高频共模电压，共模电流和阻抗的测量技术

--------------以反激变换器的辐射电磁干扰诊断为例

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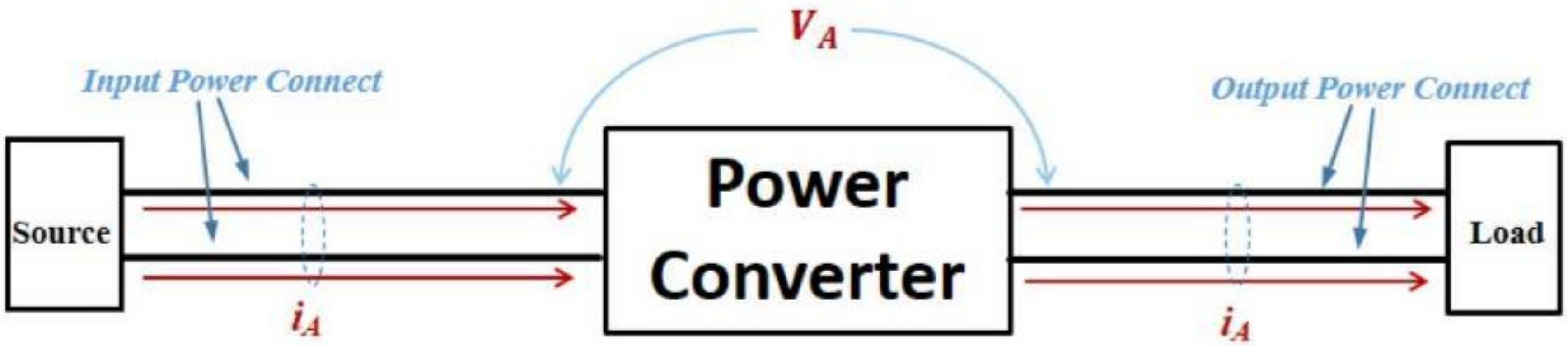
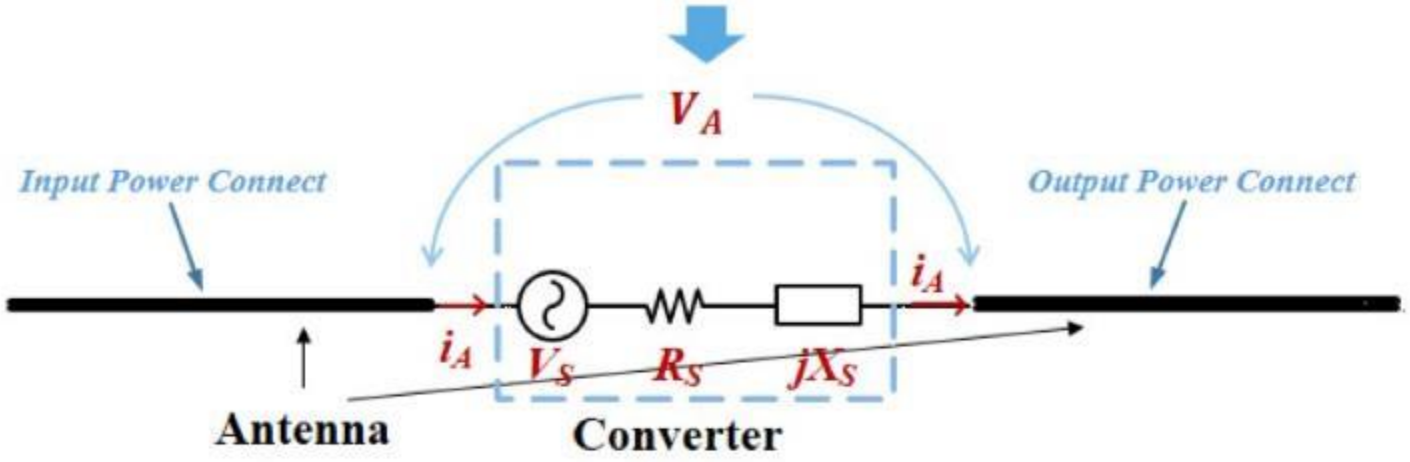
Radiated EMI in Power Electronics Systems





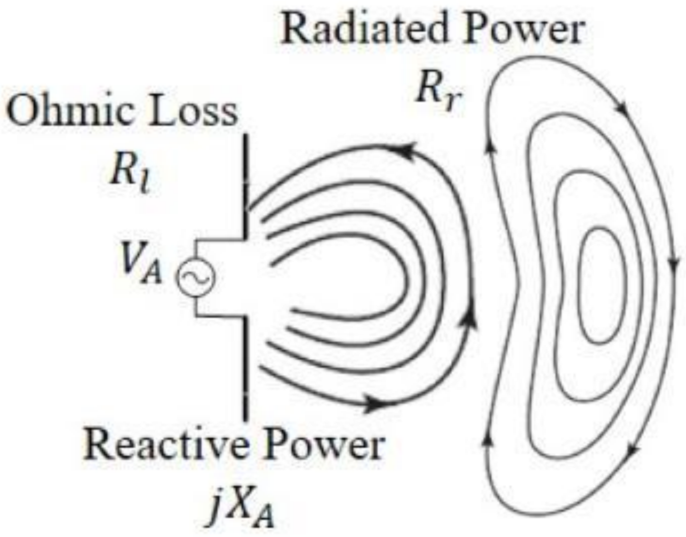
Radiation Conditions:

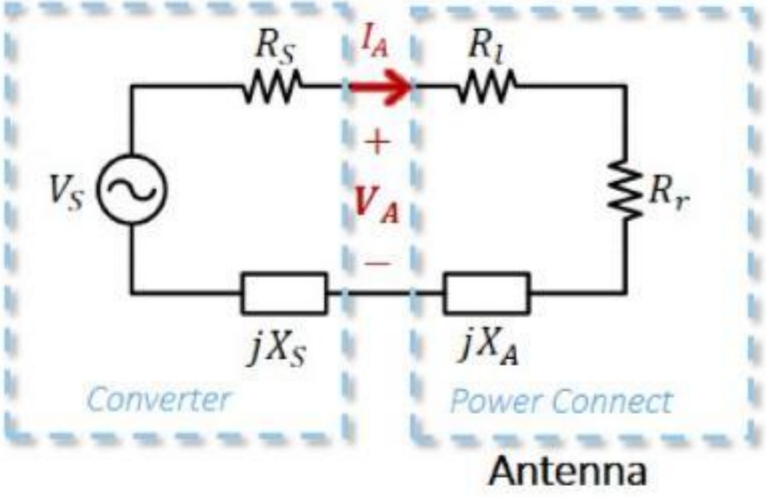
1. Input and output cables are undesired antenna
2. CM voltage between input and output cables are excitation voltage

Critical Parameters:

1. Noise source V_s
2. Excitation voltage V_A
3. Radiation current i_A
4. CM impedance:
   1) Source impedance
   2) Antenna impedance

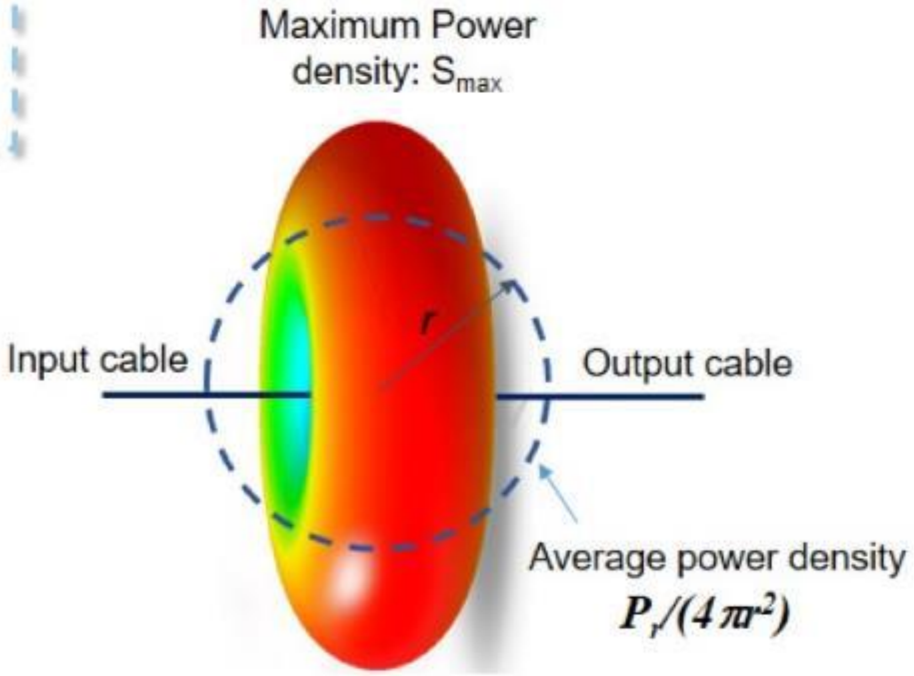
Antenna Basics





Radiated Power:

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



Lumped Model of the Antenna

- R_r – Radiation Resistance → Radiated Power
- R_l – Loss Resistance → Ohmic Power Loss
- jX_A – Antenna Reactance → Reactive Power

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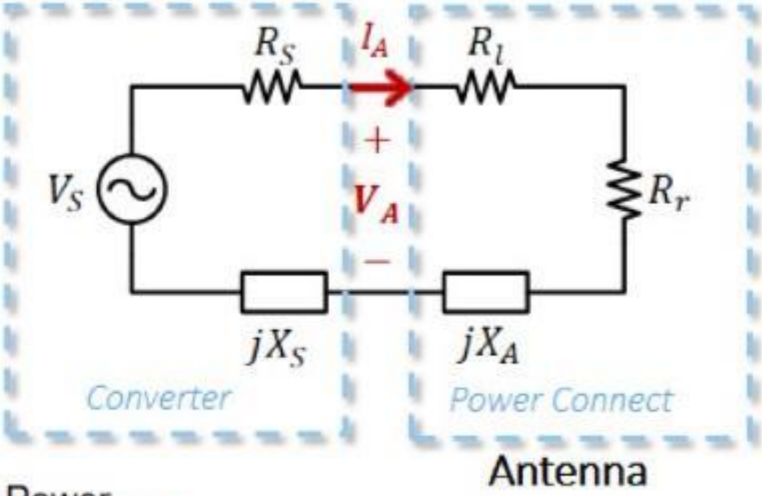
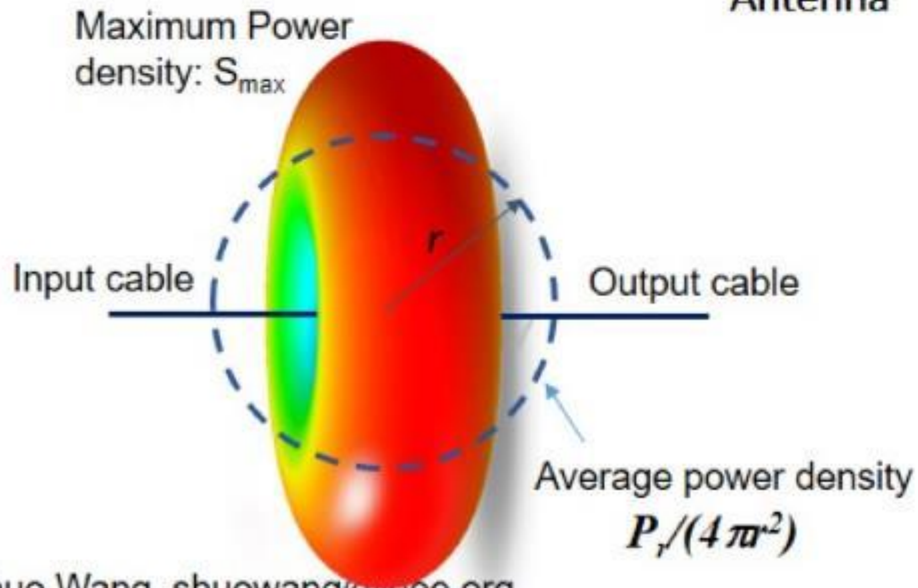
Maximum Electric Field determined by Noise Source and Impedances





Directivity D: $\frac{\text{Maximum power density}}{\text{Average power density}}$

$D=S_{max}(4\pi r^2) / P_r$

$S_{max}=E_{max}^2/2\eta$ (η: wave impedance)

$$E_{max} = \sqrt{\frac{R_r \eta D}{4\pi r^2}} \times |I_A|$$

$$= \sqrt{\frac{\eta D}{4\pi r^2}} \times |V_S| \times \frac{\sqrt{R_r}}{\sqrt{(R_S + R_r + R_l)^2 + (X_S + X_A)^2}}$$

