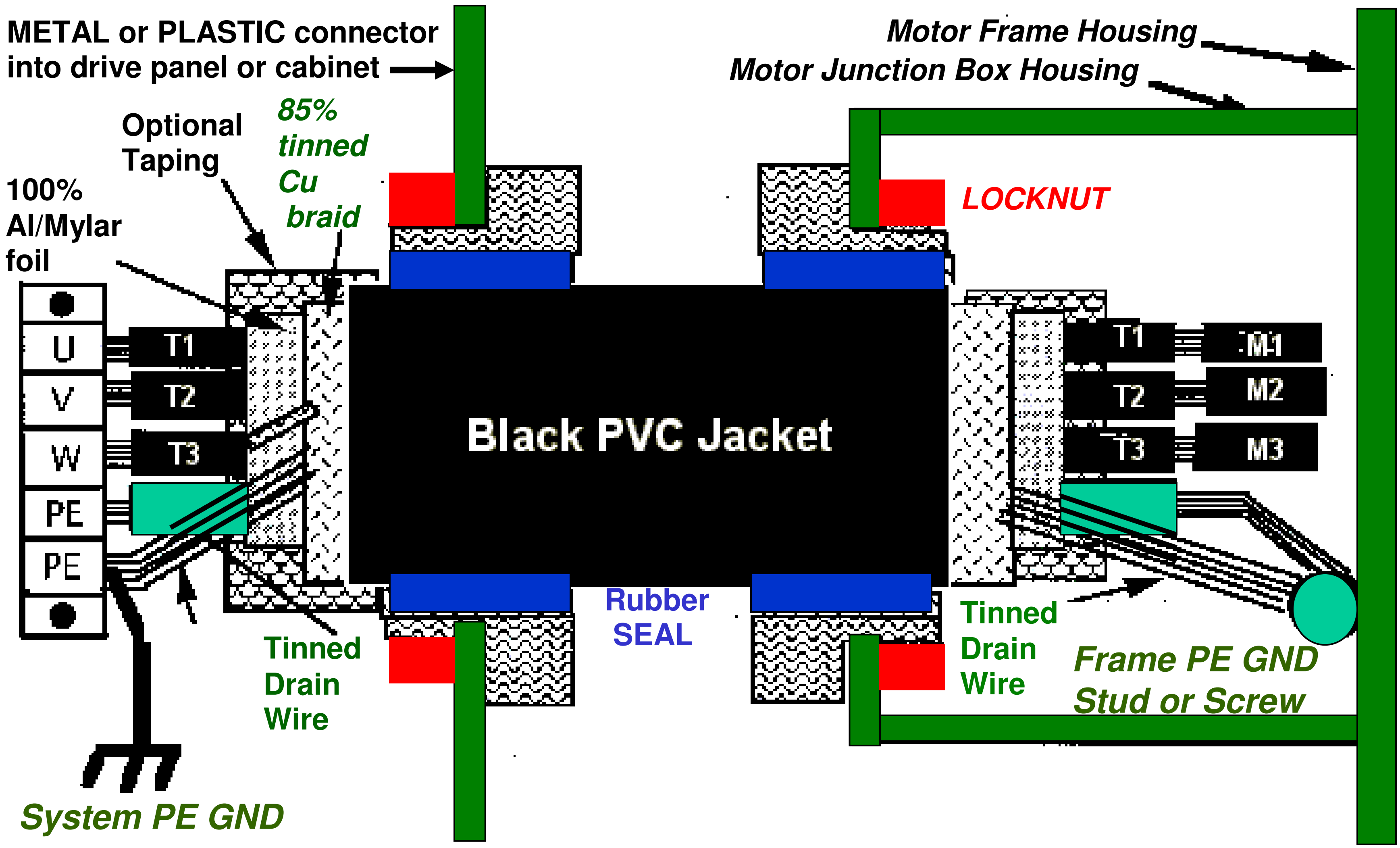
Radiated emission reduction [in dBuV/Mhz] is α LOG [A_{new} / A_{old}]

- **Conclusion:**
  - *** OLD drive had widely interspersed Inter-bus connection between Brake IGBT, Diode bridge & IGBT modules leading to large radiating surface area of PWM & SMPS noise**
  - *** NEW drive has tightly integrated power connections & board layout**
- **Conclusion: Integrated module ⇨ substantial reduction in radiated noise**

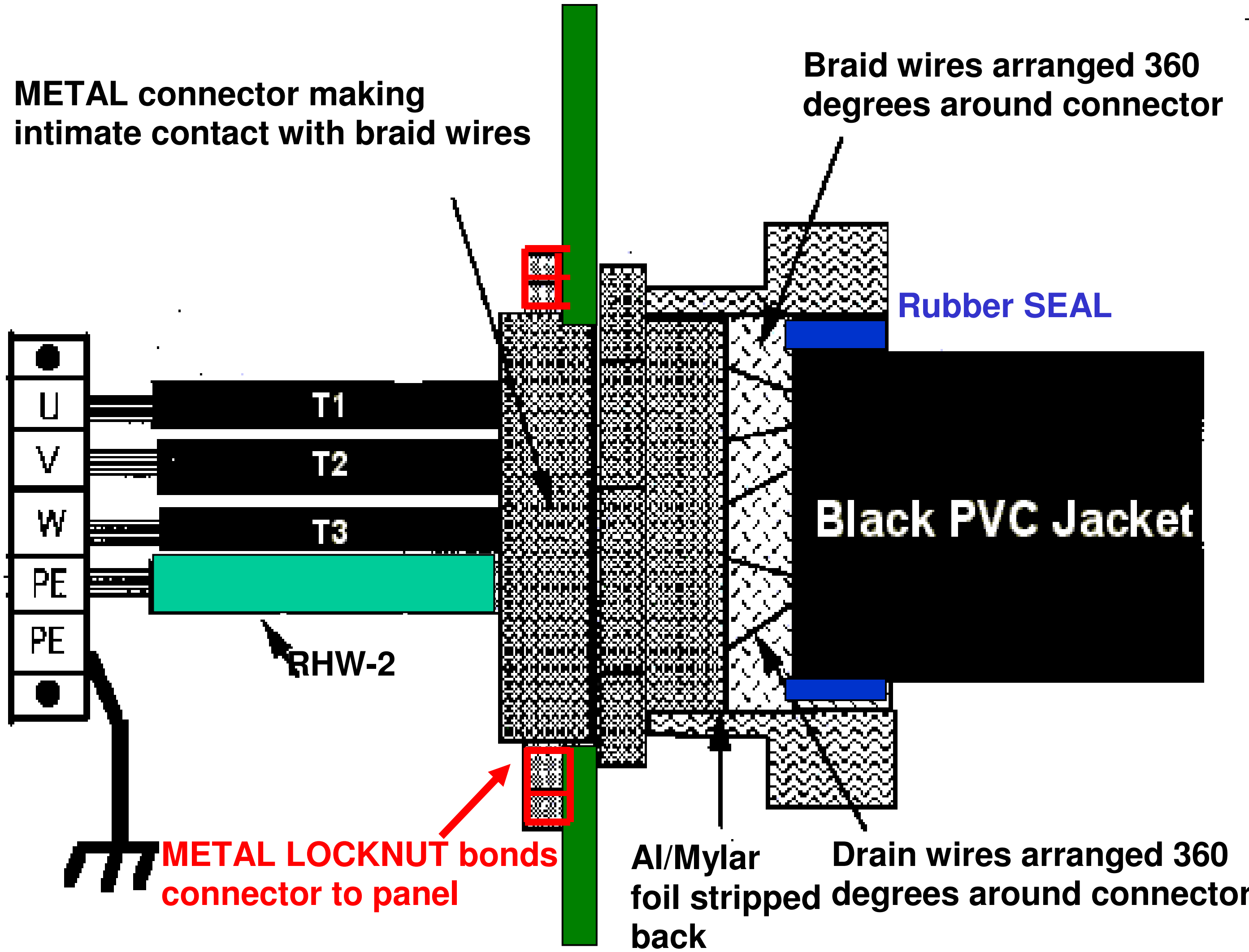
Power Circuit Radiated Emissions: Shield Connections

- Metallic end plate bonded to Chassis makes a 10 dBuV/Mhz improvement
- allows EMI type 360 degree braid contact connector fitting

Cable Connectors for Industrial use

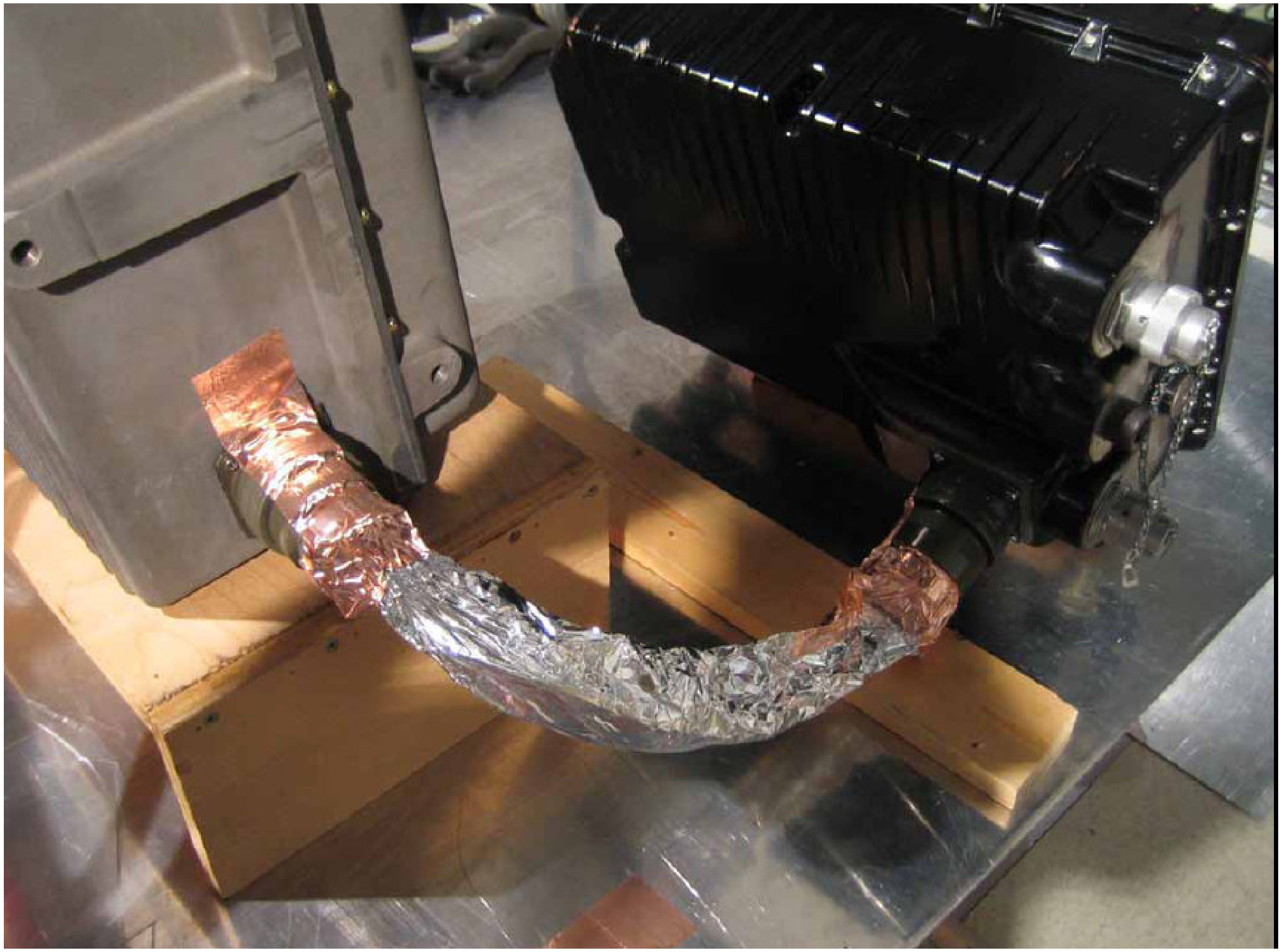


Cable Connectors for Full CE EMI Compliance



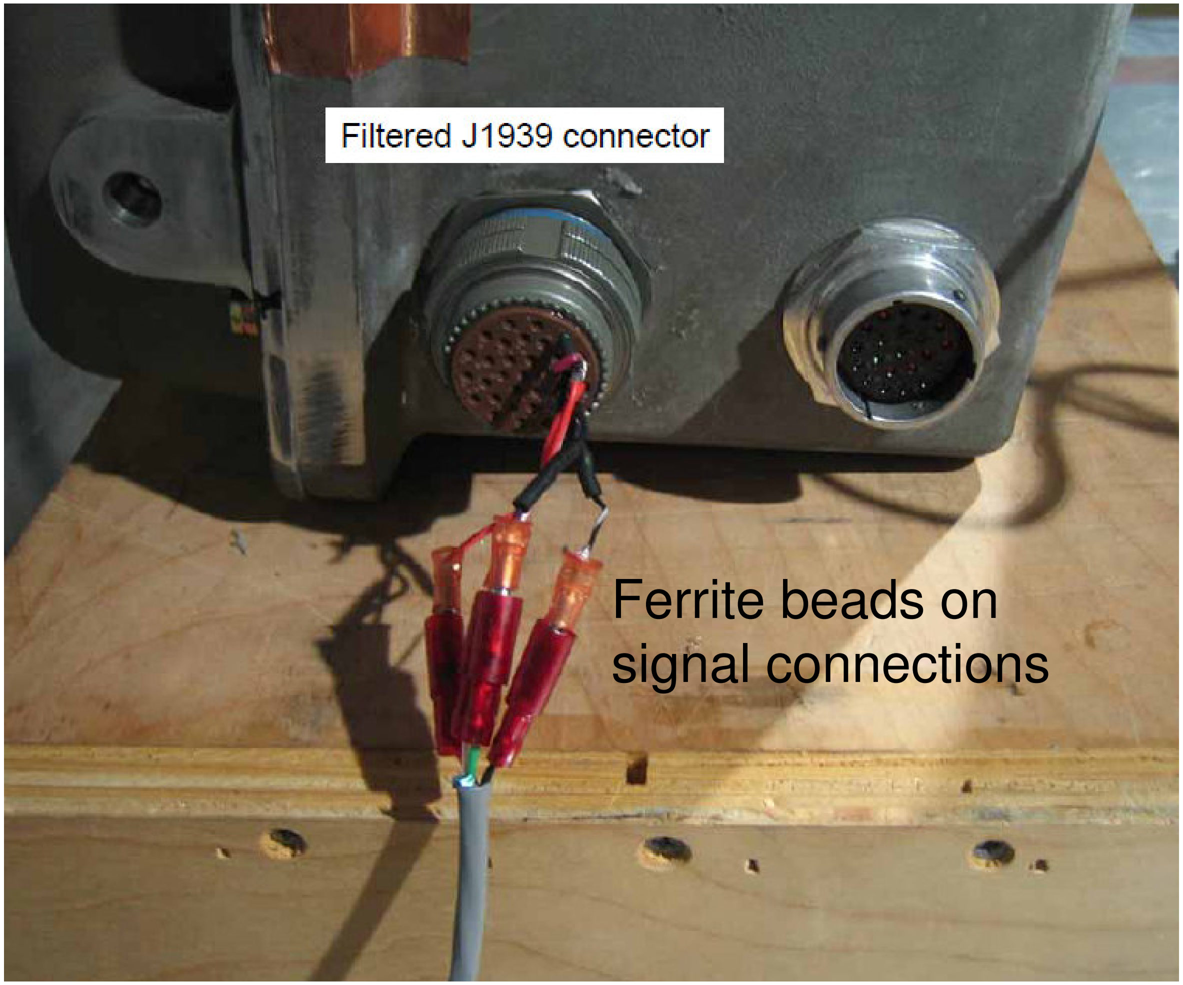
- 360 degree metal connector makes ~ 10 dB difference in EMI > 10 MHZ
- Remember leakage area makes radiated emissions
- Emissions in dB uV /m so any large Milli volt drop can make connector antenna

Cable Connectors for Full CE EMI Compliance



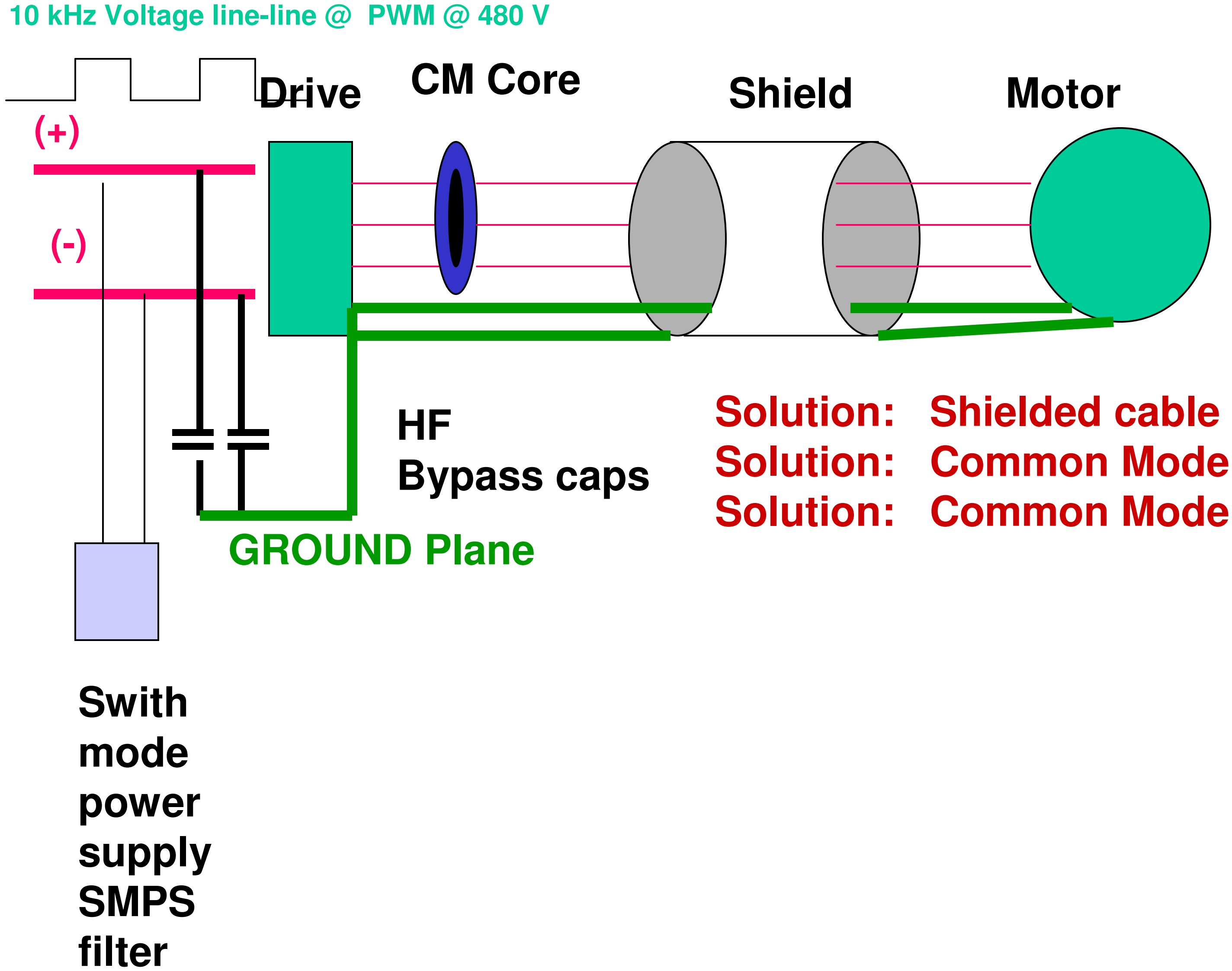
Connector leakage problems always end up this way !!!

Cable Connectors for Full CE EMI Compliance



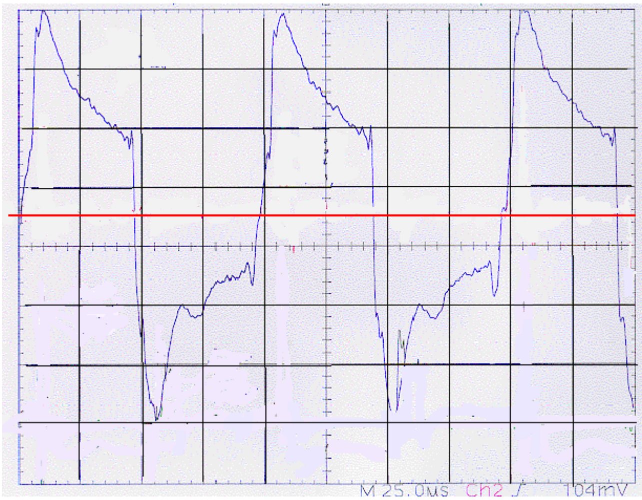
Connector leakage problems always end up this way !!!

