# The Causes and Impact of EMI in Power Systems; Part 1

**Chris Swartz** *Principal Applications Engineer*

# Agenda

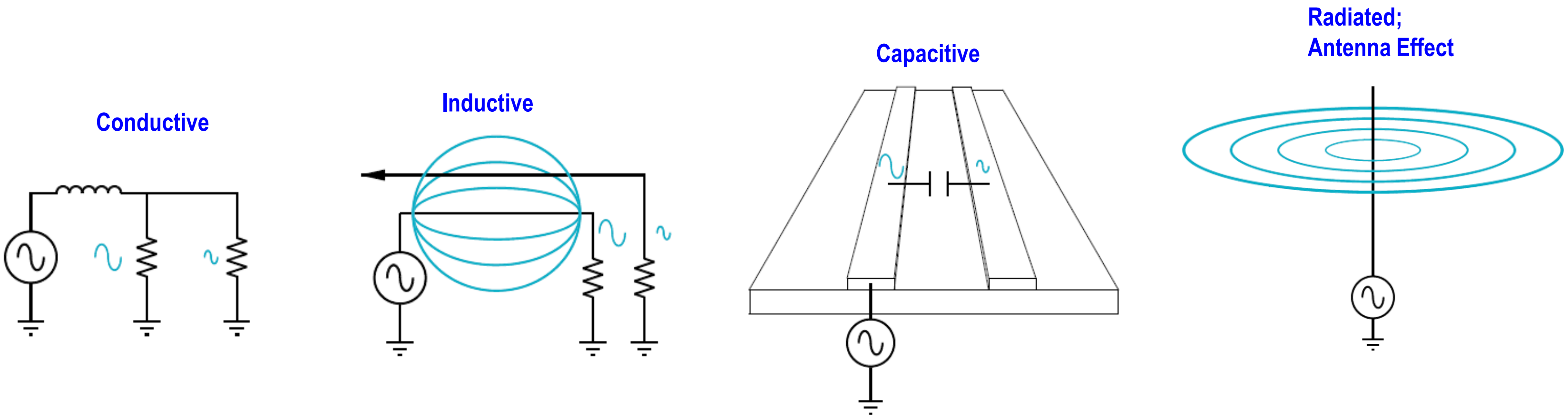
- Welcome and thank you for attending. Today I hope I can provide a overall better understanding of the origin of conducted EMI in power systems. The topics we will cover in Part 1 of our two part series will be:
  - The definition of conducted EMI to include types, categories, coupling mechanisms and measurement standards for ITE type equipment
  - I will discuss how conducted EMI is measured, test setups, measuring methods and the line impedance stabilization network
  - The origin and characterization of differential mode EMI using a simulated Buck converter and a real world isolated DC-DC converter
  - Common mode noise origins, paths and characterization using a simulation model of an isolated Full Bridge converter
  - Finally, I hope to provide some tips on converter selection to help achieve lower EMI in your power system

# What Is EMI?

- EMI stands for "Electromagnetic Interference" and it has been used to describe many different types of noise phenomena observed in modern power electronic systems in use today.
- The term "interference" is used somewhat loosely today. Interference means that one piece of equipments actual operation is disrupted by either another piece of equipment or an external signal source. Actual interference is not usually implied by the term EMI unless describing a prevention device, method or test.
- The two basic types of EMI are:
  - Radiated EMI; measured in the far field using antennas
  - Conducted EMI; measured at the power entry port using a line impedance stabilization network (LISN)
- There are two general categories of Conducted EMI (the focus of this seminar):
  - Differential Mode Noise (sometimes referred to as Normal Mode)
  - Common Mode Noise

# How is EMI Coupled?

- There are four basic noise coupling mechanisms in electrical systems:
  - Conductive; caused by direct contact with metal conductors ( ripple or grounding issues)
  - Capacitive; caused by fast changing voltages applied to capacitance between conductors
  - Inductive; caused by fast changing currents flowing in a loop (transformer action)
  - Radiated; caused by far field electromagnetic coupling (antenna effect)



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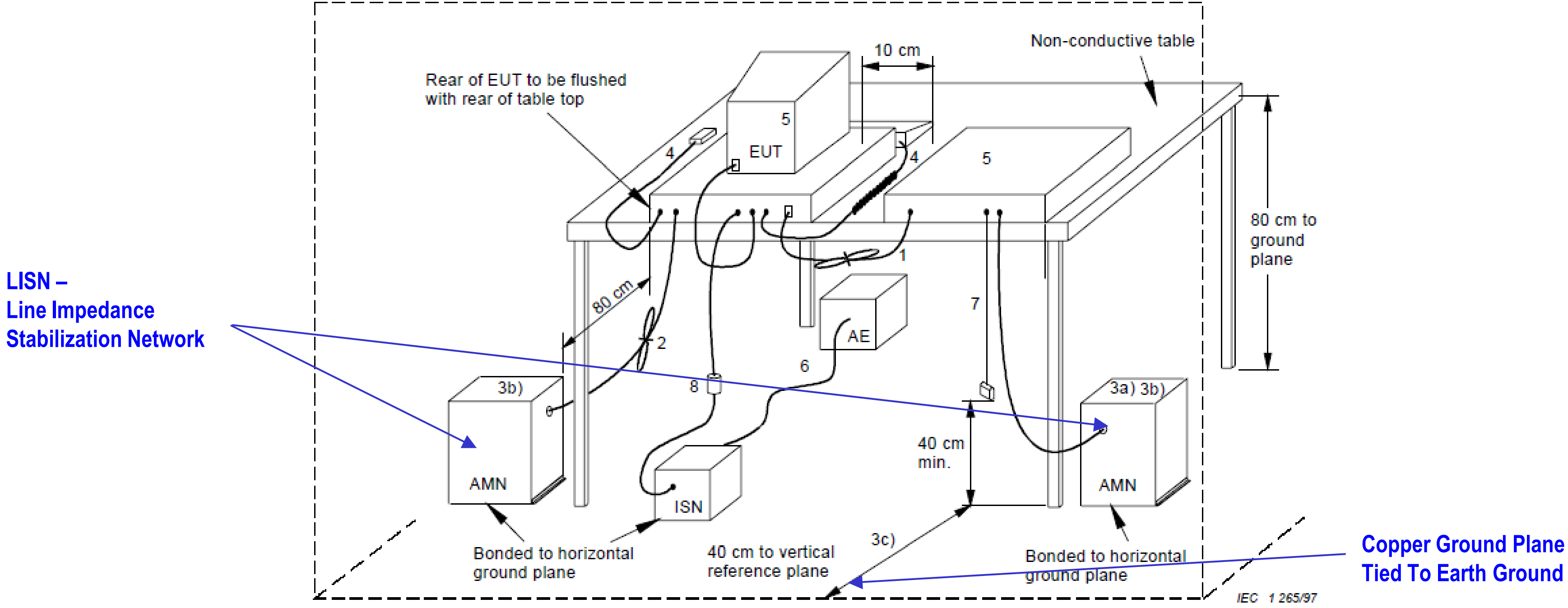
# What Are The Required Commercial Measurement Standards?

- There are conducted EMI standards for just about every kind of commercial electronics application and governing bodies that determine the test standards depending on the country where the equipment will be sold.
- Fortunately, most countries (including the US) have adopted the International Electro-technical Commission's (IEC) International Special Committee on Radio Interference (CISPR) standards for conducted EMI. Always check to see if other standards may apply for a particular country where the equipment may be sold for use.
- For Information Technology Equipment (IT or ITE) we are concerned with CISPR 22, which is the same standard as FCC Part 15 and the European EN55022. You may hear them used synonymously when referring to conducted EMI.
- Per CISPR 22, ITE equipment is divided into two (2) commercial classes:
  - Class A Equipment – Class A  is industrial type equipment not intended for use in a domestic environment.
  - Class B Equipment – Class B equipment can be used in either industrial or domestic environments.

# What Are The Required Military Measurement Standards?

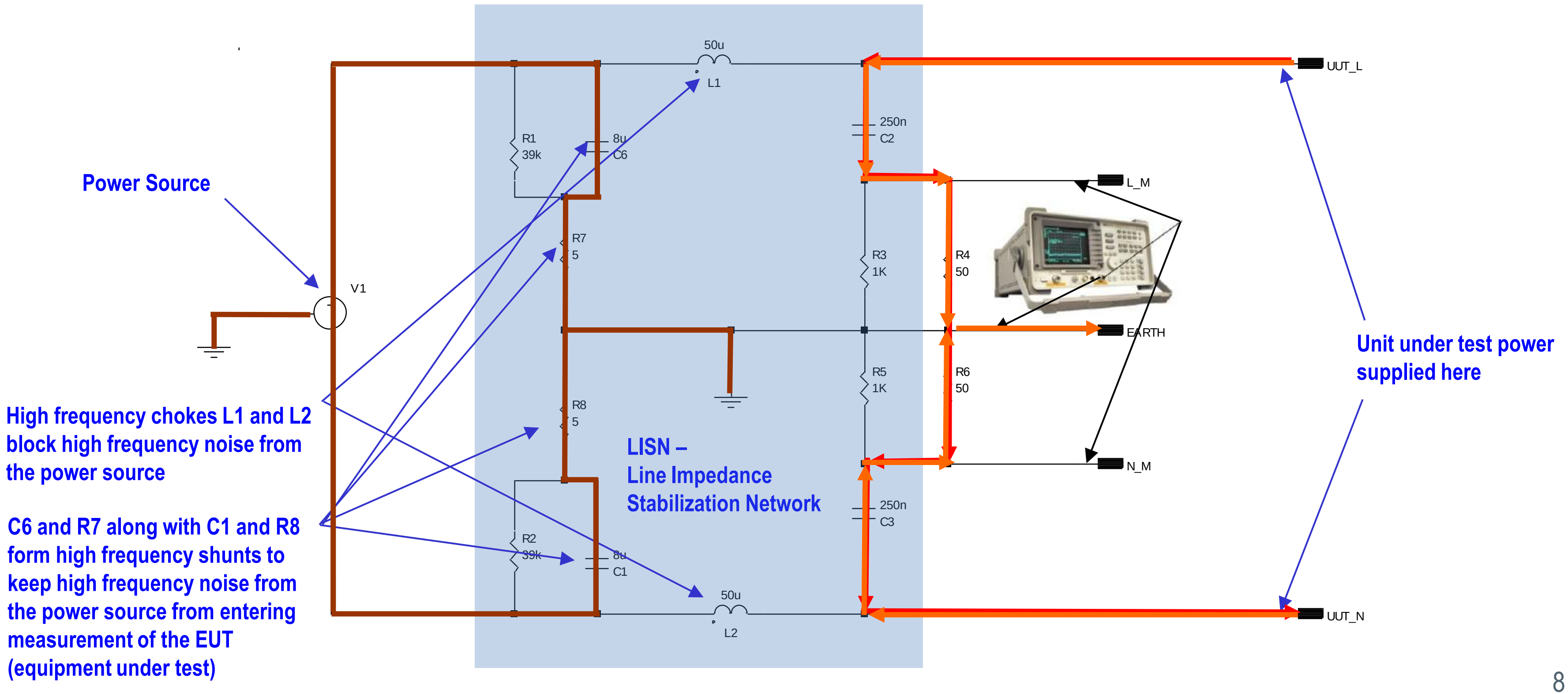
- For most military power applications in the US and also many other NATO countries, the main standard to consider is MIL-STD-461 (latest revision). This standard covers not only conducted emissions and susceptibility but also radiated emissions and radiated susceptibility.
- For conducted emissions produced by power supplies:
  - CE101 – measured at the power leads using a LISN from 30 Hz to 10 kHz
  - CE102 – measured at the power leads using a LISN from 10 kHz to 10 MHz
- MIL-STD-461 documents which applications require CE101, where CE102 compliance is usually mandatory

