电力电子系统高频传导和辐射电磁干扰的分析和抑制

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电力电子系统高频传导干扰

传导干扰的产生，传播和高频传导干扰的抑制

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Content

I. Identify EMI sources and propagation paths

II. Some common mechanisms for high frequency (HF) conductive EMI

A. HF EMI due to the spectrum of EMI noise sources

B. HF DM EMI caused by inductor impedance valleys on DM propagation paths

C. HF CM EMI caused by the resonances and parasitic couplings on CM noise propagation paths

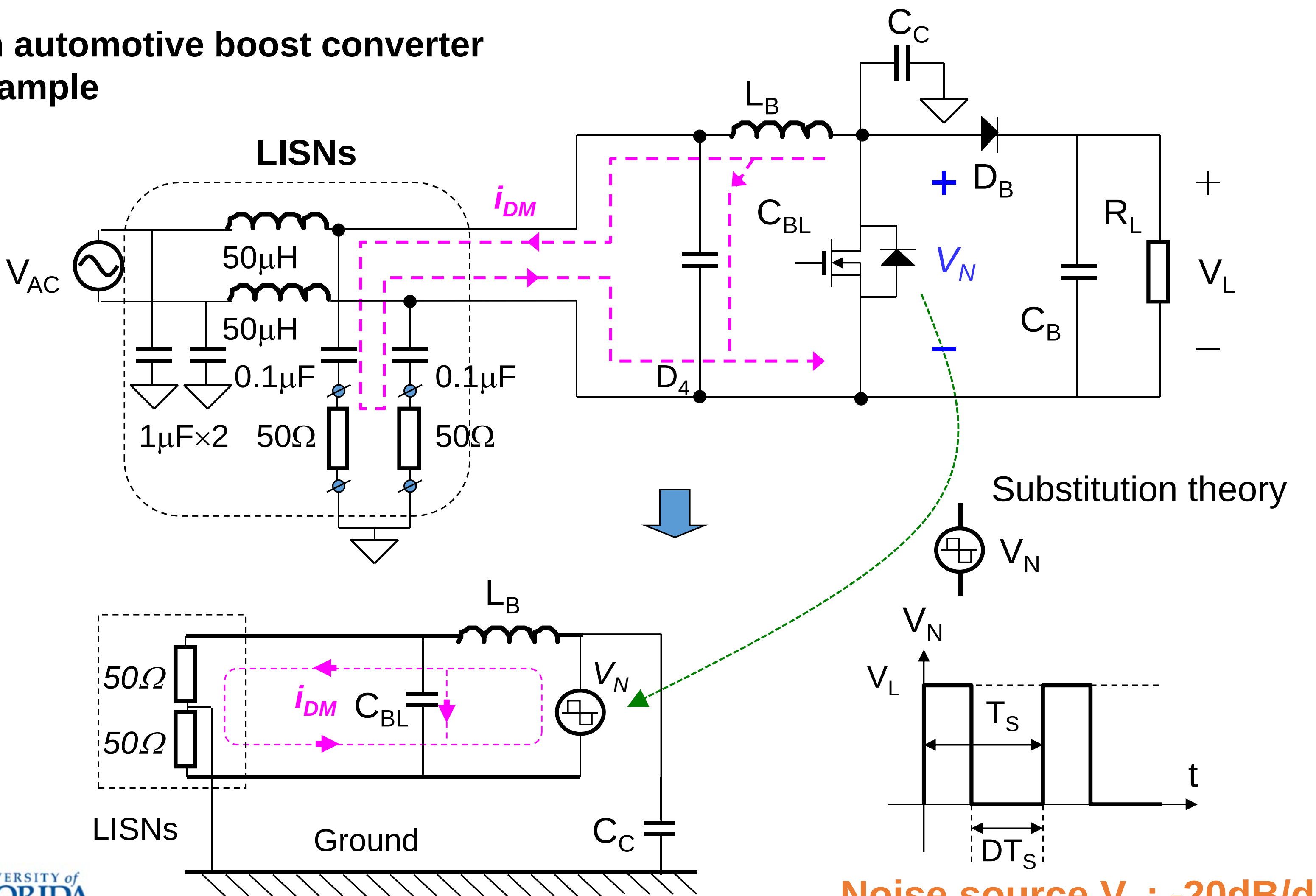
D. HF EMI due to parasitic near magnetic couplings with magnetic components

E. HF EMI due to bad PCB layouts

I. Identify EMI sources and propagation paths

Identify DM EMI Noise Sources and Propagation Paths

An automotive boost converter example



Noise source V_N: -20dB/dec

- **DM EMI noise sources are equivalent voltage or current sources for switching devices**
- **DM propagation paths include all impedances on and between two power delivery lines**

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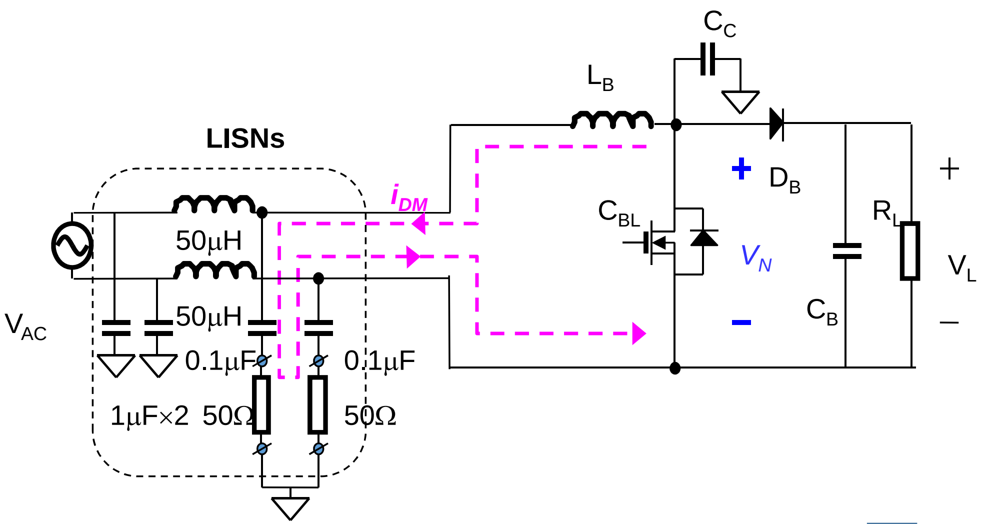
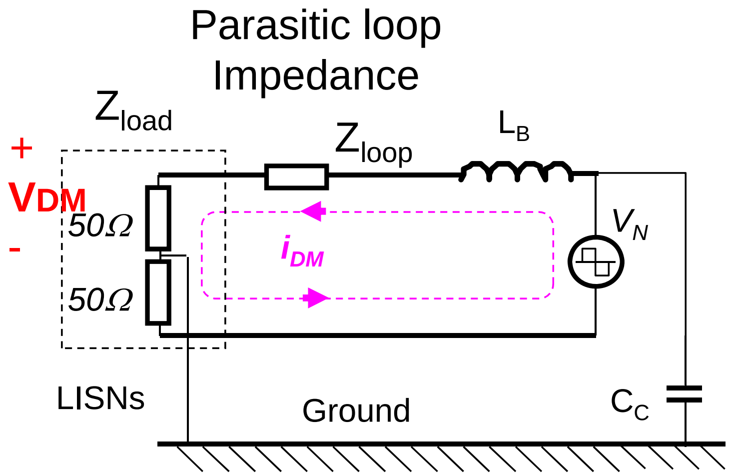
Effects of Noise Source and Path Impedance on DM Noise





DM Noise Spectrum:

$$20\log V_{DM} = 20\log\left(\frac{0.5Z_{load}}{Z_{Load}+Z_{LB}+Z_{loop}} \bullet V_N\right)$$

$$= 20\log V_N - 20\log(Z_{Load}+Z_{LB}+Z_{loop}) + 14\log Z_{Load}$$

Noise source **Path Impedance**

- **DM EMI spectrum is determined by both switching waveforms and impedances on propagation paths**

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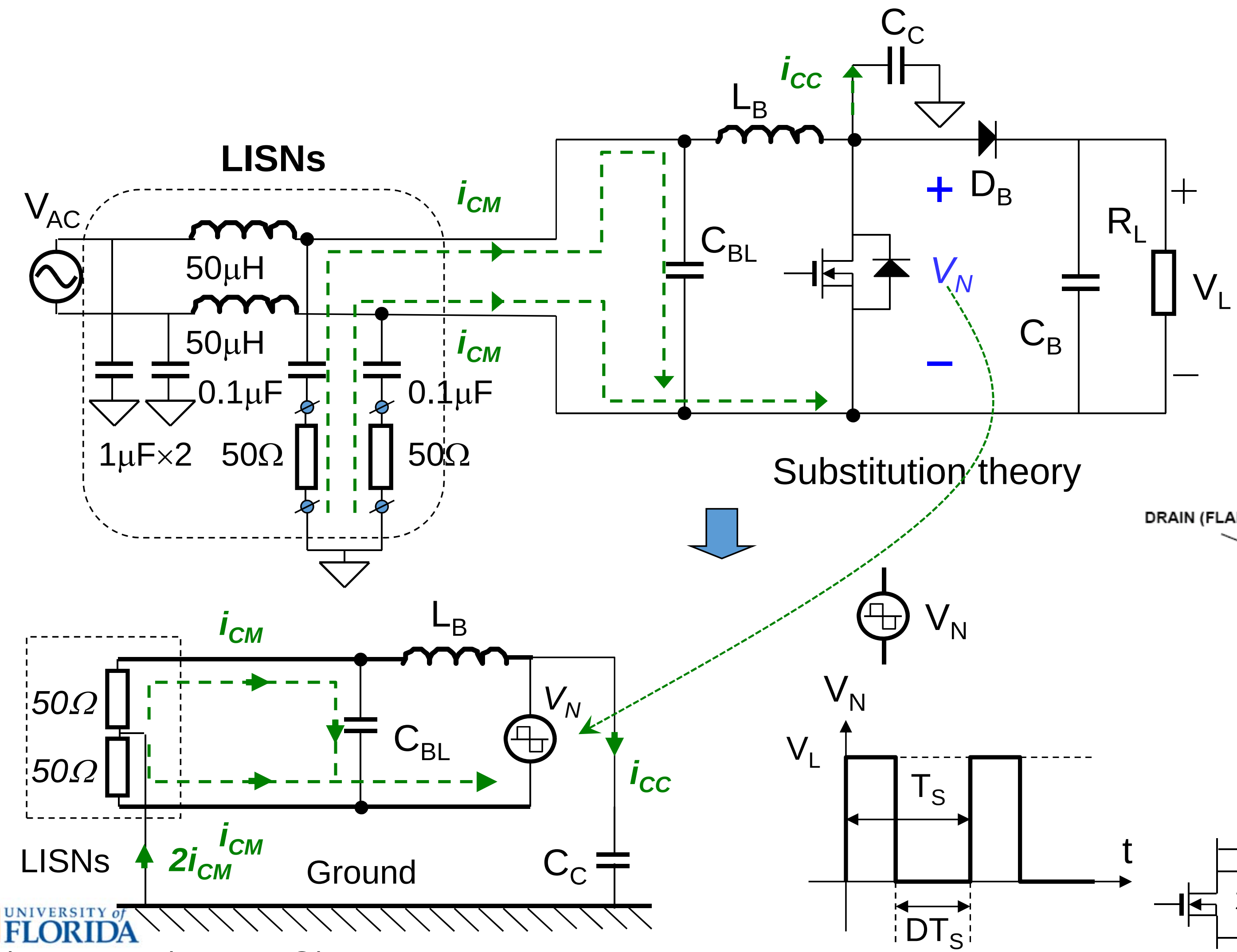
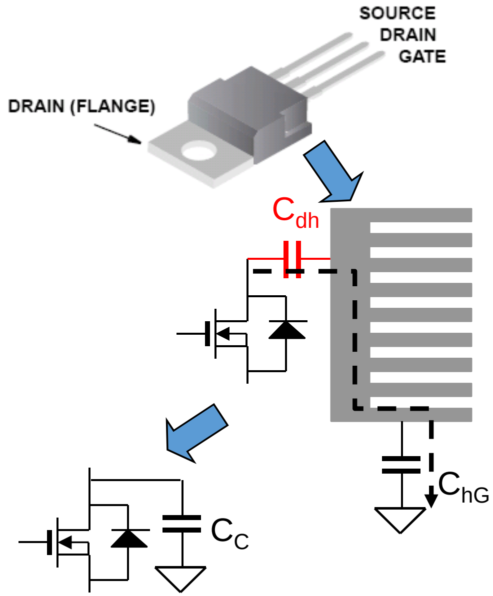
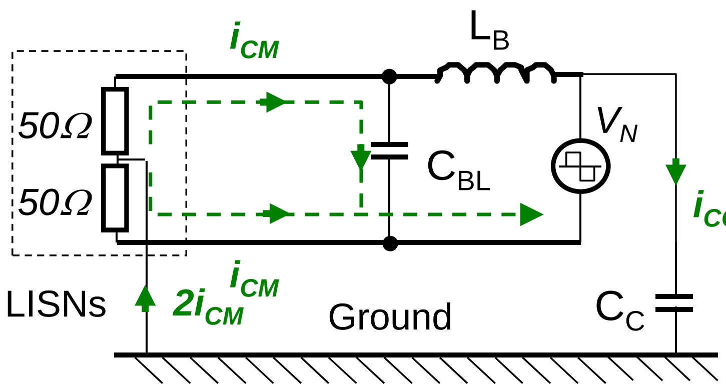
Identify CM EMI Noise Sources and Propagation Paths

