Practical Design Considerations For The Reduction Of Conducted EMI; Part 2

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Agenda

- Welcome and thank you for attending. Today I hope I can provide a overall better understanding of the practical design aspects of managing conducted EMI in power systems. The topics we will cover in Part 2 of our two part series will be:
  - The determination of input capacitance for our Buck Converter model continued from Part I of the series.
  - Measurement of insertion loss will be explained using circuit simulation.
  - How to determine if a given input filter network is stable with a particular DC-DC Converter.
  - Passive Differential and Common Mode Filter Schemes
  - The Picor Active EMI Filter Topology
  - Case histories and troubleshooting topics

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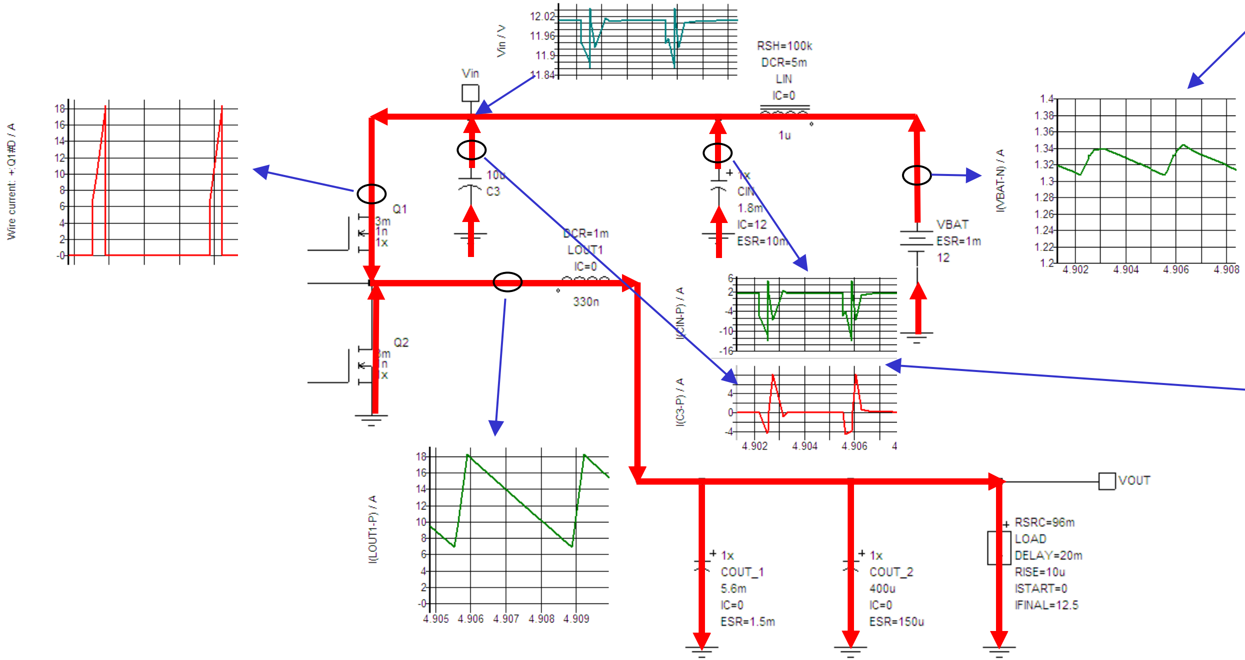
Differential Mode Noise Ideal Buck Converter Review

- Consider the ideal buck converter shown below:



This ripple current is responsible for the differential mode EMI that will be measured at the LISN.

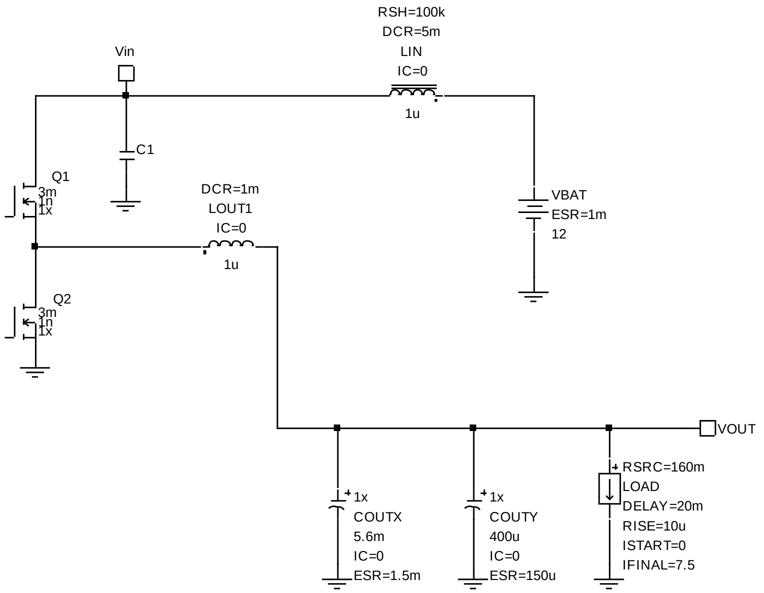
We are concerned about these ripple currents, as they are responsible for the ripple voltage measured at the node Vin. This ripple voltage is the source for the differential mode EMI that occurs at the fundamental as well as the much of the harmonic content.

Input Capacitor Selection For Our Ideal Buck Converter

- The typical Buck regulator will usually require two different types of input capacitors. One type must carry all of the high frequency switching ripple current and the second type must supply input voltage hold up time in the event an input inductor is used to isolate the high frequency differential current from the source.
- X5R or X7R ceramic capacitors will be used to carry the high frequency ripple current because they have the lowest ESR and ESL. In order to reduce the switching ripple voltage to an acceptable level, multiple ceramic capacitors will be used in parallel to reduce the overall ESR and ESL even further. The equations that follow are general in nature and do not include ESR and ESL when calculating the actual capacitance value required. For designs that have very high ripple current with very fast transients, a more rigorous study may be required.
- The input bulk capacitor is required to prevent the input voltage from sagging below the converter under voltage lockout during a load transient. A low ESR Oscon or Aluminum Electrolytic capacitor will be required if an input inductor of a significant value is used or if the DC-DC requires EMI scans using a LISN.

Input Capacitor Selection - Ideal Buck Converter

- 10V to 15V input, 1.2V output at 15A max
- Normal output is 7.5A with pulse load to 15A 20ms after start up
- Lout is 1uH
- Switching frequency is 300kHz



Input Capacitor Selection - Ideal Buck Converter

$Vin_{min} := 10 \qquad V_{out} := 1.2 \qquad \eta := .9$

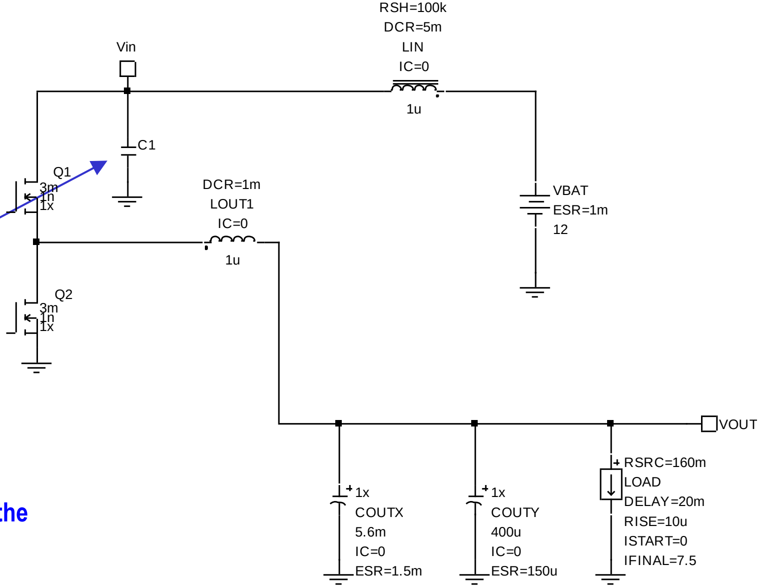
$F_{switch} := 300000 \qquad I_{outmax} := 15 \qquad Vripple_{pp} := .075$

$$D_{on} := \frac{V_{out}}{Vin_{min} \cdot \eta}$$

$$D_{on} = 0.133$$

$$Cin_{ceramic} := \frac{I_{outmax} \cdot D_{on} \cdot \left(1 - D_{on}\right)}{F_{switch} \cdot Vripple_{pp}}$$

$$Cin_{ceramic} = 7.704 \times 10^{-5}$$

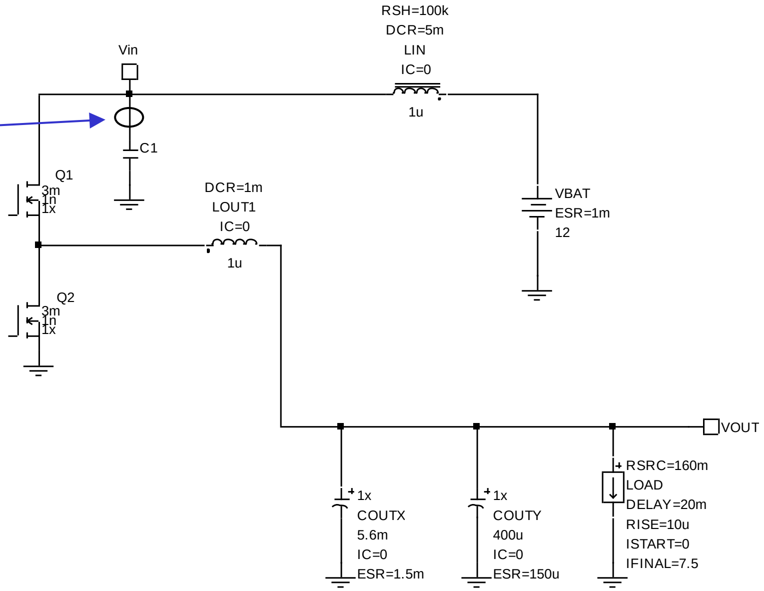


The calculation determines the minimum input ceramic capacitance value for a continuous mode Buck regulator. We will use 80uF total.

Input Capacitor Selection - Ideal Buck Converter

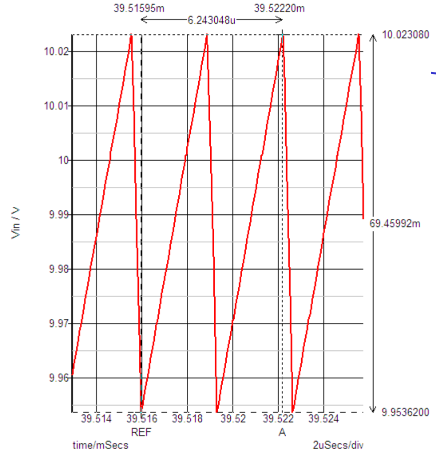
$$Cin_{RMS} := \frac{I_{outmax}}{Vin_{min}} \cdot \sqrt{V_{out} \cdot \left(Vin_{min} - V_{out}\right)}$$

$$Cin_{RMS} = 4.874$$

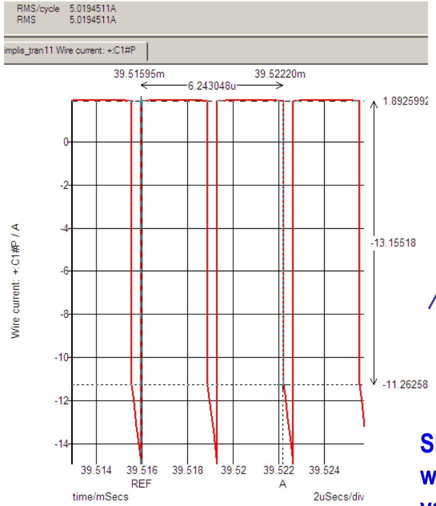


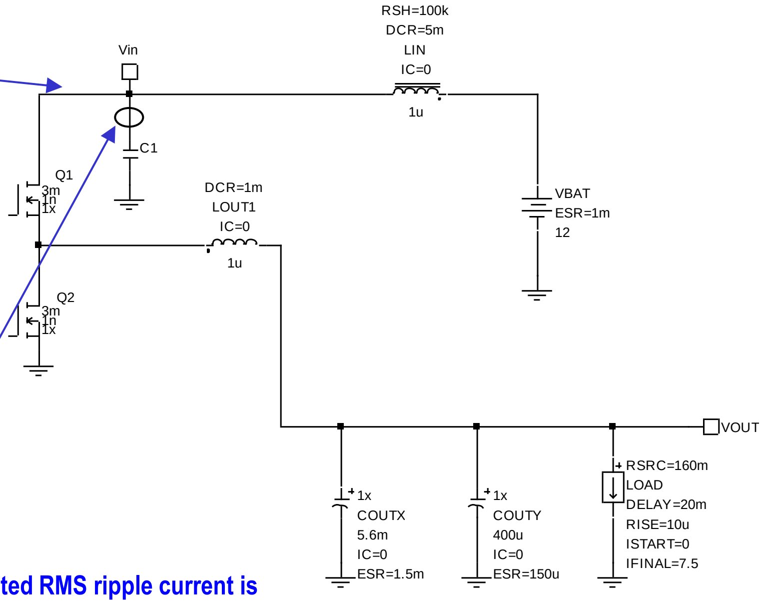
This equation is fairly accurate so long as the inductor ripple current is not a significant percentage of the total output current. Stated another way, the higher the ripple current, the less accurate the equation is.

