Power Supply Design Seminar

Practical EMI Considerations for Low-Power AC/DC Supplies

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Texas Instruments

Practical EMI Considerations for Low-Power AC/DC Supplies

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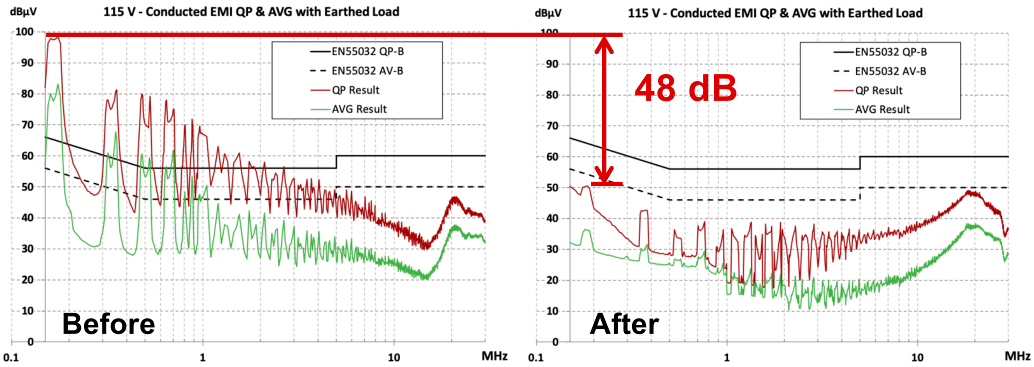
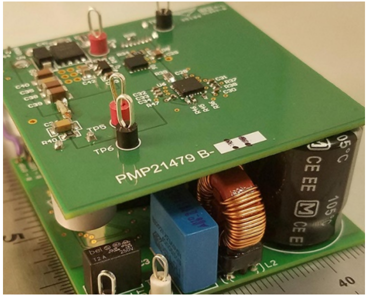
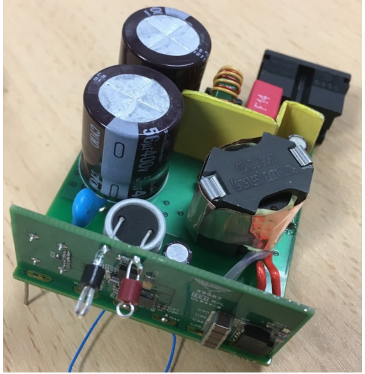
Electromagnetic interference (EMI)

- I built my 65 W adapter prototype and resolved all functional issues
- I ran first-pass EMI scan – and my design failed – badly! ~100 dBµV
  - *How can I fix the EMI?*
  - *Where do I start?*
- This presentation will show how to get to a result like this, without necessarily adding a big EMI filter







Agenda

- Introduction to EMI testing
- What causes EMI
- Differential-mode vs common-mode EMI
- EMI mitigation options
- Analyzing the transformer
- Troubleshooting & debug
- 65 W USB-PD example design using active clamp flyback (ACF) topology

Conducted emissions (CE) standards

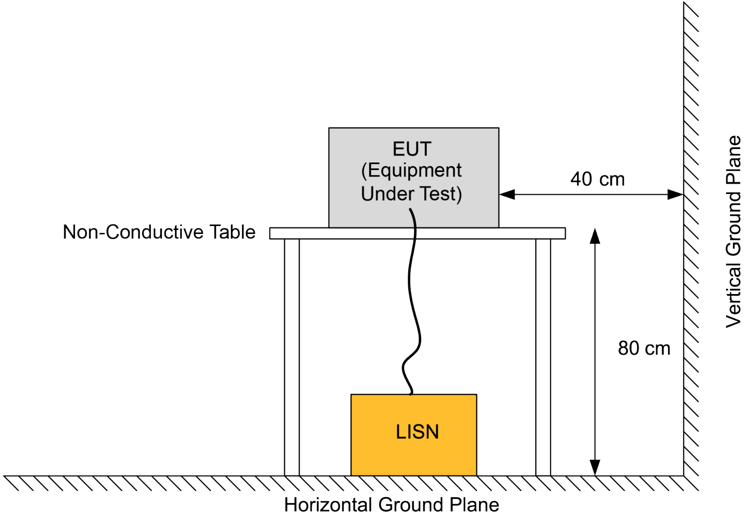
- Summary of main product standards for conducted emissions

Product Sector	CISPR Standard	EN Standard	FCC Standard
Automotive	CISPR 25	EN 55025	--
Multimedia	CISPR 32	EN 55032	Part 15
ISM	CISPR 11	EN 55011	Part 18
Household appliances, electric tools and similar apparatus	CISPR 14-1	EN 55014-1	--
Lighting equipment	CISPR 15	EN 55015	Part 15/18

Reference:
Timothy Hegarty, "An overview of conducted EMI specifications for power supplies," http://www.ti.com/lit/wp/slyy136/slyy136.pdf

How conducted EMI is measured

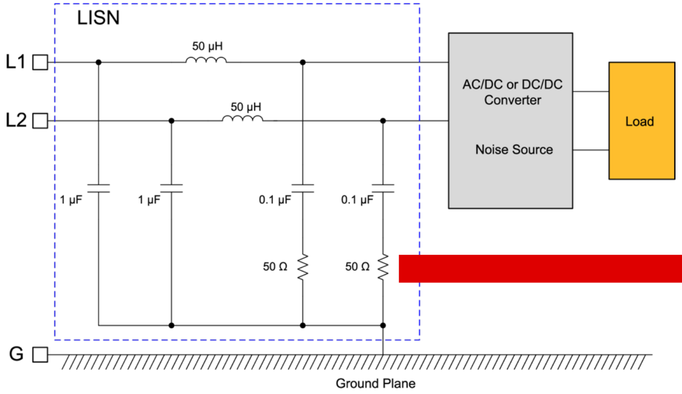
- Equipment under test (EUT) placed on non-conductive table
- Horizontal & vertical ground planes
  - Or screened room
- EUT powered through line impedance stabilization network (LISN)
- Measure high-frequency (HF) emissions from LISN



[1] EN55022, 2010, "Information technology equipment – Radio disturbance characteristics – Limits and methods of measurement"

LISN – Line impedance stabilization network

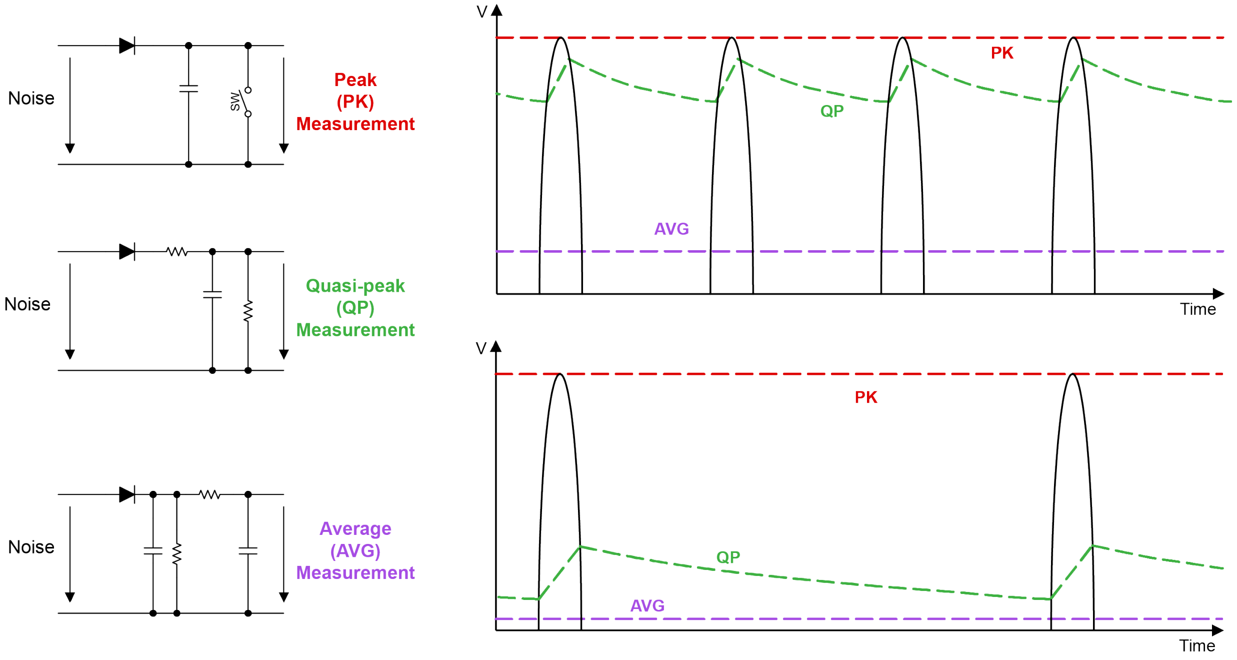
- Presents stable, consistent & repeatable line source impedance
- Separation of power source noise current for measurement
  - *Low frequency power current passes straight through from AC source*
- "**Total**" noise levels measured separately on **L1** (live) and **L2** (neutral)