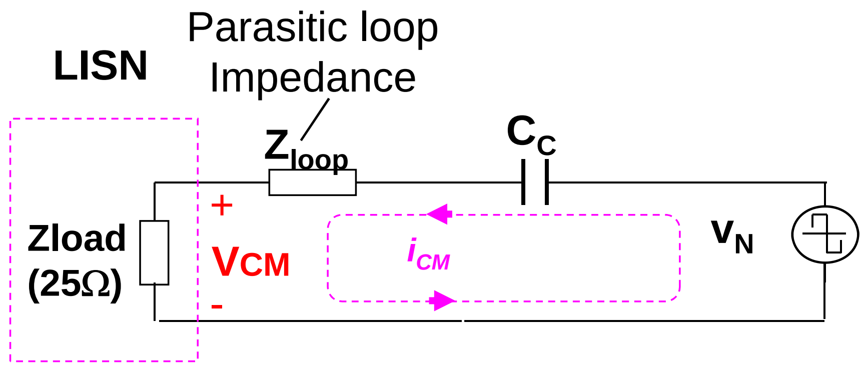


- **CM EMI noise sources are equivalent voltage or current sources for switching devices**
- **CM EMI flows from voltage pulsating nodes to parasitic capacitance, to ground and back to the main circuit.**



Effects of Noise Source and Path Impedance on CM Noise





$$20\log V_{CM} = 20\log\left\{\frac{Z_{Load}}{Z_{Cc}+Z_{loop}+Z_{Load}}V_N\right\}$$

$$\approx 20\log V_N - 20\log(Z_{Cc}+Z_{loop}+Z_{Load}) + 20\log Z_{Load}$$

Noise source **Path Impedance**

- **CM EMI spectrum is determined by both switching waveforms and impedances on propagation paths**

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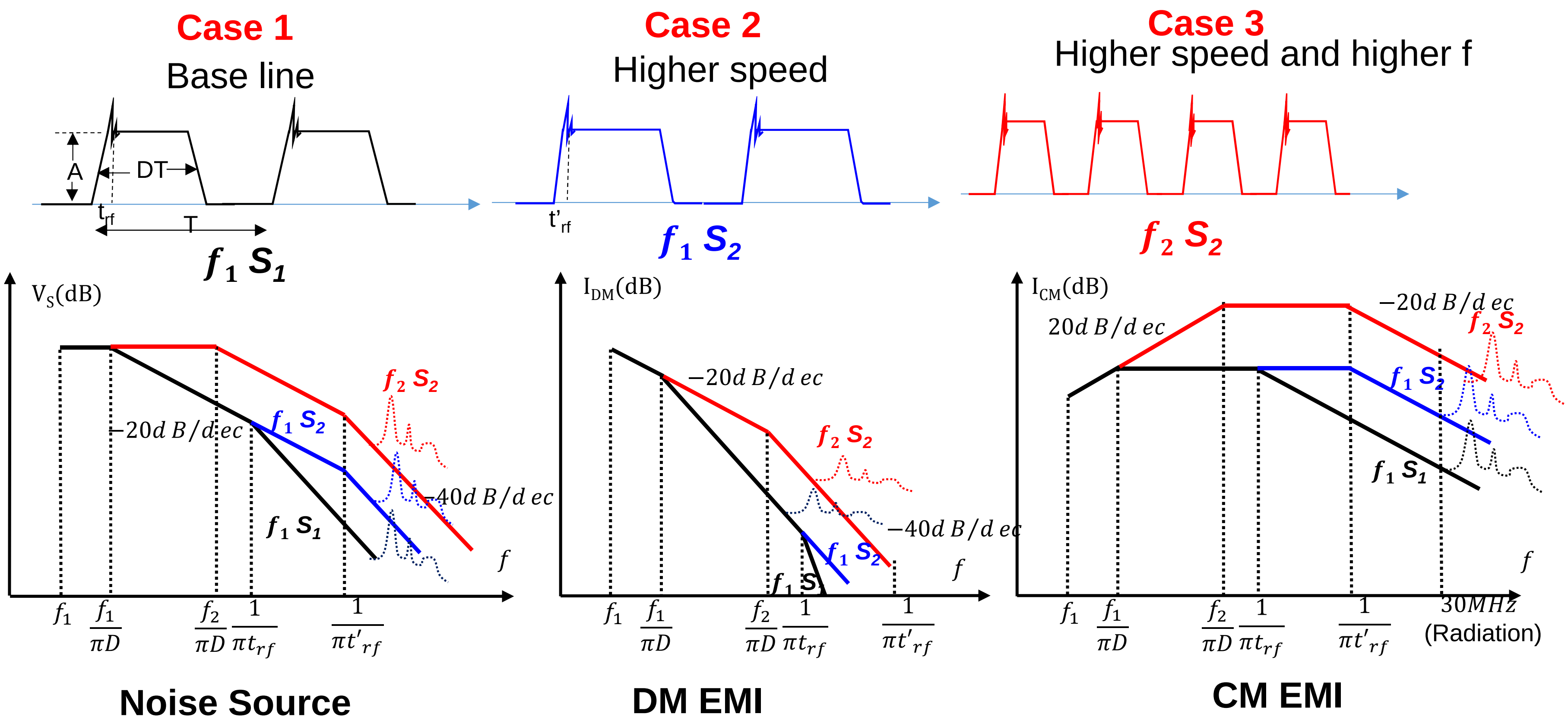
II. Some Common Mechanisms for High Frequency (HF) EMI

A. Effects of noise sources: switching frequency, speed and ringing on EMI spectrum (for the boost converter case)

Switching frequency f=1/T: $f_2 > f_1$ **Speed $S=A/t_{rf}$: $S_2>S_1$**



- **Higher speed and higher f -> CM and radiative EMI are more significant**

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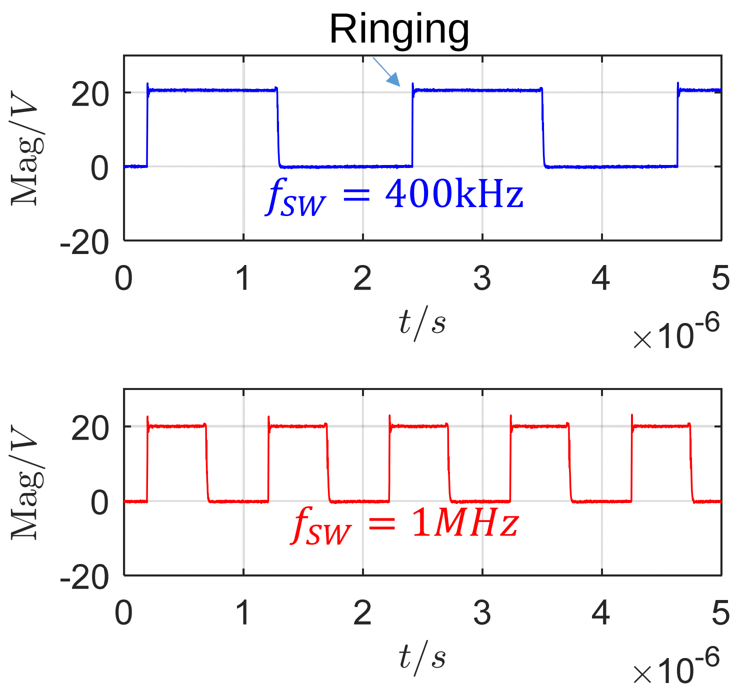
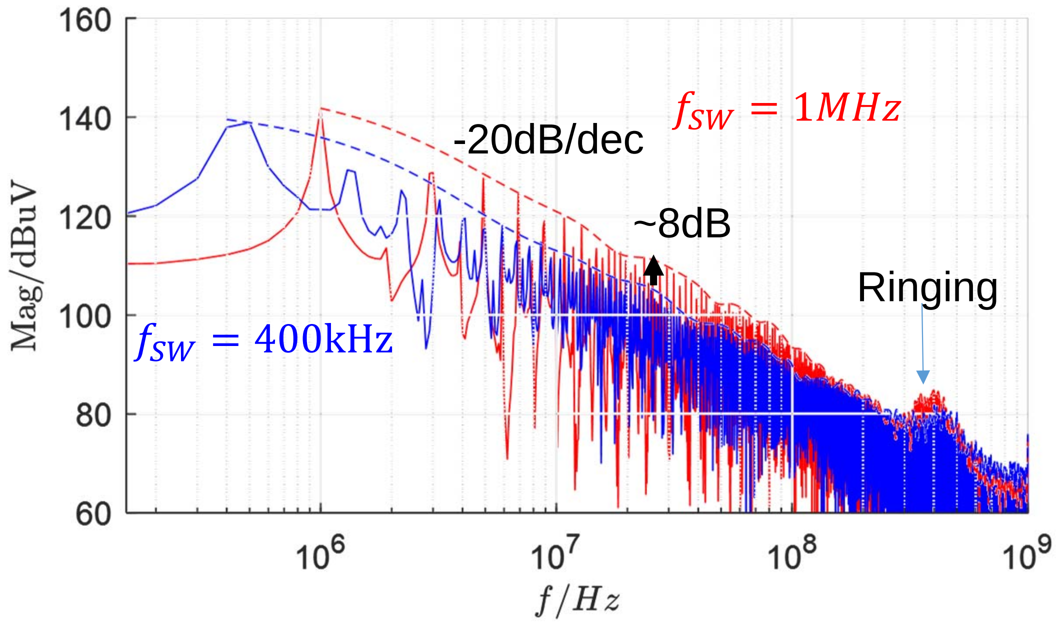
Measured Noise Source Waveforms and Spectrum at Different Frequency but Similar Speed





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Technical Solutions based on Noise Source Spectrum

1. Try to use Monolithic solution like MPQ4436 which has very low ringing

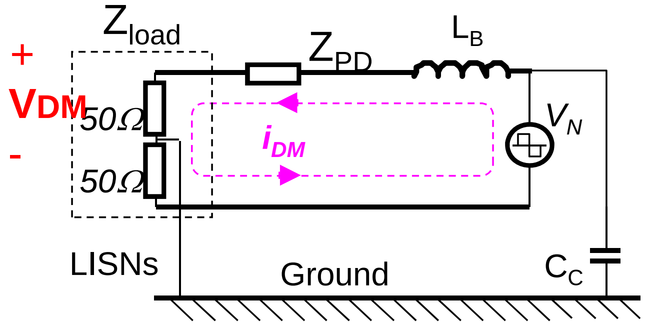
2. Try to utilize the energy stored in parasitics to reduce ring:
   Using soft switching technique such as ZVS and active clamp to absorb parasitic ringing due to parasitics

