Power Supply Design Seminar

Power-Conversion Techniques for Complying with Automotive Emissions Requirements

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TEXAS INSTRUMENTS

Power-Conversion Techniques for Complying with Automotive Emissions Requirements

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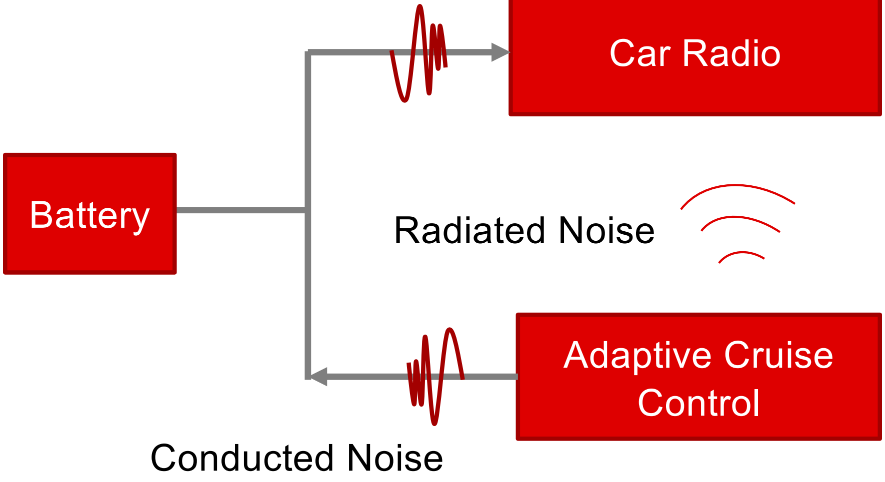
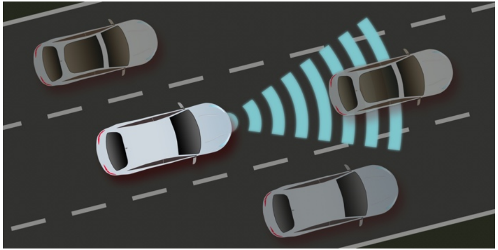
Why be concerned about emissions and immunity?

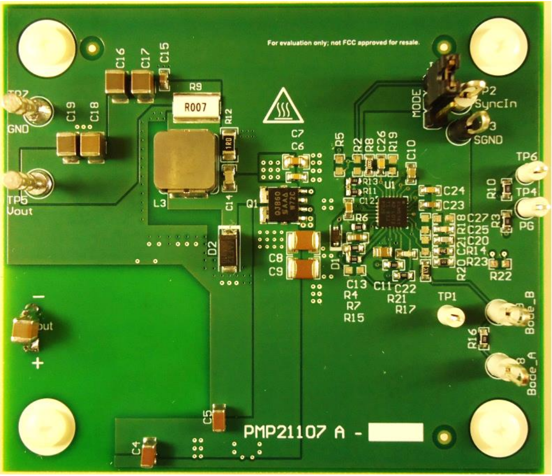




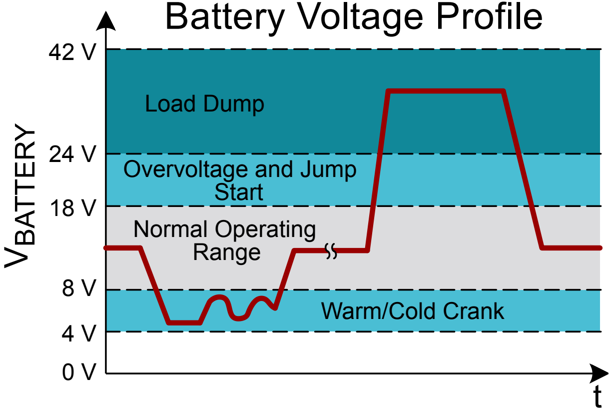
Agenda

- Importance of designing to EMC (electromagnetic compatibility)
  - Sources and types of emissions
  - EMI standard limits (CISPR 25)
- Methods to mitigate emissions
  - Filtering
  - Component selection
  - Board layout
  - Circuit techniques
- Case study: passing CISPR 25 Class 5 for a 13.5 V input to 3.3 V, 5 A output example converter

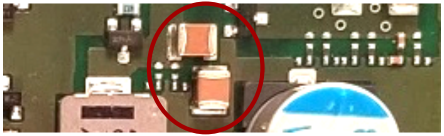
Case Study Converter



General automotive converter design challenges

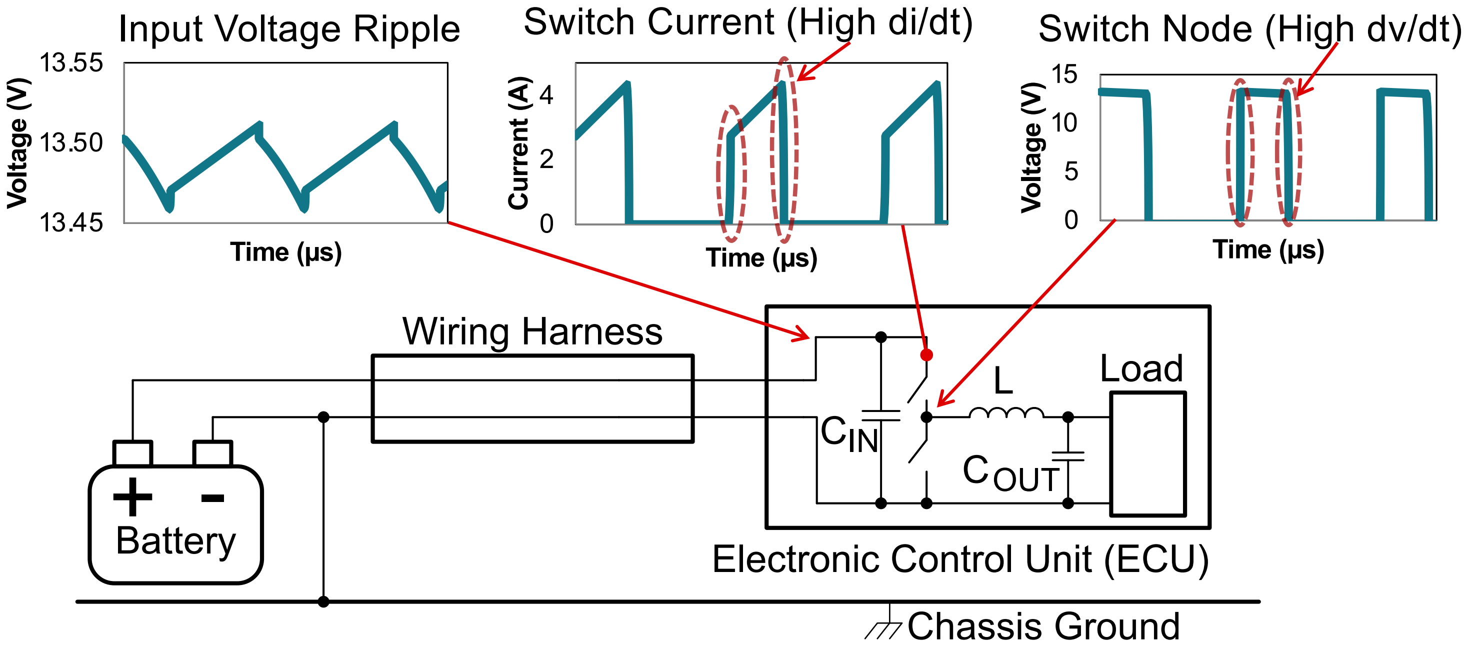


Two caps placed at 90 degrees



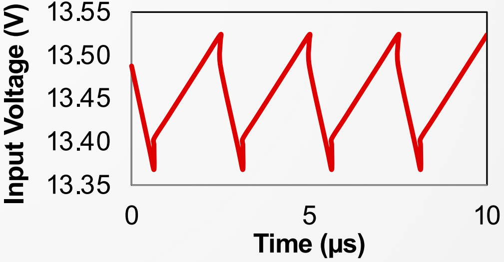
- Wide input voltage range of the "12 V" off-battery converters: ~4 V to ~42 V
  - Requires higher voltage rated FETs
- Vibration/mechanical stress
  - Cannot use certain low EMI power stage construction methods
  - Two caps at 90 degrees → increased ESL and poorer EMI performance
- Temperature range (-40ºC to 125ºC typ.)
  - No fan cooling at times (e.g., USB charger)
- Visual inspection of solder joints
  - Sometimes prefer leaded packages which can increase EMI issues

