EMC Compliance Techniques for Silicon Carbide (SiC) Power Converters

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Part 1

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STC

Solving your difficult EMI/EMC problems.

Outline

- **Filtering concepts**
  - **Line Impedance Stabilization Network – LISN**
  - **Concept of filtering - impedance mismatch**
- Differential-mode (DM) and common-mode (CM)
  - Understanding DM and CM current paths
  - Filtering for DM and CM currents
- Flyback converter filter
  - Designing the DM & CM filter
- Separation of DM/CM components
  - Measurement method & components
- EMI using SiC power semiconductors
  - EMI impact of faster switching & transitions

EMI is All About Current Paths

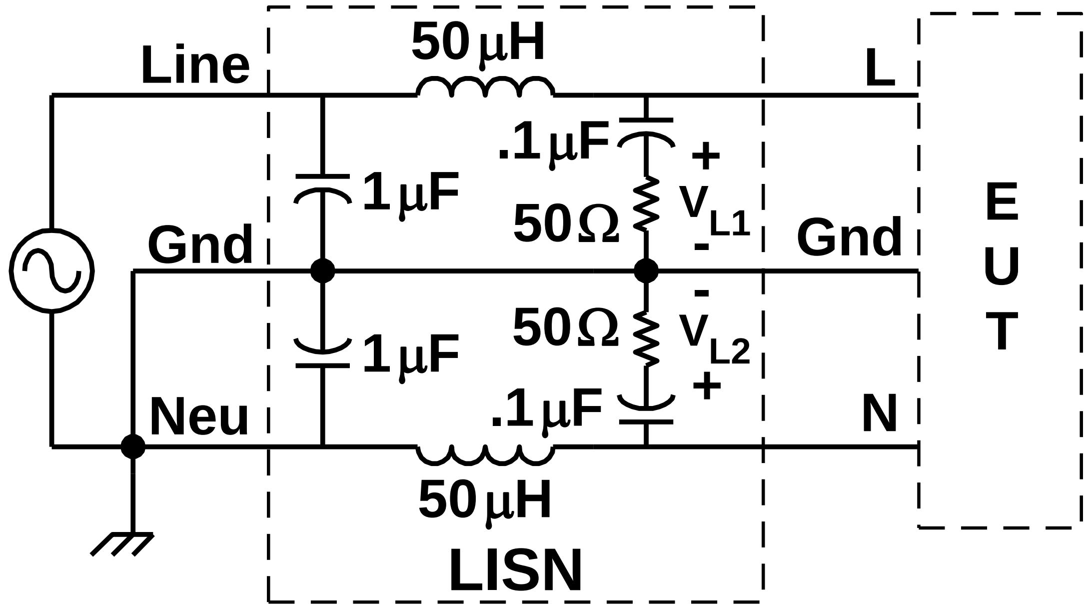
EMI Golden Rule: Return currents back to their source in a defined and compact path. Current must ALWAYS return back to its source in a closed path.

Returning currents compactly is the most effective and lowest cost solution for both conducted and radiated EMI problems. Filtering and shielding are "band-aids" that address symptoms of high-frequency currents flowing in problematic paths. Get as much EMI margin as possible using good layout and design practices (e.g. returning currents compactly) before adding costly filtering and shielding.

12 μA of DM or CM current (12 μA into 50 $\Omega \rightarrow$ 600 μV = 56 dBμV) fails FCC-class B conducted limits (.15 - 30 MHz). 5 μA_{RMS} of CM current flowing in a large path fails FCC-class B radiated limits (>30 MHz).

EMI problems are due to poor current paths

Line Impedance Stabilization Network



One of the 50 Ω resistors is located inside the spectrum analyzer. The other is added at the LISN BNC connection.

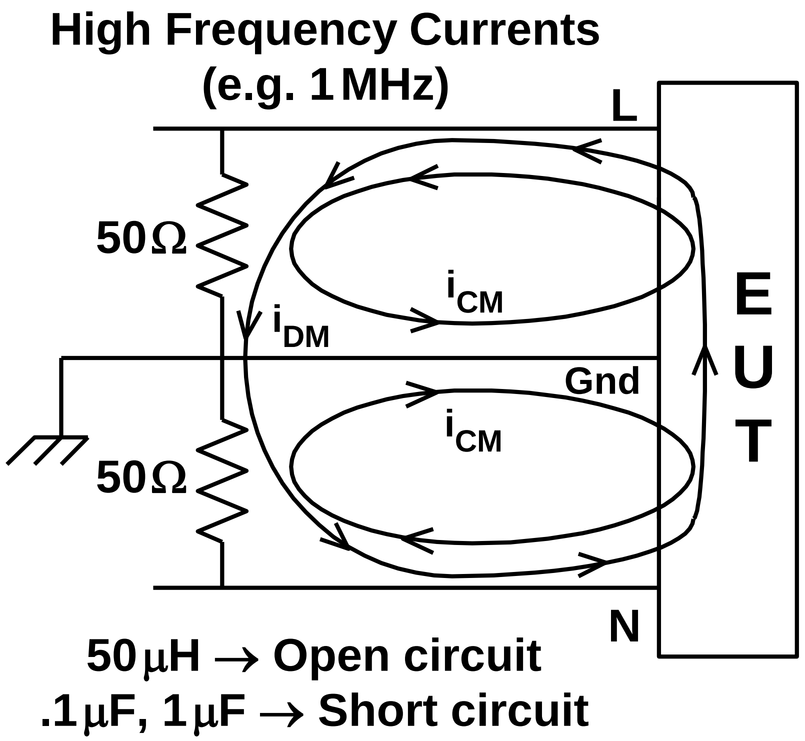
Note: The LISN shown is a functional equivalent circuit, not a complete schematic.

The LISN is used for conducted EMI measurements. The voltage across the 50 Ω resistor is measured and must always be less than a specified limit over a frequency range. The LISN provides a repeatable conducted EMI measurement. Low frequency currents go thru the 50 μH inductors, high frequency (noise) currents go thru the 50 Ω resistors. The noise voltage is the noise current into 50 Ω.

LISN makes repeatable conducted EMI measurements

LISN High Frequency Equiv. Circuit

At high frequencies (e.g. > 150 kHz), the 0.1 μF capacitor in series with the 50 Ω resistor acts like a low impedance, and the 50 μH inductor acts like a high impedance. High frequency currents from the equipment under test (EUT) flow into the 50 Ω LISN resistors as shown below.



Note: Noise currents flow through the 50 Ω resistors, thus they are measured as noise voltages.

At 1 MHz:

50 μH → j 310 Ω

.1 μF → -j 1.6 Ω

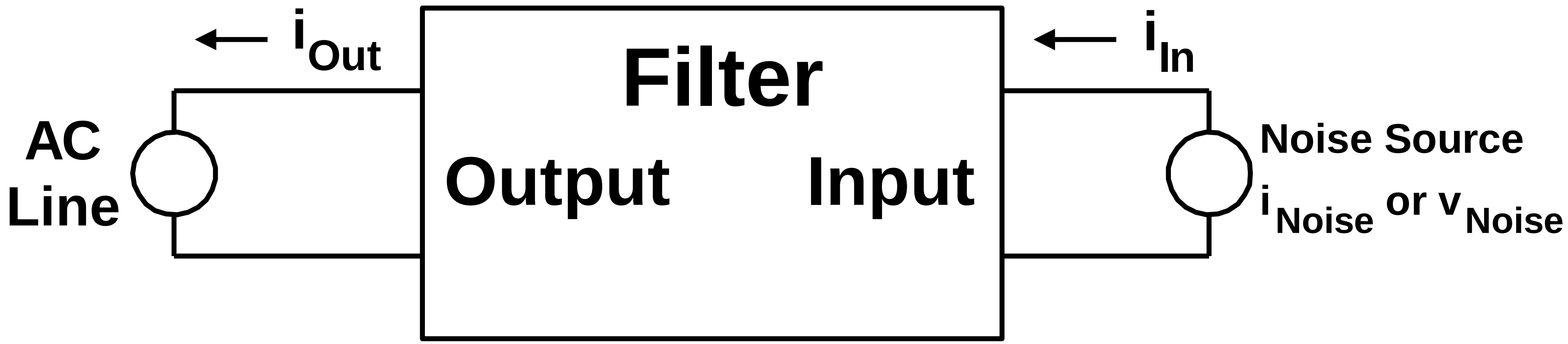
High freq. EUT currents flow in 50 Ω LISN resistors

Filtering &
Impedance Mismatch

Filtering Introduction (1)

There are two choices for augmenting a lossless (no resistors) filter:

1) High series impedance : Inductor
2) Low shunt impedance : Capacitor



Note: The noise source (input) is shown to the right, since this is the normal configuration in actual systems.

The filter output current would normally be measured using a LISN.

Filtering is minimizing high frequency currents at AC line

Filtering Introduction (2)

Filtering is about "maximizing impedance mismatch" between successive filter stages.

Remember that a voltage source is a low small-signal output impedance, a current source is a large small-signal output impedance.

$$Z_{Small-Signal} = \Delta v / \Delta i$$

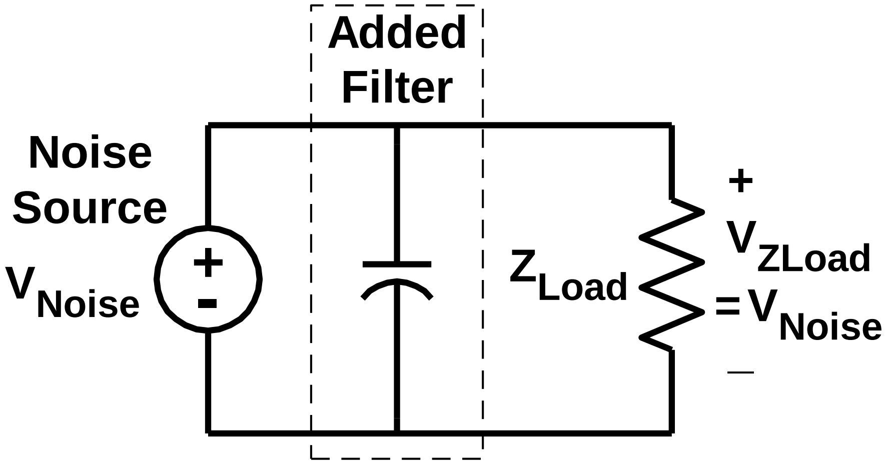
A voltage source keeps the output voltage constant ($\Delta v = 0$) for a change of current through it ($\Delta i \neq 0$), $\therefore Z_{Sm\text{-}Sig} \rightarrow 0\,\Omega$.

A current source keeps the output current constant ($\Delta i = 0$) for a change of voltage across it ($\Delta v \neq 0$), $\therefore Z_{Sm\text{-}Sig} \rightarrow \infty\,\Omega$.

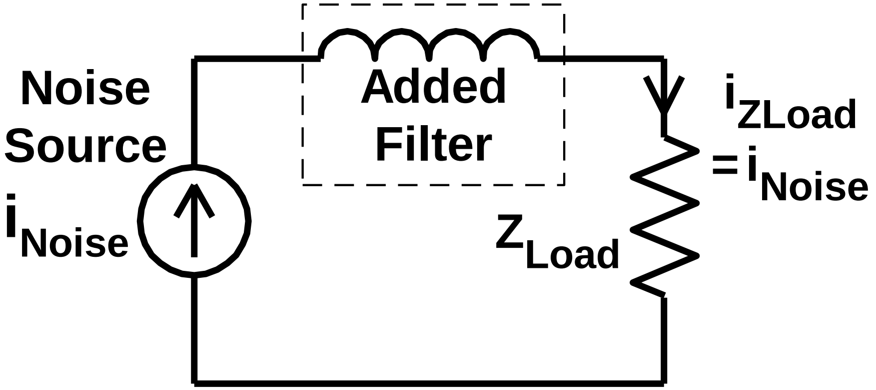
Impedance Mismatch - 1

A capacitor (low Z) in parallel with a voltage source (or low impedance), or an inductor (high Z) in series with a current source (or high impedance) does not provide attenuation.

Ineffective Filters:



No reduction in noise voltage, since putting a low Z part (C) in parallel with a low Z noise source (voltage source).

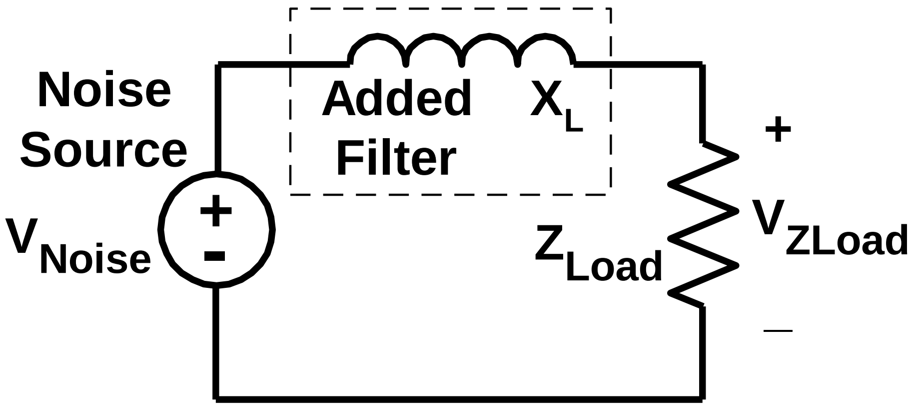


No reduction in noise current, since putting a high Z part (L) in series with a high Z noise source (current source).