Simple EMI System Fixes to Reduce Radiated Emissions

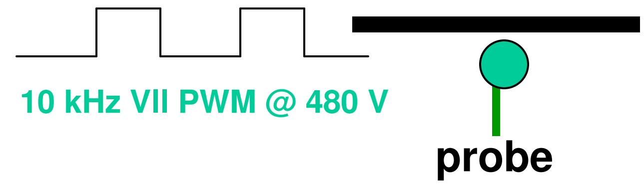


Solution: Shielded cable
Solution: Common Mode Output Core
Solution: Common Mode Caps on DC bus

Qualitative Radiated Emission Test with Probe On PWM Wire



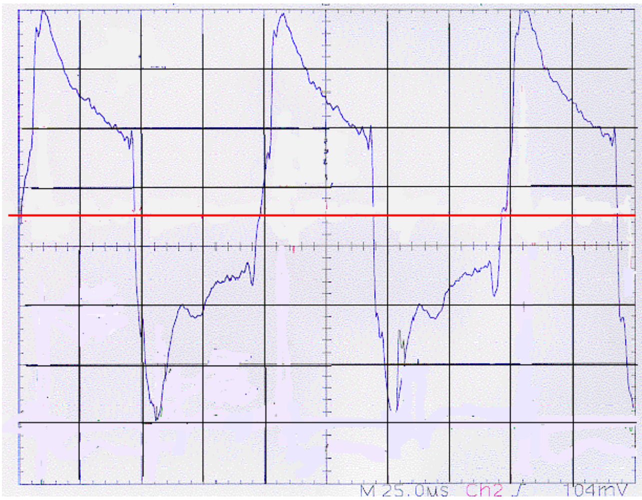
Input Conditions



No Solution

1.6 Vpk Large Area coupled to probe

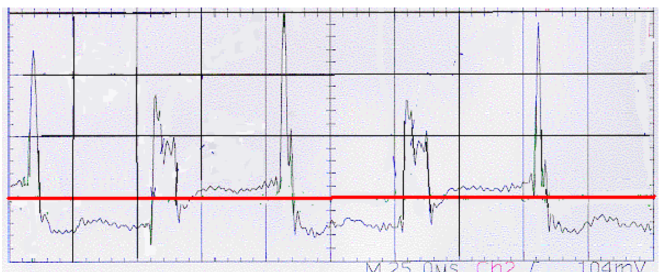
Qualitative Radiated Emission Test with Probe On PWM Wire



Input Conditions

No Solution

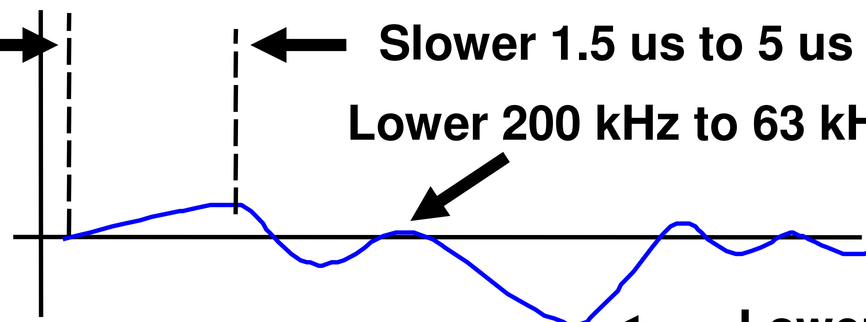
1.6 Vpk   Large Area coupled to probe



CM Core & No Shield

1.2 Vpk   Lower Area coupled

I_line – ground Current With Common Mode Chokes

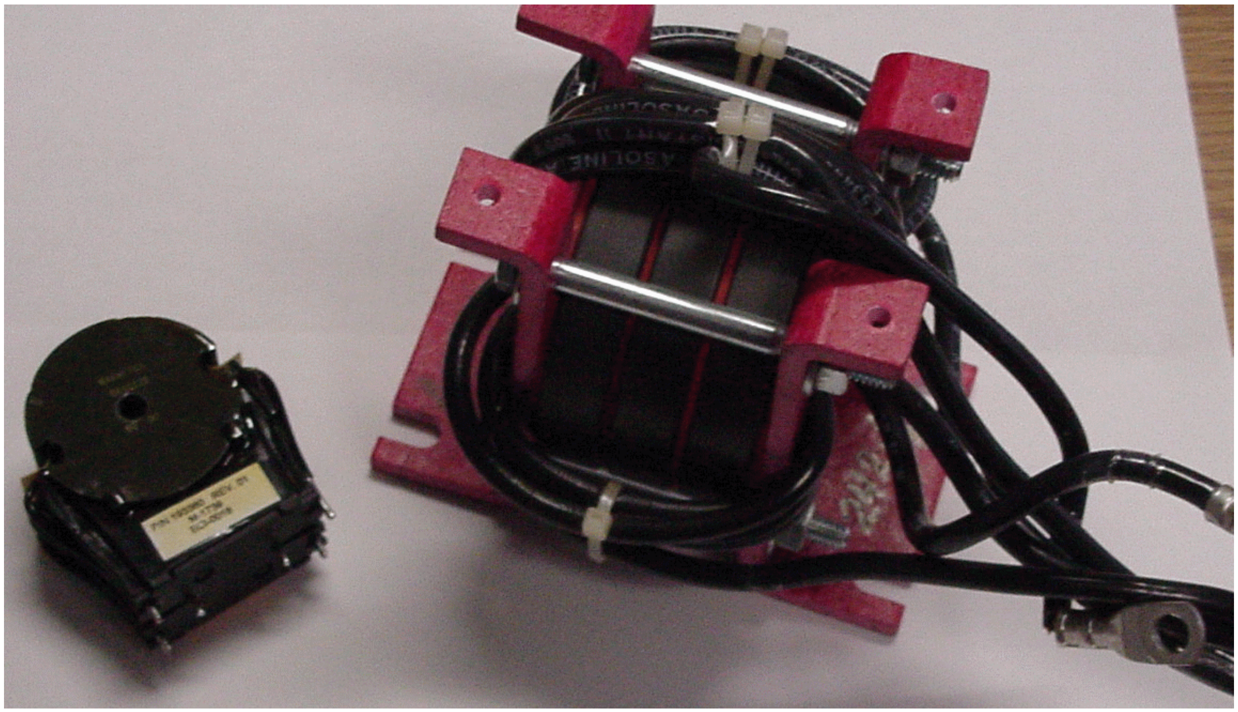


Slower 1.5 us to 5 us risetime

Lower 200 kHz to 63 kHz Oscillation

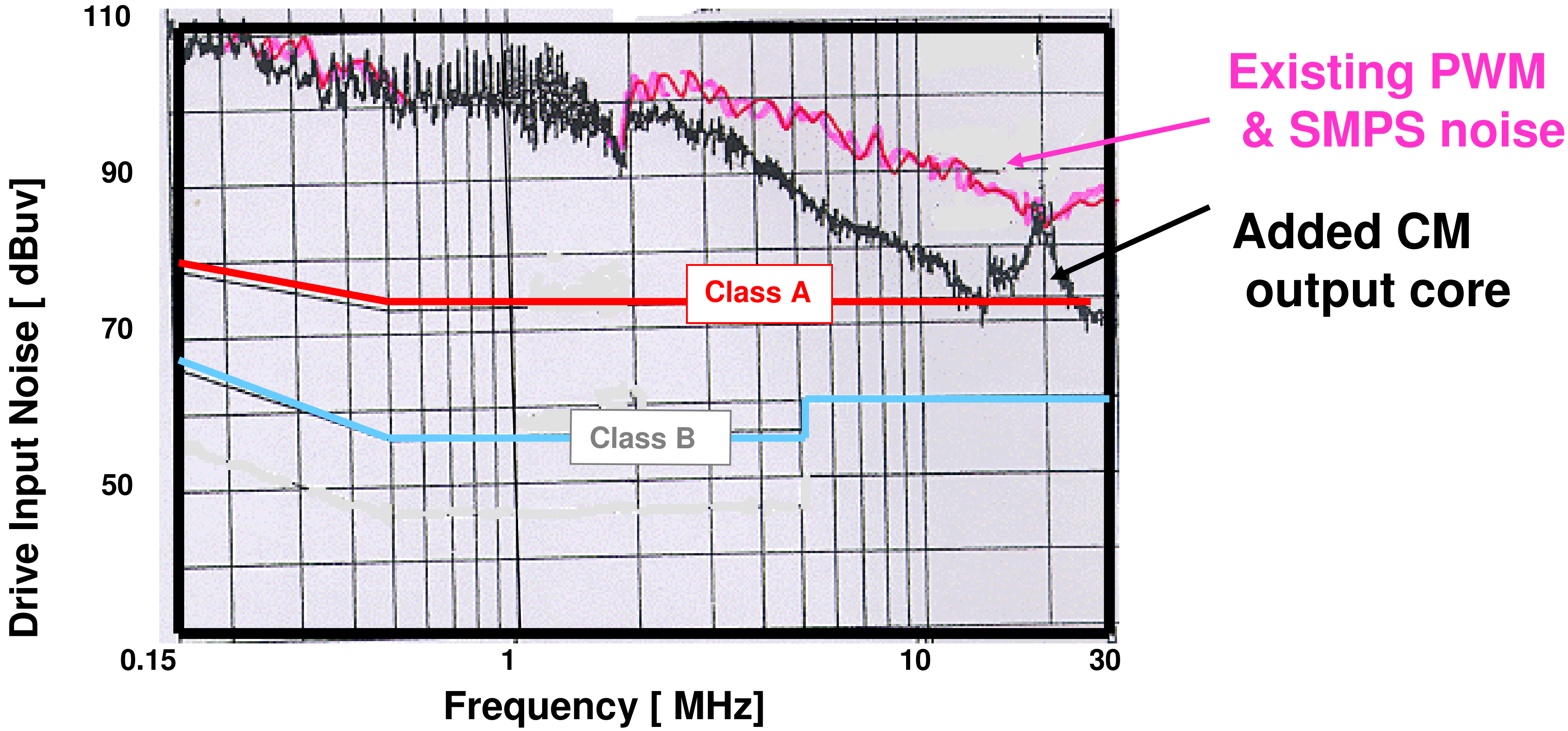
Lower 1/3 Ipeak

Qualitative Radiated Emission Test with Probe On PWM Wire



- Common mode core 3 phase output 5 rurns thru 3 ferrite cores ~125 uh
- built-in Common mode pot core contains radiated leakage flux vs. old style
- substantial smaller size

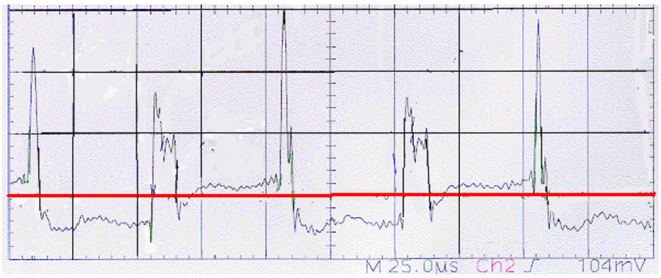
Qualitative Radiated Emission Test with Probe On PWM Wire



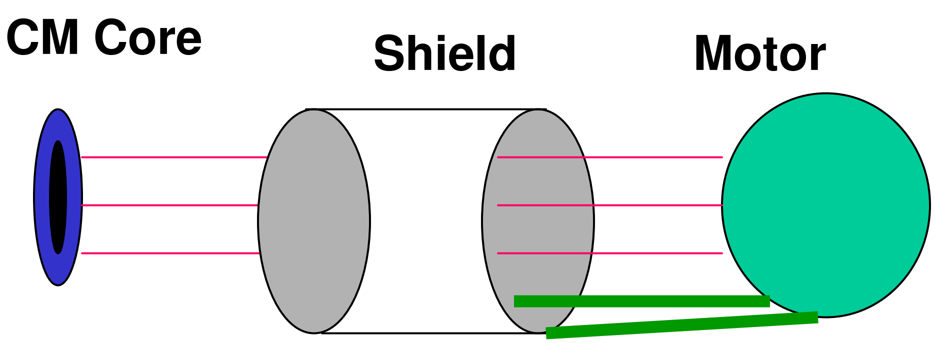
- Common Mode Core attenuates IGBT risetime component 1 MHz -10 MHz region, solves most non working system problems
- However, by itself it cannot meet CE "Class A" 80 dBuV requirement

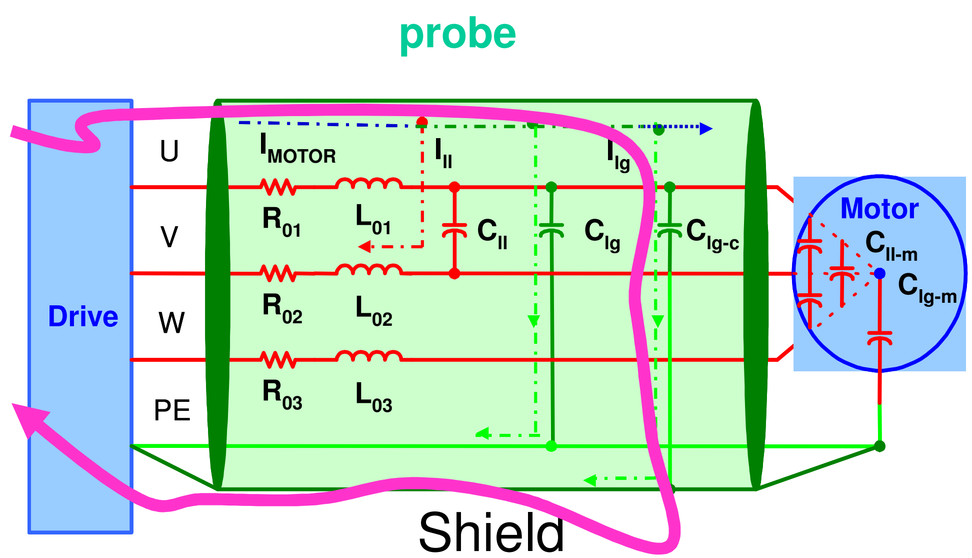
Why ? It has no cap in LC to work with: only cable motor parasitic caps

Qualitative Radiated Emission Test with Probe On PWM Wire



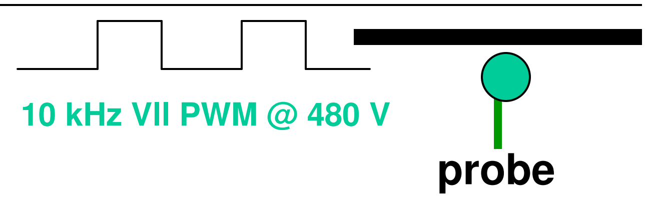
CM Core & No Shield 1.2 Vpk Lower Area coupled



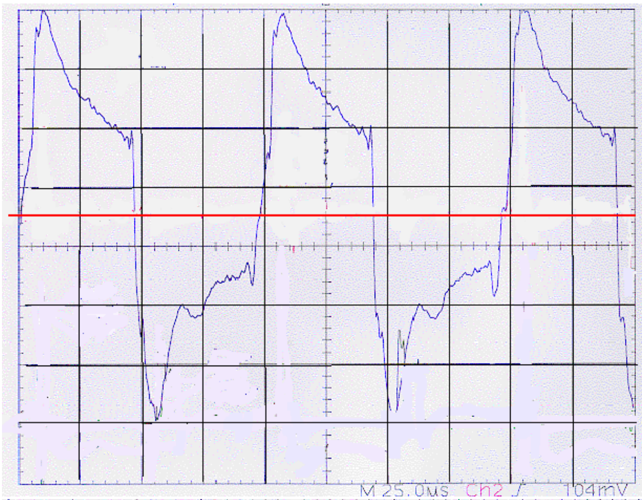


Common mode Inductance to ground plane of single core ferrite not high but works with stray cable & motor capacitance to form L-C filter

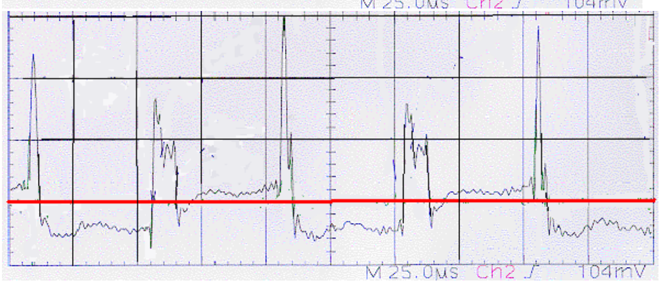
Qualitative Radiated Emission Test with Probe On PWM Wire



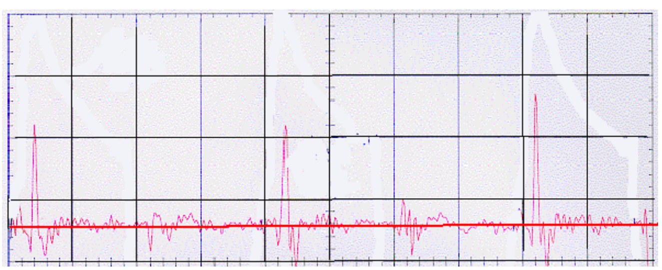
Input Conditions



No Solution — 1.6 Vpk — Large Area coupled to probe

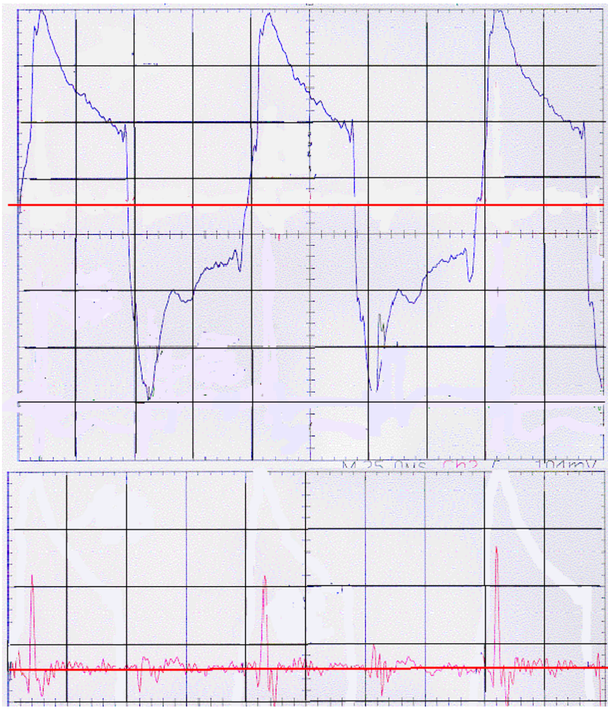


CM Core & No Shield — 1.2 Vpk — Lower Area coupled

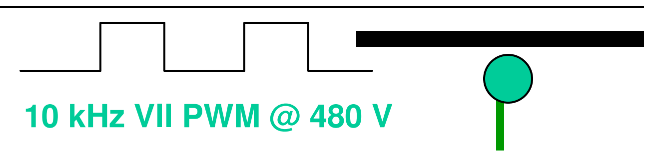


No CM Core & Shield — 0.8 Vpk — Spike Area coupled

Qualitative Radiated Emission Test with Probe On PWM Wire



Input Conditions



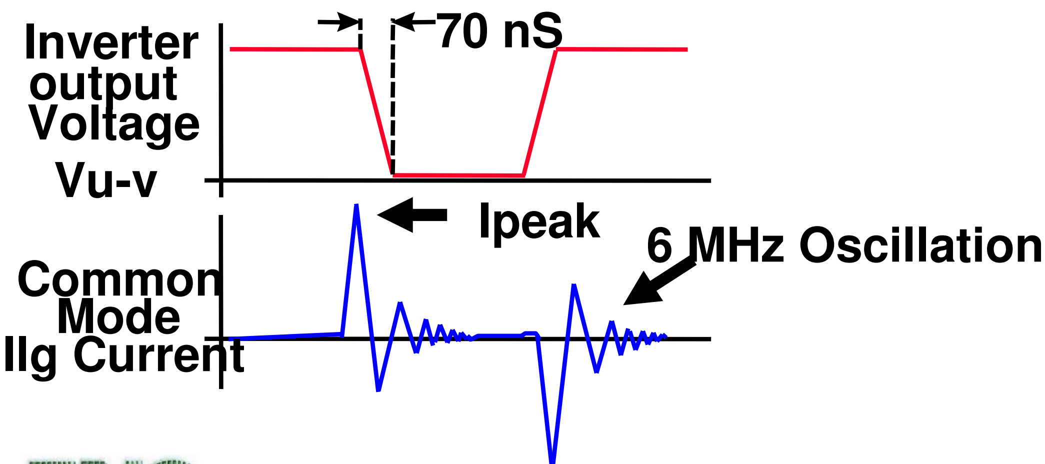
10 kHz VII PWM @ 480 V

No Solution

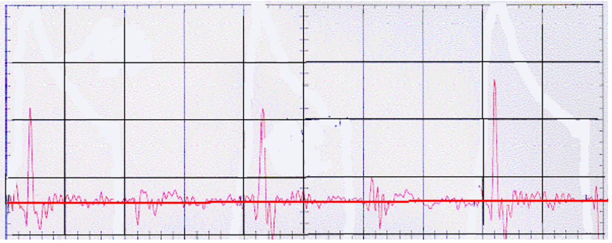
1.6 Vpk Large Area coupled to probe

No CM Core only Shield

0.8 Vpk Only Spike Area coupled

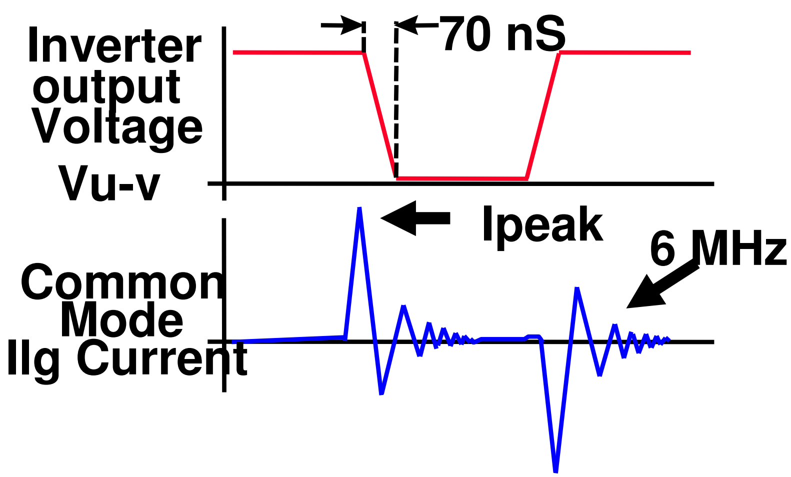


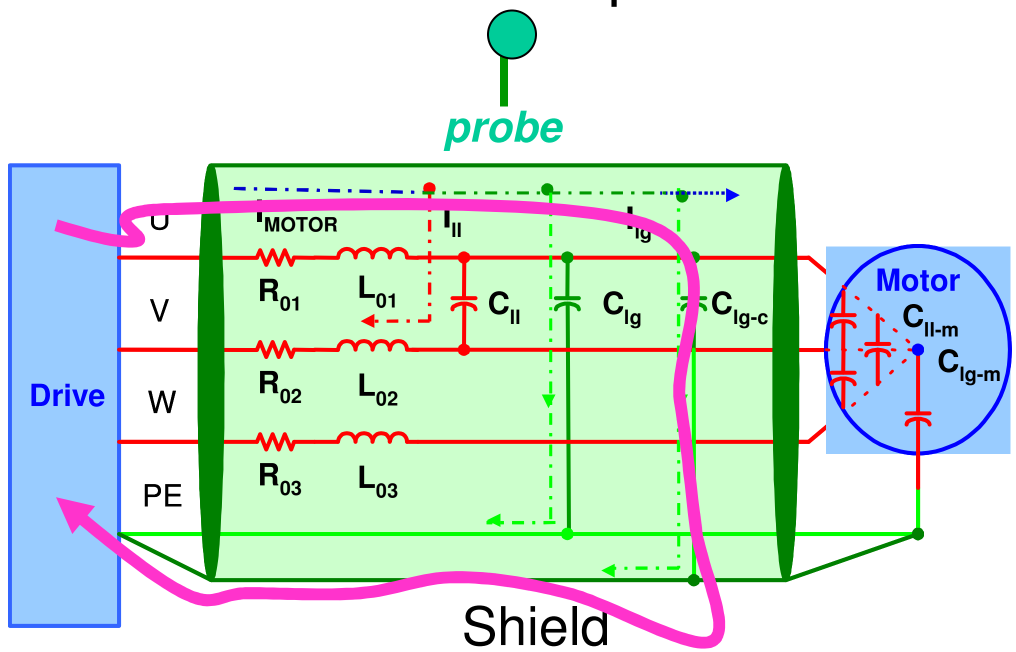
Qualitative Radiated Emission Test with Probe On PWM Wire



No CM Core only Shield

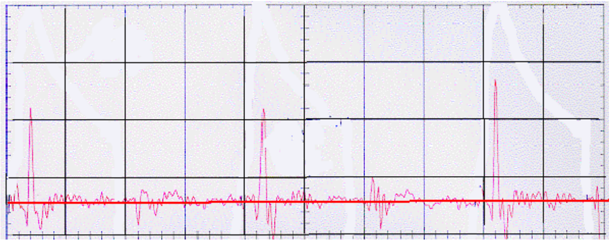
0.8 Vpk coupled **Spike Area**



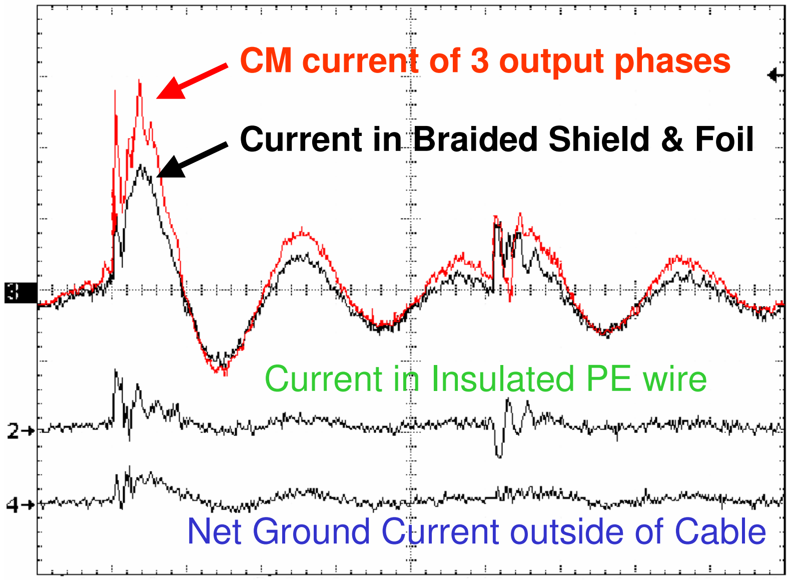


Ring frequency ~ cable length Short cable rings 1-6 MHz
Want low high frequency resistance of shield to not develop voltage
Investigate transfer impedance to shield for shield effectiveness