EMI Receiver

*** Functional equivalent circuit of a LISN, not a complete schematic ***

EMI receiver – Built-in detector types

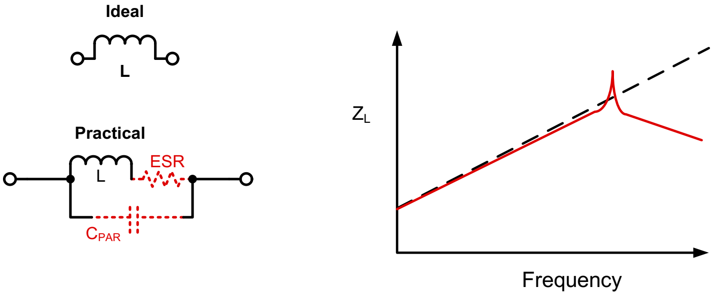


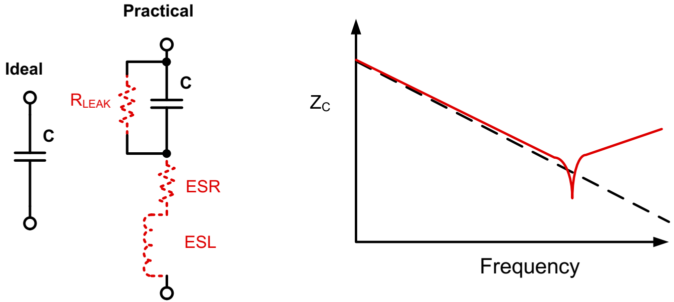
Component parasitics

- Parasitic elements are the ***dominant cause*** of EMI issues

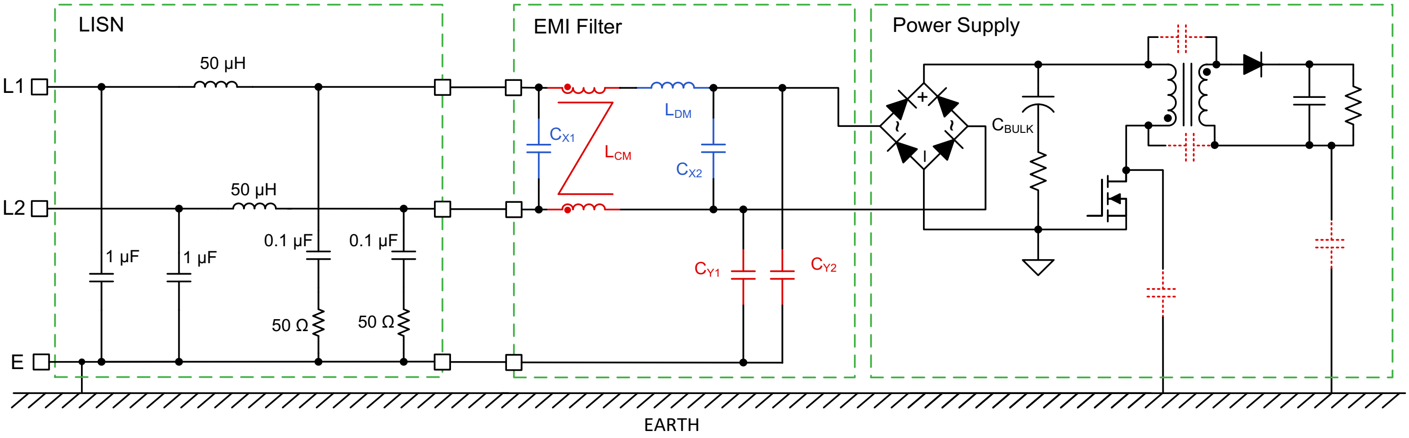
- EMI noise is ***coupled & propagated*** through parasitic elements:
  - Capacitive coupling
  - Inductive coupling

- EMI filter performance is ***dominated*** by parasitic elements at higher frequency:
  - Parasitic capacitance of inductors
  - Parasitic inductance of capacitors





LISN + EMI filter + power supply



LISN – measures noise

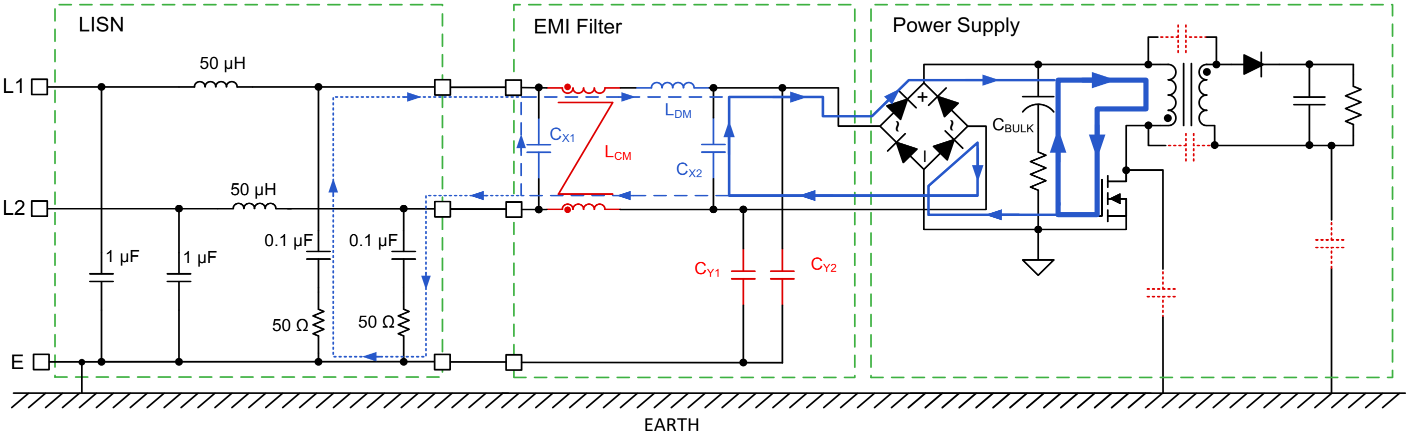
EMI filter – limits noise that gets to the LISN

(CM – red, DM – blue)

Power supply – generates the noise

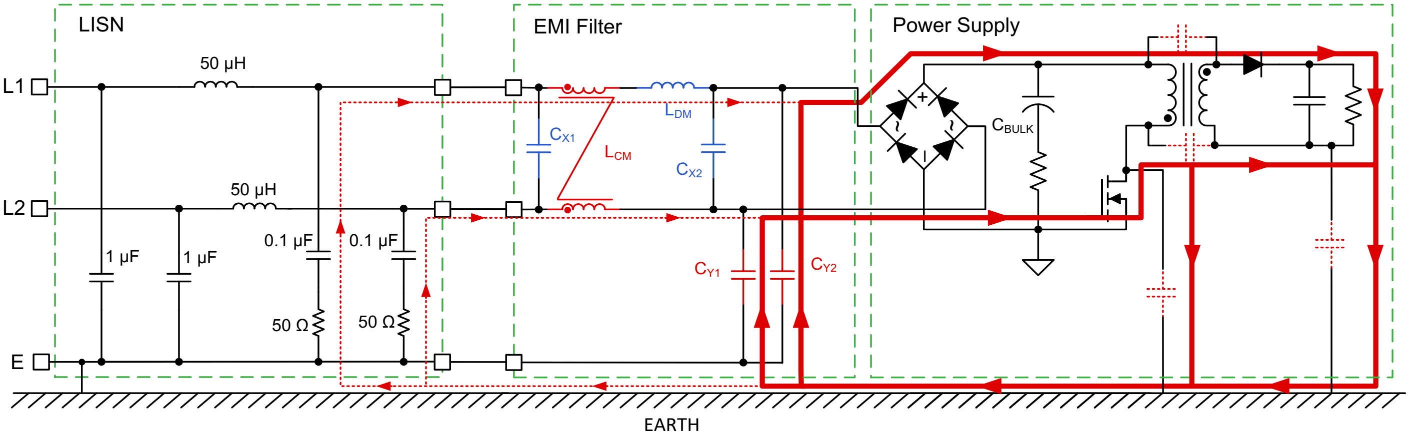
(parasitic cap – red dotted)

DM EMI filter and current path



- DM EMI filter limits DM noise that gets to the LISN
  - X-caps divert current away from LISN, keep local to power supply
  - DM choke high impedance reduces size of current flowing to LISN

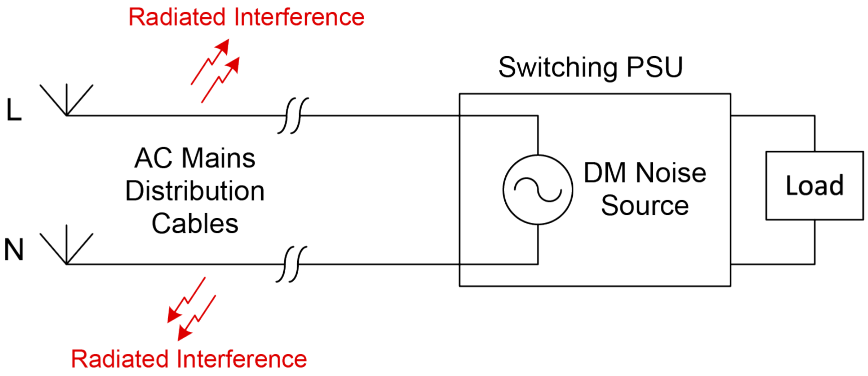
CM EMI filter and current path



- CM EMI filter limits CM noise that gets to the LISN
  - Y-caps divert current away from LISN, keep local to the power supply
  - CM choke high impedance reduces size of current flowing to LISN

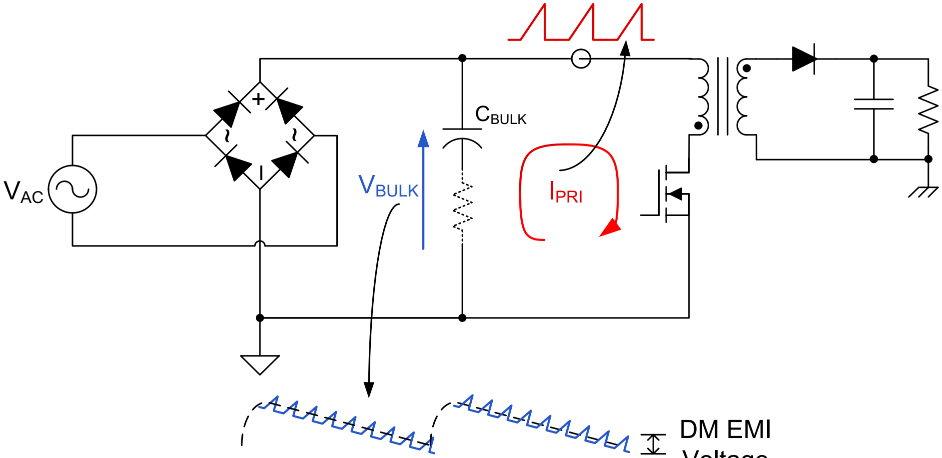
Why care about differential-mode (DM) EMI?