Impedance Mismatch - 2

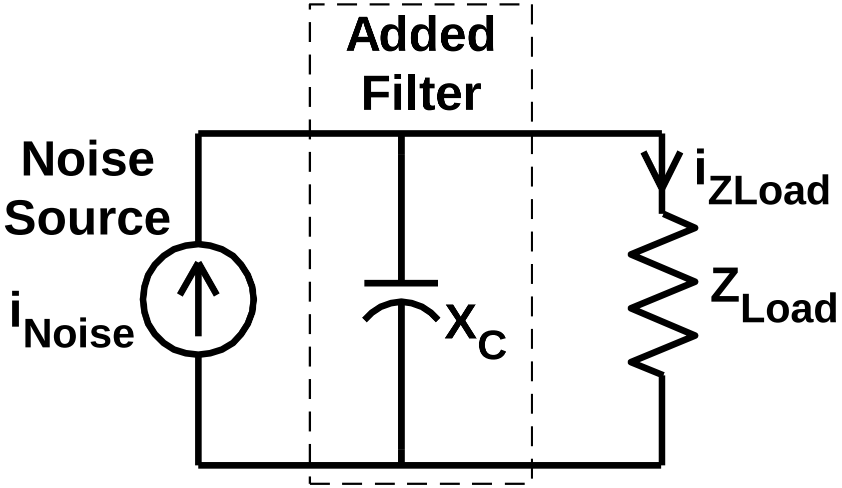
An inductor in series with a voltage source (or low impedance), or a capacitor in parallel with a current source (or high impedance) does provide attenuation.

Effective Filters:



$$v_{ZLoad} = v_{Noise} \frac{z_{Load}}{z_{Load} + x_L}$$

If Z_{Load} is small relative to X_L, then there is a large attenuation



$$i_{ZLoad} = i_{Noise} \frac{x_C}{z_{Load} + x_C}$$

If Z_{Load} is large relative to X_C, then there is a large attenuation

Impedance Mismatch - 3

EMI filtering is about maximizing noise voltage or noise current attenuation at RF frequencies. That is, we want to minimize EMI. We will accomplish this using the impedance mismatch concept. Both the next and the previous filter stages should be impedance mismatched.

If the previous {or next} filter stage consists of a low impedance (voltage source or capacitor), then the next {or previous} stage should be high impedance (inductor).

If the previous {or next} filter stage consists of a high impedance (current source or inductor), then the next {or previous} stage should be low impedance (capacitor).

Proper filter design requires impedance mismatch

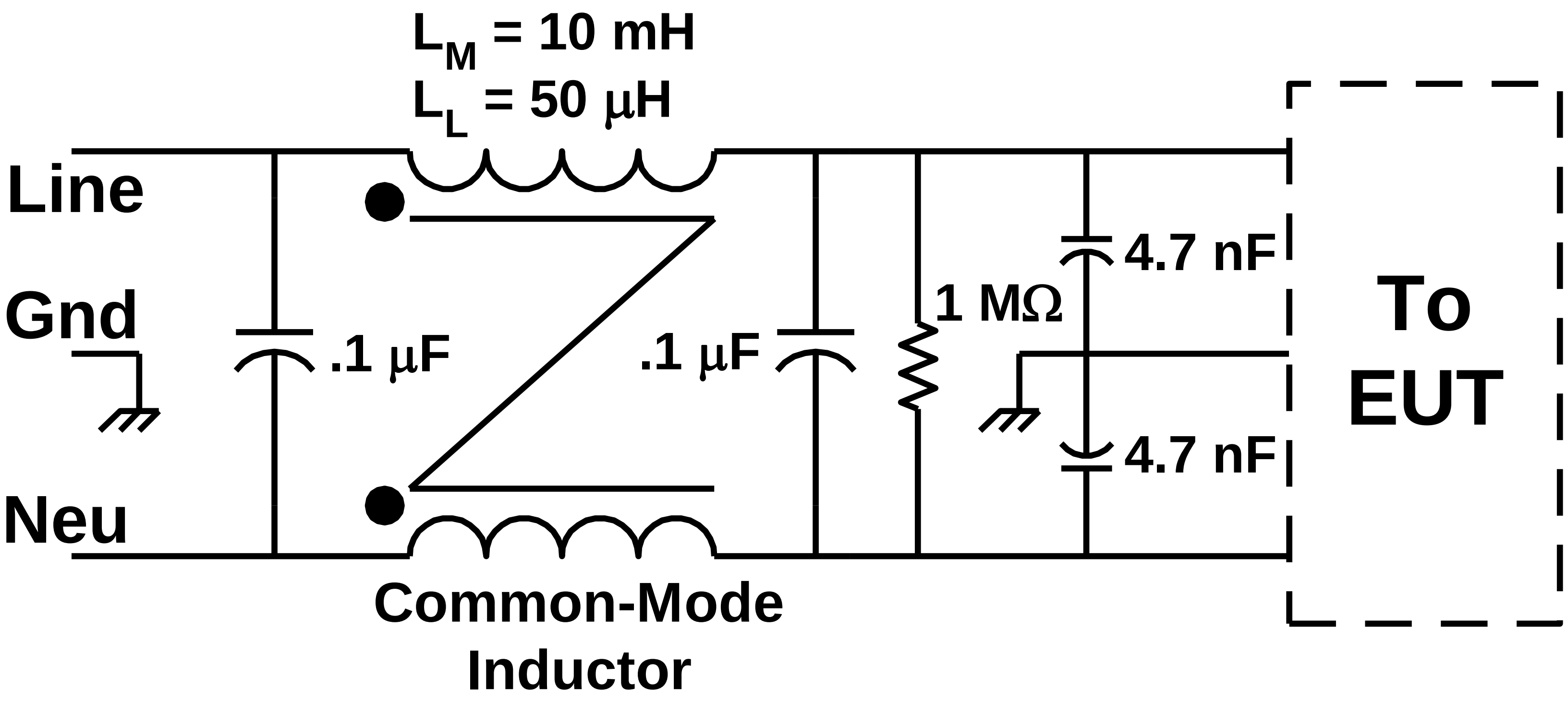
Differential-Mode (DM) and Common-Mode (CM) Currents

It is a fundamental property of electrical circuits that current must always return back to its source.

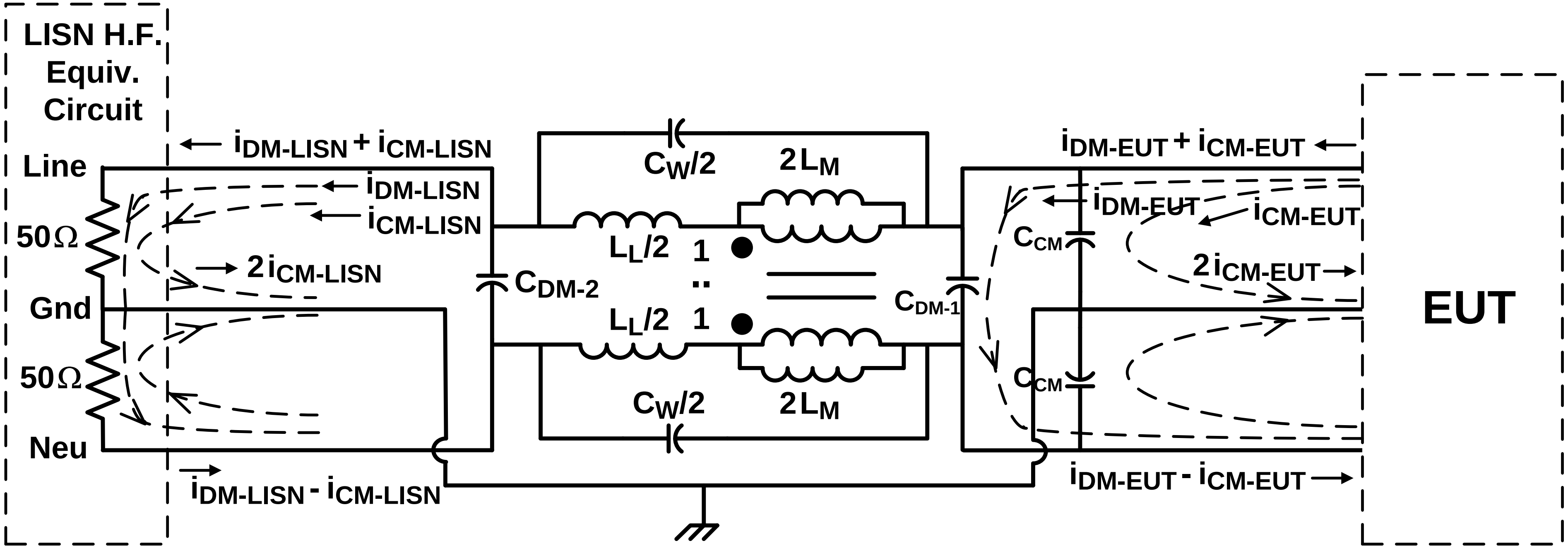
The fundamental difference between DM and CM currents is the electrical path they take, and how close the return current path is to the sending current path. DM currents have a “close” current return path, while CM currents do not have a “close” return path.

The closer the return current path is to the sending current path, the more effective the cancellation of radiation creation mechanisms. Thus DM currents are less of a radiation problem than CM currents.