Noise source

Due to Impedances

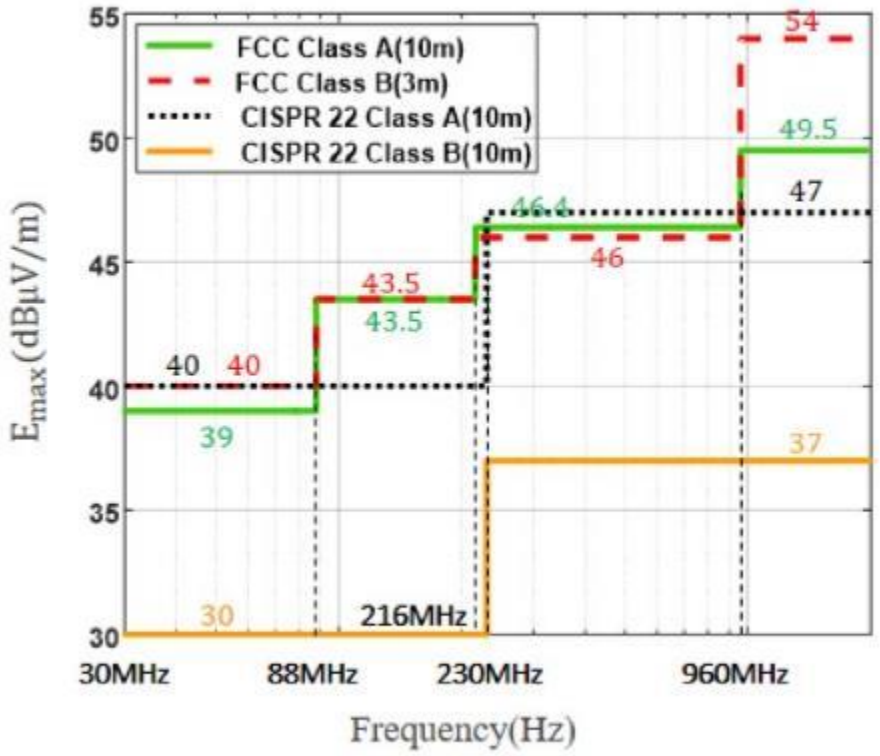
Some International Standards for Radiated EMI

1. FCC Part 15 Subpart B --Unintentional Radiators

Frequency (*MHz*)	Class A (10m) (*dBμV/m*)	Class B (3m) (*dBμV/m*)
30-88	39	40
88-216	43.5	43.5
216-960	46.4	46
>960	49.5	54

2. CISPR 22

Frequency (*MHz*)	Class A (10m) (*dBμV/m*)	Class B (10m) (*dBμV/m*)
30-230	40	30
>230	47	37



Class A – commercial, industrial, business
Class B – residential

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Evaluate the Radiation of a Power Converter

- CM Currents
  - CM Currents on input and output cables
- CM Impedances
  - Antenna Impedance
  - Power converter CM impedances
- CM Voltages
  - Voltage source voltage
  - Excitation voltage

Conclusion: accurately measure high frequency CM impedances, CM voltages and currents are very important

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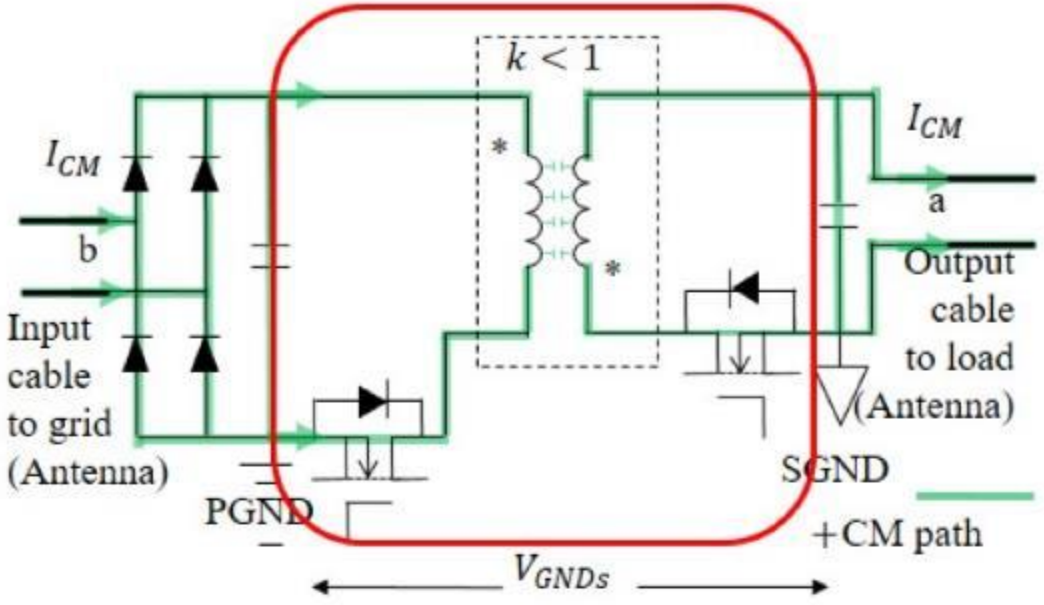
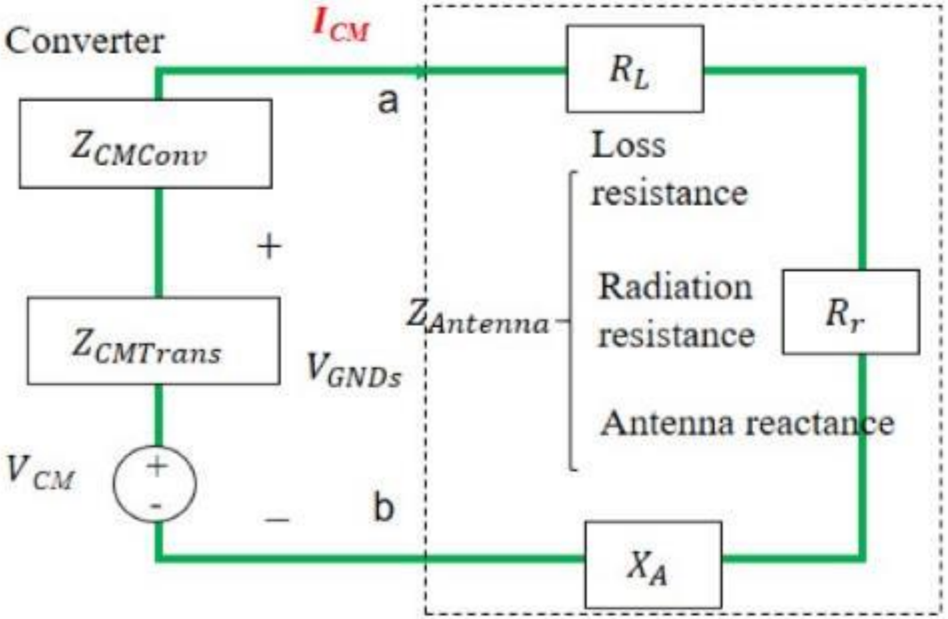
Radiated EMI Model for Flyback Power Converters



Circuit, Excitation Voltage and CM Currents

Due to the impedance of its junction capacitance is much smaller than Antenna impedance, the diode bridge's impedance can be ignored even is not turned on.



Radiation model

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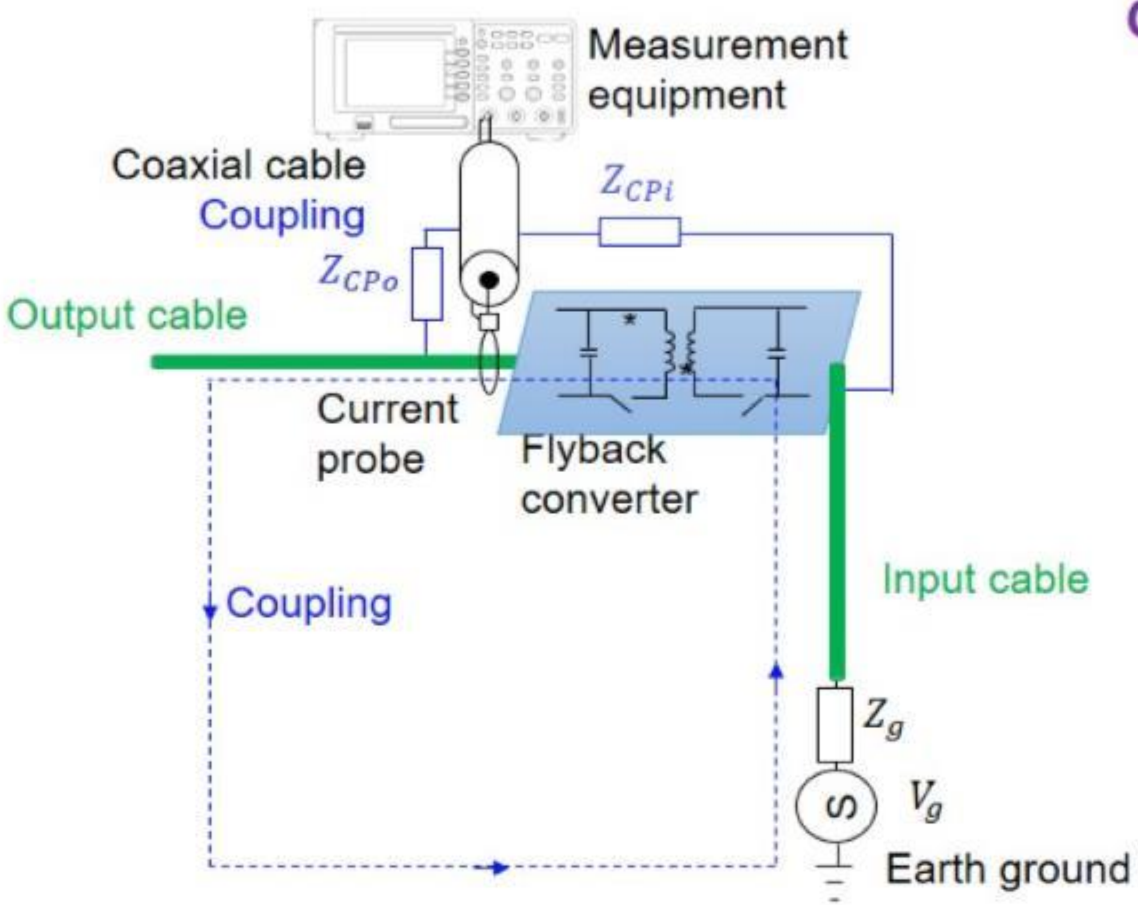
CM Current Measurement and Issues