Sources of emissions from within power supplies



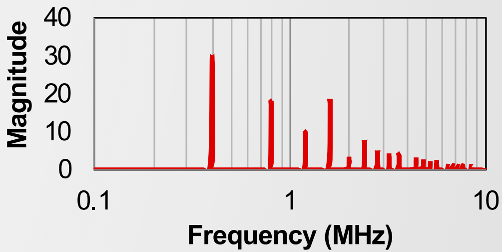
Frequency spectrum of noise (ripple)

Time Domain

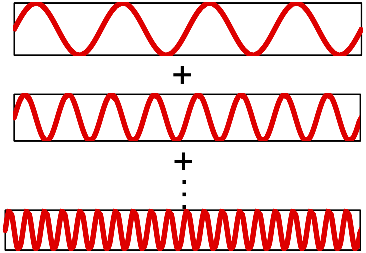


Fourier Transform

Frequency Domain



A periodic signal can be expressed as the sum of sinusoidal waveforms

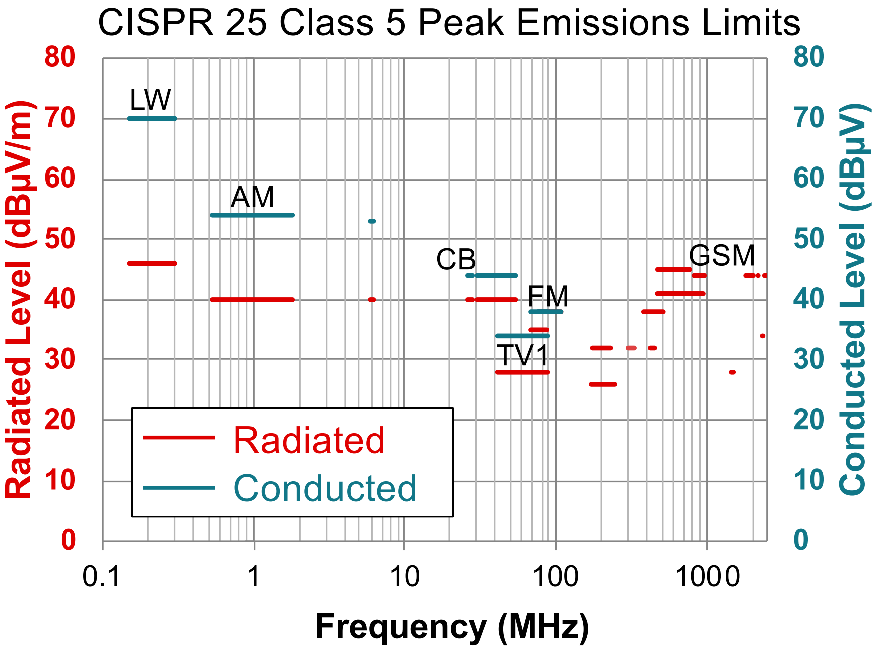


Fourier series

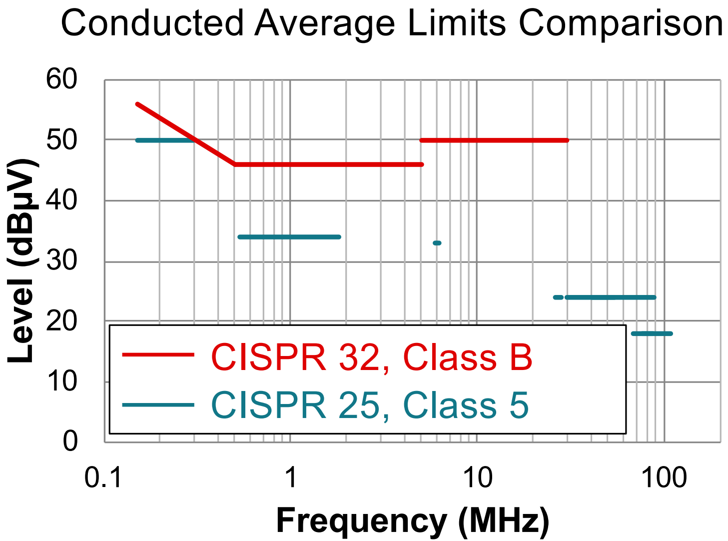
$$f(t) = \sum_{n=0}^{\infty} c_n \cos(n\omega t + \theta_n)$$

Automotive emissions requirements

- CISPR 25 is a common emissions standard in automotive
  - Conducted limits apply from 150 kHz to 108 MHz
  - Radiated limits apply from 150 kHz to 2.5 GHz
- Power converters generally avoid the AM band
  - Typically have <450 kHz or >2 MHz switching frequency



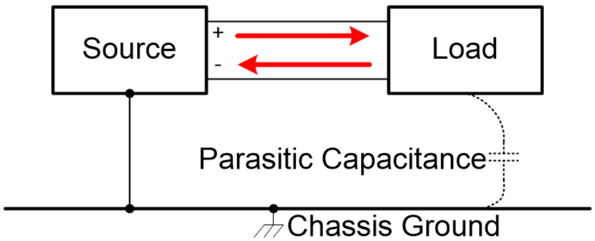
Automotive vs. IT/industrial conducted EMI limits



- CISPR 32 (formerly 22) is an EMI standard for IT equipment
  - Continuous line across the frequency spectrum up to 30 MHz
- Conducted limits for automotive applications (CISPR 25) are more challenging
  - Go higher in frequency (108 MHz)
  - Have lower limit levels
  - But have gaps in between frequencies

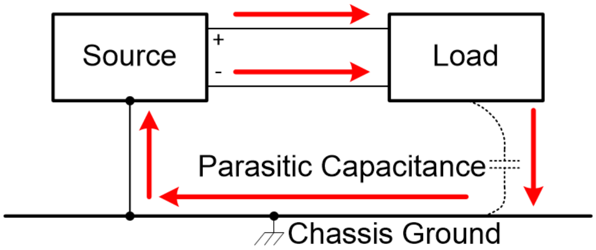
Differential mode vs. common mode noise

Differential Mode



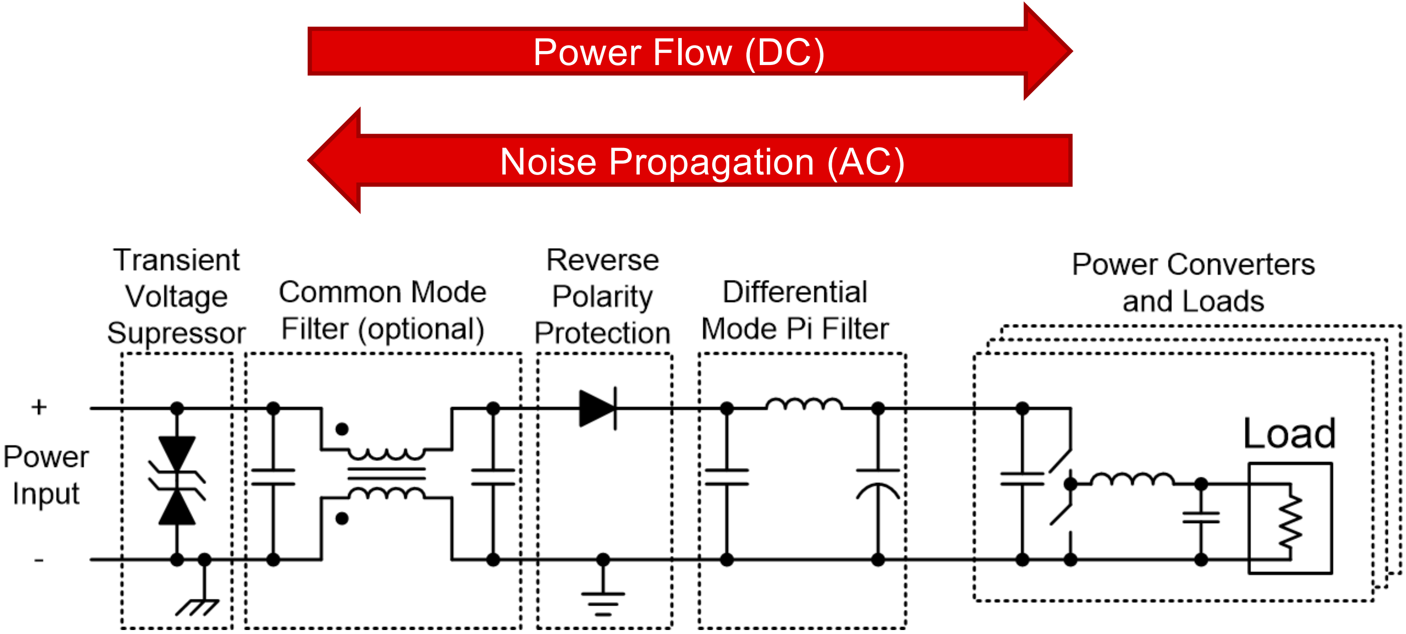
- Signal (noise) flows out on one wire (+) and returns on the other wire (-)
- Increases with load current
- Attenuated with a pi filter