Typical EMI Filter

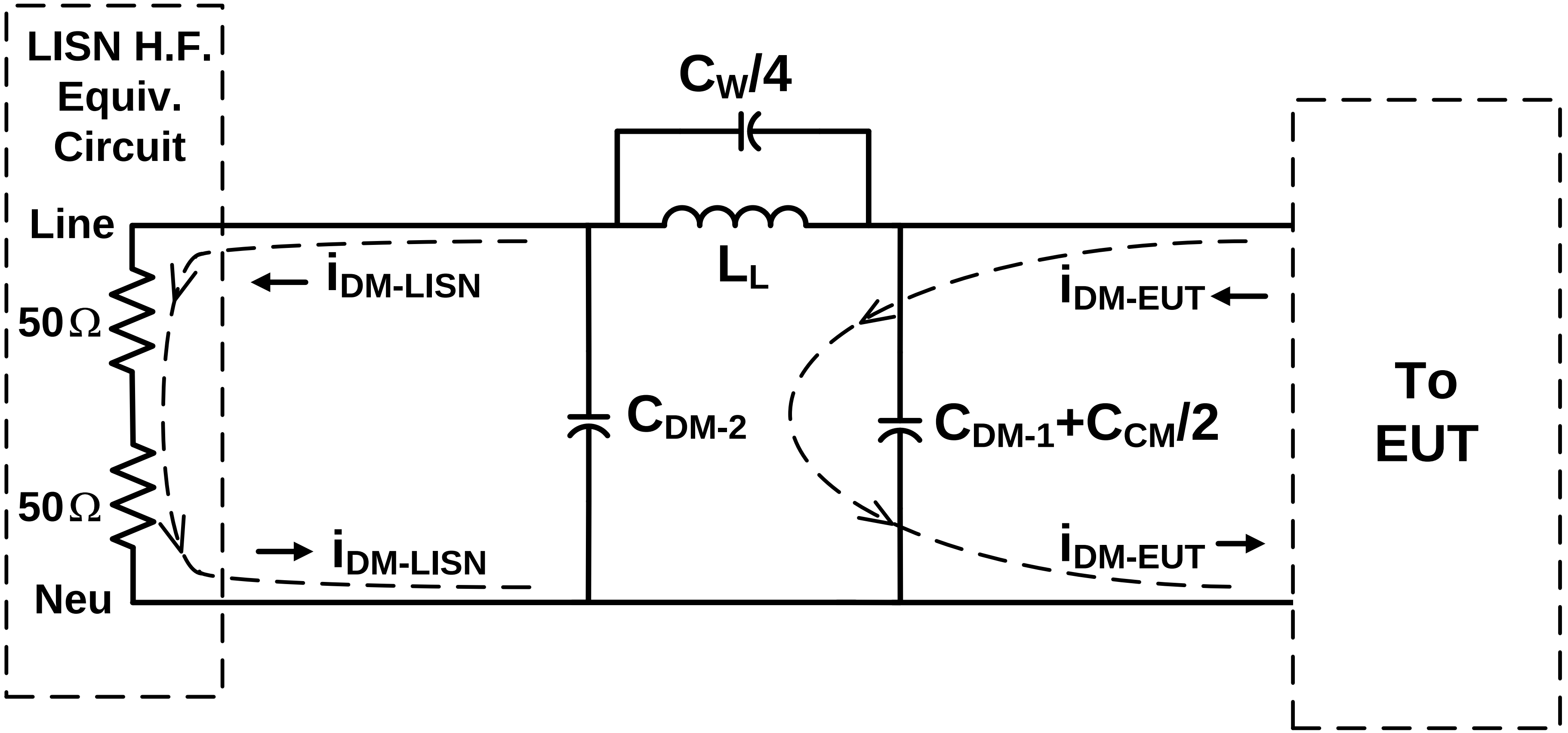


DM and CM Currents



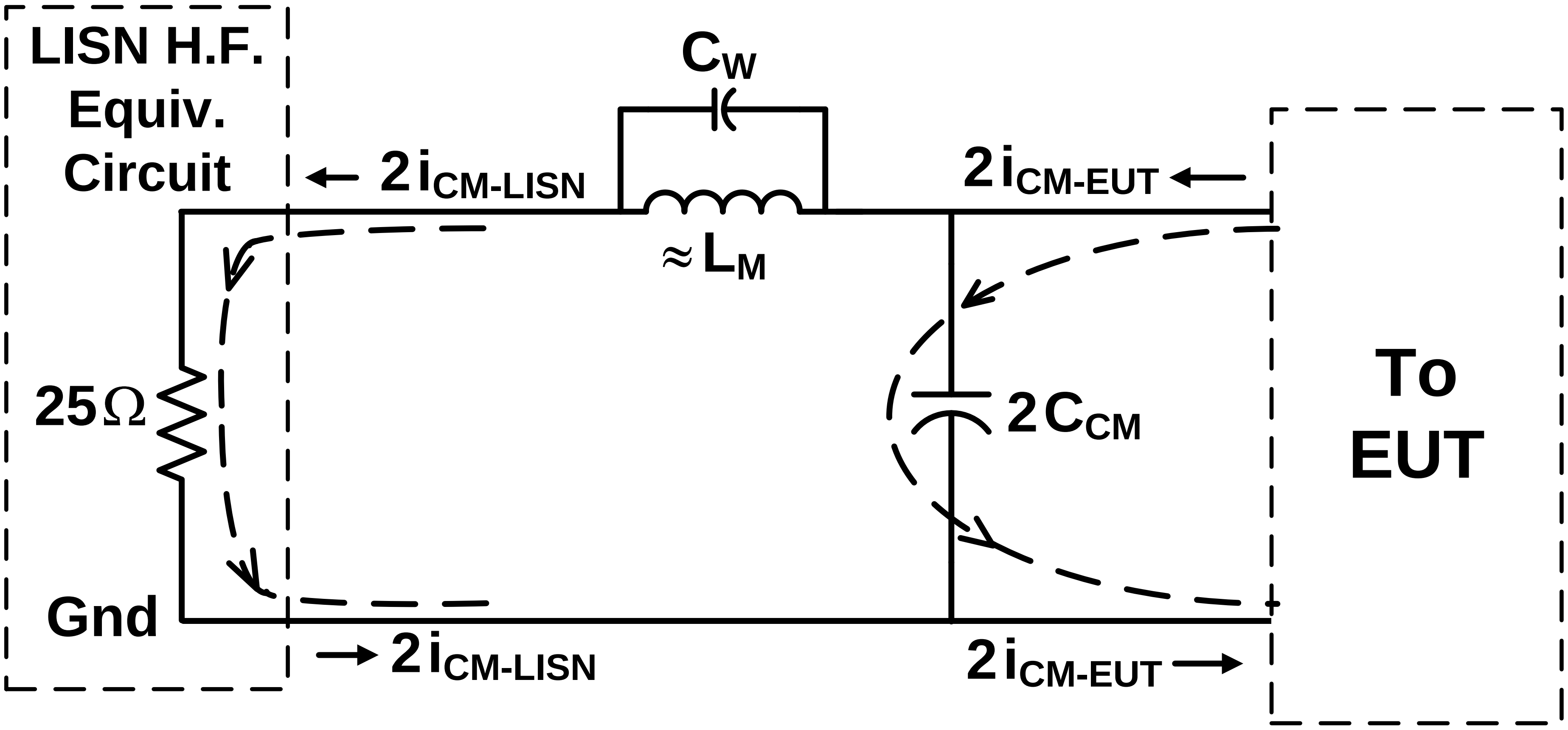
There are actually two filters in this circuit. One to filter the differential-mode (DM) current, another to filter the common-mode (CM) current. Impedance mismatch is used for both cases.

Equivalent DM Filter Circuit



For DM currents, LISN looks like 100Ω

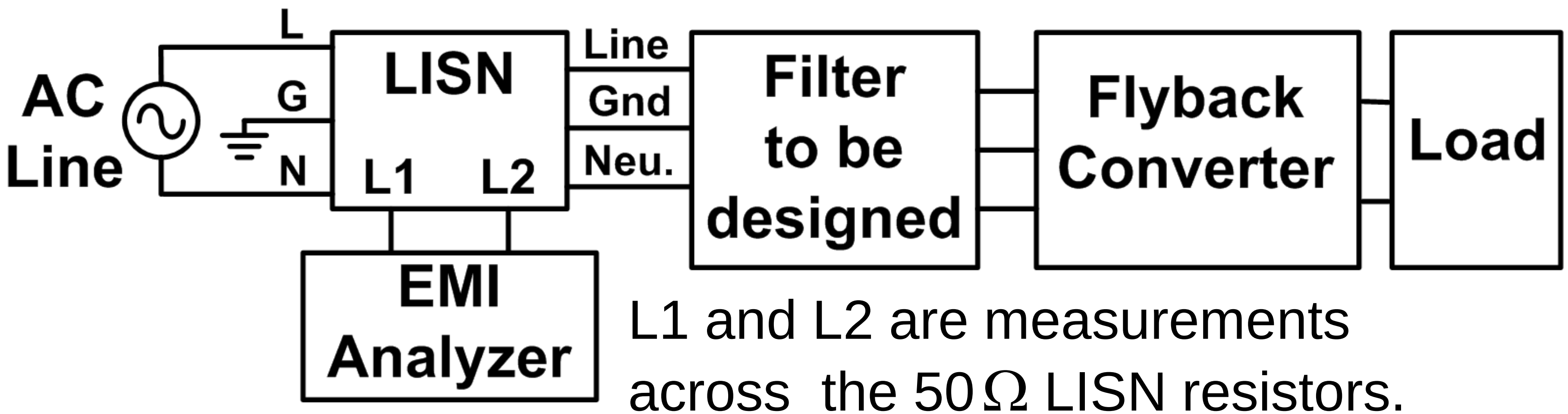
Equivalent CM Filter Circuit



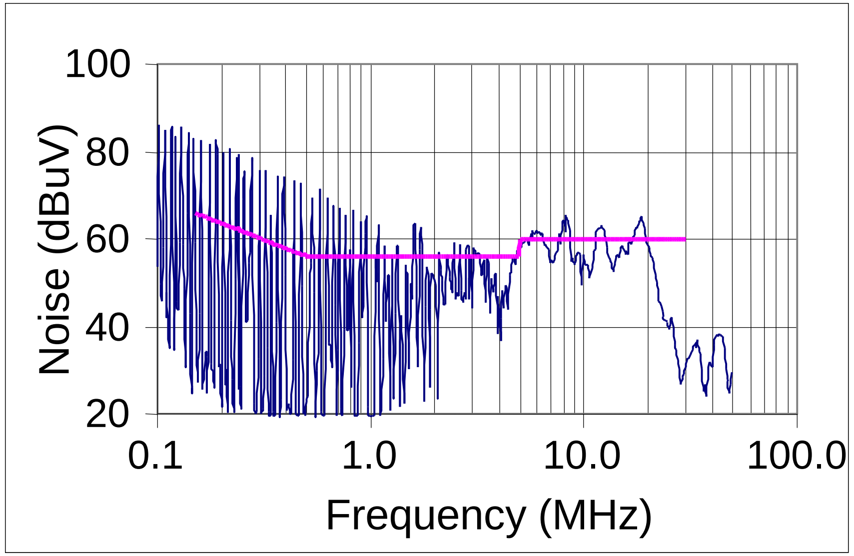
For CM currents, LISN looks like 25Ω

Flyback Converter Example

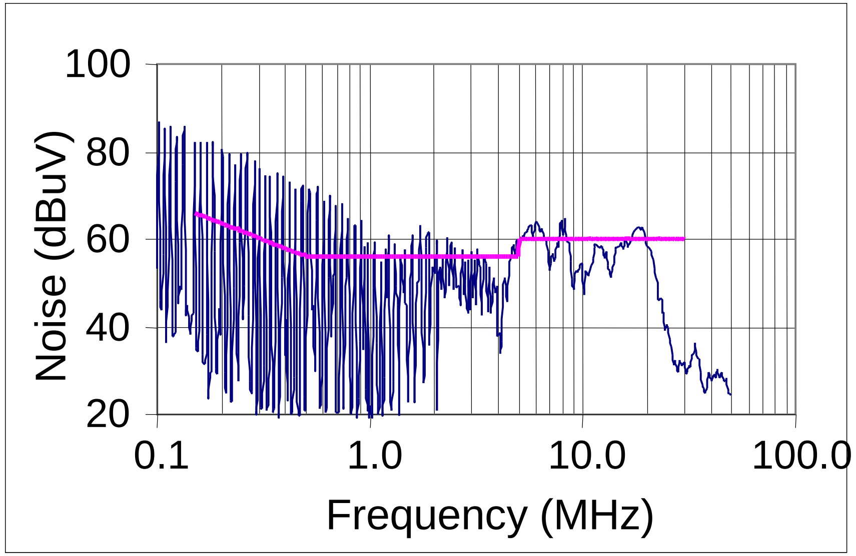
Flyback Converter Filter Design



L1 and L2 are measurements across the 50 Ω LISN resistors.



L1 Measurement – No Filter



L2 Measurement – No Filter

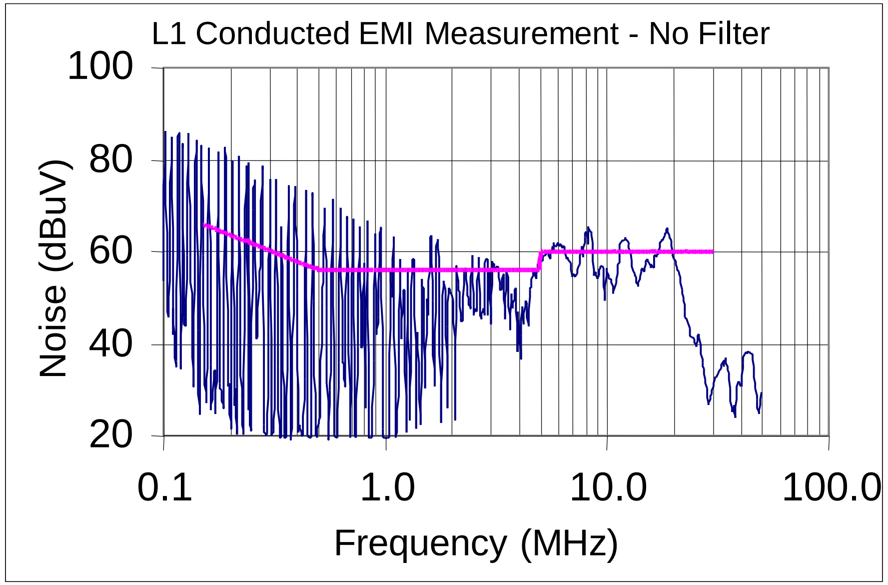
Required Attenuation

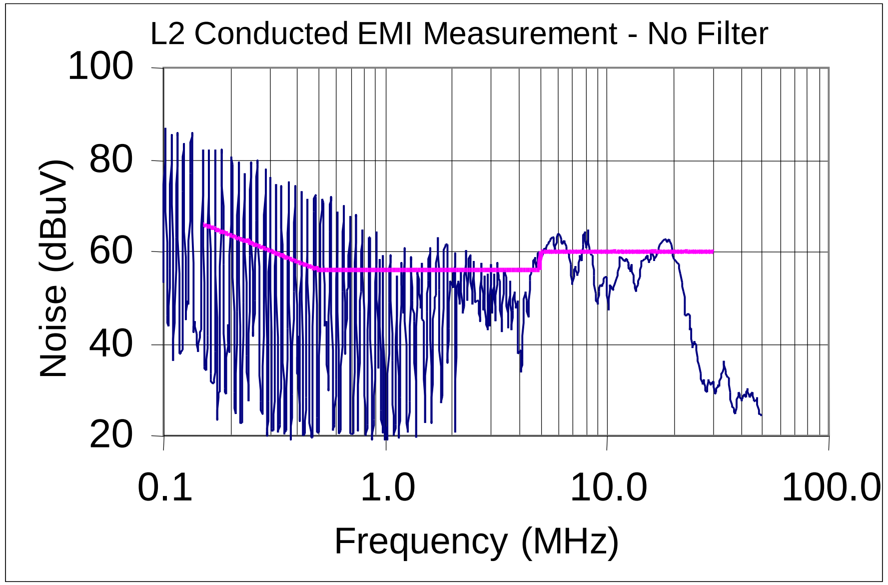
The difference between the measured conducted EMI and the limit line (with an added safety margin, e.g. 6-10 dB) provides the required attenuation.

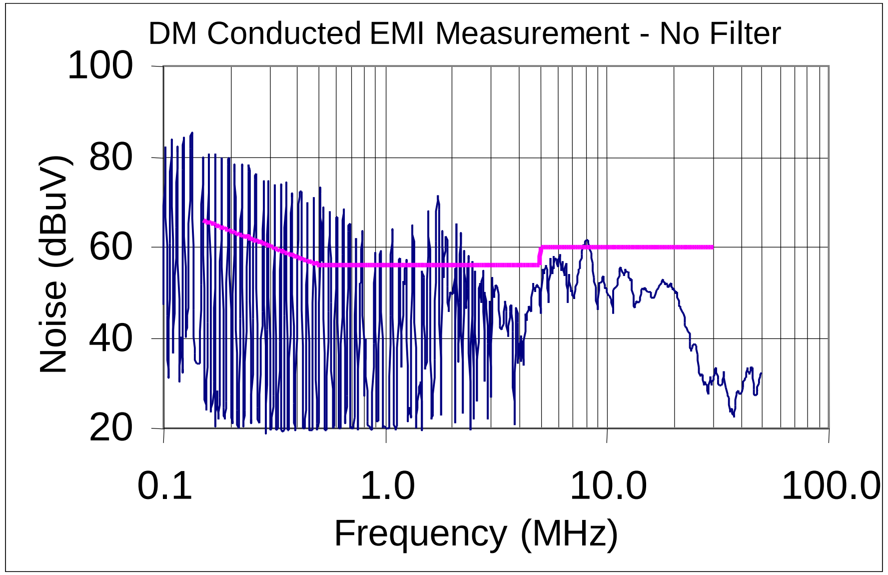
The LISN L1 and L2 signals are not the correct inputs for filter design purposes, they should be transformed to differential-mode and common-mode signals. This allows a systematic procedure for designing both the DM and CM filter stages.