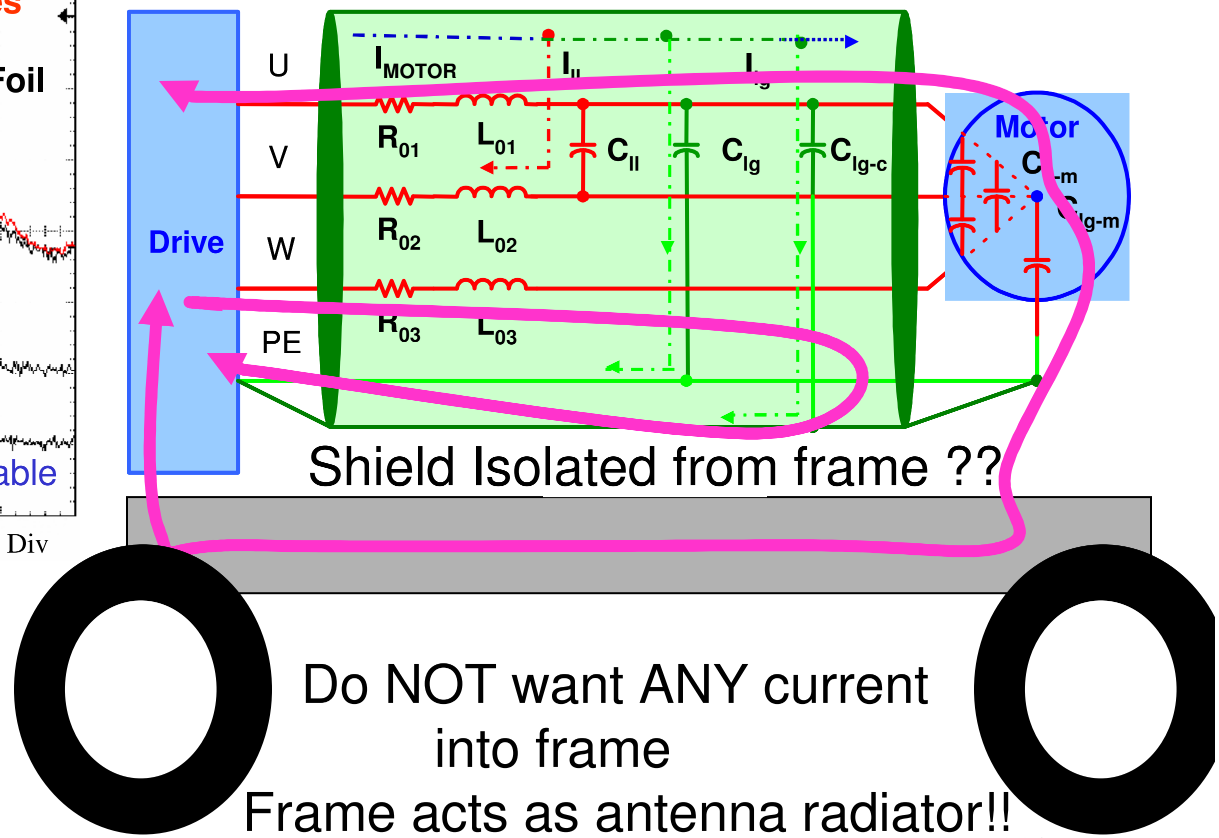
Qualitative Radiated Emission Test with Probe On PWM Wire



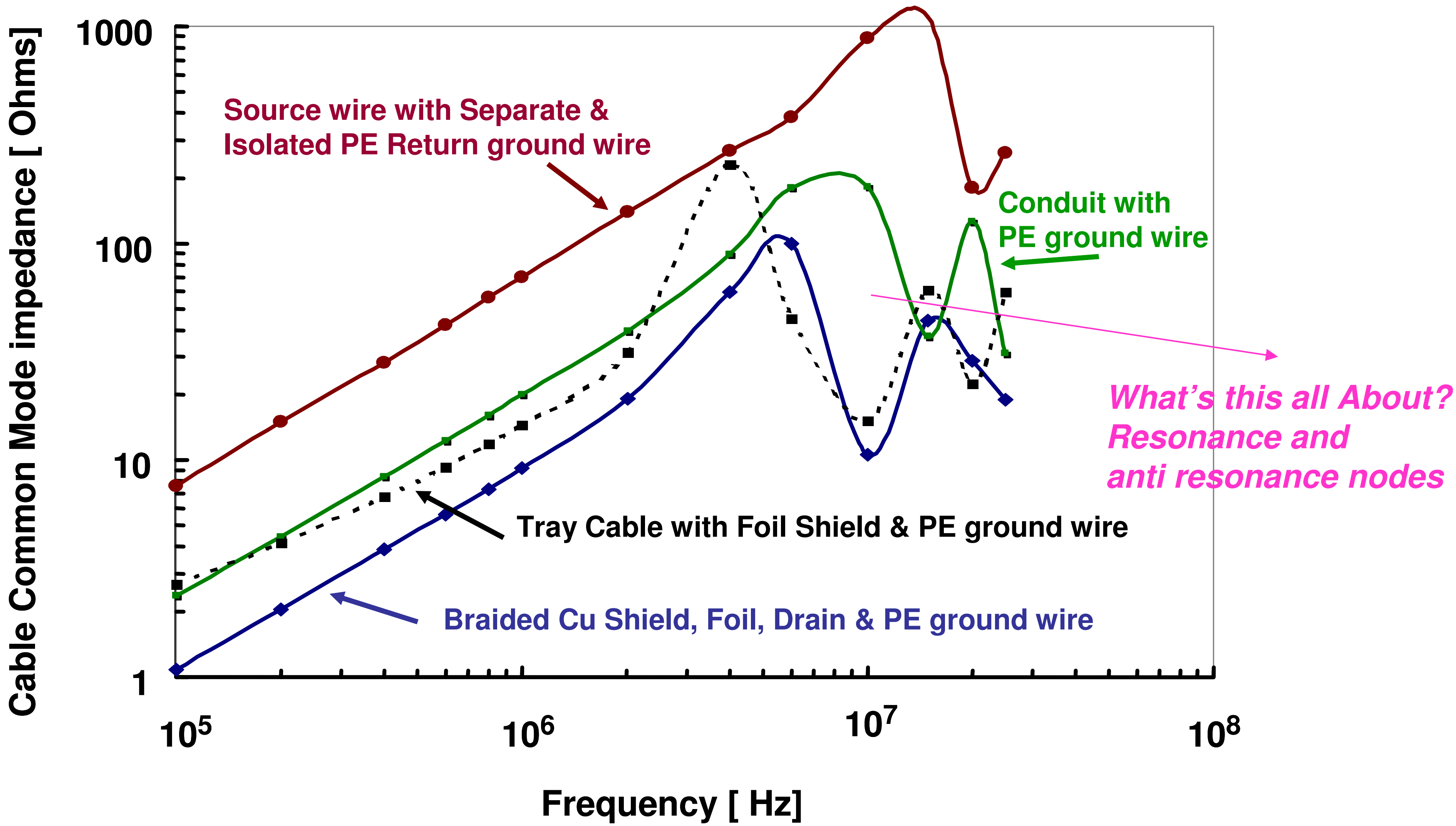
No CM Core only Shield **0.8 Vpk coupled** **Spike Area**



All traces: 2 Amps / Div 10 microseconds / Div



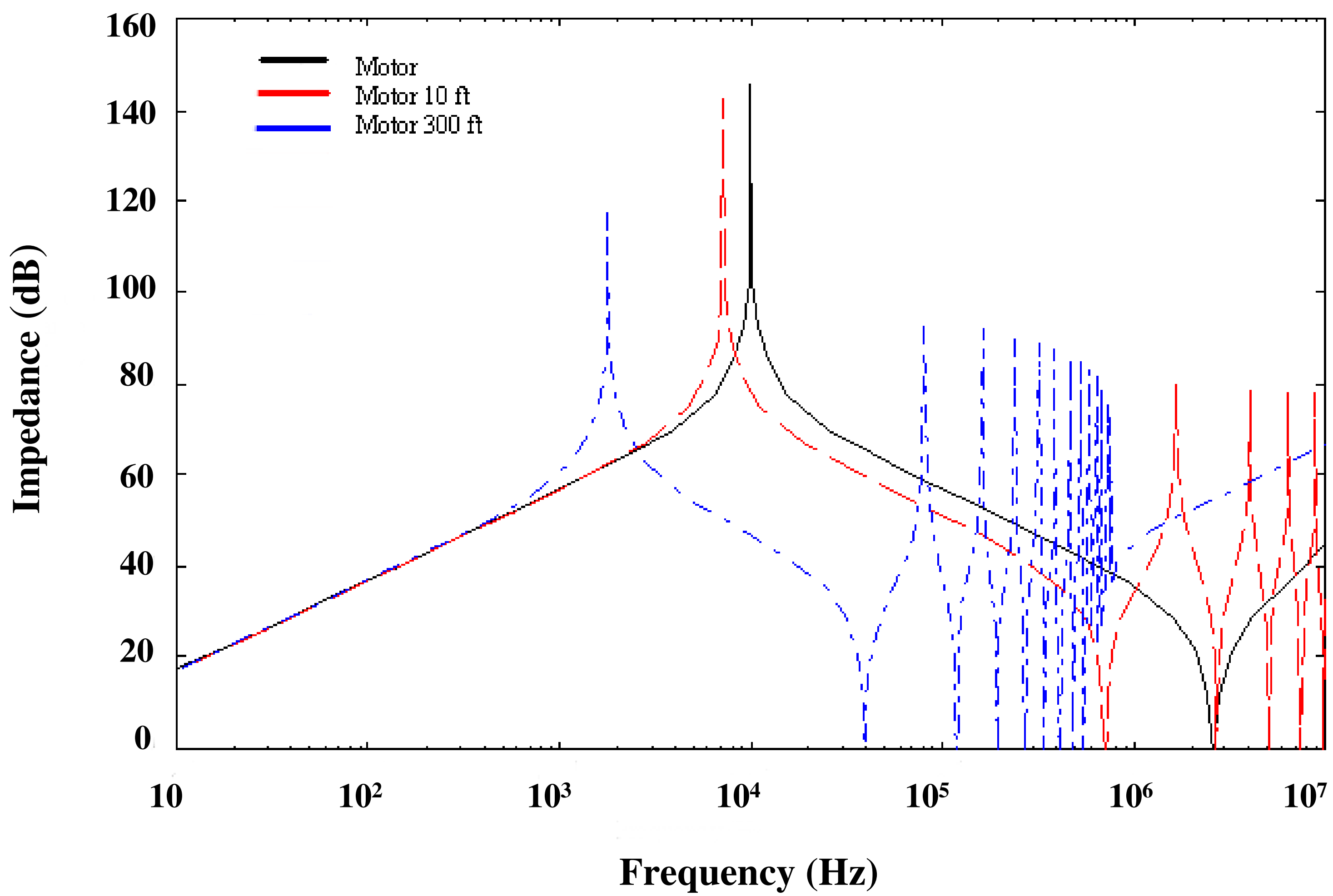
Qualitative Radiated Emission Test with Probe On PWM Wire



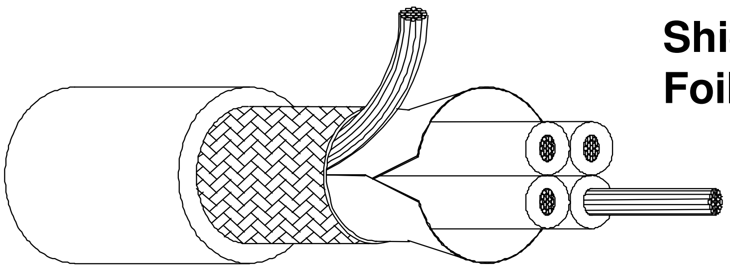
Shield: 85% braid wire coverage
Foil: Mylar metallized oil

Qualitative Radiated Emission Test with Probe On PWM Wire

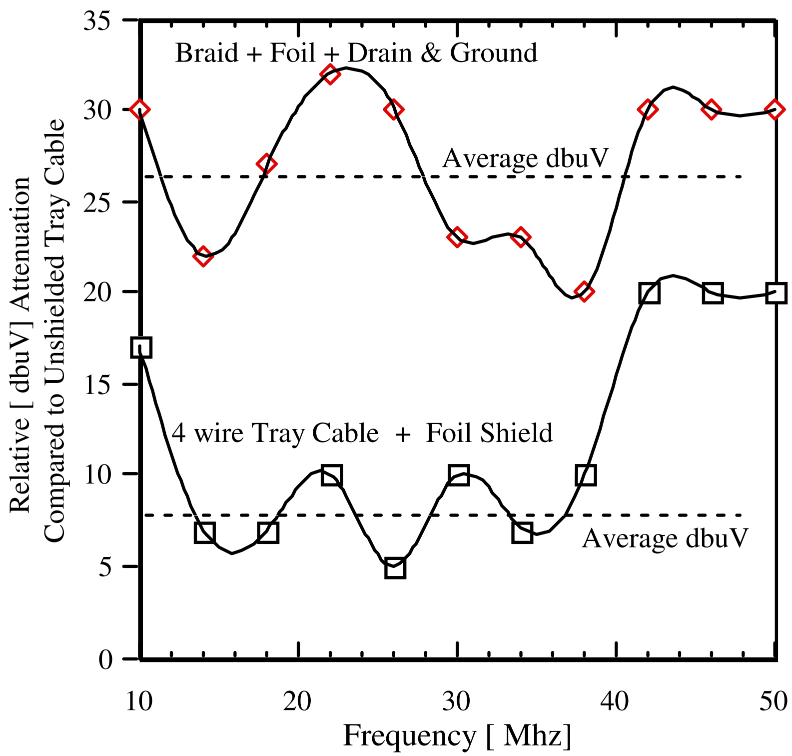
Resonant and anti-resonant nodes for different cable length & same motor



Qualitative Radiated Emission Test with Probe On PWM Wire



Shield: 85% braid wire coverage ~ 25 dB - 7 dB = 18 dB
Foil: Mylar metallized foil ~ *7 dB*

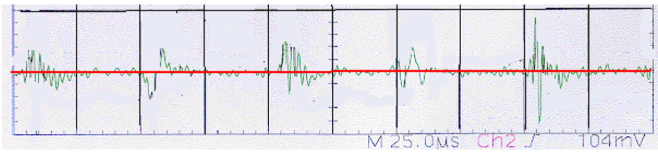


Relative high frequency shielding effectiveness

tray cable
vs.
cable plus foil
vs. cable braid/foil/ground wire system

What frequencies to attenuate??
What overall braid coverage ?
What awg braid wire,resistance inductance ?
Metallized foil use ??
Individual braid tied at one end ?

Qualitative Radiated Emission Test with Probe On PWM Wire



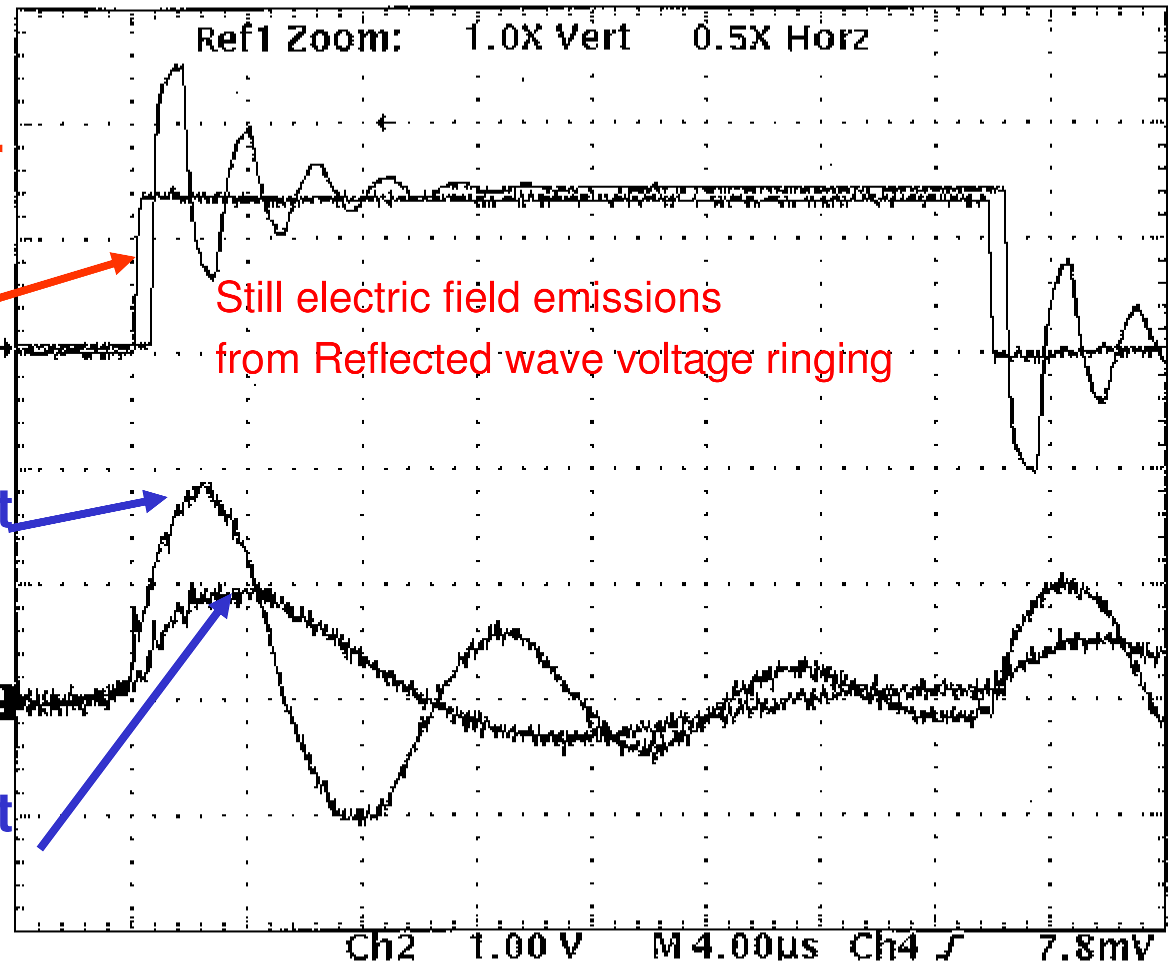
CM Core & Shield **0.3 Vpk** **No Area coupled**

PWM voltage Pulse @motor

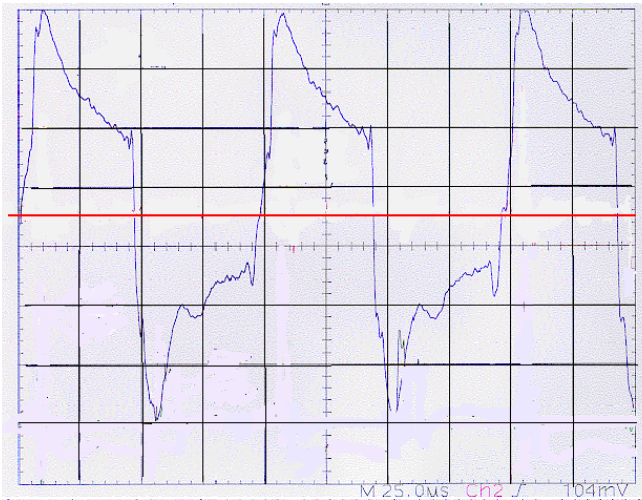
PWM voltage Pulse @drive

PWM transient noise current

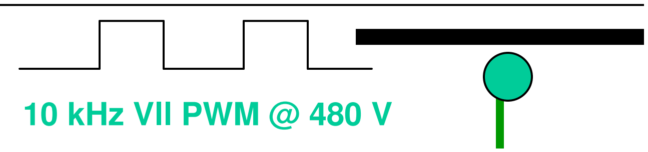
PWM transient noise current With CM core



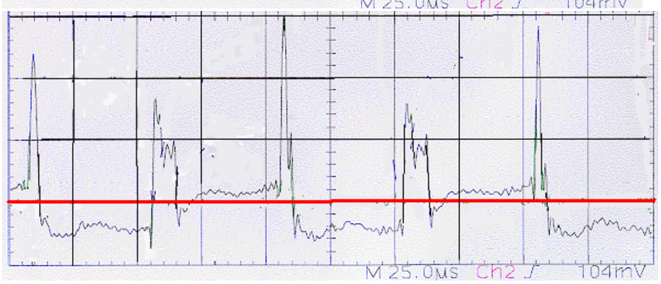
Qualitative Radiated Emission Test with Probe On PWM Wire



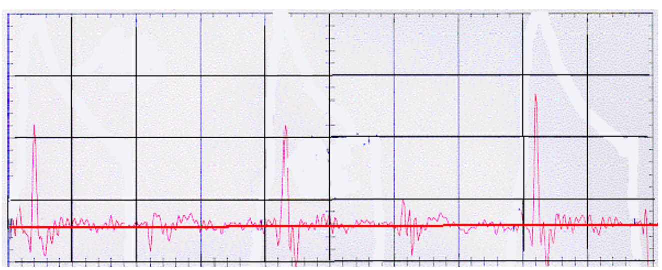
Input Conditions



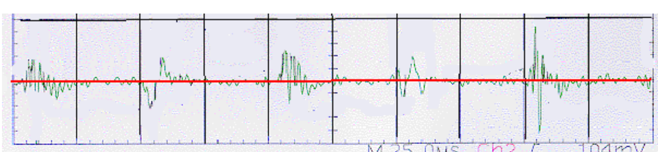
No CM Core & No Shield — 1.6 Vpk — Large Area coupled to probe