Common Mode

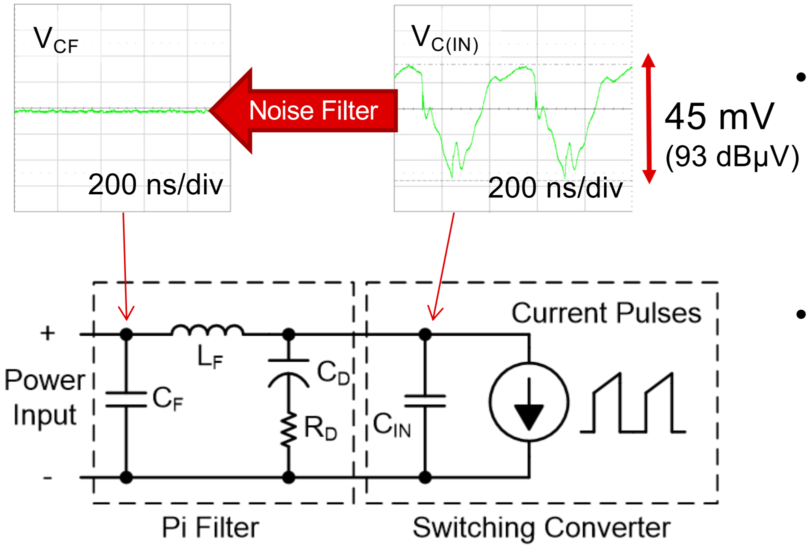


- Noise flows out in the same direction on both wires and returns via stray capacitance and chassis ground
- Mostly independent of load current
- Filtered with a common mode choke

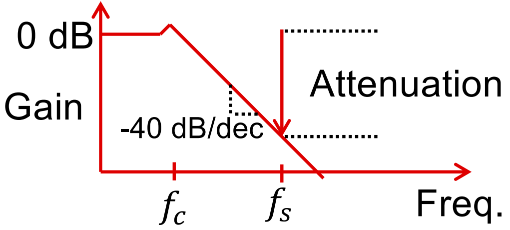
Overview diagram



Differential mode EMI filter

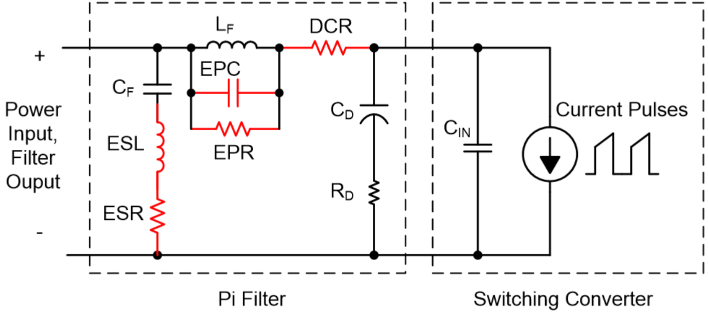


- Buck converters pull pulses of current causing C_{IN} voltage ripple
- A pi (π) filter reduces conducted differential mode noise
  - L_F and C_F form a low pass filter
  - C_D and R_D included for stability (reduce EMI filter output impedance peak)
- Select L_F and C_F to get desired attenuation at f_s

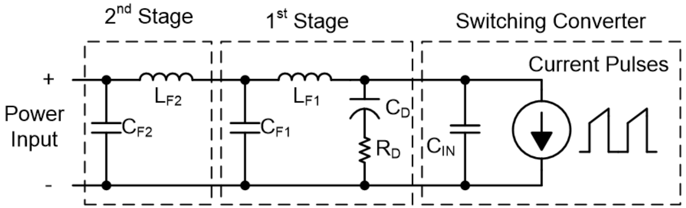


Impact of parasitics

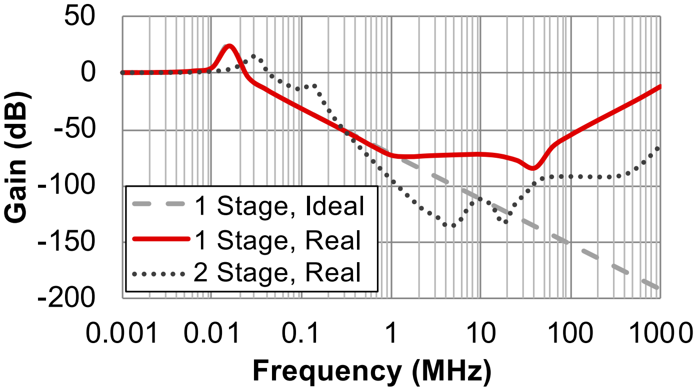
Parasitic Elements in a Pi Filter



Two Stage Pi Filter



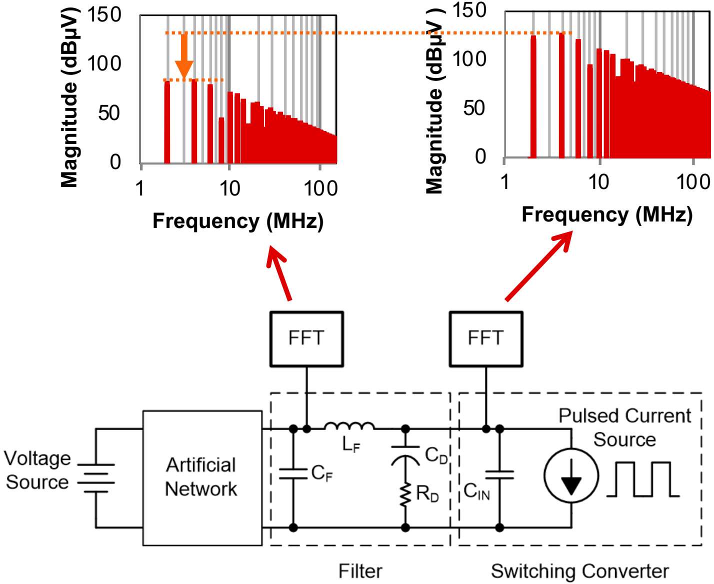
- High frequency performance of pi filters degrade due to parasitic elements



- A two stage pi filter can be used
  - A ferrite bead used in 2nd stage (L_{F2})

Simulation of differential mode noise

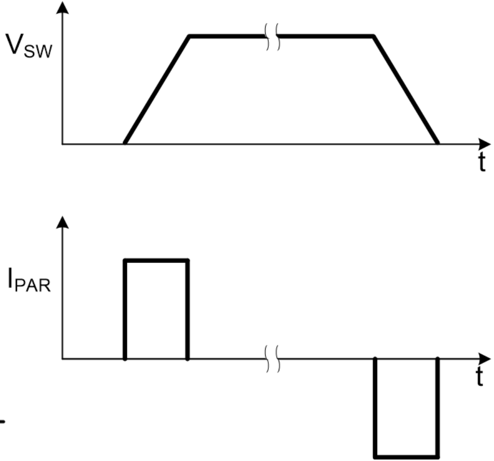
- Circuit simulations can provide insight to EMI filter performance
  - **Caution**: Accuracy at higher frequencies will be limited due to unknown parasitics
  - Understand simulator options
- Power converter(s) modeled as pulsed current sources
  - Can add phase interleaving, spread spectrum, etc.
  - Circuit simulator with FFT function used
- WEBENCH® has an input filter design tool