3. Trade off between switching speed and switching power loss
   Control switching speed by control driving currents

4. Reduce switching frequencies with both EMI and efficiency benefits, possibly power density benefit too

5. Frequency jittering to spread EMI energy. MPS has the most effective jittering strategy

B. HF EMI due to Inductor Impedance on DM EMI Propagation Paths

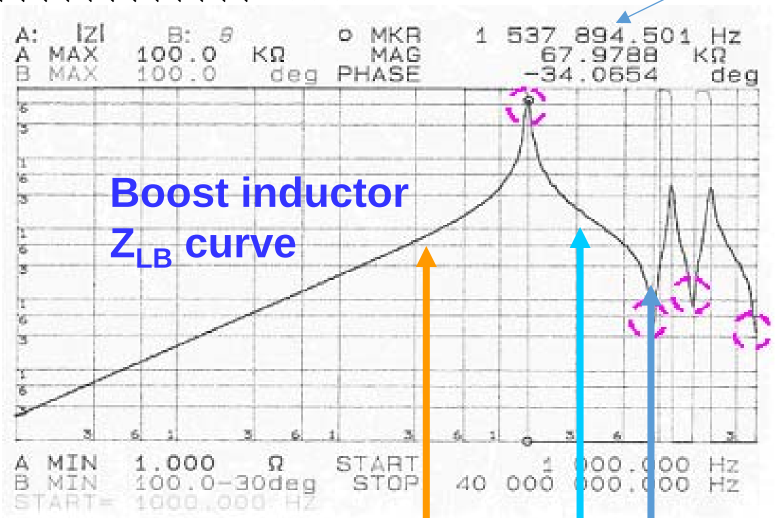


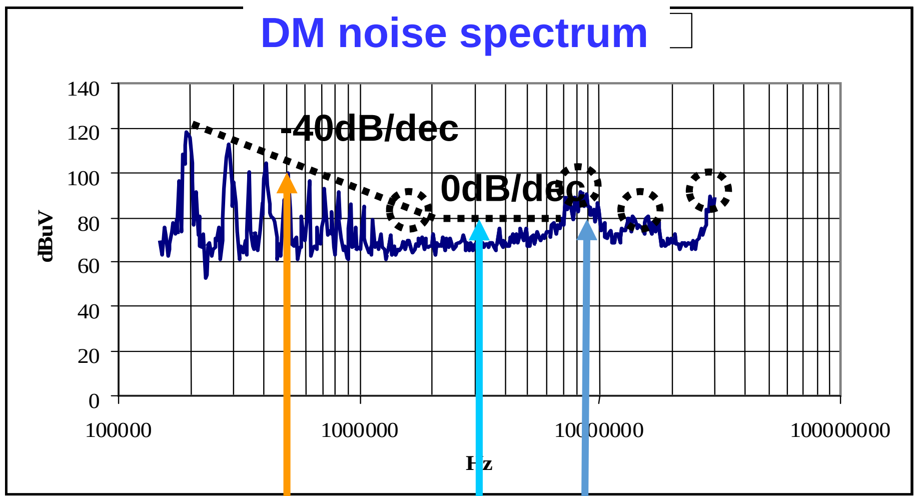
$$20\log V_{DM} = 20\log\left(\frac{0.5Z_{load}}{Z_{Load}+Z_{LB}+Z_{loop}}\bullet V_N\right)$$

$$\approx 20\log V_N - 20\log Z_{LB} + 14\log Z_{Load}$$

-20dB/dec

- **Noise source and Inductor impedance shape the DM EMI spectrum**





20dB/dec

Valleys

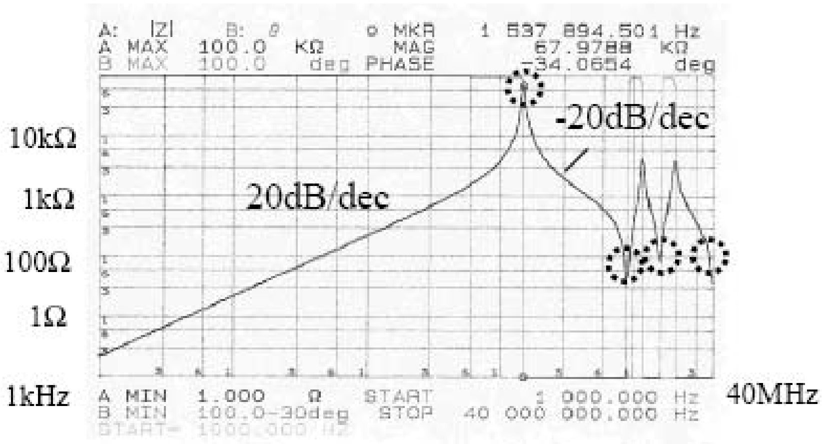
-20dB/dec

-20-20 = -40dB/dec

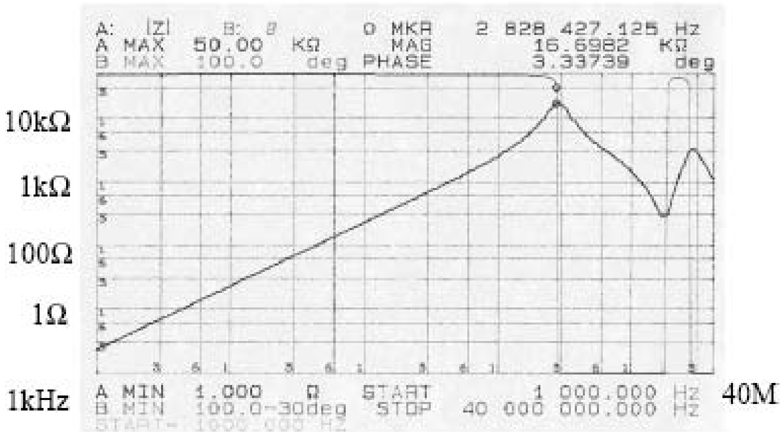
-20-(-20) = 0dB/dec

Valleys -> Spikes

Reduce HF DM EMI with Inductor Design



Original (Cool Mu)



Redesigned (Iron Powder)

Core materials:

Original: Cool Mu; ur=60

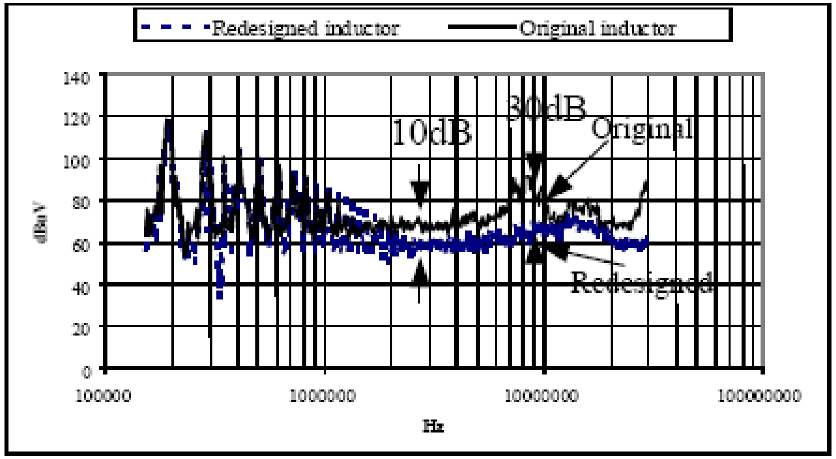
Redesigned: Iron Powder; ur=100

(1) Higher HF core loss(0.46W higher);

----Higher damping at resonant frequencies

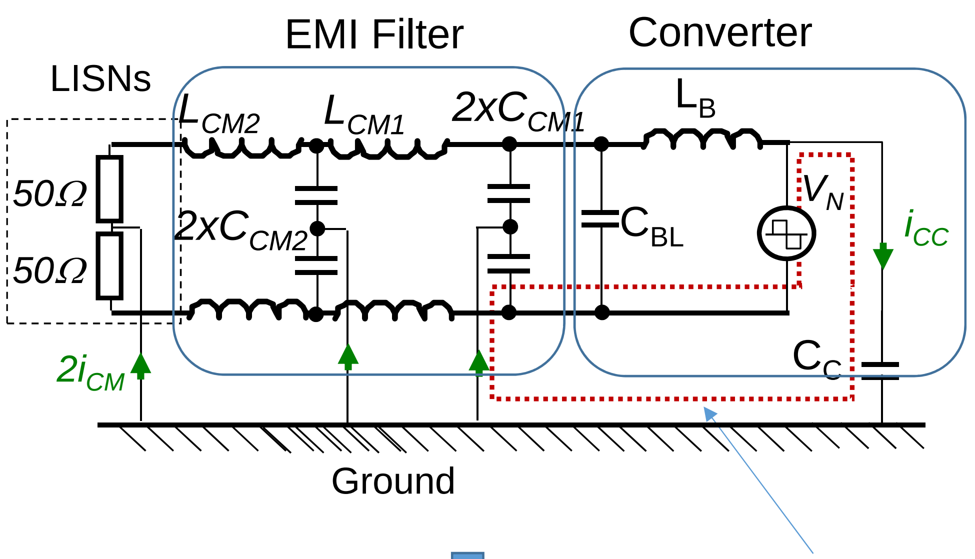
(2) Higher permeability therefore fewer number of turns and smaller parasitic capacitances

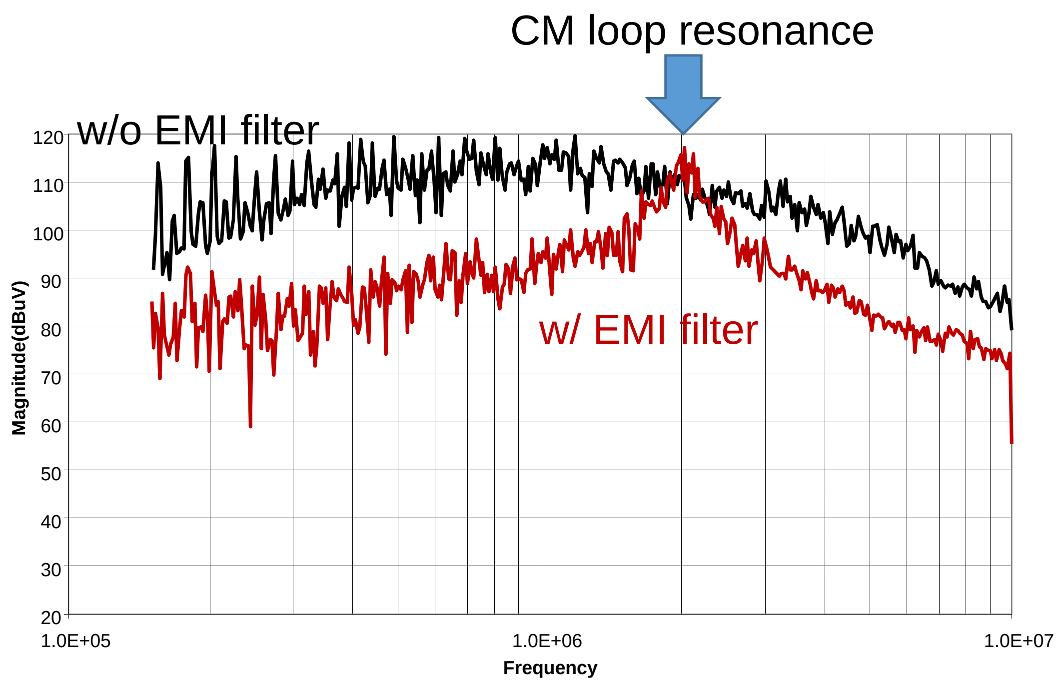
----Higher first peak frequency. Extending self-attenuation to higher frequency.

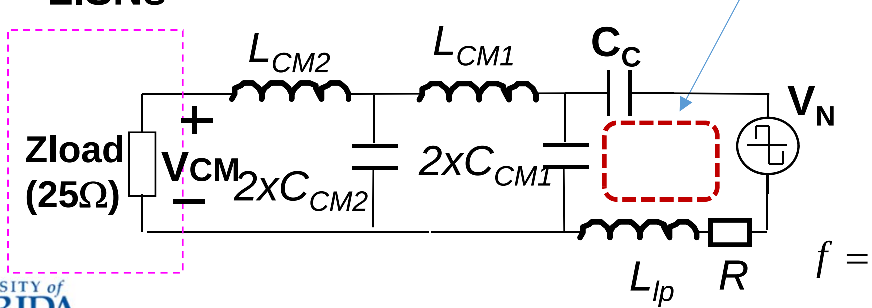


- **Lossy inductor is good for HF EMI reduction**
- **Always sweep inductor impedance**