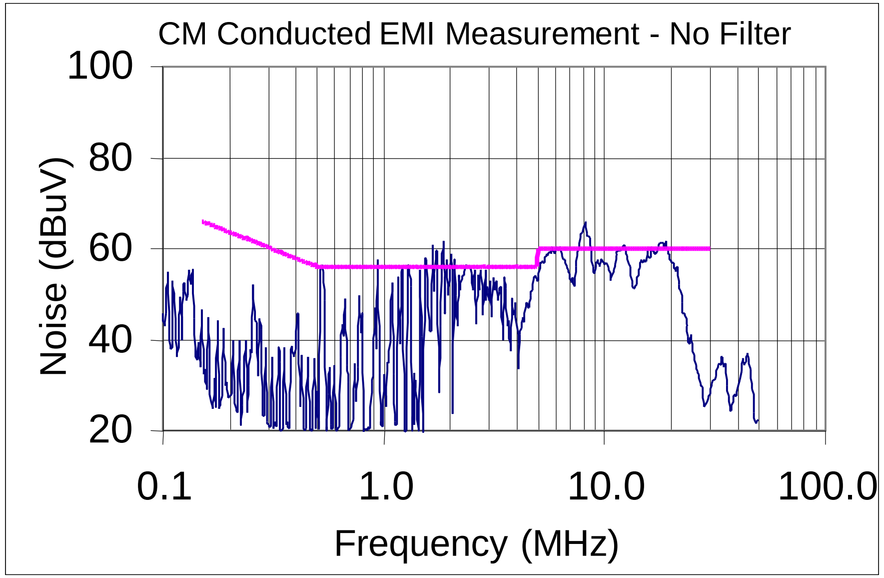
Design EMI filter with 6-10 dB margin

EMI Measurements

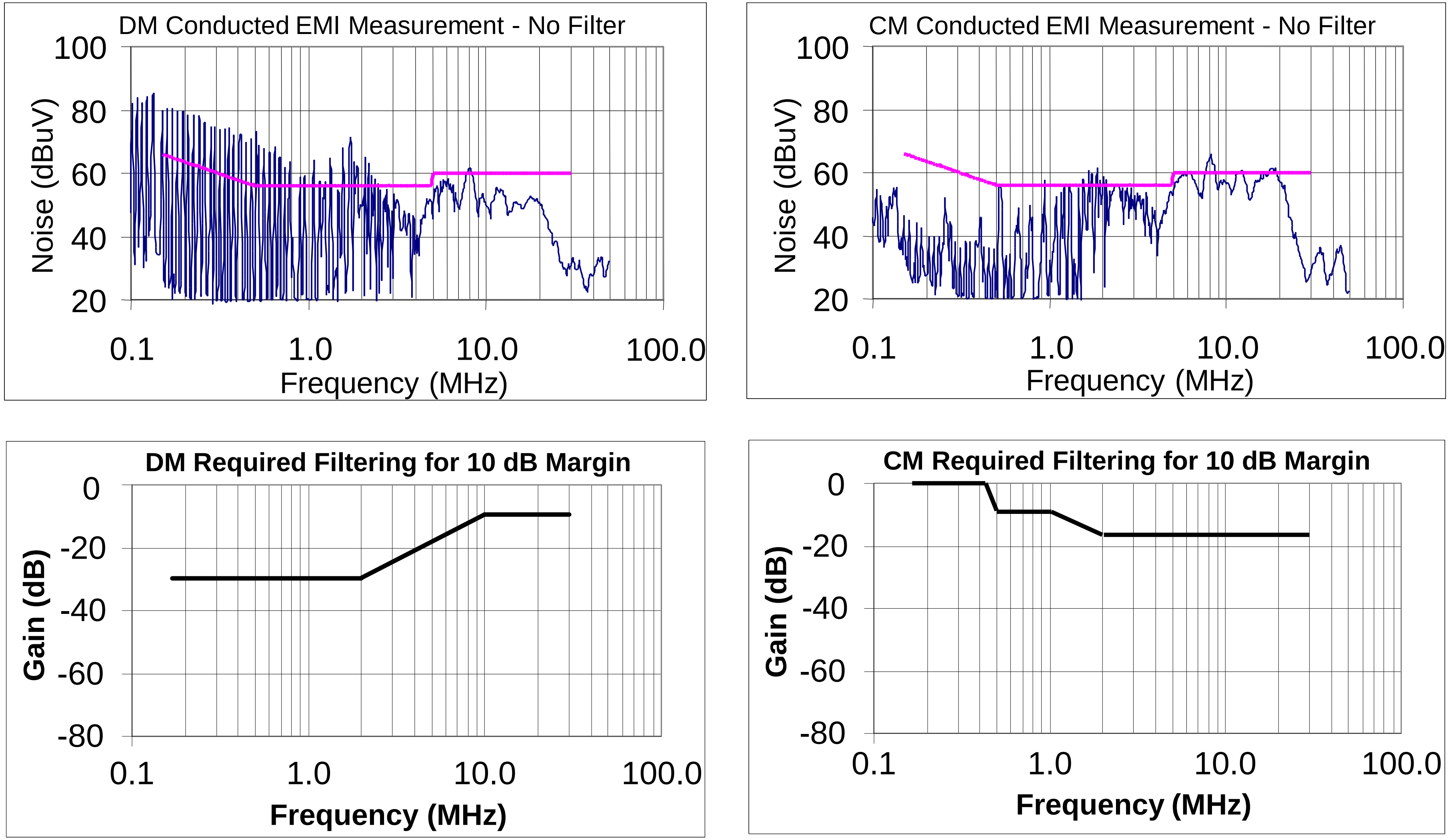






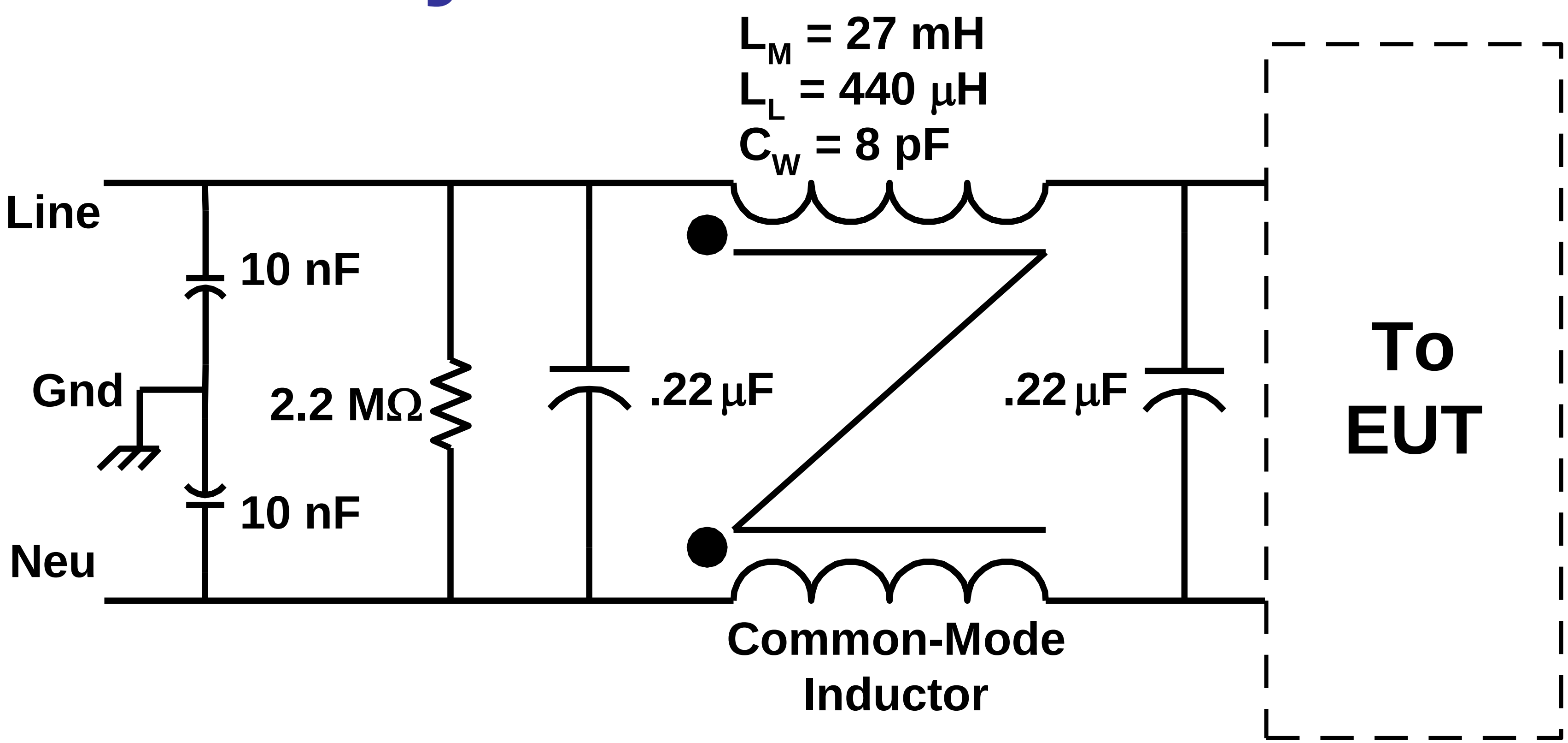


Measured Conducted EMI
Flyback Converter - No Filter



Filter attenuation determined by system EMI performance

Flyback EMI Filter

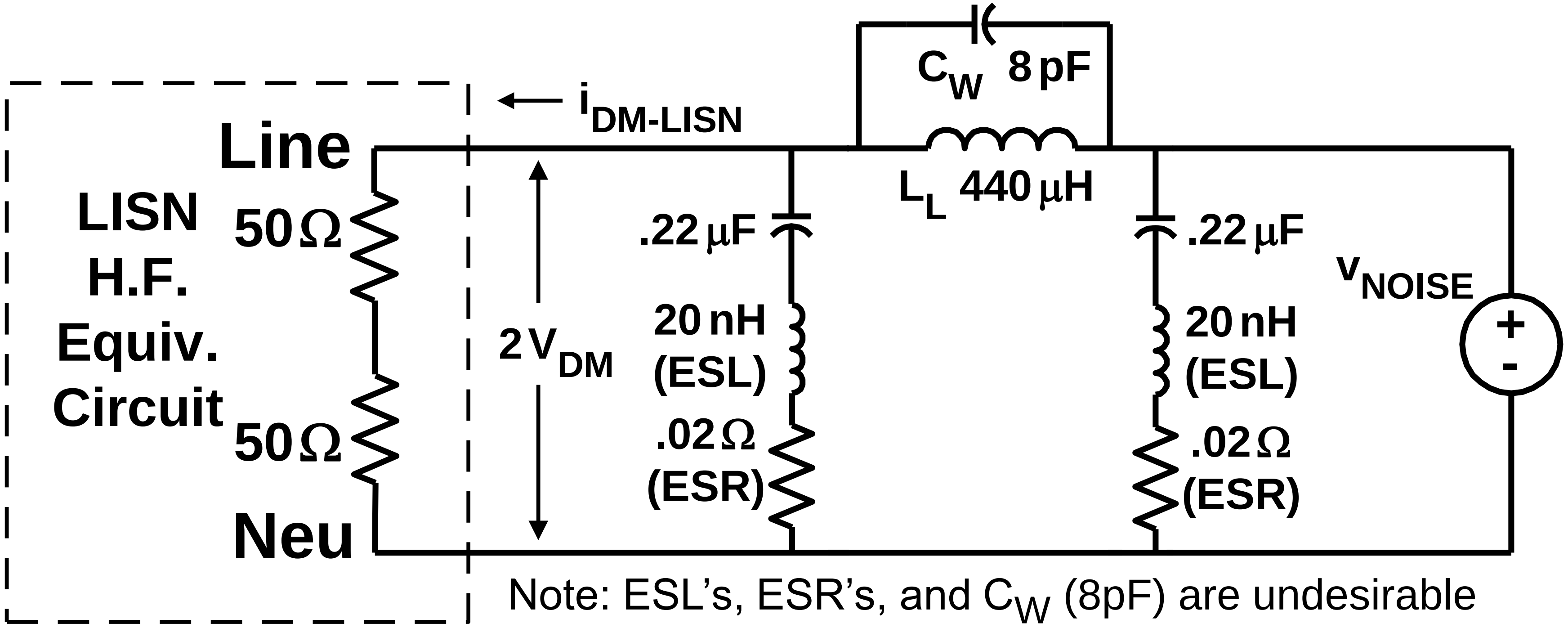


L_M is the desirable magnetizing inductance.
L_L is the desirable leakage inductance.
C_W is the undesirable parasitic winding capacitance.

Note: the 10 nF "y-capacitors" are on the wrong side of the common-mode inductor!!! DM filter OK.