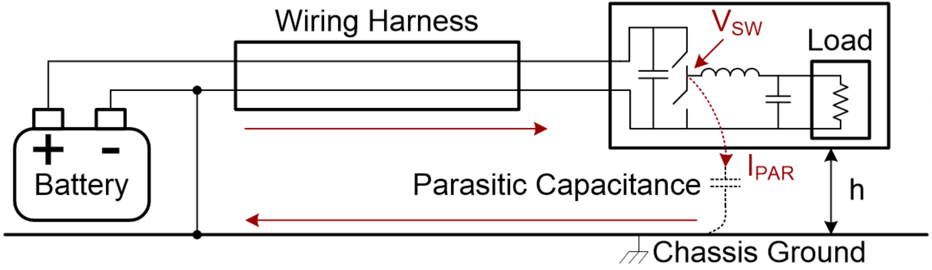


Source of common mode noise

- The primary source of common mode noise is **parasitic capacitive coupling**
  - 5 cm is the standard testing height (h) above chassis ground set by CISPR 25
  - Higher/lower would alter parasitic capacitance

- The switch node (V_{SW}) pumps common mode current (I_{PAR}) each switching cycle

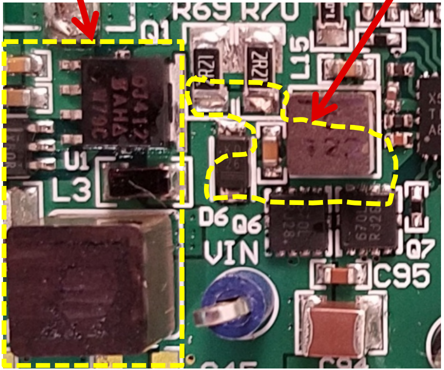




Layout tip 1: Reduce capacitive coupling

EMI filter and reverse polarity protection FET

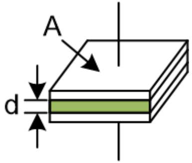
Switching nodes area



Bad layout example: strong capacitive coupling

- Minimize capacitive coupling
  - **Reduce area (A)** of switching nodes
  - **Increase distance (d)** between switching nodes and sensitive circuits

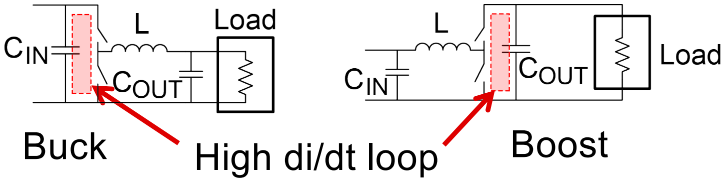
$$C = \frac{\varepsilon A}{d}$$



- Avoid placing switching nodes (SW, BOOT, snubber components, etc.) near the EMI filter components/input connection or on the bottom layer of the PCB
- Connect start lead of inductor to switch node
- Beware of heat sinks connected to switching nodes

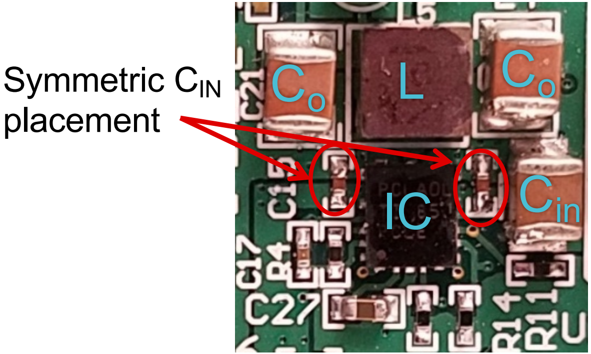
Layout tip 2: Avoid making antennas

- Minimize **area** of loops carrying high di/dt currents
  - Buck: input capacitor is key
  - Boost: output capacitor is key



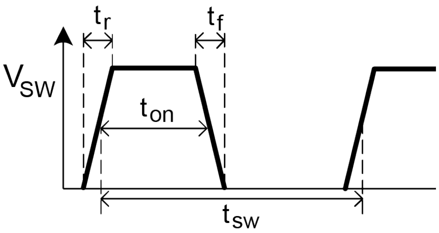
- Have an uncut **ground plane** where eddy currents create opposing fields
- Use inductors/transformers with closed magnetic paths (“**shielded**”) to reduce stray magnetic coupling

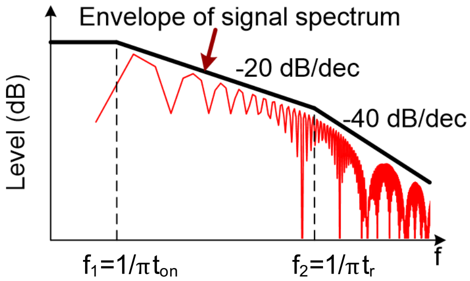
- Some converters have **symmetrical input** pinouts designed to cancel magnetic fields (reducing inductance)
- Place small, **low ESL capacitors** as close to IC as possible



Slowing down switch node transition

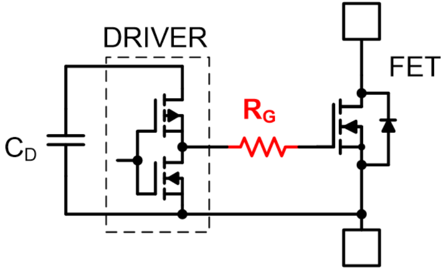
- High frequency noise reduced by slowing down switch node



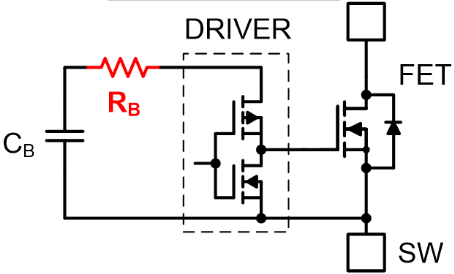


- Adding a resistor in the gate drive path can lengthen turn-on time
  - \+ Increases switch node rise/fall time
  - \+ Reduces switch node ringing
  - – Increases switching loss

Gate Resistor

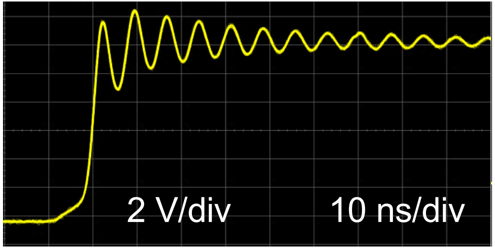


Boot Resistor

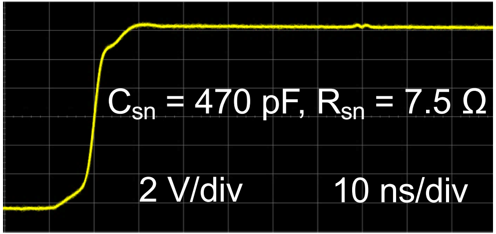


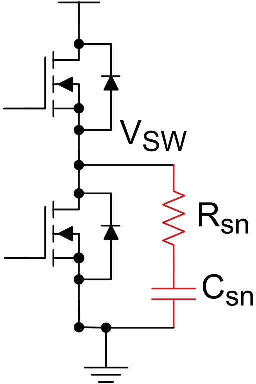
Using a snubber circuit

SW node **without** snubber



SW node **with** snubber





- Snubber circuits shape the switch node waveform and reduce ringing
  - Can be a simple resistor and capacitor
  - Increase power loss

$$P = C_{sn} V^2 f_{SW}$$

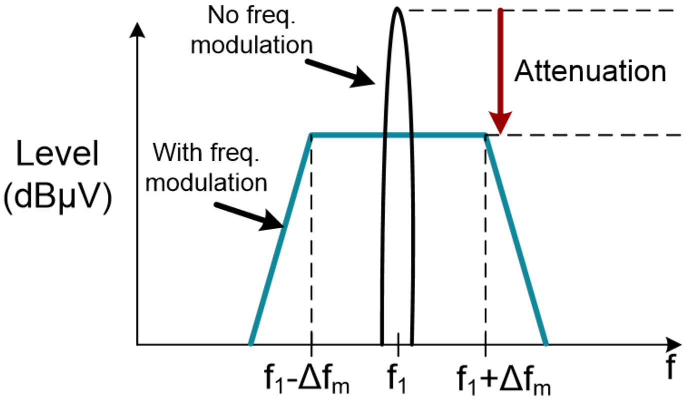
- Start by selecting a resistor based on parasitic inductance and capacitance of the switching loop

$$R_{sn} = \sqrt{L_p / C_p}$$

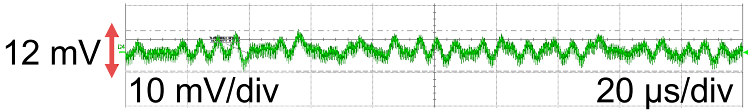
- Typically choose $C_{sn} > 3C_p$

Switching frequency dithering (spread spectrum)