- DM noise conducts to the AC utility supply network
- Long AC distribution cables – act as good dipole antenna
- Will inadvertently radiate switching noise and interfere with radio communications
  - *(E.g., noise @ ~100 MHz will affect FM radio)*



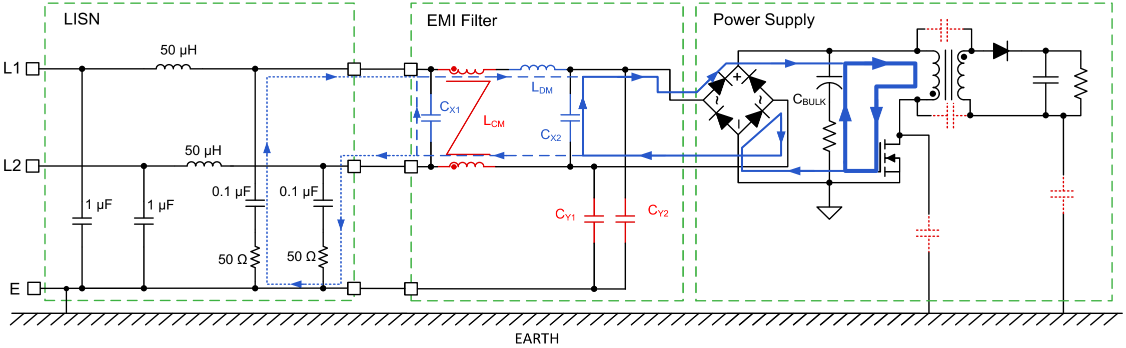
How is DM EMI generated?

- Switching ripple current produces ripple voltage across ESR (& ESL)
- Ripple voltage is the DM noise that needs to be attenuated/filtered



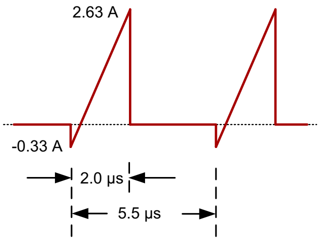
Mitigation options for DM noise

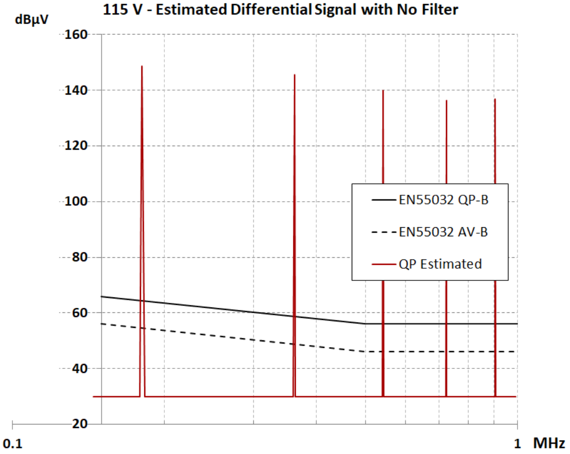
- Include EMI at the design phase
  - Make design & component choices to minimize DM EMI signal amplitude
  - Chose frequency, inductance, etc. to minimize PK-PK ripple current
  - Choose capacitors with low ESR to minimize PK-PK ripple voltage
  - Good PCB layout important to minimize EMI
- Design sufficient DM LC filter to reduce the ripple that gets onto the AC line input



DM filter design methodology

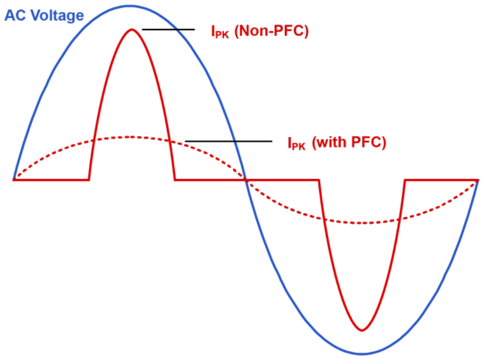
- Measure, simulate or calculate time-domain current waveform
- Fourier analysis of time-domain switching current
  - *Convert waveform into harmonic components*
- Establish required attenuation at each frequency
  - *To get sufficient margin below the required EMI limit*
- Design the DM filter to achieve required attenuation
  - *Need to check all frequencies of interest*
  - *Typically limited by lowest frequency inside measurement band*
  - *Typically EMI starts at 150 kHz for AC/DC PSU to meet EN55022 or EN55032*

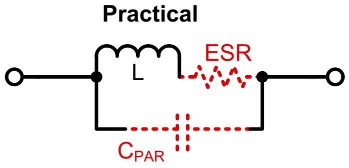




DM filter choke practical considerations

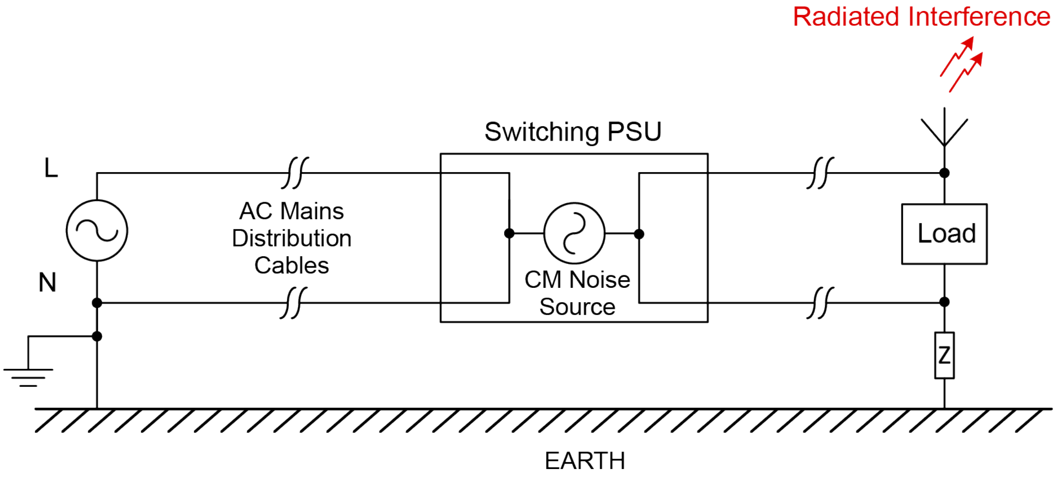
- Choke requires high attenuation over wide bandwidth:
  - *Load current amplitude typically several amps*
  - *At 50 dBμV, current in LISN 50 Ω resistor only ~6.3 μA*
- Beware inductance roll-off with DC-bias
  - *Must not saturate to be effective – needs high current rating*
  - *Consider the peak line current for non-PFC – high crest factor*
- Switching power stage has fast changing magnetic fields
  - *Beware filter bypassing & noise coupling*
- Parasitic capacitance across DM inductor very important
  - *Reduces effectiveness, especially at high frequency*
- Example: To filter 300 kHz component, typically set LC freq. ~30 kHz
  - *Expect ~40 dB attenuation at 300 kHz (double-pole ⇒ 40 dB/decade)*
  - *With parasitic cap ⇒ more like 30 dB attenuation only – even worse at higher frequency*





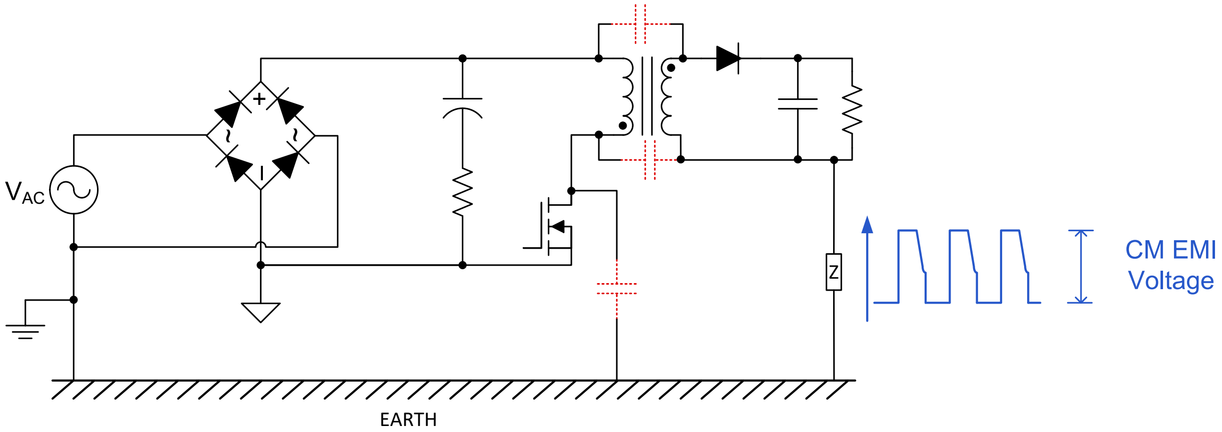
Why care about common-mode (CM) EMI?