# How Is Conducted EMI Measured In Commercial Equipment?

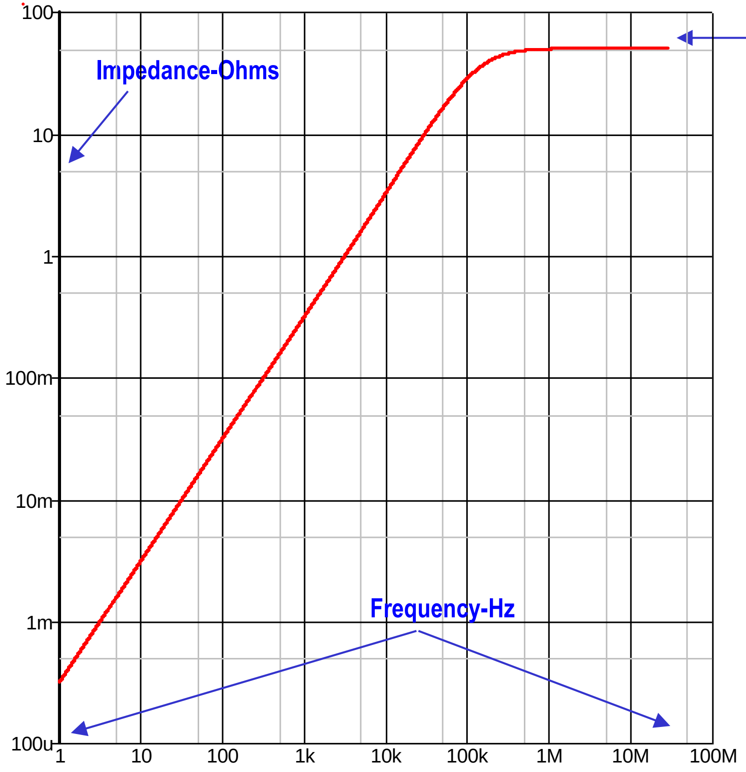



AMN = Artificial mains network
AE = Associated equipment
EUT = Equipment under test
ISN = Impedance stabilization network

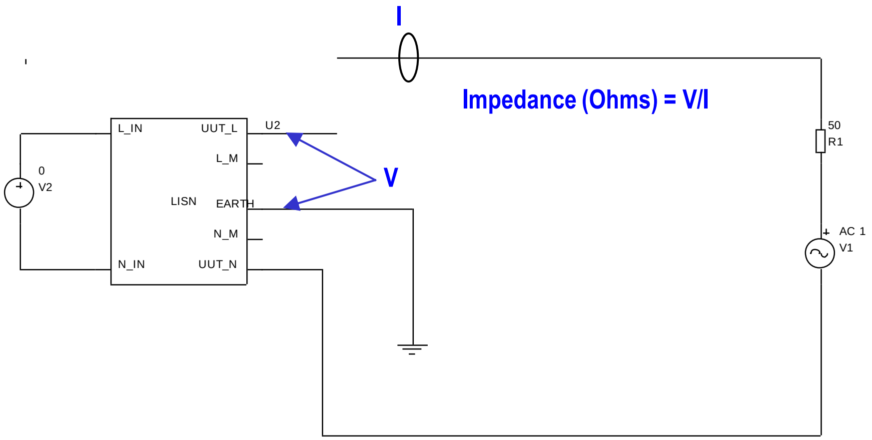
# The Line Impedance Stabilization Network (Commercial Products)



# The LISN Impedance Plot (Simulated)




Impedance approximates 50 Ohms from 150kHz to 30MHz, the measurement standard for conducted EMI



# Measurement Requirements To Meet CISPR 22

- The CISPR 22 standard requires that a unit meet the following conducted noise levels as measured between each conductor and earth ground using the specified measuring filters:

**Class A**

| Frequency (MHz) | Quasi-Peak | | Average | |
|---|---|---|---|---|
| | µV | dBµV | µV | dBµV |
| 0.15-0.5 | 8912.5 | 79.0 | 1995 | 66.0 |
| 0.5-30 | 4467 | 73.0 | 1000 | 60.0 |

**Class B**

| Frequency (MHz) | Quasi-Peak | | Average | |
|---|---|---|---|---|
| | µV | dBµV | µV | dBµV |
| 0.15-0.5 | 1995-631 | 66.0-56.0 | 631-199.5 | 56.0-46.0 |
| 0.5-5 | 631 | 56.0 | 199.5 | 46.0 |
| 5-30 | 1000 | 60.0 | 316 | 50.0 |

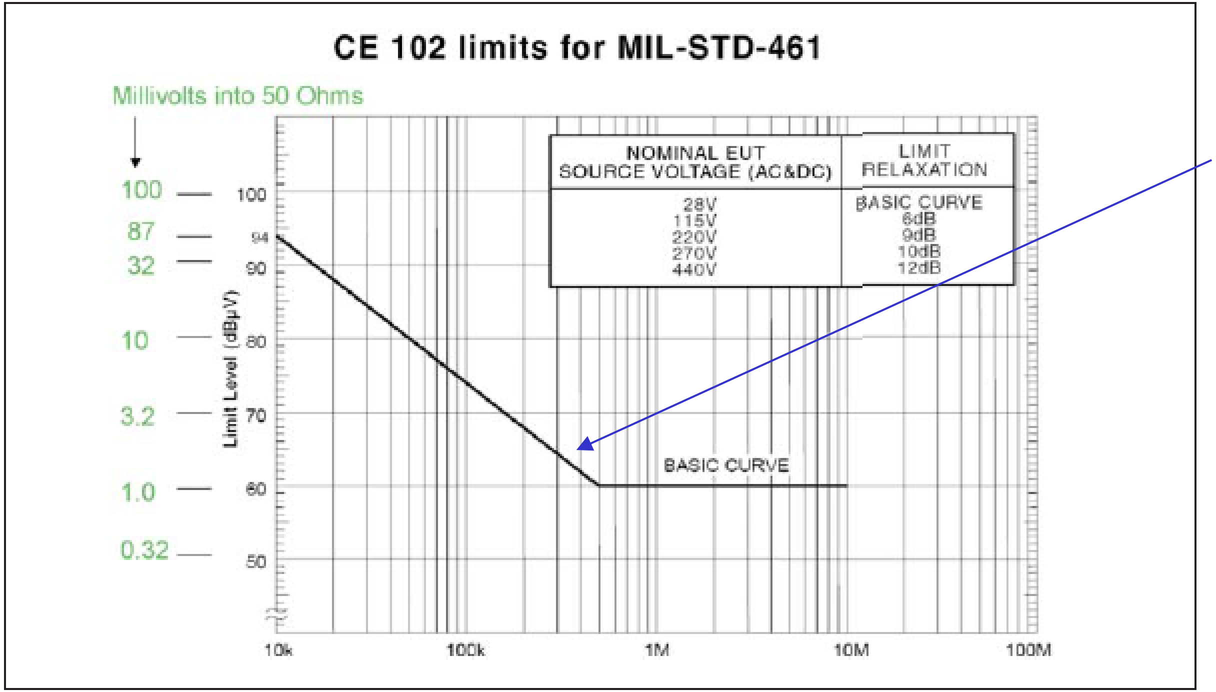
**This equation allows determination of the measured voltage for any level of conducted emission where $V_{ref}$ = 1uV.**

$$dB_{\mu V} = 20 \cdot \log\left(\frac{V_{unknown}}{V_{ref}}\right)$$

$$V_{unknown} = 10^{\frac{dB_{\mu V}}{20}} \cdot V_{ref}$$

**For Class B at 500kHz, current measured at the LISN is: 199.5 uV / 50 Ohms = 4 uA!**

# The CE102 Limits For Military Products




Based on peak measurements only. There are no quasi-peak or average limits in CE102

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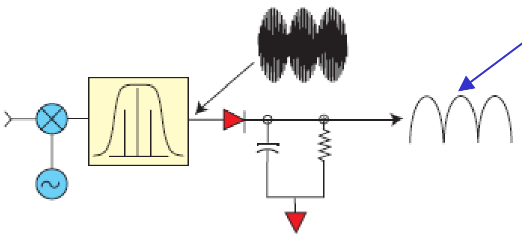
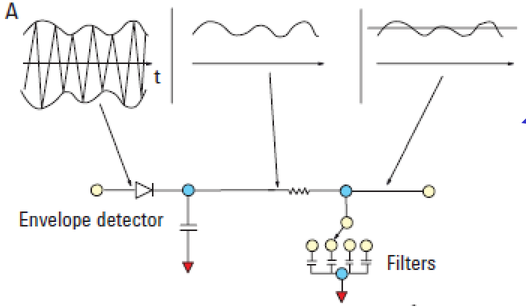
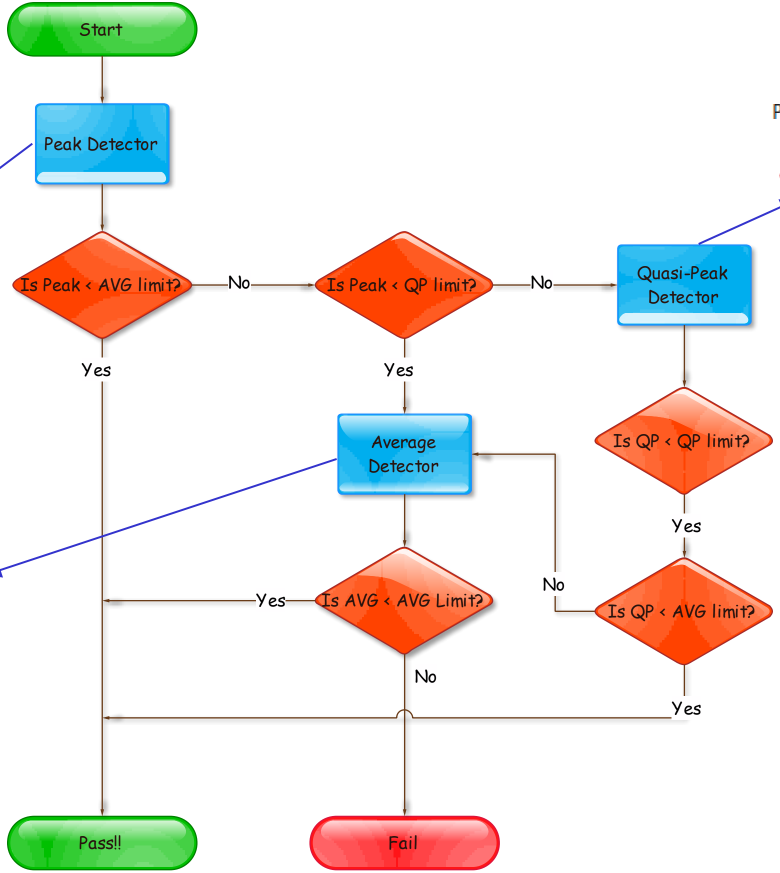
# Measurement Filters

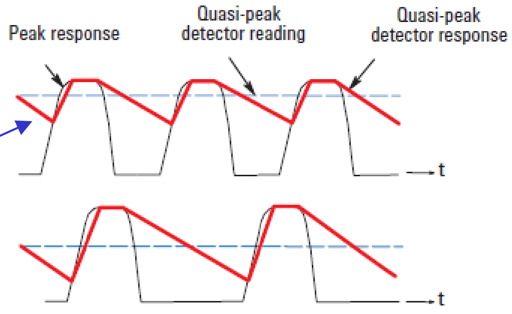
- There are several measuring filter techniques that you should know about:
    - Peak Detection – This method is the fastest of all EMI scans. It also generates the highest amplitude results as well. An envelope detector is employed that can respond very quickly to amplitude changes in the envelope but without the ability to track the instantaneous value of the input signal.
    - Quasi-Peak Detection – This detection method is a form of weighted averaging that has a fast rise time constant but a slow fall time constant. Narrow duty cycle signals will measure a lower value than peak but as frequency or duty cycle increases, the measured value will start to approach peak detection. Quasi-Peak detection takes the longest of all EMI sweeps. Quasi-Peak Detection has higher limits to allow for an “annoyance factor” of the offending signal.
    - Average – This method is peak detection followed by a filter with a bandwidth that is lower than the resolution bandwidth. The result is that the higher frequency peaks get averaged to a lower value. Average detection is slower than peak but faster than quasi-peak.