CM Core & No Shield — 1.2 Vpk — Lower Area coupled



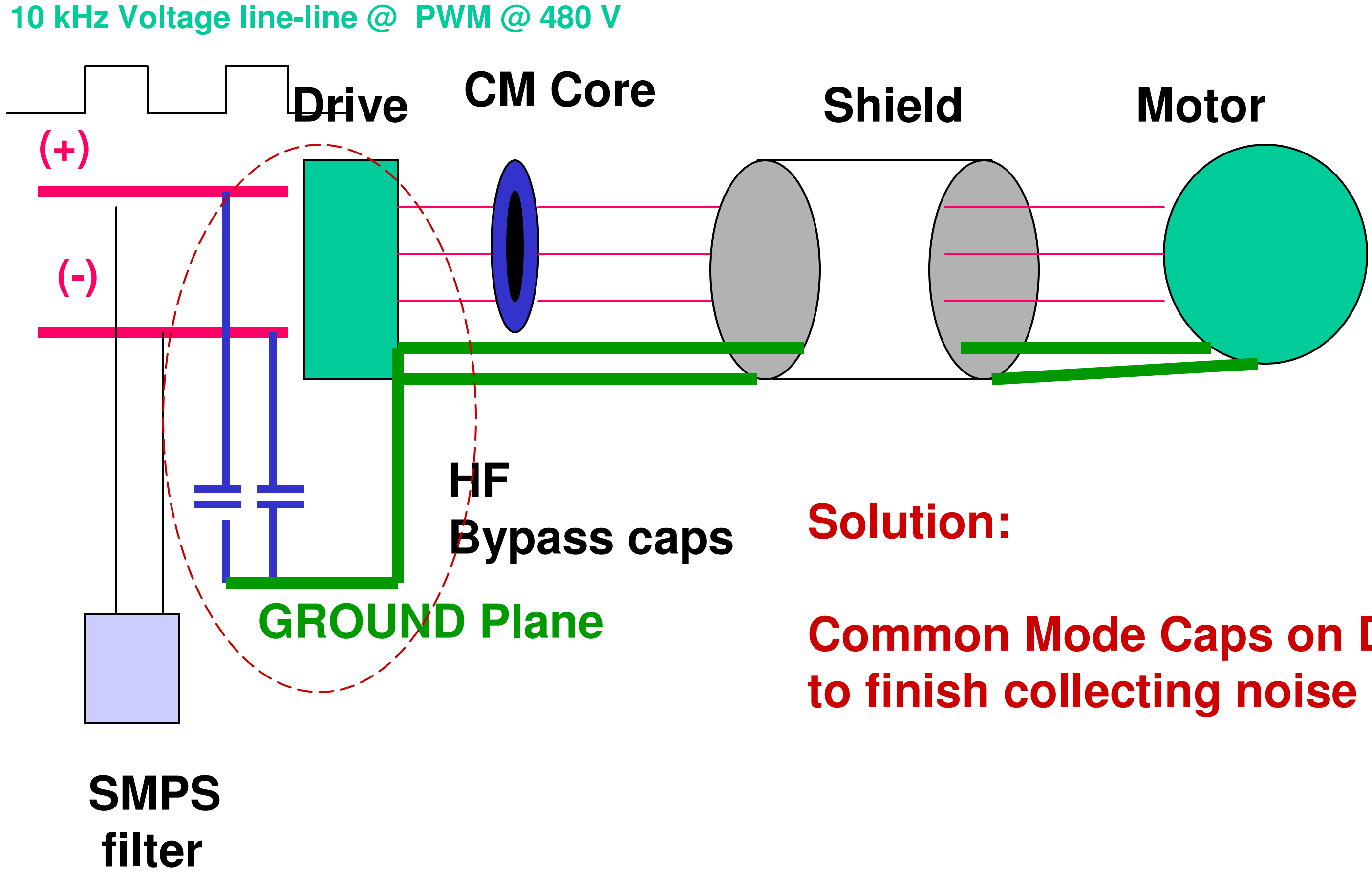
No CM Core only Shield — 0.8 Vpk — Spike Area coupled



CM Core & Shield — 0.3 Vpk — No Area coupled

5:1 reduction 1.6 Vpk: 0.3Vpk

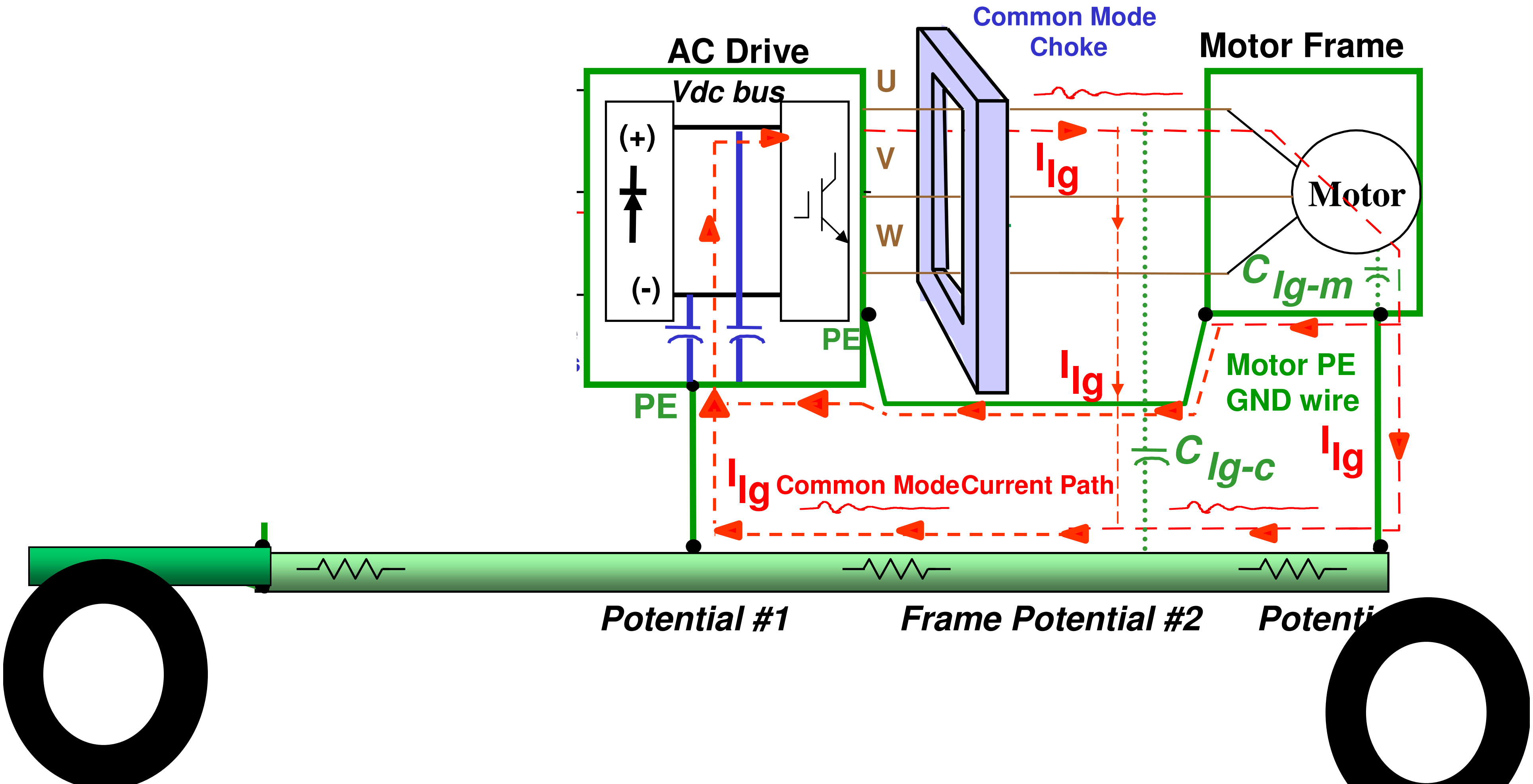
Simple EMI System Fixes to Reduce Radiated Emissions



Solution:

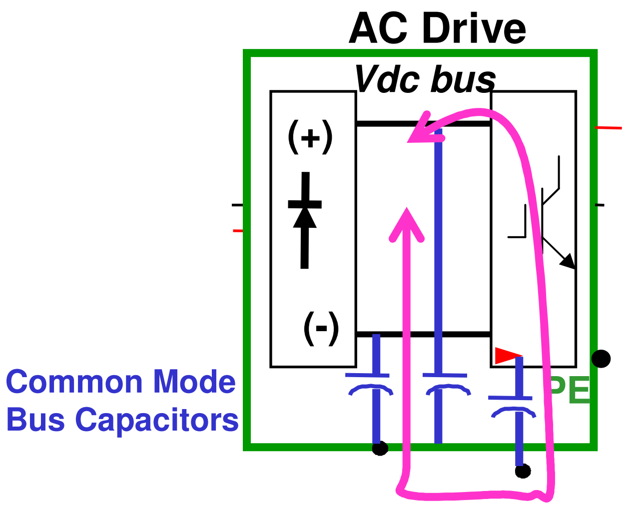
Common Mode Caps on DC bus to finish collecting noise if in frame

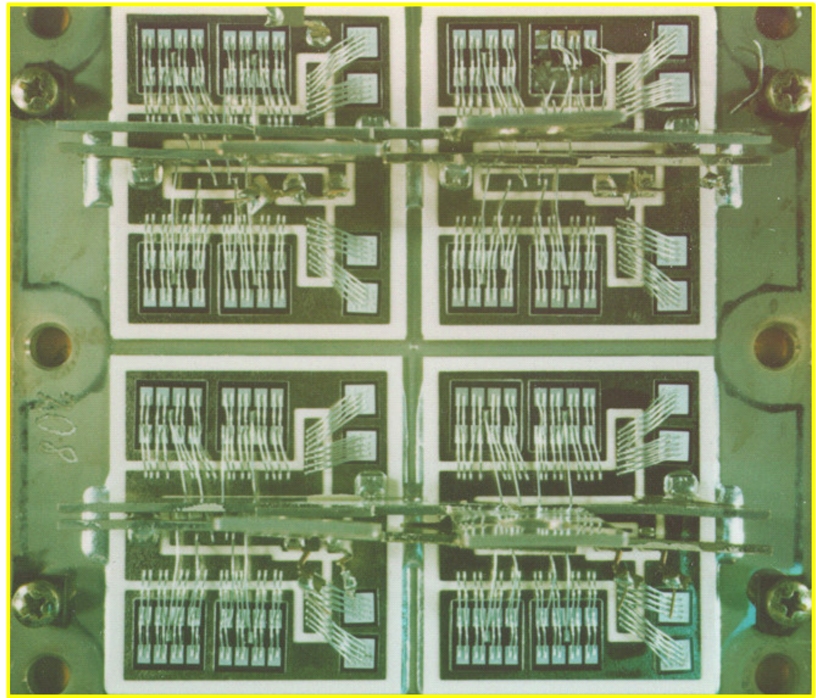
Simple EMI System Fixes to Reduce Radiated Emissions



- Keep drive cable motor distance as short as possible
- Common Mode bus Caps capture leakage noise and return it back to drive
- keeps noise out of frame antenna

Simple EMI System Fixes to Reduce Radiated Emissions

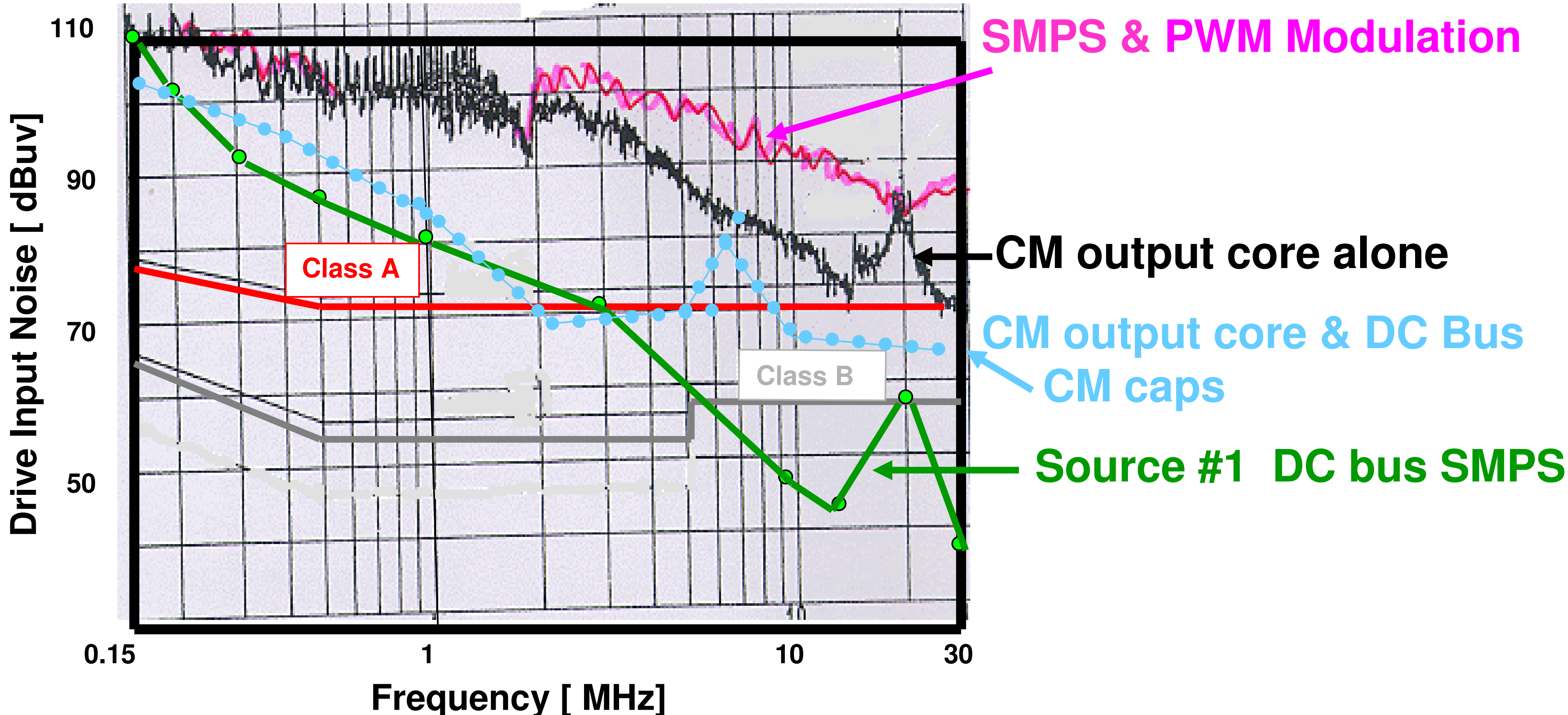




Locally control EMI to ground with low loop area by

CM cap values 2x to 10x module IGBT –ceramic –base plate capacitance

Simple EMI System Fixes to Reduce Radiated Emissions

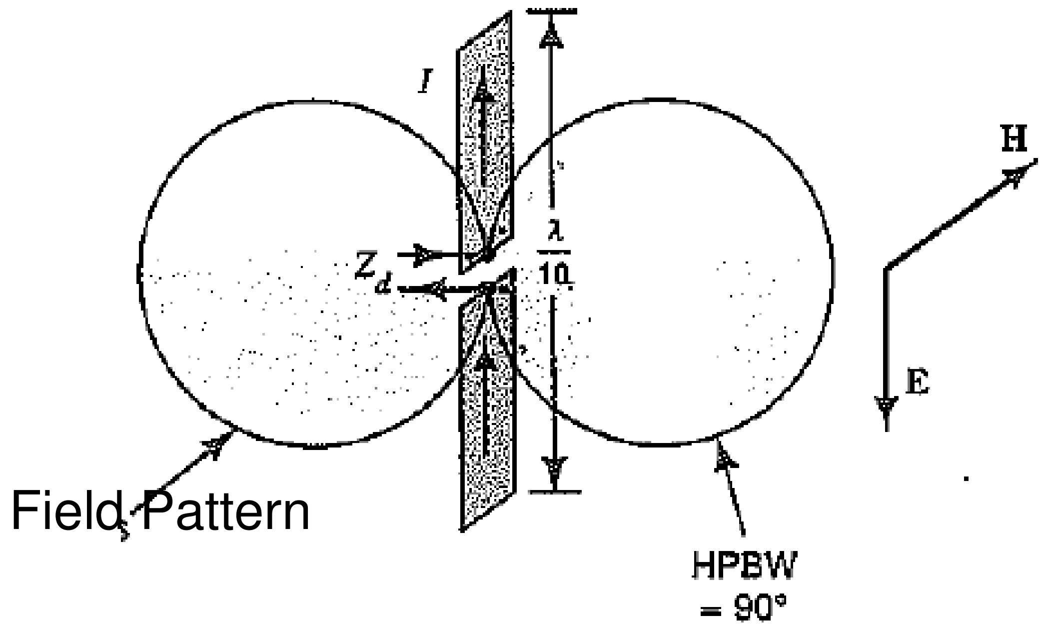


- CM core & CM cap good form 40 db/ decade attenuated L-C filter to 2 MHz
- Why > 2 MHz looks bad?
    - CM caps look line inductors > 2 MHz
    - CM core ferrite > 1 MHz just to radically drop inductance
    - But also form new resonance peak

The Dipole Antenna Problem of Radiated Emissions

Short Dipole

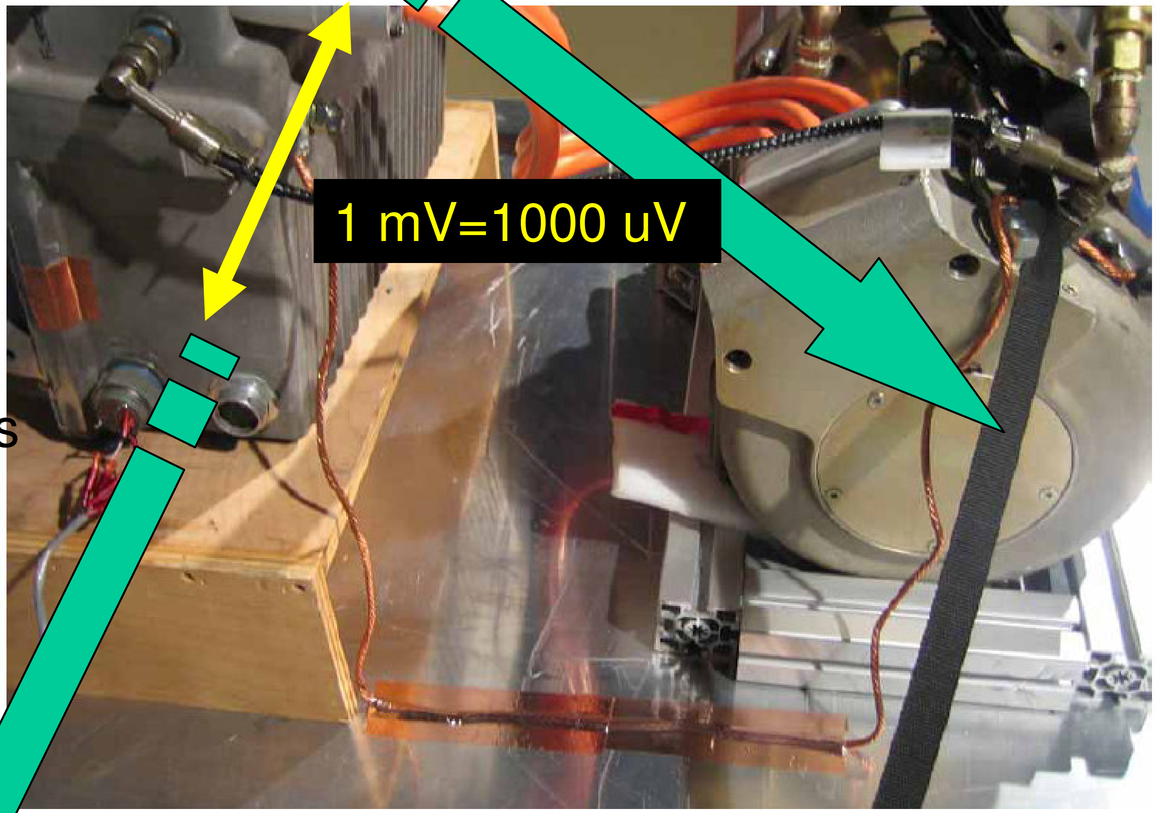
$D = 1.5$



The Dipole Antenna Problem of Radiated Emissions

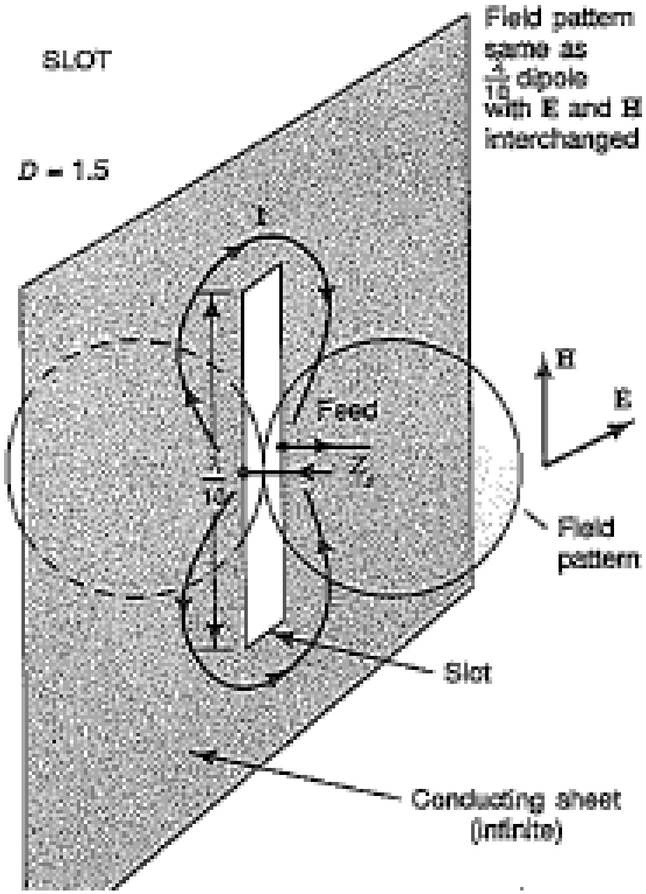
Power connectors

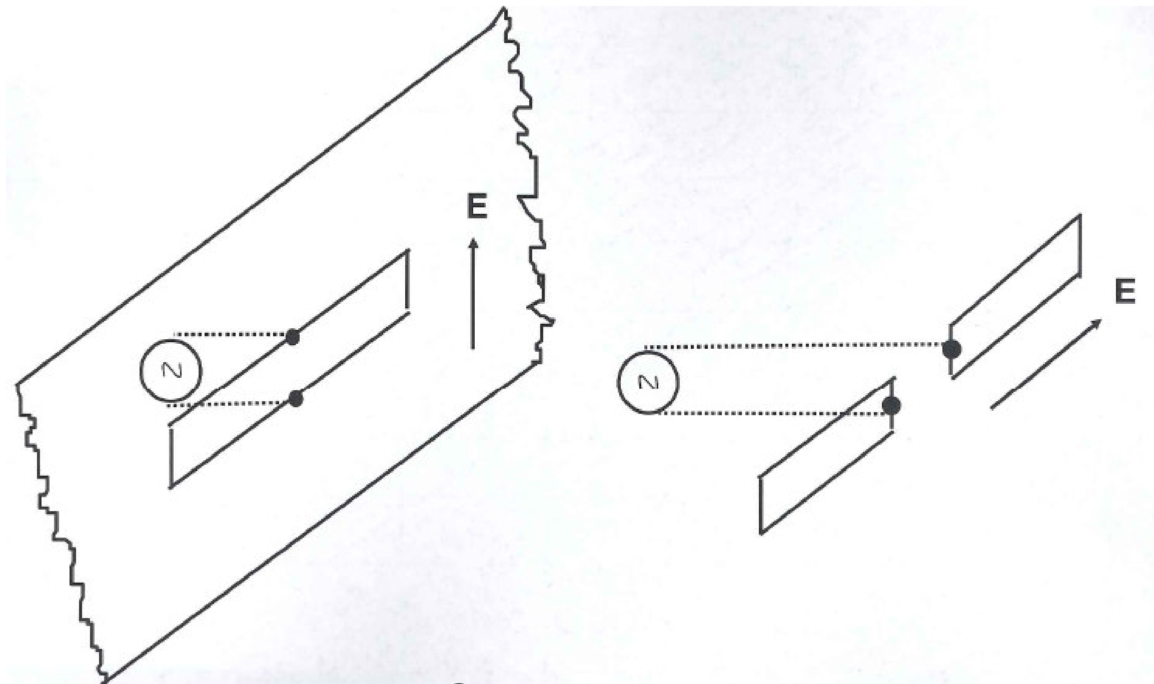
Signals connectors



What's wrong here ???
It's a dipole antenna you'll never pass emissions

The Slot Antenna Problem of Radiated Emissions



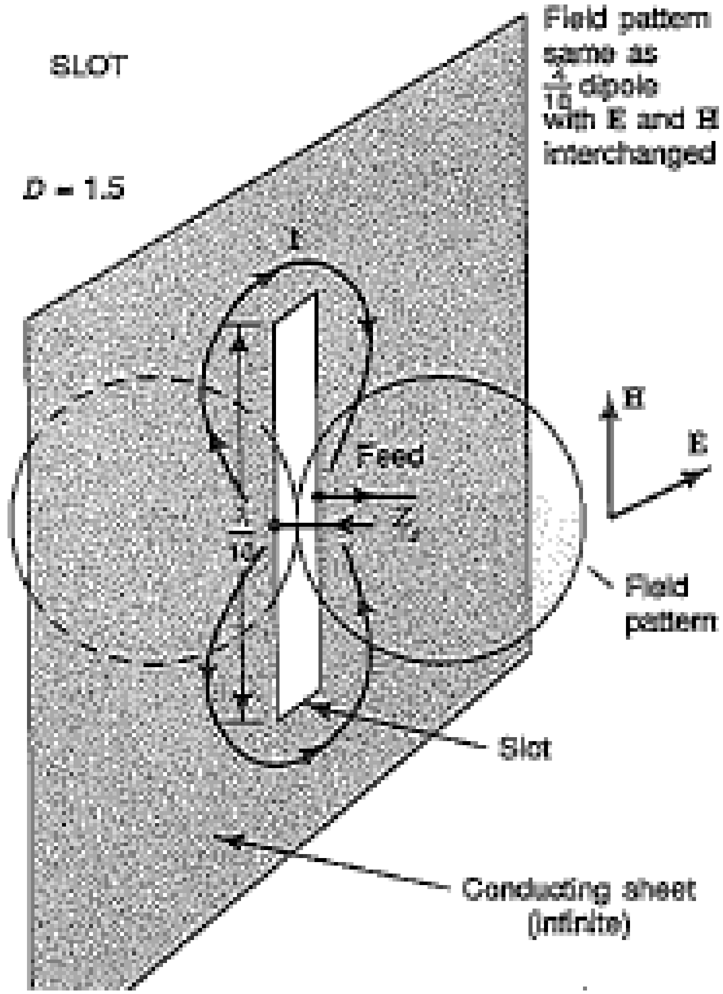


Starts to look like a dipole !