- Modulating the switching frequency can spread out the emitted noise over a wider frequency range
  - Lowers emissions at the fundamental frequency and harmonics
- Common dithering schemes include:
  - Triangular
  - Pseudo-random
- Can cause additional output voltage ripple
- May cause audible noise if dither frequency is in the audible range



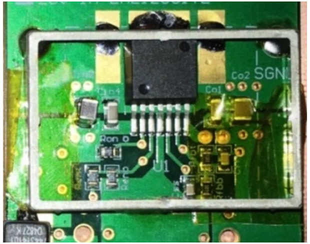
1 V_{DC} Output with Spread Spectrum



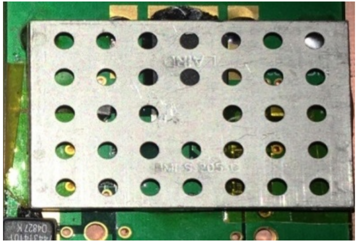
Additional noise mitigation techniques

- **Shielding**
  - Grounded metal shielding should be accounted for in layout
  - Need to keep noise away from unshielded bottom side of board
- **Clamp-on ferrites** on power lines
  - Act to reduce common mode noise
  - Attached to wiring cables
  - Often cheaper and more commonly used than shielding
  - Ferrites can also be slip on type

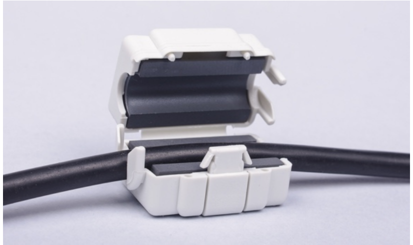
Partial Shielding



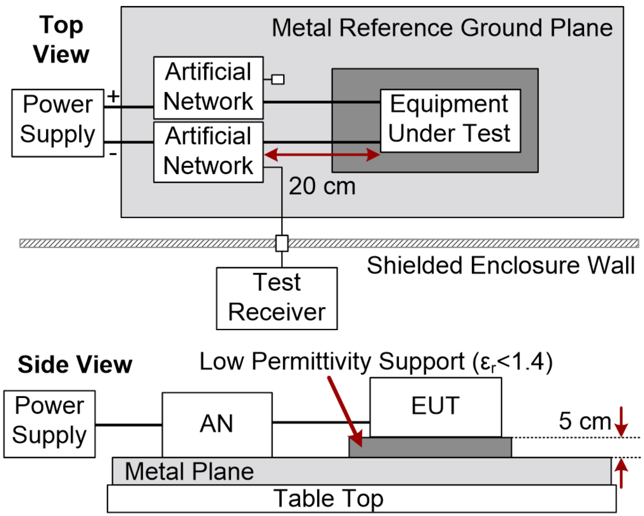
Full Shielding

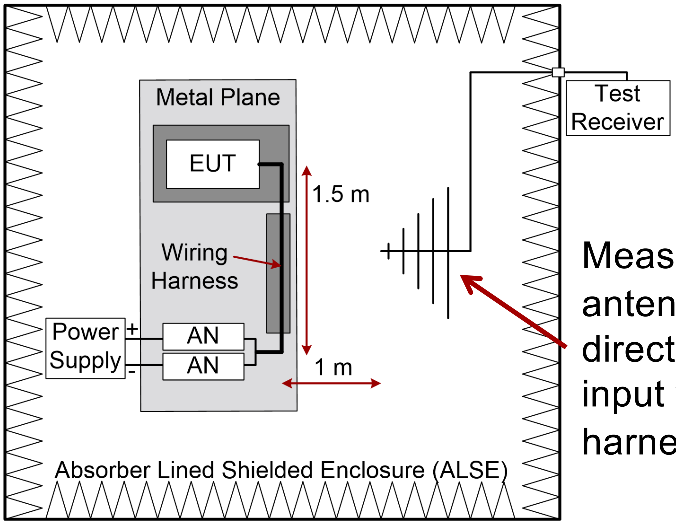


Clamp-On Ferrite



CISPR 25 emissions test setup





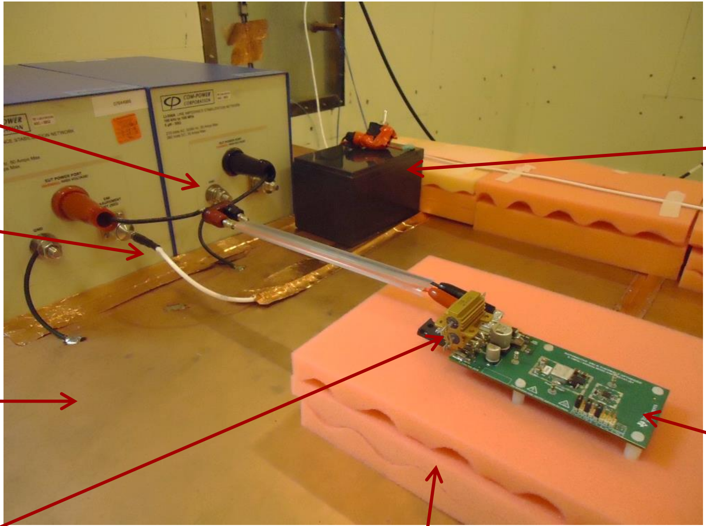
Measuring antenna directed at input wiring harness

Address conducted emissions before testing radiated emissions

Conducted emissions test setup

2 artificial networks
- One terminated with 50 Ω
- One to receiver

Copper top table tied to back wall (grounded)



