# High Frequency Power Measurements: Are Your Oscilloscope and Probes Telling You the Whole Truth.

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## Introduction:

Modern power supplies are edging upward in their frequency of operation. The benefits are obvious; a reduction in size, weight and an increase in energy density. To accomplish this, the designers and manufacturers are migrating to the newer high frequency power switch and rectifier technologies. The traditional planar or trench MOSFETs switches in the 30 – 60 nanosecond range, power switches such as, the high-performance D3 superjunction MOSFET, GaN MOSFET, SiC MOSFET and SiC schottky rectifier, switch in less than 10 nanoseconds.

To view such fast transitions, one typically needs at least a 1 GHz oscilloscope. Average commercially available voltage and current probes are woefully inadequate for these high frequency signals. The high frequency voltage probes often cost greater than $12,000 and slightly better current probes start at $4,000.

The average oscilloscope probe has a bandwidth of less than 300 MHz, and the current probe, less than 60 – 100 MHz. For we power engineers, who work for mid-sized companies, there is only one path – build your own probes.

Designing and building HF voltage and current probes, requires a good understanding of RF, parasitics, transmission-line theory, and field theory.

## The Shortcomings of Standard Commercial Probes:

Commercially available oscilloscope voltage and current probes are robust, ergonomically well designed, and accurate. They have served their markets wonderfully for generations of engineers. These applications were overwhelmingly much less than 1 GHz. The operating frequencies and the edges are exceeding 1 GHz and rise and fall times in the sub 5 ns range. The commonly available voltage probe has a bandwidth of only 300 MHz.

Commercial probes have several challenges with high frequency circuits and signals. The bandwidth of the probe can create a major limitation to accurate measurements.. These oscilloscope probes have become ubiquitous fixtures in the lab. Slow rise and fall times are often taken for granted and the thought there might be missing information can be easily overlooked. Second is the common probe’s connection to the signal source. These have a significant length of unshielded connecting leads; particularly the ground lead. This 4 – 6 inch (10 – 15 cm) lead can pick-up radiated noise from the circuit and inject it into the coax cable as a differential-mode signal. This unrecognized noise adds to the real signal.

Figure 1. is the recognizable standard, over-the-counter voltage probe. As noted above, it contains a length of unshielded signal or ground wire which acts as a loop antenna. The area of this loop is proportional to the amount of noise energy and noise spectrum. This noise can be viewed if one clips the ground lead to the probe tip and held near the target circuit board.

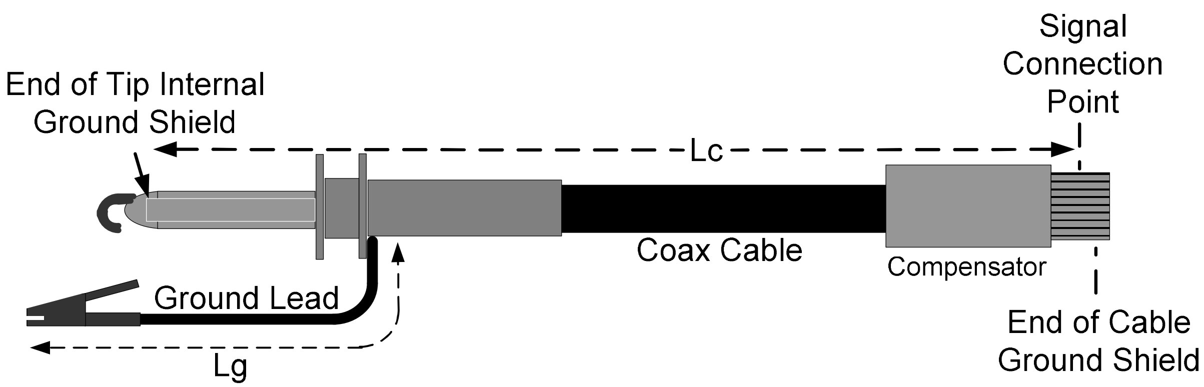



Figure 1. Common Voltage Oscilloscope Probe Construction

**Construction of 50Ω Voltage Probes:**

The overall goals of constructing 50Ω voltage probes are:

1. Construct a known, quiet, high frequency signal path from the circuit to the oscilloscope.
2. Provide shielding as much as practically possible along the signal's path.
3. Gain the ability to control as many parasitic influences as possible.

By constructing custom 50Ω voltage probes, the designer can best define and understand what is really happening within the design.

**The 1:1 Shielded Coax Voltage Probe:**

For those signals below the maximum input voltage rating of the oscilloscope input, one could use a cut length of a 50Ω BNC coax cable. The length of the unshielded center conductor and the shield pigtail should be kept to less than 1 inch (25 cm) to minimize noise pick-up. For viewing a particular signal at a particular node, the center conductor should be soldered directly to that node, and the ground lead should be soldered to the closest associated ground. That is, not to a ground that has a long PCB trace length between the probe and the node of interest. This probe only provides high frequency, signal shielding from the target circuit to the oscilloscope. The input termination setting of the oscilloscope scope should be 1 MΩ. The 1:1 shielded probe can be seen in Figure 2.