Input Capacitor Selection - Ideal Buck Converter



Input ripple voltage measures 70mV p/p versus our target of 75mV p/p at the 15A load condition at low line.





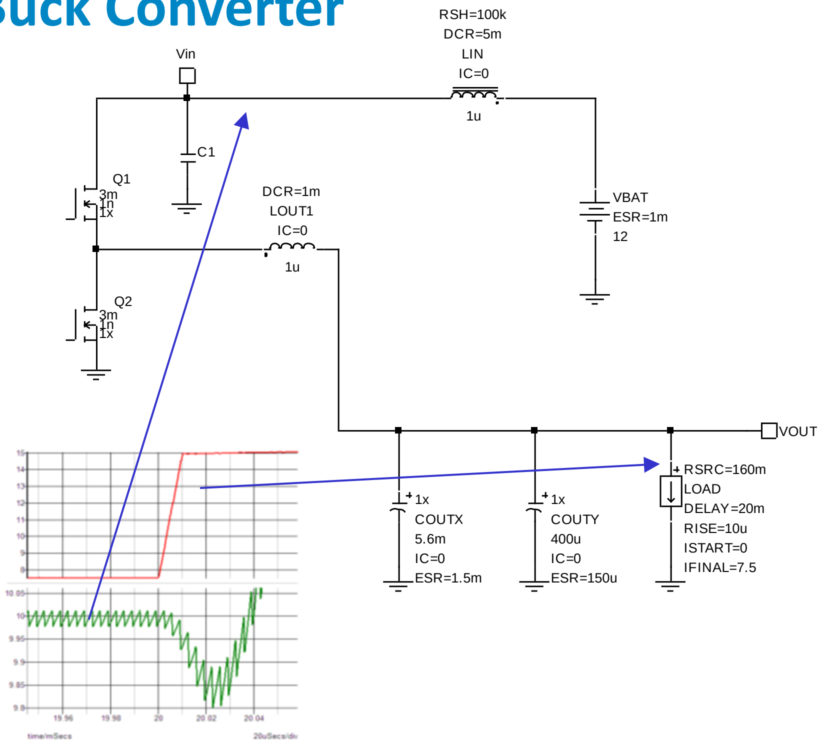
Simulated RMS ripple current is within 2.9% of the calculated value at 5.019A

Input Bulk Capacitor Selection - Ideal Buck Converter

- Since we have an input inductor, C1 is isolated from Vin from a transient standpoint.
- C1 would need to supply nearly all of the entire average current until the input inductor current equals the converter average current.
- For our converter, this should be no problem since LIN is small. At 10V input, a 50% load step is an increase of input current of 1A average. So, Vin will change by:

$$\Delta Vin := 1.1 \cdot I_{tr} \cdot \sqrt{\frac{L_{filt}}{C_{in}}}$$

$$\Delta Vin = 0.123$$



Input Bulk Capacitor Selection - Ideal Buck Converter

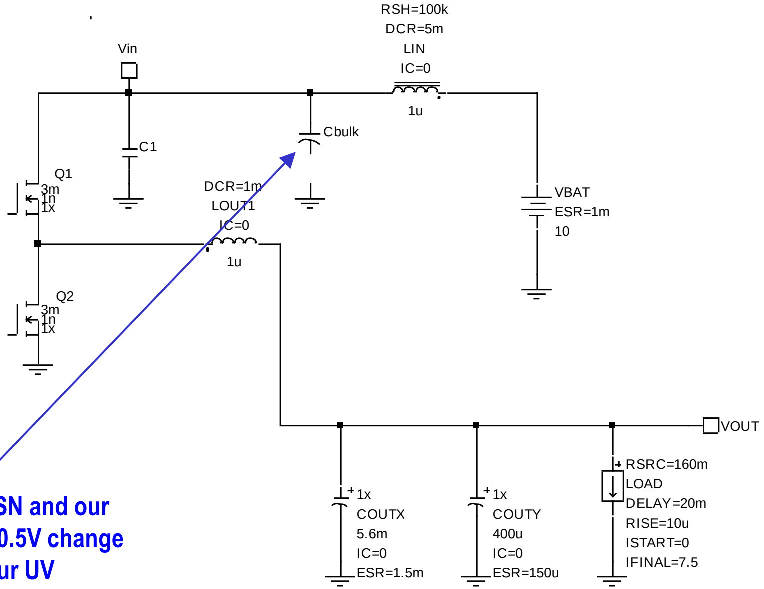
- If this converter were connected to a 50 Ohm LISN, the input inductance would be 100uH (50uH in series with each lead). In that case, our input Vin would drop 1.23V for the same load transient. If the UV lockout had 1V of hysteresis, the converter could shut down at low line due to the step.

$C_{in} := .000080 \qquad L_{filt} := .000101$

$\Delta V := 0.5 \qquad I_{tr} := 1.0$

$$C_{total} := \frac{1.21 \cdot I_{tr}^{2} \cdot L_{filt}}{\Delta V^{2}} \qquad C_{total} = 4.888 \times 10^{-4}$$

$$C_{bulk} := C_{total} - C_{in} \qquad C_{bulk} = 4.088 \times 10^{-4}$$



To operate with a LISN and our 1uH inductor with a 0.5V change in Vin to remain in our UV hysteresis window, an additional 410uF for bulk storage is needed.

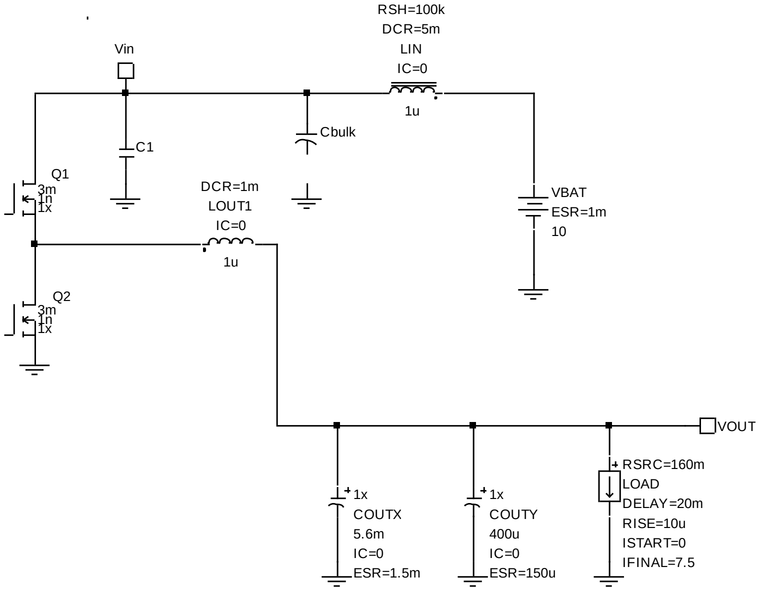
Input Bulk Capacitor Selection - Ideal Buck Converter

- The RMS ripple current in Cbulk is:

$$Cbulk_{ESR} := .035$$

$$Cbulk_{RMS} := \frac{\left(\frac{1}{2\cdot\sqrt{3}}\cdot Vripple_{pp}\right)}{Cbulk_{ESR}}$$

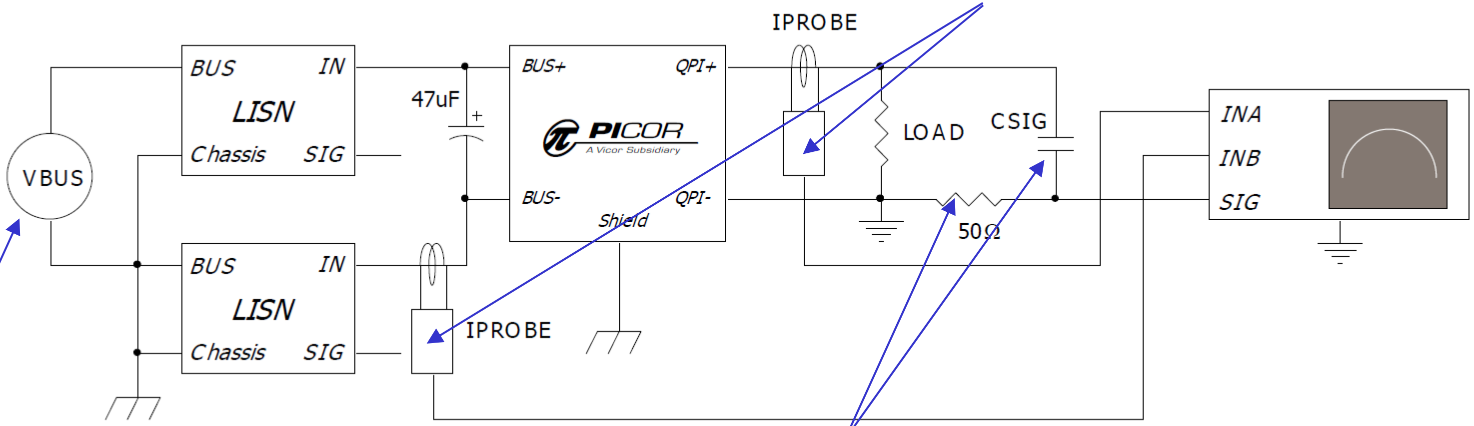
$$Cbulk_{RMS} = 0.619$$



Measuring Insertion Loss Of A Filter

- Consider the EMI filter below. It is both a common mode and differential mode filter.
- First we will look at the differential mode measurement……………

Connect high bandwidth AC current probes to your network analyzer. We are intending to measure the relative loss

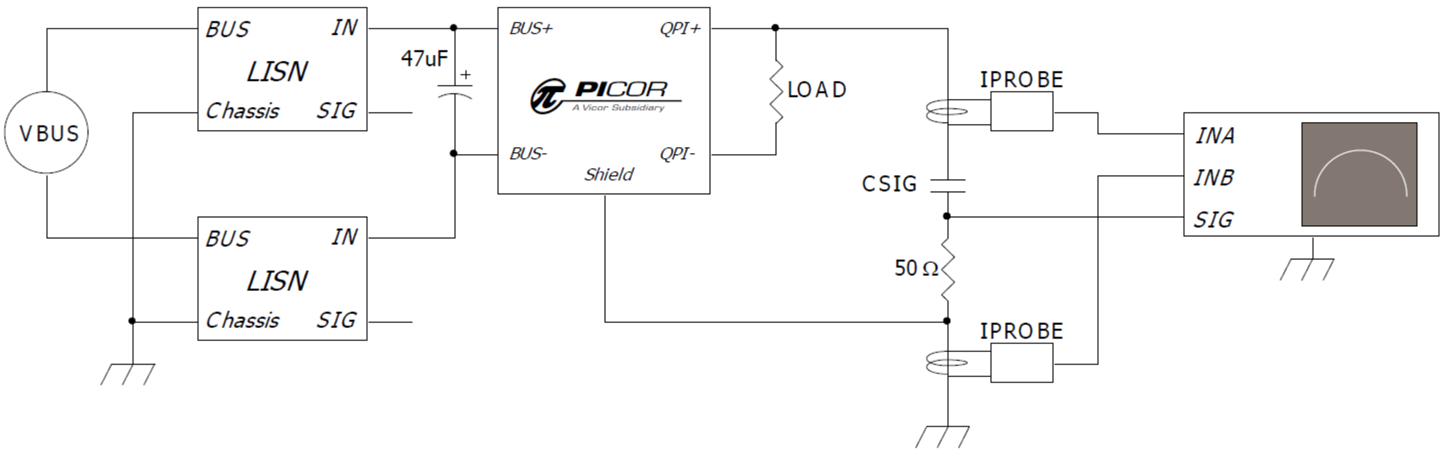


The filter must be DC biased so that the internal capacitors assume the value with bias applied. Ceramic capacitors capacitance value can change with DC bias.

Use a signal injection isolation capacitor to keep DC bias off the network analyzer. Use a 50 Ohm termination resistor as shown.