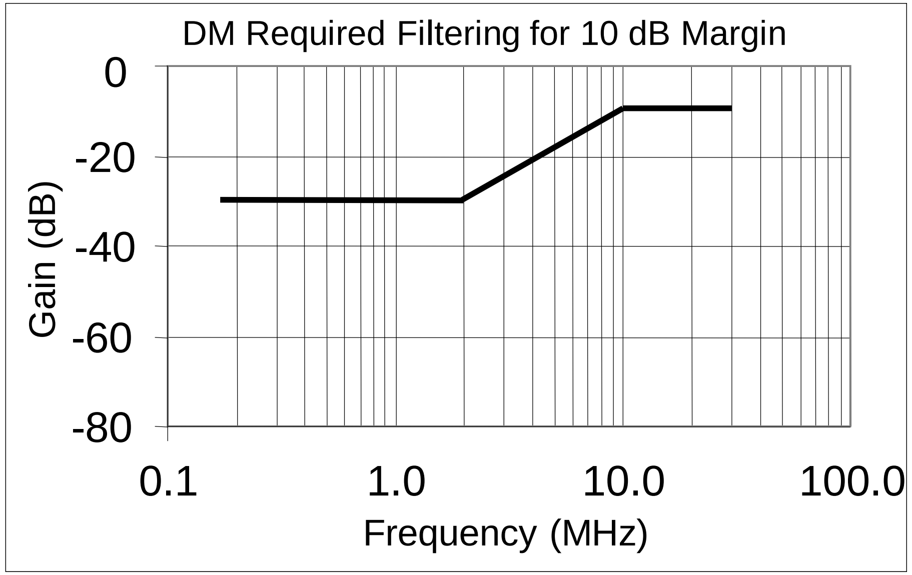
Flyback DM EMI Filter

The EUT is a flyback converter input that has several large and small capacitors across the DC link, thus it looks like a voltage source (low impedance), so the .22 μF cap closest to the EUT (V_{NOISE}) is not effective.

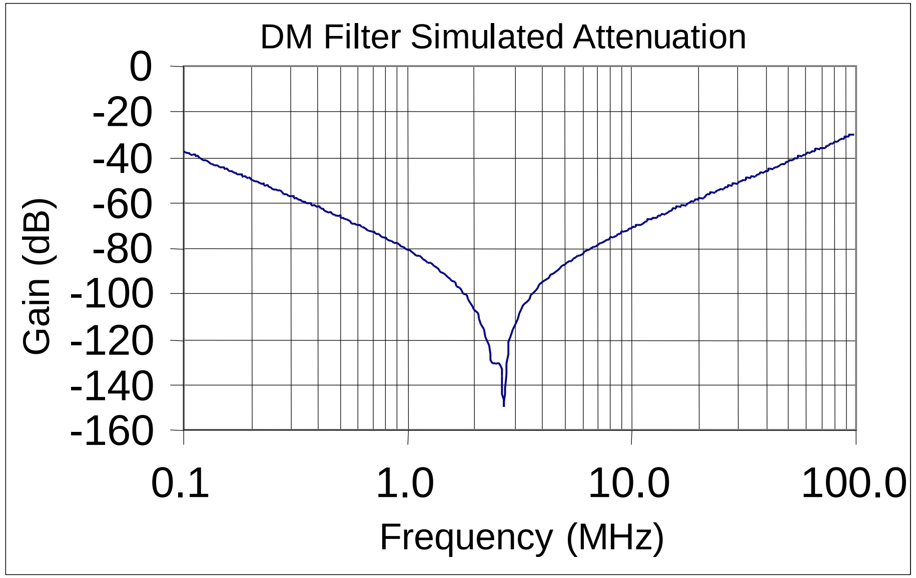


Note: ESL's, ESR's, and C_W (8pF) are undesirable parasitics. L_L is the desirable leakage inductance.

DM Filter Attenuation



Required DM attenuation

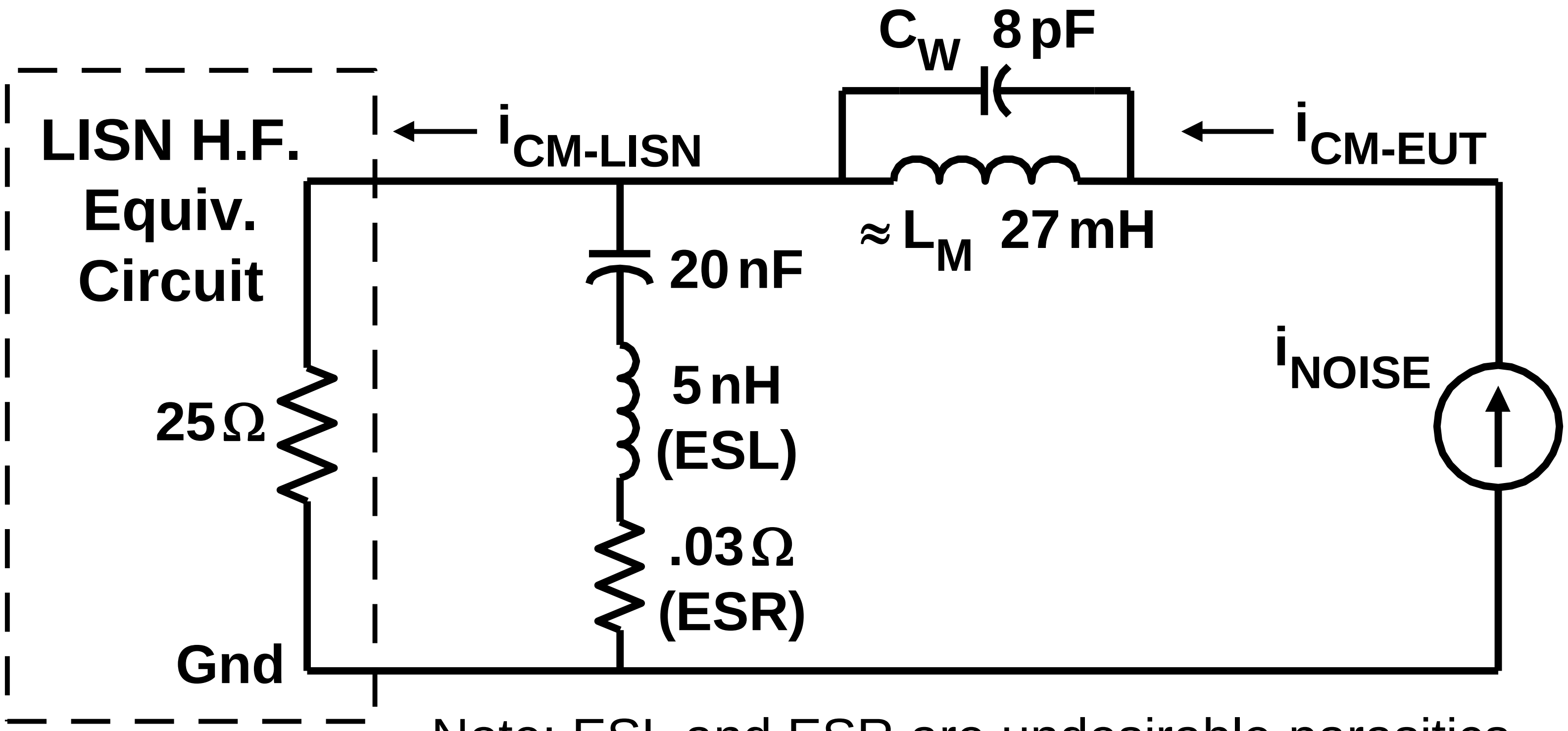


Spice simulated DM attenuation

More attenuation than required is OK

Flyback CM EMI Filter

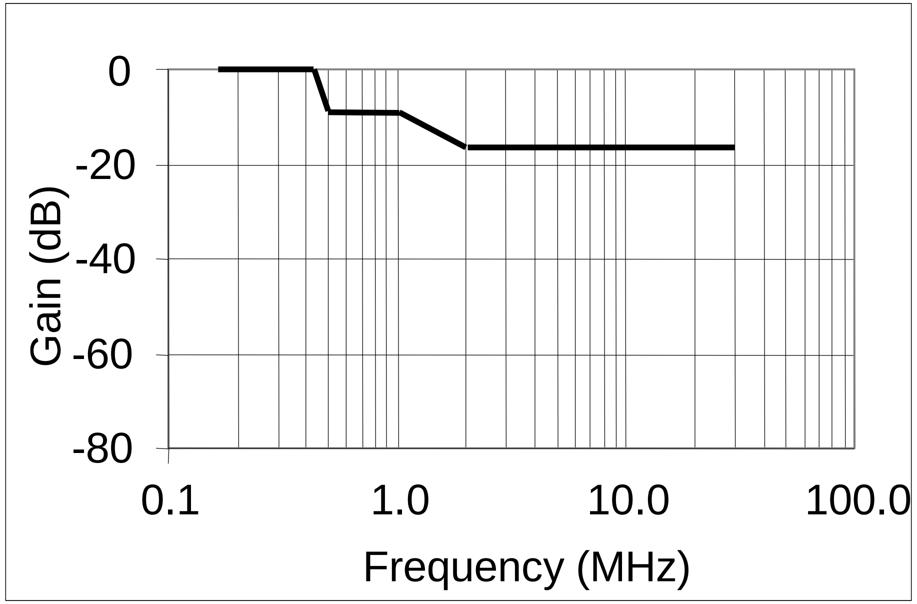
The flyback converter common-mode noise sources are modeled by i_{NOISE}. Common-mode noise sources are generally current driven (high impedance).



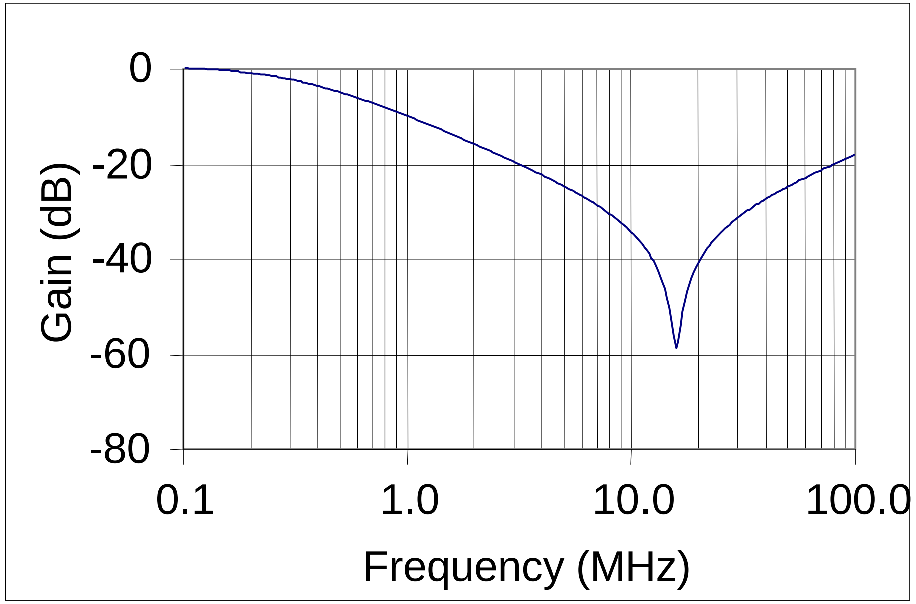
Note: ESL and ESR are undesirable parasitics.

Current source flows right through the inductor, poor use of filtering. Not obeying impedance mismatch rules.