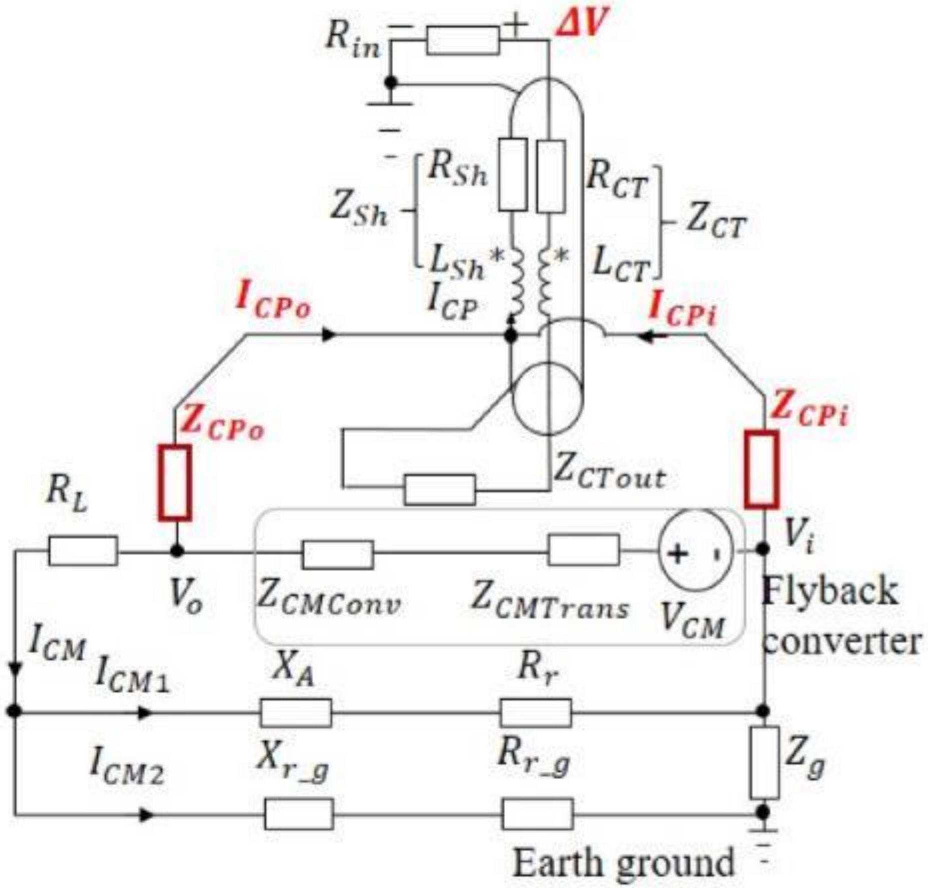


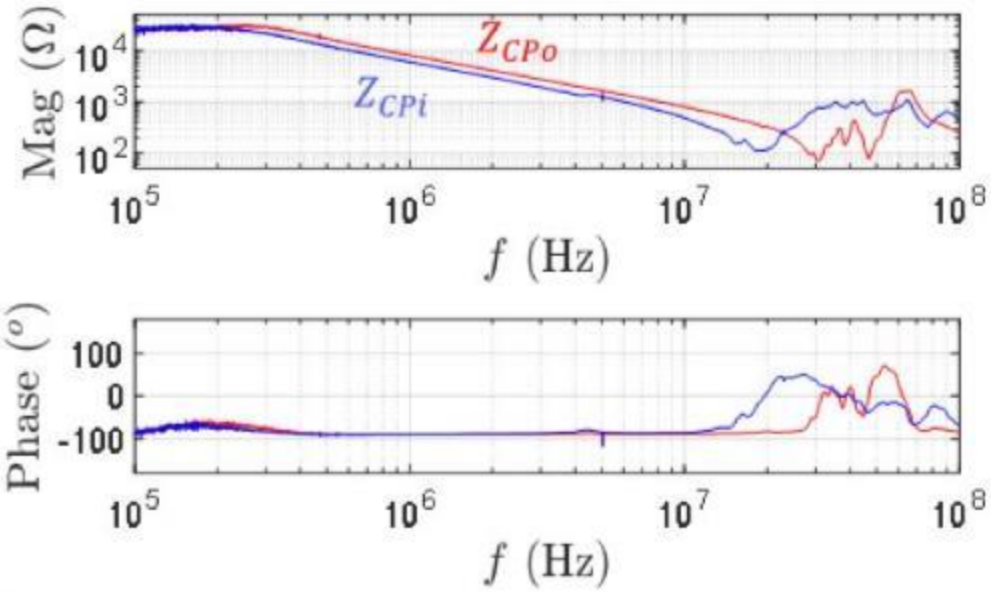
Two couplings influence the accuracy of CM current measurement:

Coupling 1:
Z_{CPi}, Z_{CPo}: coupling impedances between input or output cable and the outer conductor of the coaxiable of current probes

Coupling 2:
Grid impedance between input and output cables
From noise source to input cable, to power grid, to ground, to output cable and back to noise source

Effect of the Couplings Z_{CPo} and Z_{CPi} on Measurement Errors

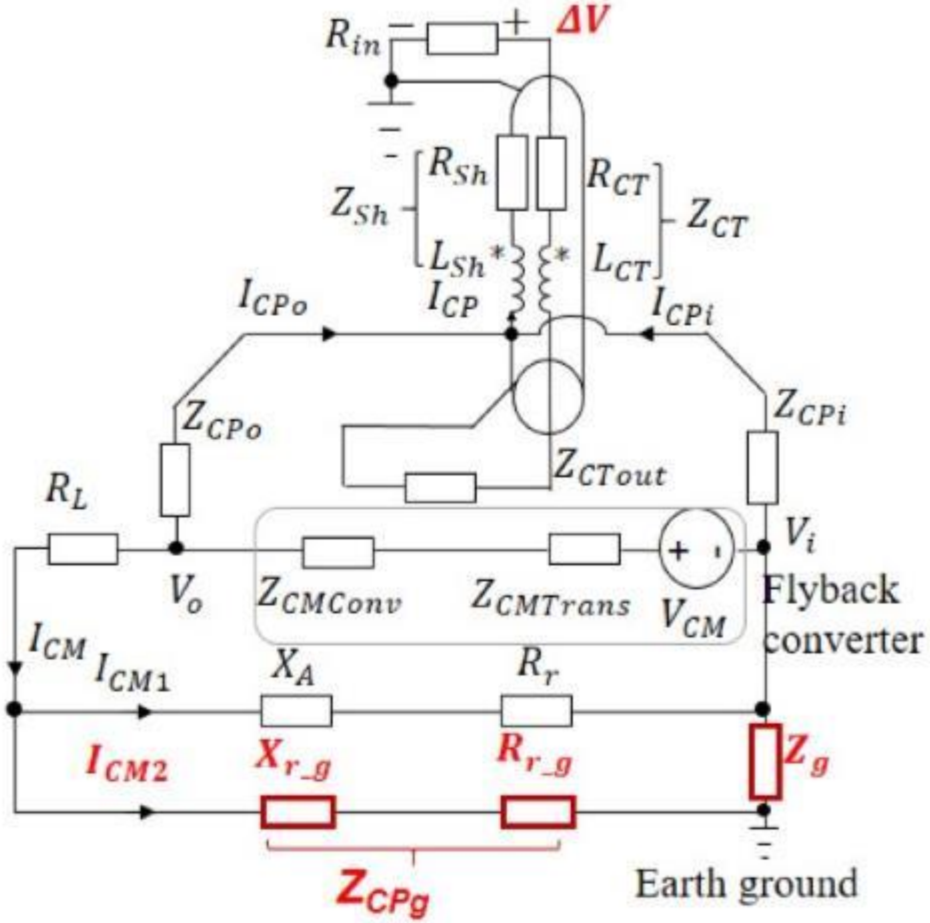


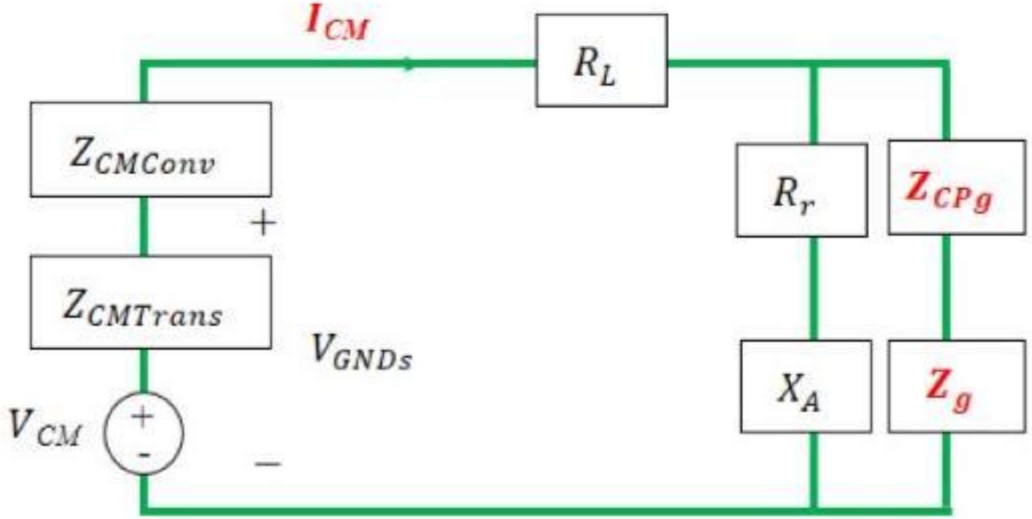


Measurement errors:

$$\Delta V \approx \frac{(Z_{CPi}V_o + Z_{CPo}V_i)R_{in}}{Z_{CPi}Z_{CPo}\left(1+\frac{R_{CT}}{R_{Sh}}+\frac{R_{in}+Z_{CTout}}{R_{Sh}}\right)+(Z_{CPi}+Z_{CPo})(R_{CT}+R_{in}+Z_{CTout})}$$

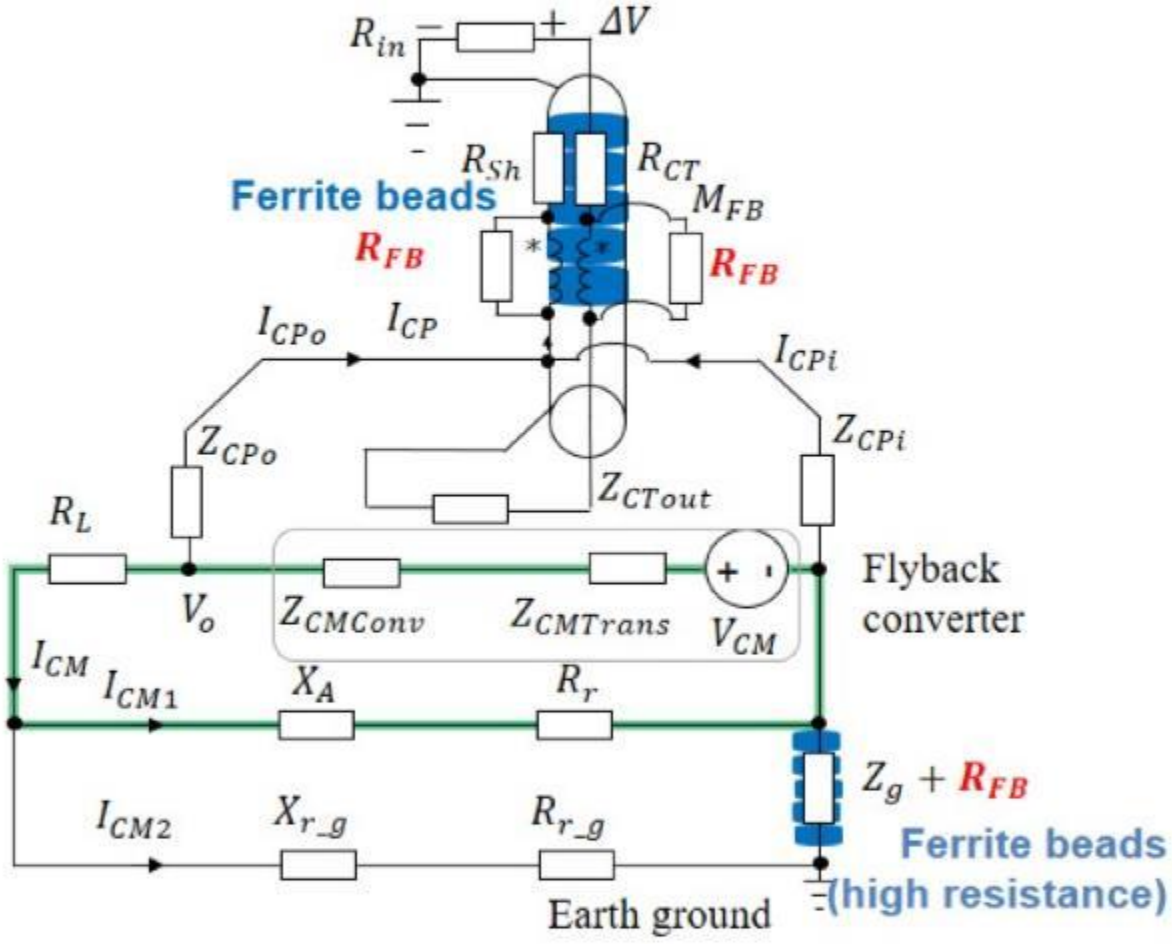
Effect of the Grid Impedance $jX_{r\_g} + R_{r\_g}$ on Measurements





Impact: the measurement result is not repeatable due to the uncertainty of the grid impedance