Electromagnetics,
J. Krause Mcgraw hill

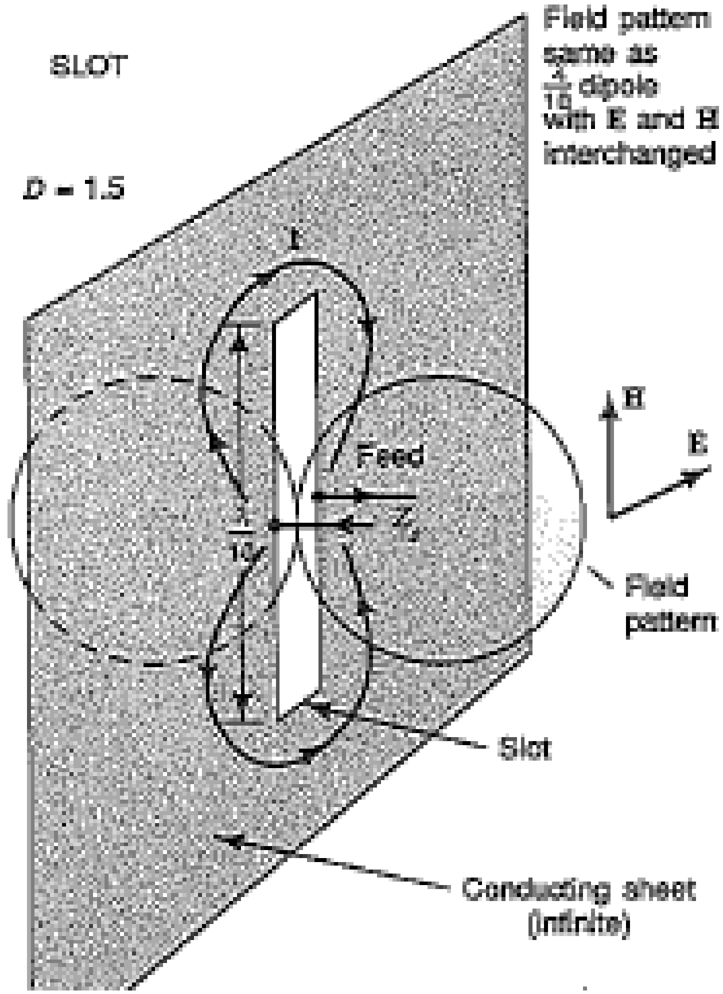
2010 EMC seminar, Milwaukee
Henry Ott

The Slot Antenna Problem of Radiated Emissions



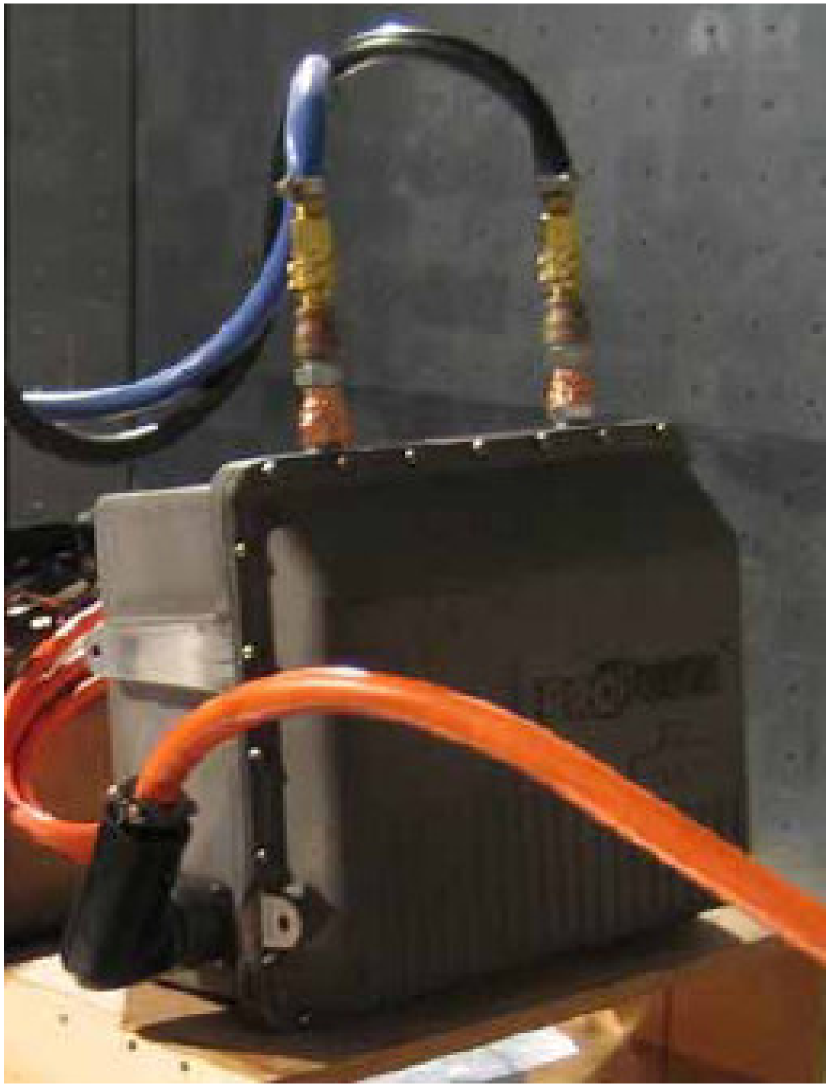
Slots in PC board ground planes are typical problems

The Slot Antenna Problem of Radiated Emissions

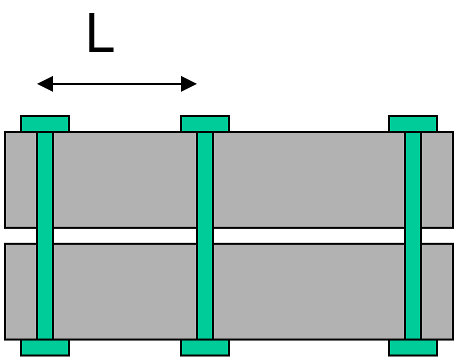


Seams of enclosed cases
are slot antennas !

The Slot Antenna Problem of Radiated Emissions



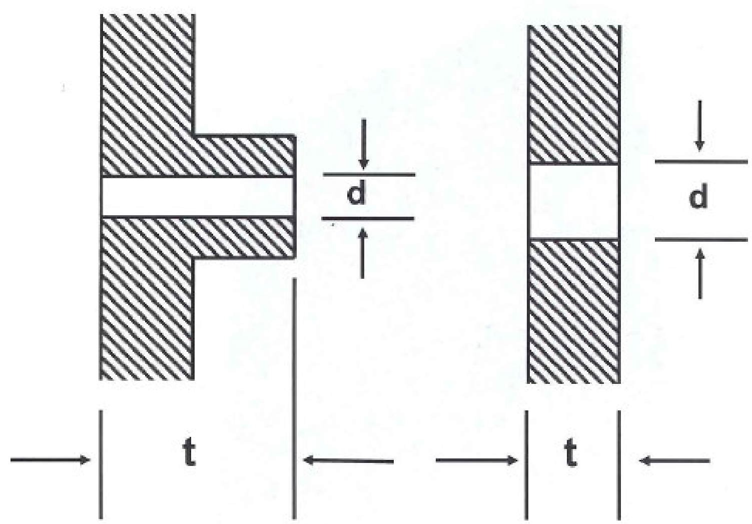
Seams are slot antennas !



$$S = 20 \log \frac{150}{F\,(MHz)\; L\,(m)}$$

Shielding effectiveness for L < 1/2 wavelength

The Slot Antenna Problem of Radiated Emissions



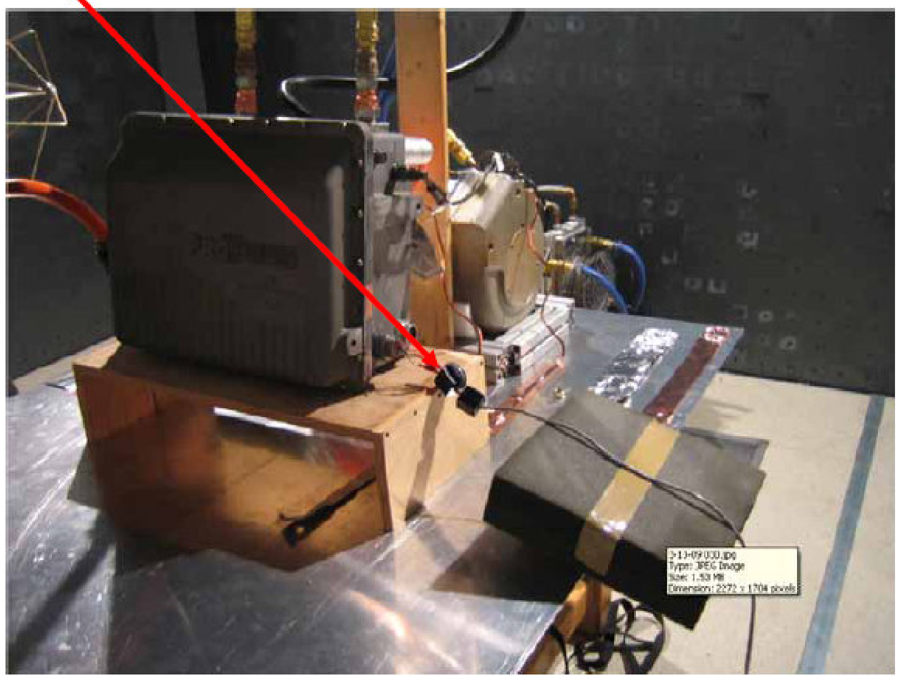
$$S = 32\ t / d\ \text{(dB)}$$

Waveguide attenuation built into enclosure

Can supplement with EMI gasket

The Worst Radiated Emission Offender: Com's & CAN

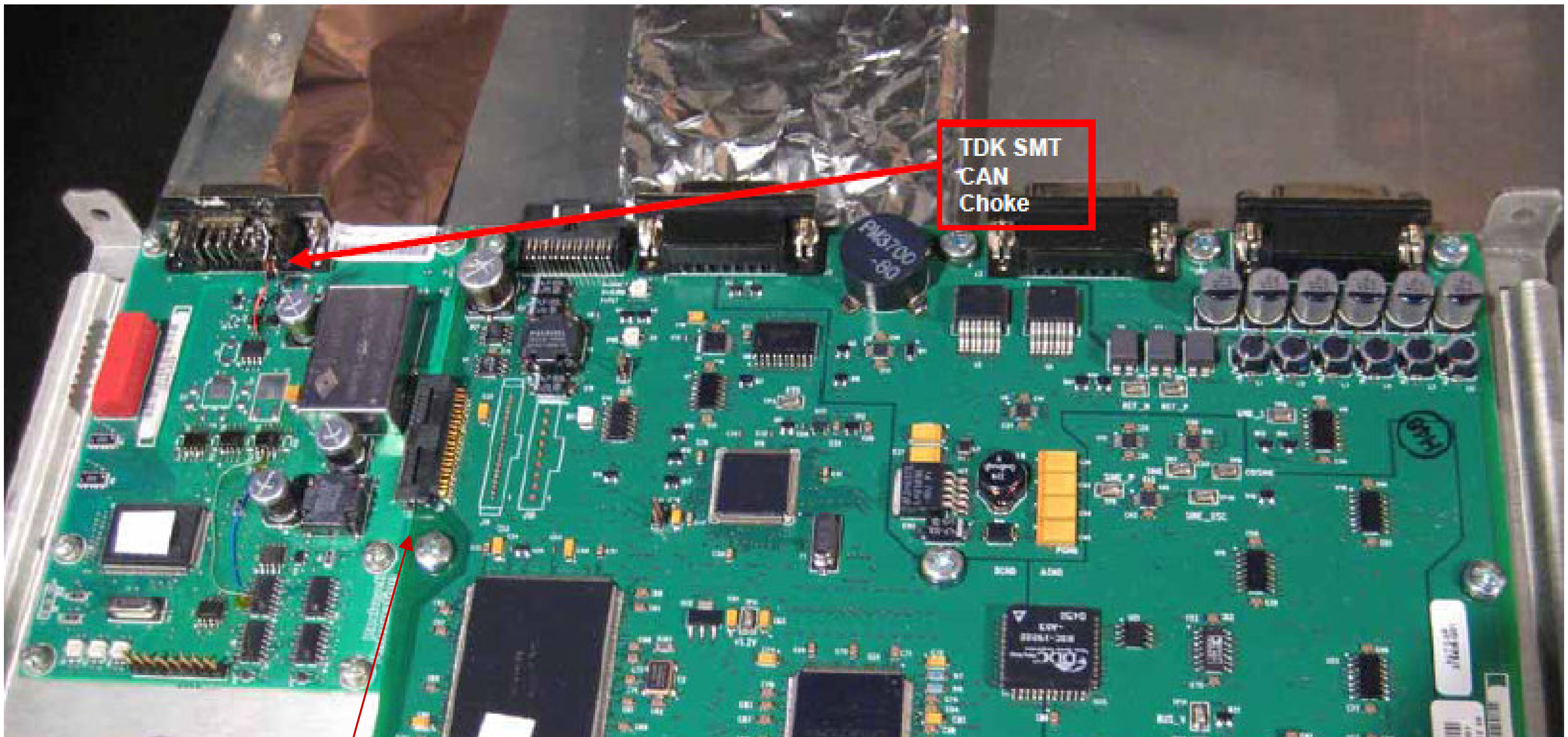
A3 TD with Steward 28A2024-0A2 CM
Ferrites (3 turns) on COMMs cable



Why ? because Com and Power Ground not next to each other

The Worst Radiated Emission Offender: Com's & CAN

Why Ferrite ? because CAN line Switching edge extremely fast



Here's another problem area? Impedance discontinuity at connectors

Reverse Dipole Transmitter Problem of Radiated Emissions

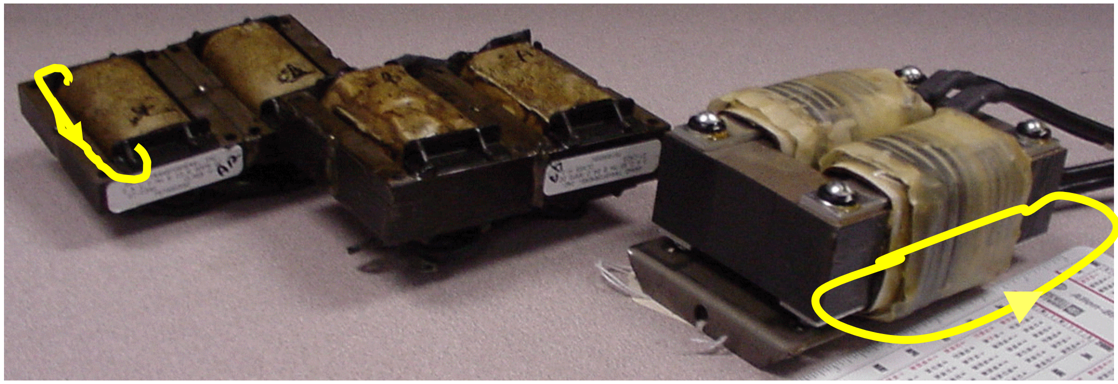
Truck seems to meet all applicable 3 m 10 m EMI susceptibility tests

However, Fireman turns on walkie talkie going up ladder

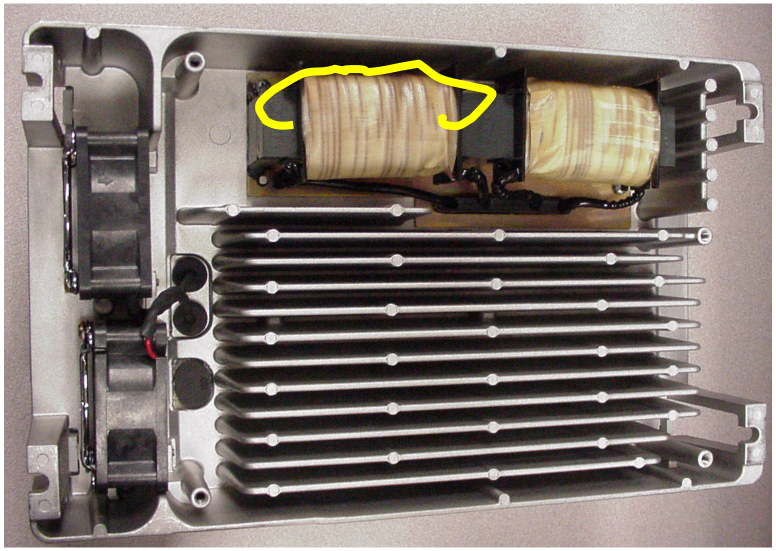
Proximity sensors on ladder rungs turn on extending ladder into air

Solution: shield wires to cab and bond to metal enclosed sensor

Other Tricks to Reduce Radiated Emissions



• shell core of PF700 choke contains radiated leakage flux vs. old style



• casting contains radiated leakage flux of PF70 choke

Cable & AC Induction Motor High Frequency Models

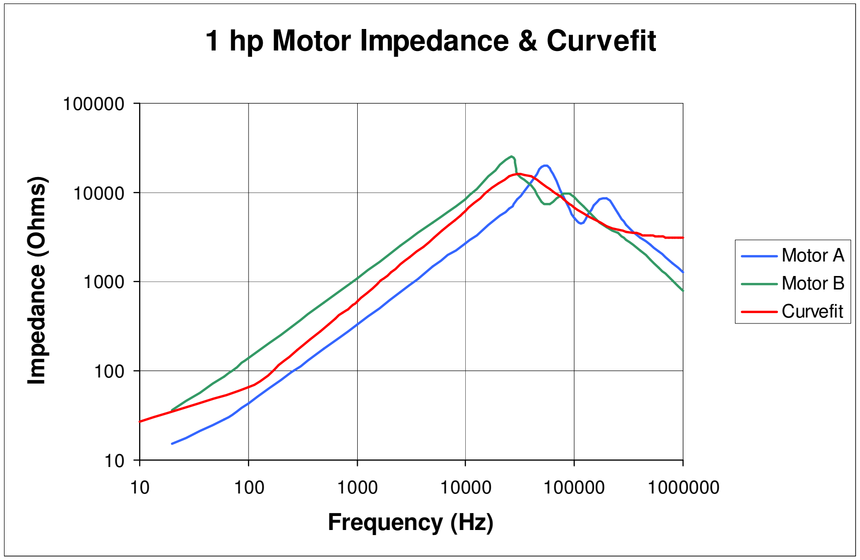
G. L. Skibinski

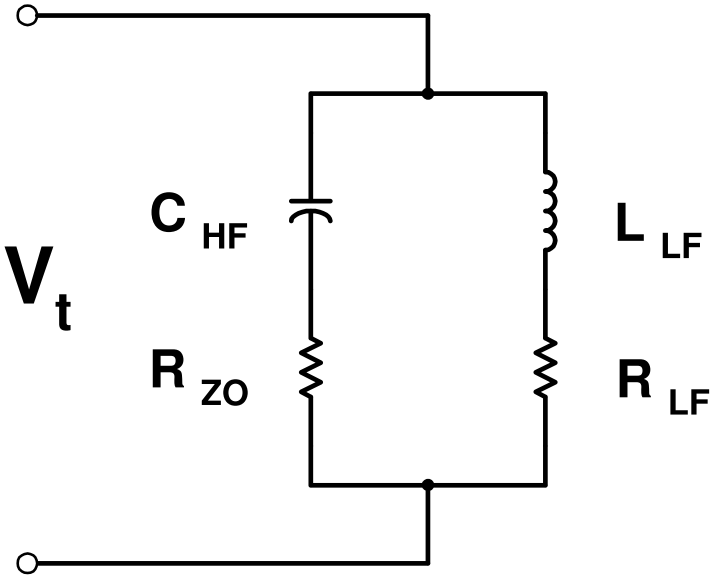
AC Induction Motor
High Frequency Models

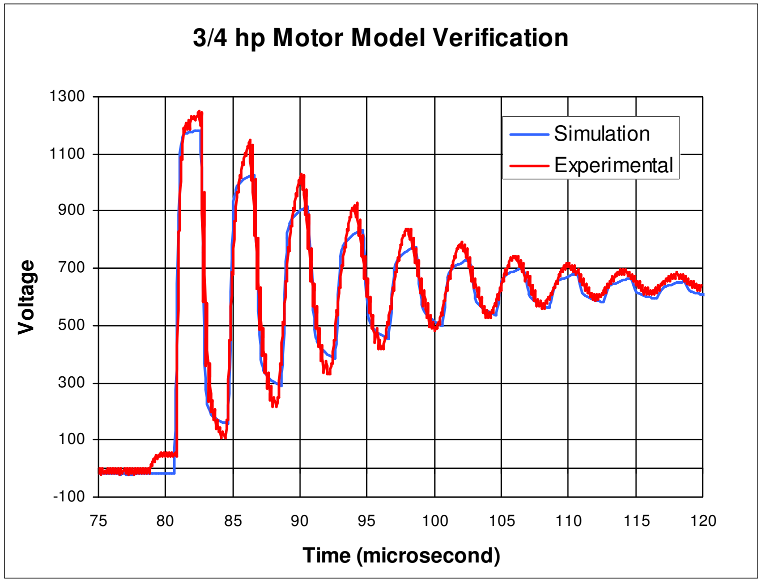
to simulate reflected wave voltage and EMI Common mode currents