# Measurement Flow





# Recap

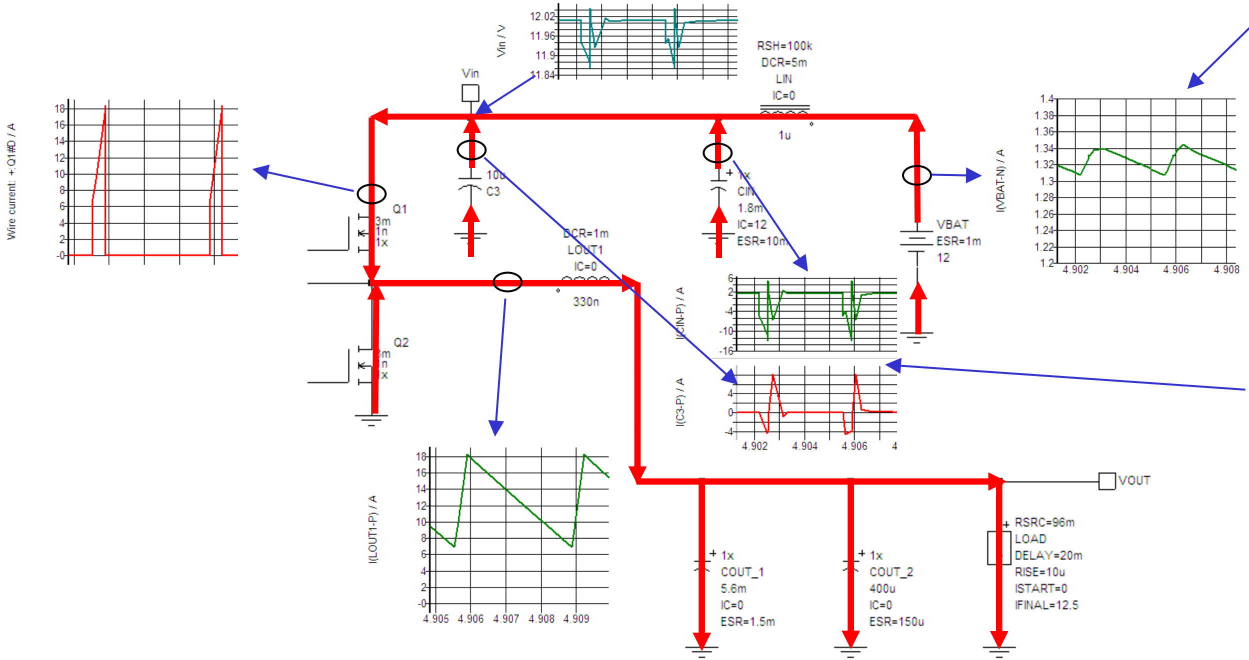
- Covered testing…..
- Now discussing noise sources…..

# Differential Mode Noise (A.K.A. Normal Mode)

- Differential mode noise is sometimes referred to as Normal Mode noise. There is a good reason for this. It results from an applied voltage differential ( of opposite polarity) between the noise source and the noise return.
- It can be caused by any or all (hopefully not!) of the four coupling methods previously discussed.
- Normal circuit operation is also differential in nature.
- Differential noise requires only two wires or a single wire and ground.
- Differential noise currents flow in opposite directions in input feeds or AC line and Neutral.
- Input voltage ripple, output voltage ripple are common examples of differential mode noise.
- Differential noise appears in all forms of power feeds both 2 wire feeds and three wire feeds.

# Differential Mode Noise Ideal Buck Converter

- Consider the ideal buck converter shown below:



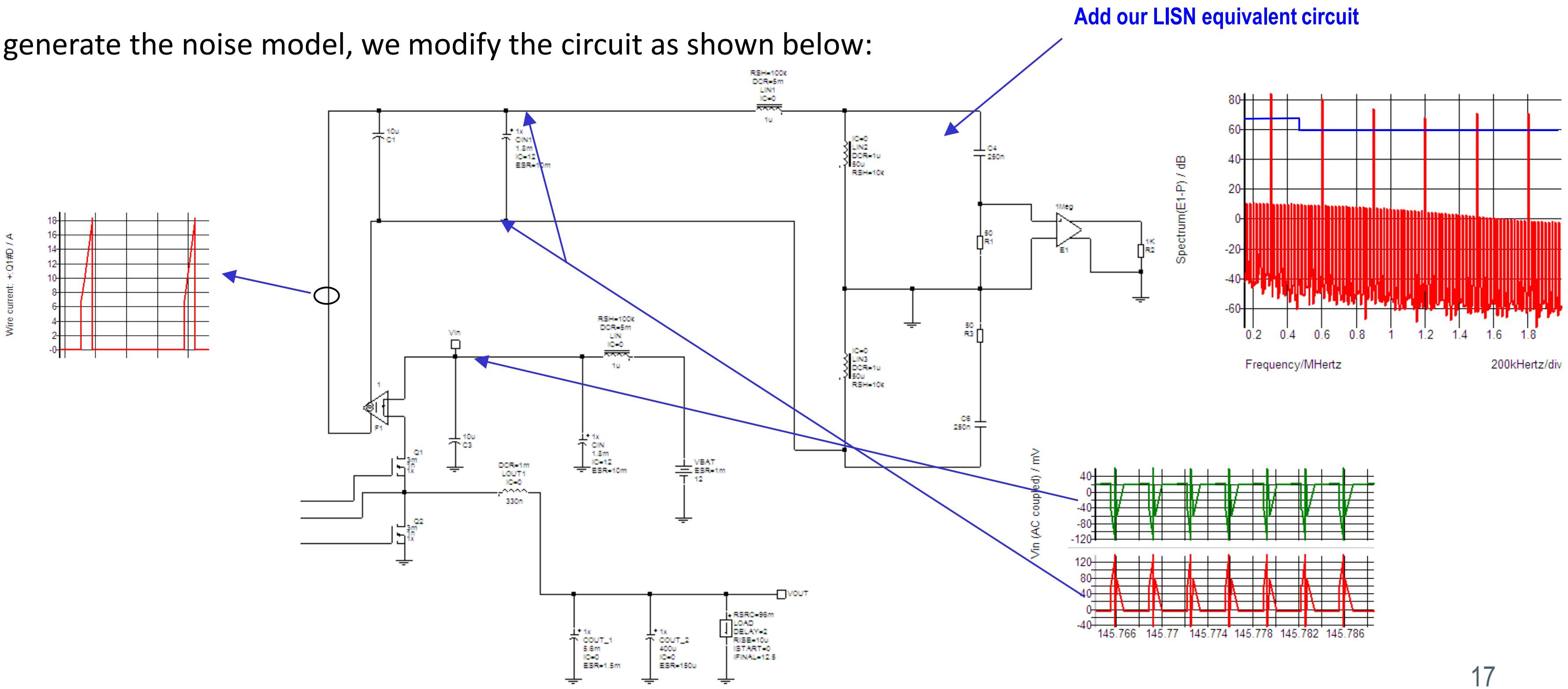

This ripple current is responsible for the differential mode EMI that will be measured at the LISN.

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.

Differential Mode Noise Ideal Buck Converter

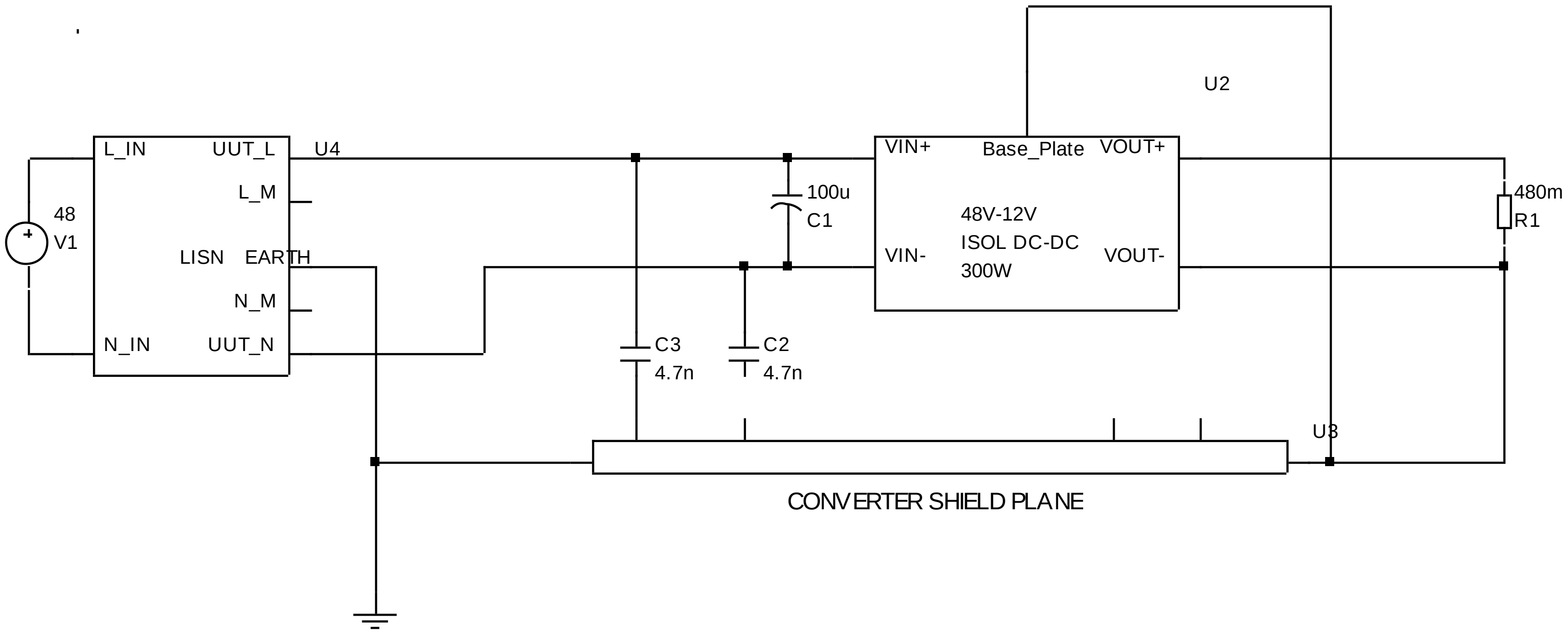
# Differential Mode Noise Ideal Buck Converter