Techniques to Reduce the Effect of Couplings

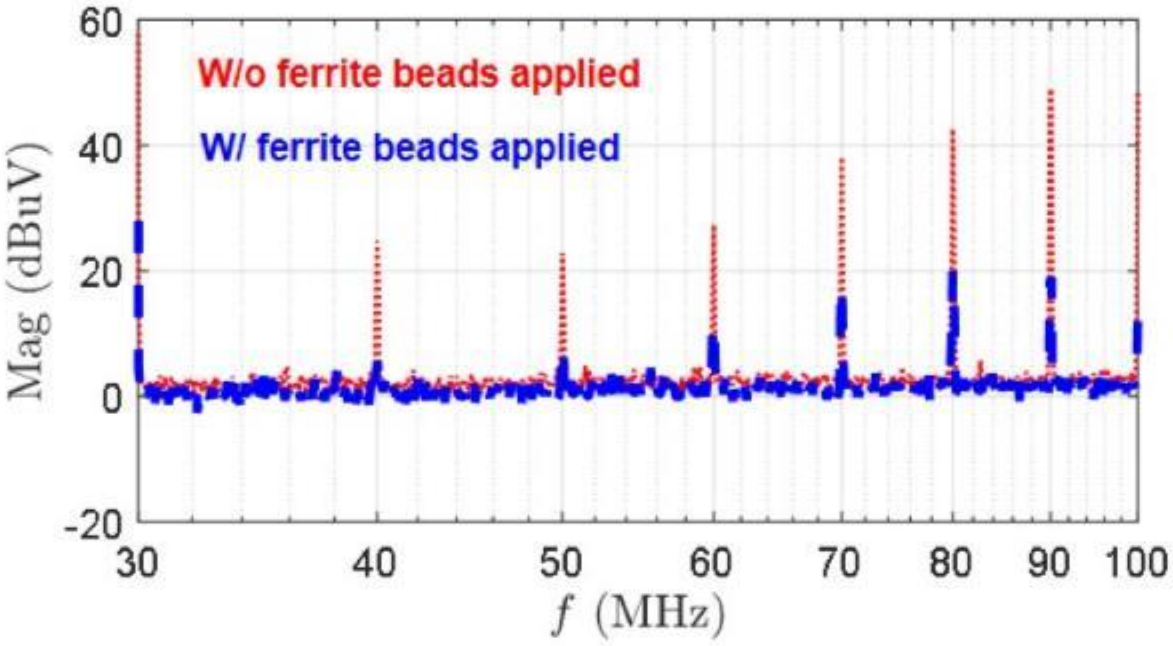


1) Multiple Ferrite beads have CM resistance above kΩ
2) Equivalently increase R_{sh} and R_{CT}
3) Measured CM current signal flows through the DM loop in the probe and the coaxial cable.
3) Ferrite beads will not affect CM current measurement

1) Ferrite beads can isolate grid impedance from input and output cables
2) CM currents will only flow through cable antenna

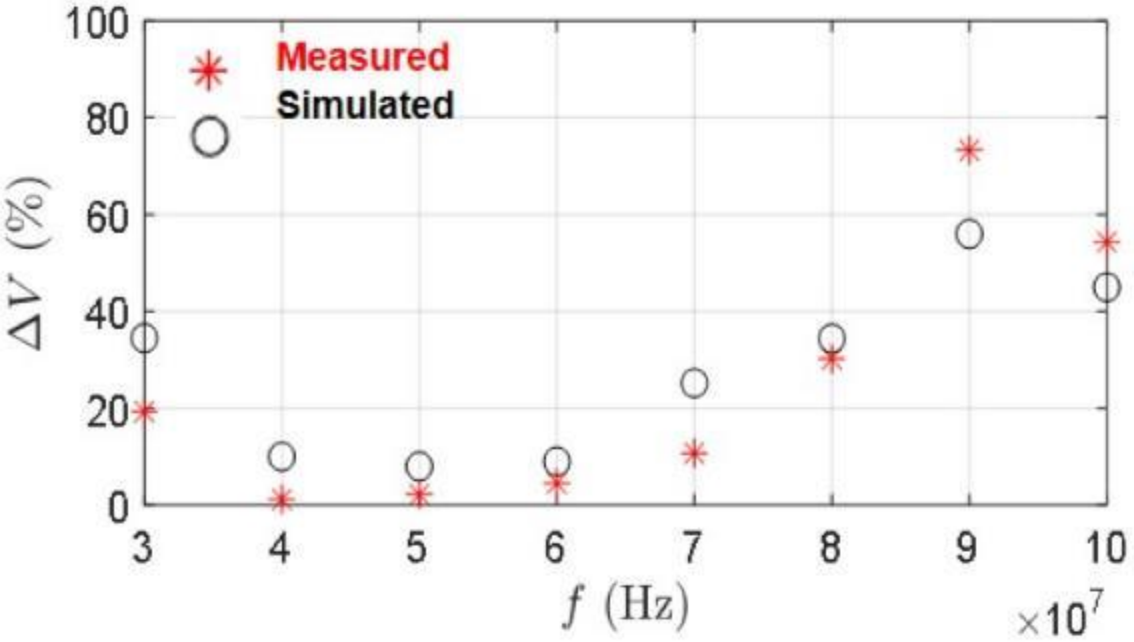
Improvement of Measurement w/ Ferrite Beads

Current probe is not clamped to the cable (but at the same position as when it is clamped)



1) The coupling is not ignorable
2) Ferrite beads can greatly reduce the couplings

Measurement errors due to the couplings



1) The developed model agree with measurement
2) The couplings lead to significantly errors

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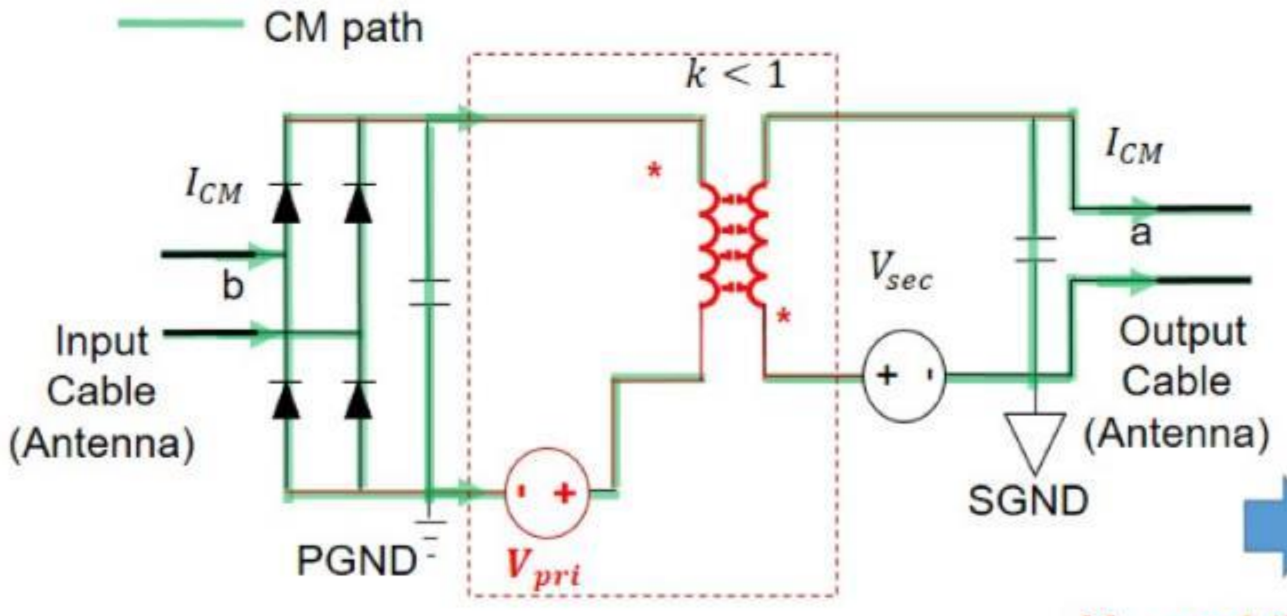
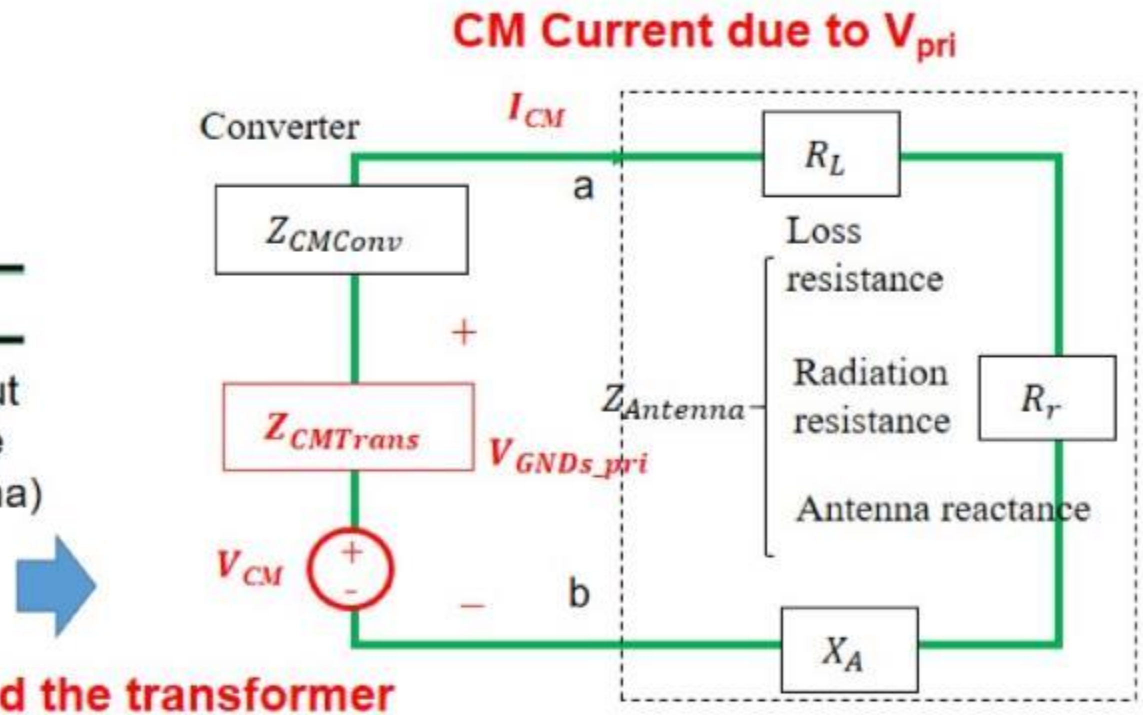
CM Current due to Primary Switching Voltage

1) Both V_{pri} and V_{sec} contribute to V_{GNDs} and generate CM current
2) Their contributions can be analyzed separately