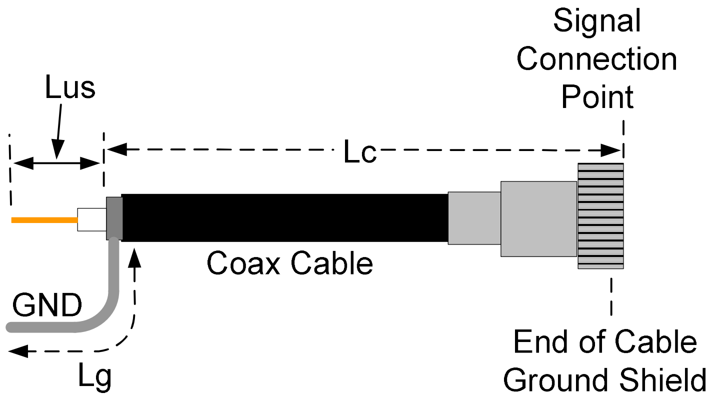


Figure 2. The 1:1 Shielded Voltage Probe Construction.

**The n:1 50Ω Voltage Probe Construction:**

The n:1 probe is intended for signal amplitudes (including any spikes) that exceed the maximum voltage rating of the input amplifier of the oscilloscope. This probe is a bit more complicated to construct. Its simplified schematic is shown in figure 3.

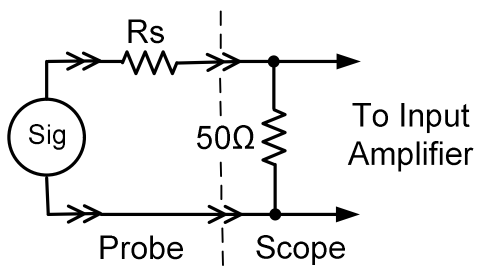


Figure 3. Simplified schematic of the n:1 Voltage Probe.

This brings us to the first and important step of determining the value of the sense resistor (Rs). This is not as straight forward as one might think. There are several factors which should be taken into consideration.

The oscilloscope's input termination should be set to 50Ω. The internal 50Ω terminating resistor becomes the bottom resistor of a resistor divider circuit. One can safely assume that this resistor has better than a 0.1% tolerance, and its power dissipation should not exceed 0.25 watts. This then sets the maximum current that can enter the oscilloscope's input connector.

Several additional considerations are: the maximum amplitude of the signal across the 50Ω terminating resistor, the power dissipated within the series sense resistor (Rs), and loading on the input circuit. All of these considerations must be balanced between each other and will dictate the gain setting of the oscilloscope input amplifier. If the signal is too low, the oscilloscope input gain must be set in the <100 mV range. The displayed signal becomes noisy because the input signal is very close to the *noise floor* of the input amplifier. This noise is the reduction in resolution of the input A-to-D. The signal may only be acquired by the lowest 4-bits of the A-to-D. What is seen are the *quantization steps* of the

LSBs. This is somewhat unavoidable, especially in probes with a high step-down ratio. A typical display of a 1000:1 50Ω probe is shown in figure 4.

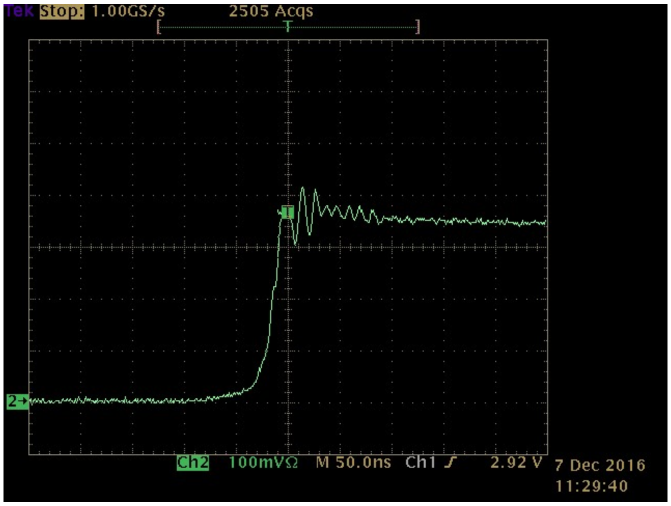



Figure 4. Plot showing the quantization Noise on Low-level Oscilloscope input Signals

The basic construction of an n:1 voltage probe can be seen in Figure 5.