- To generate the noise model, we modify the circuit as shown below:



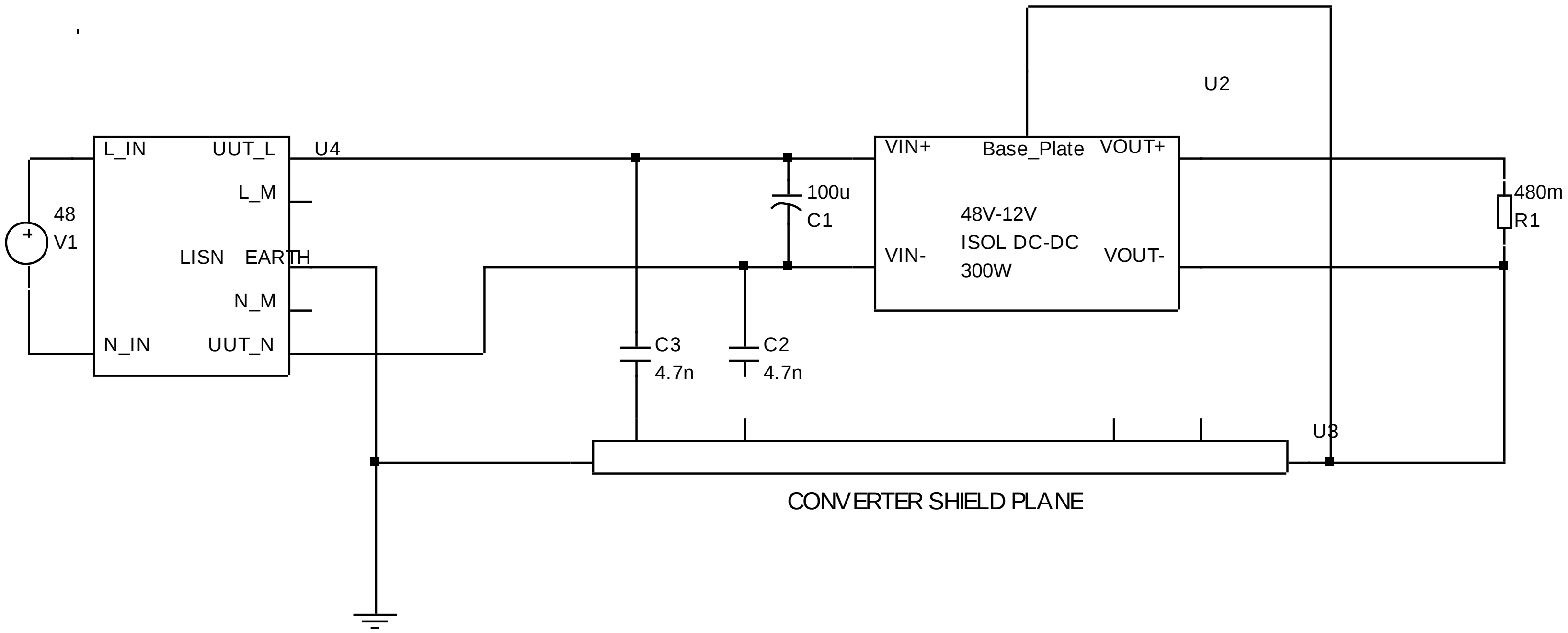
# What If You Don't Know How The Design Works?

- Consider the circuit below, an isolated DC-DC Converter 48V-12V @ 300W



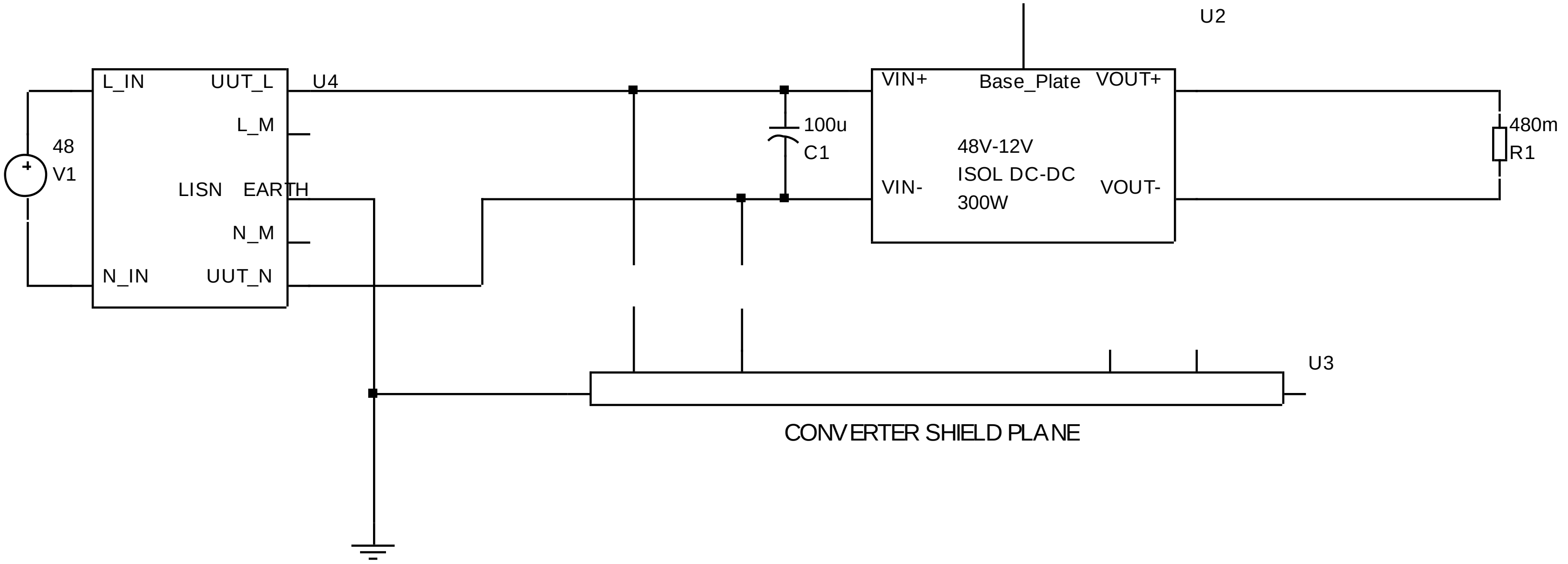
# What If You Don't Know How The Design Works?

- The data sheet called for C1 to be 100uF Electrolytic Capacitor and gave a part number for C1



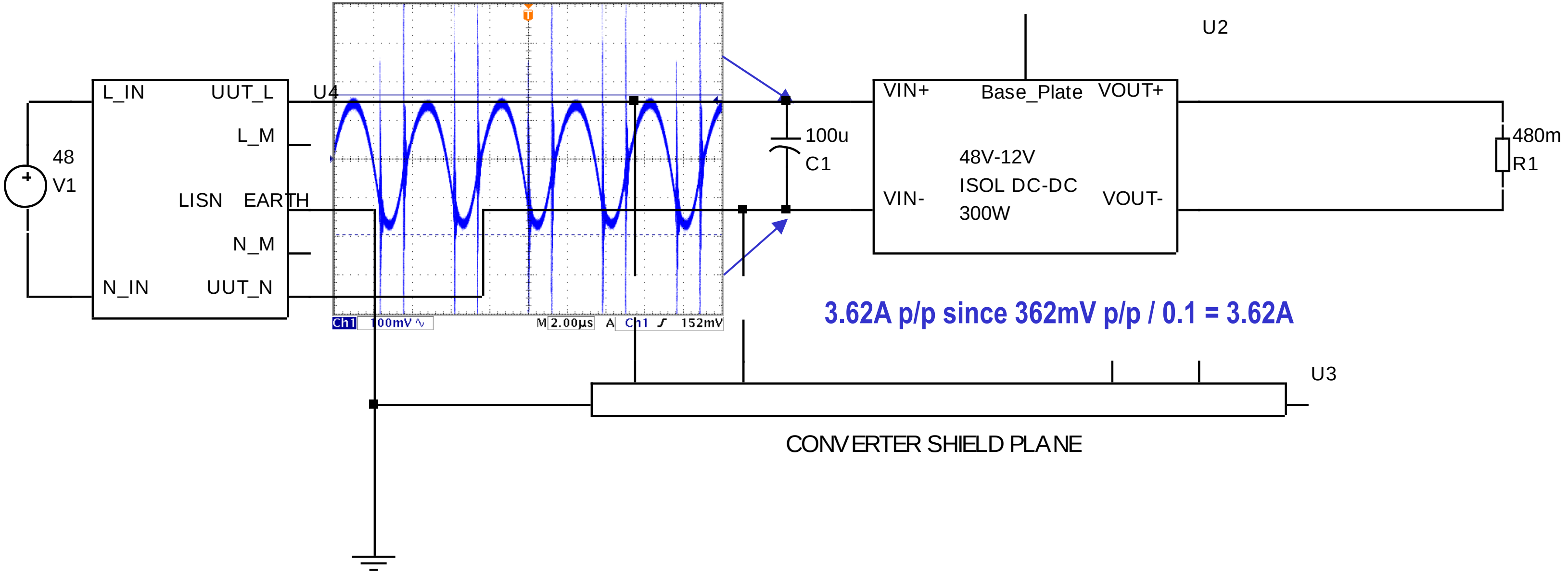
# What If You Don't Know How The Design Works?

- Step 1 – Remove C2, C3 "Y" capacitors – to isolate common mode noise sources (more about that later)
- Step 2 – Disconnect base plate and VOUT- from converter shield plane (common mode isolation)



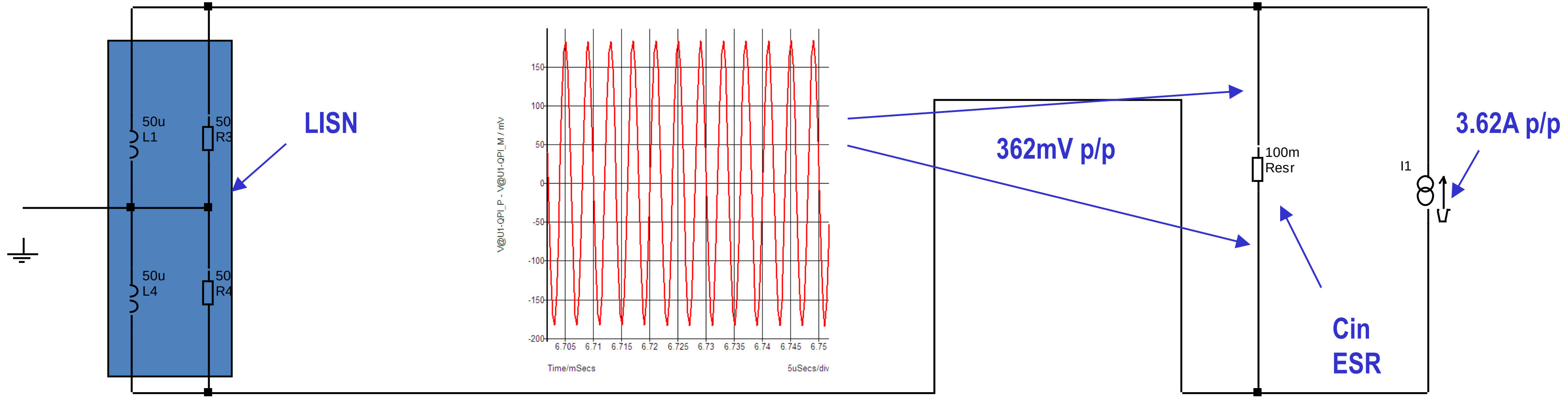
# What If You Don't Know How The Design Works?