- Again, AC distribution cables and output load cables act as good uni-polar antenna
- CM noise will radiate from the cables and interfere with radio communications



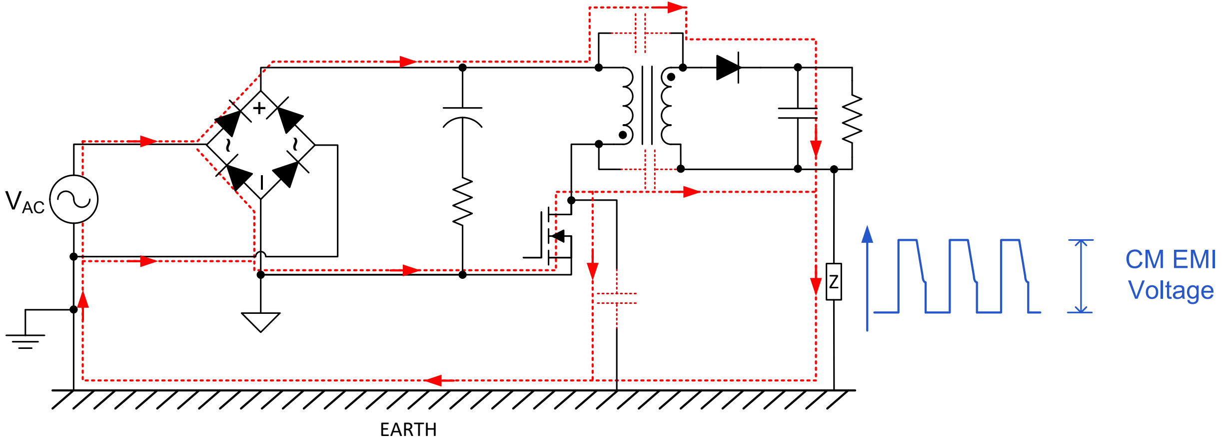
How is CM EMI generated?

- Switching voltage across parasitic capacitance causes CM current flow to EARTH



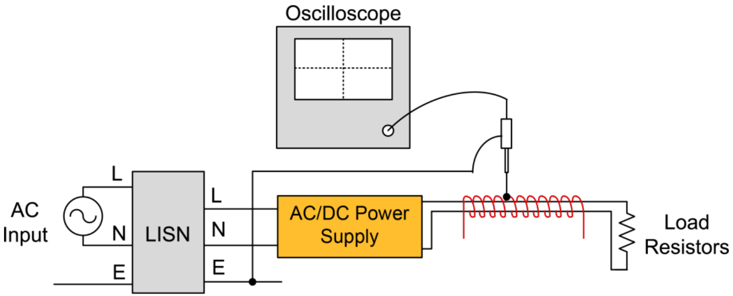
How is CM EMI generated?

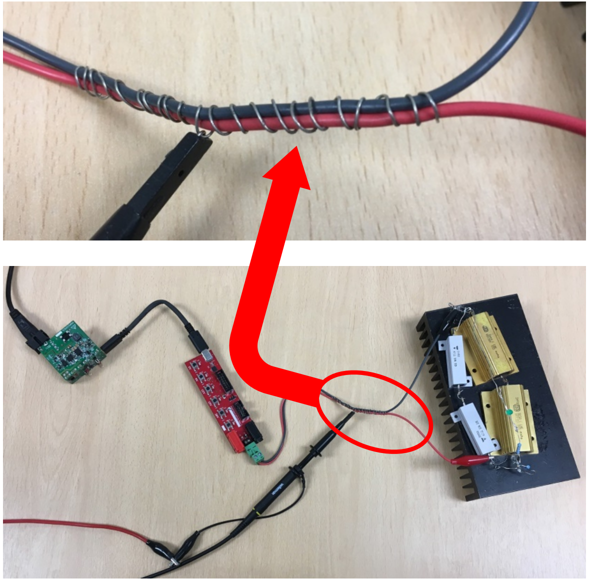
- Switching voltage across parasitic capacitance causes CM current flow to EARTH
- CM noise also radiated to other circuit nodes



Observing the time-domain CM signal at the output

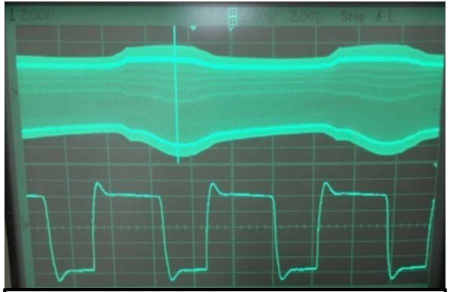
- Useful debug technique – ball-park indication of CM performance
  - Remove Y-cap temporarily (maximize signal)
  - Power EUT through LISN, with resistor loads
  - Wind several turns of wire around the load cables to create capacitive sensing coil (pickup coil)
  - Connect scope EARTH lead to LISN EARTH
  - Connect scope tip to sensing coil
  - Scope plot shows how much CM is coupled to output



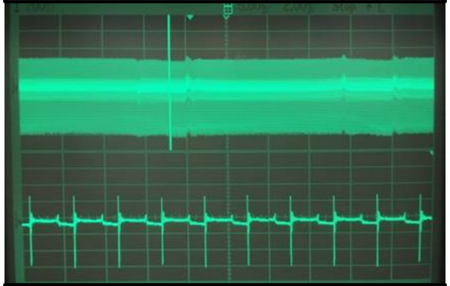


Interpretation of time-domain CM signal

- Will see "switch-node" shaped waveform – coupled to output
- Large PK-PK amplitude ⇒ bad CM noise
  - *Will require significant CM filtering to suppress*
  - *Result from ACF example with 100 dBµV EMI*
- Small PK-PK amplitude ⇒ good CM noise
  - *"Balanced" structure giving low CM*
  - *Will require much smaller CM filter*
- Residual HF "spikes" ⇒ should only need small HF CM choke



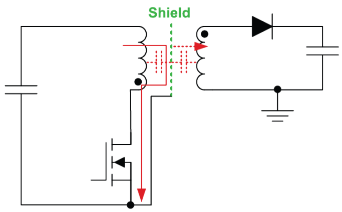
2 V/div, 2 µs/div



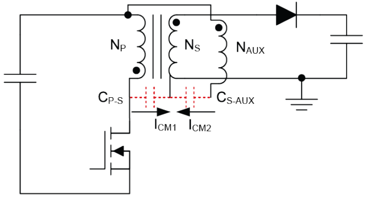
200 mV/div, 10 µs/div

Mitigation options for CM noise

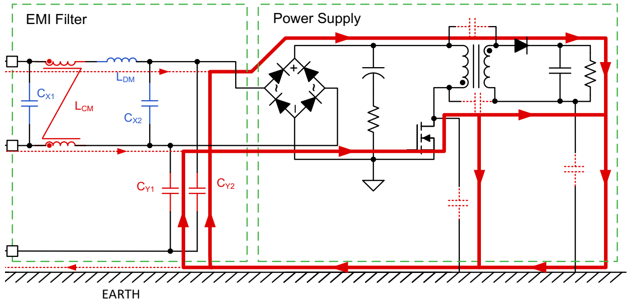
1. **Shielding:**
   – Reduce flow of HF current to EARTH



2. **Cancellation:**
   – Arrange transformer and power stage for balanced CM



3. **Filtering:**
   – Increase impedance of the EARTH return path
   – Provide alternative routes for the HF current



1. CM mitigation by shielding

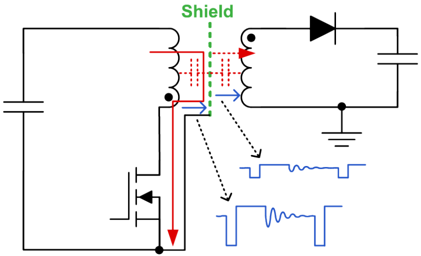
1. Shielding inside the transformer
   – Internal shields between pri & sec

2. Shielding outside the transformer
   – GNDed flux-band

3. Shielding of noisy circuit nodes
   – GNDed heatsinks over/around high-voltage switching nodes

4. Shielding of EMI filter from switching cct.
   – GNDed shields/enclosures around filter

1



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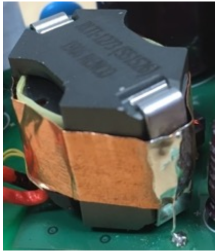