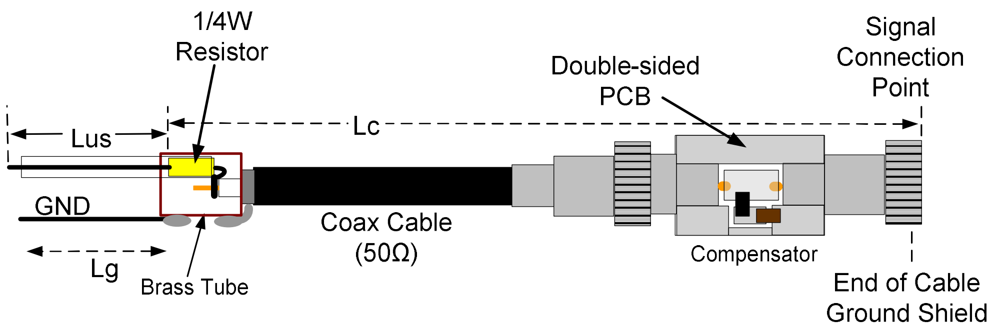



Figure 5. The Basic Construction of an n:1 50Ω Probe.

The design procedure is essentially:

1. Determine the resistor reduction ratio desired to result in an oscilloscope signal amplitude (including spikes), for the desired channel gain setting. It is typically nice to choose a decade-multiple resistor reduction ratio, since the displayed *v/div* setting differ only in the placement of a decimal point from the input voltage.

$$n = V_{CH}/V_{in} \qquad \text{[Eq. 1]}$$

2. The typical input amplitude should not exceed the power rating of the internal input 50Ω terminating resistor. To produce the desired channel voltage, a current must pass through the 50Ω terminating resistor.

$$I_{sense} = V_{CH}/50\Omega \qquad \text{[Eq. 2]}$$

The power must be less than the power rating of the terminating resistor:

$P_{Rt} = I_s^2 \text{ x } 50\Omega$ [Eq. 3]

3. Calculate the value of the sense resistor (R1) by:

$R_S = nR_T - R_T$ [Eq. 4]

4. Now check the power dissipation of the sense resistor.

$P_{RS} = I_S^2 \text{ x } R_S$ [Eq. 5)

5. Also check for the loading of the circuit to be viewed. Here you must understand and determine the effects upon the targeted circuit. If the probe draws too much sense current, then the probe will change (sometimes drastically) the operation of the target circuit. A general rule of thumb is:

$Z_{probe} > 100Z_{target}$ (Eq. 6]

There are instances where the initial considerations are met, but the probe overloads the target circuit. Then one must then go back to step 1 and use a sense current lower than the current originally selected.

*Noise Considerations in the n:1 Voltage Probe Design:*

In hard-switched applications (i.e. non-resonant-transition switching) where the semiconductor switch determines the dV/dt on its drain, the switching speeds are typically less than 10 nS. This can produce real voltage and current spikes within the circuit with edges equal to or higher than the power switch. Within self-designed 50Ω probes, the transmission line effects must be considered. Every connection whether a connector connection or a solder connection, creates impedance discontinuities within the transmission line model. This creates points of signal edge reflection for the high frequency components of the signal (edges). A representative transition line model can be seen in Figure 6.

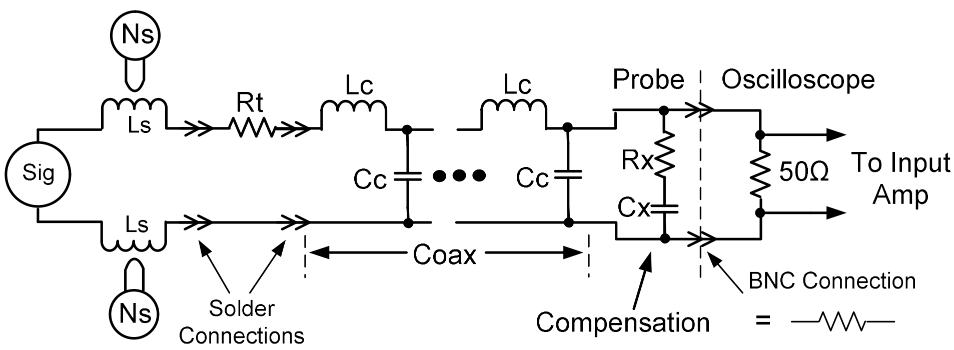
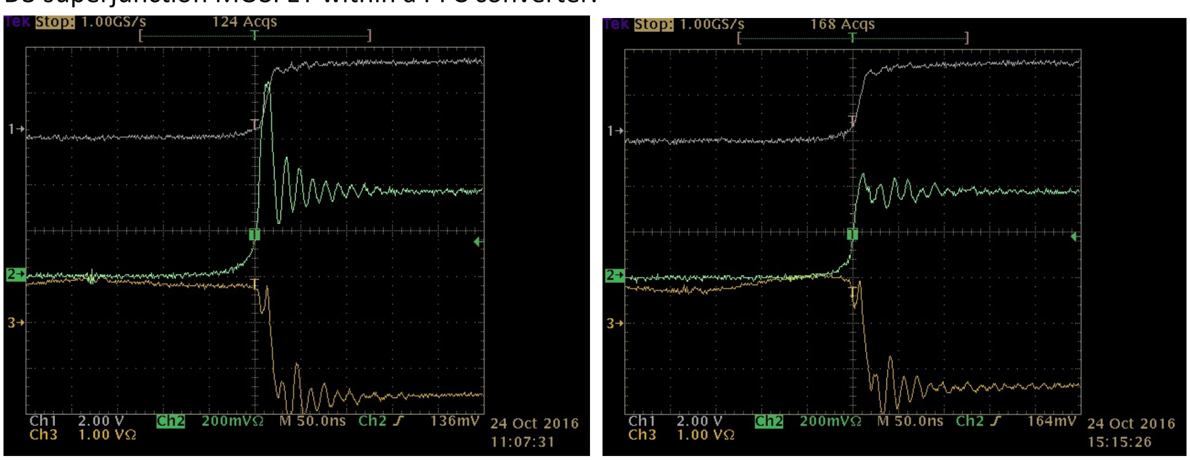