- Step 3 – measure p/p AC ripple voltage across C1 carefully. If possible, measure the current with a current probe. In my case, adding the current probe was not possible. The manufacturer's datasheet listed a typical ESR of 100 mOhms.



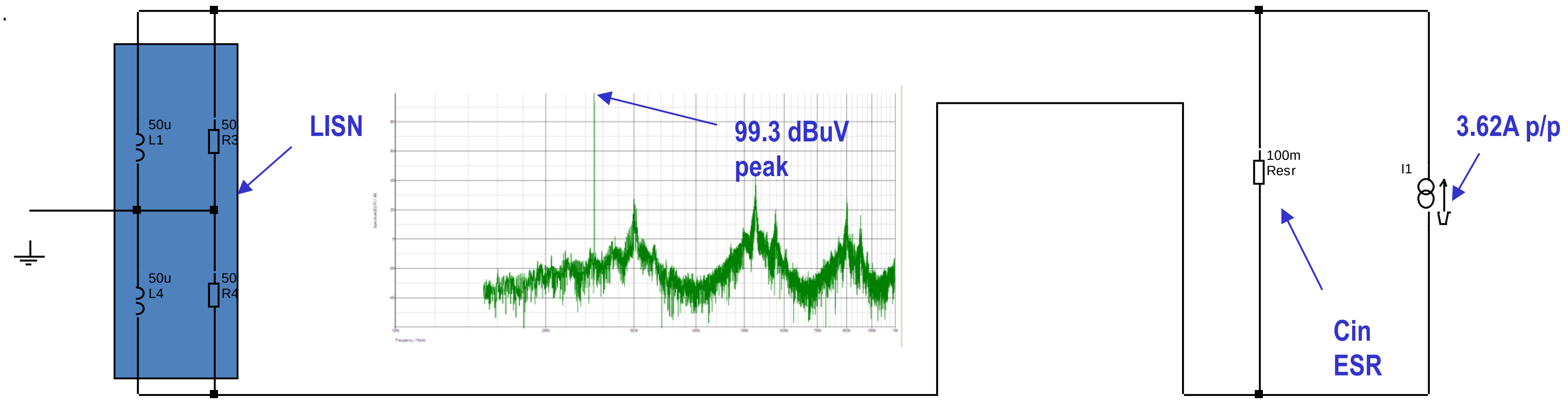
# What If You Don't Know How The Design Works?

- Step 4 – Create your noise source model by replacing the current determined previously with a PWL or Current generator. Add the ESR in parallel with the current source and add your LISN model.



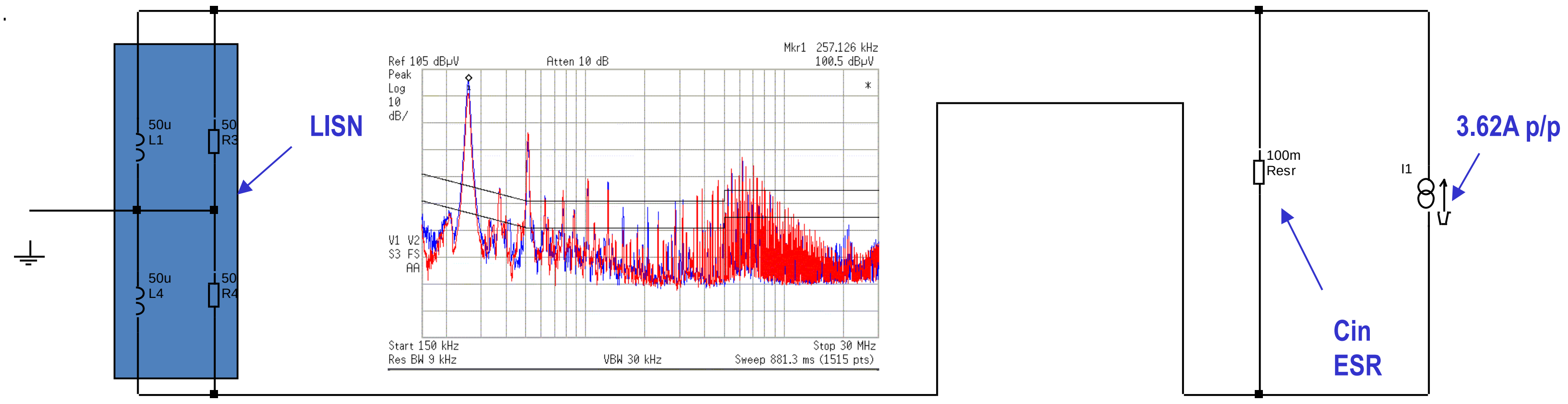
# What If You Don’t Know How The Design Works?

- Step 5 – Take FFT of voltage of simulated LISN.



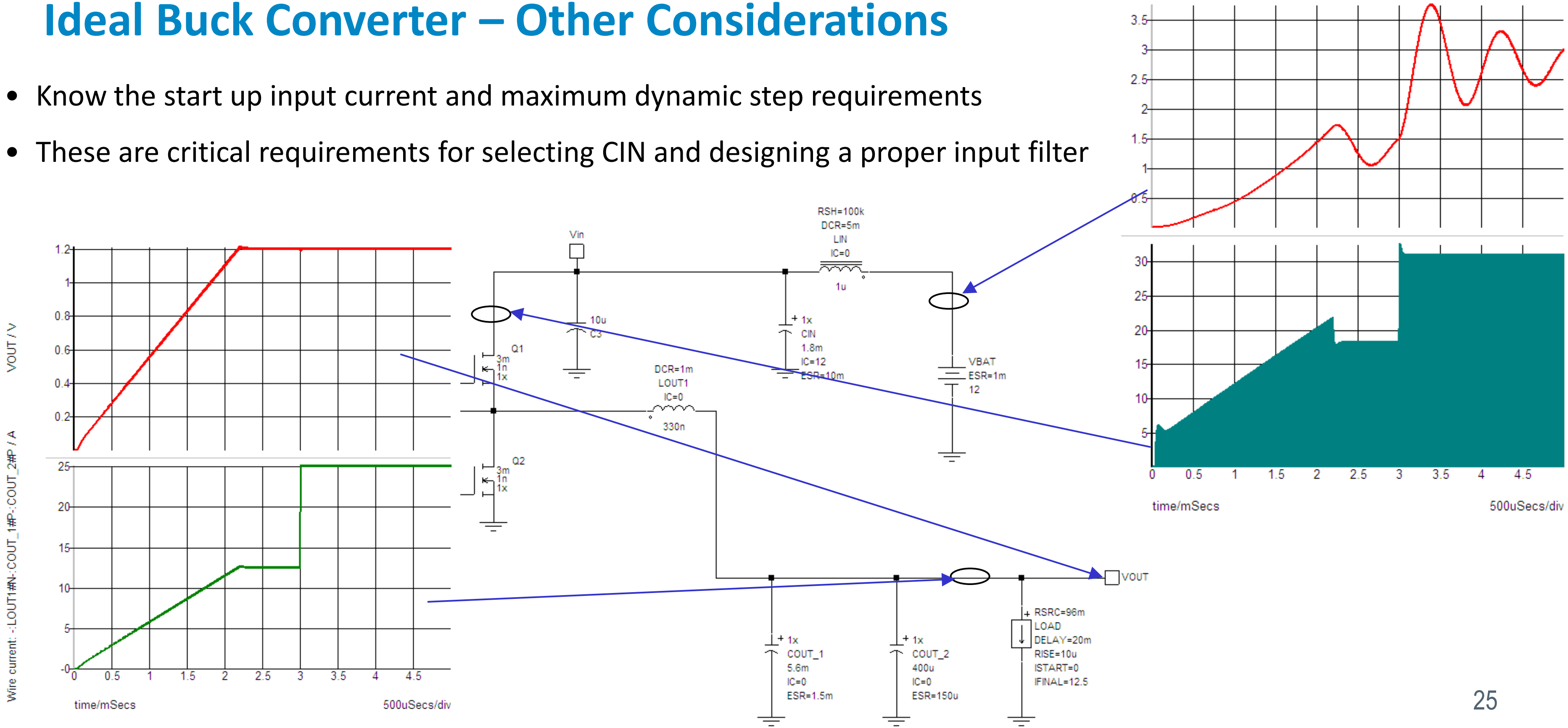
# What If You Don't Know How The Design Works?

- Step 6 – Take a scan of the power supply with a real LISN. Very close agreement observed.



# Ideal Buck Converter – Other Considerations

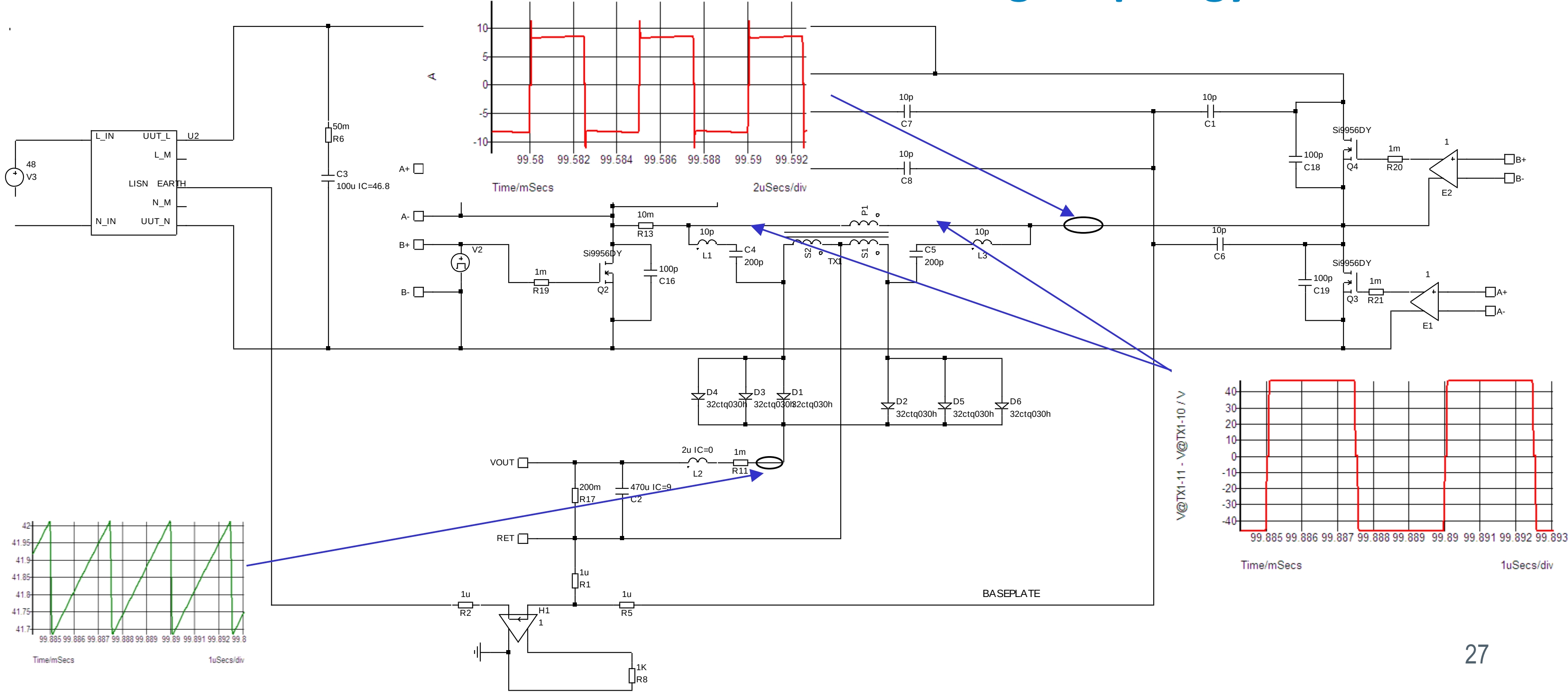
- Know the start up input current and maximum dynamic step requirements
- These are critical requirements for selecting CIN and designing a proper input filter