G. L. Skibinski

First attempt at high frequency motor model

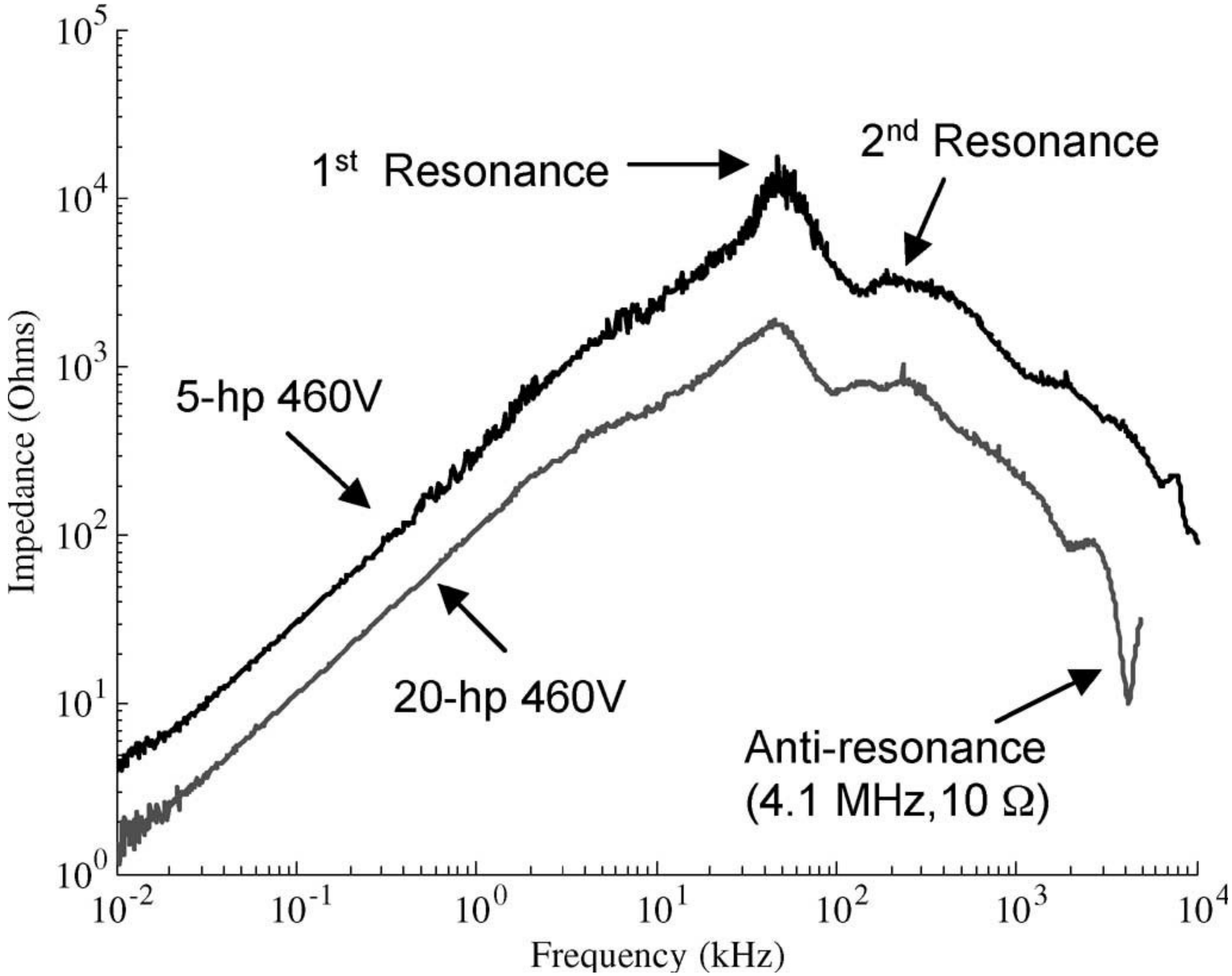






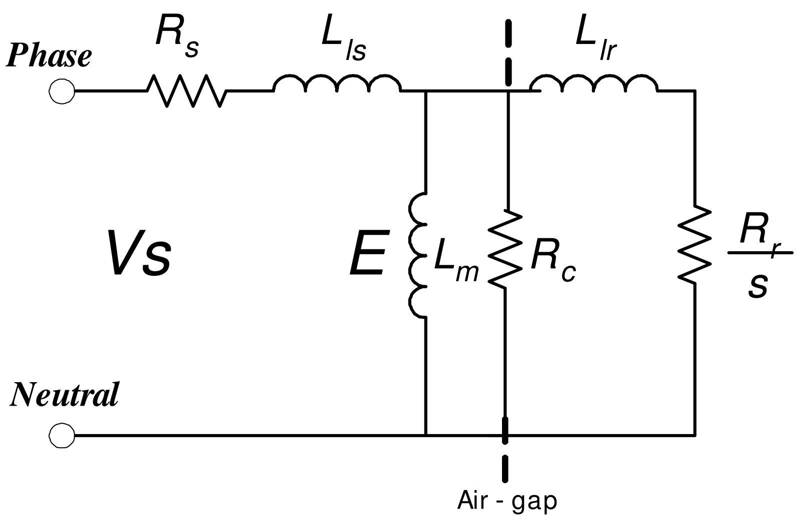
Resonant pole curve fit model
Worked OK
But not real values
compared to motor

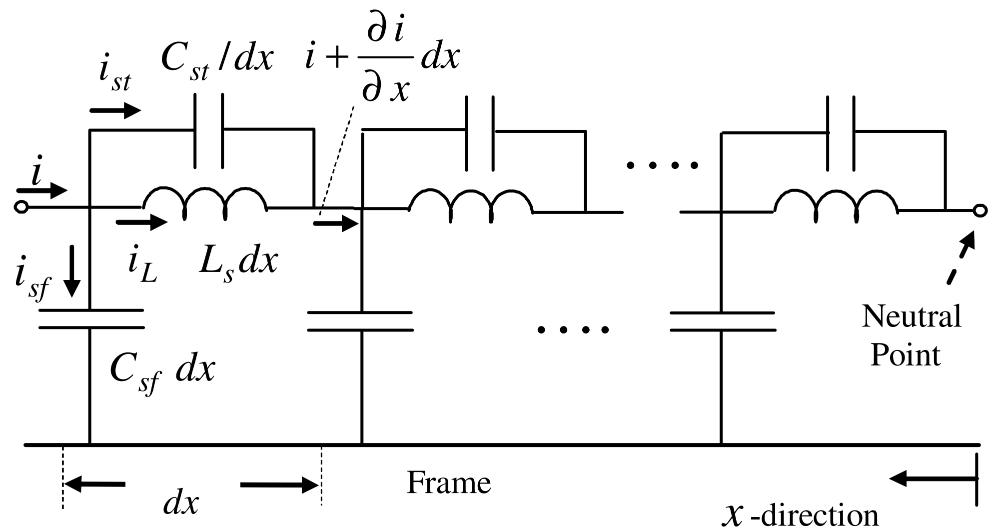
2nd attempt high frequency motor model



Measured 460V 5 & 20 hp induction motor
DM impedance (magnitude) vs. frequency

2nd attempt high frequency motor model

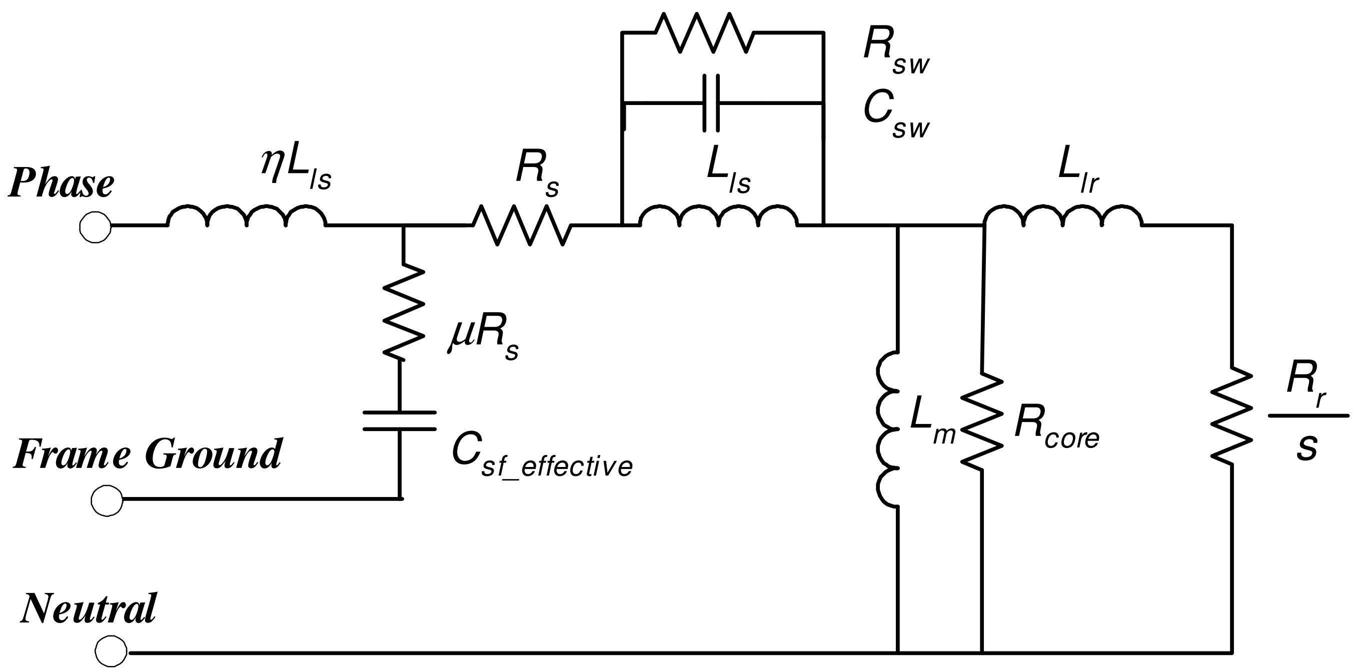




IEEE 112 recommended per phase low frequency equivalent circuit.

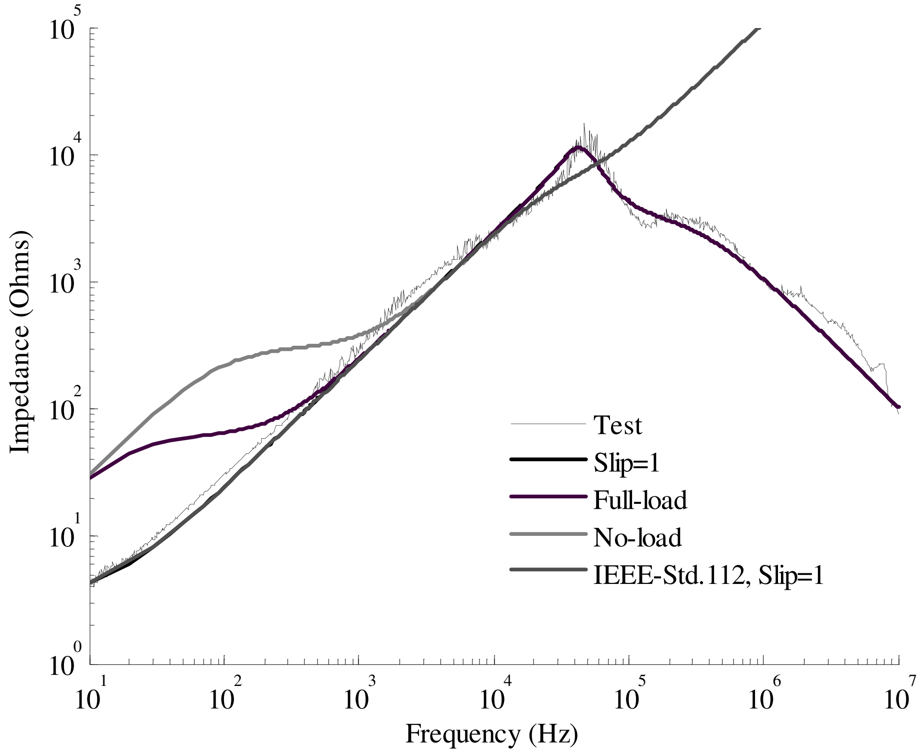
Distributed high frequency parameter model for stator windings.

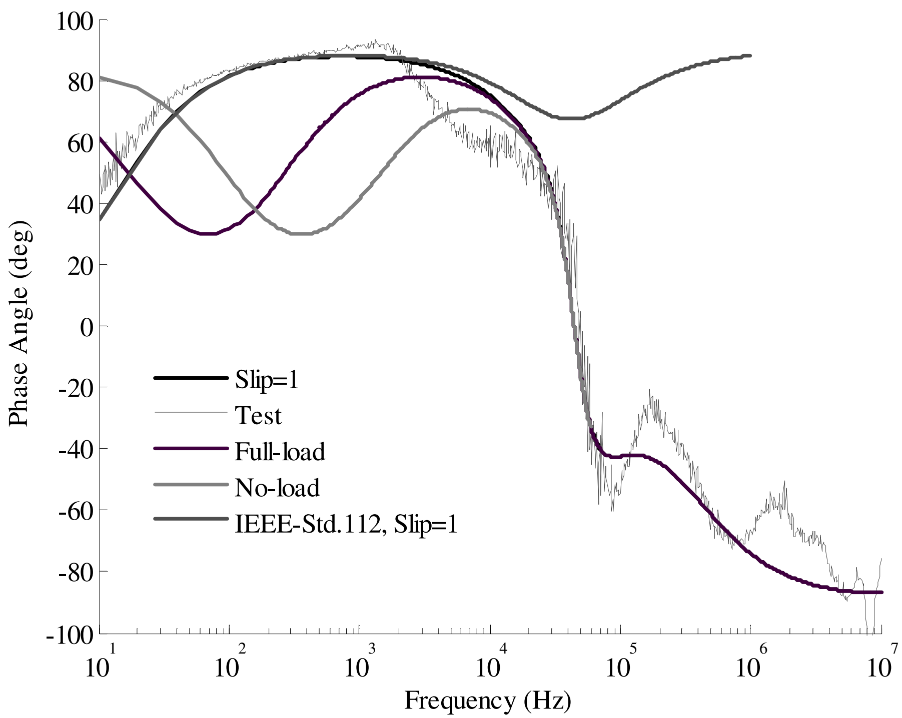
Proposed high frequency motor model



Proposed per phase universal induction motor model.

Proposed per phase high frequency motor model

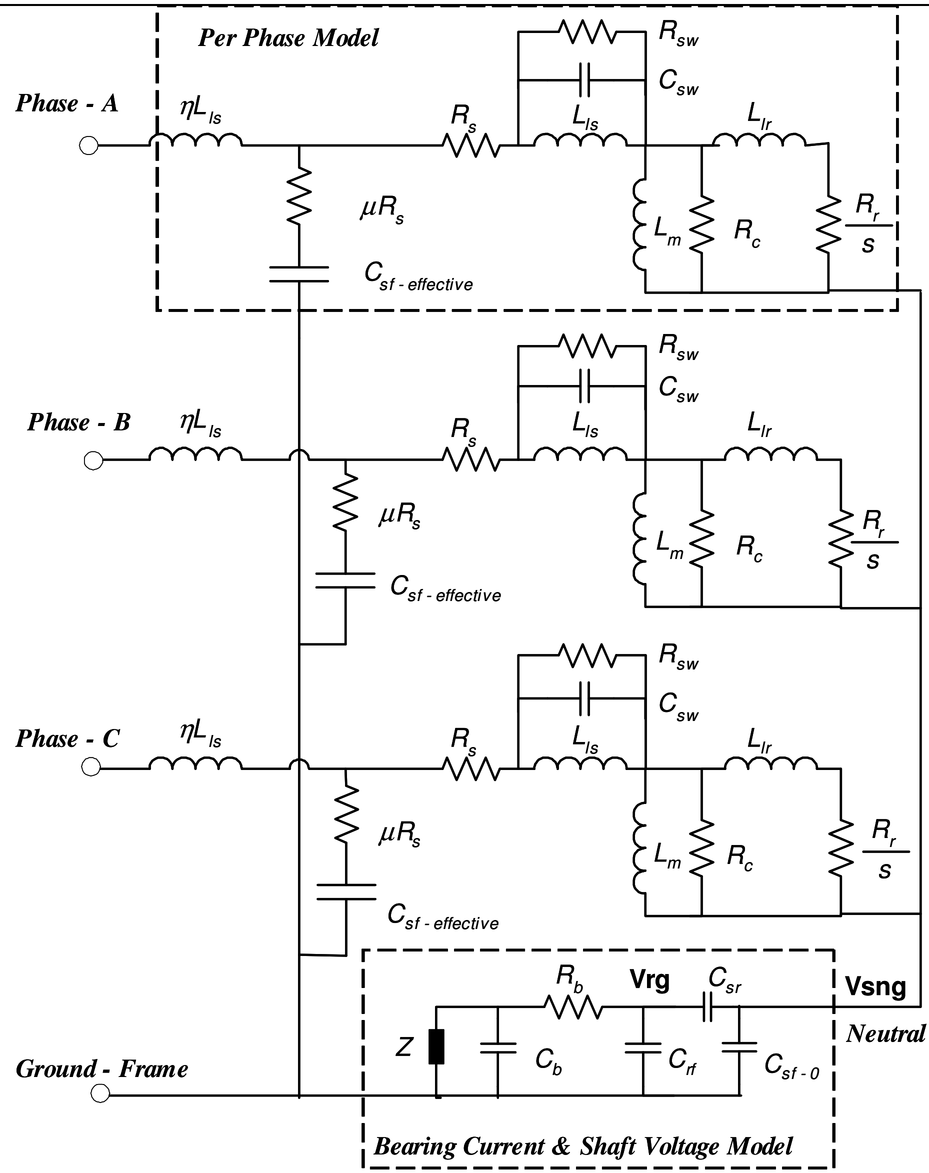




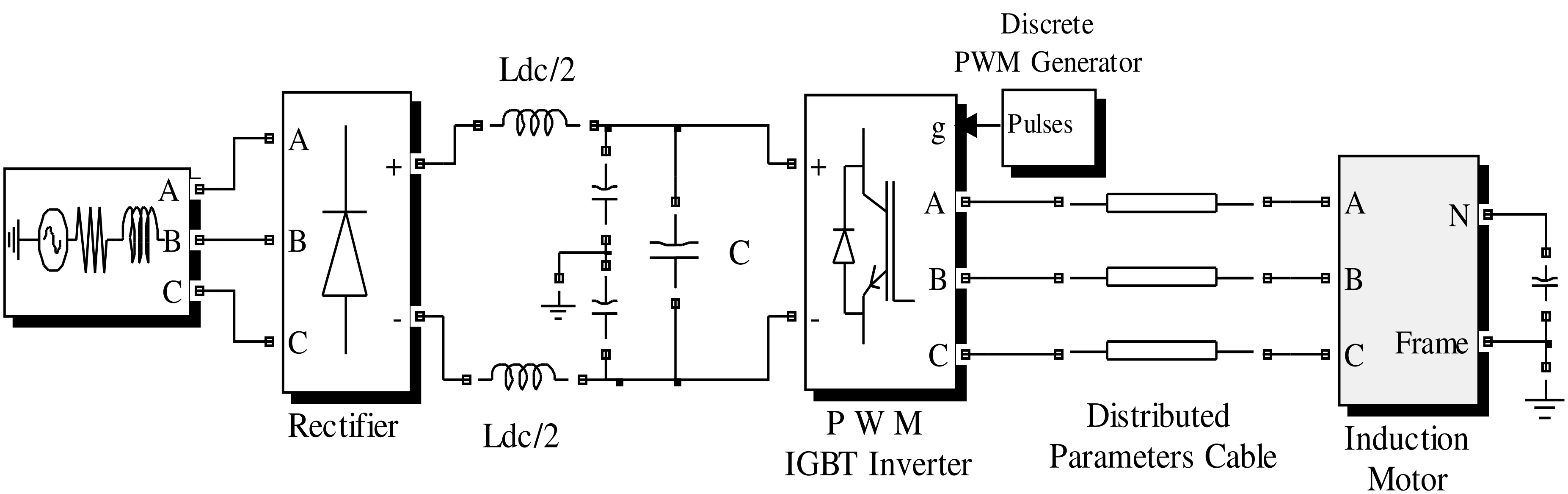
Measured versus calculated (Slip=1)
5 hp 460V induction motor
differential-mode impedances
(magnitude) versus frequency.

Measured versus calculated (Slip=1)
5 hp 460V induction motor
differential-mode impedances
(phase-angle) versus frequency.

Proposed 3 Phase high frequency motor model

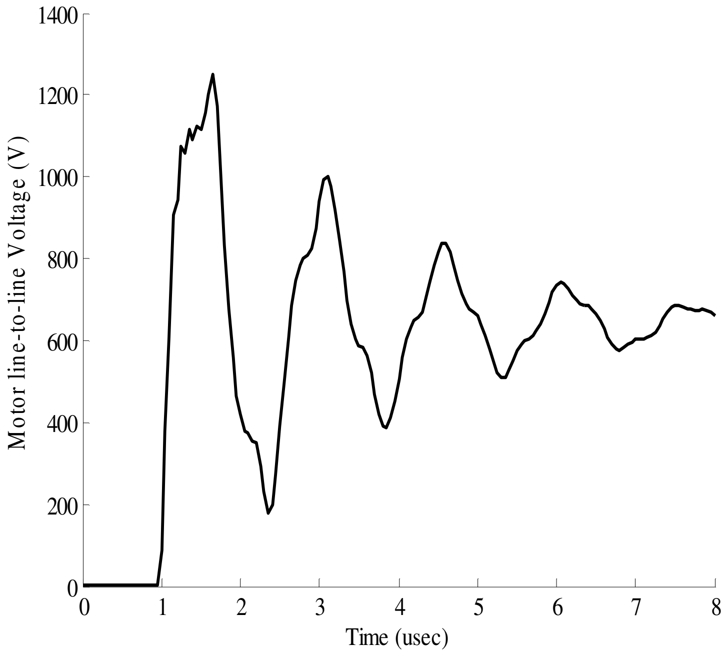


Simulation of 3 Phase high frequency motor model

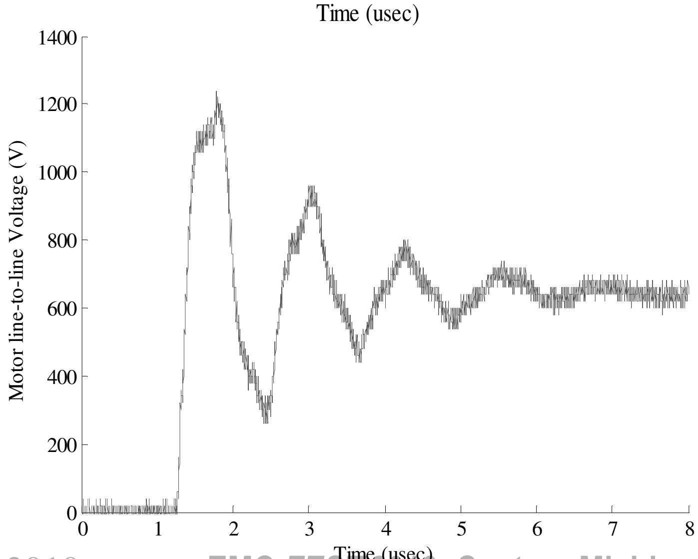


Typical drive / long cable / motor system
with distributed parameter cable model of Matlab
and proposed three-phase induction motor model.