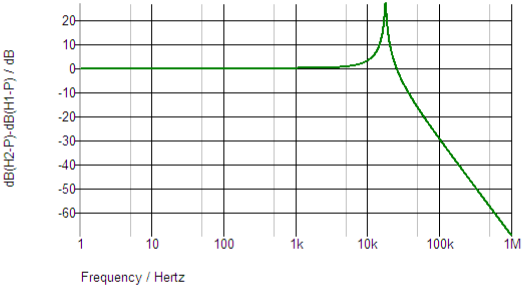
Measuring Insertion Loss Of A Filter

- Next, we will look at how to measure the common mode portion of the filter…………

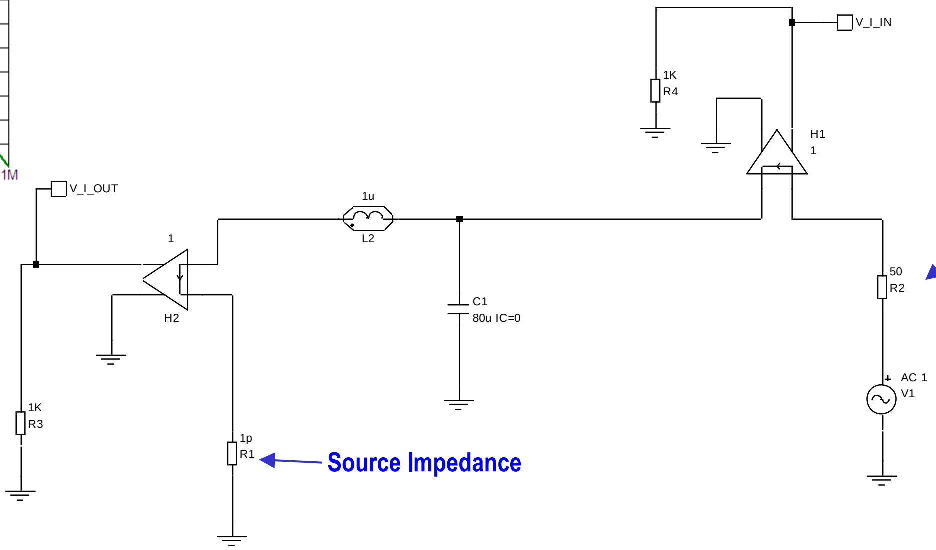


Measuring Insertion Loss Of A Filter

- Let’s measure our LC filter from the Buck Regulator example shown earlier……….

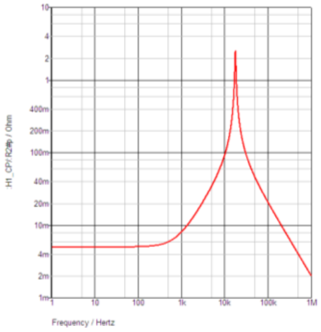


Attenuation



Source Impedance

Input Impedance



Filter Output Impedance

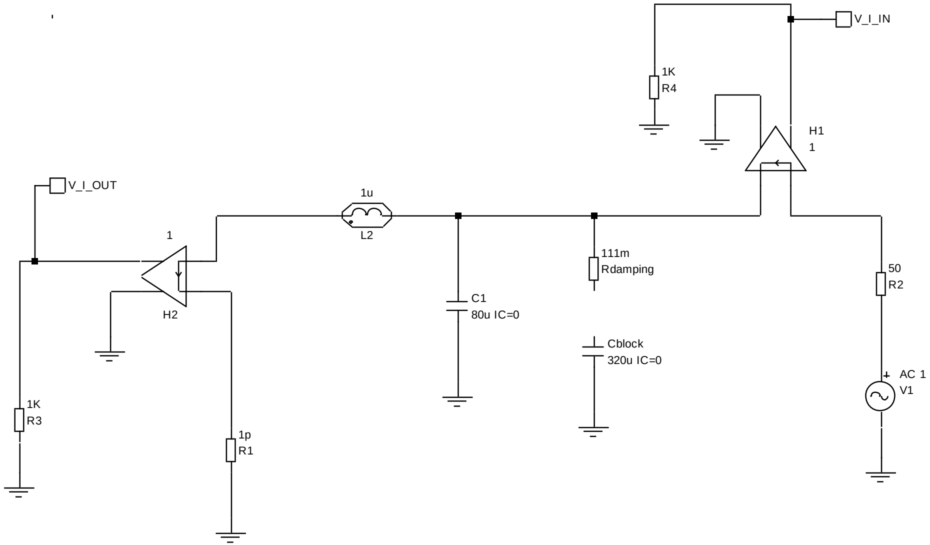
The output impedance of the input filter shows very high peaking at the resonant frequency of the input filter. This filter requires damping to prevent this problem.

Measuring Insertion Loss Of A Filter

- There are several ways to damp an input filter. A robust method is to add a series R-C in parallel with the ceramic capacitors. The idea is that at the resonant frequency of the input filter, the series R of the parallel combination is dominant.

$$C_{block} := 4 \cdot C_{in} \qquad C_{block} = 3.2 \times 10^{-4}$$

$$R_{damping} := \sqrt{\frac{L_{filt}}{C_{in}}} \qquad R_{damping} = 0.112$$

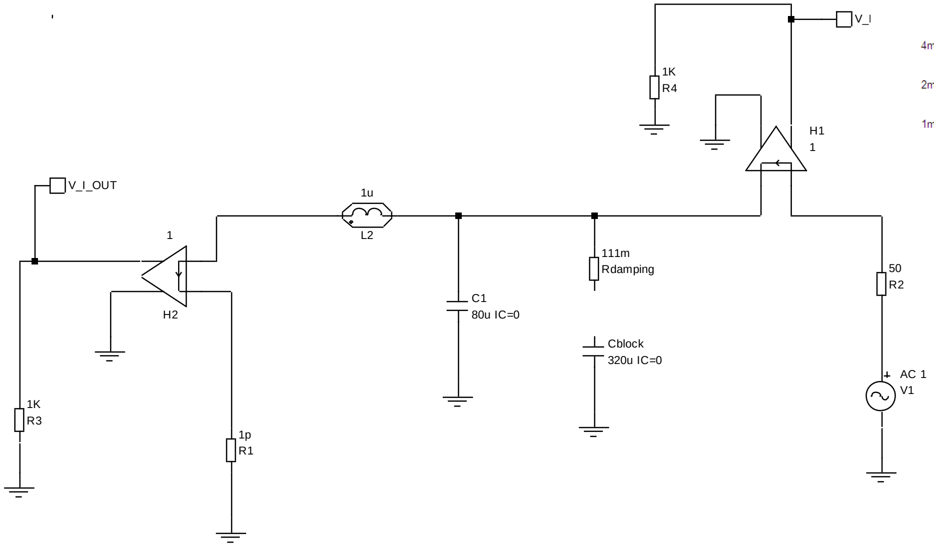


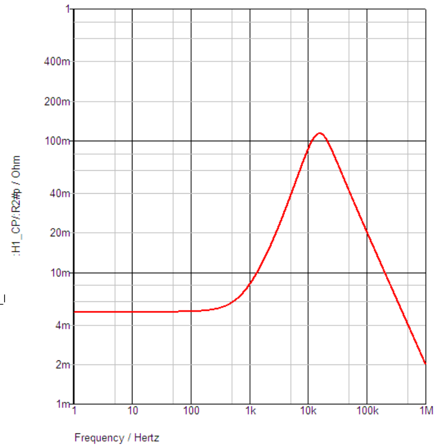
Measuring Insertion Loss Of A Filter

- The damping network

The damping network reduces the impedance peaking very significantly and should improve transient response of the filter

Attenuation

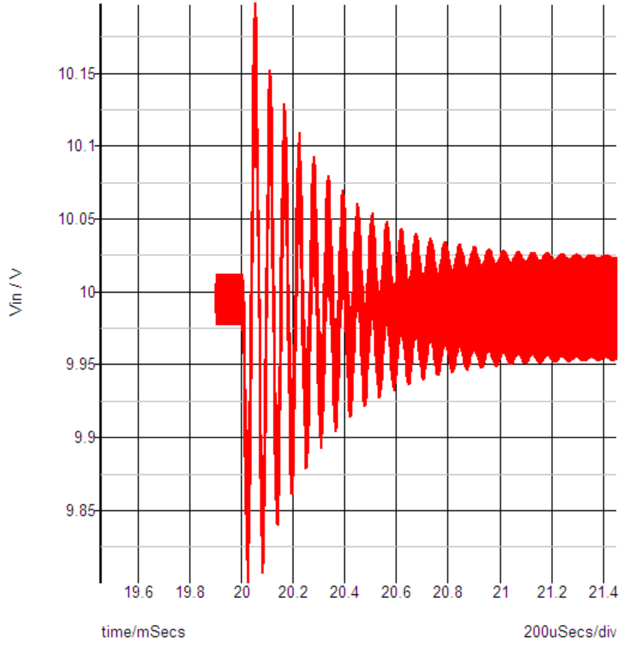




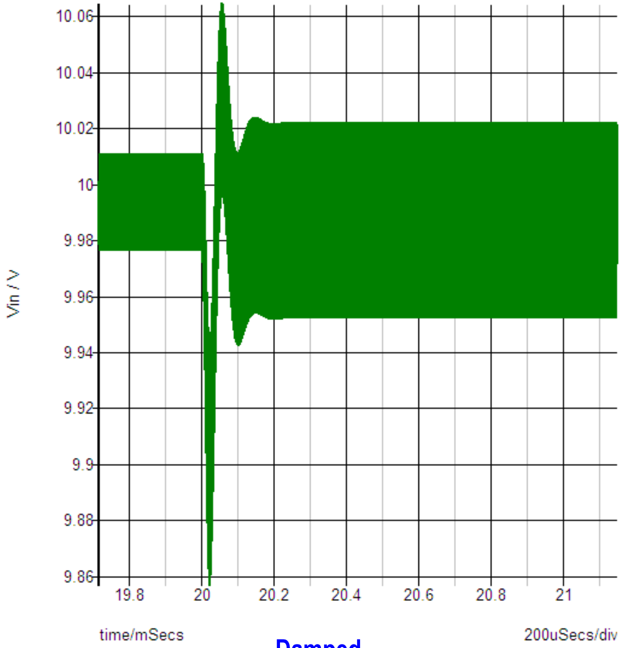
Filter Output Impedance

Measuring Insertion Loss Of A Filter

- The Ideal Buck Model input voltage before damping and after damping transient response



Un-damped



Damped

Avoiding Input Filter Instability – Using A Case History

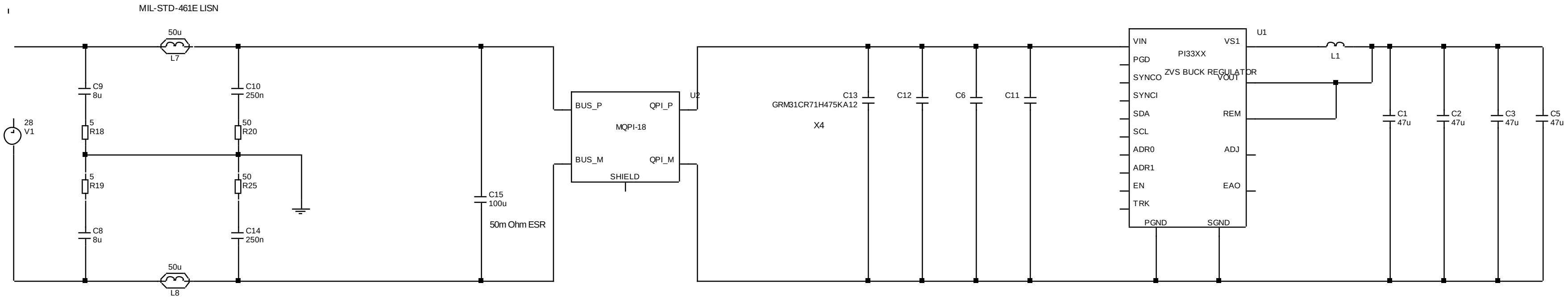
- A closed loop DC-DC converter exhibits a “negative input impedance”. This means that due to the internal feedback loop and voltage feed forward circuitry, as the input voltage goes up, the input current goes down.
- A DC-DC converters input impedance is lowest at low line and highest at high line. The input impedance can be approximated by (for our Ideal Buck Regulator)

$$RIN_{min} := \frac{Vin_{min}}{\left[\frac{\left(\frac{V_{out} \cdot I_{outmax}}{\eta}\right)}{Vin_{min}}\right]} \qquad RIN_{min} = 5$$

- This means that if the output impedance of the input filter is 5 Ohms, we now have created a negative resistance oscillator.
- The onset of this instability is manifested by a sinusoidal input current and voltage oscillation that will perturb the output and create all sorts of havoc, including overshoots and possible damage.