V_{pri} and the transformer are equivalent to

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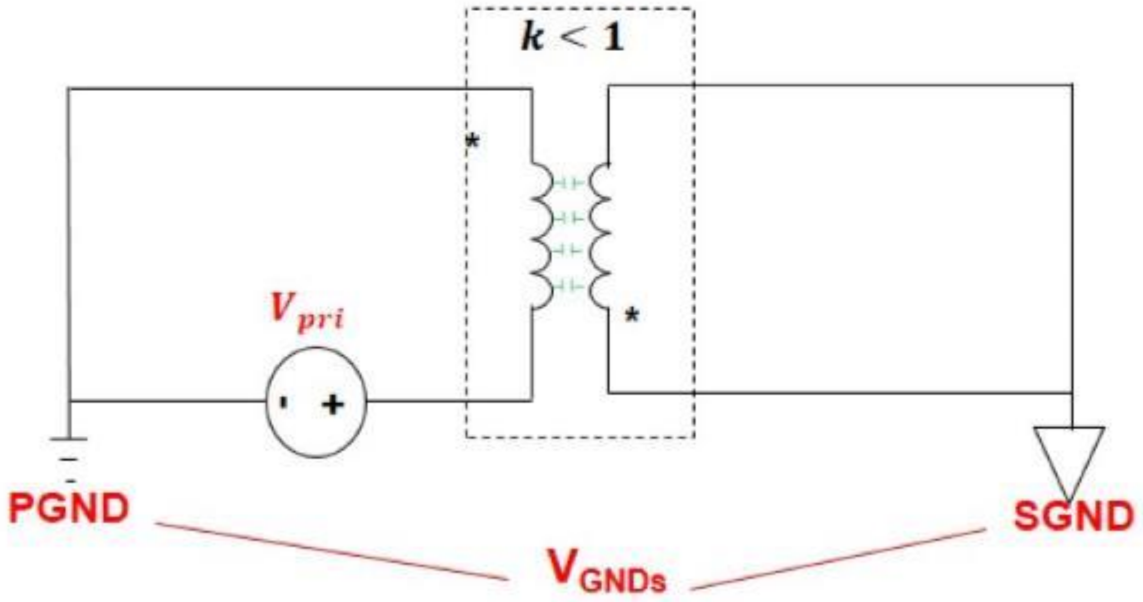
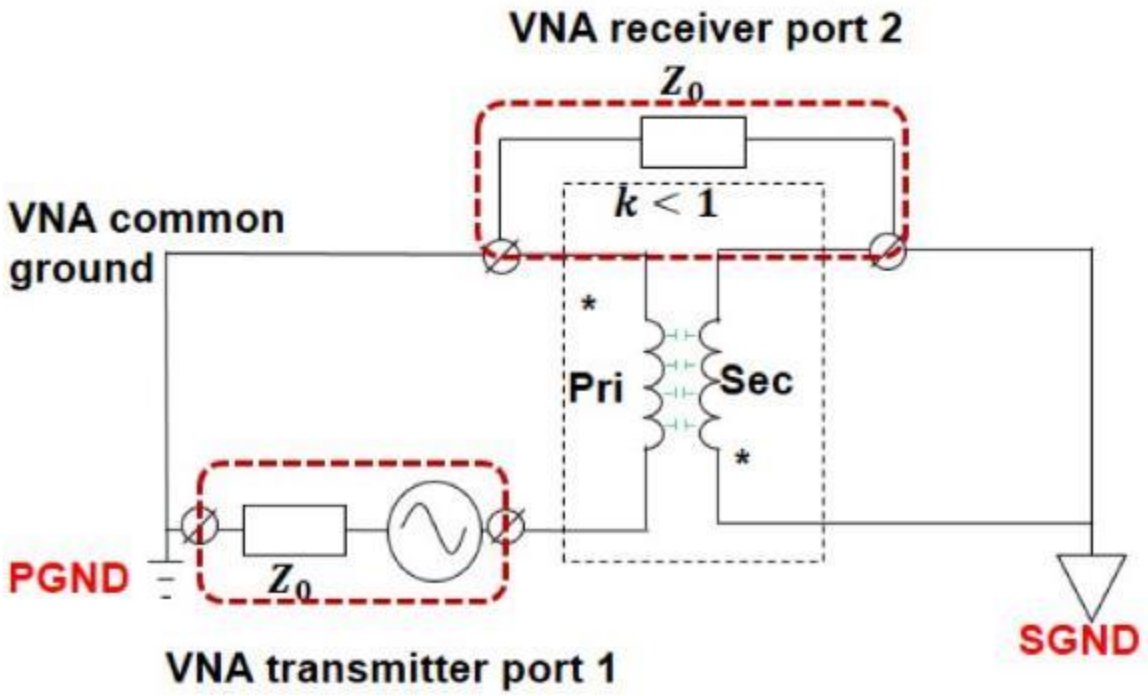
Measure Voltage Transformation from V_{pri} to V_{GNDs}





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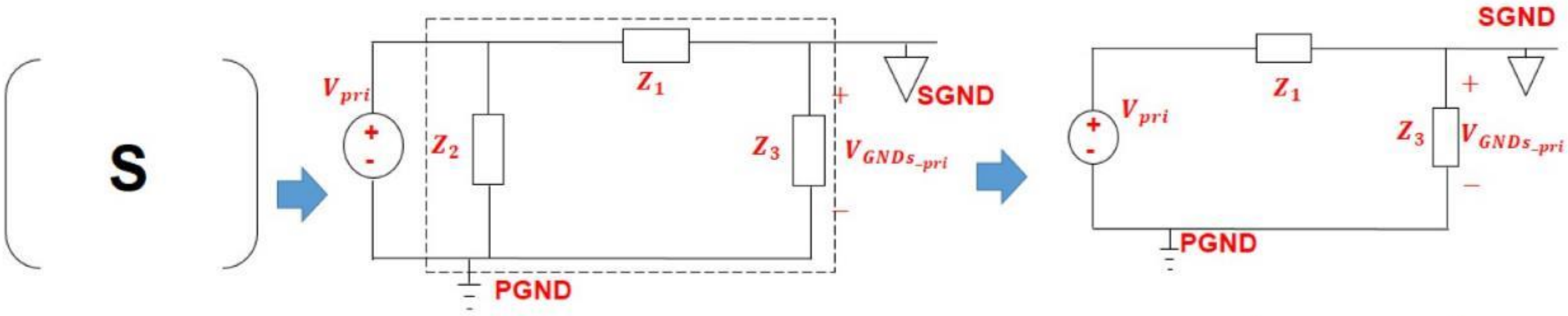
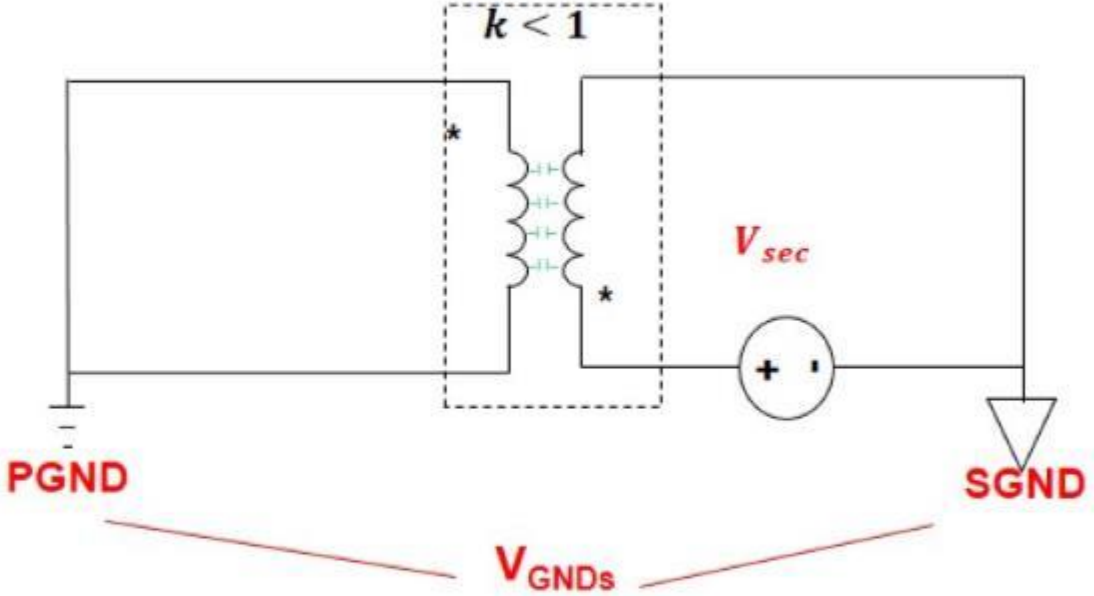
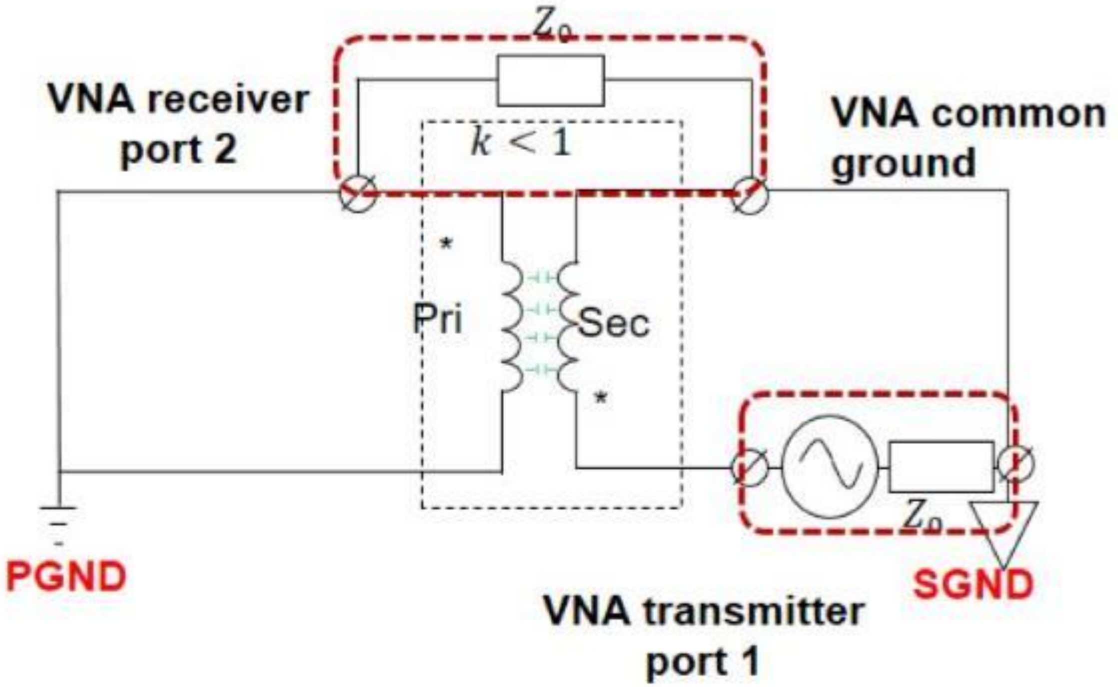
Network Parameters to An π Impedance Network



$$CMTG_{pri} = \frac{V_{GNDs\_pri}}{V_{pri}} = \frac{Z_3}{Z_1 + Z_3}$$

Measure the Transformation from V_{sec} to V_{GND}





$$V_{GNDs} = V_{pri} \cdot CMTG_{pri} + V_{sec} \cdot CMTG_{sec}$$

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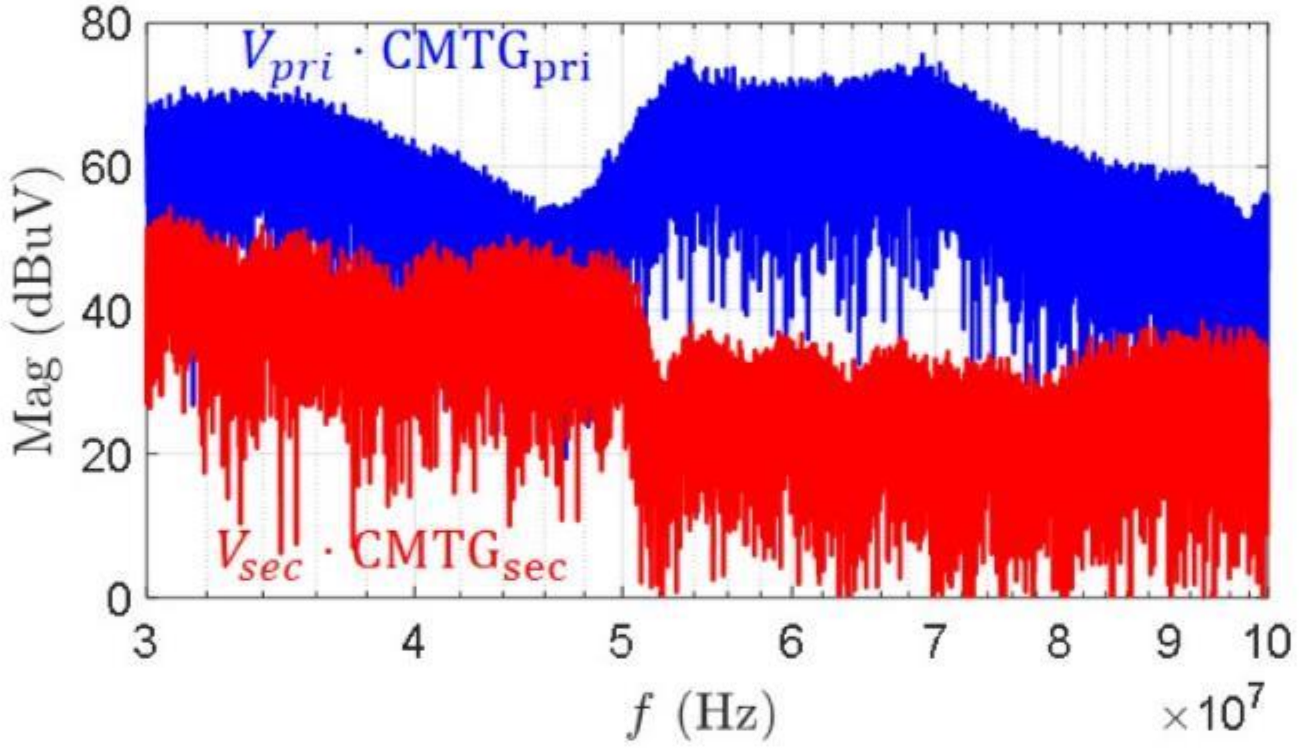
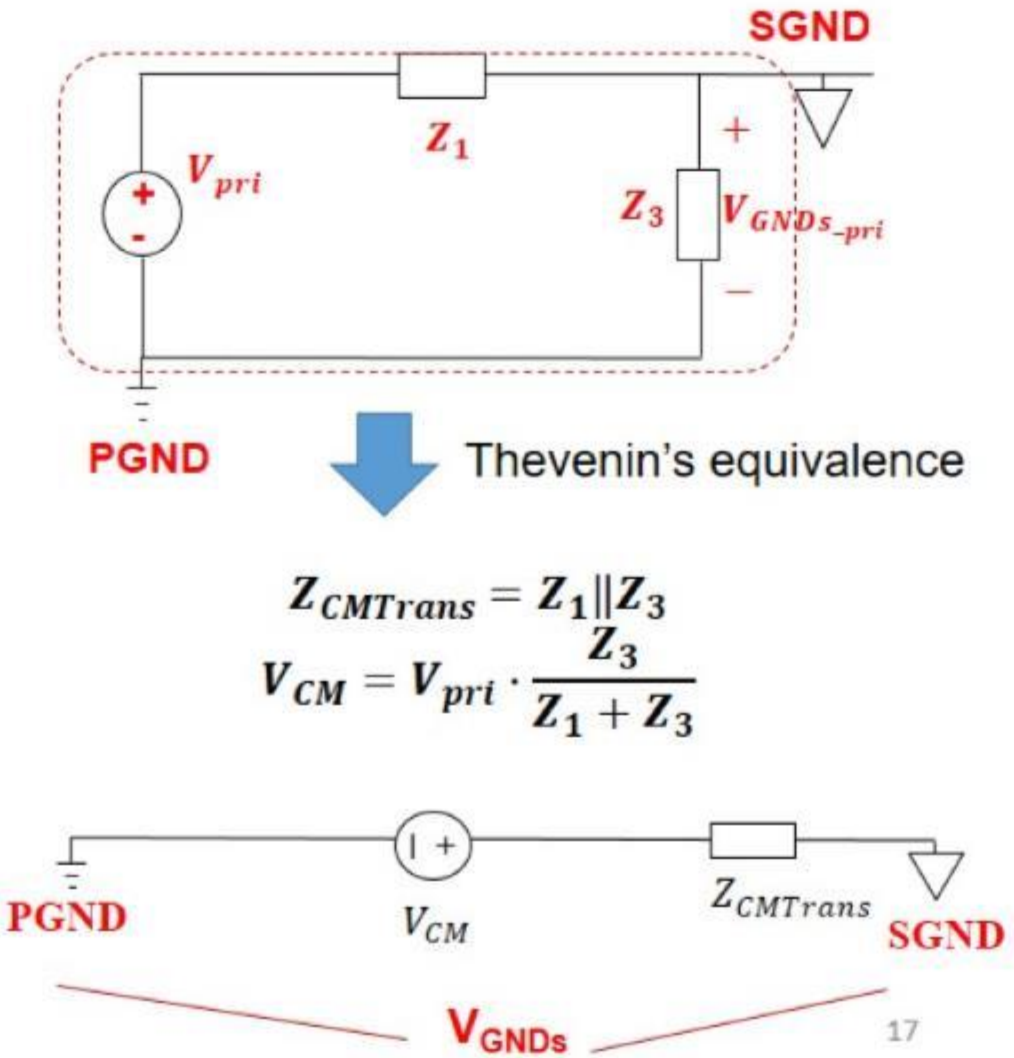
Comparison of V_{GNDs} Contributions