Low noise lab source or car battery, connected to AN input

Equipment under test, 20 - 40 cm from ANs

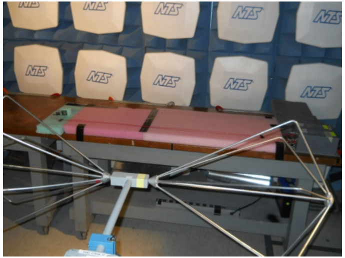
Load resistors

5 cm low permittivity support

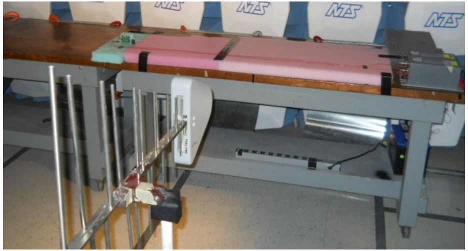
Radiated emissions test setup

Vertical Monopole

Biconical

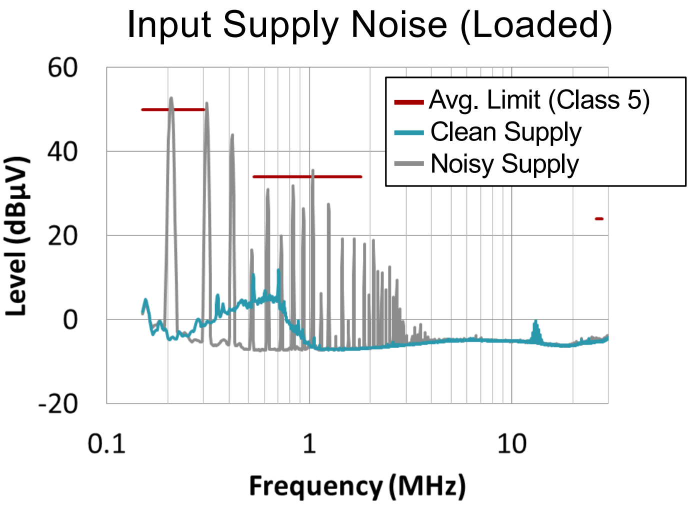


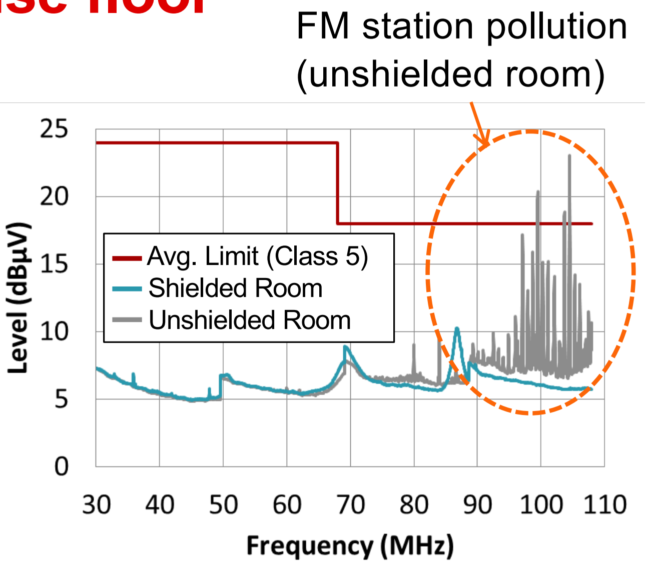
Log-Periodic



- Tested in a semi-anechoic chamber (absorber lined shielded enclosure)
  - Walls/ceiling have absorbers
  - Floor does not have absorbers
- Typically 3 or 4 antennas are used to measure across the frequency range
  - Vertical monopole: 150 kHz to 30 MHz
  - Biconical: 30 MHz to 300 MHz
  - Log-periodic: 200 MHz to 1 GHz
  - Horn or log-periodic: 1 GHz to 2.5 GHz
- Horizontal and vertical polarization for measurements from 30 MHz to 2.5 GHz

Ensure setup has a low noise floor





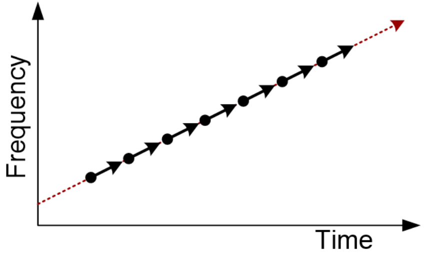
- A **shielded room** with low noise supplies are needed (especially above 30 MHz)
- A **battery** will provide the lowest noise supply but needs to be recharged

EMI test receiver capabilities

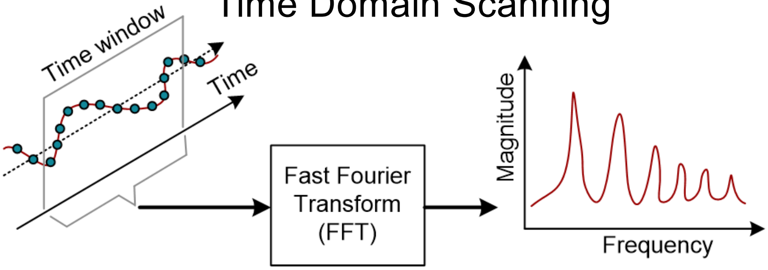
- Classical scanning receivers and sweeping spectrum analyzers are slow
  - Step through measurements **sequentially**
  - Total time = # of points × dwell time
- **Time domain scanning** (TDS) available in newer EMI test receivers
  - Sample the signal in the time domain
  - **Utilize FFTs** to compute frequency domain waveform

150 kHz - 30 MHz Scan Type	Stepped Scan Time	Time Domain Scan Time
Peak	**>15 min.**	**<150 ms**

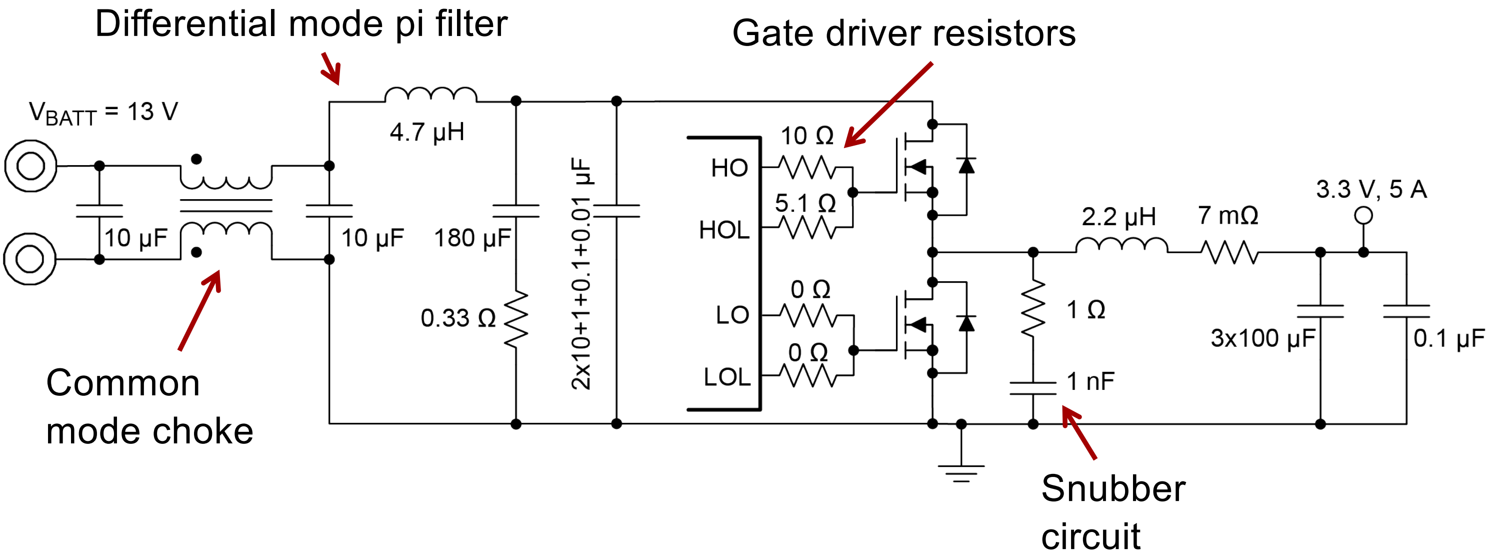
Sequential Measurements



Time Domain Scanning

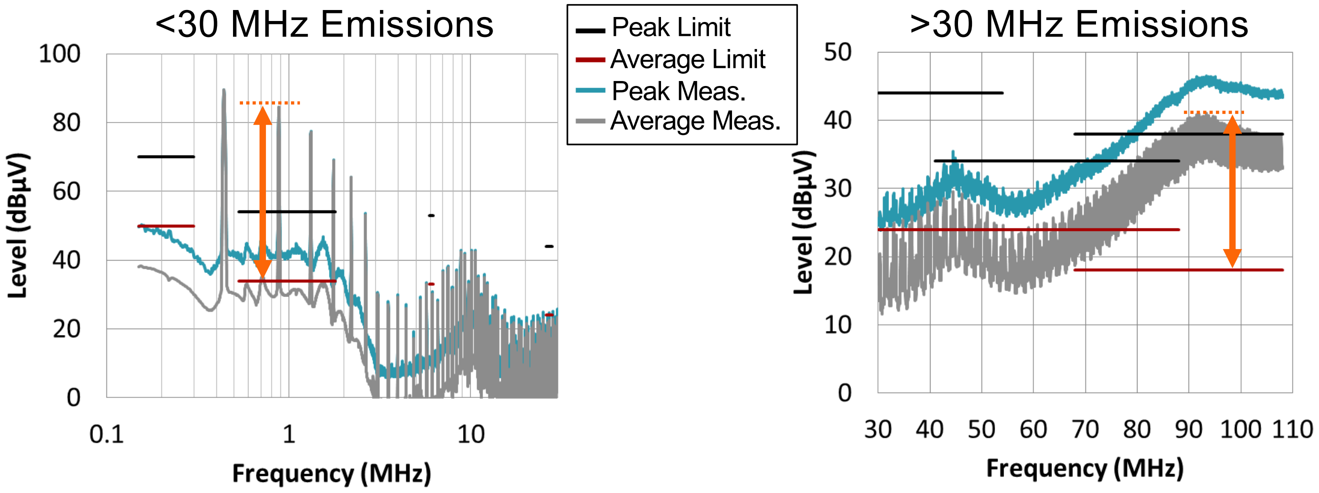


Case study: 3.3 V, 5 A supply using LM25141



Examine EMI mitigation technique's effect on conducted emissions in an application