Figure 6. The n:1 Voltage Probe, Transmission-Line Equivalent Model.

The performance of the n:1 50Ω voltage probe is much more complicated than that of just two resistors. The high frequency components of the signal see the reactive elements within the transmission line model and are amplified and reflected by its elements.

The shield, essentially, forms a Faraday cylinder around the center conductor where no external E-M field penetrates. As seen In Figure 6, the lengths of the unshielded leads at the target source are susceptible to E-M noise energy and are not part of the “real” signal. This noise becomes summed into the real signal and can only be reduced by reducing the length on the sense leads (and any additional PCB trace lengths).

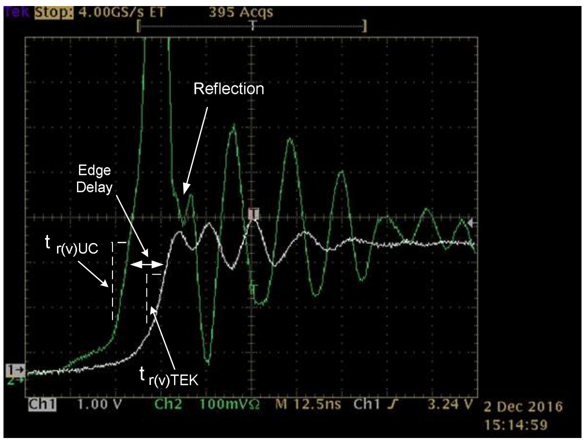
Once the signal enters the coaxial cable, the situation becomes a transmission line issue. Here the signal travels through the cable at approximately 0.67 times the speed of light. When the signal encounters an impedance discontinuity such as a connector, a portion of the signal is reflected back to the source, which is also summed into the input signal. It appears as an inverted edge and at 2 times the one-direction travel delay. Now the question is “What part of the signal is real and what part is summed-in transmission line effects?”. To reduce the effects of the transmission line effect, one can dampen the cable constituents. This is called *compensation*. This is typically done by adding a series R-C across the BNC connector signal-to-ground connections (as also seen in figure 6). Its intent is to nullify the reactive impedance presented by the coaxial cable. This will reduce the parasitically induced signal being summed into the real signal. But, nothing comes without a price. The bandwidth of the probe will be slightly reduced. By how much, is a matter of the operator’s aesthetic preferences. Figure 7A shows an oscilloscope plot of an uncompensated 1,000:1 50Ω voltage probe on the drain of a high-performance D3 superjunction MOSFET within a PFC converter.



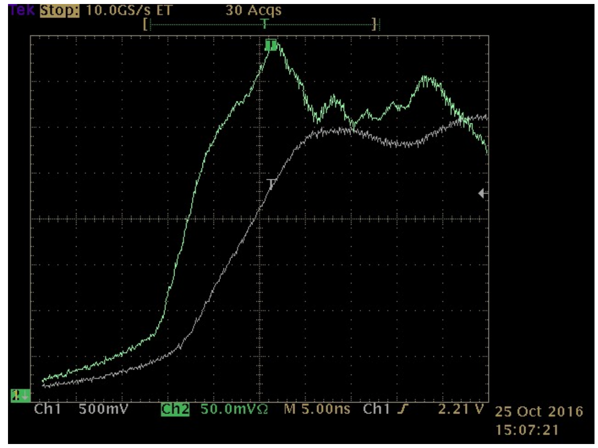

(A.) (B.)

Figure 7. Scope Plots of a 1,000:1 50Ω Voltage Probe. A – uncompensated, B. compensated with a 10Ω resistor and 470 pF capacitor. (White- VD (300MHz Tek Probe, Green – 50Ω Probe, Yellow – Drain current.

When we compare the relative rise and fall times of the drain signals as seen in Figure 8, one sees a slight reduction in the switching speeds.




(A.)




(B.)

Figure 8. Scope Plots of 1,000:1 50Ω Voltage Probe Transition Times. A. Uncompensated, B. Compensated with 10Ω resistor and 470 pF capacitor. White - 300 MHz Tek probe, Green - 50Ω Probe.