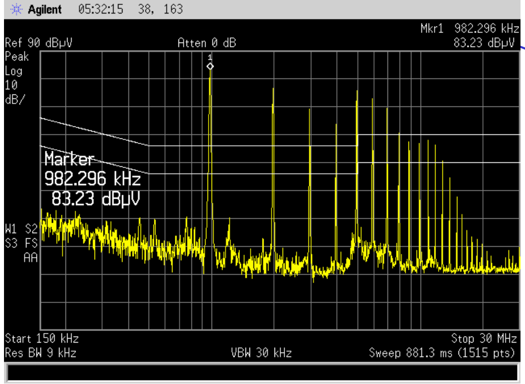
Avoiding Input Filter Instability – Using A Case History

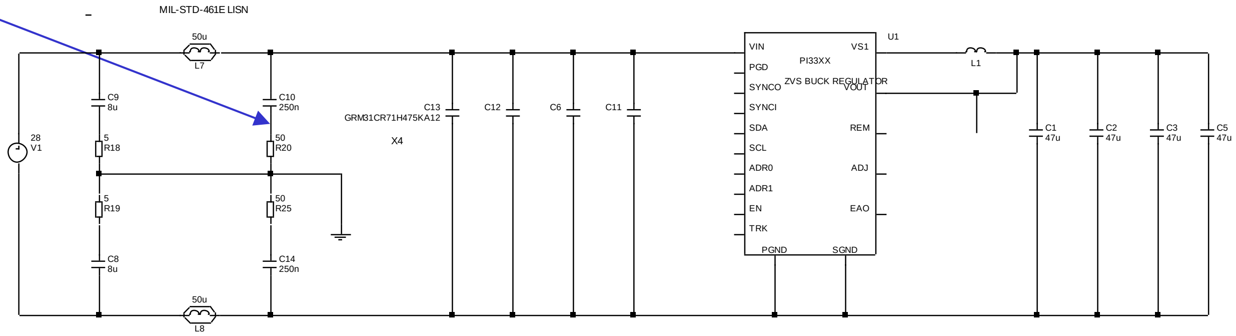
- A military customer of ours designed in our ZVS Buck Regulator (PI3302) and our MQPI-18 EMI Filter module
- The filter module is ultra small and can handle 7A. It provides both common mode and differential attenuation. The customer did not need the common mode section but chose the filter because of it's size and high frequency performance. The ZVS Buck regulator switches at 1 MHz



Avoiding Input Filter Instability – Using A Case History

- First, the customer measured the raw EMI signature without any filter and saw very high EMI as expected.





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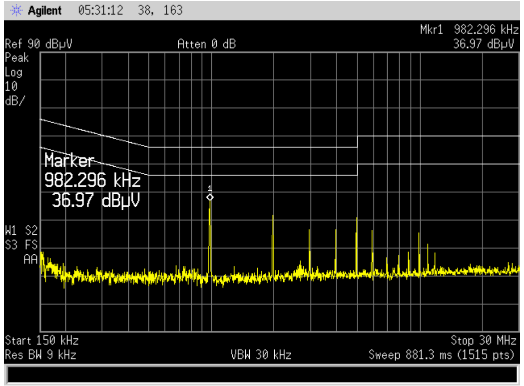
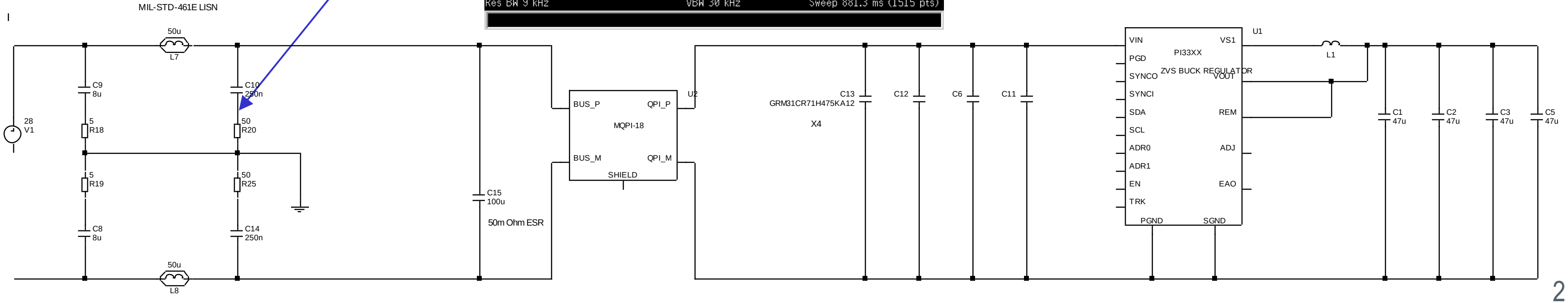
Avoiding Input Filter Instability – Using A Case History

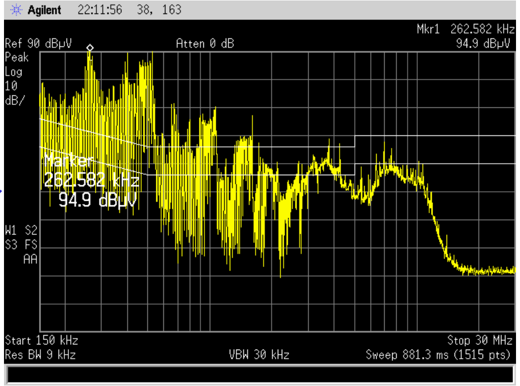
- Next, the customer installed the MQPI-18 filter measured the EMI signature again. He was thrilled until………..

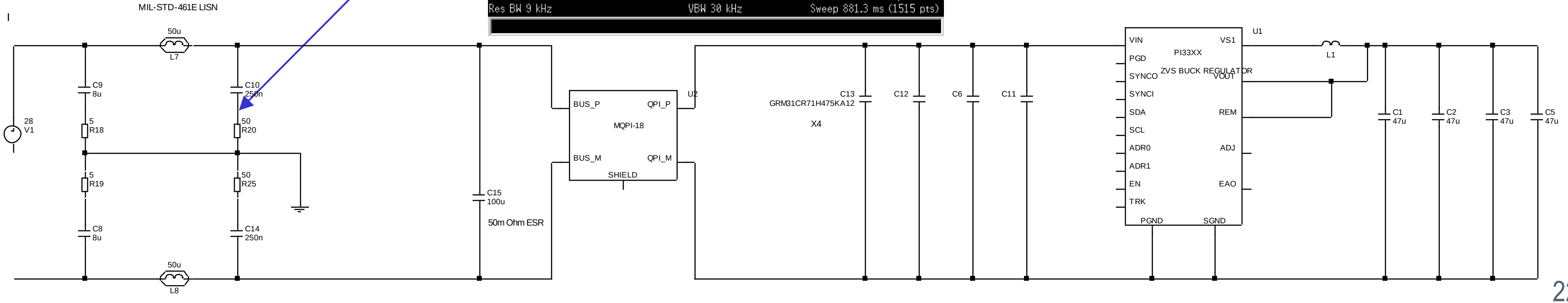




Avoiding Input Filter Instability – Using A Case History

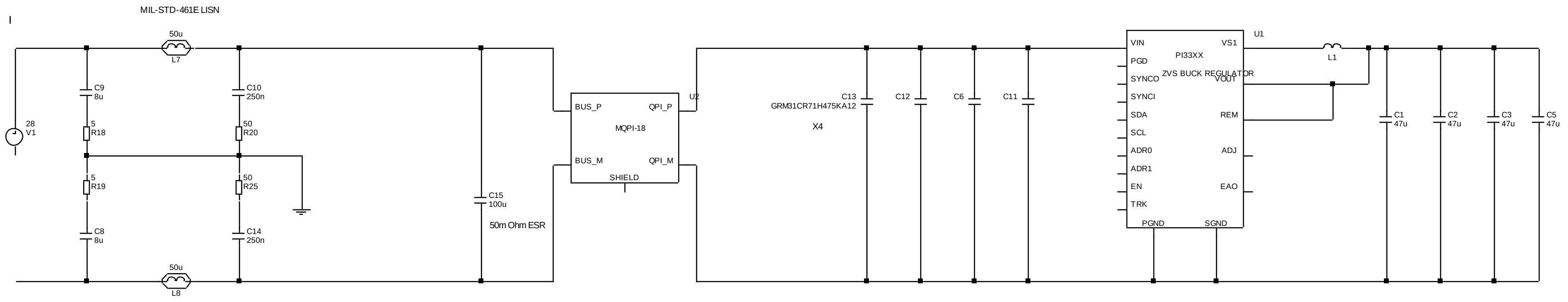
- He started to vary the line voltage. As he got to about 9.8V, the EMI plot went horrific. That's when my phone started ringing, I think.



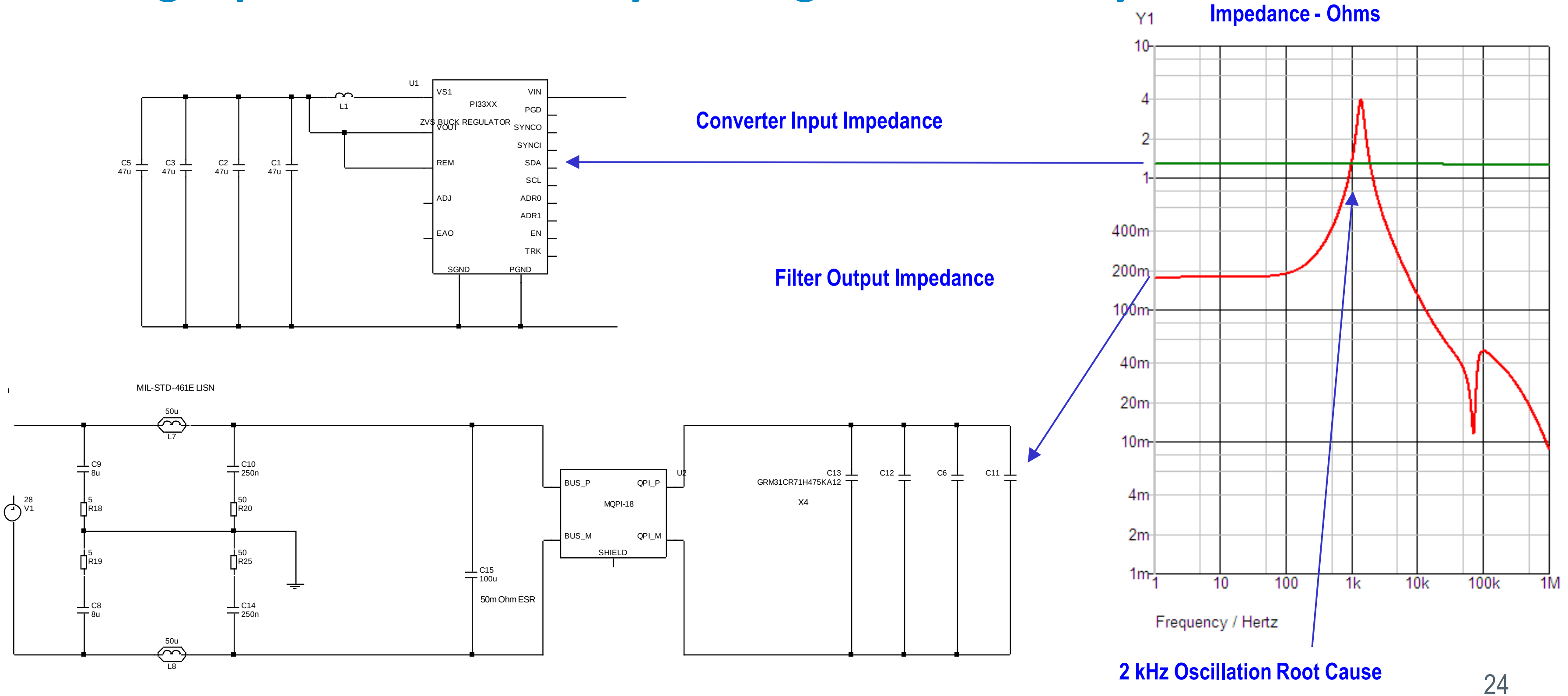


Avoiding Input Filter Instability – Using A Case History

- A current probe was connected to the LISN output cables. It revealed a very rich high current 2kHz sine wave. The input voltage to the converter was ringing below the UV lockout, causing the converter to turn on and off every 30ms. This resulted in the poor EMI plot, as the converter was oscillating on and off.