C. HF EMI due to the CM resonance of EMI filter and the converter







- **CM loop resonance can generate HF spikes**

$$f = \frac{1}{\sqrt{L_{lp}C_C}}; Q = \frac{1}{R}\sqrt{\frac{L_{lp}}{C_C}}$$

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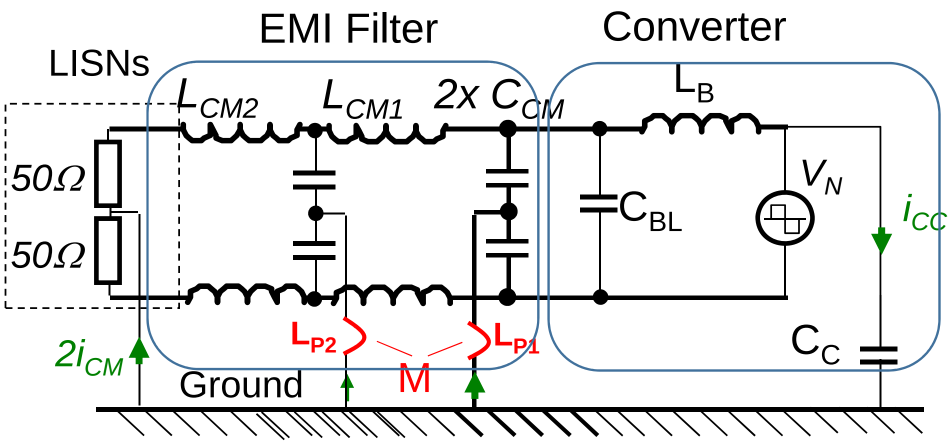
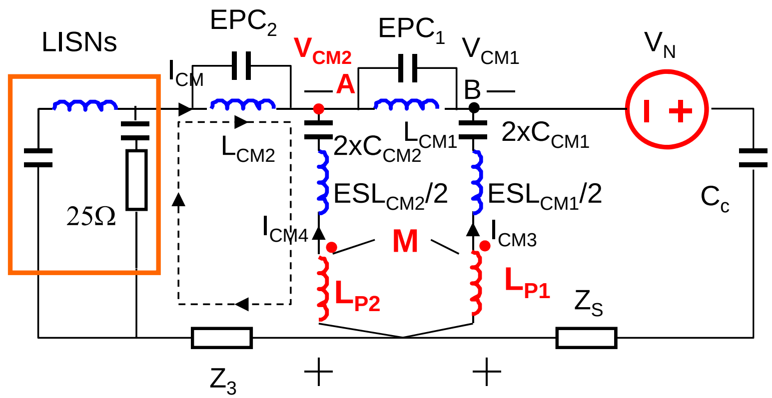
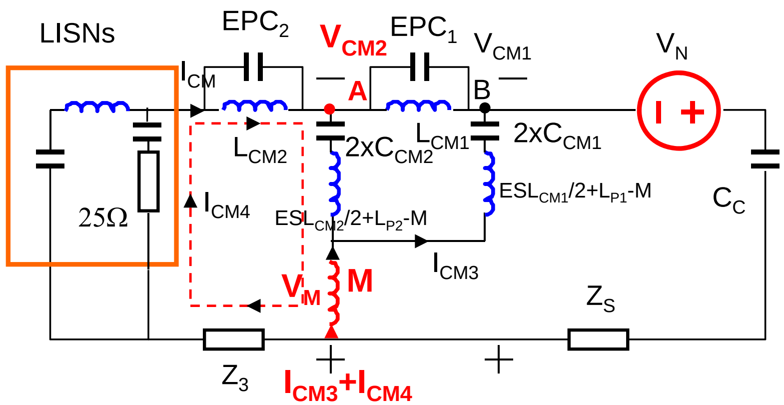
HF EMI due to the coupling between grounding paths







Noise is amplified by n times:

Lp's effect **M's effect**

$$n \approx \frac{2(L_{P2}-M)}{ESL_{CM2}} + 2\frac{I_{CM3}}{I_{CM4}}\frac{M}{ESL_{CM2}}$$

- **M's effects are amplified by I_{CM3}/I_{CM4} times, I_{CM3}/I_{CM4} =40dB/dec,**
- **M's effects would be dominant at HF**

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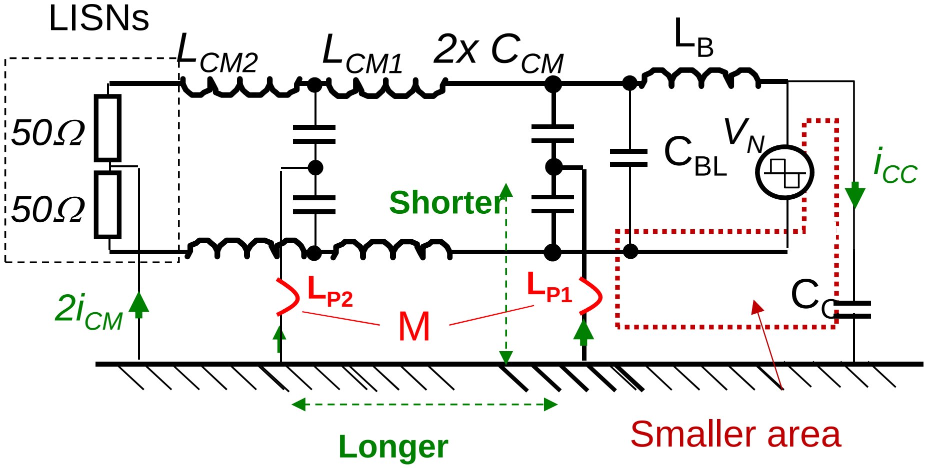
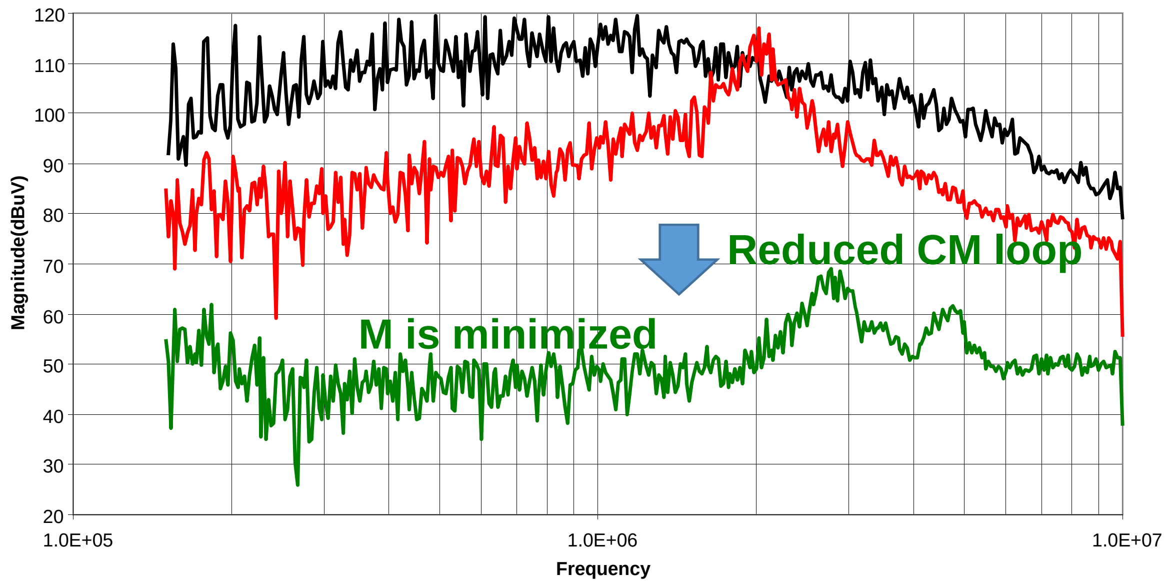
Techniques to reduce CM resonance and coupling between grounding Paths

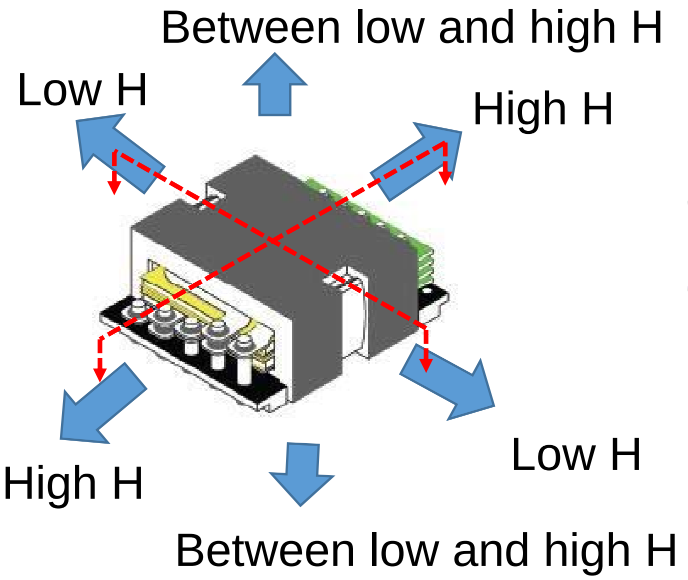
- **Reduce converter input CM loop area**
- **Move two grounding paths far away**
- **Reduce lengths of grounding paths**

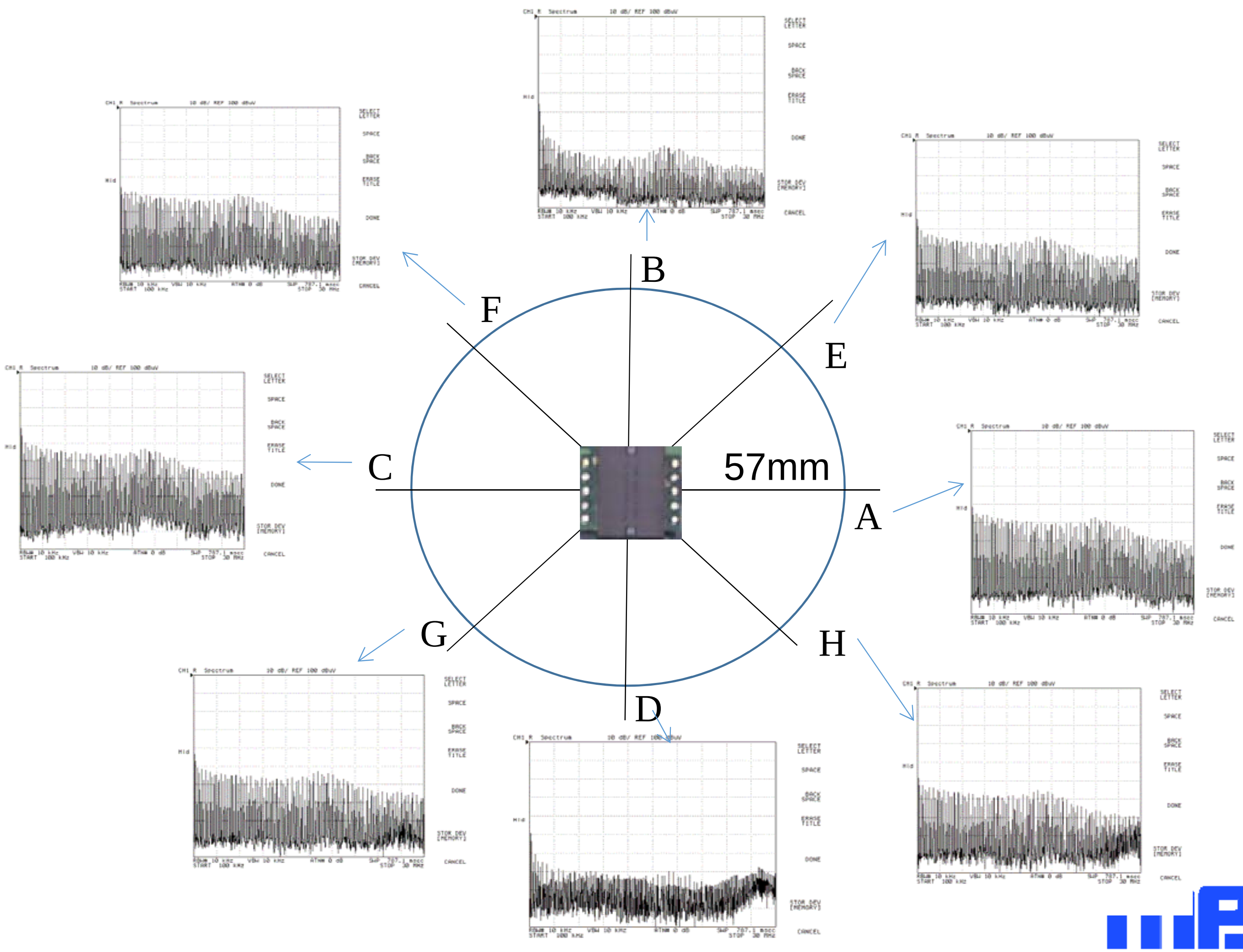




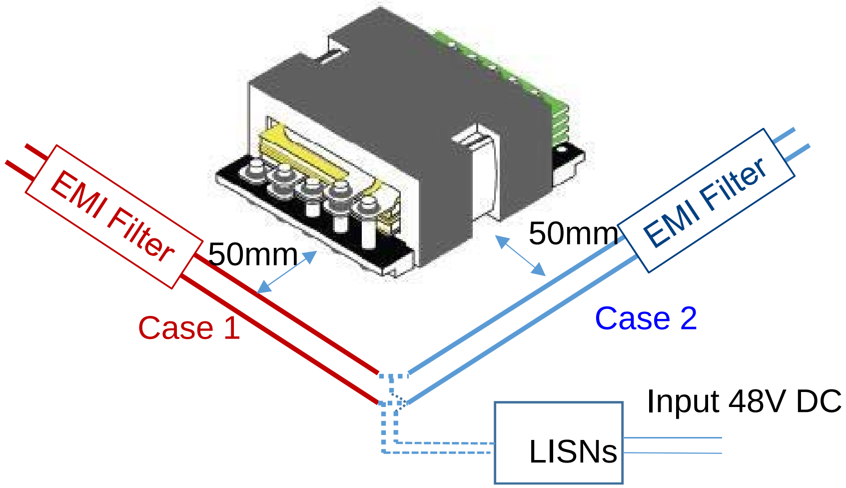
D. High Frequency CM Noise due to Parasitic Couplings with Magnetic Components