As one can see in Figure 8A, the leading edge spike and the ringing is horrendous, but it is the most accurate view of the turn-off voltage risetime ($t_{rv}$). It also shows evidence of a reflection, just behind the leading edge spike. Figure 8B is the same probe with compensation. The waveform is more aesthetically acceptable. It attenuates the ringing, but also slows the risetime (it is still better than the TEK probe). The obvious solution is to use the uncompensated probe for all rise and fall time (dV/dt) measurements and the compensated probe for all other power supply operational observations.

## The Effects of the Compensating Element Values upon the Resulting Signal.

The assignment of compensating R and C values can be attempted by attempting to model the probe system. This means trying to define the undefinable. Eventually one just has to sit on the bench and manually tweek (adjust) the final values to a *qualitative* “optimum” solution. This can be tedious, when working with small PCBs and surface mount parts which must be manually unsoldered and soldered into the PCB with every change that is made.

There are a number of R and C value combinations that result in similar results. Some tips and observations from more experienced persons may help you along the way.

1.) Don’t reinvent the wheel. The 50Ω probe is very similar in construction to commercially purchased probes. So start with the R & C compensation values used by the big companies.
2.) Larger Cs will slow your displayed rise and fall times (BW) and will lower the resonance frequencies of the reflected signals.
3.) The R affects the amount of damping of the reflected signal – to a point. R values that are too high tend to isolate the compensating capacitance from the distributed Ls & Cs of the coax cable.

This is illustrated in Figure 9.

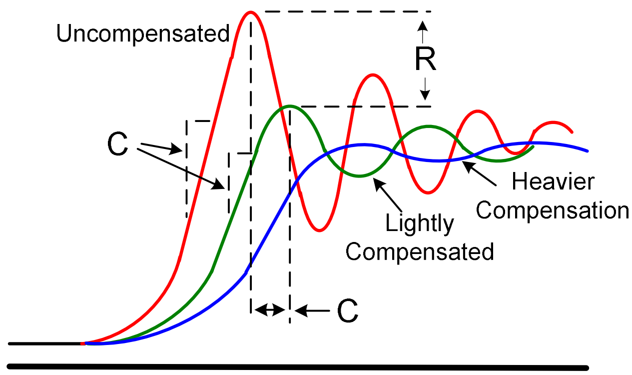



Figure 9. The Effects of the Compensating R & C upon the Output Waveform.

From my experience the optimum resistor value range seems to be from 10Ω to 47Ω. Values above this range appear to increase the amplitude of the resonant spikes on the signal. The industry appears to use a capacitance value of around 470 pF. This is a good starting point with the compensating resistor installed, try a capacitance value below and above this value. The desire is to determine the minimum value of capacitance that will yield in the desired results. Higher values of capacitance will slow the rise and fall times and the peak amplitudes of the real signal. Capacitance values of between 470 pF to 680 pF appear to result in a reasonable compensated wave shape.

## A n:1 50Ω Voltage Probe Design Example:

It is always figuratively better to look over the shoulder of someone DO'ing, than to have all of the design factors generally described.

*Requirements:* Build a 50Ω probe for a >1GHz oscilloscope to examine the power signals of a 110 – 220VAC, 300W power factor correction circuit.

*Maximum voltage:* +400VDC + any spike voltages.

*Devices under Test:*
1. D3 superjunction MOSFET, part number: D3S340N65B-U ($V_{DSS}$=650V, $I_D$=12A, $R_{DS(on)}$ = 360 mΩ(nom), $t_f$ < 6.5 nS)
2. CREE SiC Schottky Rectifier, part number: C3D04060A, (600V, 7.5A)

*Procedure:*
1. Cut a length of RG174 (50Ω) cable to approximately 5 feet (12.5 cm). Preferably, already having a BNC connector on one end.
2. Strip 0.5 inches (12 mm) for the insulating Jacket from the cable. Unbraid the shield to the jacket. Strip 0.25 in (6 mm) from the center conductor insulation.
3. Cut a length of 0.5 in (12 mm) of 0.5 in brass tubing and debur ends.

4. The maximum voltage the probe will see is 400VDC. Watch the V(max) rating of the capacitor. The desired display voltage is 100 mV per division (1000:1), which is 100 mV across the 50Ω scope terminating resistor. The current (Is) through tip sense resistor is:

   ISENSE = 0.1V/50Ω = 2 mA

   The value of the sense resistor is:

   RSENSE = (100V - 0.1V)/2 mA = 49.95 KΩ make 50 KΩ

5. Check the power dissipation in the sense resistor:

   PD(SENSE) = (2 mA)2 x 50 KΩ = 0.2 Watts

   **Note:** This power is within the power ratings of a single ¼ watt resistor, but it will get hot. I will use 2 100K, ¼ watt resistors in parallel.