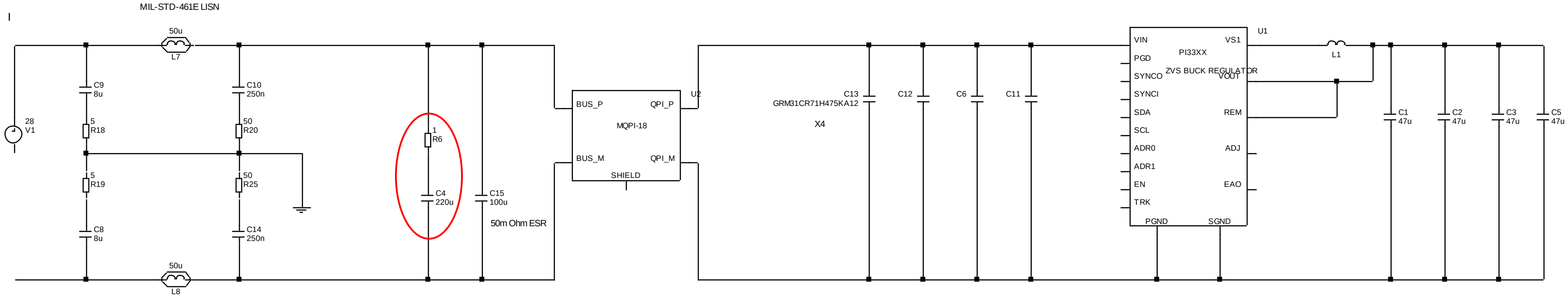


Avoiding Input Filter Instability – Using A Case History

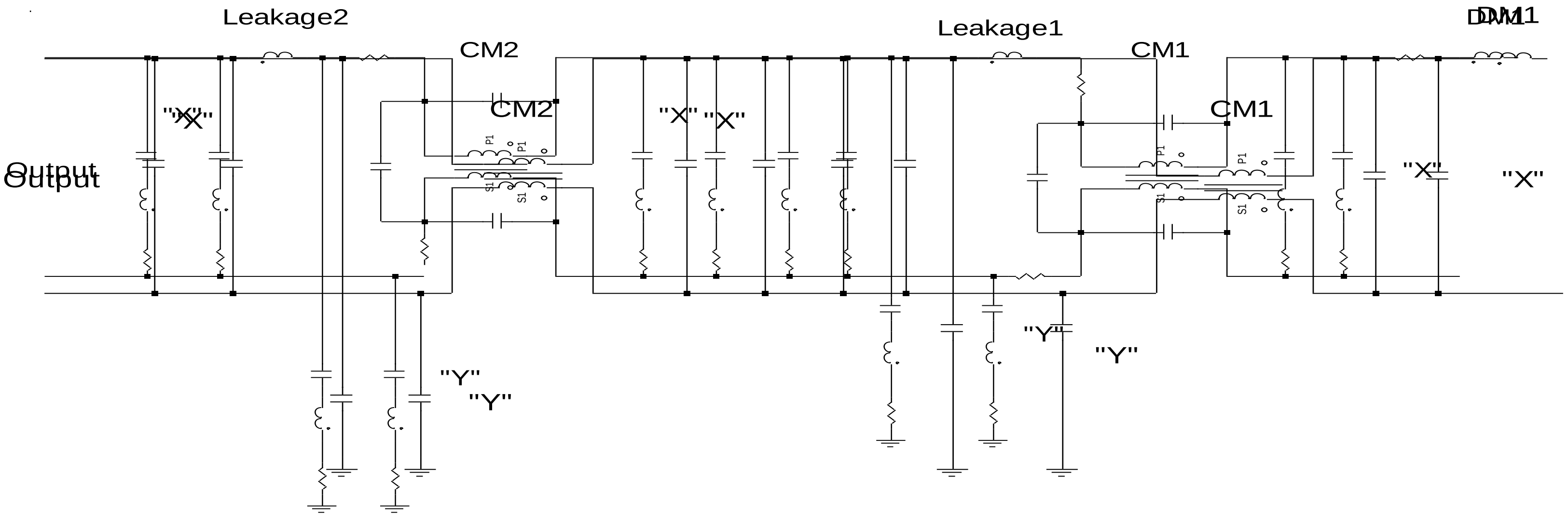


Avoiding Input Filter Instability – Using A Case History

- The root cause of the instability was the LISN resonating with the ceramic capacitors inside the MQPI-18 filter and the PI3302 input capacitors. The resonant frequency of 2kHz was responsible for the input filter instability at low line. Adding a series R-C in parallel with the entry port provided the necessary damping of the LISN and eliminated the instability. Taking a page out of the late great Johnnie Cochrane’s book, “You must design with the LISN in mind!”



Passive Discrete EMI Filter Example



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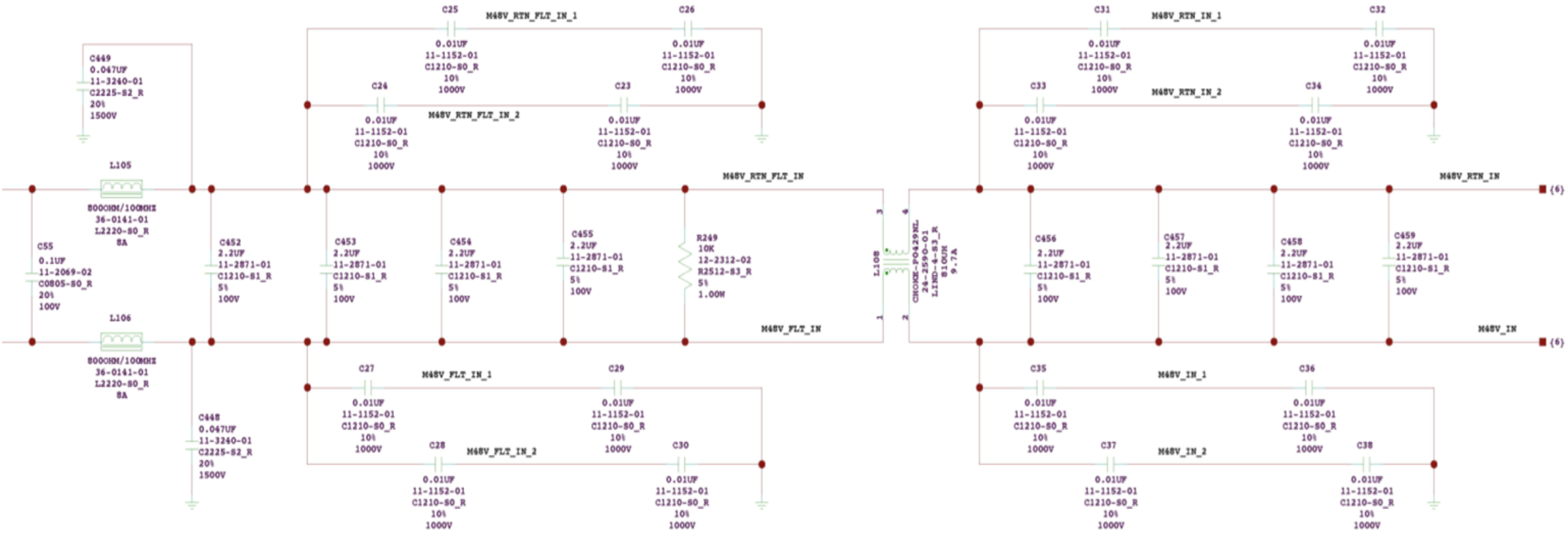
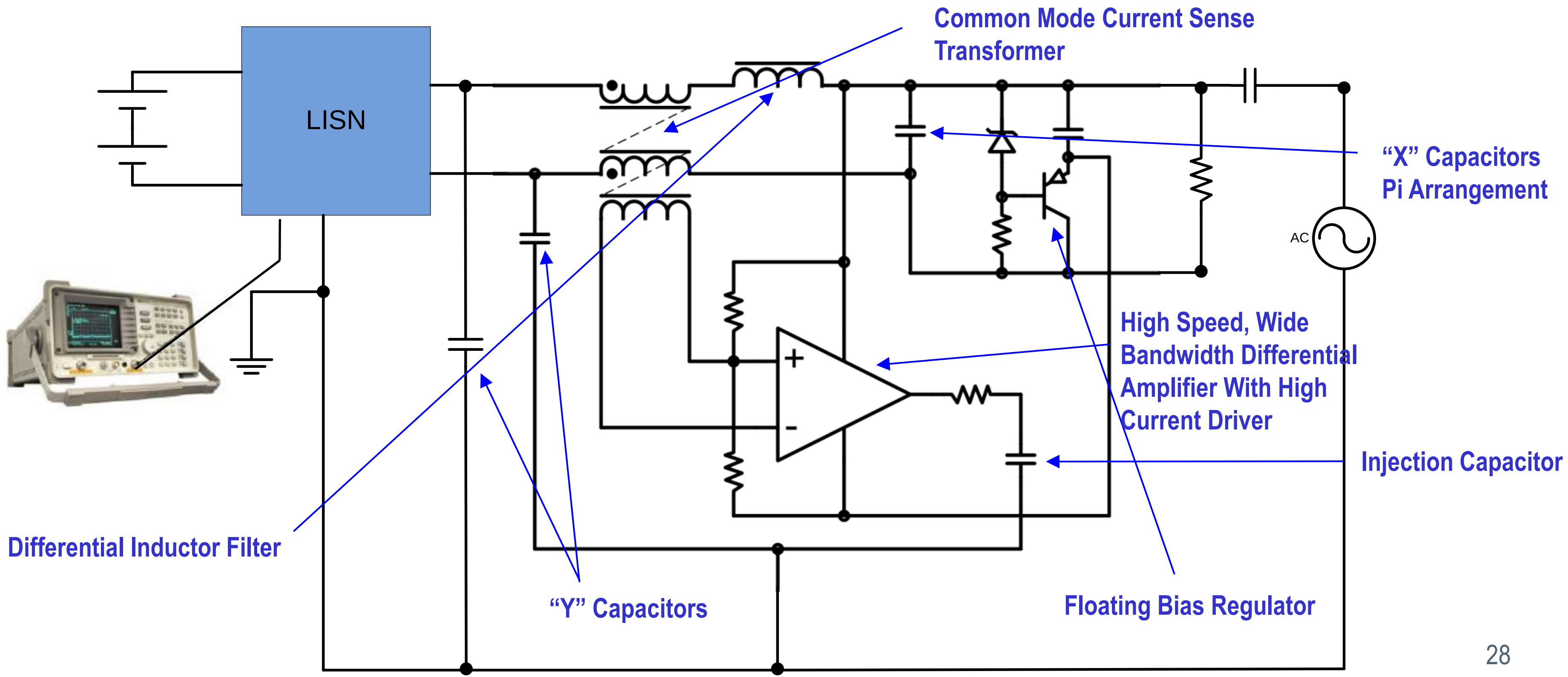
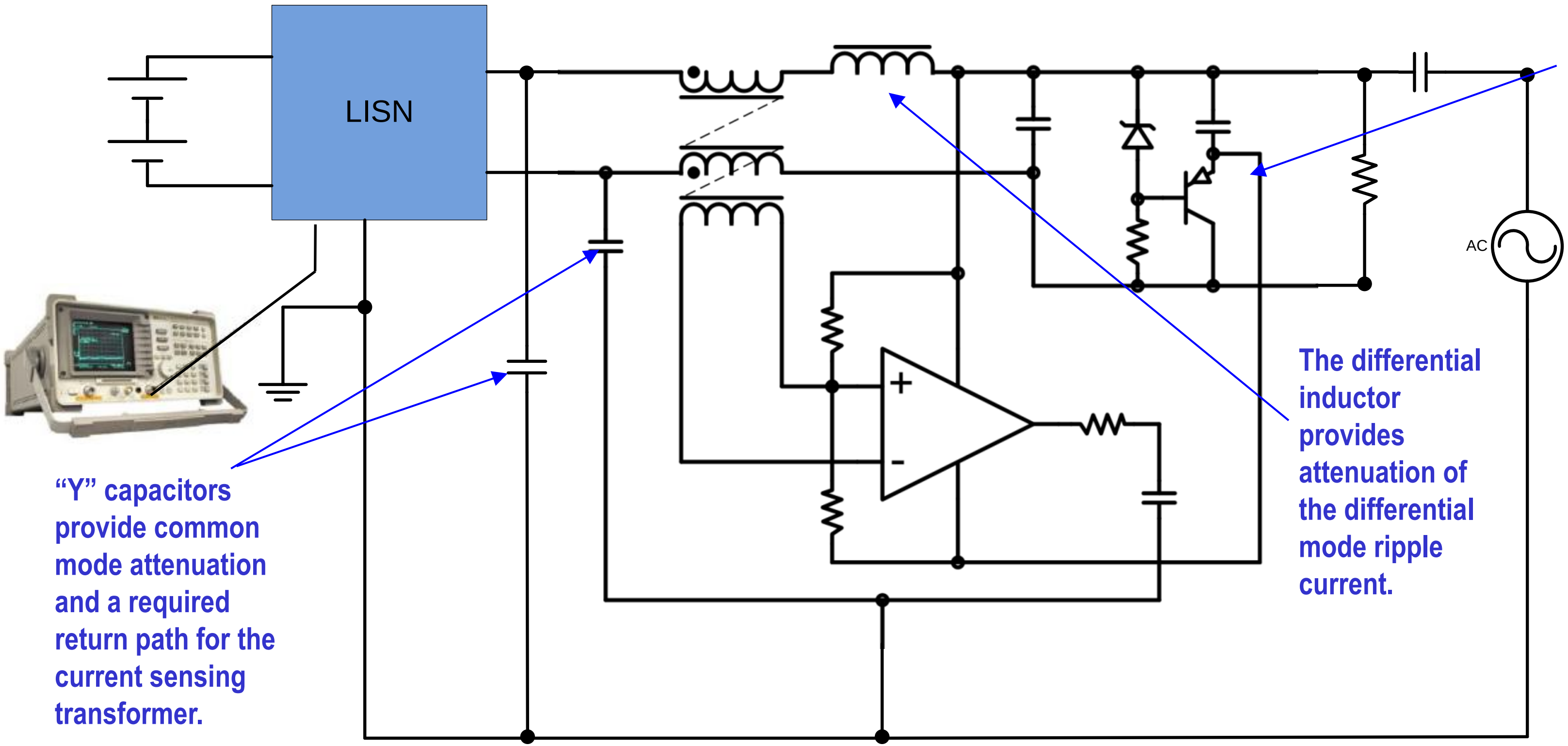
9 Amp Passive Filter Example Schematic