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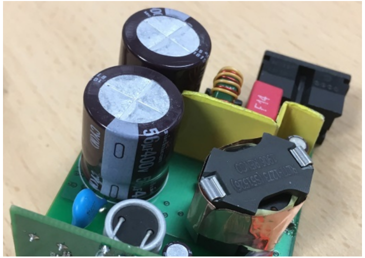
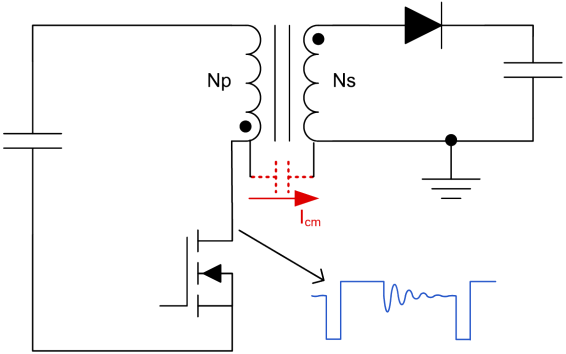
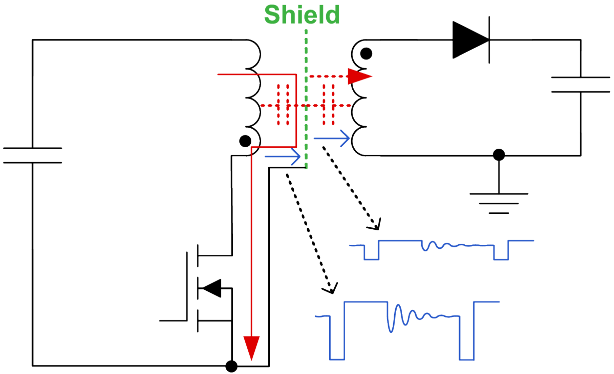


3

Transformer internal shielding

- Shield added to keep most of CM current local to primary
- Shield is 1-turn winding ⇒ lower induced voltage, less voltage across parasitic capacitance between shield & sec ⇒ less CM current flows
- Shield must be thin (< 50 μm) ⇒ minimize induced eddy current loss
  - *Eddy currents get very significant as F_{SW} increases*

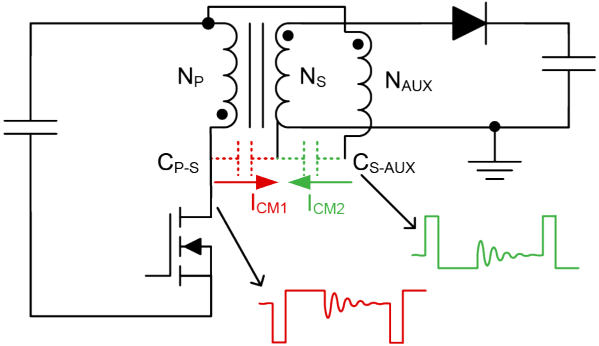




2. CM mitigation by cancellation/balance

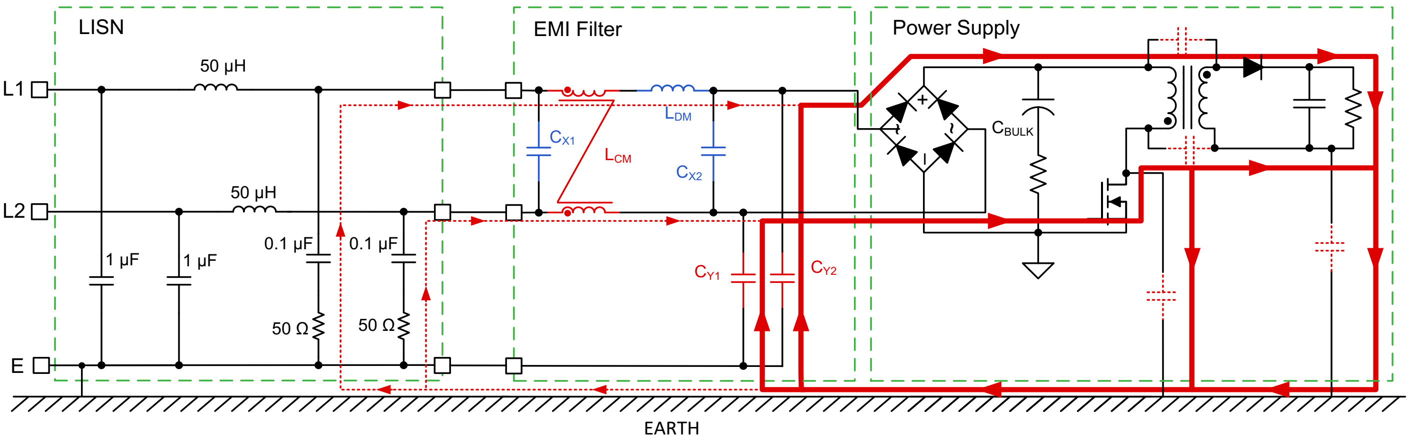
- Single-ended topologies – can add explicit additional cancellation elements
  - Add auxiliary (AUX) transformer winding
  - AUX voltage proportional to CM waveform
  - Arrange AUX polarity for opposite phase

  - Capacitor to inject cancelling current, I_{CM2}, to balance CM current from primary, I_{CM1}
  - Injection capacitor explicit physical component added to design
  - Or can use parasitic capacitance, e.g., $C_{S\text{-}AUX}$, part of transformer structure



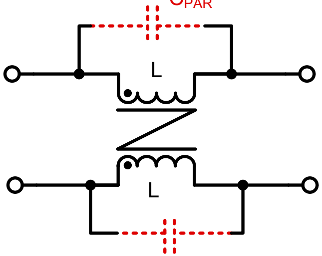
3. CM mitigation by filtering

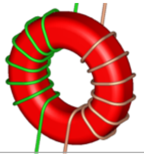
- CM filter uses high-impedance CM chokes and low-impedance Y-capacitors
- CM choke limits the flow of CM current from EARTH through the LISN
- Y-cap provides low impedance to keep CM current local to primary GND and away from LISN



CM filter choke practical considerations

- **Frequency response of core material**
  - High-μ cores ⇒ high L value @ low freq, but roll off fast at higher freq
  - High-freq cores ⇒ low-μ, smaller L value @ low freq, better vs freq
  - Sometimes need to use 2 CM chokes, 1 for LF & 1 for HF
- **Split-wound vs bifilar-wound toroid**
  - Split-wound popular, lower cost, “free” DM choke from leakage field
  - Bifilar ⇒ 1-side insulated wire, higher cost, but better noise immunity
- **Parasitic input-output cap – multi-layer windings**
  - Parasitic cap depends on number of turns & layers
    - High C_{PAR} input-output cap ⇒ worse @ HF
  - Less layers ⇒ lower L, but also lower C_{PAR}
  - Sectional bobbins – used to reduce C_{PAR}





Split-Wound*

Bifilar-Wound*

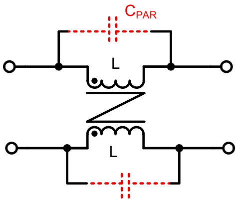
Multi-Section

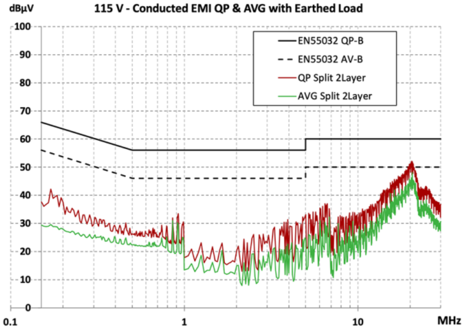
CM choke 3-D images reproduced with permission of Wurth Elektronic

CM filter choke – Impact of C_{PAR}

Split-Wound 2L

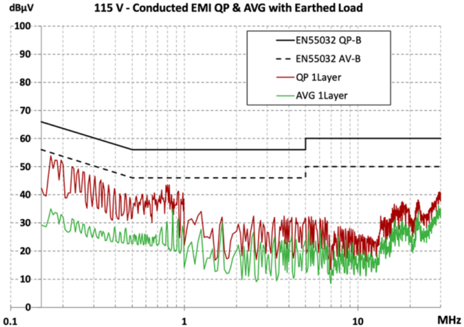
- Split-wound 2-layer:
  - 25T, 5.1 mH
  - Excess pass margin @ LF
  - Low pass margin @ 20 MHz





Bifilar-Wound 1L

- Bifilar-wound 1-layer:
  - 14T, 1.1 mH
  - Low input-output C_{PAR}
  - Lower L at LF, but better at HF
  - Better balance across frequency span

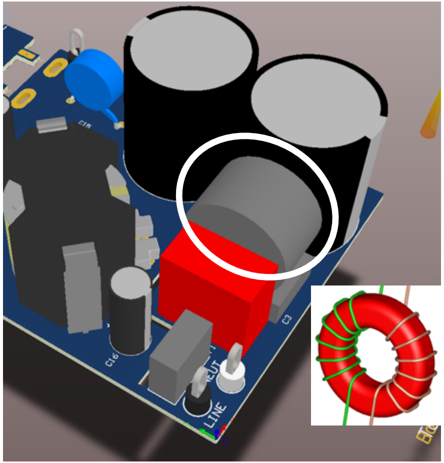


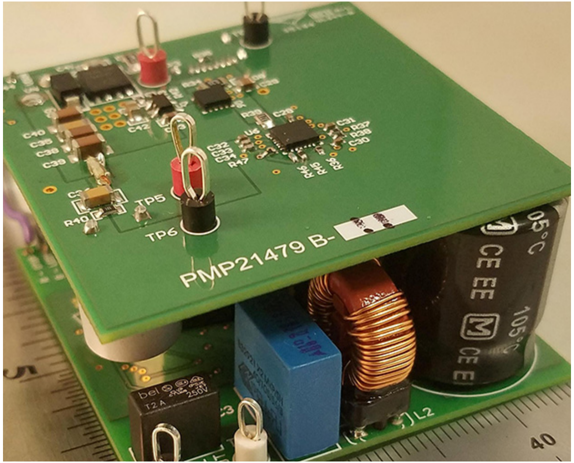
Split-Wound 1L

- Split-wound 1-layer:
  - 14T, 1.4 mH
  - Similar low input-output C_{PAR}
  - Similar result as bifilar-wound

CM choke example

- Initial split-wound choke had issues due to asymmetric noise coupling from transformer
  - Shows up as big difference in EMI on L vs N