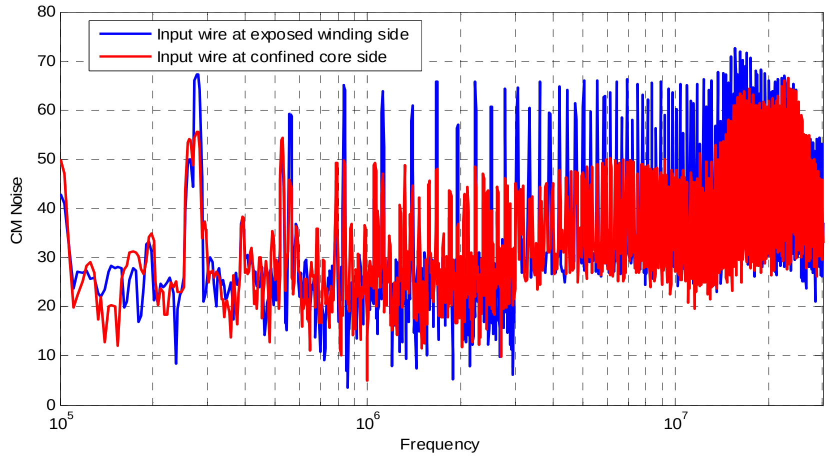
A planar transformer example

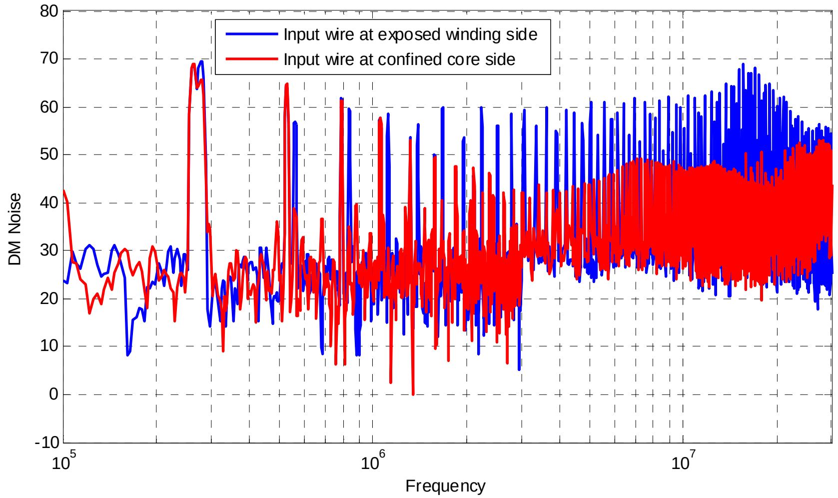




High Frequency CM EMI due to Magnetic Couplings







- **The winding openings of a transformer have high near magnetic field**
- **Avoid sensitive circuits close to winding openings**

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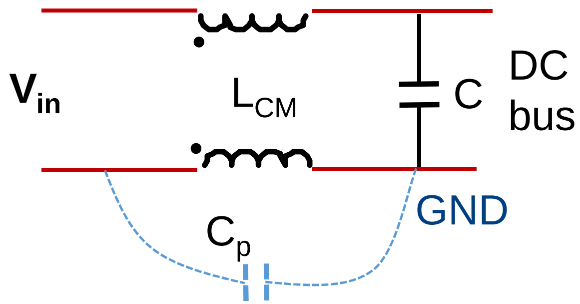
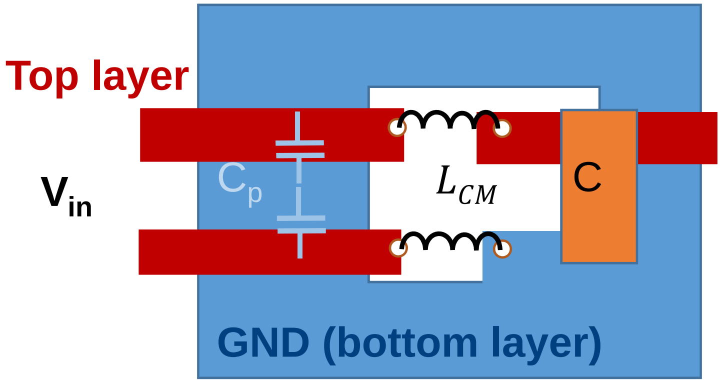
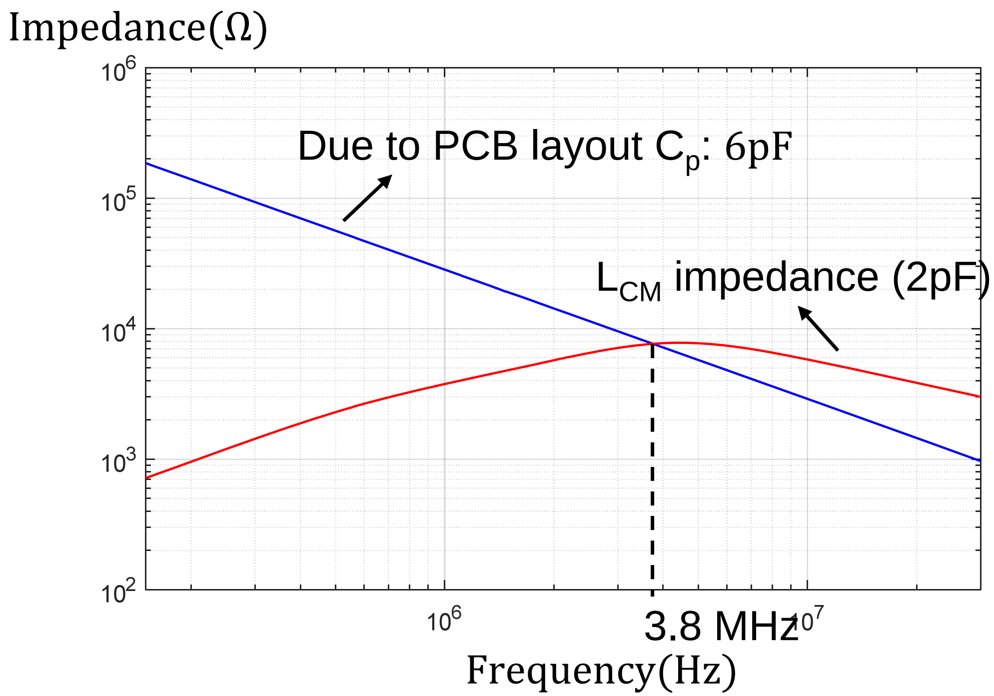
E. High Frequency EMI due to PCB Layout







- **If the grounding layer is not quiet, the grounding layer should not be close to the sensitive input**

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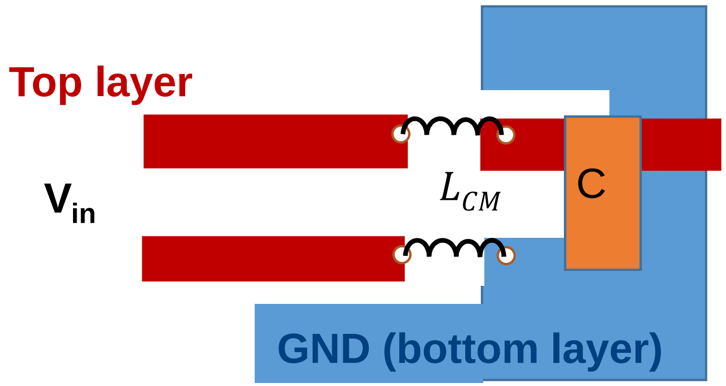
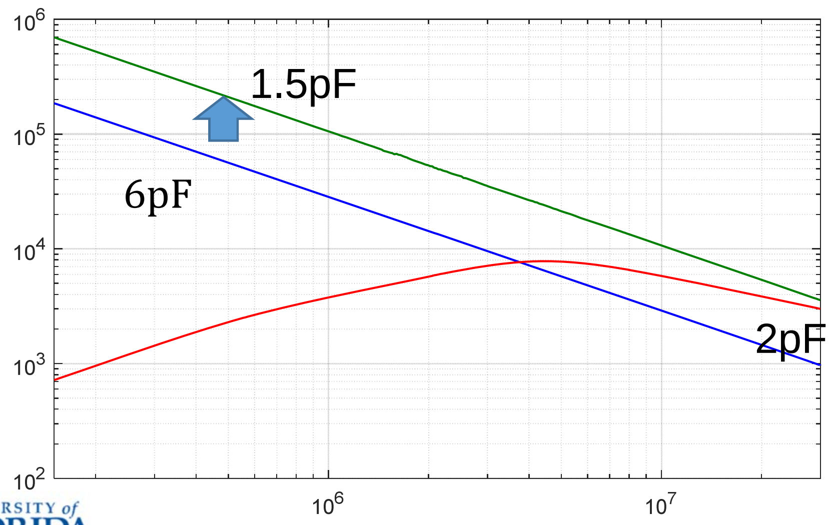
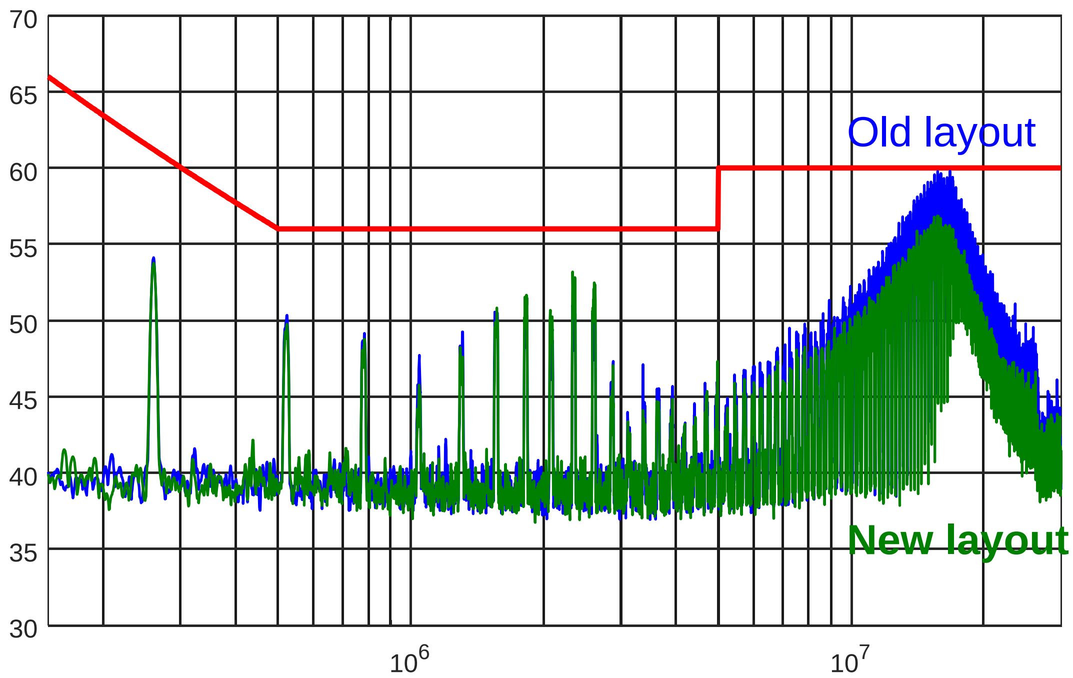
Improve PCB Layout to reduce High Frequency EMI