The V_{GNDs} due to V_{pri} is much bigger than that due to V_{sec} due to the big magnitude of V_{pri}.

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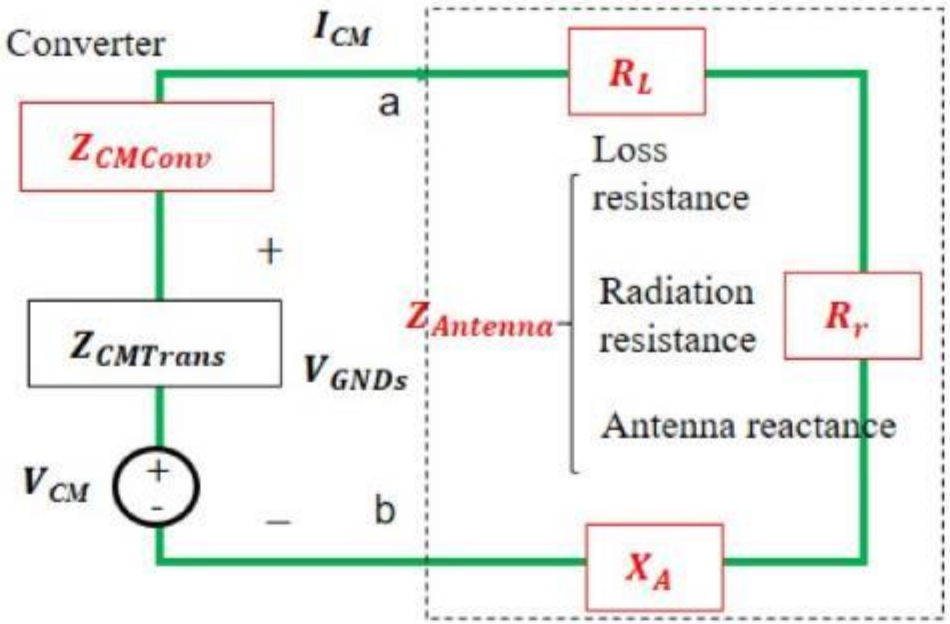
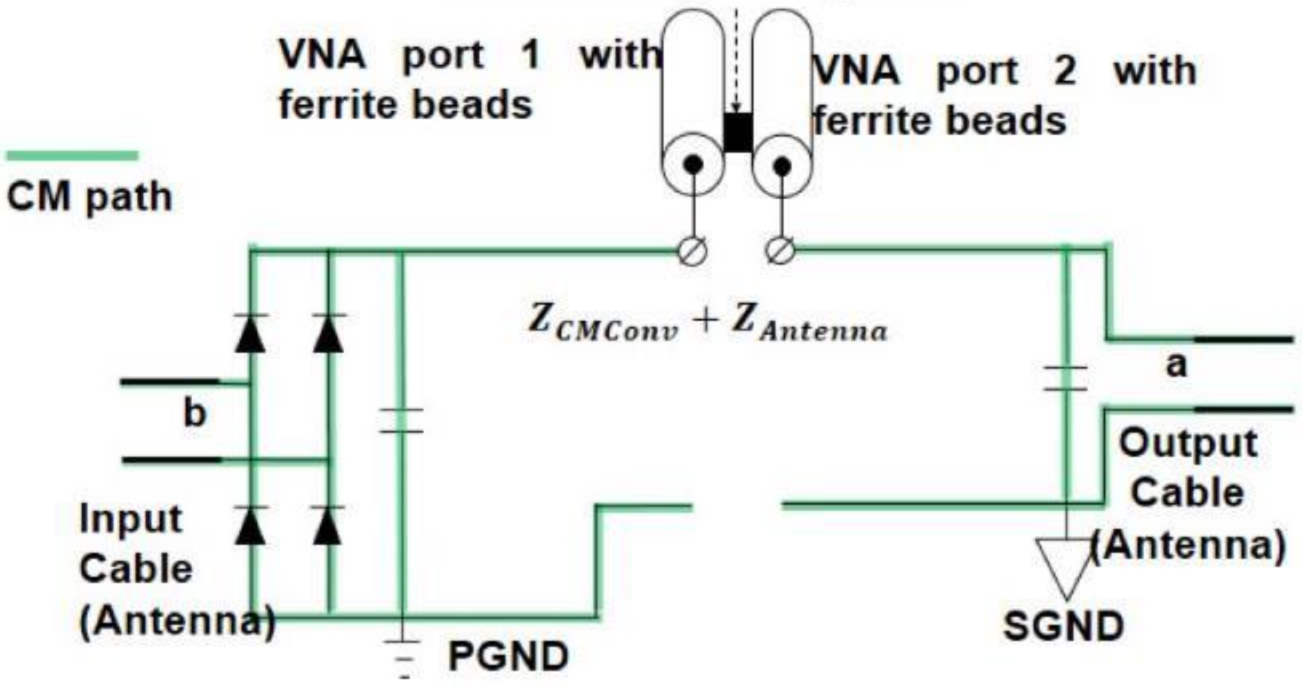
Flyback Converter and Cable Antenna Impedance





Transformer is removed

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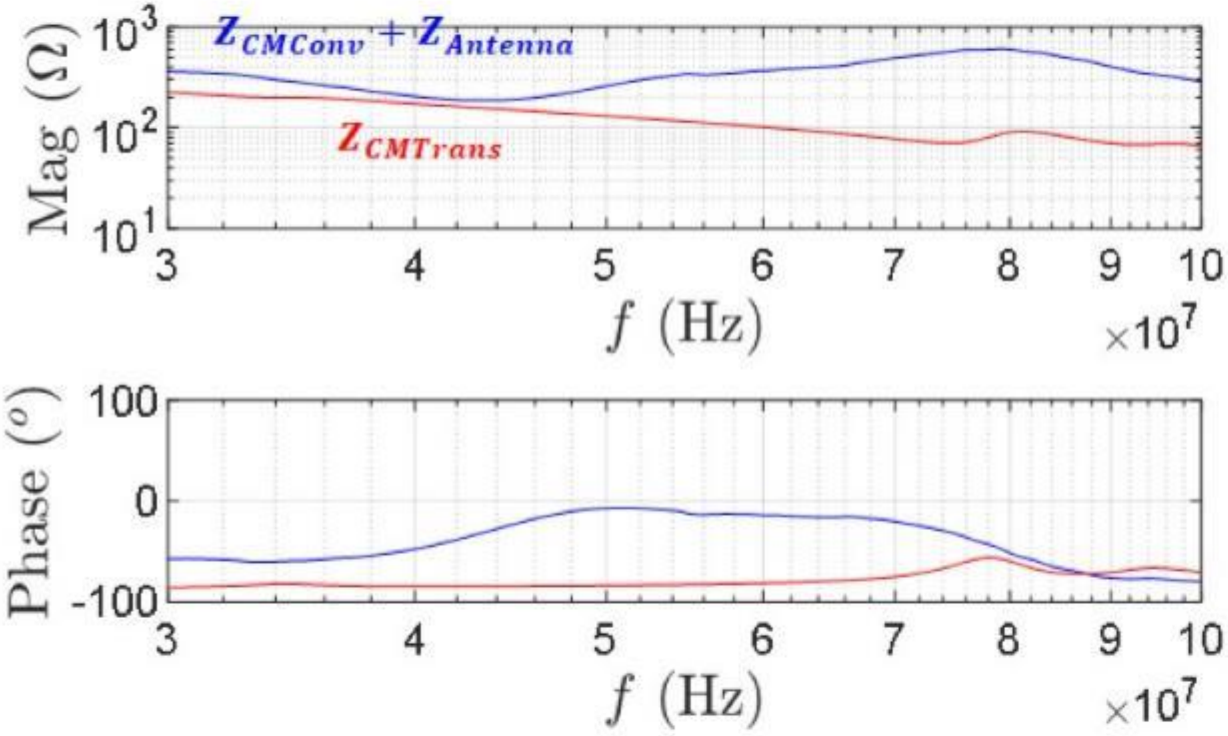
Measured Converter and Antenna impedances



1) **For radiated EMI, transformer CM impedance can be ignored**
2) **Transformer is important for V_{CM} but not for the CM impedance**