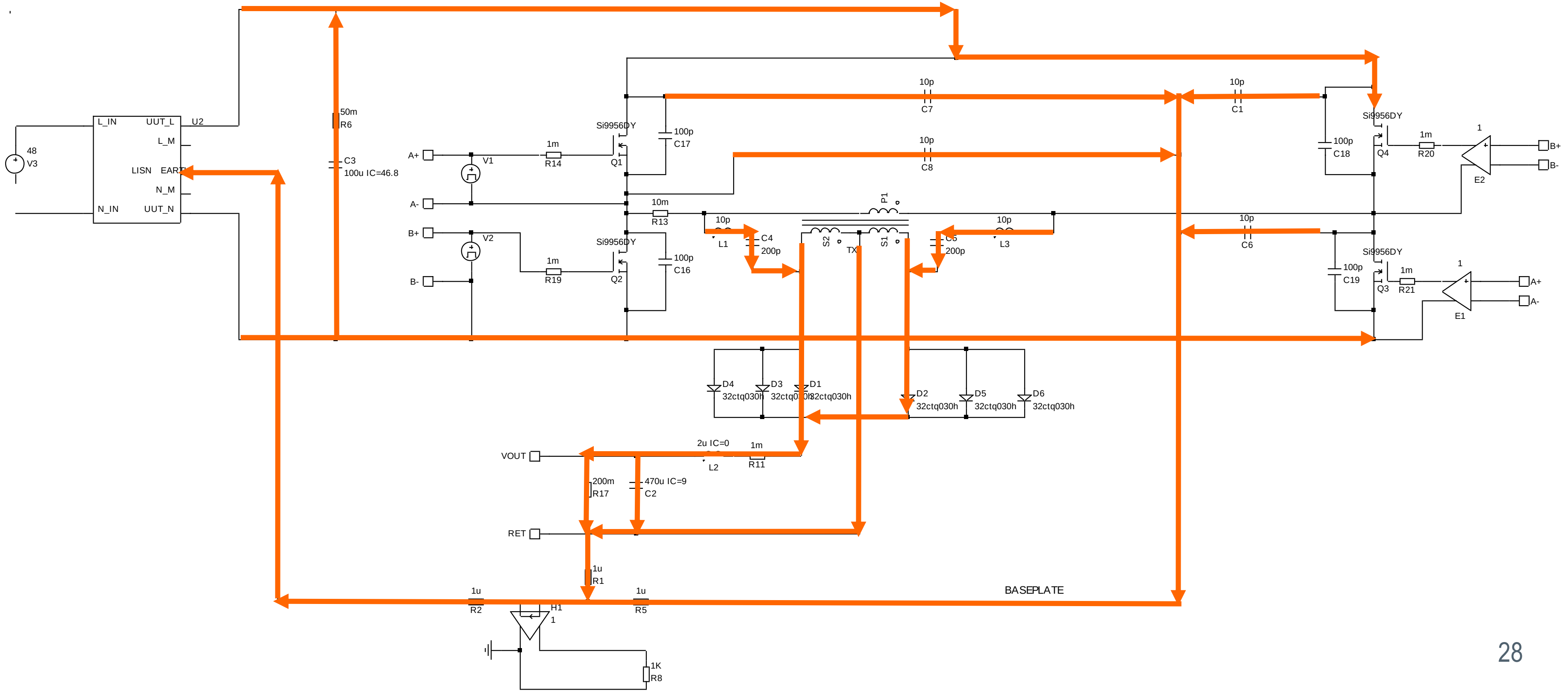
# Common Mode Noise

- Common mode noise always flows in the same direction in both input feeds (L and N) from an applied voltage between those common lines and earth ground (chassis, baseplate, test equipment etc.)
- It can be most difficult to determine the path since it can involve virtually any equipment connected to earth ground.
- Earth ground or a three wire system with an isolated ground is required.
- Non-isolated DC-DC Converters need not have much consideration for common mode noise.
- Test equipment can be very vulnerable based on the type of circuitry being measured.
- Isolated converters that connect output (-) to earth ground will have common mode + differential mode ripple at the output.
- Common mode noise can cause problems with non-isolated DC-DC converters if grounded test equipment has high common mode noise flowing between them.

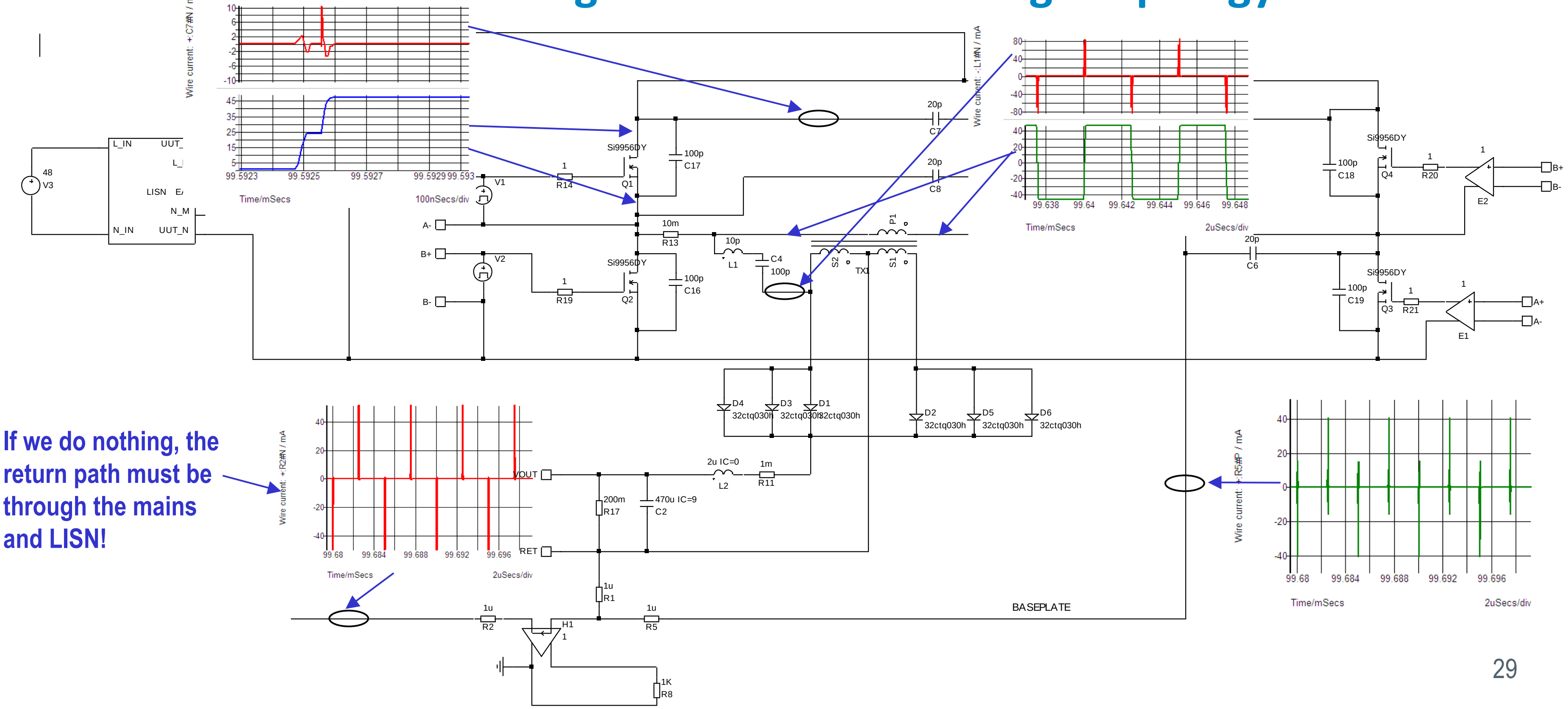
# Common Mode Noise Origin – Isolated Full Bridge Topology



# Common Mode Noise Origin – Isolated Full Bridge Topology



# Common Mode Noise Origin – Isolated Full Bridge Topology




If we do nothing, the return path must be through the mains and LISN!

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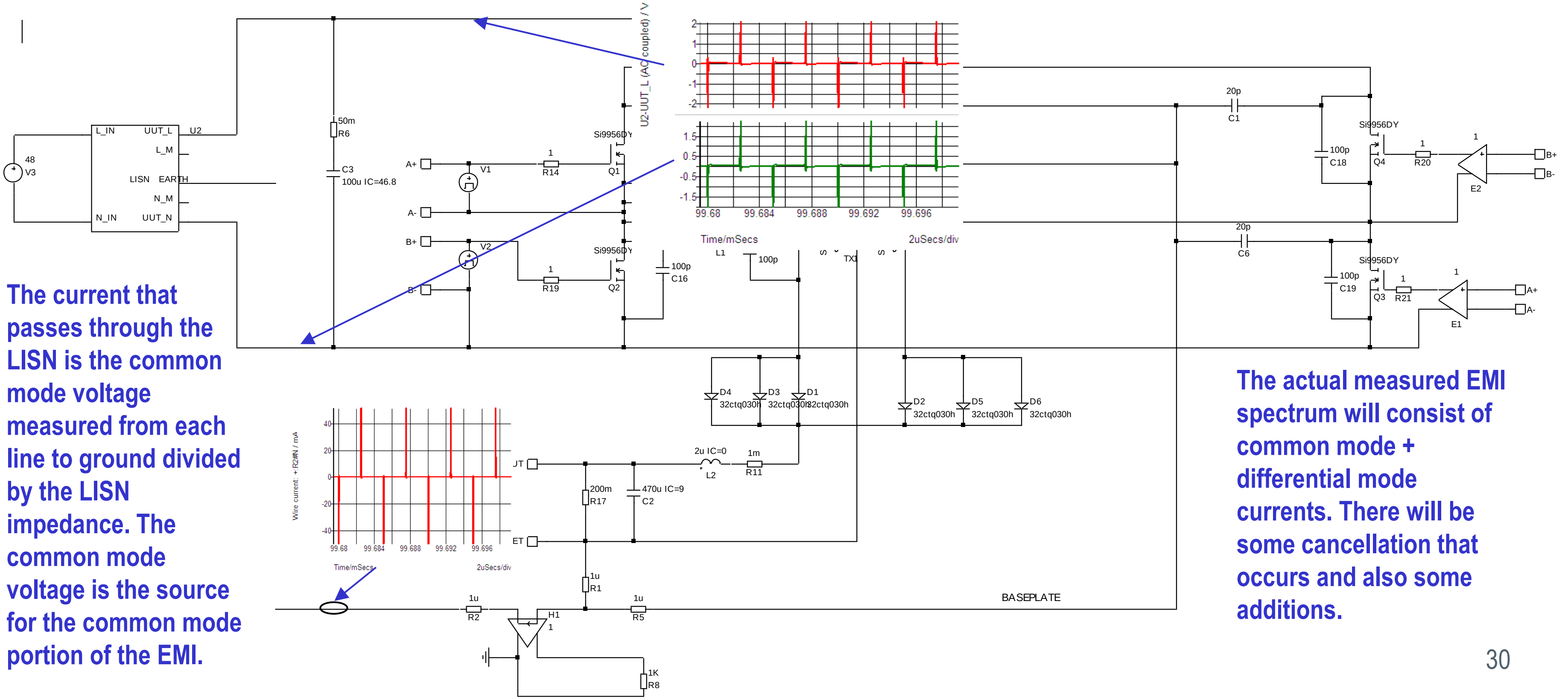
# Common Mode Noise Origin – Isolated Full Bridge Topology