The Picor QPI-21 Active EMI Filter Topology Simplified Block Diagram



The Picor QPI-21 Active EMI Filter Topology Simplified Block Diagram

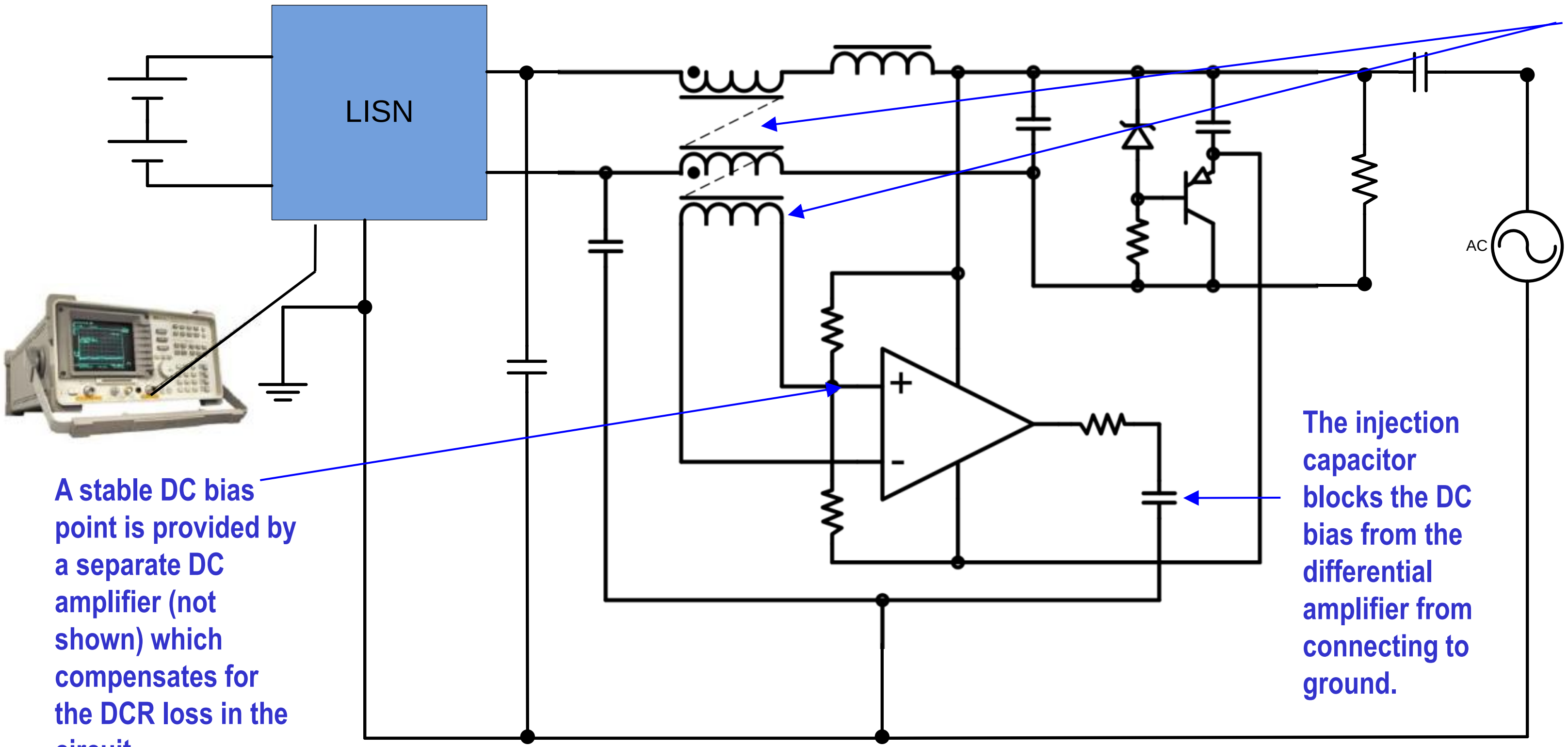


"Y" capacitors provide common mode attenuation and a required return path for the current sensing transformer.

The differential inductor provides attenuation of the differential mode ripple current.

The floating bias supply provides bias power for the high speed OPAMP, so it can either source or sink high current as required to reduce the common mode noise.

The Picor QPI-21 Active EMI Filter Topology Simplified Block Diagram

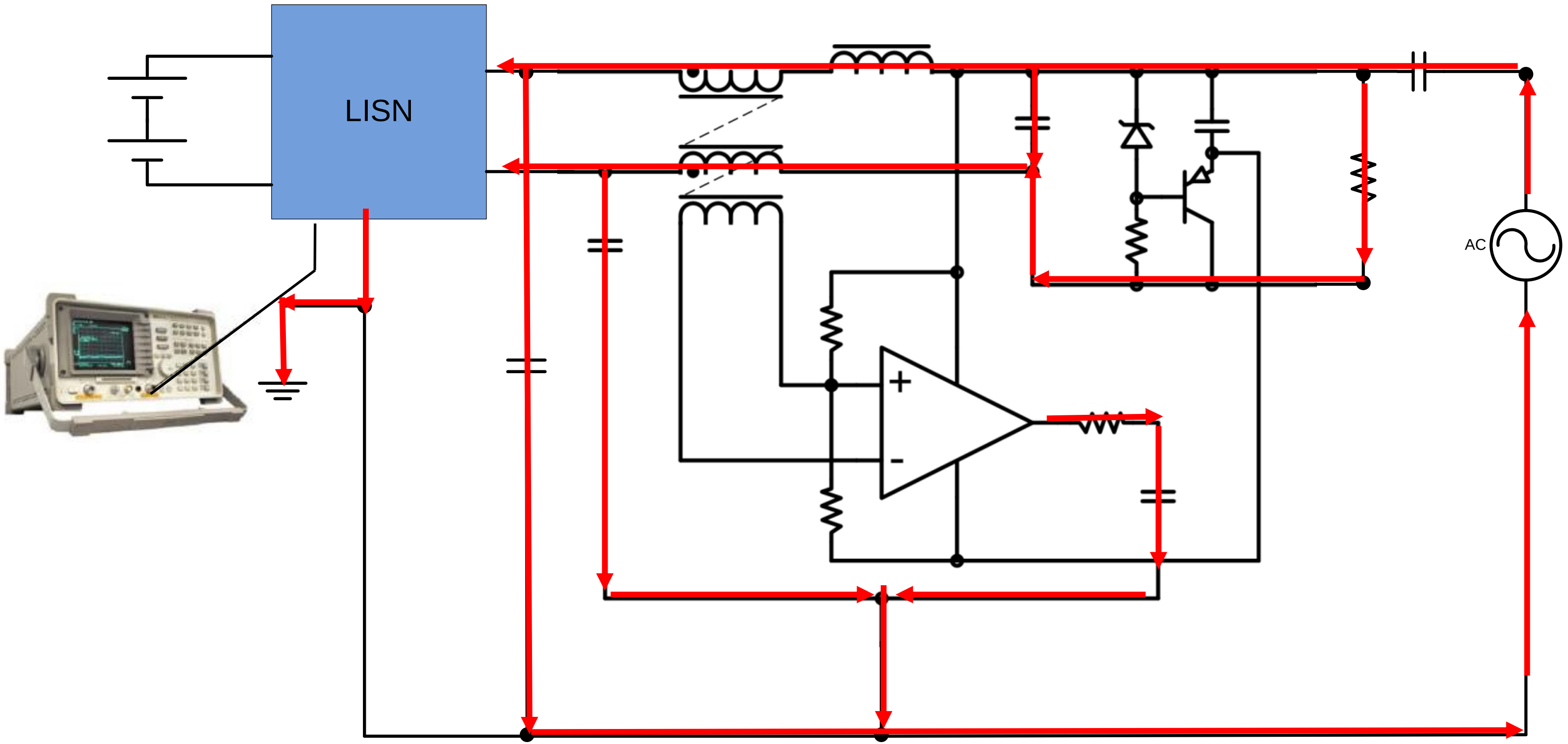


A stable DC bias point is provided by a separate DC amplifier (not shown) which compensates for the DCR loss in the circuit.

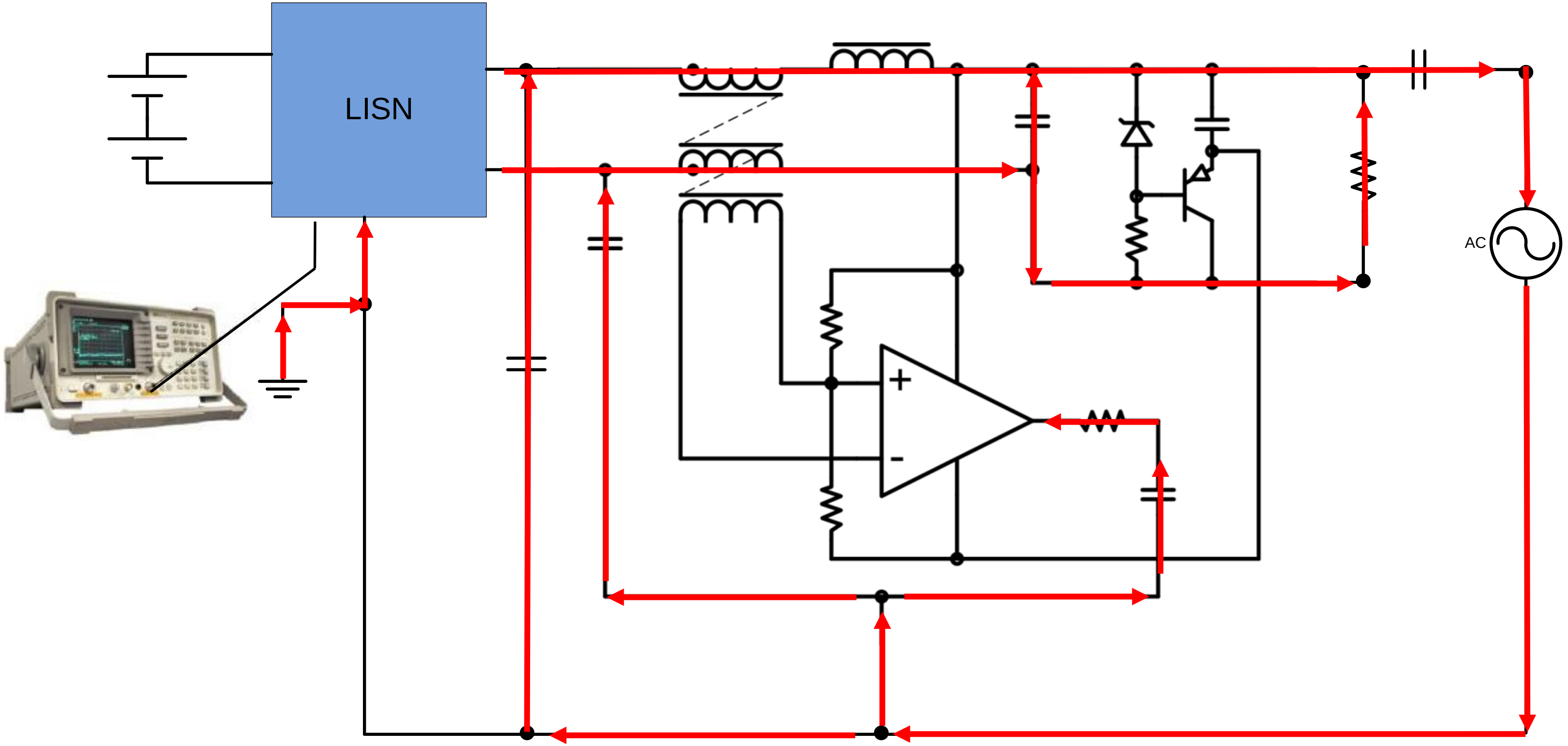
The injection capacitor blocks the DC bias from the differential amplifier from connecting to ground.

The common mode inductor with current sense winding can be very small (2uH) made with single turn windings and a multiple turn current sense winding. It separates DM from CM and applies common mode current sense to the differential amplifier.