CM Filter Attenuation



Required CM attenuation
for 10 dB margin

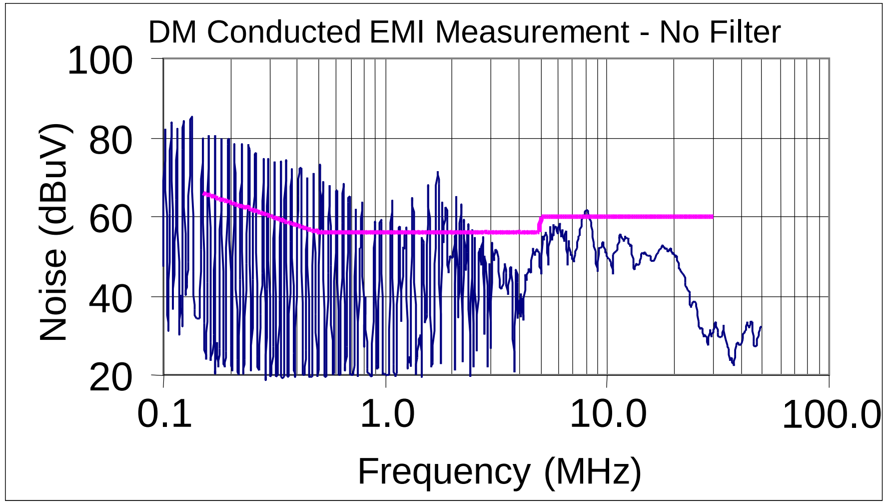


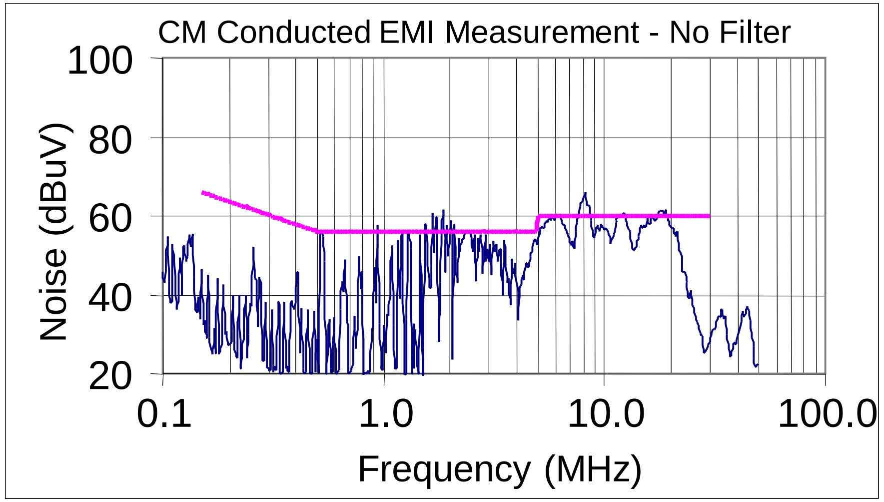
Spice simulated CM attenuation

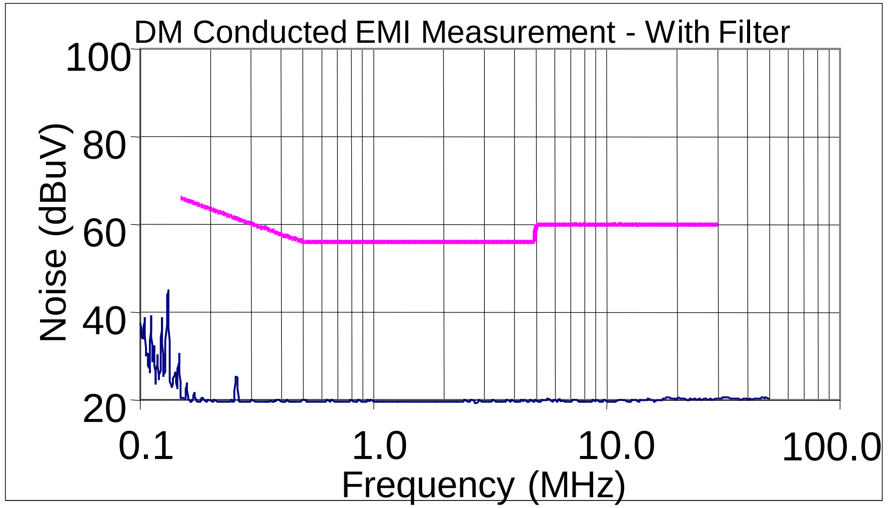
Very little common-mode attenuation. CM filter did not properly utilize impedance mismatch concept.

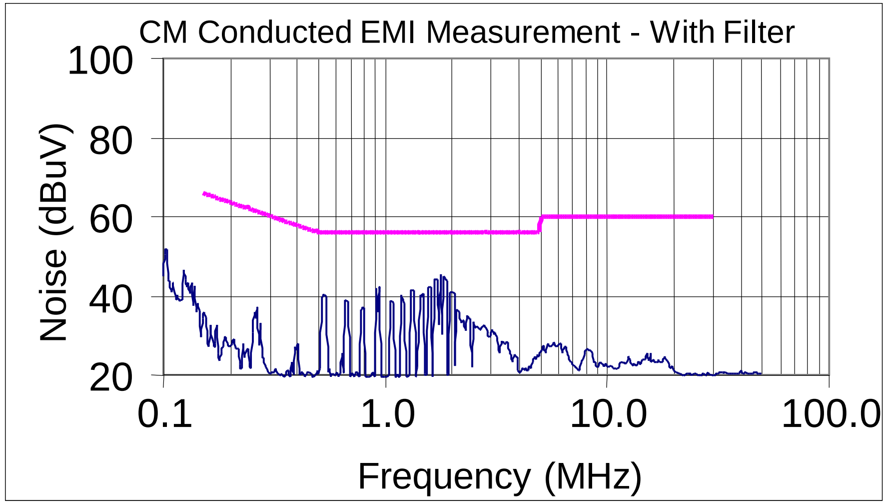
Poor filter construction limits performance

Measured Conducted EMI Flyback Converter With Filter



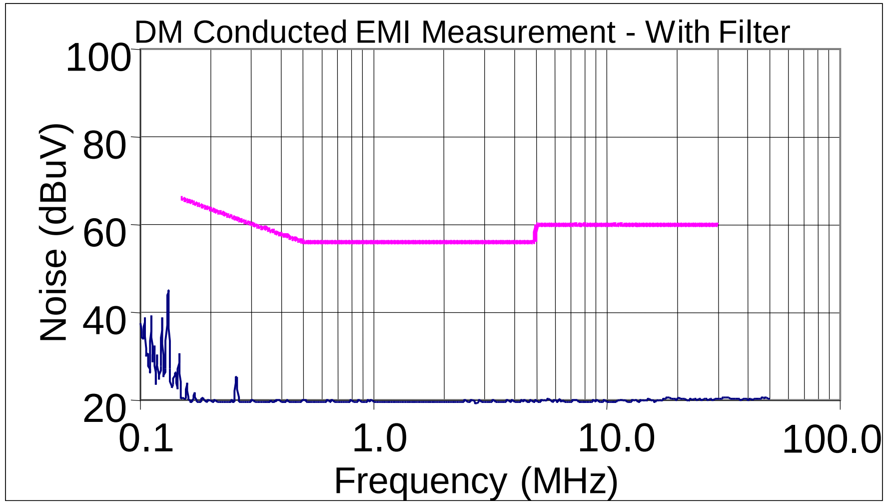


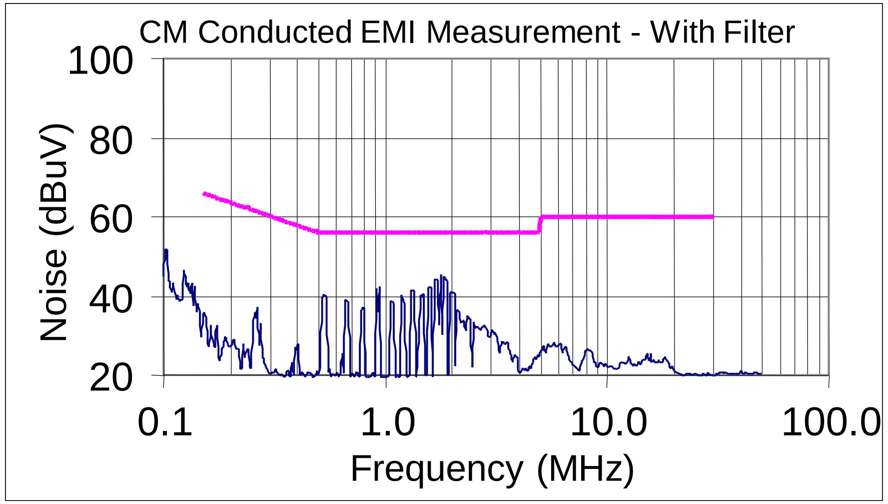


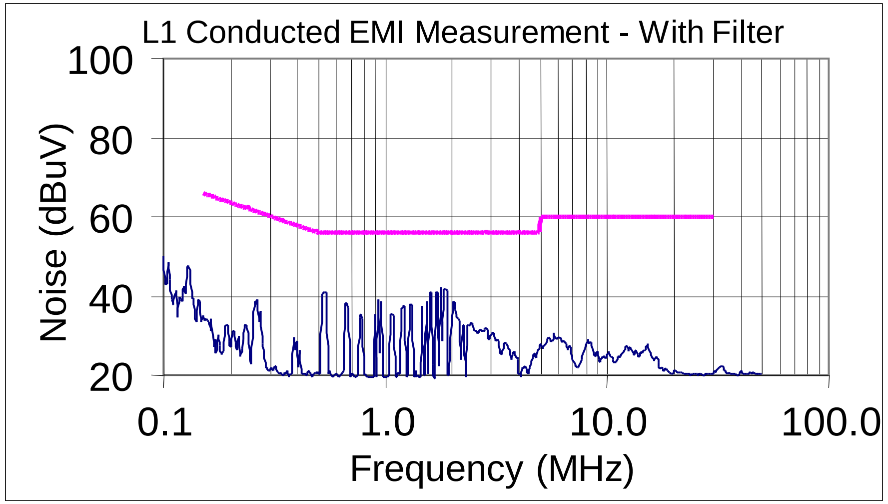


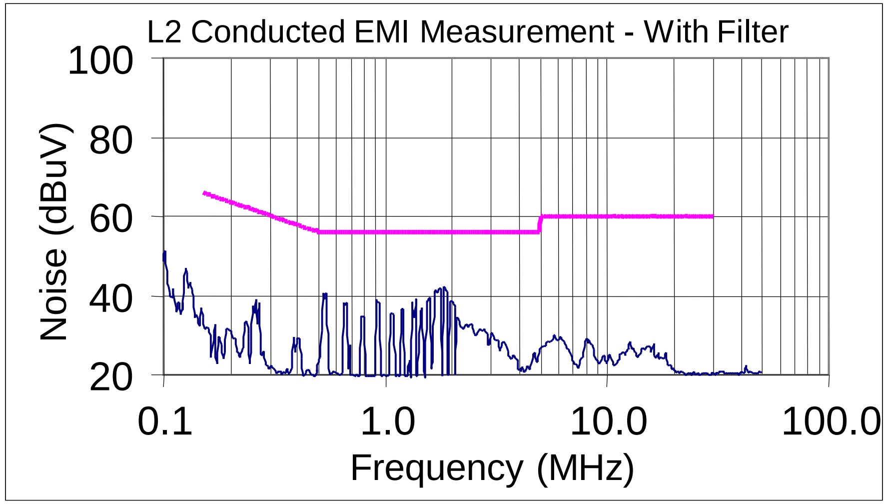
Large DM EMI reduction, smaller CM EMI reduction

Measured Conducted EMI
Flyback Converter With Filter









Remaining filtered EMI mostly common-mode currents

DM/CM Separation

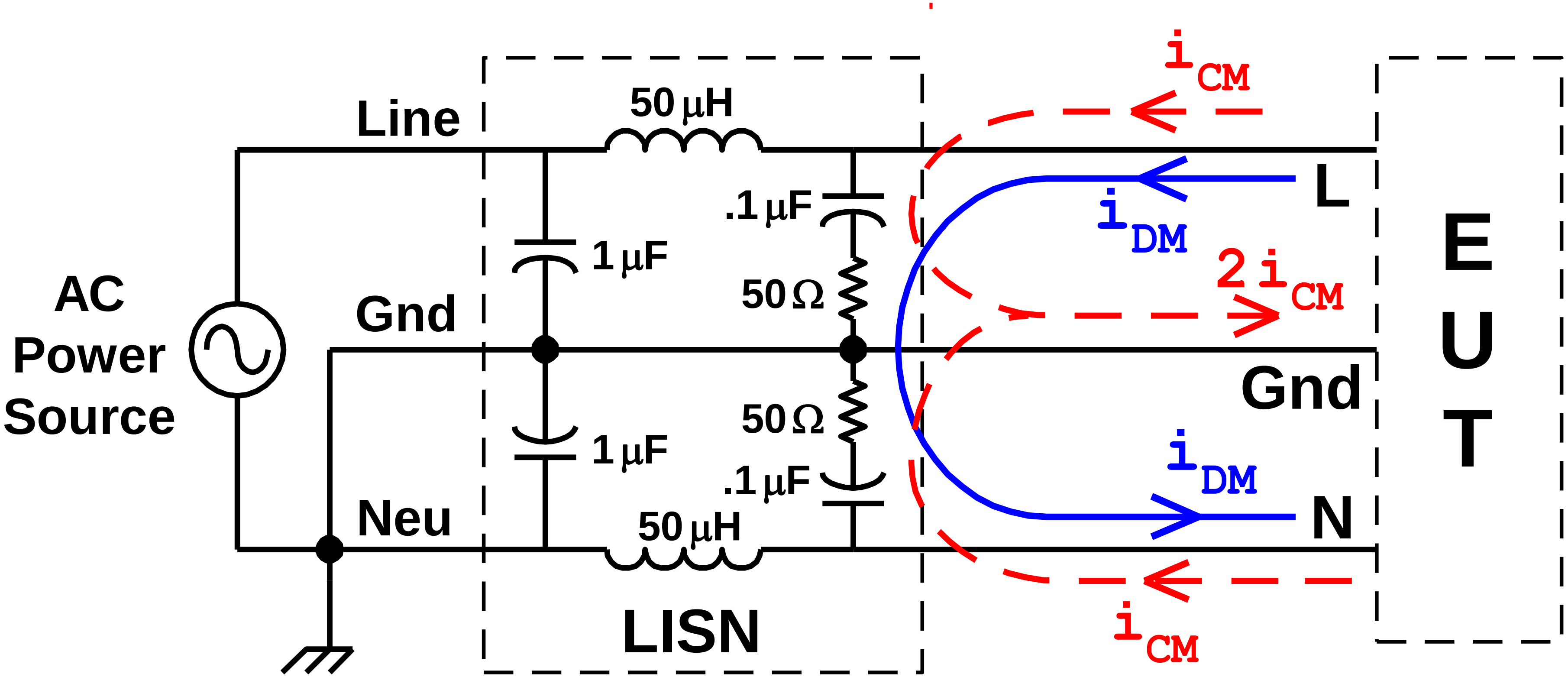
Separation of DM/CM

Separating differential-mode and common-mode currents from the L1 and L2 LISN measurements (across the 50Ω resistors) is not as simple as post-processing the spectrum analyzer L1 and L2 signals. This is because the spectrum analyzer is a superhetrodyne signal processor, and only magnitude information of L1 and L2 is retained, phase information is lost.