Simulation vs Measured Motor Model Reflected wave Results

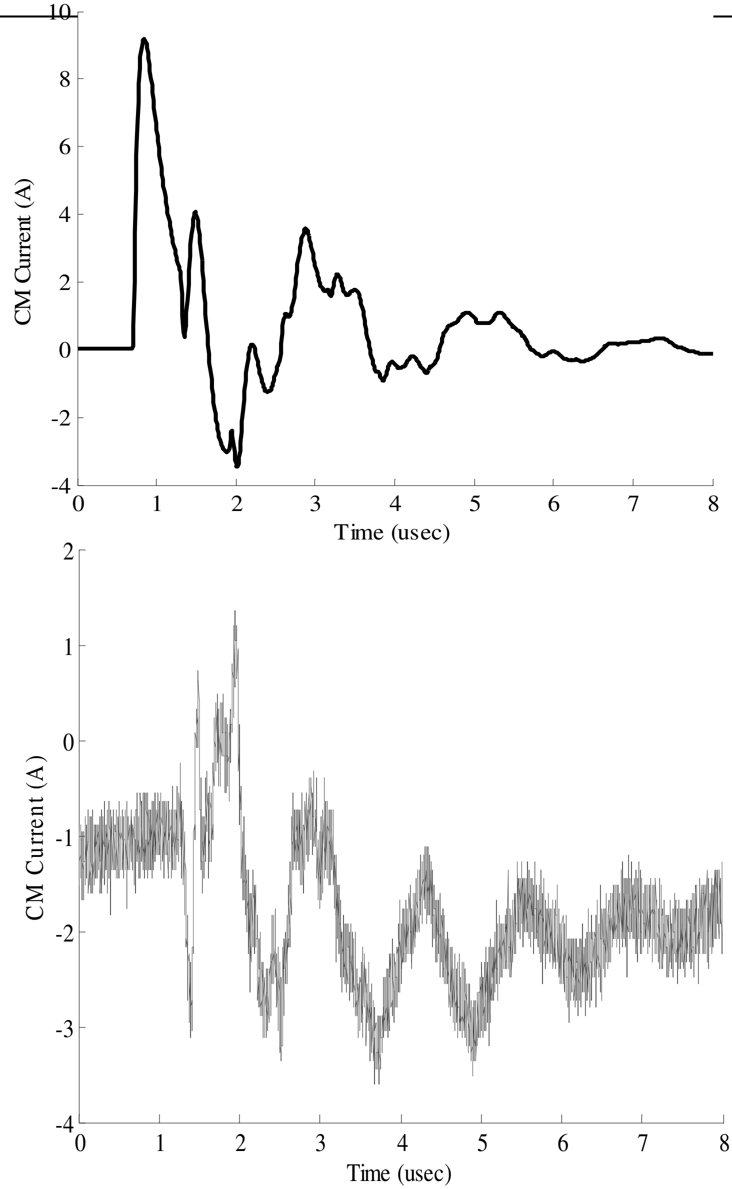


Simulated



Measured

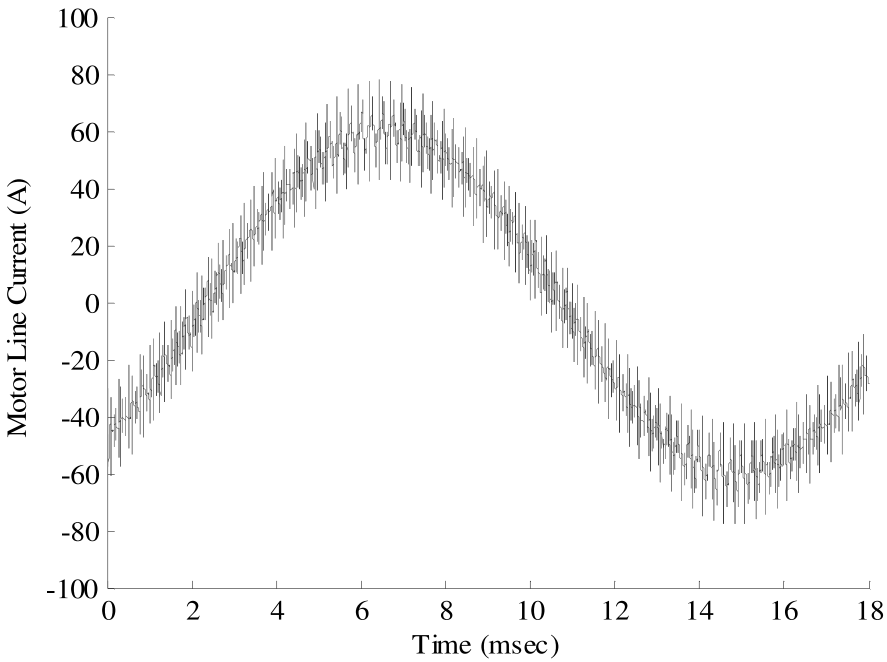
Simulation vs Measured Motor Model CM Current into Motor

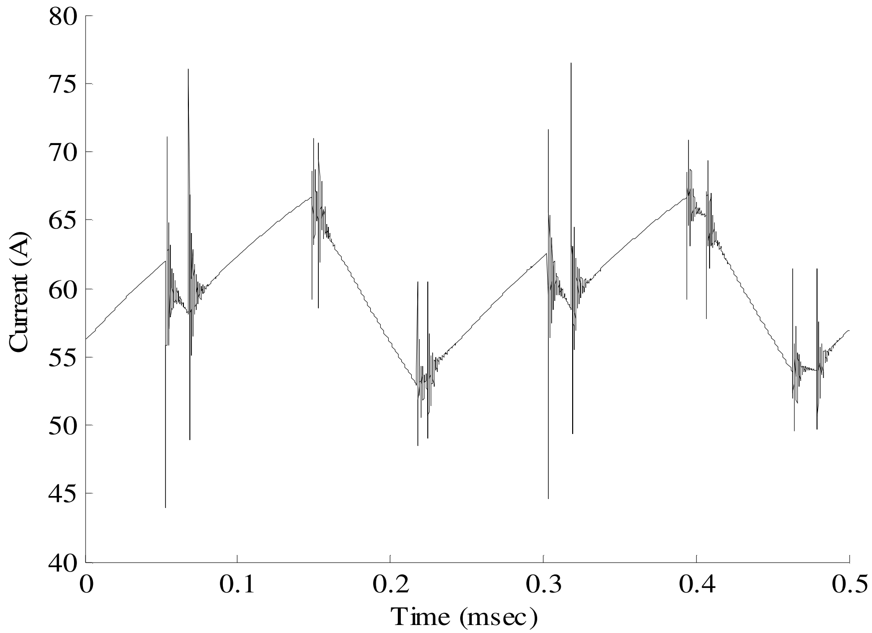


Simulated

Measured

Simulation vs Measured Motor Model DM Current into Motor





Low frequency fundamental current

PWM ripple current

Model accurate for 4khz PWM ripple & low frequency fundamental current

OVERALL CONCLUSION: Model looks promising to simulate motor EMC issues

High Frequency Motor Model References

A Failure Mode for PWM Inverter-Fed AC Motors Due to the Anti-Resonance Phenomenon,
IEEE 2008 Industry Applications (IAS) Conf. a;lso Sept/Oct 2009 IEEE Trans. Industry Appl.)

Determination of Parameters in the Universal Induction Motor Model,
2007 IEEE Industry Applications (IAS) Conference

Universal Induction motor model with low-to-high frequency response characteristics,
2006 IEEE Industry Applications Conference (IAS)

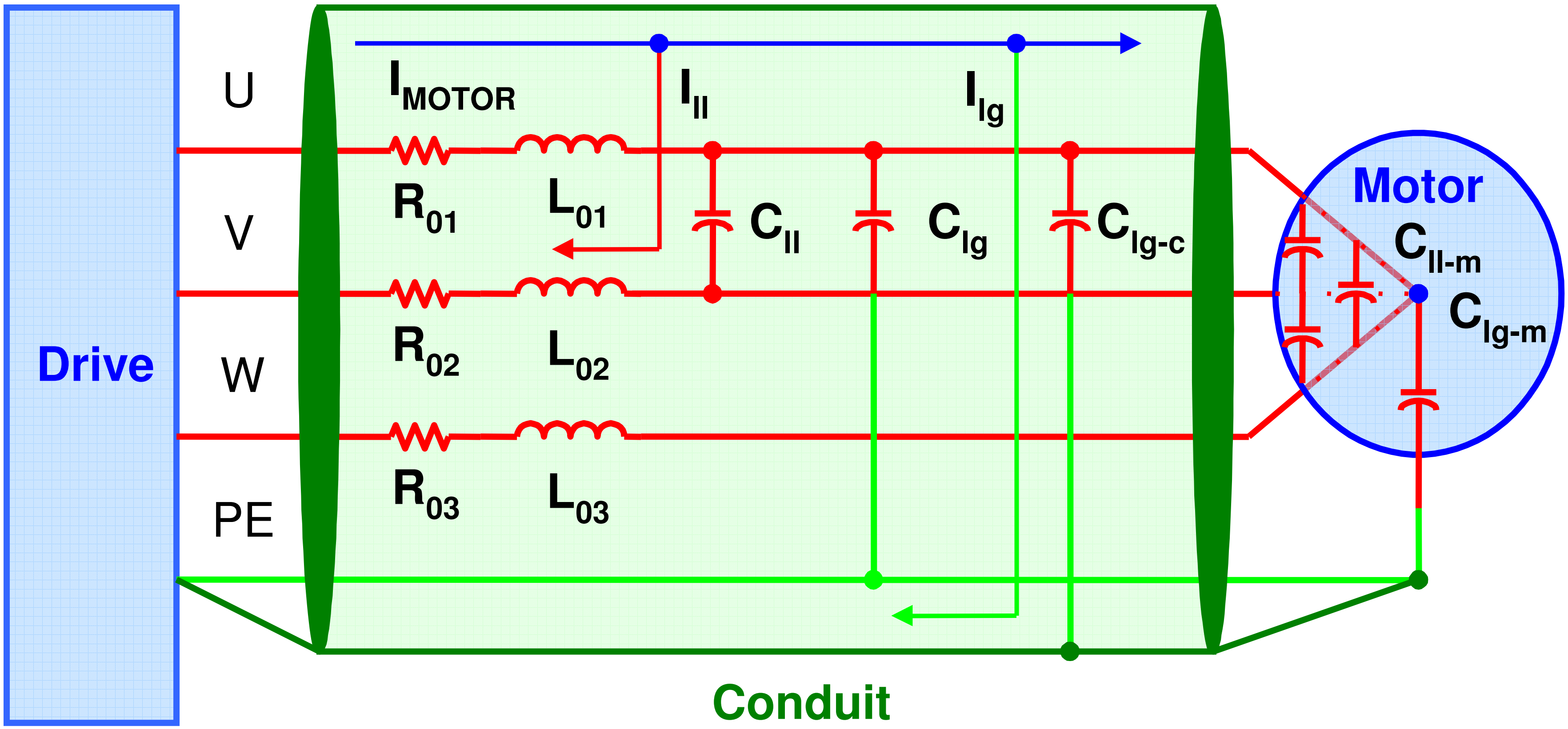
Resonant Tank Motor Model For Voltage Reflection Simulations With PWM AC Drives,
IEEE 1998 IEMDC International Electric Machines and Drives Conference

Cable Models

G. L. Skibinski

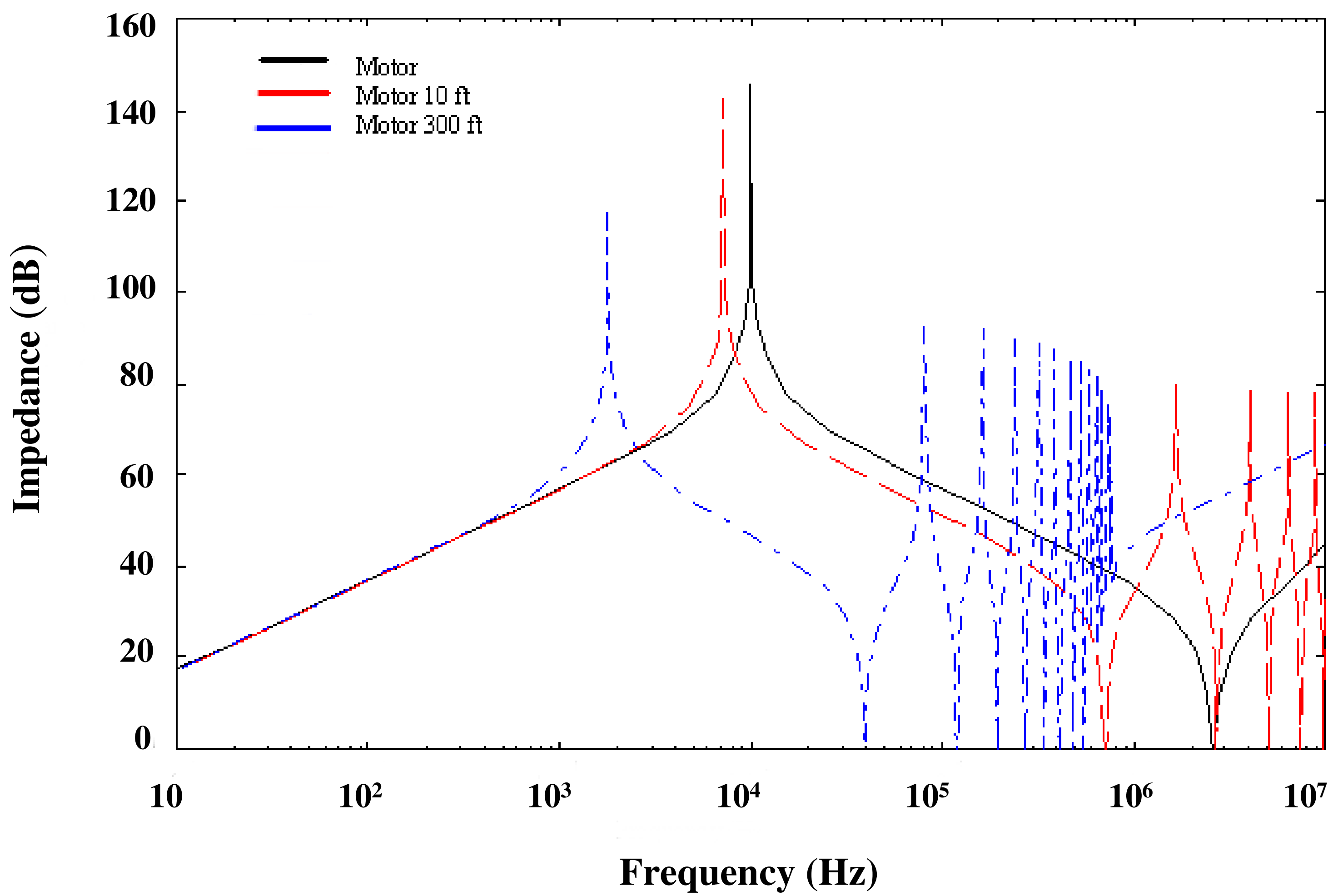
Common mode - and Differential- Mode Analysis of 3-phase cables for PWM ac drives.
2006 IEEE Industry Applications Conference (IAS)

Simplified Cable Model: one section R-L–C per unit length

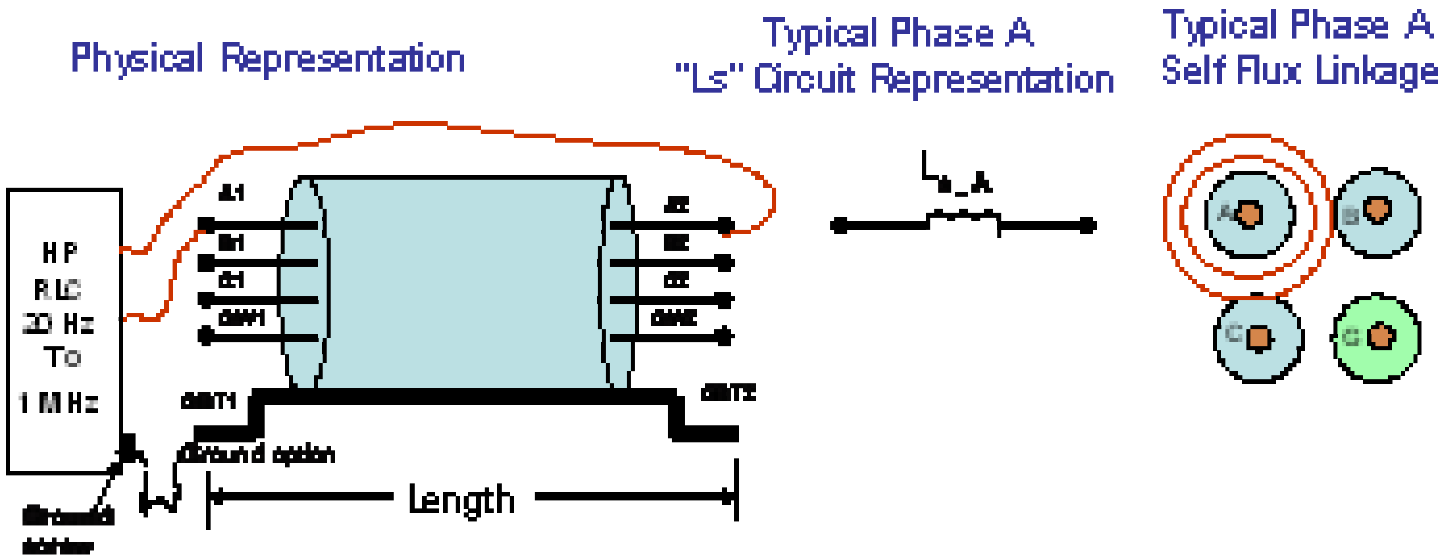


Line-to-line & line-to-ground simplified capacitive charging current path into cable /conduit / armor and/or motor

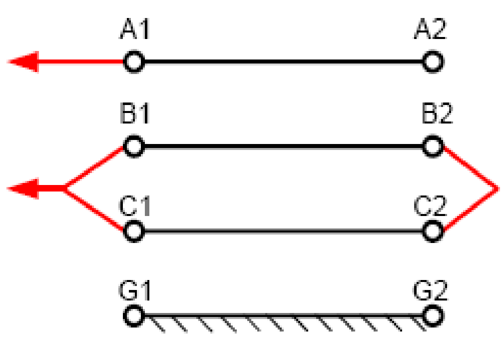
Resonant and anti-resonant nodes for different cable length & same motor



Differential mode: Self Inductance & C line-line testing



per phase self inductance and series equivalent resistance



(a)

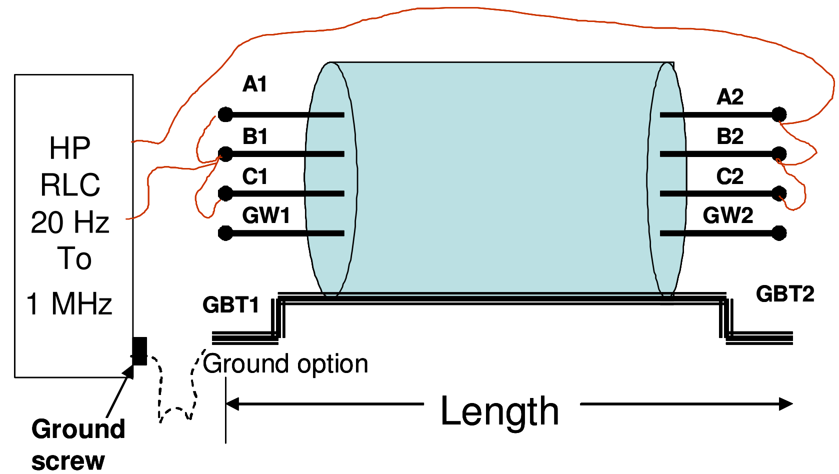
Cable configurations to measure capacitance (Cp, Rp)
Differential-mode line-line three wire

Differential mode: Mutual Inductance testing

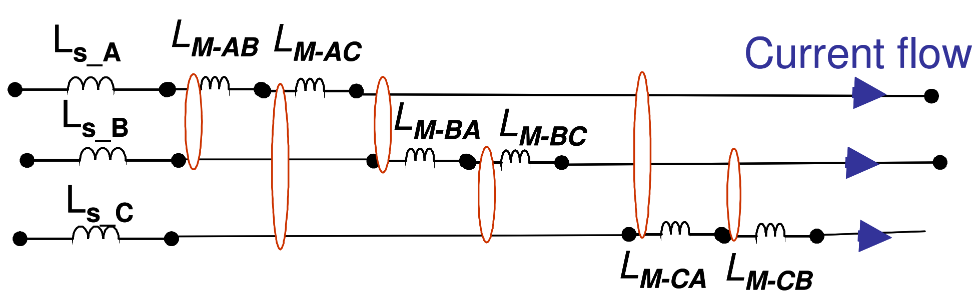
$$L_{readout} = \left(\frac{L_s + 2L_m}{3} \right)$$

Readout
Ltest_M @ 100 Hz

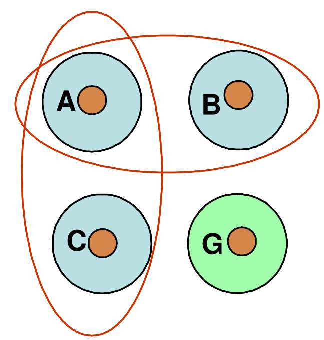
Physical Representation



Typical Phase A
"Ls" Circuit Representation

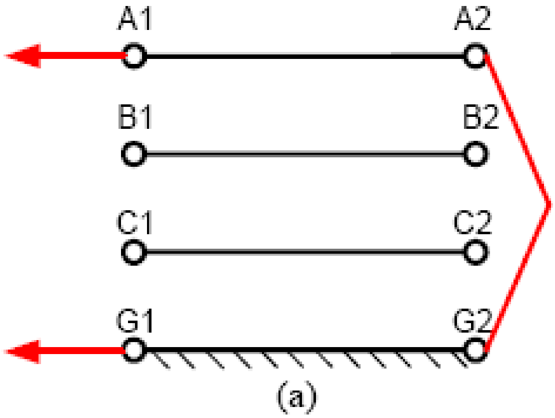


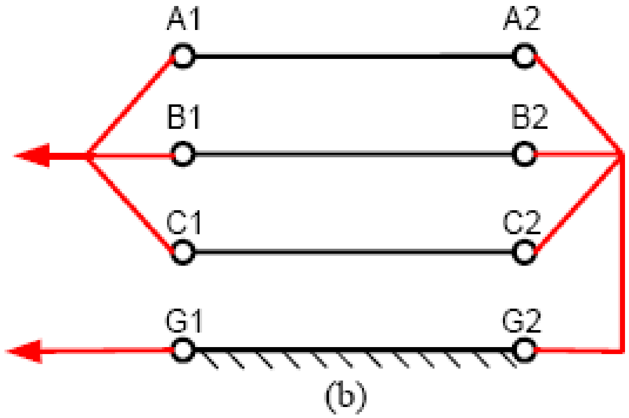
Typical Phase A
Mutual Flux Linkage



Common mode: Rs - Ls – Cp- Rp Inductance testing

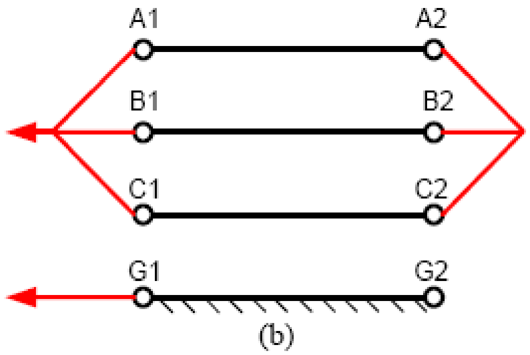
(a) Line-line two-wire (b) Line-line three-wire



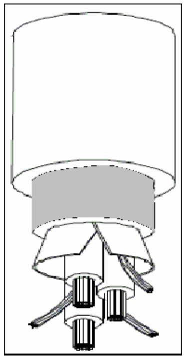


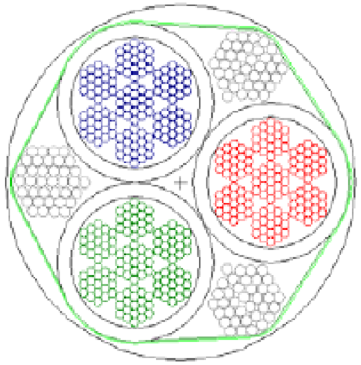
determine inductance Ls & series resistance Rs

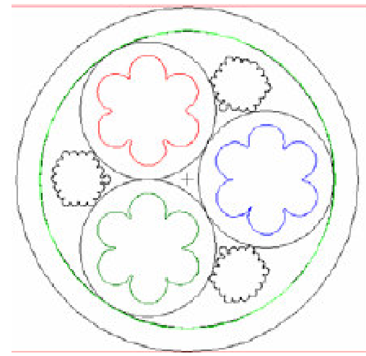
Cable configurations
to measure capacitance (Cp, Rp).
Common-mode line-ground three-wire.