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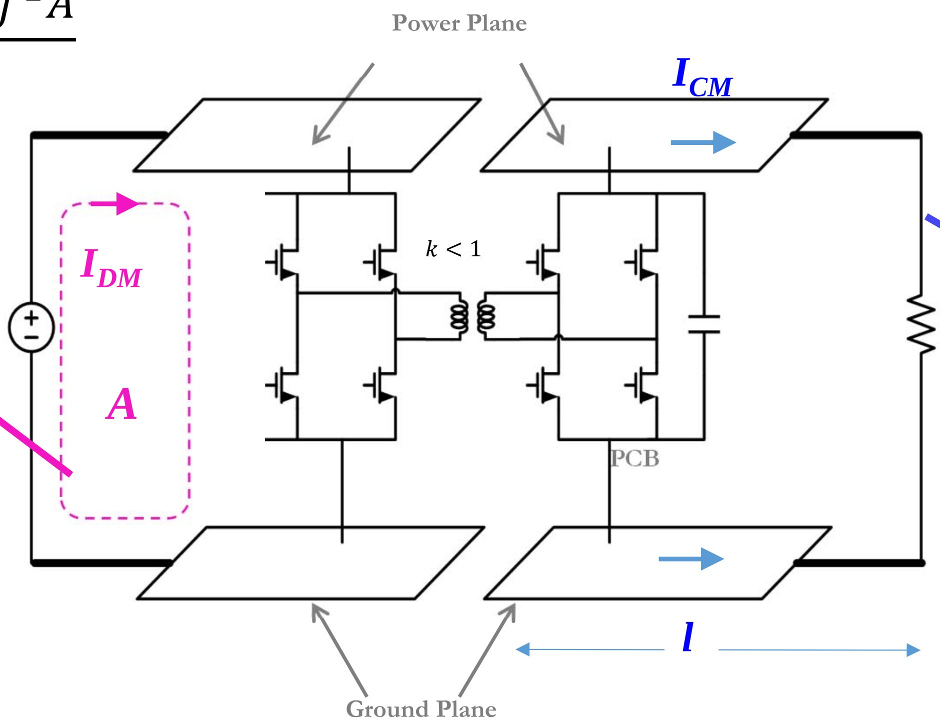
Content

I. DM and CM currents, which contributes more to far field radiation?

$$E_{DM} = \frac{131.5 \times 10^{-16} I_{DM} f^2 A}{r}$$

$$E_{CM} = \frac{2\pi \times 10^{-7} I_{CM} f l}{r}$$

$$E_{DM} \propto \frac{A I_{DM} \omega^2}{r}$$

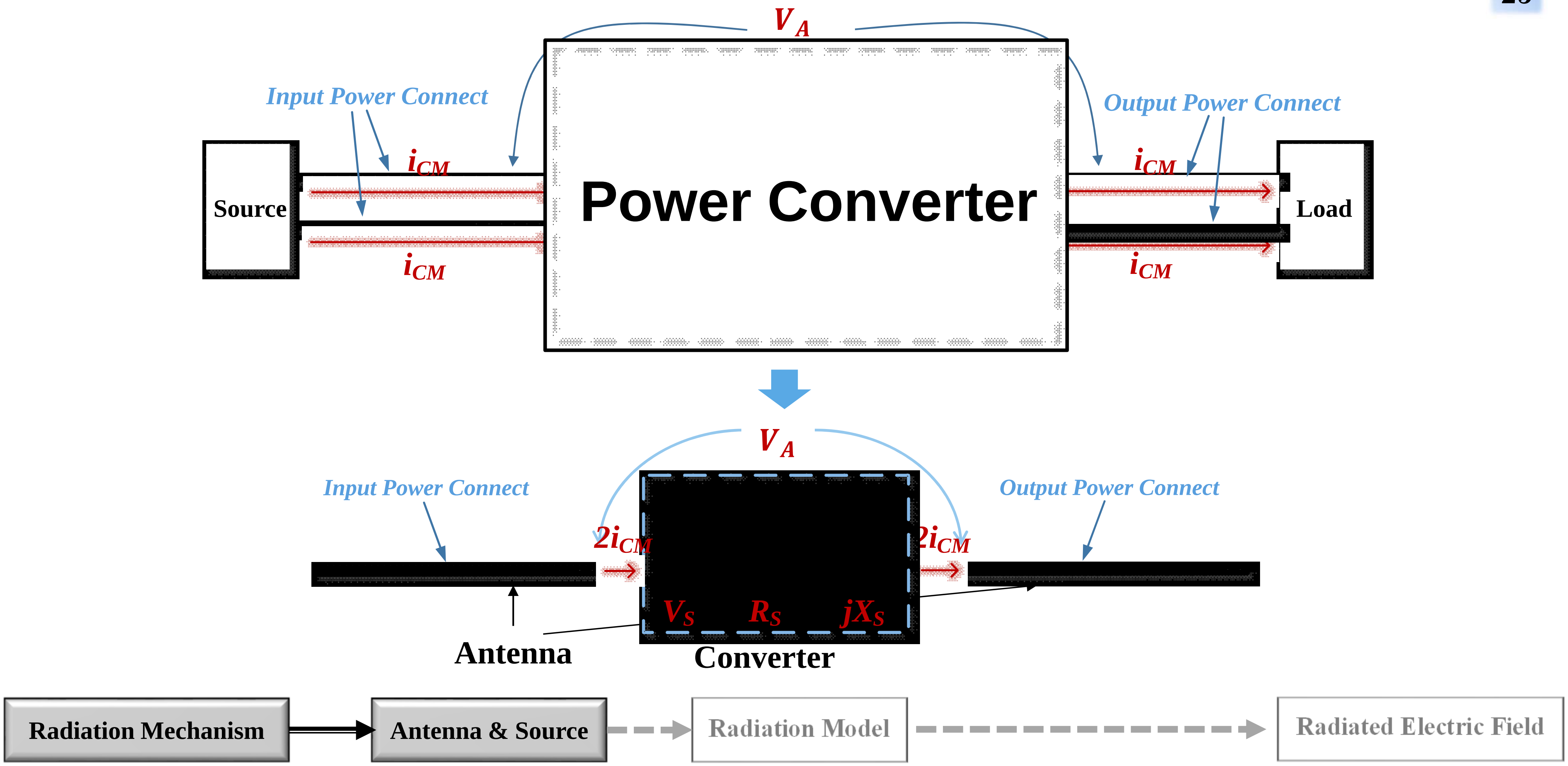


$$E_{CM} \propto \frac{\omega I l}{r}$$

$$\frac{E_{DM}}{E_{CM}} = 2.1 \times 10^{-8} \times f \times \frac{A}{l} \times \frac{I_{DM}}{I_{CM}}$$

- **Radiation due to CM current is usually dominant if AI_{DM}/lI_{CM} is not too big at HF**

II. Radiation Model for Power Converters



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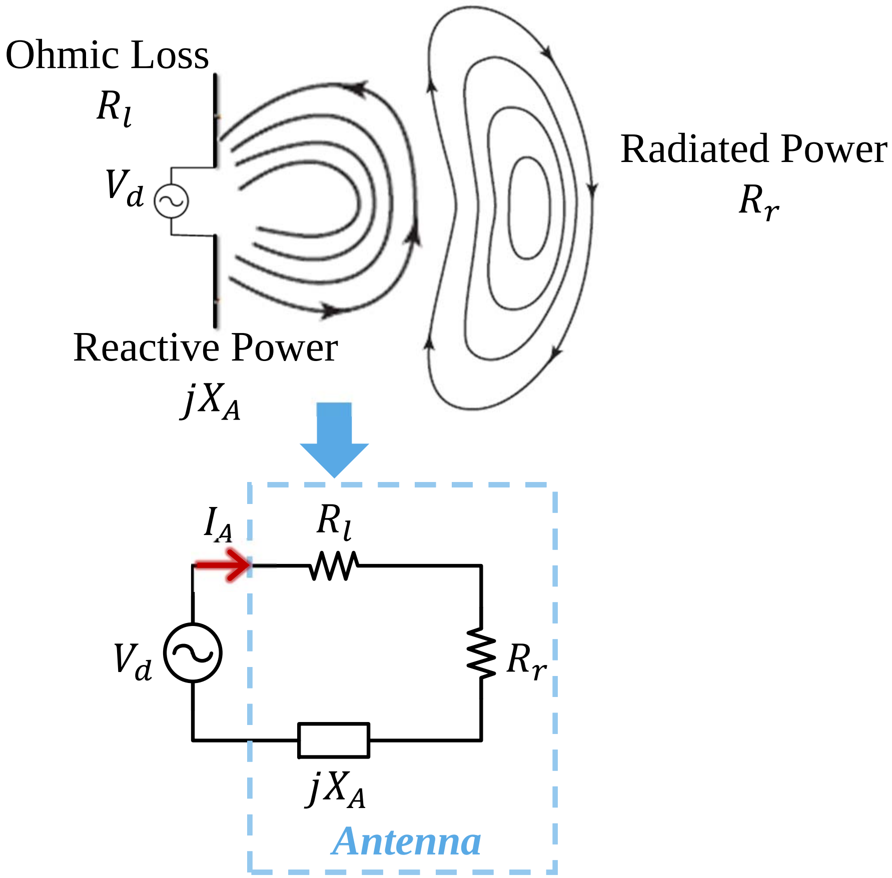
Antenna Model for Cable (power interconnect)



Lumped Model of the Antenna

- $\boldsymbol{R_r}$ – Radiation Resistance → Radiated Power
- $\boldsymbol{R_l}$ – Loss Resistance → Ohmic Power Loss
- $\boldsymbol{jX_A}$ – Antenna Reactance → Reactive Power

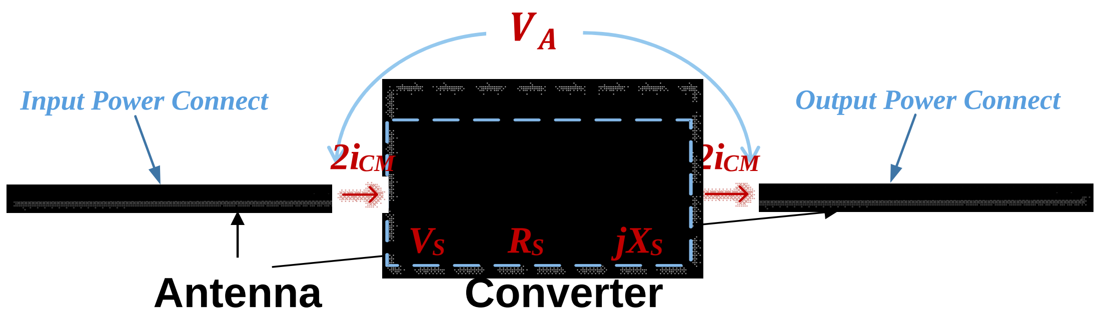
Radiated Power

$$P_r = \frac{1}{2}|I_A|^2 R_r$$

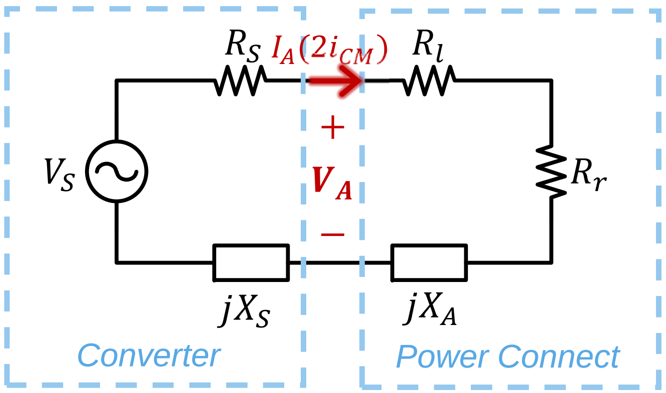
$$= \frac{1}{2}|V_d|^2 \frac{R_r}{(R_r + R_l)^2 + {X_A}^2}$$

Radiation Mechanism → Antenna & Source → Radiation Model → Radiated Power ⇢ Radiated Electric Field

Full Radiation Model



$$|I_A| = \frac{|V_S|}{\sqrt{(R_S + R_r + R_l)^2 + (X_S + X_A)^2}} = \frac{|V_S|}{\sqrt{(R_S + R_A)^2 + (X_S + X_A)^2}}$$



$$E_{max} = \sqrt{\frac{\eta G_o}{4\pi r^2}} \times |I_A|\sqrt{R_A} = \sqrt{\frac{\eta G_o}{4\pi r^2}} \times |V_S| \times \frac{\sqrt{R_A}}{\sqrt{(R_S + R_A)^2 + (X_S + X_A)^2}}$$

Noise source

Due to Impedances

- **Radiation is determined by both the noise source and propagation path impedances**

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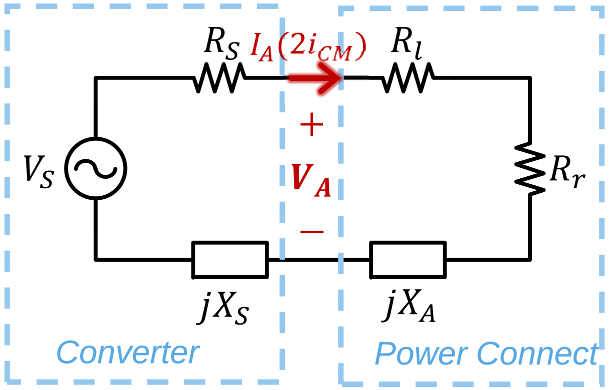
Development of Converter and Antenna Radiation Model