Initial conducted emissions (no mitigation used)

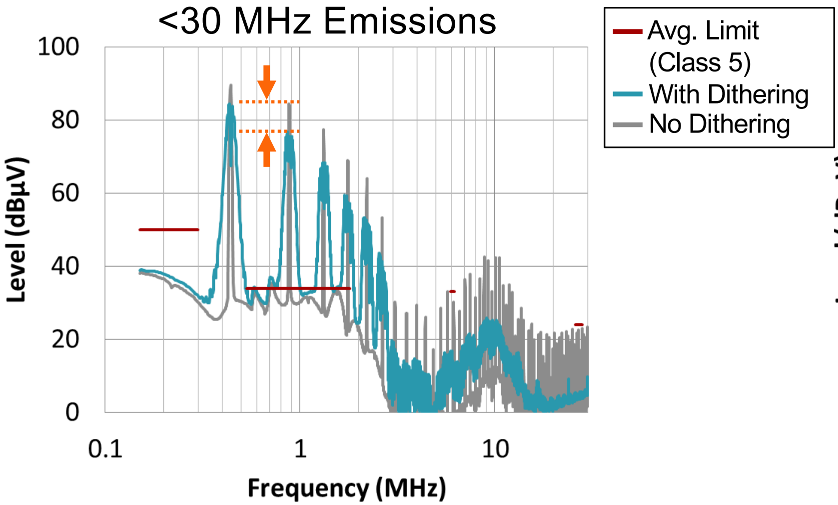


Failing Class 5 by >50 dB (avg)

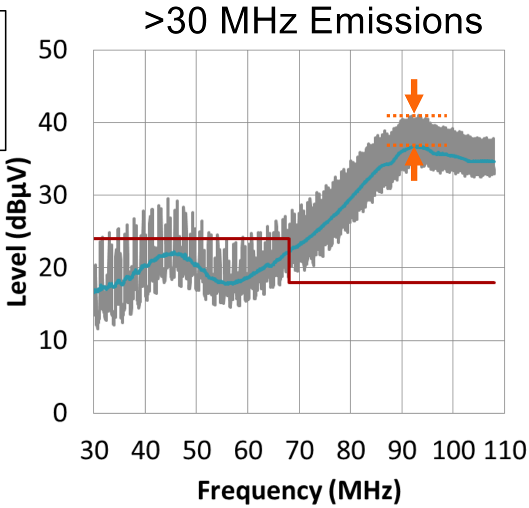
Failing Class 5 by >20 dB (avg)

To pass EMI requirements, it is necessary to utilize EMI mitigation techniques

Frequency dithering (spread spectrum) enabled



Failing by >40 dB

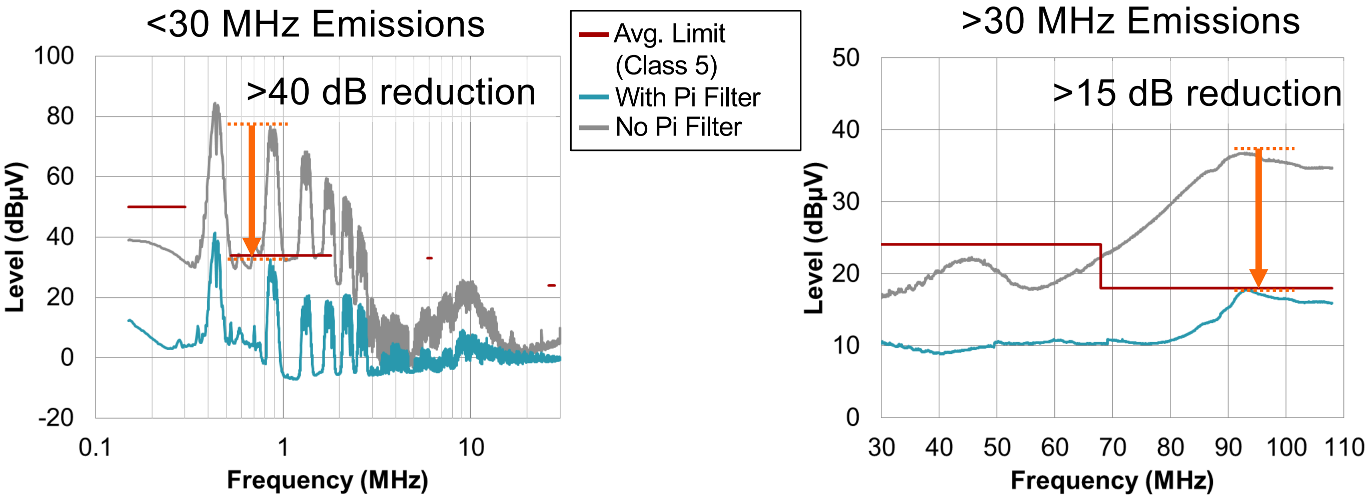


Failing by >15 dB

Emissions reduced by 5 - 10 dB but not enough to pass – need to add a filter

Note: No EMI filters installed in this result

Differential mode (pi) filter installed

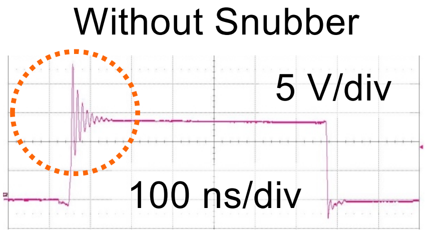


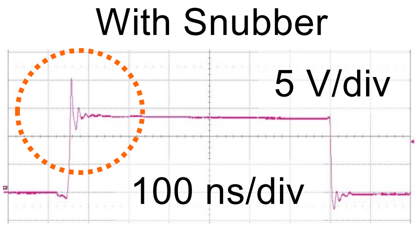
Passing by <2 dB **Passing by <0.5 dB**

Passing with a pi filter included but only by a very small margin

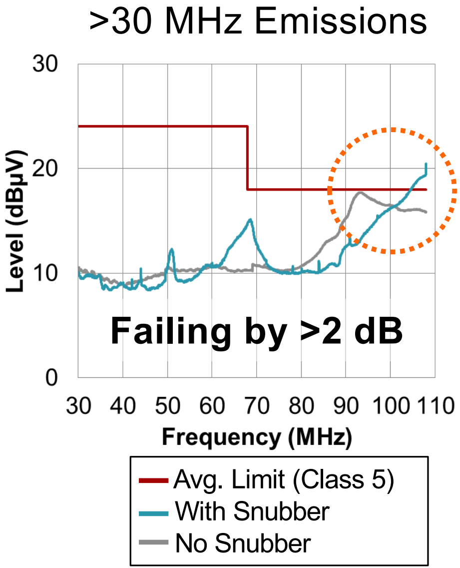
Note: Dithering is enabled in this result

Snubber circuit effect





Switch node measurements (R_{sn} = 1 Ω, C_{sn} =1 nF)



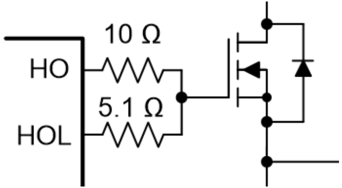
- Reduced switch node ringing
- Increased EMI (no longer passing Class 5)
- Added 63 mW of loss