It is necessary to process the L1 / L2 signals directly from the LISN outputs before being applied to the spectrum analyzer.

DM/CM separation required for proper filter design

Separation of DM/CM – 1

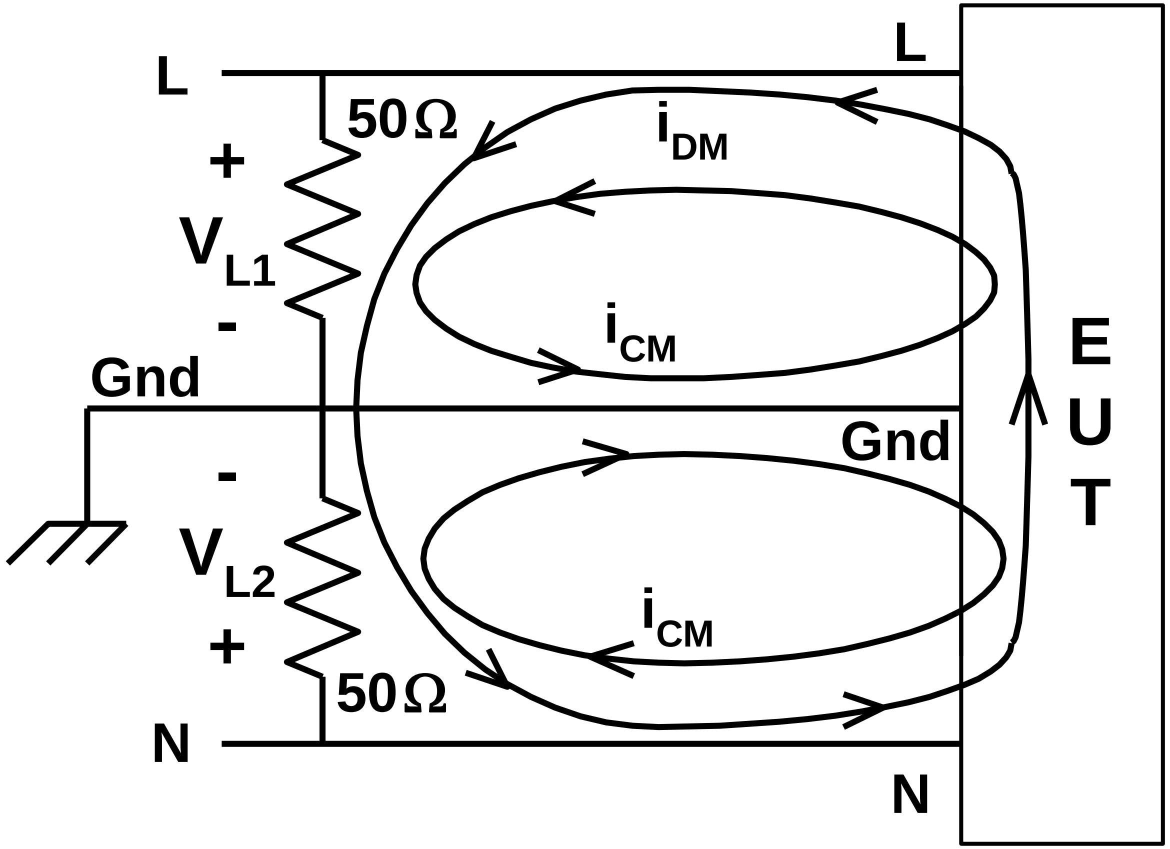


LISN shown is a functional equivalent circuit, not a schematic.

$$i_L = i_{DM} + i_{CM} \qquad i_N = -i_{DM} + i_{CM}$$

Conducted EMI due to CM and DM currents

Separation of DM/CM – 2



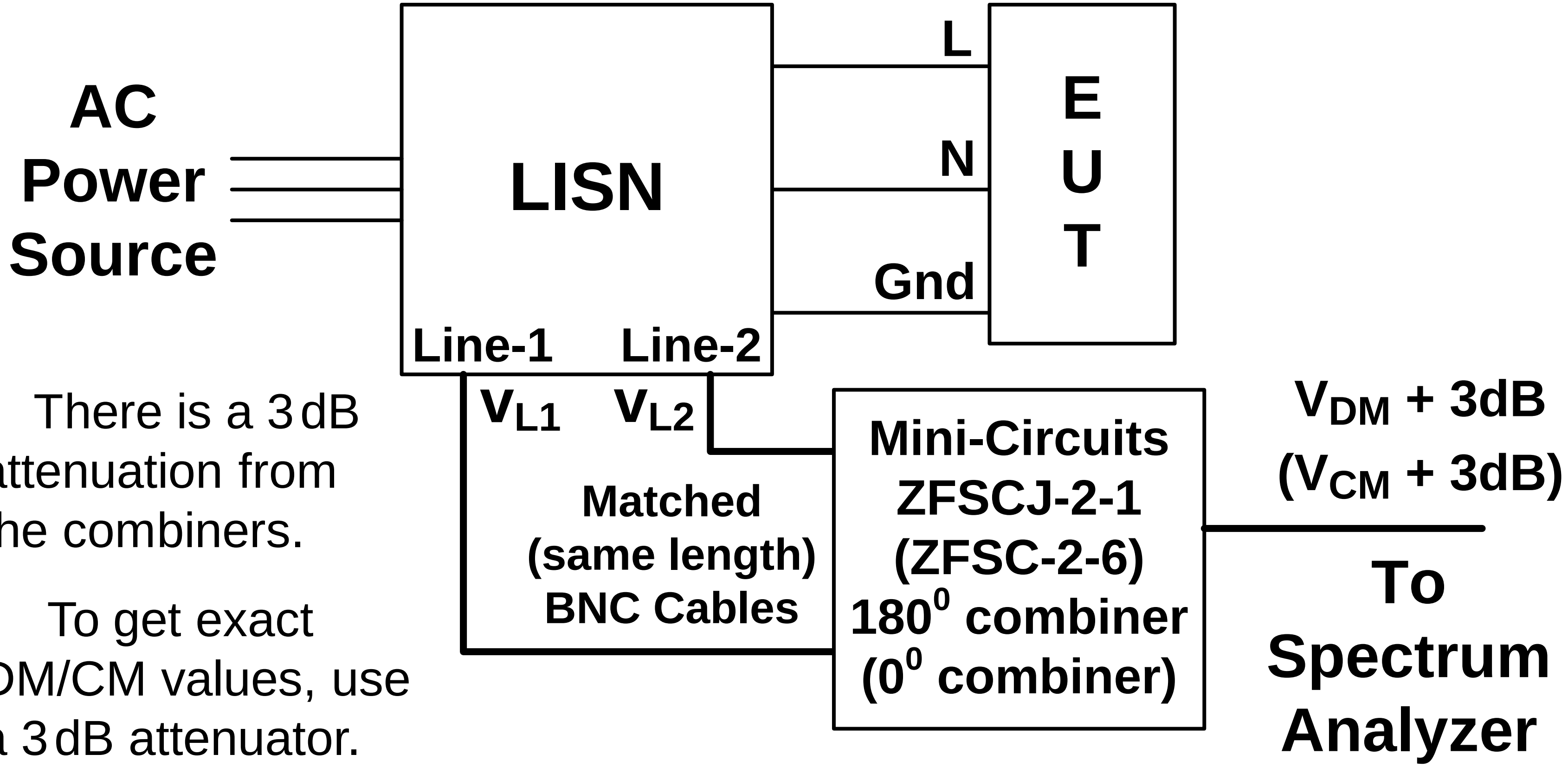
$$v_{L1} = 50\left(i_{DM} + i_{CM}\right) \qquad v_{DM} = 50\, i_{DM} = \tfrac{1}{2}\left(v_{L1} - v_{L2}\right)$$

$$v_{L2} = 50\left(-i_{DM} + i_{CM}\right) \qquad v_{CM} = 50\, i_{CM} = \tfrac{1}{2}\left(v_{L1} + v_{L2}\right)$$

Separation of DM/CM – 3

Technique for DM/CM separation

$$v_{DM} = 50 i_{DM} = \tfrac{1}{2}(v_{L1} - v_{L2}) \qquad v_{CM} = 50 i_{CM} = \tfrac{1}{2}(v_{L1} + v_{L2})$$



There is a 3 dB attenuation from the combiners.

To get exact DM/CM values, use a 3 dB attenuator.

Simple, repeatable, low-cost DM/CM separation

SiC Power Semiconductor EMI Impact

SiC Power Semiconductors

SiC Power MOSFET advantages over Si:

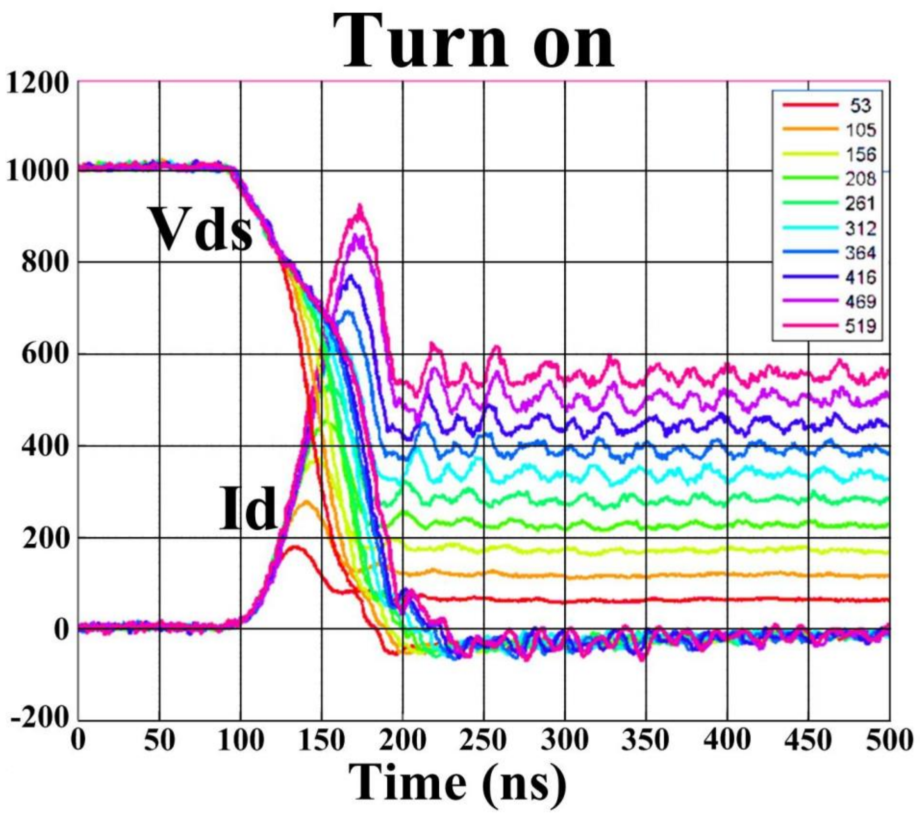
- High temperature operation
- Low switching loss
- High switching frequency
- High voltage operation
- High power density
- Simplified topologies

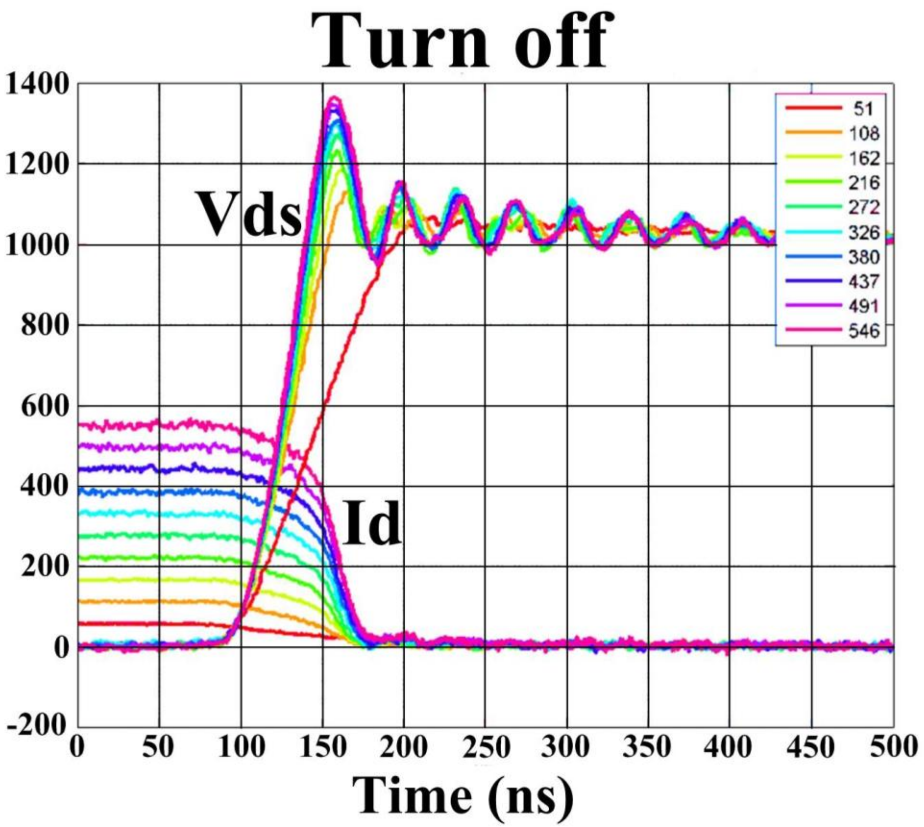
However, there is one big disadvantage:

Electromagnetic Interference (EMI)

This creates issues with meeting regulatory requirements, filter design, susceptibility, …

1700 VDC SiC MOSFET Switching Waveforms



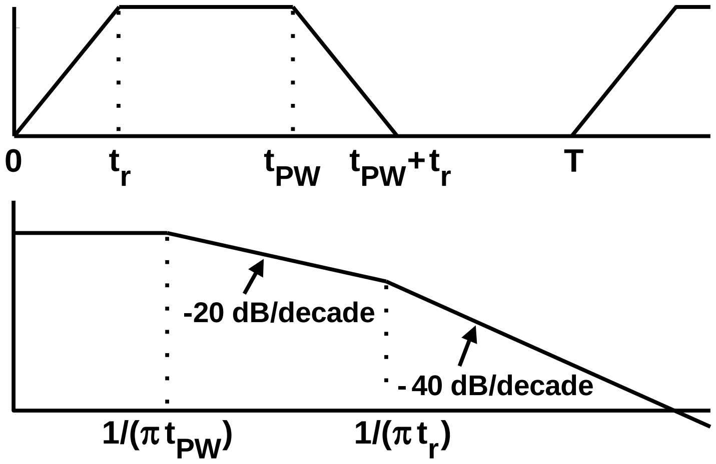


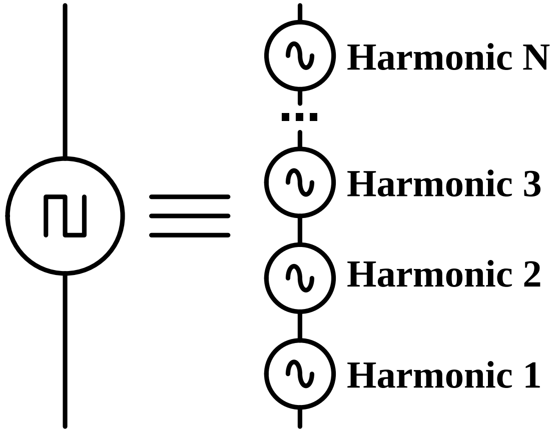
di/dt: 23 A/ns
dv/dt: 24 V/ns

di/dt: 21 A/ns
dv/dt: 24 V/ns

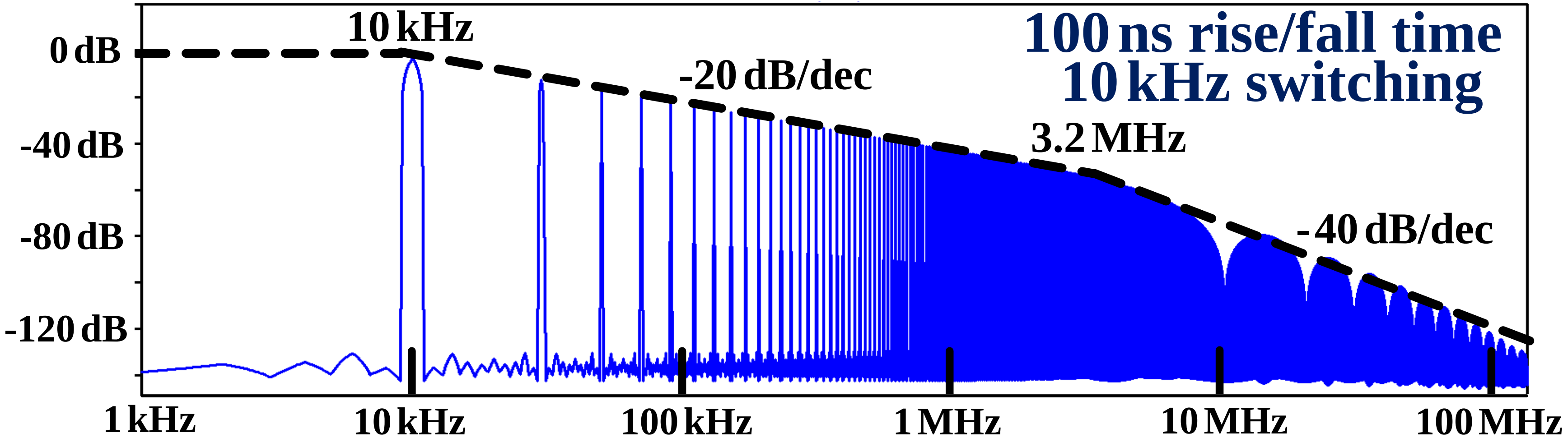
Frequency Content of Switching Waveform

Faster switching edges increase high frequency harmonics



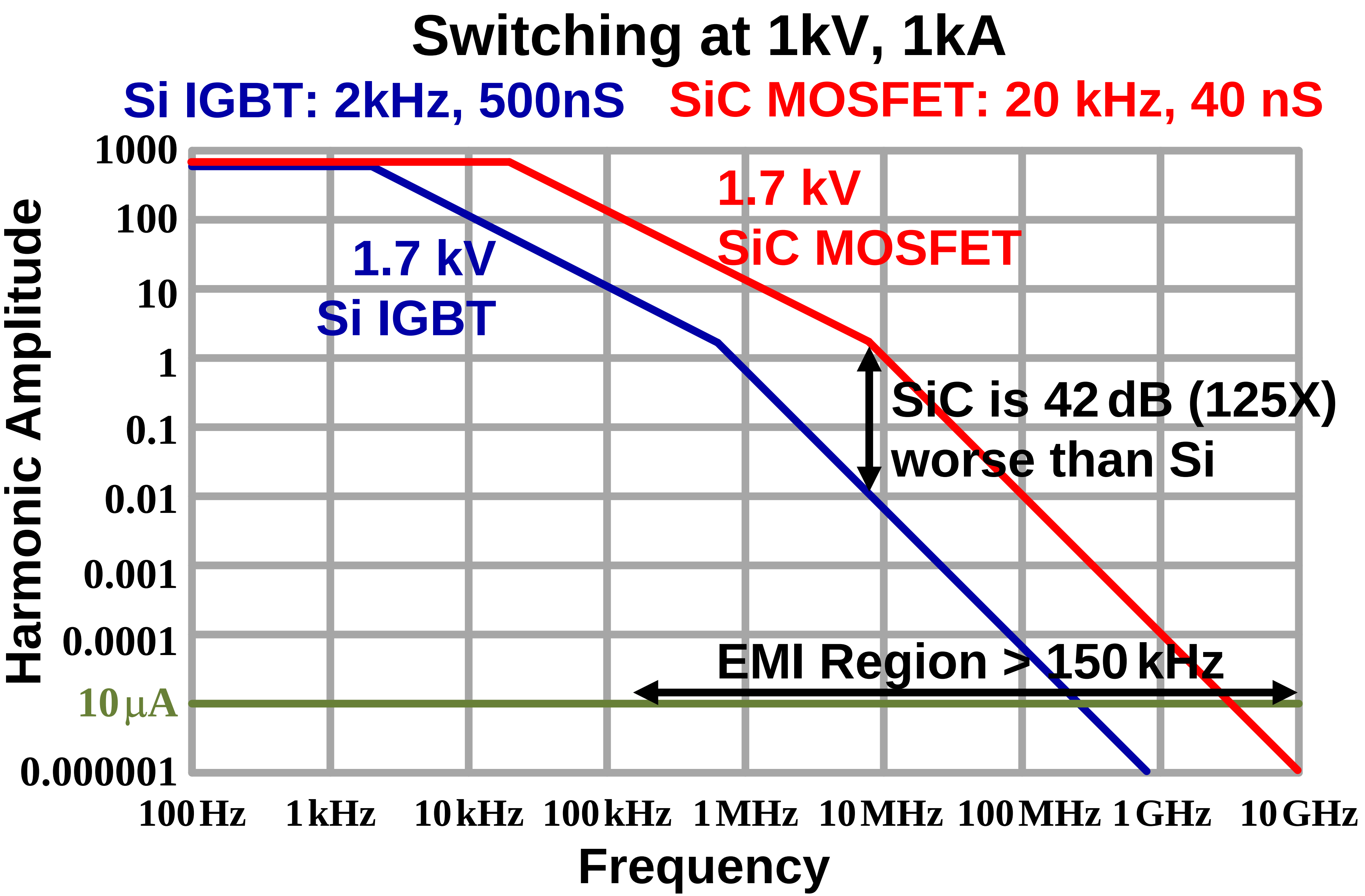


Normalized Harmonic Spectrum: 10 kHz, 100 ns edges



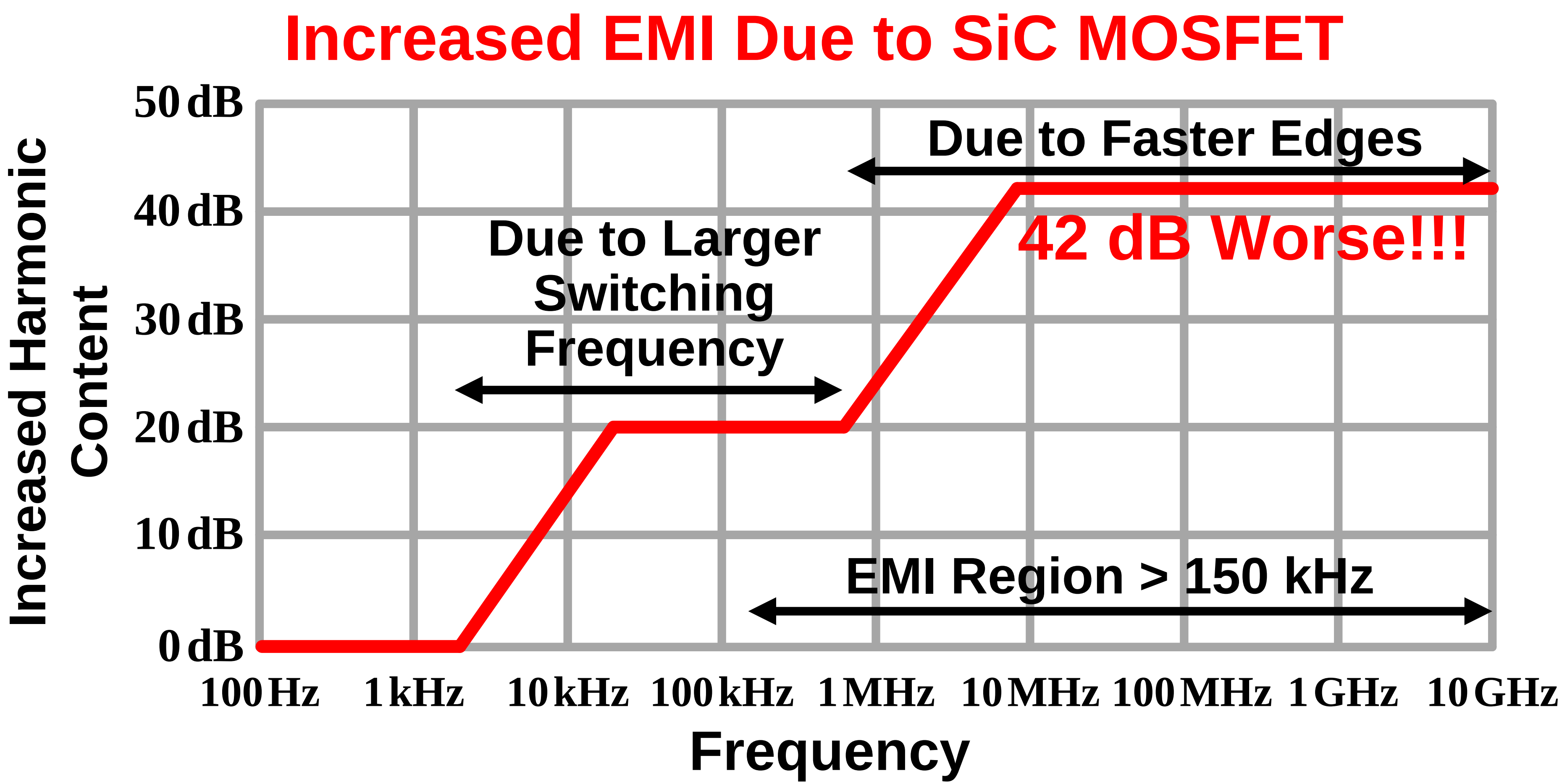
Harmonic envelope depends upon Fs & edges

Harmonic Comparison of Si & SiC



SiC has increased high frequency harmonics

SiC EMI Impact



Linear System

SiC increases high frequency EMI problems!

Can SiC power electronics meet EMI???

1 MW SiC inverter: Conducted EMI measurement
1700 VDC SiC, 20 kHz switching, minimal filtering

YES, but need to understand EMI issues!!!

SiC Susceptibility Concerns

Susceptibility is the ability of the equipment to operate in the presence of electromagnetic energy without issues or failures.

- Larger H.F harmonics of SiC can cause problems
  - Random lockups, failures, noisy, unexpected operation
  - Very difficult to simulate susceptibility problems
  - Requires EMC robust layout techniques
  - Don’t just drop SiC devices into Si system
- Use EMI hardening tools on critical electronics
  - Gate drives, interface cards, control electronics
  - Need to harden up to 100’s of MHz
  - Near field injection techniques & bulk current injection techniques are useful