Antenna

Converter radiation model:

Base on Substitution Theory and Thevenin Theory:

1) Replace switching devices with voltage or current sources in the converter circuit
2) Disconnect cable antenna, measure open loop impedance R_S+jX_S between input and output of the converter after short voltage sources (semiconductor switches) and open current sources (semiconductor switches) in the converter circuits
3) Open loop voltage V_S between the input and output of the converter cannot be directly measured due to the impedance of the voltage probe, it can be derived based on the probe impedance or V_A can be derived based on network analyzer measurements (see reference [5][6])

Cable antenna model:

Impedance R_l+R_r+jX_A of the cable antenna can be measured with the converter disconnected

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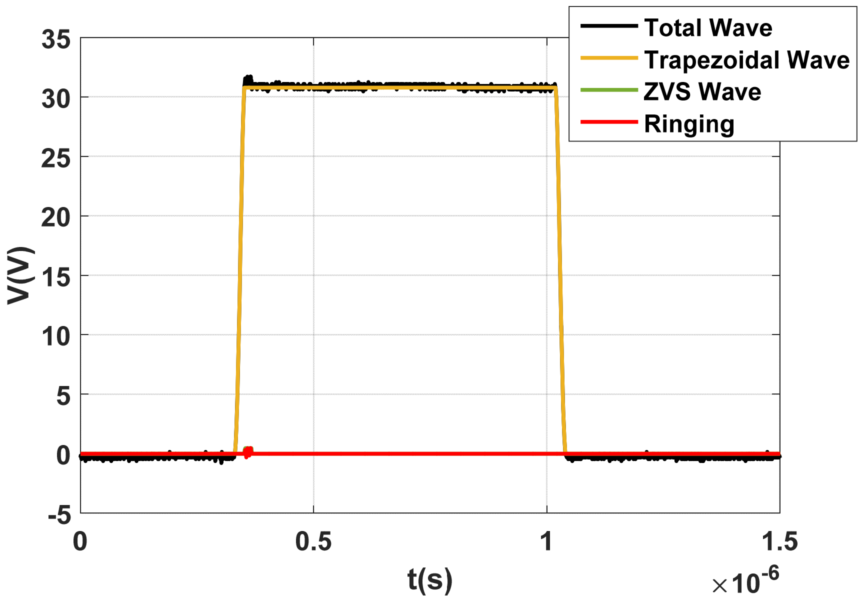
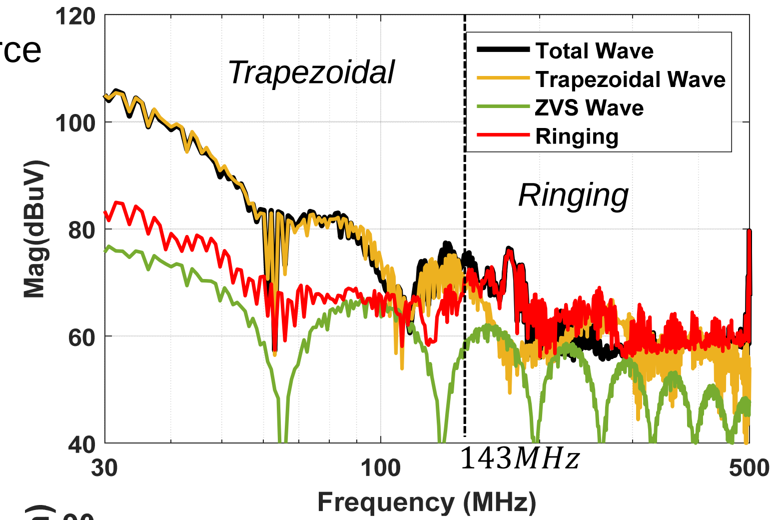
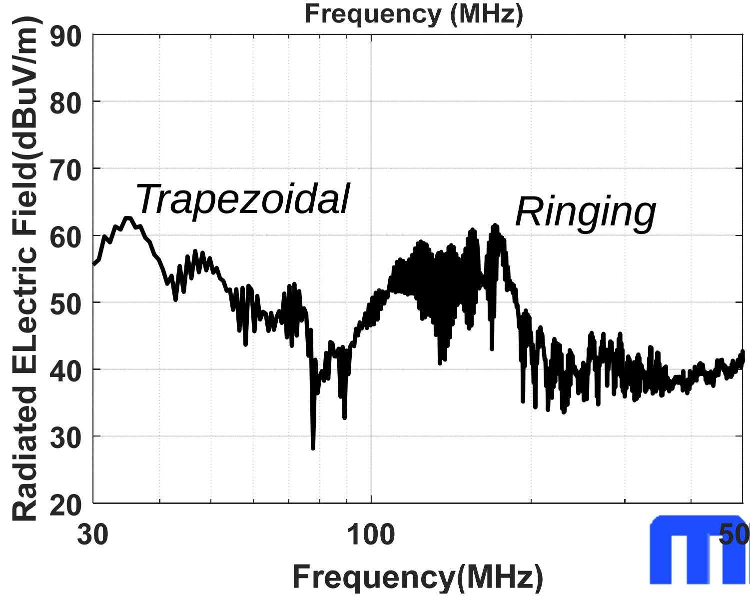
III. Noise Sources and Its Effects on Radiation



Noise Source Spectrum

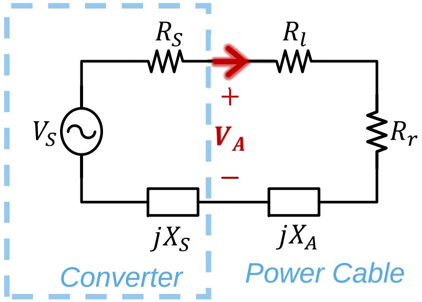


Measured E Field (3m semi Anechoic chamber)



- **Low-frequency radiation is determined by trapezoidal wave**
- **High-frequency radiation is determined by parasitic ringing**

IV. Interaction between Noise Source and the undesired Antenna



Antenna

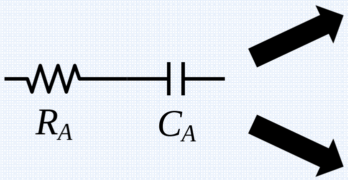
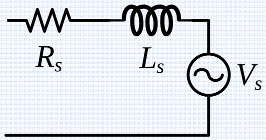
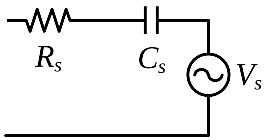
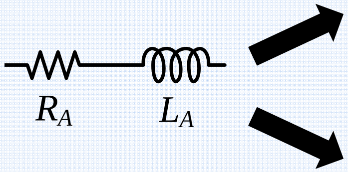
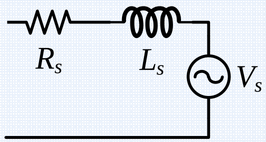
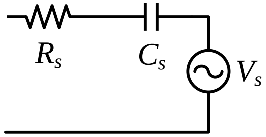
$$E_{max} = \sqrt{\frac{\eta G_o}{4\pi r^2}} \times |V_S| \times \frac{\sqrt{R_A}}{\sqrt{(R_S+R_A)^2+(X_S+X_A)^2}}$$

Interaction of Impedance

Conditions for high radiation:

1. $X_S + X_A = 0$ (series resonance)
2. R_S and R_A are small

- **Radiated EMI spikes happen when imaginary part is canceled and loop resistance is small**

Antenna	Converter	Possible Effect on Radiation
Series Resonance 		High radiated EMI may be generated at resonant frequency, especially when resistance is small.
		Level of radiated EMI mostly depends on the impedance and the source voltage
 Series Resonance		Level of radiated EMI mostly depends on the impedance and the source voltage
		High radiated EMI may be generated at resonant frequency, especially when resistance is small.

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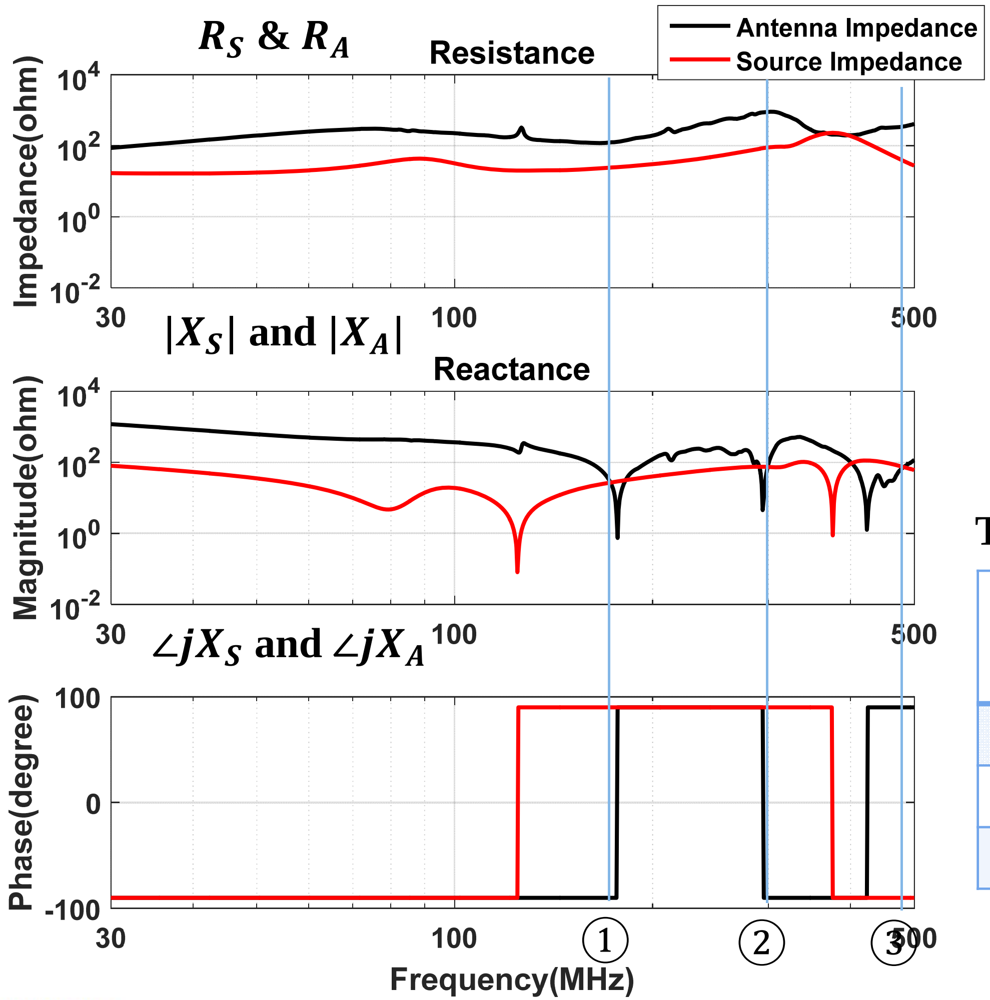
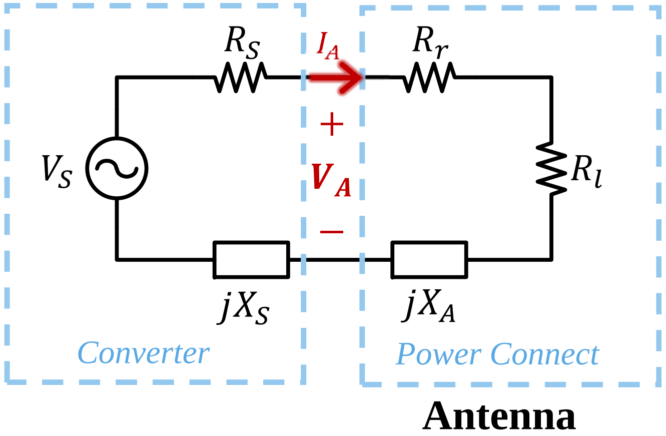
Resonance due to Impedance Interaction





$$R_A = R_r + R_l$$

Three Resonances

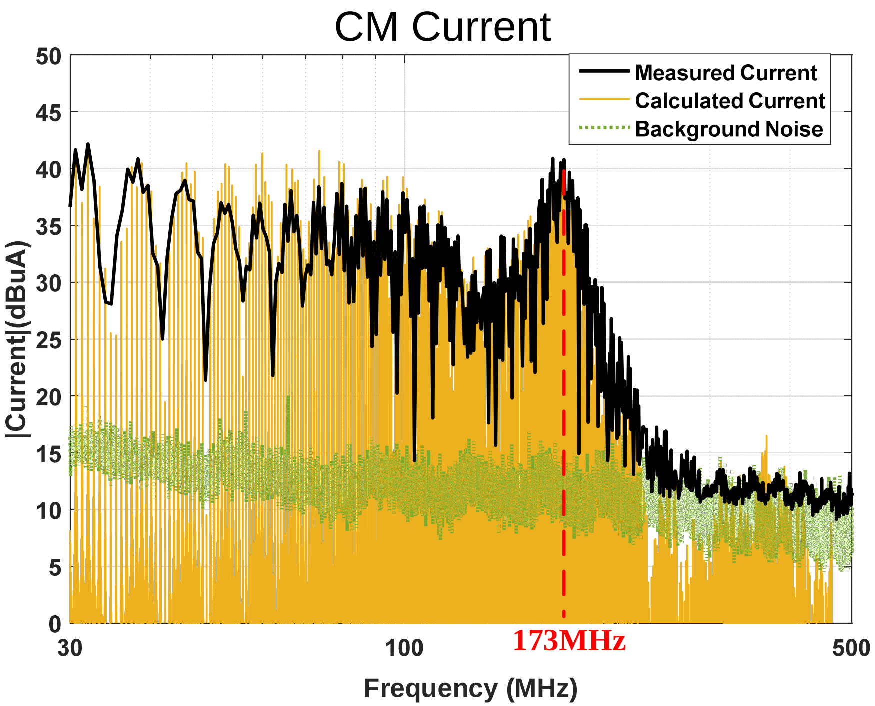
Number	Frequency (MHz)	R_S (Ω)	R_A (Ω)	
①	173	24	125	Low R, low damping
②	300	90	909	High R, high damping
③	475	43	344	High R, high damping