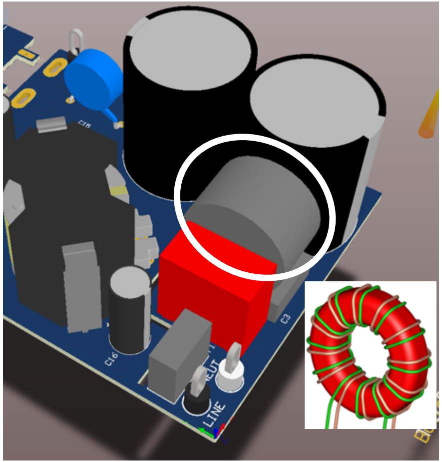




**CM choke 3-D image reproduced with permission of Wurth Elektronic*

CM choke example

- Changed to bifilar-wound choke, much better EMI result; less difference L vs N
- Much better noise immunity



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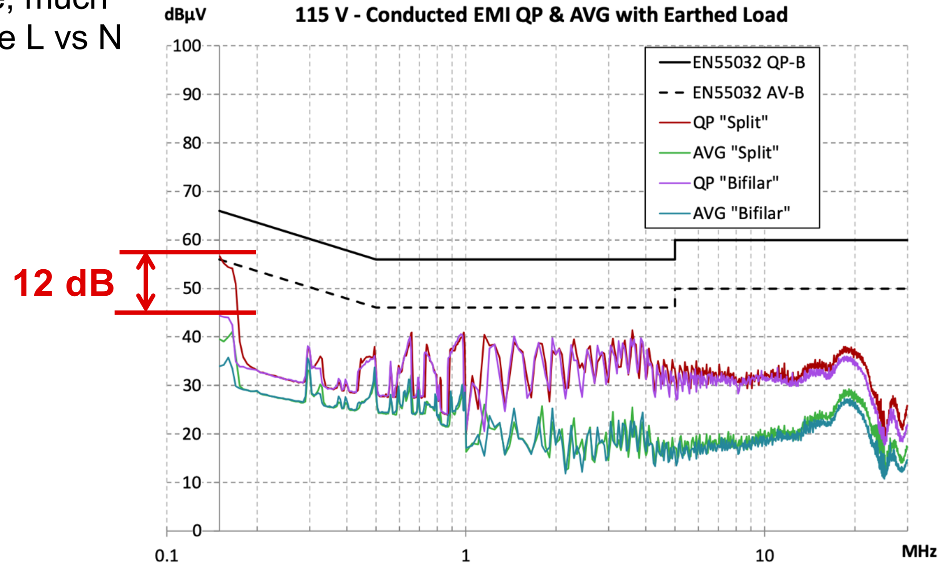
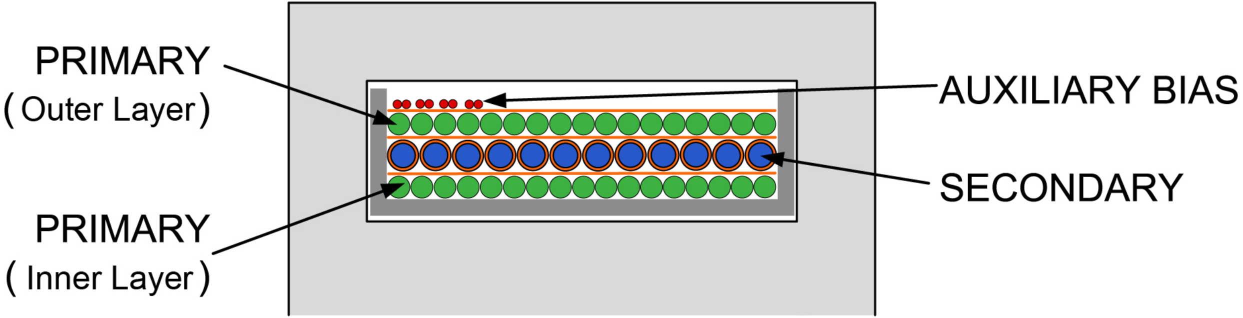


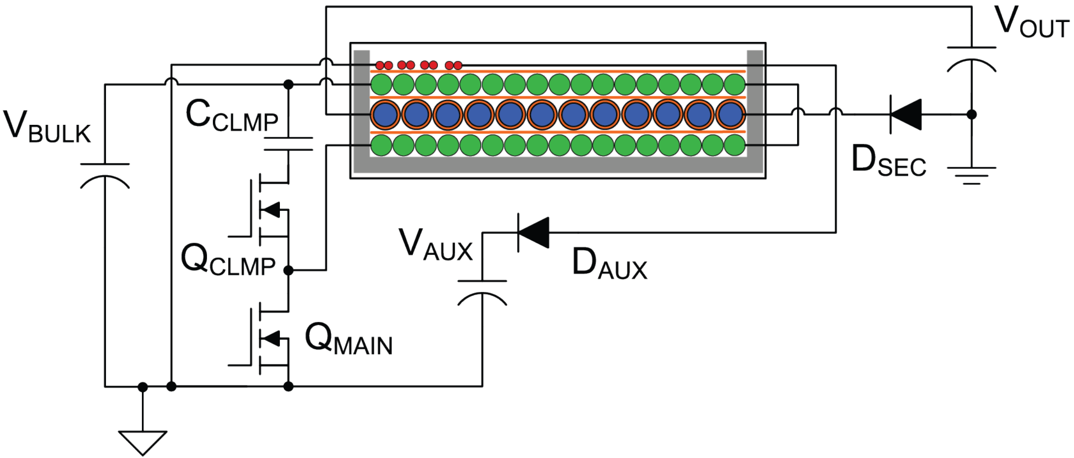
Transformer CM noise analysis – PMP21479 ACF

- Initial design – interleaved flyback transformer construction, no internal shielding
- Same transformer used for initial test with poor 100 dbµV EMI result



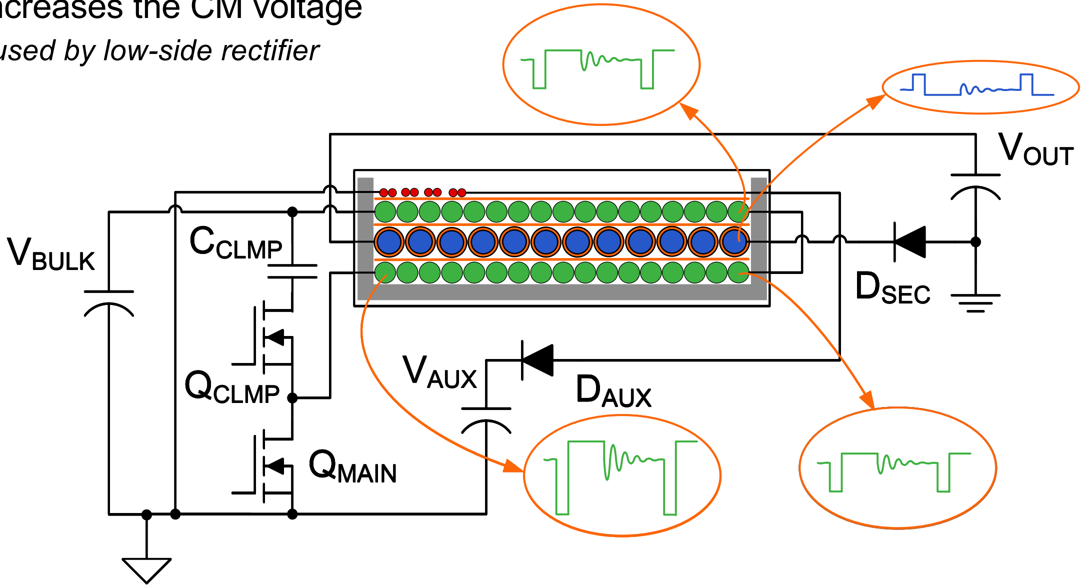
Transformer CM noise analysis – PMP21479 ACF

- Circuit connections to the ACF power stage
- Note the secondary low-side rectifier – causes inverted secondary winding polarity



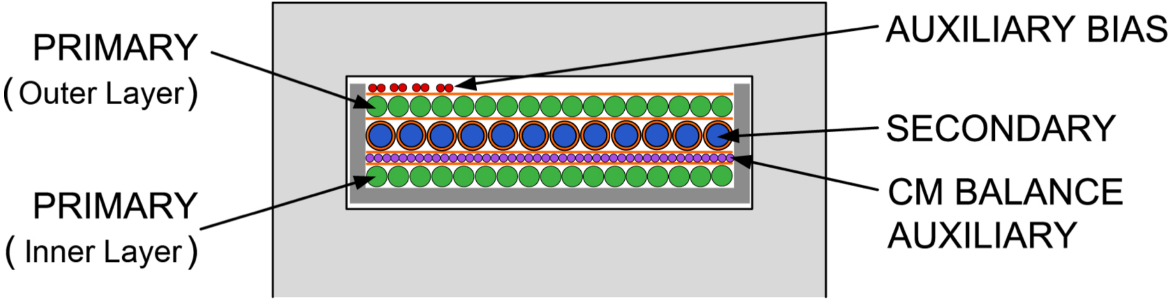
Transformer CM noise analysis – PMP21479 ACF

- Note that primary and secondary waveforms are inverse of each other
- This increases the CM voltage
  - *Caused by low-side rectifier*