Finite Element Analysis: R-L C matrix





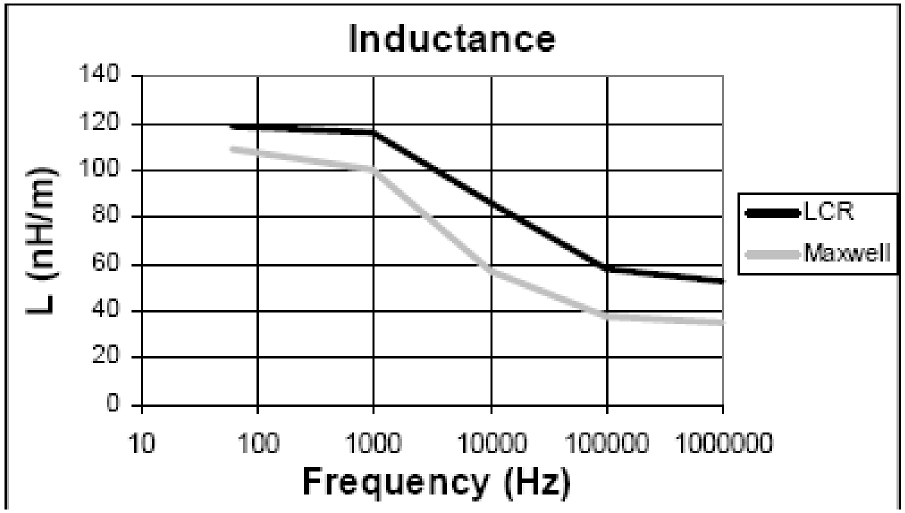


3D physical outline (b) Cross section geometry (c) Simplified FEA geometry

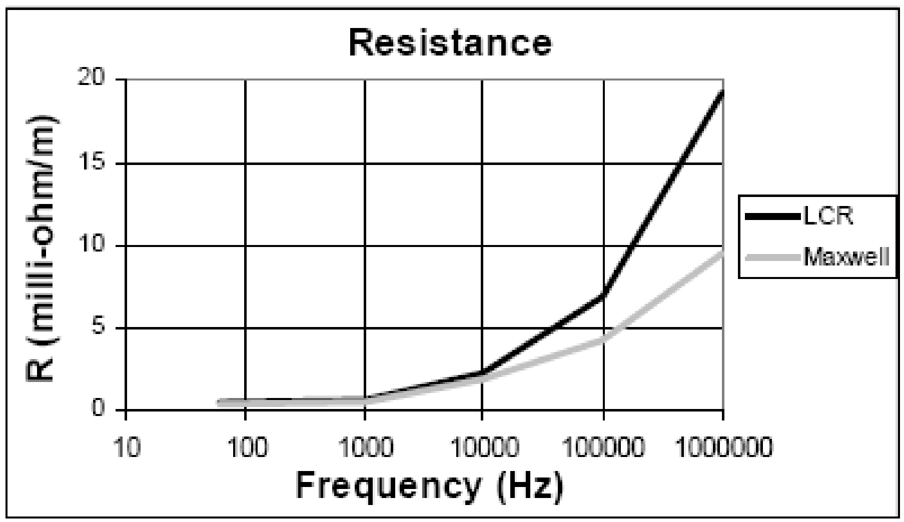
$$\mathbf{R} = \begin{bmatrix} R_g & R_{ga} & R_{gb} & R_{gc} \\ R_{ga} & R_a & R_{ab} & R_{ac} \\ R_{gb} & R_{ab} & R_b & R_{bc} \\ R_{gc} & R_{ac} & R_{bc} & R_c \end{bmatrix}, \quad \mathbf{L} = \begin{bmatrix} L_g & M_{ga} & M_{gb} & M_{gc} \\ M_{ga} & L_a & M_{ab} & M_{ac} \\ M_{gb} & M_{ab} & L_b & M_{bc} \\ M_{gc} & M_{ac} & M_{bc} & L_c \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} C_{ag} & C_{ab} & C_{ac} \\ C_{ab} & C_{bg} & C_{bc} \\ C_{ac} & C_{bc} & C_{cg} \end{bmatrix}$$

R and **L** matrices vary with frequency (*f*)
while the **C** matrix does not show significant change with *f*.

Finite Element Analysis: R-L C matrix



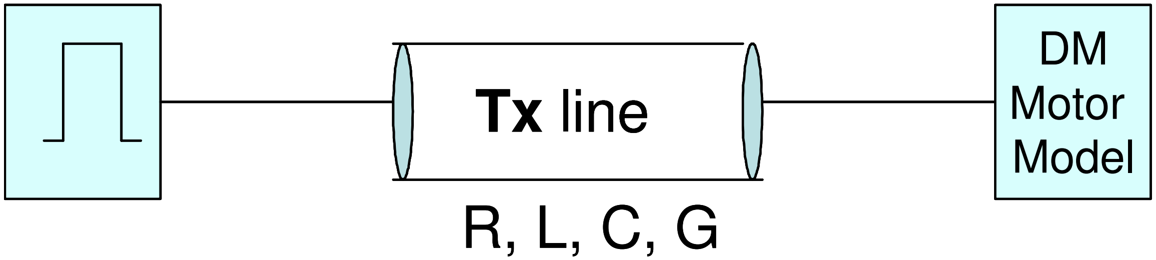
AC skin effect of inductance



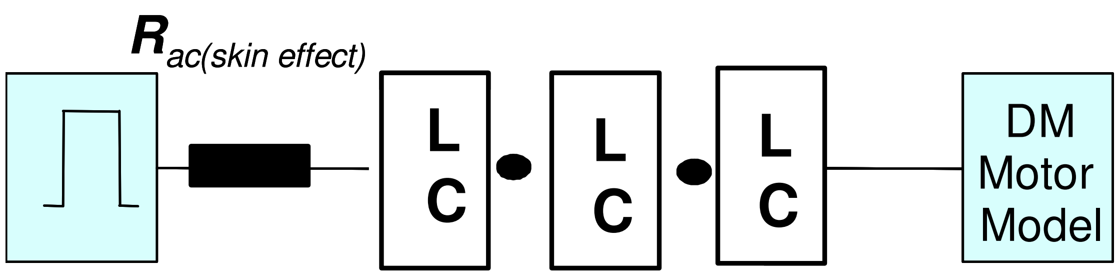
AC skin effect of resistance

Focus Cable: Inductance & resistance for line-line three-wire common mode

Comparison of Transmission line to Segment line Model:

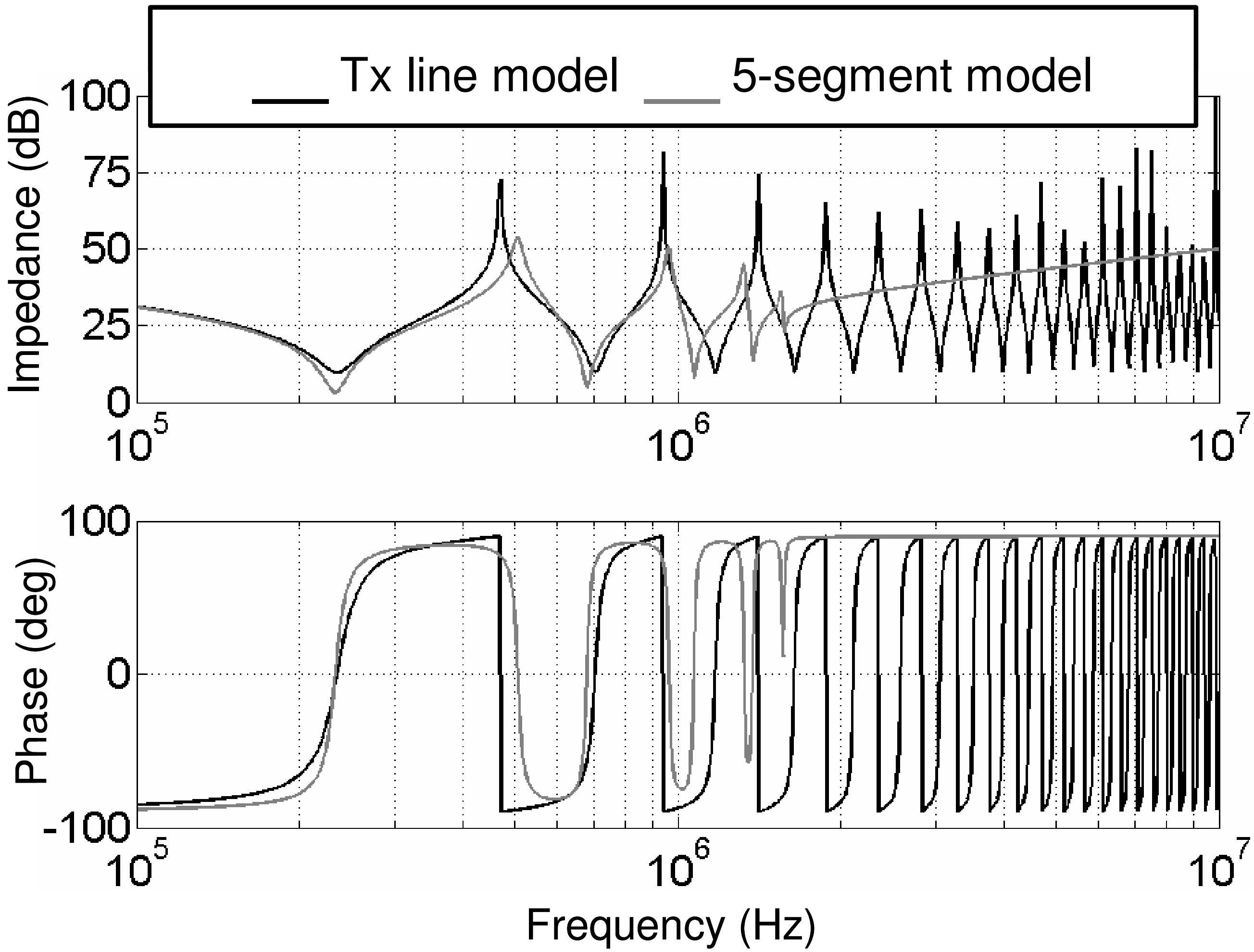


Case 1: Lossy line R = *Rdc*



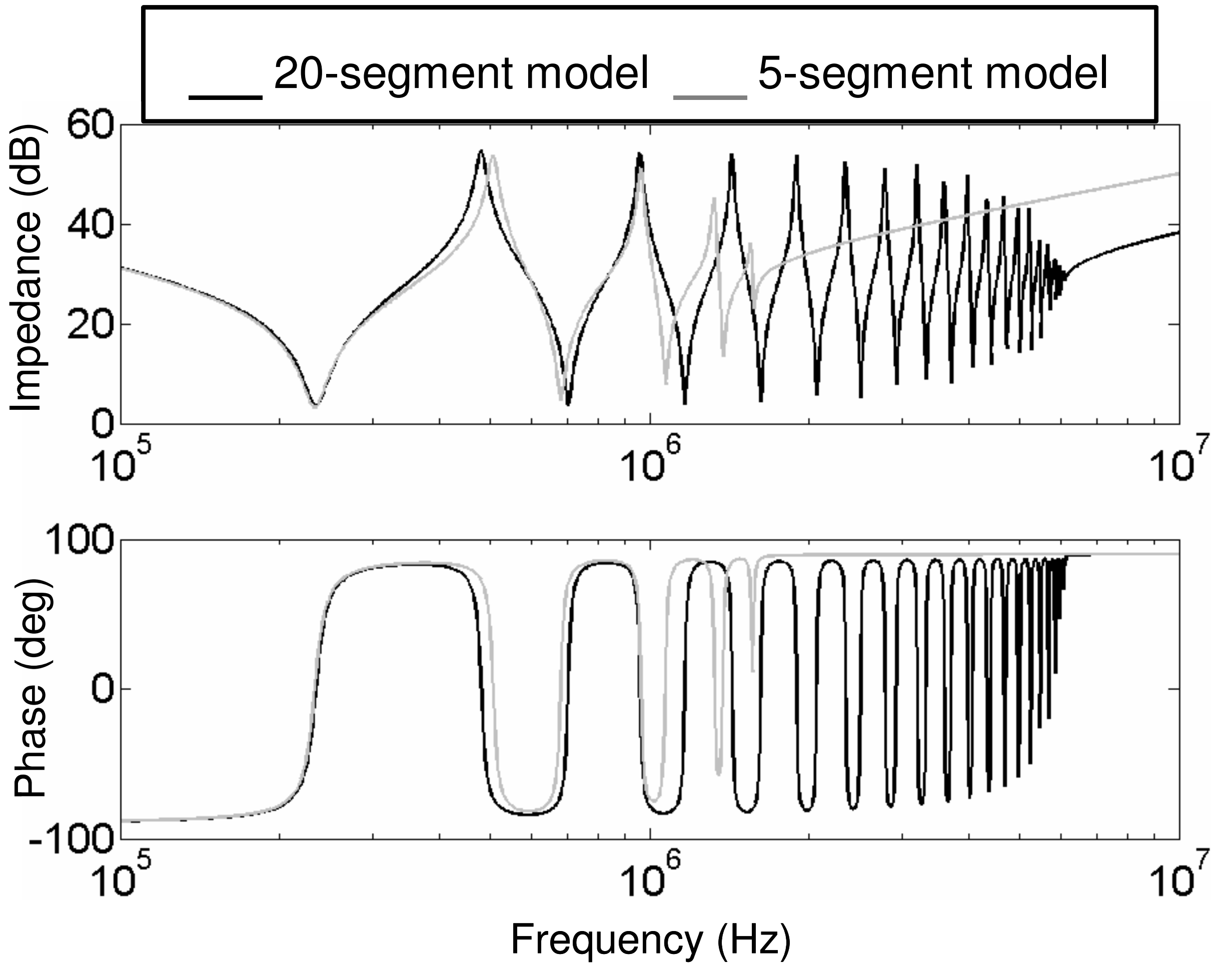
Case 5: Segmented line with *Rac(skin effect)* lumped at source: 5 or 20 segments

Comparison of Transmission line to Segment line Model:



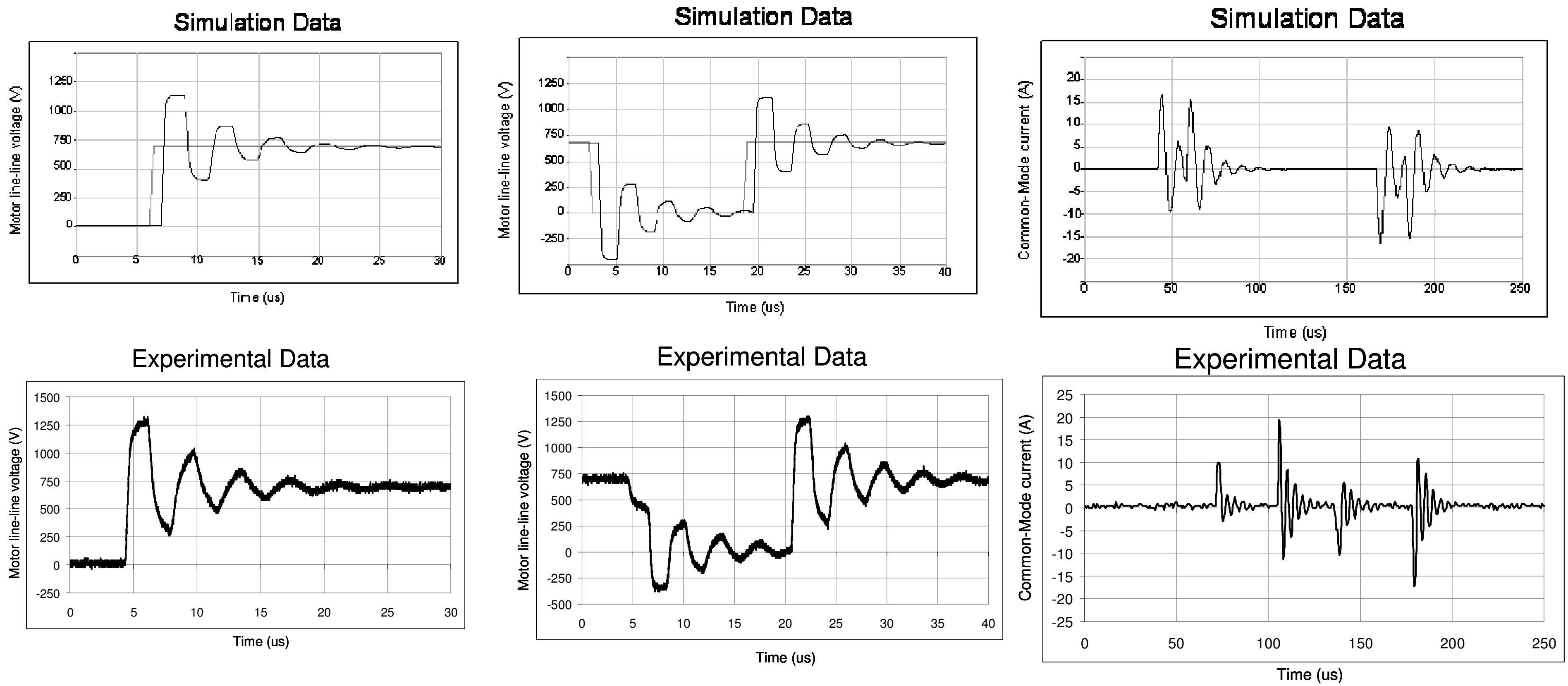
Magnitude and Phase comparison of Tx line and 5 segment line

Comparison of Transmission line to Segment line Model:



Magnitude and Phase comparison of 20 segment and 5 segment line

Comparison of Transmission line to Segment line Model:

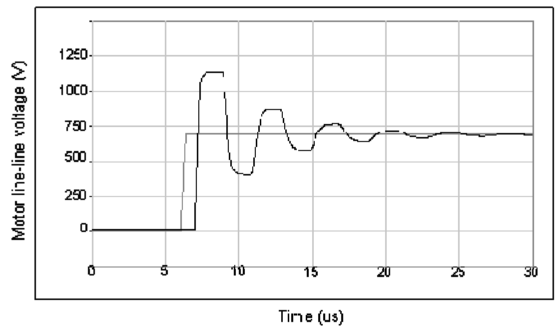


Measured vs.Simulated 460V 20 hp setup with #6 AWG braided shielded cable: DM reflected wave Voltage @ motor terminals, CM current to ground @ drive end

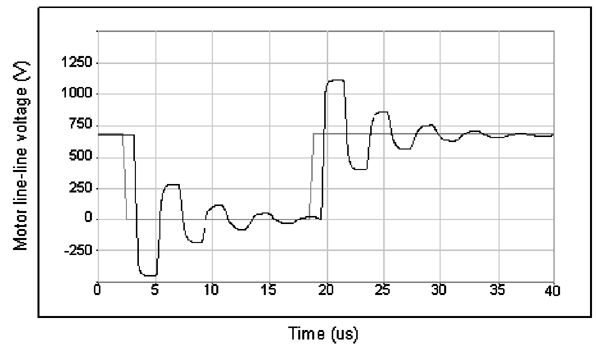
Conclusion: segment Model easier to simulate and is accurate

Comparison of Transmission line to Segment line Model:

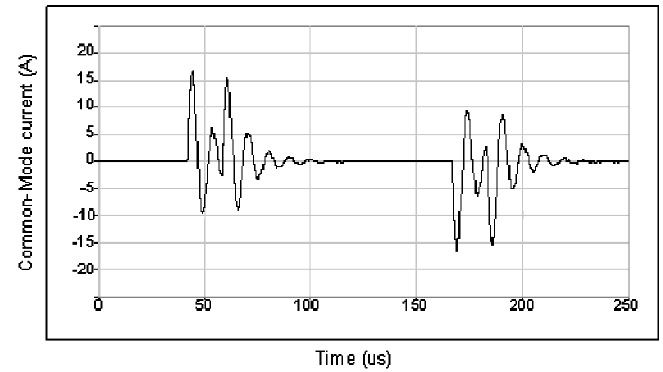
Simulation Data



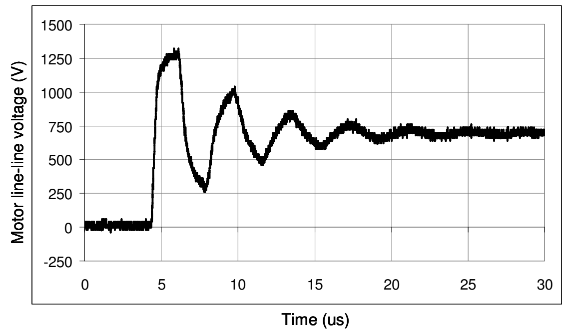
Simulation Data



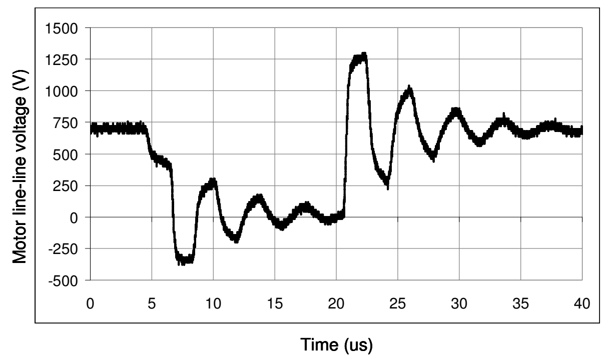
Simulation Data



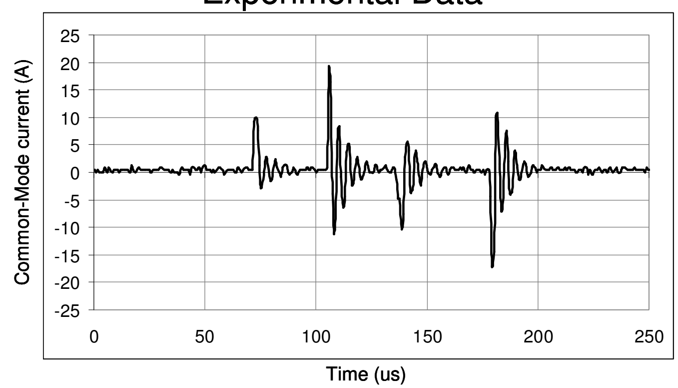
Experimental Data



Experimental Data



Experimental Data



Measured vs.Simulated 460V 20 hp setup with #6 AWG braided shielded cable: DM reflected wave Voltage @ motor terminals, CM current to ground @ drive end

Conclusion: segment Model easier to simulate and is accurate

EMC Guy Philosophy:

" When I was younger I knew everything……….

as I get older I realize I really don't know nothing "

Thanks !!

The opportunity is now for EV !!!!

Lets get Charged !!!!

Lets get Rolling !!!!