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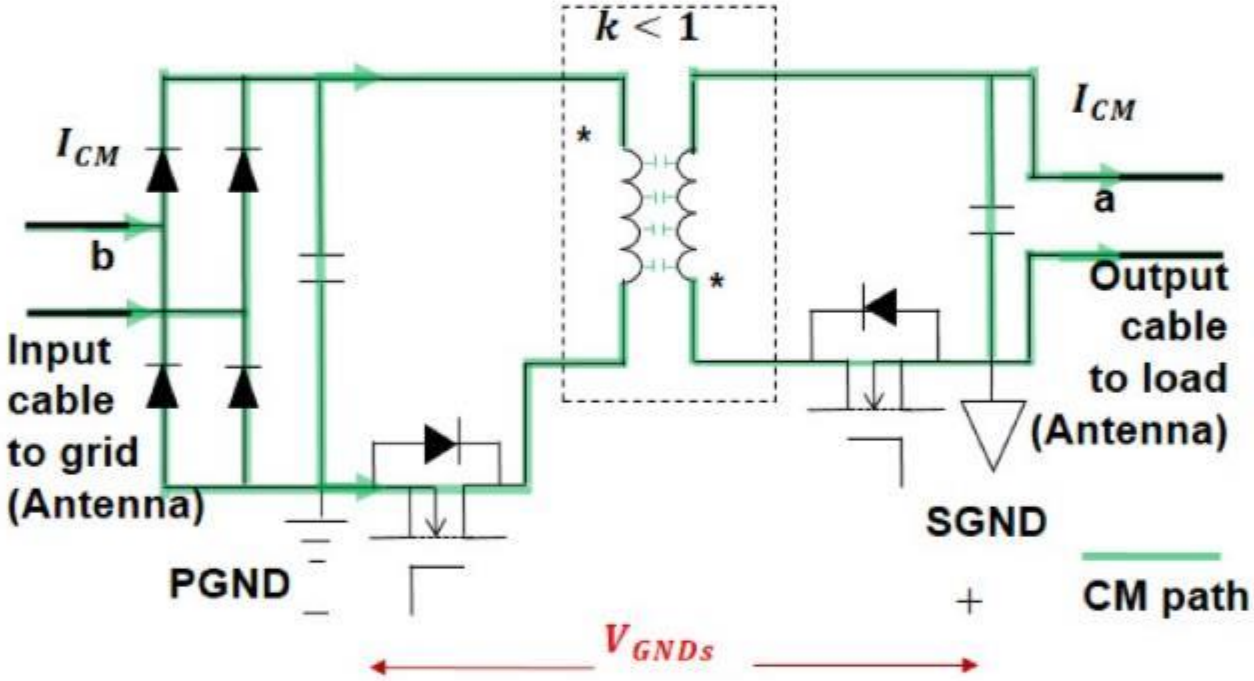
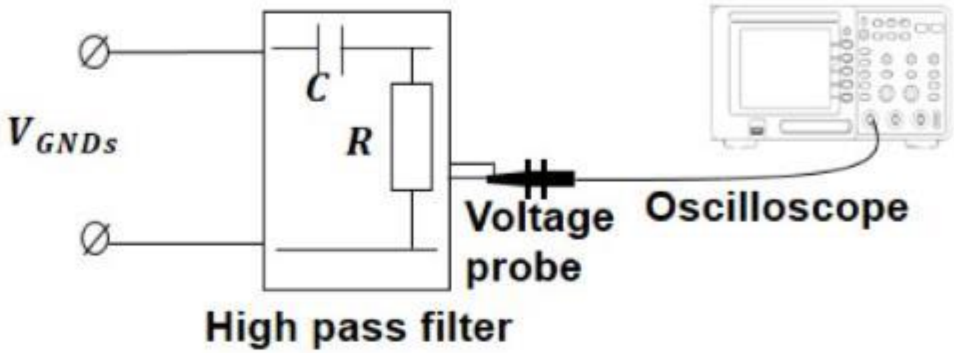
CM Voltage V_{GNDs} Measurement



1) V_{GNDs} has both 50/60Hz signal and switching noise
2) The magnitude of 50/60Hz signal could be much higher than switching noise
3) Due to the limitation of oscilloscope resolution, 50/60Hz signal must be excluded to increase noise measurement accuracy
4) A high-pass filter can be used to filter out 50/60Hz signals



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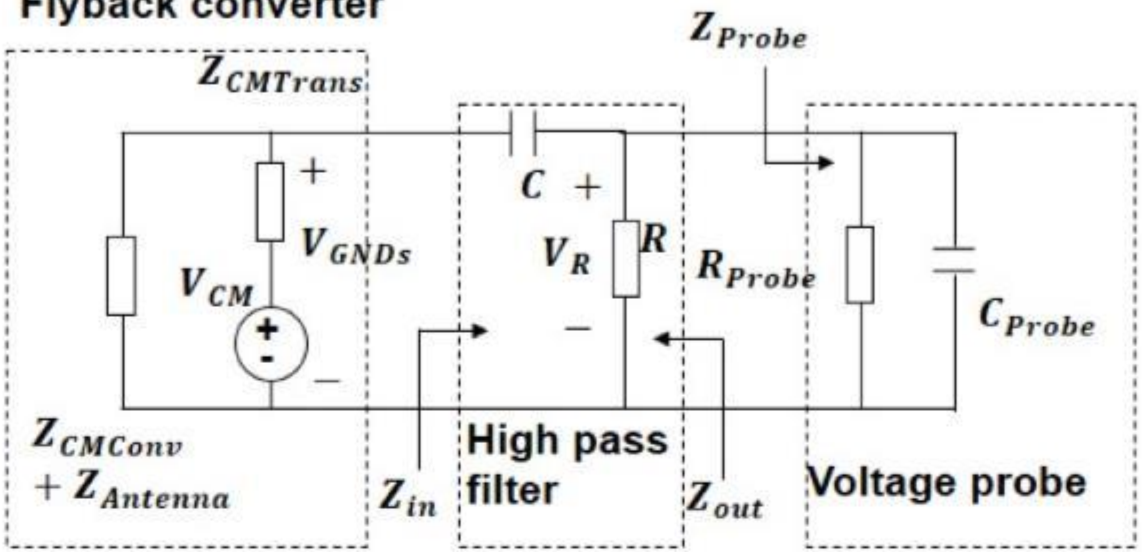
Issues in High-pass Filter Design



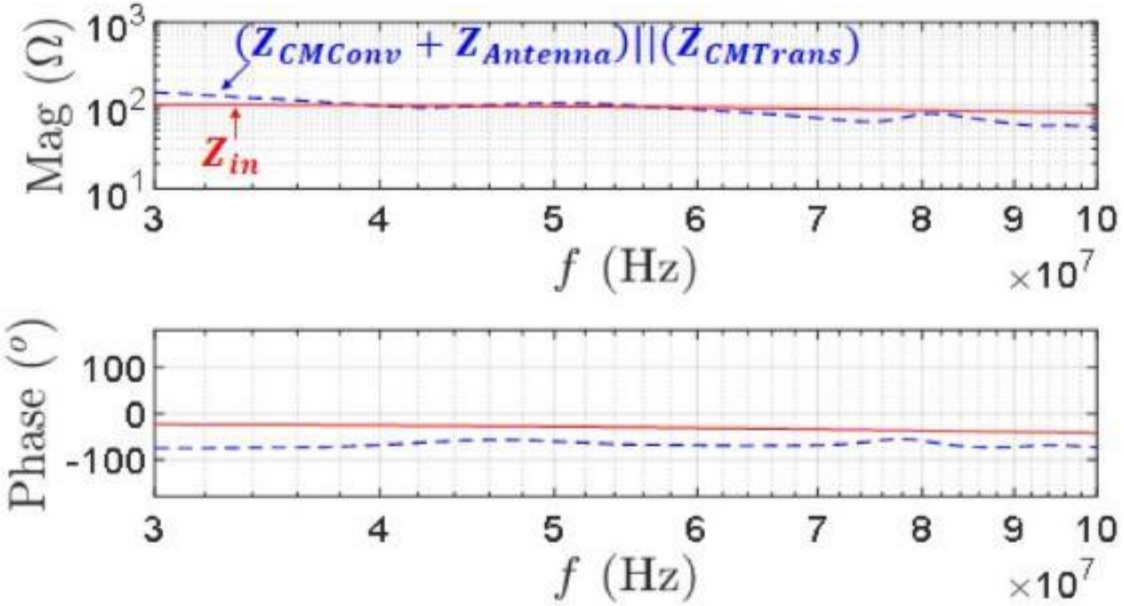
Conditions: $Z_{in} \gg (Z_{CMConv} + Z_{Antenna}) \| Z_{CMTrans}$

$$Z_{out} \ll Z_{Probe}$$

$$f_c = \frac{1}{2\pi RC} > 5\text{MHz}$$

$$Z_{in} = R \| Z_{Probe} + \frac{1}{j2\pi fC}$$

Cannot meet all conditions



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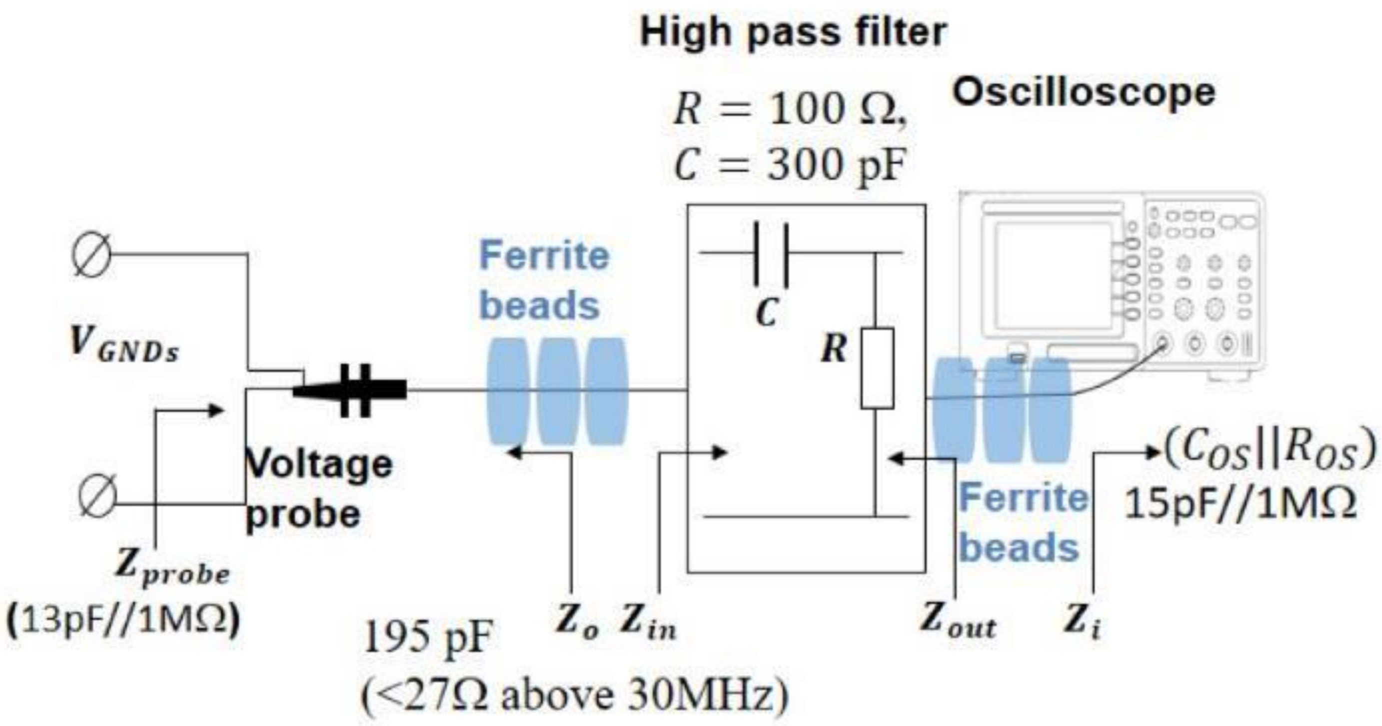
Improve High-pass Filter Design

Switch the voltage probe and high-pass filter positions



All conditions can be met

$$|Z_{out}| \ll \left| \frac{1}{\frac{1}{j2\pi f C_{OS}} + \frac{1}{R_{OS}}} \right|$$