Transformer CM balance – PMP21479 ACF

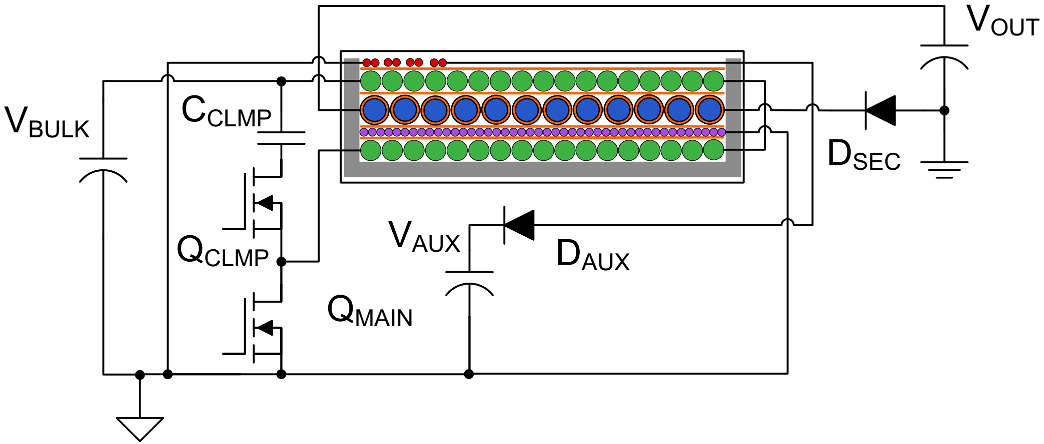
- Add CM balance auxiliary layer (purple) in-between inner PRI (noisier) to SEC interface:
  - *Fill layer completely – acts as shield between PRI & SEC*
  - *Add turns to create CM balance, inject current to balance other PRI-SEC interface*



- NOTE: this example shows one way to add CM balance
- But there are many different ways to achieve the same CM result

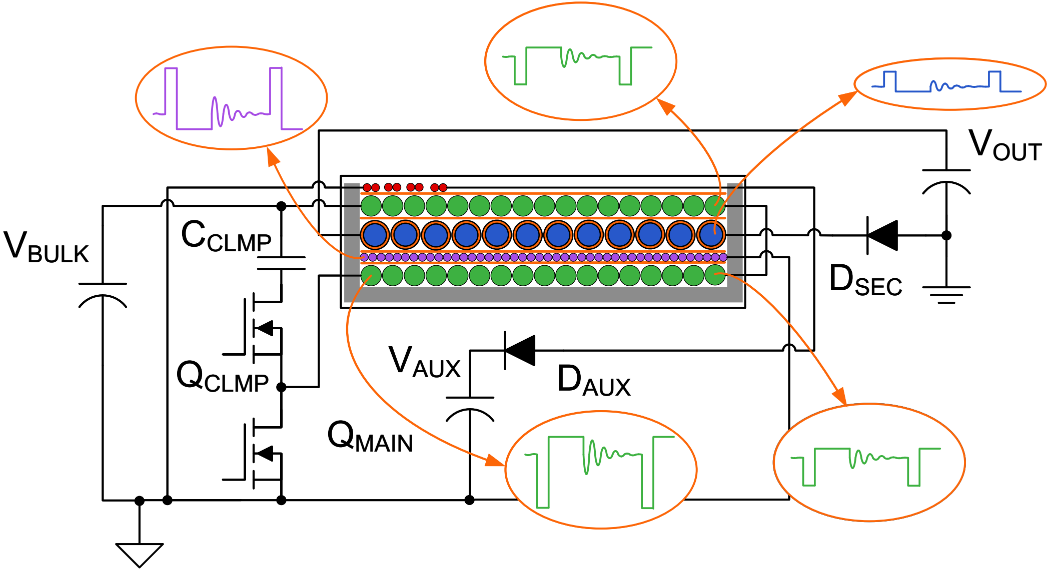
Transformer CM balance – PMP21479 ACF

- PRI, SEC & AUX bias connections same as before
- CM auxiliary layer starts at PRI GND, and winds in SAME direction as SEC



Transformer CM balance – PMP21479 ACF

- Waveforms – PRI & SEC same as before
- CM AUX – same phase as secondary – *but amplitude increased to compensate for outer PRI*



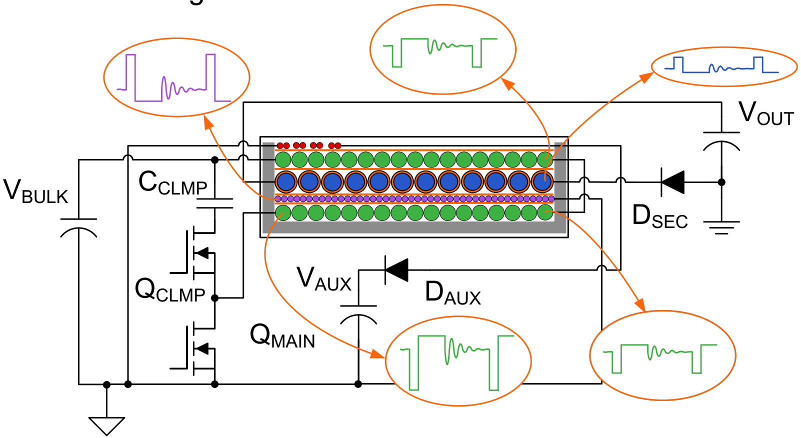
Transformer CM balance – PMP21479 ACF

- CM AUX – need to adjust number of turns to balance the CM nulling
- Waveforms showing:

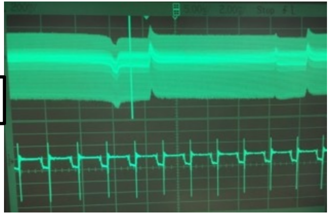
  A: Slightly under-compensated

  B: Slightly over-compensated

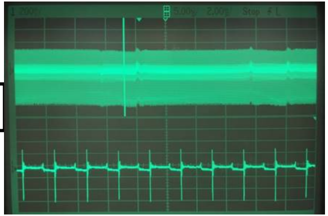
  C: “Just right”



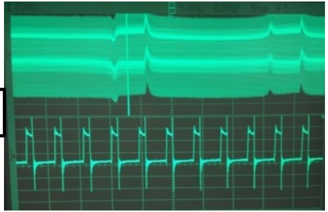
A: 0.2 V/div, 5 µs/div



C: 0.2 V/div, 10 µs/div

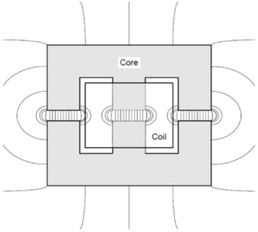


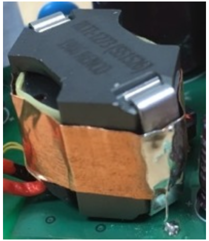
B: 0.2 V/div, 5 µs/div

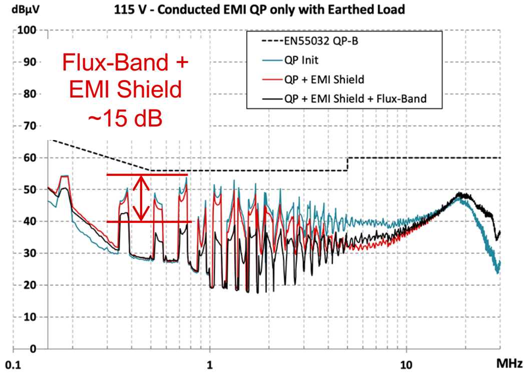


Transformer "housekeeping" best practices

- Center-leg air-gaps only – outer legs will radiate
- "Noisier" windings on inside of layer structure
- Tie ferrite core to local primary GND
- Flux-band to minimize stray coupling
  - GNDing & flux-banding can give >10 dB improvement!
- Interleaving trade-offs
  - Lower leakage inductance
  - Higher pri-sec parasitic capacitance, higher CM
- Be aware of internal construction
  - Average CM voltage across the pri-sec capacitance
  - Arrange winding layers to minimize voltage difference
    - *Minimizes CM current*

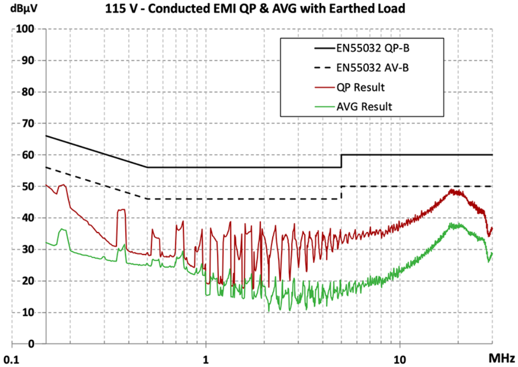


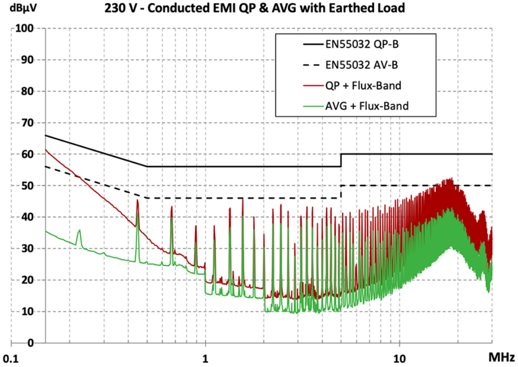


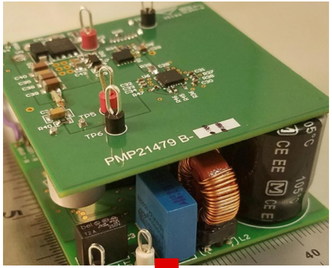


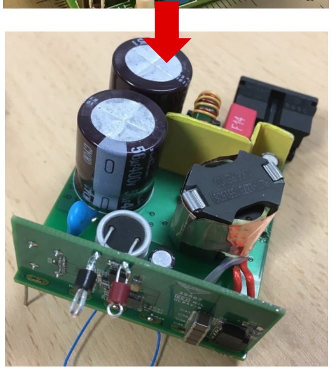
PMP21479 65 W ACF USB-PD – Final result

- Improve transformer structure, add CM balance/shield winding layer
- Add transformer grounding & flux-banding + EMI shield
- Improve CM choke to bifilar-wound type
- Improve output capacitor location, improve PCB orientation
  - ***Largely "low-cost" improvements***
  - ***Small efficiency penalty (eddy loss in cancellation layer)***