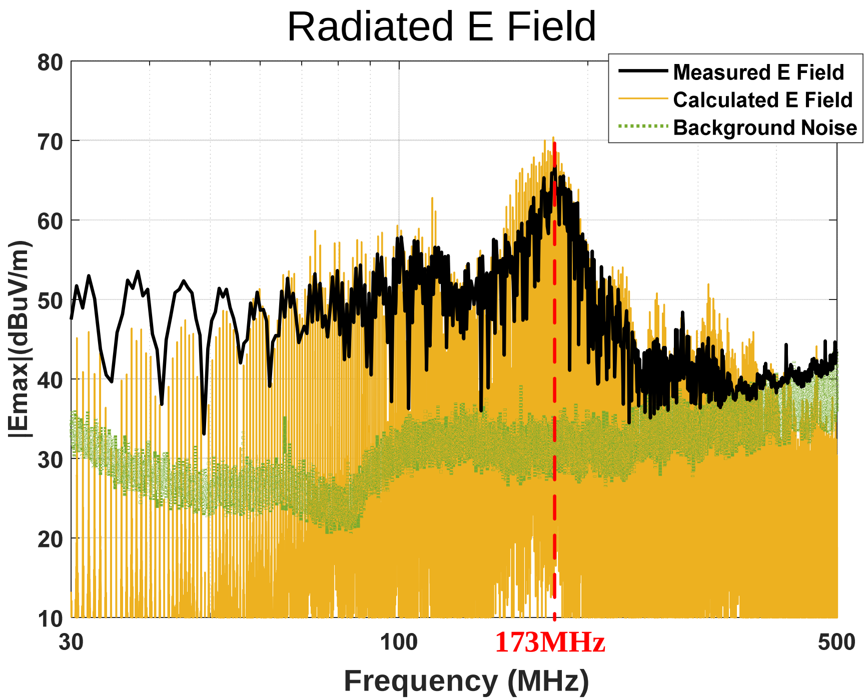
173MHz has EMI Spike

Verification of the Effects of Impedance Interactions on Radiation

$$|I_A| = |V_S|\underbrace{\frac{1}{\sqrt{(R_S+R_A)^2+(X_S+X_A)^2}}}_{K_1}$$

$$E_{max} = \sqrt{\frac{\eta G_o}{4\pi r^2}} \times |V_S| \times \underbrace{\frac{\sqrt{R_A}}{\sqrt{(R_S+R_A)^2+(X_S+X_A)^2}}}_{K_2}$$





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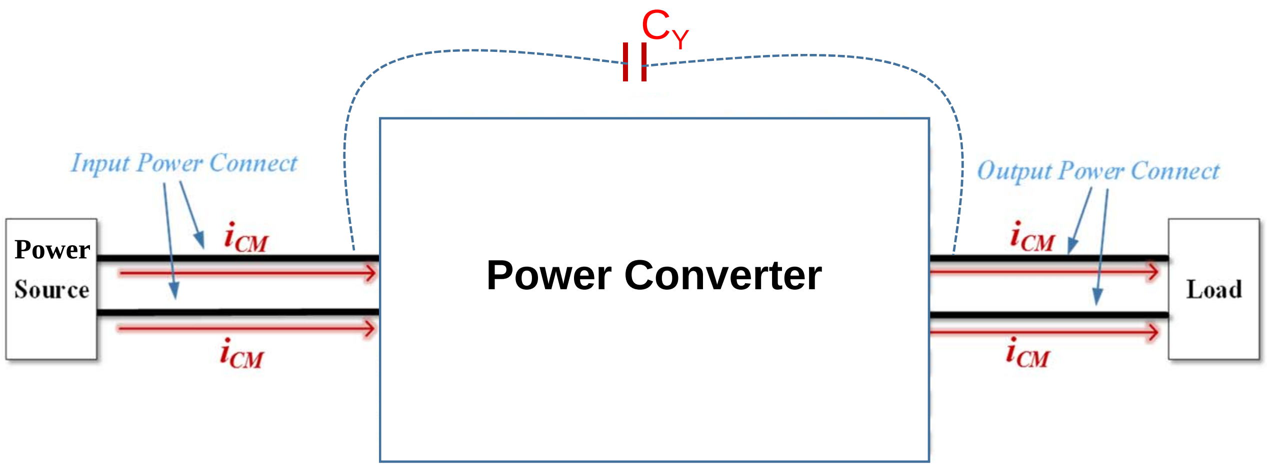
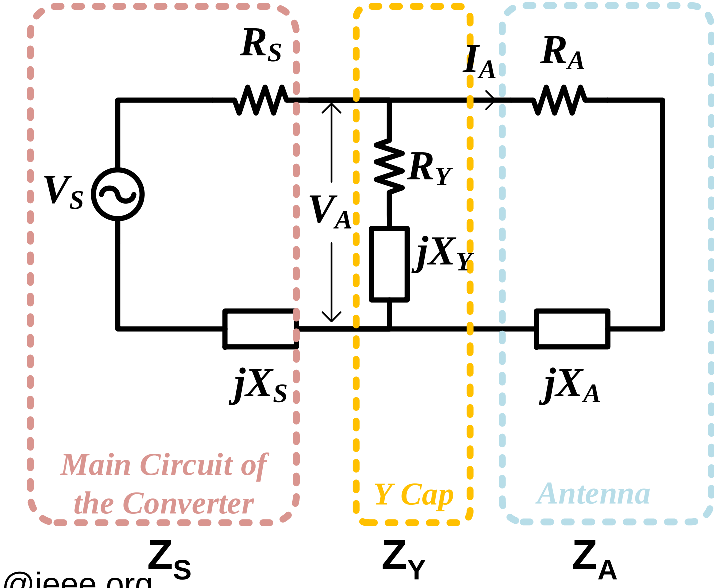
V. Reduction of Radiation with a Y-Capacitor



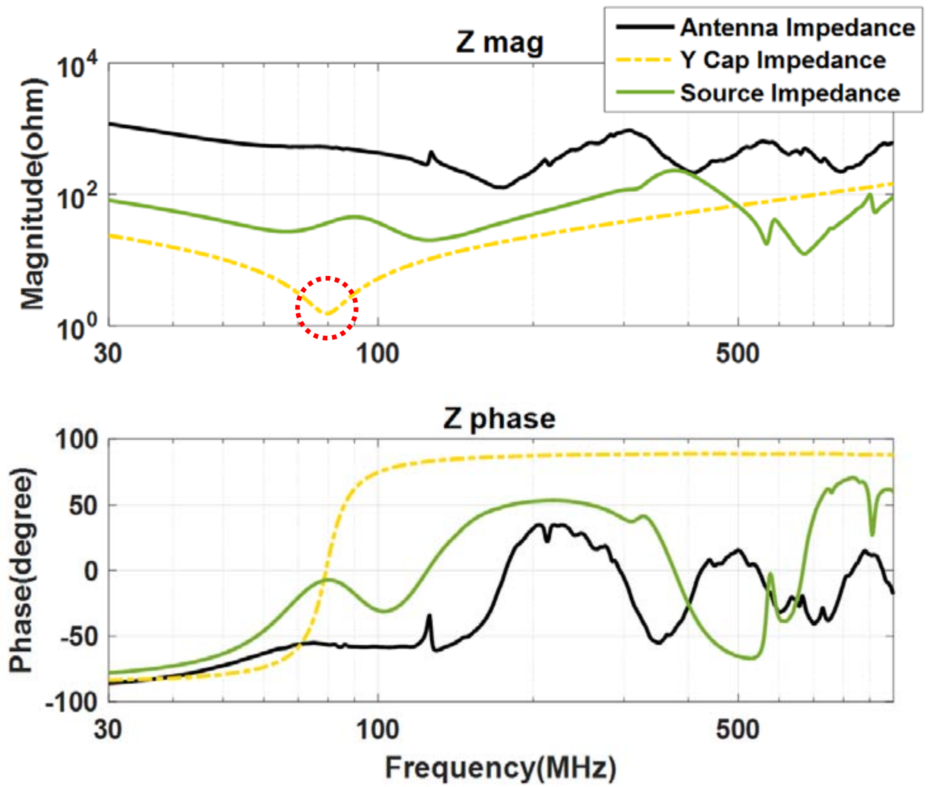


$$V_{A\_new} = V_S \times \frac{Z_Y \parallel Z_A}{Z_Y \parallel Z_A + Z_S}$$

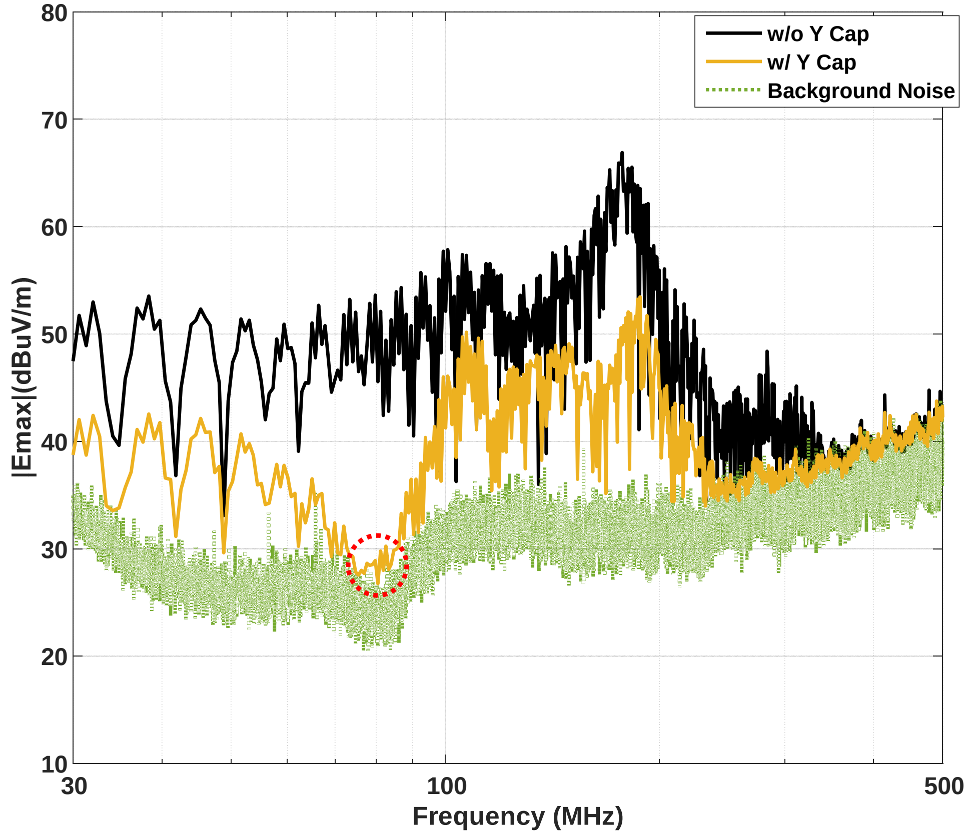
Effective if $Z_Y < Z_A$ and Z_S

- **Y-cap can reduce V_A added to antenna, so the radiation is reduced**

Radiated EMI Reduction with a Y Capacitor



Measured E field in a 3m semi anechoic chamber



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Questions or Comments?

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