6. Assemble the sense-end of the cable as in figure DE-1.

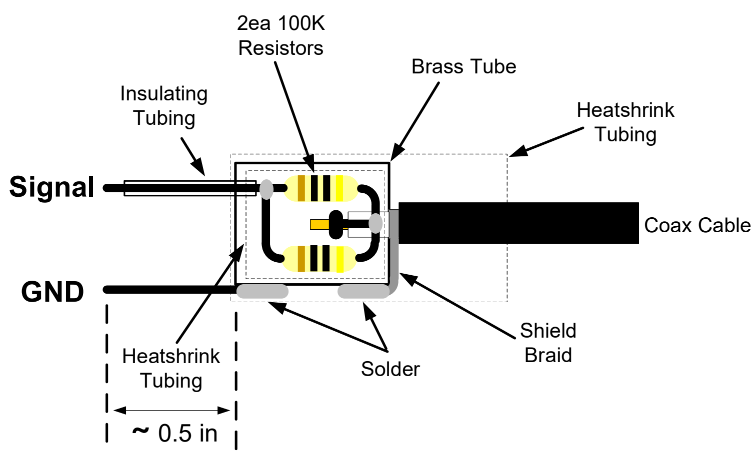



Figure DE 1. Example: Construction of a 1,000:1 50Ω Voltage Probe.

## The High Frequency Current Probe:

The common commercially available current probes have bandwidths from 60 to 120 MHz. Viewing the high frequency current wave form is important for estimating the switching losses within the high frequency semiconductor switches. So a higher bandwidth current probe may be desired. An example current probe can be seen in Figure 10.

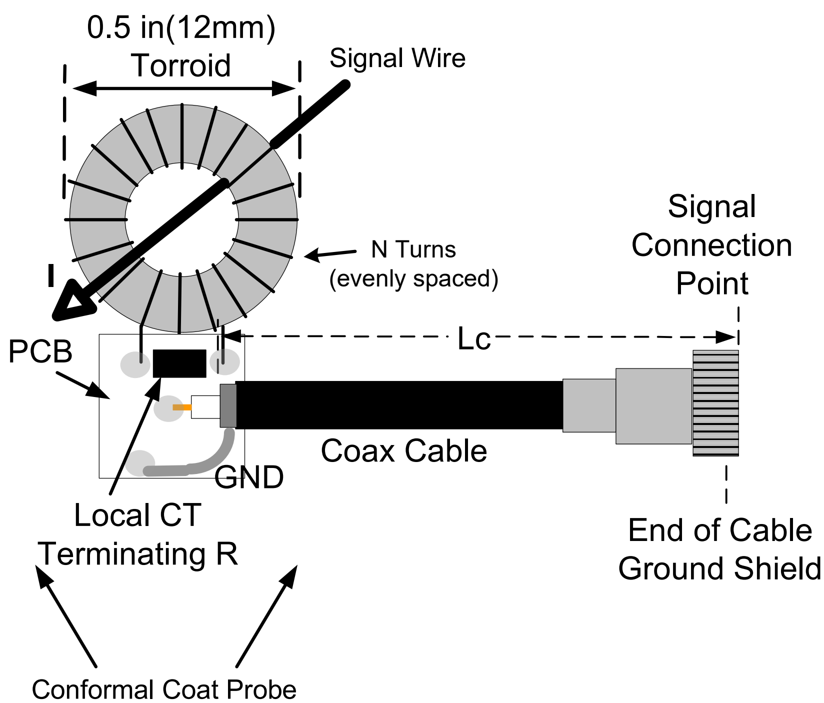



Figure 10. A High Frequency Current Probe.

The current probe, shown in Figure 11, is essentially a 1:n forward-mode, transformer, with a high leakage ¼ turn primary. Since the primary is not an ideal 1 turn, its final accuracy will be addressed during its final calibration. The secondary turns are placed evenly around the toroid core.

The preferred construction is shown in Figure 10. It is important the terminating resistor be placed immediately adjacent to the wound toroid. This does not allow the transmission-line effects of the coax cable to be a significant portion of the oscilloscope input signal by not allowing high signal currents to enter the cable. The oscilloscope termination should be set to 1MΩ. The impedance of the circuit branch through which the current is being measured, should be very low. The reflected impedance (*insertion impedance*) of the current probe should be kept as low as possible (low Rt) and still provide the desired amplitude for the oscilloscope input. .

The current induced on the secondary winding is:

$$I_{SEC} = I_{PRI}(n_1/n_2) \qquad \text{[Eq. 7]}$$

To convert this current into a voltage displayed on an oscilloscope, one places a resistance across the secondary winding. This resistance can be any value, but the higher the resistance value, the more back EMF is placed on the primary's target circuit, which manifests itself as an additional voltage drop in series with the target's current path. This does affect the primary's current flow, and its accuracy. The amount of this error is proportional to the value of the resistance placed on the secondary.

The range of AC currents that are typically observed by the current probe can range from 100's of amperes (1 kW supplies) down to milliamps (gate drive circuits). One current probe cannot address this range and still fall within the input dynamic range of the oscilloscope input. Hence several current probes are required, with differing turns ratios for the various current levels within a high frequency switching supply. The turns ratios are not cast in concrete, the common ratios are:

| | |
|---|---|
| 25:1 | 10 – 20 amps |
| 50:1 | 1 – 10 amps |
| 100:1 | 0.5 – 1 amp |

Since the secondary current is small, the wire gauge need only be #32 AWG.