Summary & conclusions

- Consider EMI right from the start – inherent part of the power supply design
- Minimize DM & CM EMI noise at source
- DM filter can be designed/calculated/simulated more easily than CM
- CM balance is important – as much as practically possible
- Debug to establish if EMI issue is CM or DM or both
- Assess CM performance in time-domain – compare different transformers
- For isolated PSU, transformer is most important component
  - Internal construction details, CM balance, shielding, parasitic capacitance, housekeeping
- EMI filter components – be aware of parasitics and HF effects
- PCB layout and component placement – be aware of stray coupling paths

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- "***Understanding and Optimizing Electromagnetic Compatibility in Switchmode Power Supplies***," Bob Mammano & Bruce Carsten, 2002 TI Power Supply Design Seminar.
  - http://www.ti.com/lit/slup202
- "***Flyback transformer design considerations for efficiency and EMI***," Isaac Cohen & Bernard Keogh, 2016/7 TI Power Supply Design Seminar.
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- "***Designing low-EMI power converters for industrial & automotive systems***," Perry Tsao, David Baba & JP Fung, 2016/7 TI Power Supply Design Seminar.
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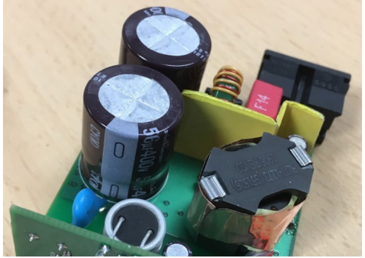
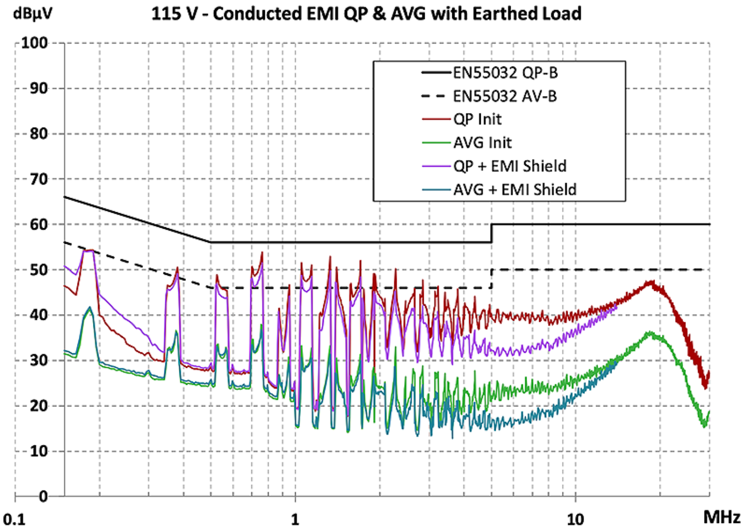
- "***Understanding Noise-Spreading Techniques and Their Effects in Switch-Mode Power Applications***," John Rice, Dirk Gerhke & Mike Segal, 2008/9 TI Power Supply Design Seminar.
  - http://www.ti.com/lit/slup269
- "**65W Active clamp flyback with Si FETs reference design for a high power density 5-20V AC/DC adapter**," PMP21479, Brian King, 2019.
  - http://www.ti.com/tool/PMP21479

APPENDIX – BACK-UP SLIDES

Transformer flux-band detailed results – 115 V

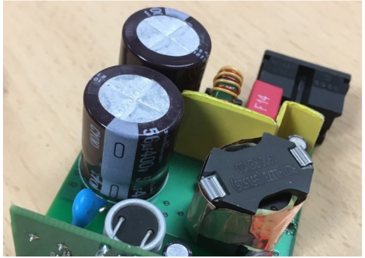
- EMI shield only (over switch-node and between EMI filter and transformer)
- NO flux-band, ferrite core floating
- Biggest improvement ~5-8 MHz

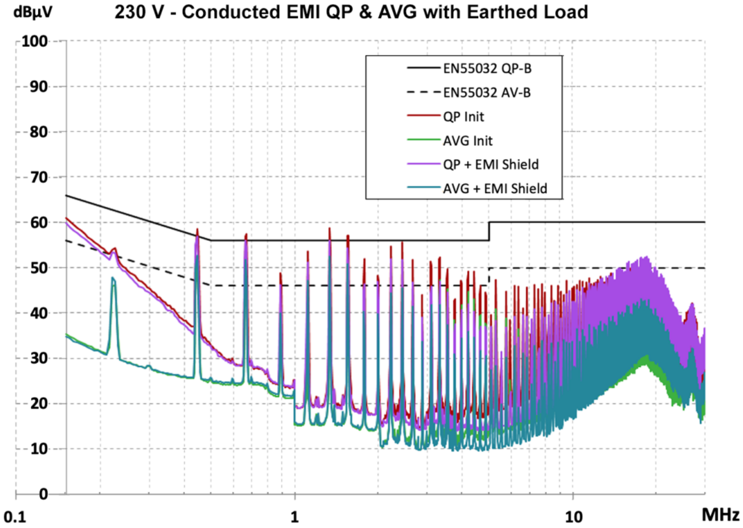




Transformer EMI shield detailed results – 230 V

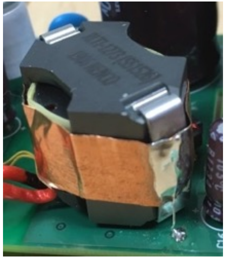
- EMI shield only (over switch-node and between EMI filter and transformer)
- NO flux-band, ferrite core floating
- Biggest improvement ~3-8 MHz

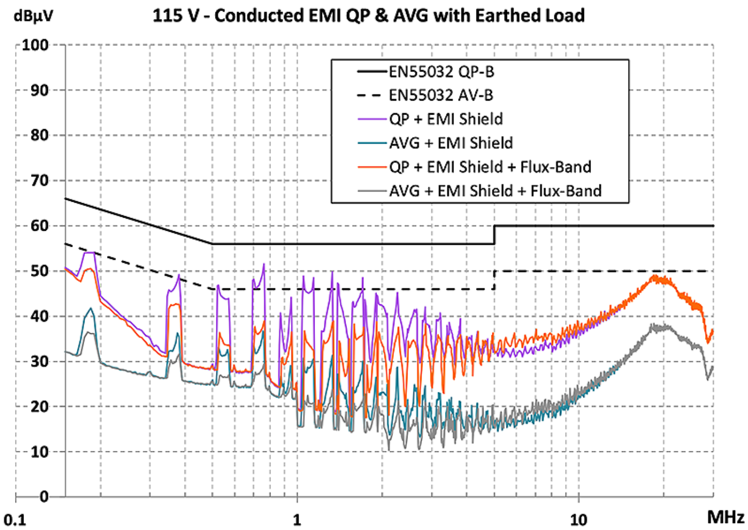




Transformer flux-band detailed results – 115 V

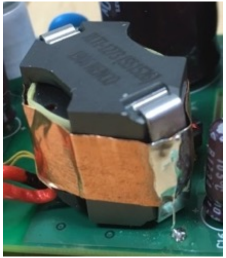
- EMI shield only (over switch-node and between EMI filter and transformer)
- Add flux-band, connected to local primary GND
- Much more significant reduction from 150 kHz to ~4 MHz

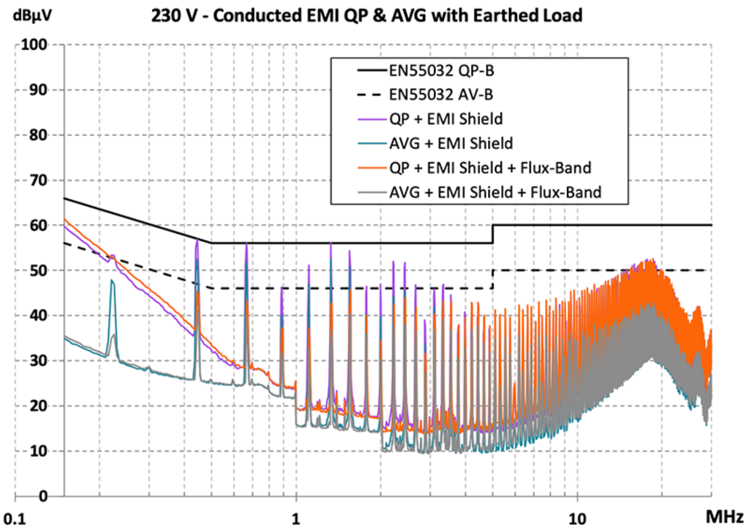




Transformer flux-band detailed results – 230 V

- EMI shield only (over switch-node and between EMI filter and transformer)
- Add flux-band, connected to local primary GND
- Much more significant reduction from 150 kHz to ~4 MHz
  - *Especially for AVERAGE, which is much tougher at 230 V*





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