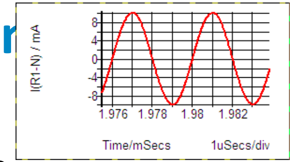
The Picor QPI-21 Active EMI Filter Topology Simplified Operation

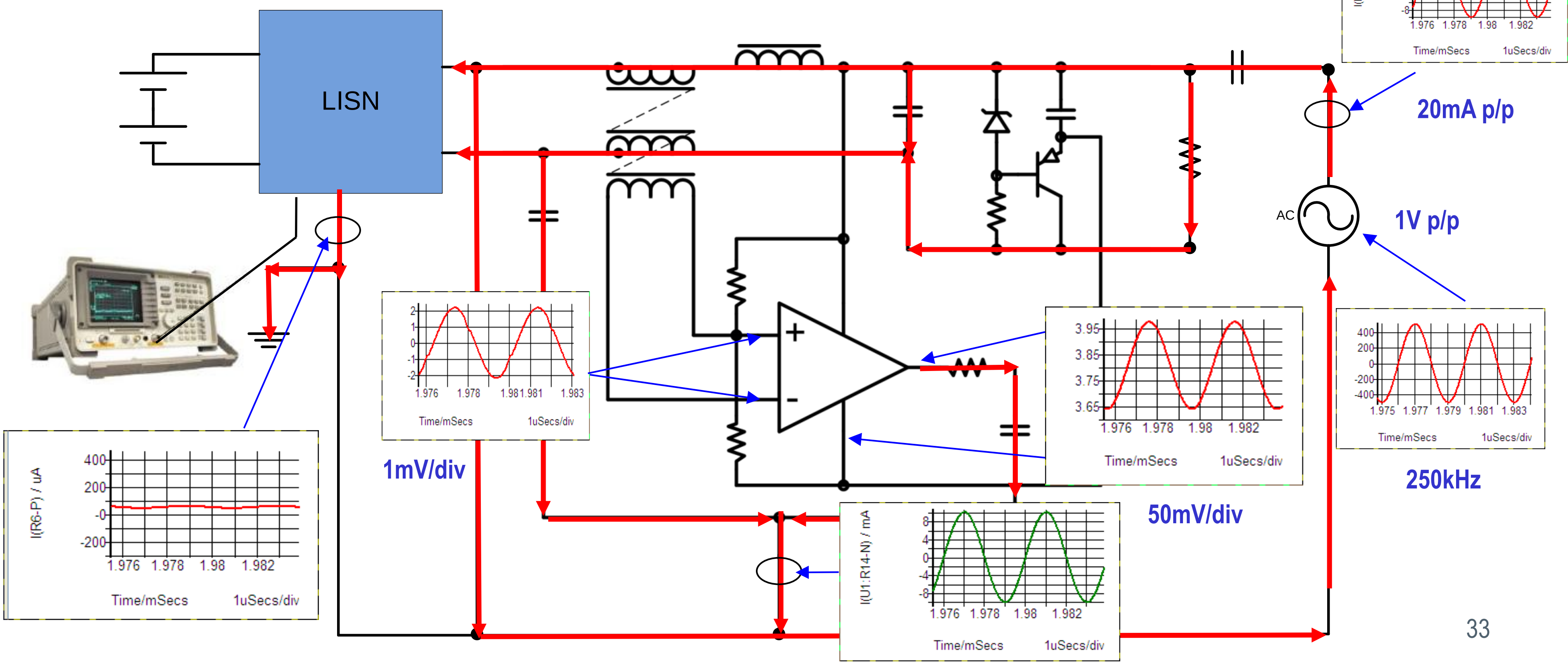


The Picor QPI-21 Active EMI Filter Topology Simplified Operation



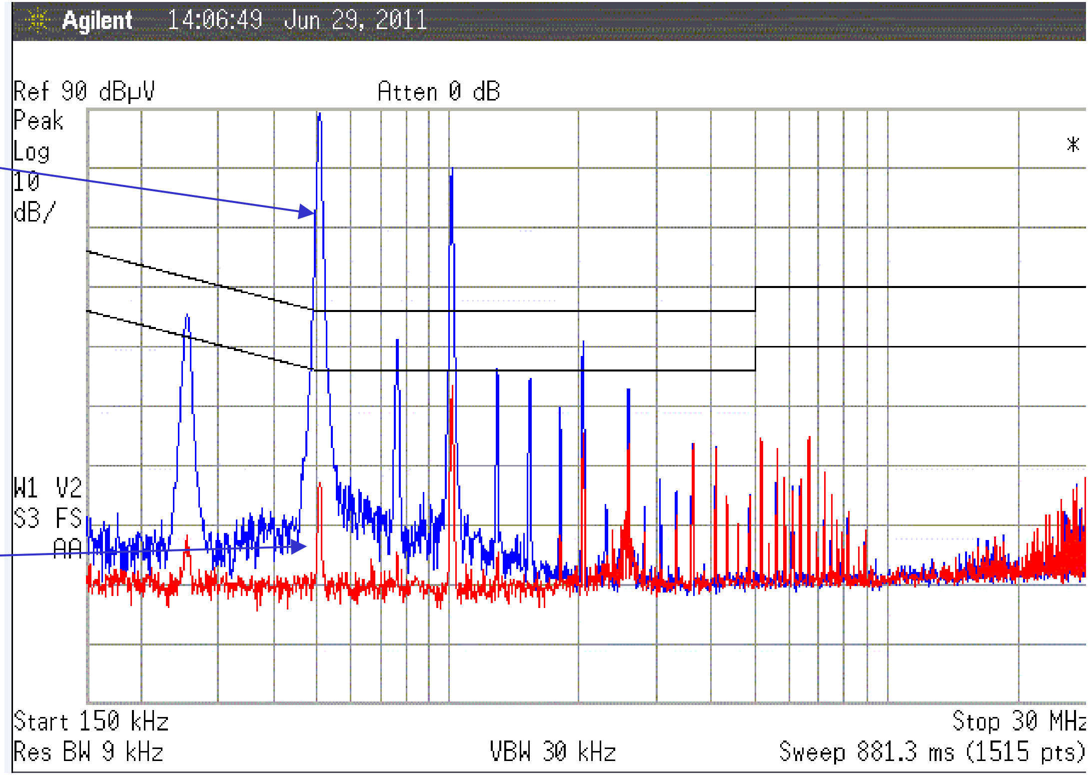
The Picor QPI-21 Active EMI Filter Topology Simplified Operation





QPI-21 EMI Performance With And Without Active Loop

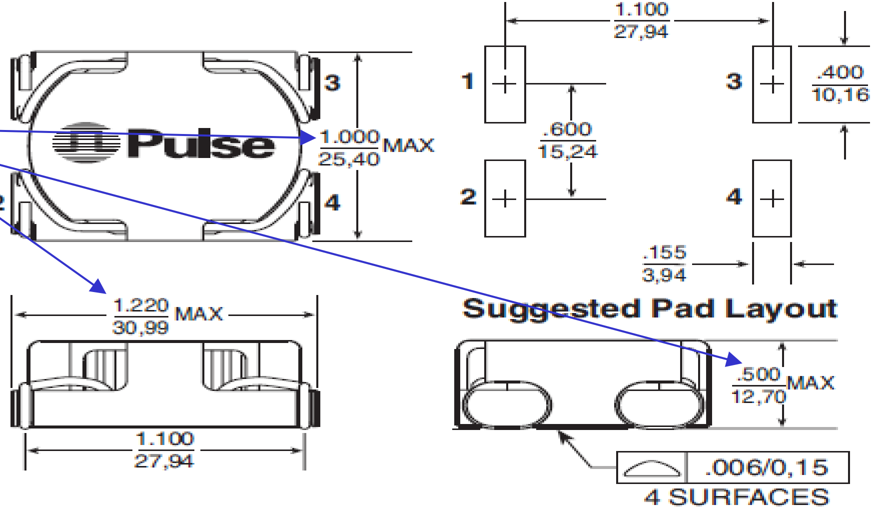
Active amplifier loop disabled



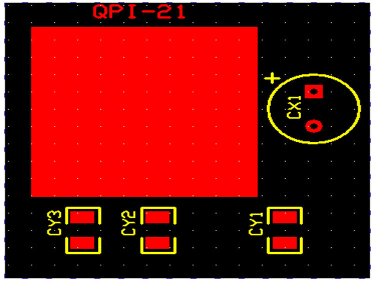
Active amplifier loop enabled

9 Amp Common Mode Filter Footprint

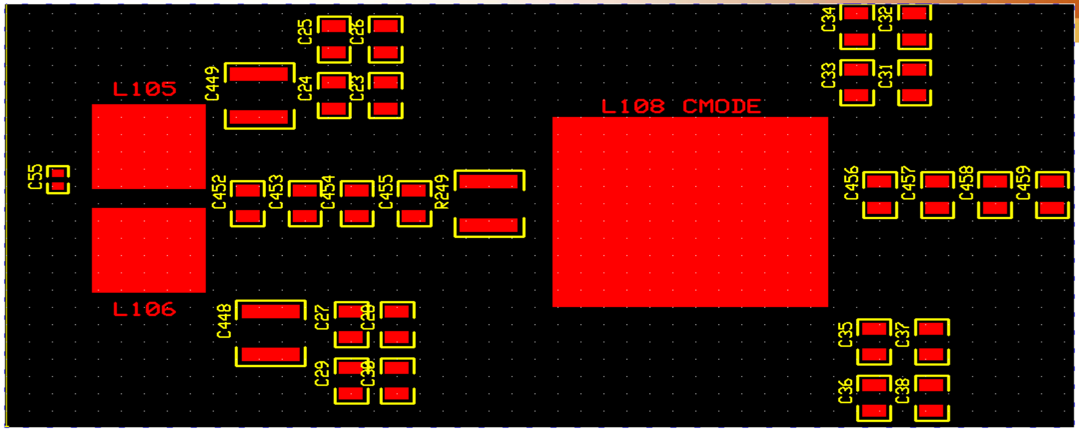
PCB area for a 9 Amp common mode inductor is longer and wider than the 14A QPI-21 filter, which contains both differential and common mode circuitry. In addition, the 9A common mode inductor is twice as high as the QPI-21.



Active Filter Example



QPI-21

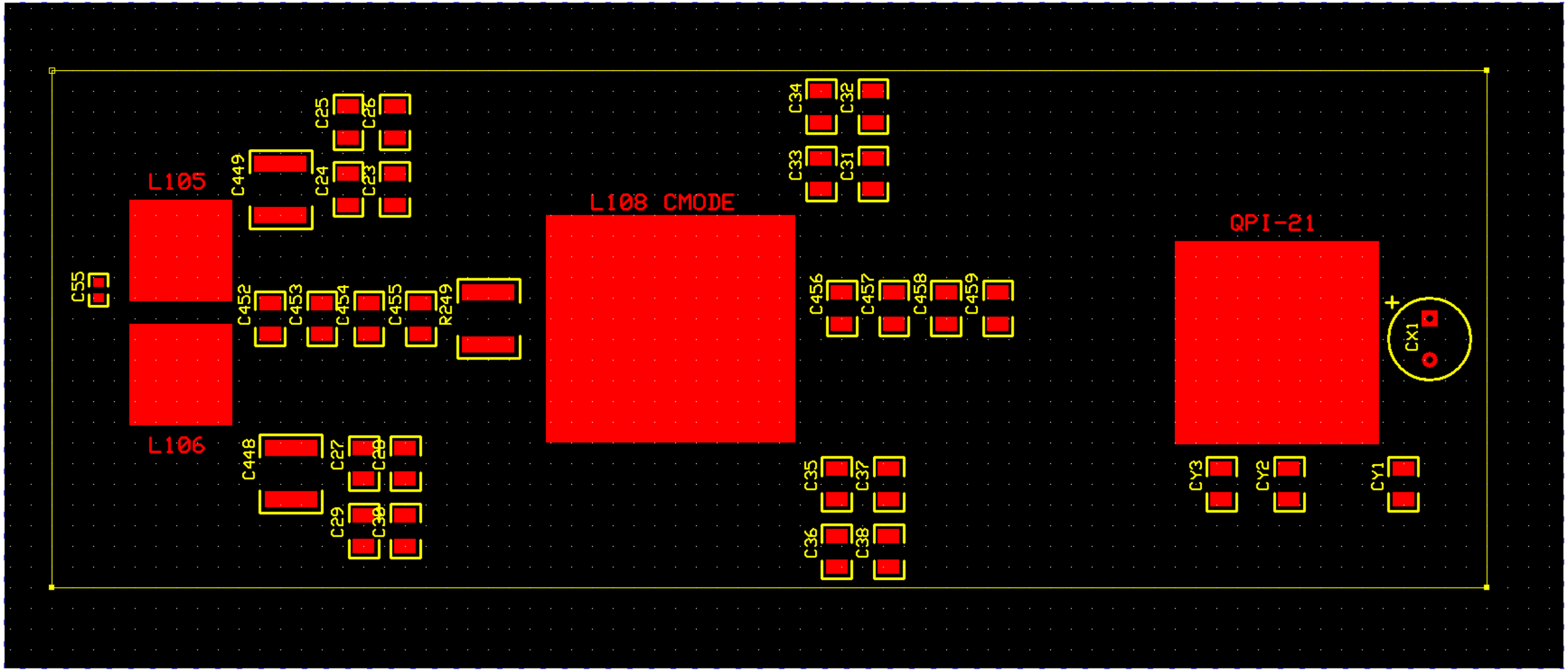


- 2.3W dissipation round trip @ 14A!
- Much smaller loop area, lower susceptibility
- EMI performance is less dependent on layout and magnetic components parasitics
- Critical layout is inside SiP and already done
- No derating until 65 degree ambient @ 14A
- EMI performance equivalent to two stage passive solution

Passive Solution

- 3.5W dissipation round trip @ 9A
- Large loop area
- Layout and magnetics quality are critical to high frequency performance
- Multiple winding chokes have higher parasitic capacitance, which tends to limit attenuation
- Many more “Y” capacitors are required
- Solution grows significantly for a higher current

Side By Side On The Same PCB!