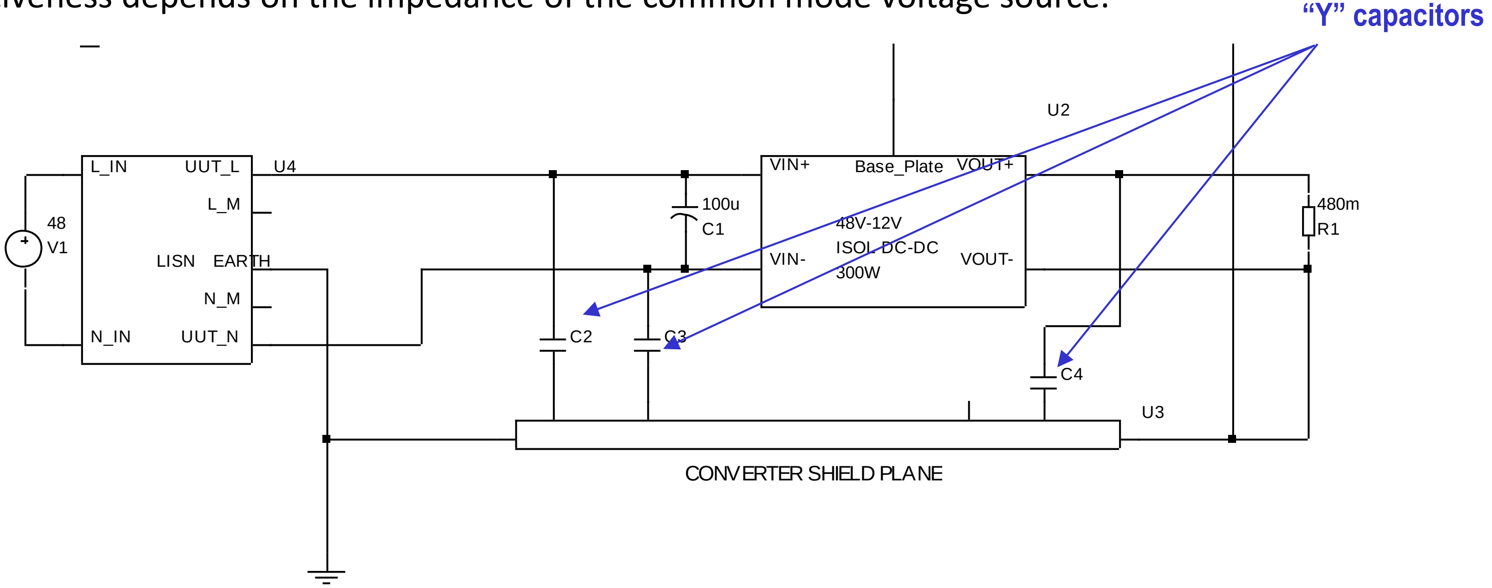



The current that passes through the LISN is the common mode voltage measured from each line to ground divided by the LISN impedance. The common mode voltage is the source for the common mode portion of the EMI.

The actual measured EMI spectrum will consist of common mode + differential mode currents. There will be some cancellation that occurs and also some additions.

# Common Mode Noise Characterization

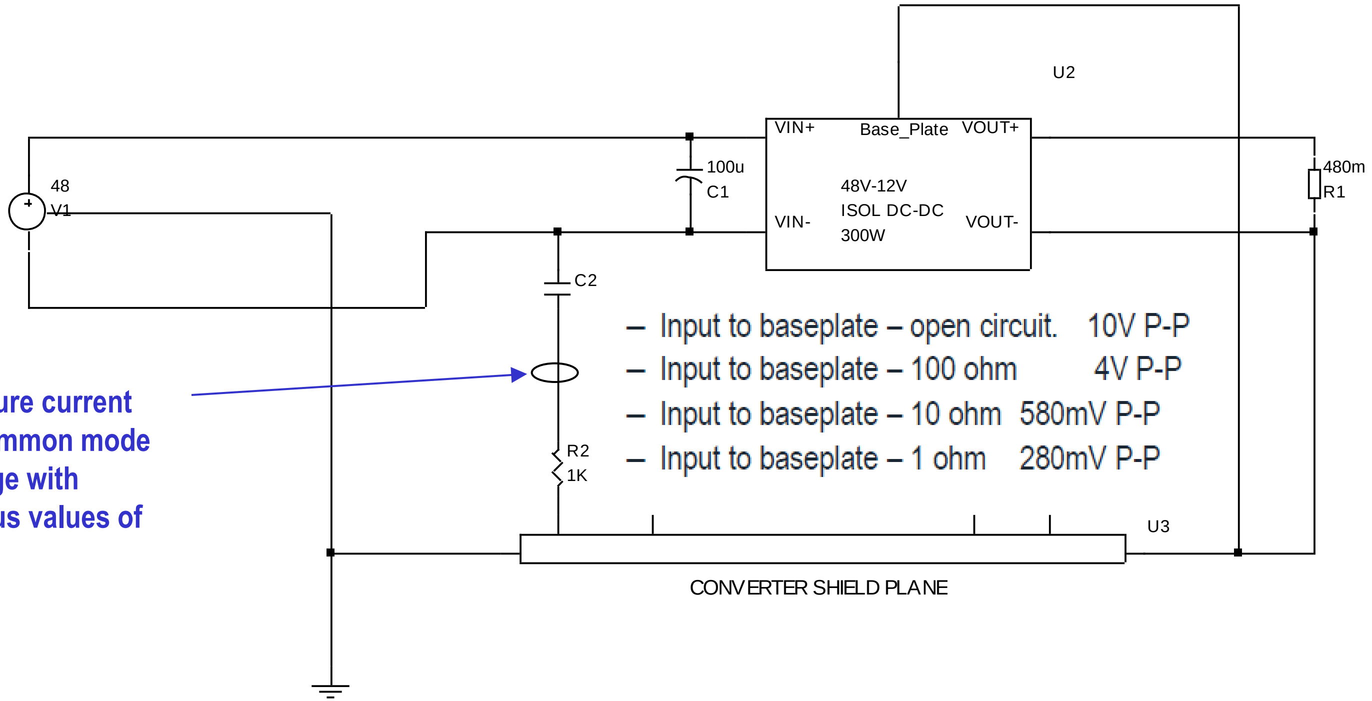
- “Y” capacitors are added to provide a lower impedance path for current to flow and to reduce the level of common mode voltage that appears between L-N and ground.
- Their effectiveness depends on the impedance of the common mode voltage source.



# Common Mode Source Impedance

- The source impedance can be crudely estimated by adding an R-C between N-E and measuring the change in common mode voltage with increases in common mode current. A load line is then created to estimate the source impedance. This method should not be attempted on off-line power supplies or any supply that has hazardous voltages.
- The capacitor should have low ESR and be as large a value as possible.
- The results may be somewhat difficult to measure as there may be resonances and high frequency ringing that changes with resistor values used.
- In most cases, some external series impedance such as a dedicated common mode filter will be required.

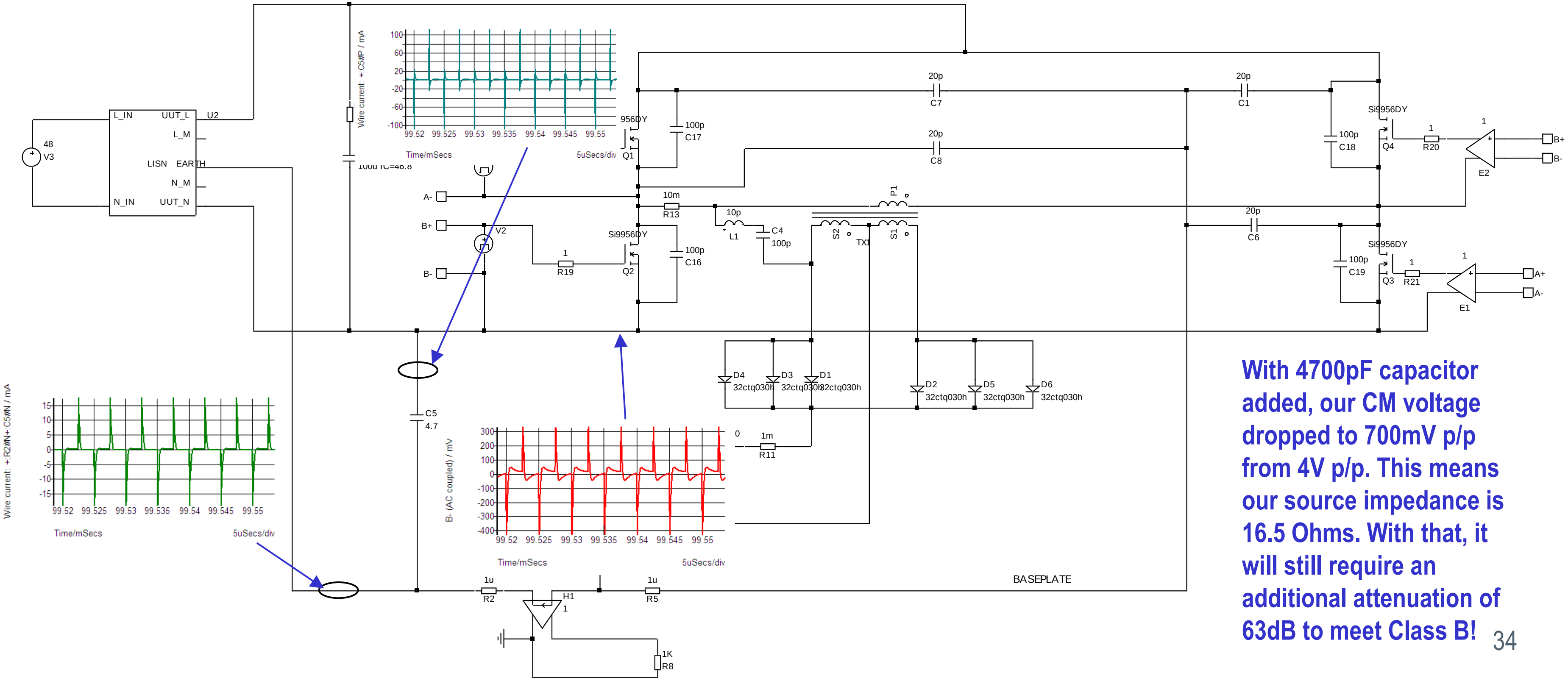
# Common Mode Source Impedance




- Input to baseplate – open circuit. 10V P-P
- Input to baseplate – 100 ohm 4V P-P
- Input to baseplate – 10 ohm 580mV P-P
- Input to baseplate – 1 ohm 280mV P-P

Measure current vs common mode voltage with various values of R2.