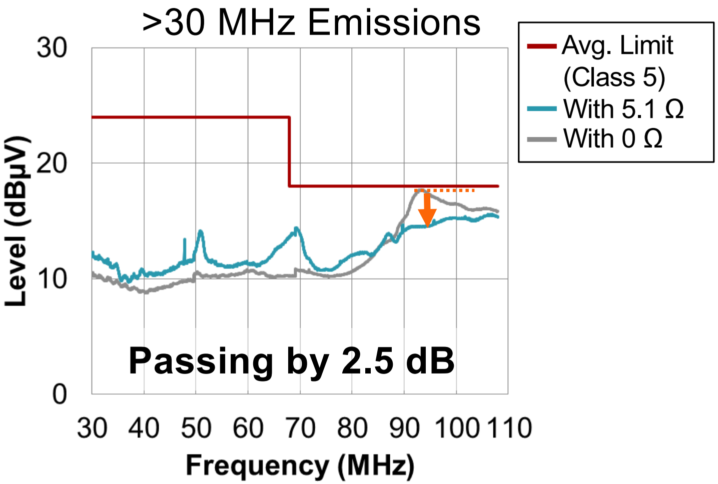
In this case, a snubber circuit did not help reduce conducted emissions

Note: Dithering and pi filter are included in this result

Increase gate resistance of high side FET

- 0 Ω resistor installed between HOL and high side switch gate replaced with 5.1 Ω resistor
  - Slows down turn-off of high side FET



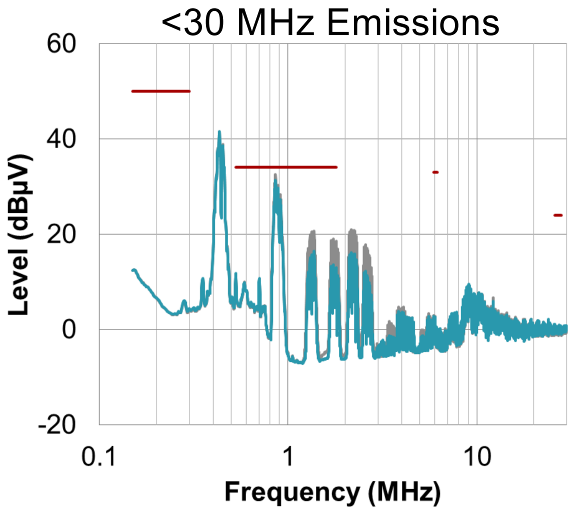


- Small amount of additional power loss measured (21 mW)

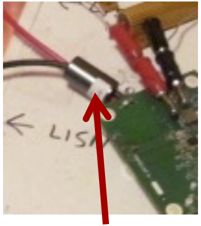
Emissions reduced by 2 dB with a simple, low cost change

Note: Dithering and pi filter are included in this result

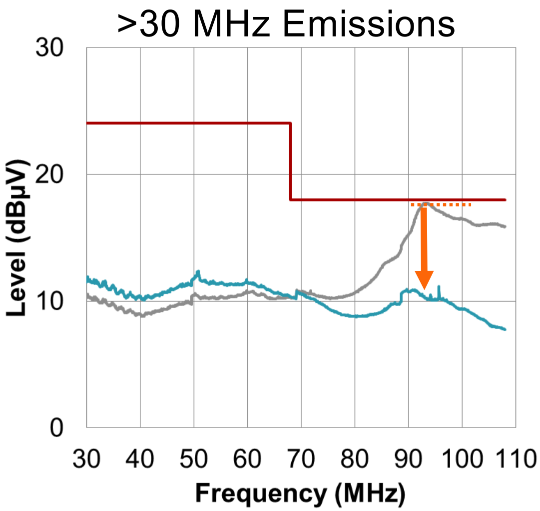
Slip-on ferrite on input lines included (optional)



Avg. Limit (Class 5)
With Ferrite
No Ferrite



Axial ferrite bead
(274 Ω at 100 MHz)



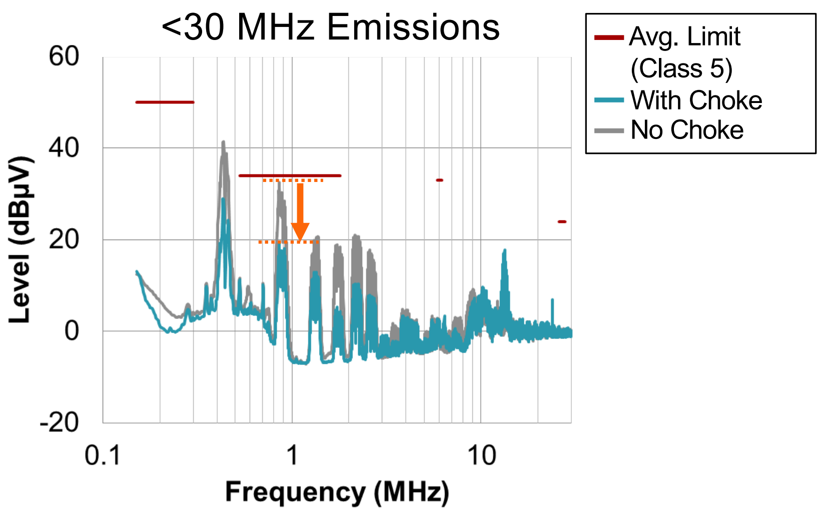
Passing by <3 dB

Passing by 7 dB

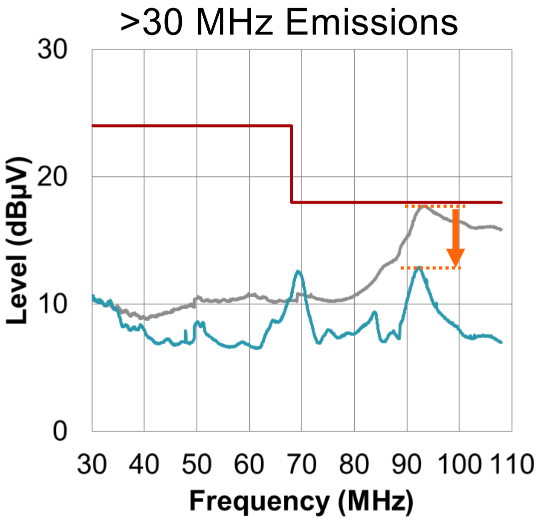
A noticeable reduction in the FM band but only a small reduction at low frequencies

Note: Dithering and pi filter are included in this result

Common mode choke installed (optional)



Passing by >10 dB



Passing by 5 dB

Reduction across the frequency spectrum enables more passing margin

Note: Dithering and pi filter are included in this result

Testing summary

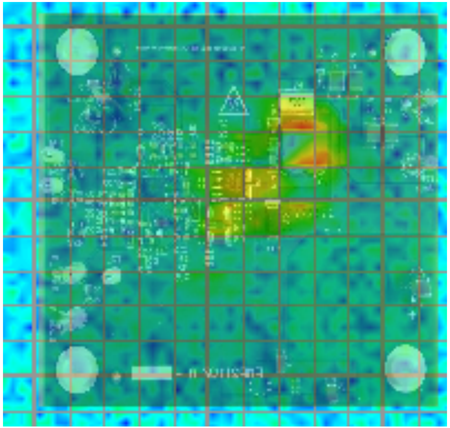
	Freq. Dithering	Differential Mode Pi Filter	Snubber	Gate Resistor	Clamp-On Ferrite	Common Mode Choke
<30 MHz reduction	5 - 10 dB	40 - 45 dB	0 dB	No impact	1 dB	>10 dB
>30 MHz reduction	5 - 10 dB	19 dB	-2 dB (got worse)	2 dB	7 dB	5 dB
Class 5	Failed by 45 dB	Passed by 0.5 dB	Failed by 2 dB	Passed by 2.5 dB	Passed by 2.5 dB	Passed by 5 dB
Additional comments		Dithering included	Dithering and pi filter included	Dithering and pi filter included	Dithering and pi filter included	Dithering and pi filter included

Note: Results focus on average emissions measurement results

General conclusions

- Passing CISPR 25 emissions requirements is important for automotive system design
  - Class 5 limits are a common target for low and moderate power levels
- Differential mode and common mode emissions can be addressed with proper filtering, design, and layout
- Six techniques to address emissions have been experimentally evaluated for a 13.5 V_{IN} to 3.3 V, 5 A output example converter

EM scan of case study board



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