Input impedance of the oscilloscope

$$|Z_{in}| \gg |Z_o|$$

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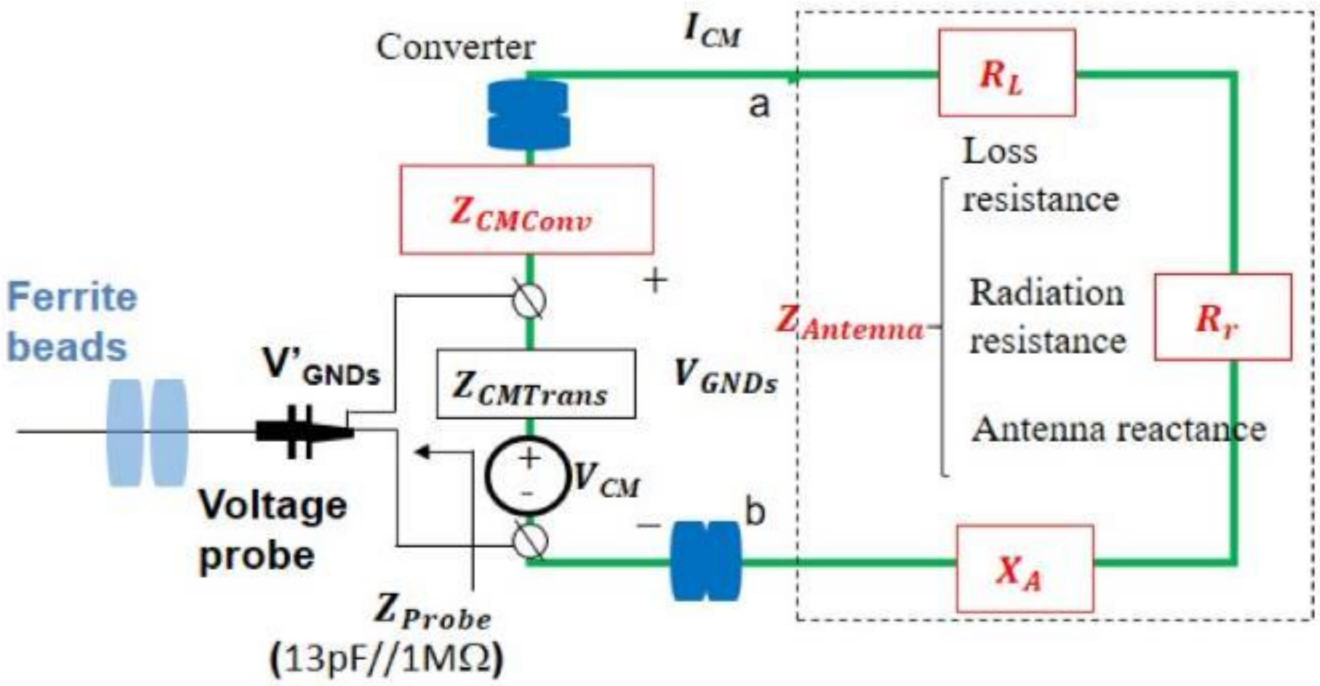
Derive V_{CM} and V_{GNDs}



1) Use ferrite beads to isolate Z_{CMConv} and $Z_{Antenna}$
2) The measured is V'_{GNDs}, NOT V_{GNDs}
3) V_{CM} can be solved based on V'_{GNDs}
4) Real V_{GNDs} can be derived

$$V_{CM} = V'_{GNDs}(1 + Z_{CMTrans}/Z_{Probe})$$
$$V_{GNDs} = V_{CM}(Z_{CMConv} + Z_{Antenna})/(Z_{CMConv} + Z_{Antenna} + Z_{CMTrans})$$

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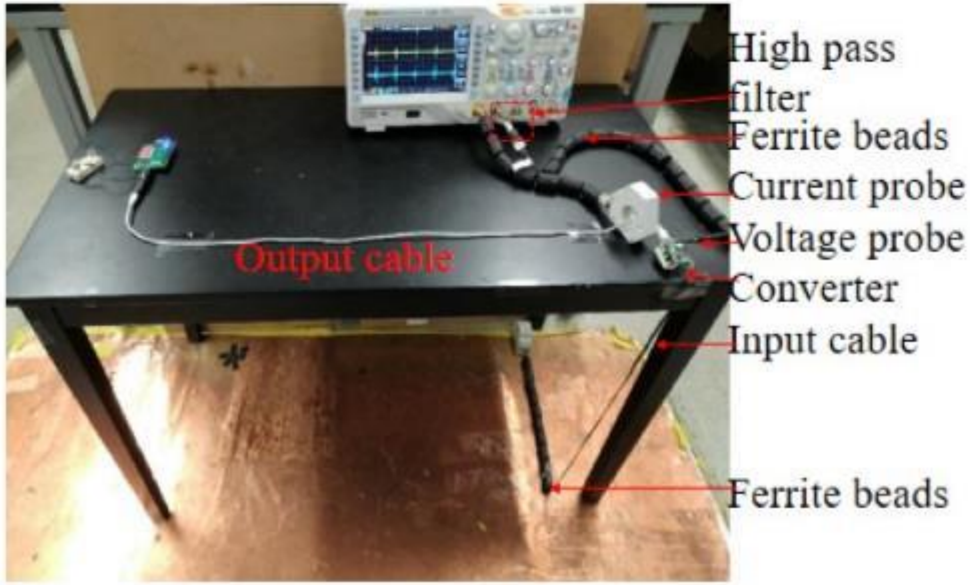
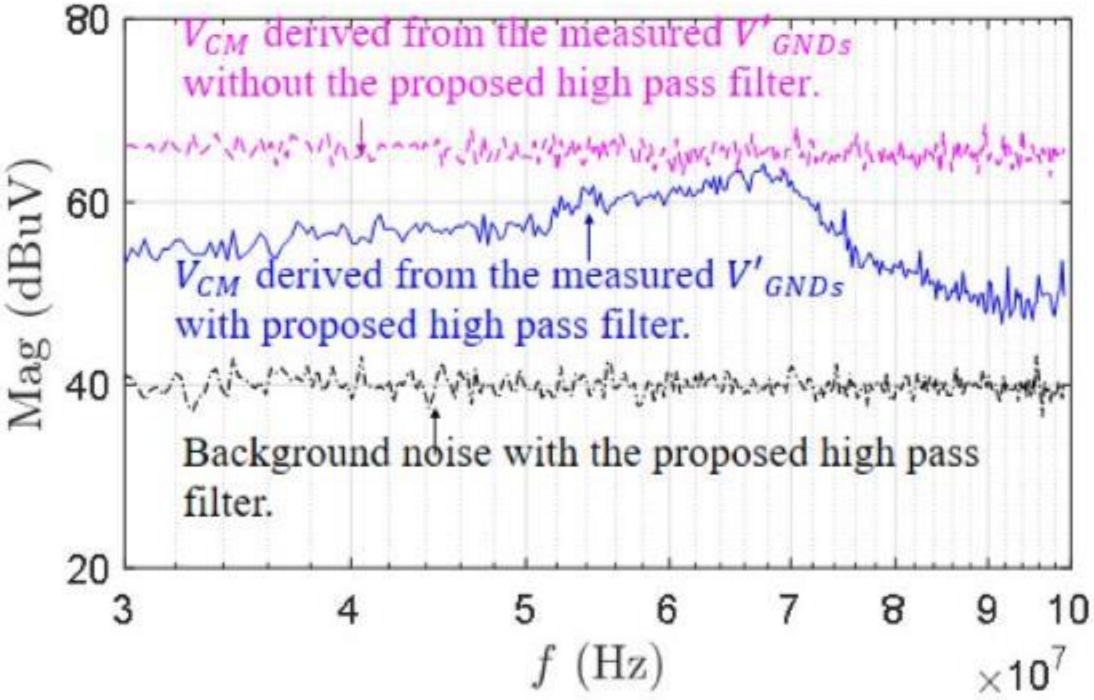
Derived V_{CM} w/ and w/o the High Pass Filter





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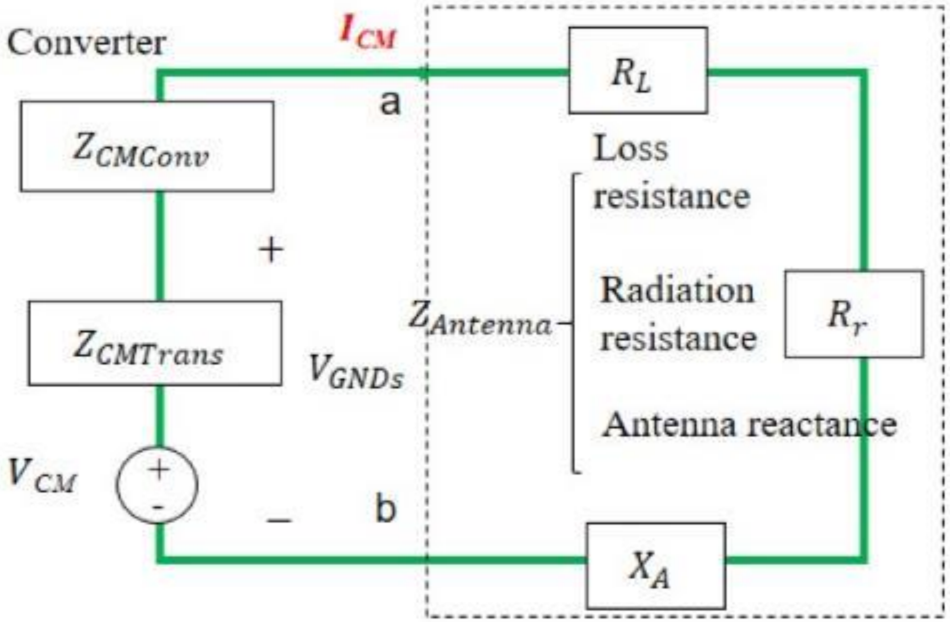
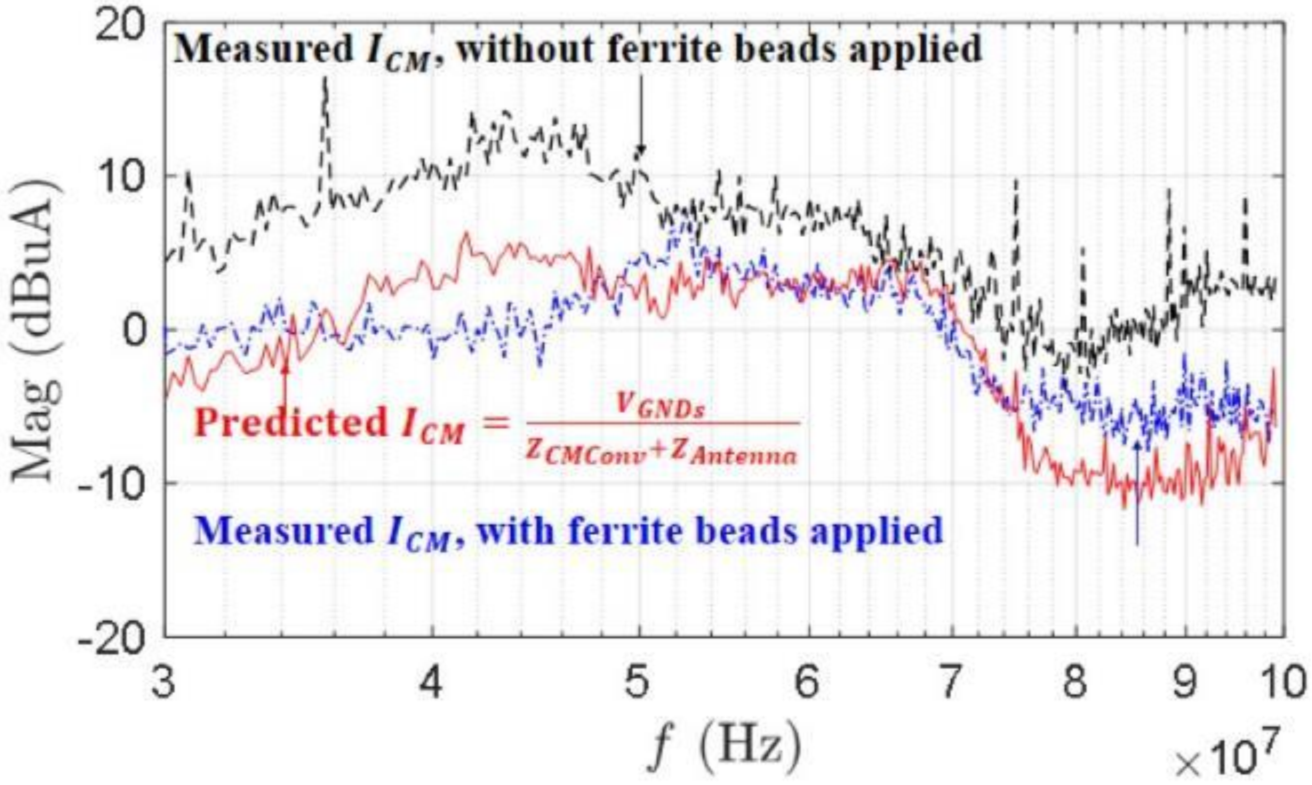
Measured CM Current I_{CM} w/ and w/o Ferrite Beads





Ferrite beads can greatly improve the accuracy

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Conclusions

- The effect of undesired couplings in high-frequency CM current measurement is analyzed and quantified
- Ferrite beads are used isolate couplings and improve the accuracy of high-frequency CM current measurement
- Measurement technique for the transformer's high-frequency DM to CM voltage transformation is proposed
- The high-frequency CM impedance measurement techniques for transformers, converters and cable antenna are proposed
- High-frequency CM voltage measurement and derivation technique are proposed (a high-pass filter is proposed)

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