# Add a “Y” Capacitor To Our Isolated Full Bridge Simulation



With 4700pF capacitor added, our CM voltage dropped to 700mV p/p from 4V p/p. This means our source impedance is 16.5 Ohms. With that, it will still require an additional attenuation of 63dB to meet Class B!

# Power Supply Selection Tips To Make EMI Compliance Easier

- As seen by our common mode EMI simulation, a rapidly changing voltage applied to a capacitance causes a high current slug into the base plate. Choosing a power supply that employs zero voltage switching can reduce this effect significantly due to resonant (slower) voltage changes.
- Be aware of power supplies that contain bipolar rectifier diodes that have snappy reverse recovery characteristics.
- For Buck regulators, look for circuits that avoid or minimize body diode conduction. MOSFET body diodes do not have desirable recovery characteristics. Snappy reverse recovery can cause high frequency broadband noise in the 15-30MHz region that can be difficult to solve. Body diode conduction reduces efficiency as well.
- High speed, hard switching can cause fast spikes and ringing at high frequency due to energy storage in parasitic inductances. Get a sample power supply and look at the waveforms. Clean waveforms = Lower EMI
- As power supplies get smaller and more efficient, there is less natural damping. Plan for filtering.

# In Summary………….

- The definition of conducted EMI including types, categories, coupling mechanisms and measurement standards was presented.
- There was a discussion of how EMI is measured, including test setups, limits, measuring filters and the line impedance stabilization network.
- The origin and characterization of differential mode EMI was presented using a simulated buck regulator and a real world example of a 300W isolated DC-DC converter.
- Finally, common mode noise origins, paths and characterization was presented using a simulation model of an isolated Full Bridge converter. Some tips were presented to help reduce EMI during the power supply selection process.

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# Part 2 Coming Attractions

- We will expand on input capacitor selection for a typical Buck regulator based on the characterization methods described here. We will also analyze some typical input filter configurations to show when input filter instability is present and how to avoid it.
- Various methods of common and differential mode filtering  will be presented along with filter insertion loss measuring techniques.
- A method to reduce the overall size of the common mode filter will be presented.
- Finally, some real world examples from my case history files of solving filter problems including do’s, don’ts and troubleshooting techniques to solve EMI problems.

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## Acknowledgements


- The following  material was used as references in the presentation of this seminar:
    - Controlling Conducted Emissions By Design by John C. Fluke (an excellent book, highly recommended)
    - Predict Differential Conducted EMI with a SPICE simulator – Christophe Basso; April 12, 1996
    - Making EMI Compliance Measurements – Agilent Technologies Application Note
    - CISPR 22 Fourth Edition
    - Vicor Application Note AN-22

# What Are The Required Commercial Measurement Standards?

## International regulations summary (emissions)

| CISPR | FCC | EN | Description |
|---|---|---|---|
| 11 | Part 18 | EN 55011 | Industrial, scientific, and medical |
| 13 | Part 15 | EN 55013 | Broadcast receivers |
| 14 | | EN 55014 | Household appliances/tools |
| 15 | | EN 55015 | Fluorescent lights/luminaries |
| 16-1-1 | | | Measurement apparatus/methods |
| 22 | Part 15 | EN 55022 | Information technology equipment |
| 25 | | EN 55025 | Automotive |
| | | EN 50081-1,2 | Generic emissions standards |

# What Are The Required Military Measurement Standards?

| Requirement | Description |
|---|---|
| CE101 | Conducted Emissions, Power Leads, 30 Hz to 10 kHz |
| CE102 | Conducted Emissions, Power Leads, 10 kHz to 10 MHz |
| CE106 | Conducted Emissions, Antenna Terminal, 10 kHz to 40 GHz |
| CS101 | Conducted Susceptibility, Power Leads, 30 Hz to 150 kHz |
| CS103 | Conducted Susceptibility, Antenna Port, Intermodulation, 15 kHz to 10 GHz |
| CS104 | Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals, 30 Hz to 20 GHz |
| CS105 | Conducted Susceptibility, Antenna Port, Cross-Modulation, 30 Hz to 20 GHz |
| CS109 | Conducted Susceptibility, Structure Current, 60 Hz to 100 kHz |
| CS114 | Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz |
| CS115 | Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation |
| CS116 | Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads, 10 kHz to 100 MHz |
| RE101 | Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz |
| RE102 | Radiated Emissions, Electric Field, 10 kHz to 18 GHz |
| RE103 | Radiated Emissions, Antenna Spurious and Harmonic Outputs, 10 kHz to 40 GHz |
| RS101 | Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz |
| RS103 | Radiated Susceptibility, Electric Field, 2 MHz to 40 GHz |
| RS105 | Radiated Susceptibility, Transient Electromagnetic Field |

# What Are The Required Military Measurement Standards?

| Equipment and Subsystems Installed In, On, or Launched From the Following Platforms or Installations | Requirement Applicability | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CE101 | CE102 | CE106 | CS101 | CS103 | CS104 | CS105 | CS109 | CS114 | CS115 | CS116 | RE101 | RE102 | RE103 | RS101 | RS103 | RS105 |
| Surface Ships | | A | L | A | S | S | S | | A | L | A | A | A | L | A | A | L |
| Submarines | A | A | L | A | S | S | S | L | A | L | A | A | A | L | A | A | L |
| Aircraft, Army, Including Flight Line | A | A | L | A | S | S | S | | A | A | A | A | A | L | A | A | L |
| Aircraft, Navy | L | A | L | A | S | S | S | | A | A | A | L | A | L | L | A | L |
| Aircraft, Air Force | | A | L | A | S | S | S | | A | A | A | | A | L | | A | |
| Space Systems, Including Launch Vehicles | | A | L | A | S | S | S | | A | A | A | | A | L | | A | |
| Ground, Army | | A | L | A | S | S | S | | A | A | A | | A | L | L | A | |
| Ground, Navy | | A | L | A | S | S | S | | A | A | A | | A | L | A | A | L |
| Ground, Air Force | | A | L | A | S | S | S | | A | A | A | | A | L | | A | |

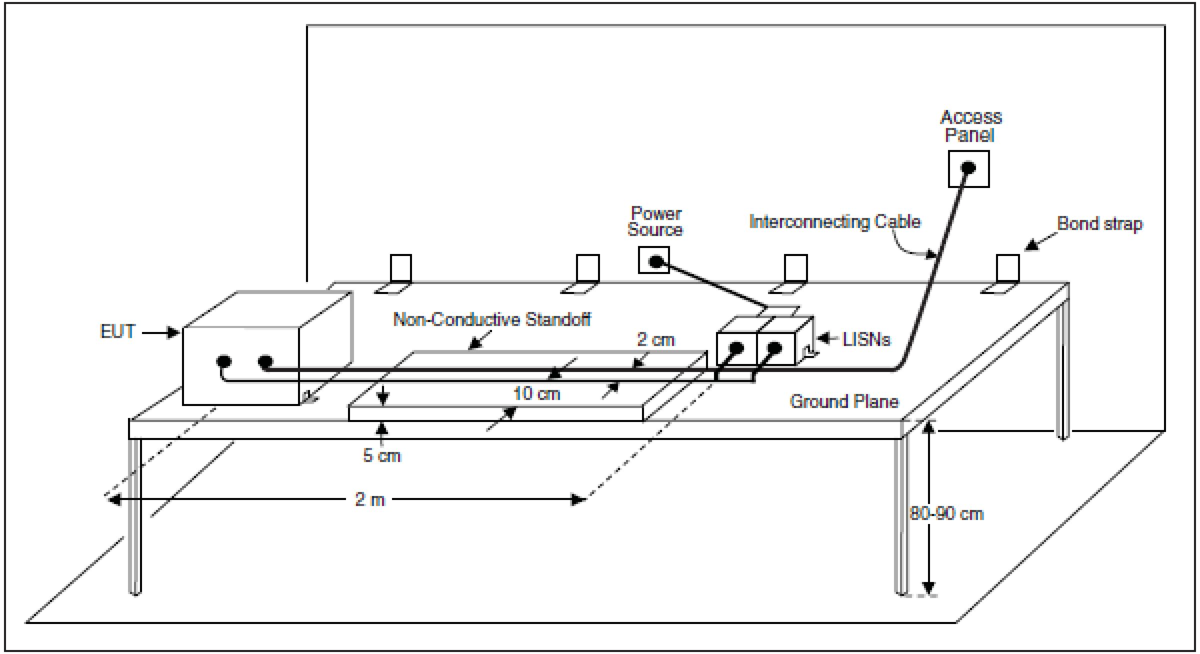
Legend:

A Applicable

L Limited as specified in the individual sections of this standard

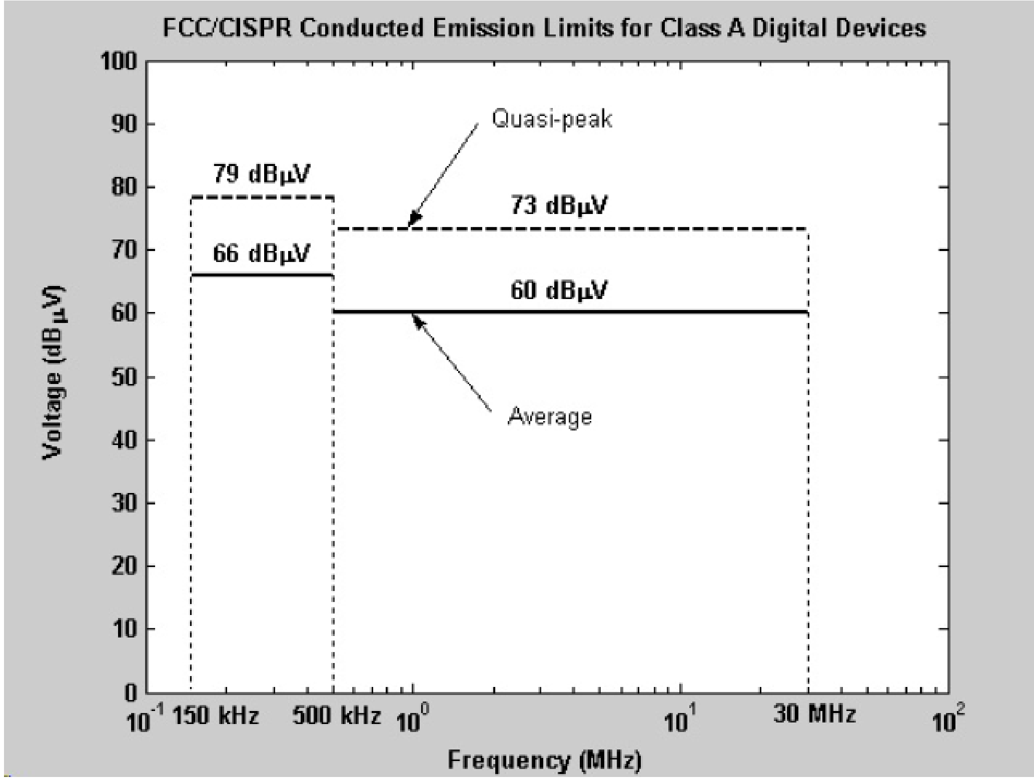
S Procuring activity must specify in procurement documentation

# How Is Conducted EMI Measured In Military Equipment?




*MIL-STD-461 Test Setup*

# The CISPR 22 Standards For Class A Commercial ITE Products



# The CISPR 22 Standards For Class B Commercial ITE Products