The terminating resistance can be estimated by:

$$R_{CS} \approx (n2 \times V_{OUT(max)})/(n1 \times I_{PRI(max)}) \qquad \text{[Eq. 8]}$$

The current probe shown in Figure 10, used a SMD resistor, so a small PCB was needed to mount the resistor and to anchor the end of the coax cable. It is important to conformally coat the entire current transformer assembly since the windings are very fragile and the coax cable can present a lot of mechanical stress to the current probe.

*Issues and Calibration of Current Transformer Probes*.

As with every AC coupled circuit, the AC current signals are passed to the secondary, but the DC portion of the output auto-corrects to zero. The DC "zero" average is at a point in the output waveform where the average positive value equals the average negative level. The short-term average zero point will vary within each signal period. Figure 11 shows this time-dependent phenomenon. Each current probe has its own time constant. This can be measured and characterized by placing a low frequency pulsed current through the primary as seen in Figure 11.

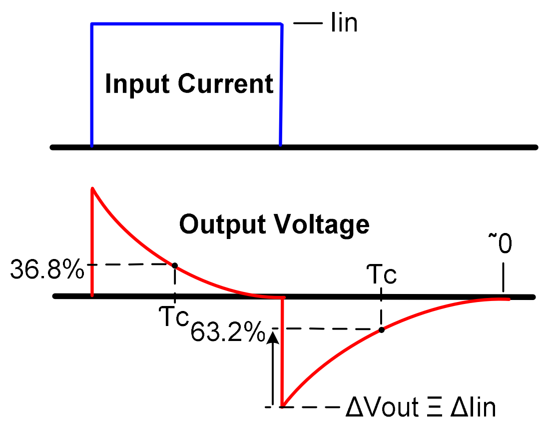



Figure 11. Calibration and Determining the Time Constant of the Current Probe.

The time constant causes distortion of the current waveform as can be seen in Figure 12.

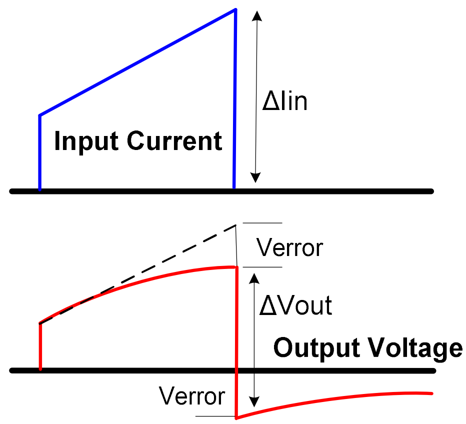



Figure 12. Current Display Error Caused by
the Transformer Time Constant.

The time constant is approximately:

$$\tau_C \approx L_{SEC}/R_{TERM} \qquad \text{[Eq. 9]}$$

It is approximate because the secondary is not a free-standing inductor, but has coupled loading from the primary. (refer to Appendix A)

When calibrating the current probe with a digital oscilloscope, one must be mindful of the sampling. When placing a low frequency rectangular current signal into the CT's primary, the oscilloscope's samples do not always coincide with the peak output voltage points. This requires one to input many input current pulses and find the output voltage peak of the highest value.

You may ask: "What data can I trust from a current Probe?". The useable (most trustworthy measurements where the distortion-induced error is very small) data is:

1. All high speed transition magnitudes.
2. Signal waveforms that have a much smaller period than the time constant of the current probe.
3. Period (time) measurements between transitions.
4. Rise and fall times that are much smaller than ($tr \lesssim 0.05\tau_C$) the probe's time constant.

Wave shapes that have periods comparable to the time constant will be distorted by the time constant. The time constant is summed into the actual signal. An example of this distortion phenomenon where the signal period is greater than ½ that of the time constant can be seen in figure 13.

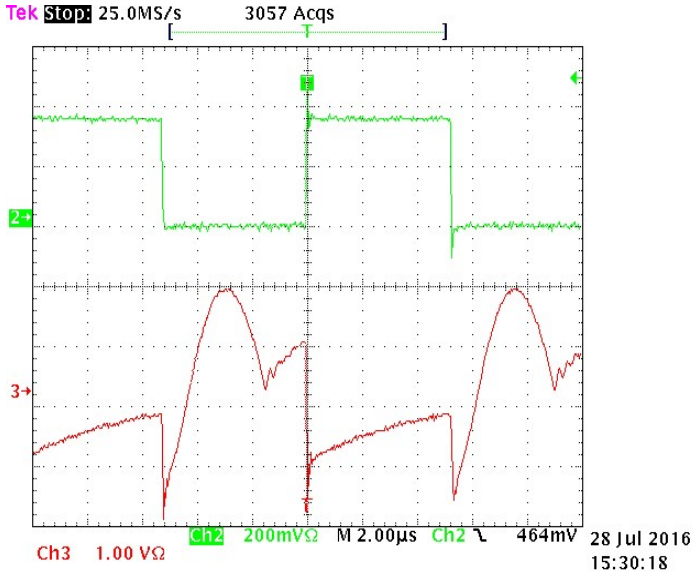



Figure 13. An Example of Current Probe Distortion when the Signal Period is Nearly Equal to the Probe's Time Constant. (ex. LLC Grn – Vdrain, Red – I drain)