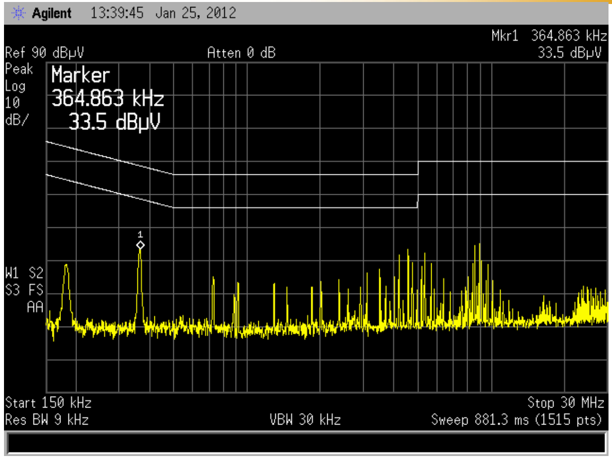


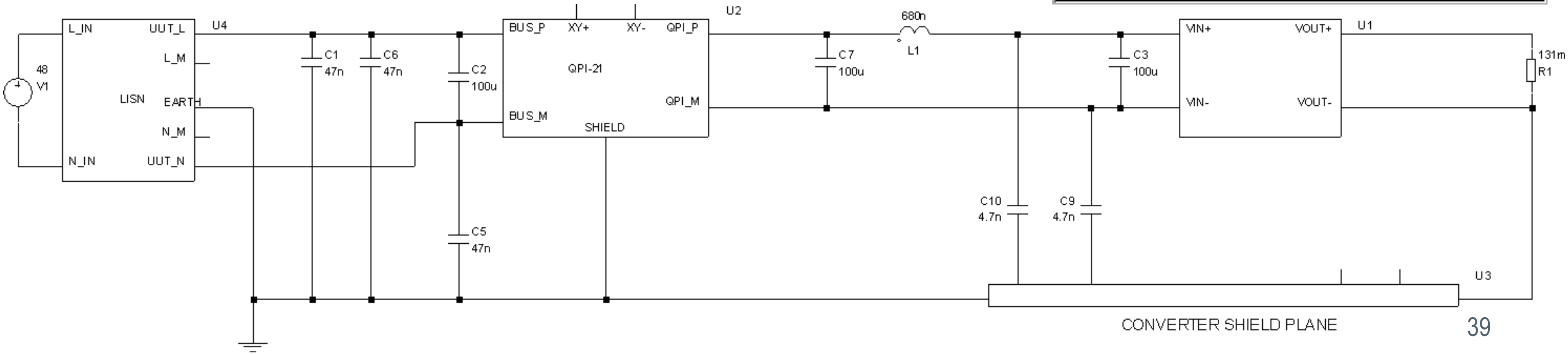
What To Do When Things Don’t Go Right With EMI

- Remember my golden rule: Theory and practice MUST match. This will help your thought process when you get frustrated.
- Buy some good diagnostic tools like noise separation filters, a near field probe (these can be made fairly easily), an old analog scope (perfect for EMI)
- Don’t be afraid to experiment.
- Call Picor
- The next few slides will explain why troubleshooting EMI can be fun and challenging, despite what your manager thinks!

What To Do When Things Don't Go Right With EMI

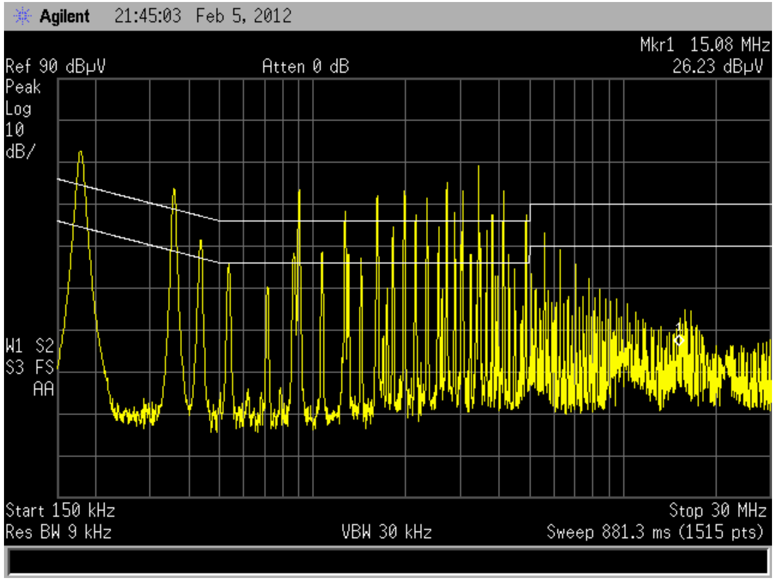
- We were asked to test our QPI-21 Active Filter with a certain 200W power supply for a top customer to design into his high end system. The full load performance was outstanding.





What To Do When Things Don't Go Right With EMI

- After the customer designed our filter into his system, he sent me the system stating he measured an EMI plot like that shown below at very light load. It is failing Class A by almost 20 dB!!

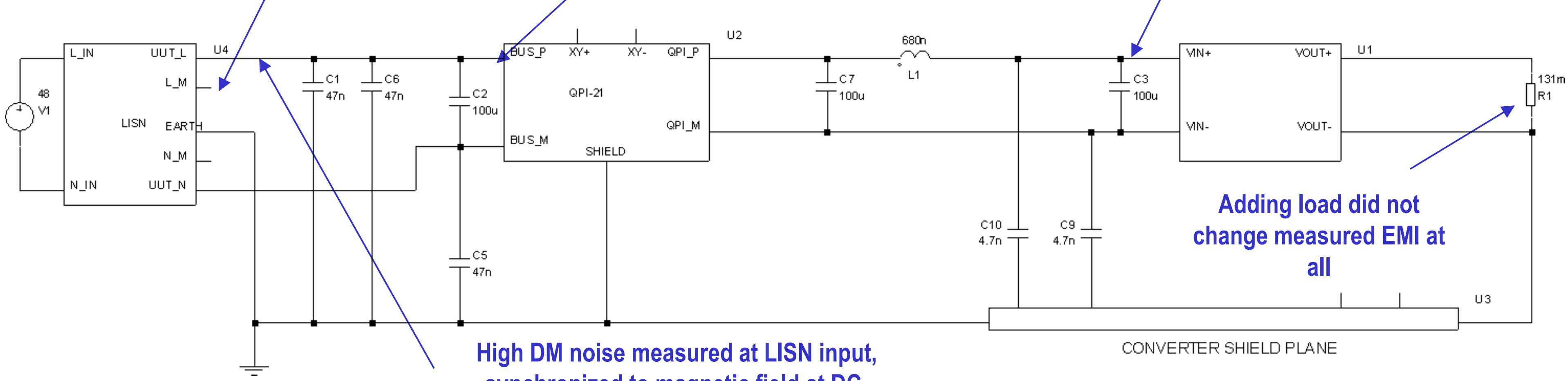


What To Do When Things Don't Go Right With EMI

Noise separator indicated DM noise, removing LISN ground had no effect

Adding current probe here showed virtually no noise current leaving QPI-21.

Ripple voltage was very low here, did not match EMI noise level

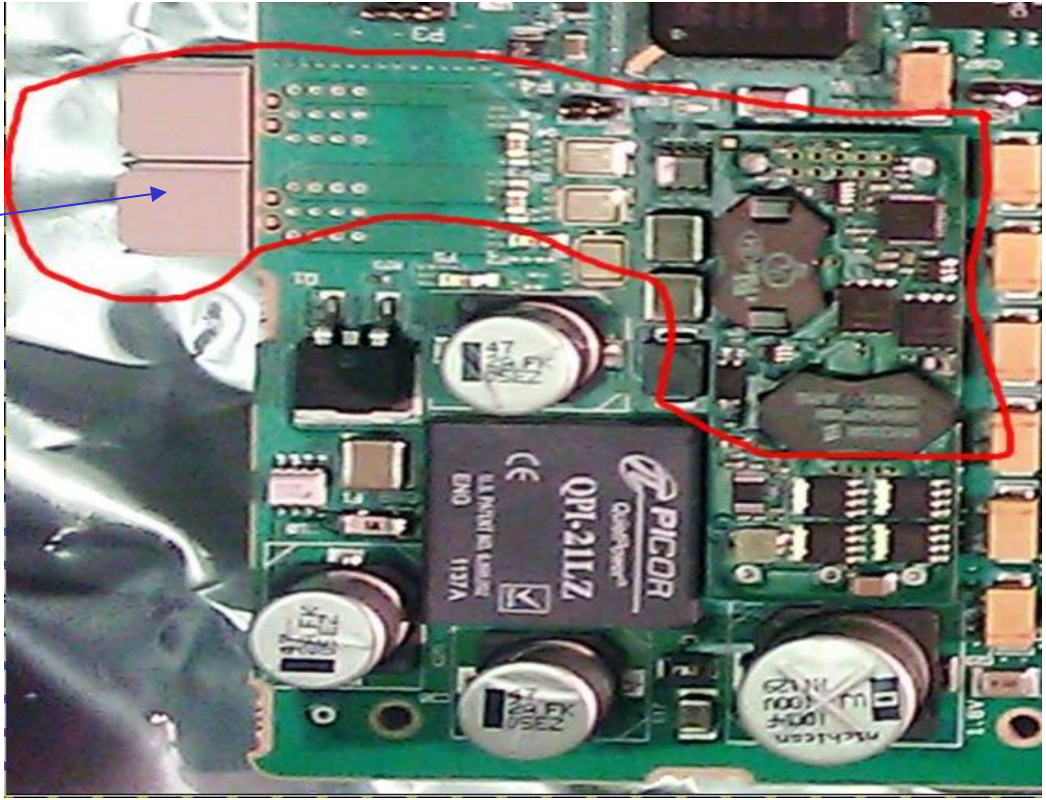


Adding load did not change measured EMI at all

High DM noise measured at LISN input, synchronized to magnetic field at DC-DC using near field probe

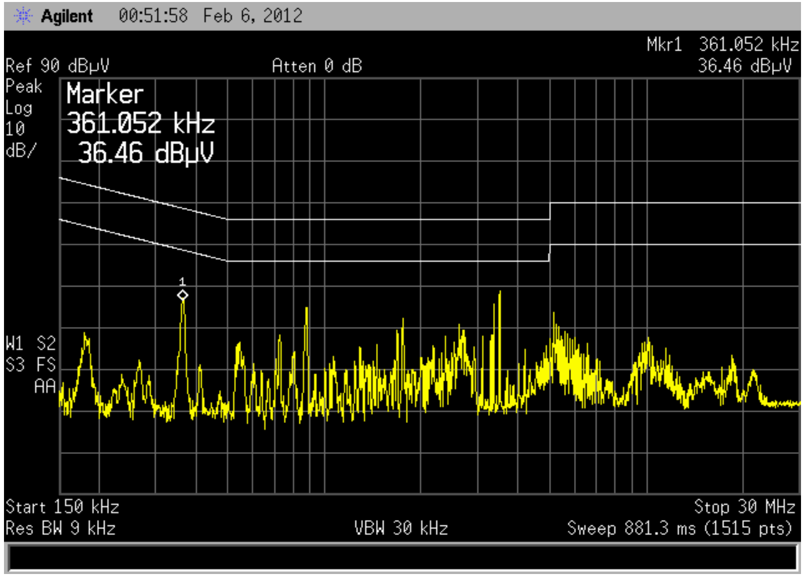
What To Do When Things Don't Go Right With EMI

Power Input



What To Do When Things Don't Go Right With EMI

Moved Location



Result

What To Do When Things Don't Go Right With EMI Final Thoughts

- Always try to make sure that the EMI filter is the closest component to the power entry ports. It is very easy to create a sneak path due to stray magnetic fields that will bypass the filter.
- Trust your measurements. EMI proficiency is not magic. Most conducted noise problems are measureable and traceable to a source.
- Try to design for EMI compliance up front. It becomes very difficult to move components around on a dense layout.

VICOR

In Summary………….

- A method was presented to design the correct amount of input capacitance for a typical Buck regulator and conf the results were confirmed using circuit simulation methods. We discussed the measurement of insertion loss and filter impedances. A method to damp the input filter of a Buck regulator was also discussed.
- A case history was presented to illustrate the problem of input filter stability and how to correct it.
- A passive common mode and differential mode filter was presented.
- The Picor QPI-21 Active Filter Topology was presented with circuit simulation and theory of operation.
- Finally, a case history illustrating how to troubleshoot an EMI problem was discussed.

Acknowledgements

- The following material was used as references in the presentation of this seminar:
  - EE Times 9/7/2007; Choosing the right input caps for your buck converter; Chris Cooper, Avnet Electronics
  - Fundamentals Of Power Electronics Second Edition; R. W. Erickson/Dragon Maksimovic