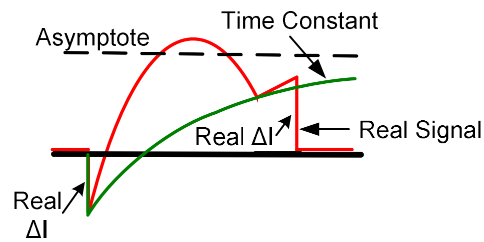



Figure 14. Current Probe Signal Components.

Figure 14 shows how the actual signal appears as it would appear when viewed across a current sense resistor in the same position within the target circuit. It is mathematically impractical to mentally subtract the time constant from the displayed signal with any accuracy. Hence the statement about display trustworthiness away from the current transitions. Of course, one could spend a lot of money on a commercially available magnetic "DC" current probe which does the math for you, but the bandwidth would be too low.

Figure 13 shows the $V_{DS}$ and $I_D$ of a 110 kHz off-line LLC converter's lower MOSFET. The voltage waveform (top) is from a 50Ω voltage probe and is undistorted. The lower curve (bottom) is the drain current. It shows a great deal of distortion. The current probe had 25 turns, a terminating resistance of 50Ω, and a time constant of 14 uS.

## Design Example: 10A High Frequency Current Probe.

This example overviews the design procedure for a 1 A to 10A current probe intended for >10 KHz, switching power supplies.

The first choice is what *core material* to use. Without getting into a lengthy magnetics tutorial, what is needed is a low permeability (µ), high frequency material. The permeability is the amount of current within a winding to produce a given change in the flux density (number of lines of flux) within the core. At high flux densities, the core begins to *saturate* (the permeability decreases and is no longer linear). This is a situation you do not want to occur!

A single closed, magnetic loop is required to channel the wire's radiated magnetic field (proportional to the current) within the core. A toroid or a gapped U-I ferrite core can be used. The ferrite core presents a mess of additional factors (fringe field effects, eddy currents due to corners, etc) that you do not want to consider. The ideal core is a *Mopermalloy Toroid*. This material is a mixture of molybdenum (a non-magnetic gap material) and ferrite. The higher the molybdenum content, the lower the permeability. A wider bandwidth is also gained by a low µ. For reasonable wire diameters, as found in low-medium switching power supplies, a good choice is a 13.5 mm (0.5 inch) toroid core (Magnetics Inc. part number **55051A2**). Larger core sizes can be used for larger diameter wires.

The common number of turns are: 25, 50, 100. A different number of turns is quite allowable. The more turns, the more voltage can be developed across a series resistor across the winding ends.

1. For my drain current I chose 25 turns which is a reasonable choice with the 0.5 to 10 A current range flowing into the drain. I also want a 1 V per ampere output. The terminating resistance should be:

   $$RT \approx (n2 \times V_{OUT(max)})/(n1 \times I_{PRI(max)}) = (25T \times 1V)/(1T \times 1A)$$
   $$= 25\ \Omega\ \ 1\%$$

   The wire gauge will be #32 AWG insulated magnet wire.
2. Wind the wire around a toroid <u>evenly</u> around the core. This helps contain the secondary wire-generated flux within the core.
3. On a small PCB or perf board, attach the wire ends to the terminating resistor. The PCB is also intended to anchor the coax cable to the PCB and terminating resistor, since the coax cable will present a lot of mechanical stress to the coil/PCB assembly. (see figure 10)
4. Test the probe with a 1A pulsing current to verify the peak transient voltage is 1 V. (see figure 11). If not, this is the time to try resistors close to 25Ω to generate a 1V peak transient value.
5. Conformally coat the entire toroid/PCB assembly. Epoxy works very well. Make sure there is a clean, but coated hole in the center of the toroid.
6. Calibrate the current probe by conducting step 4 (above) and measuring the time constant of the current probe (see figure 11).

The same procedure can be used for current probes of differing current ranges.

## Conclusions:

Many commercially available voltage and current probes do not have the bandwidth needed to view the high frequency current waveforms, and edges exhibited by high frequency power devices. To view the "real" signals, the designer really needs to build his or her own voltage and current probes. The probe construction presented within this paper are "middle of the road" designs and are a good starting point for a new probe design.

## Appendix A:

The following is the method for calculating the inductance of an inductor with known turns on a known core. This calculation is for an elementary inductor (1 winding, 1 core) without any loads reflected from other windings on the core such as within a transformer (>1 winding, 1 core).

$$L = n^2 \times A_L$$

Where:

L: inductance in Henries

n: number of turns

$A_L$ :Inductance Factor in $nH/T^2$ (provided by the core manufacturer).