

Voltage immunity

Abstract

All measuring instruments are subject to limitations. The purpose of this technical note is to explain some of those limitations and to help the engineer maximise the many advantages of PEM’s CWT current probes based on Rogowski technology. This note discusses the ability of the CWT Rogowski probe to reject interference from voltage fields coupled to the Rogowski coil, as these fields vary with both magnitude and frequency. This is particularly relevant when using Rogowski coils to measure current in fast switching semiconductors where voltage transitions close to the coil result in a harsh measurement environment.

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1. Screened (shielded) vs. unscreened Rogowski coils

Figure 1. shows a Screened and an Unscreened Rogowski coil. Screened coils are also commonly termed ‘shielded’, ‘E-field shielded’ or ‘electrostatic shielded’ Rogowski coils.

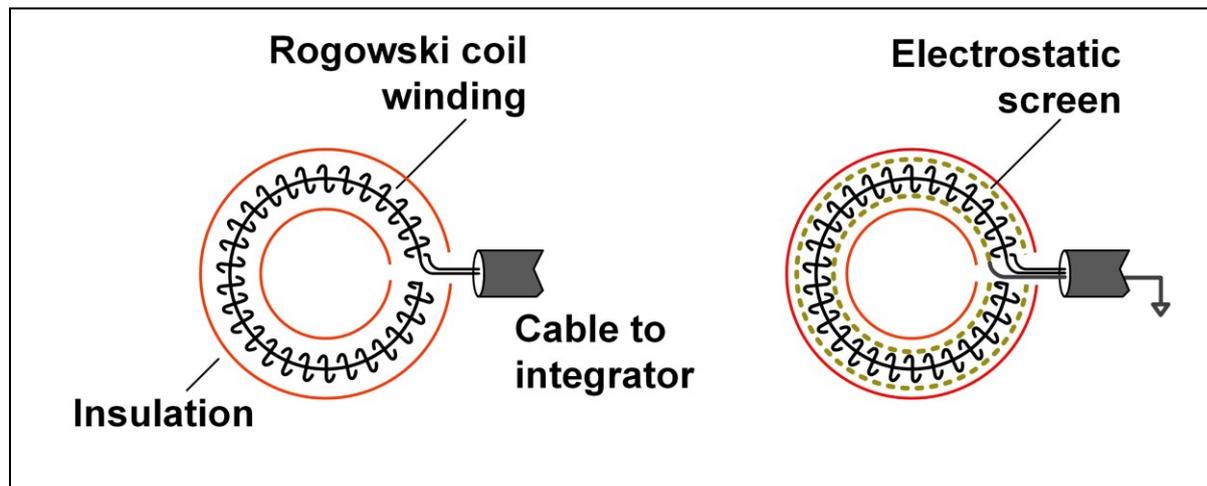


Figure 1. Screened and Unscreened coils

The screen typically takes the form of a metal braid, foil or tape on top of the coil winding but underneath the coil insulation.

The Rogowski coil sensitivity (Vs/A) determines the inherent signal-to-noise ratio (SNR) of a given Rogowski current probe. The Rogowski coil sensitivity is proportional to the thickness of the coil and the turns density of the coil winding.

The high frequency performance is determined by the inductance of the coil winding and the capacitance between the winding and the screen, and the central return conductor if it is present.

The major **advantages of Unscreened Rogowski coils**, are that for a given coil sensitivity

- they typically have a lower capacitance and therefore a higher bandwidth for a given coil sensitivity.
- they can be smaller and more flexible than the screened equivalent, for a given SNR.

The major **advantages of Screened Rogowski coils**, are that

- they can significantly attenuate interference due to voltage transients close to the Rogowski coil which are capacitively coupled to the coil winding. In recent years with the introduction of new GaN/SiC switching devices $dV/dt > 20V/ns$ are common, making screens a necessity.
- at frequencies $>3MHz$ screened coils produce the most predictable frequency response. This is because the coil capacitance is closely controlled, and coil impedance is unaffected by the measurement environment.

2. CWT ‘HF’ screened Rogowski probes

PEM has been selling the wide-band CWT range of Rogowski coils to power electronics engineers since 1991. The challenges of faster semiconductor switches, in more compact converters, with higher blocking voltages have led to the development of the CWT ‘HF’ ranges which come in a variety of coil sizes.

2.1 What does ‘HF’ mean?

PEM have a number of High Frequency (HF) CWT current probes, including the CWTHF and the CWTMini50HF. The differentiating features of these products include;

- They have screened coils, thus significantly improved immunity to interference from voltage (electrostatic) fields.
- Optimised for high frequency performance, better (-3dB) cut off and slew rate.

However the standard CWT, CWTLF and CWTMini versions have better low frequency performance for a given coil thickness. A simple comparison table is given below

Model	High frequency (HF) optimised	Low frequency (LF) optimised	Screened coil	Coil Thickness [Insulation voltage]
CWTHF	✓		✓	8.5mm [10kV peak]
CWT (and CWTLF)		✓		
CWTMiniHF	✓		✓	4.5mm [5kV peak]
CWTMini [5kV peak]		✓		
CWTMini50HF	✓		✓	3.5mm [2kV peak]
CWTMini [2kVpeak]		✓		

Table 1. A comparison of the CWT ranges

It should be noted that PEM Ltd can screen any of our coils. For example, we often supply screened versions of the CWTLF for high current measurement in applications such as short circuit testing.

If you have any custom enquiries please [contact PEM](#)

PEM have published several academic publications and a patent relating to high bandwidth screened Rogowski coils, the key publications are <http://www.pemuk.com/publications.aspx>.

- C.R. Hewson and W. F. Ray, “The effect of electrostatic screening of Rogowski coils designed for wide-bandwidth current measurement in power electronic applications” IEEE-PESC Conference Proceedings, Aachen 2004
- C.R. Hewson and J.M. Aberdeen “An improved Rogowski coil configuration for a high speed, compact current sensor with high immunity to voltage transients” IEEE-APEC Conf. Proc 2018

3. Voltage rejection with frequency – Common mode voltage rejection

All our CWT probes are CE marked and are third party tested to

IEC 61326-1:2013

Electrical Equipment for measurement control and laboratory use – EMC requirements. General Requirements.

As part of these tests the susceptibility of the probes to radiated E-fields are included, however the acceptance criteria are often at the discretion of the manufacturer, so it is hard to compare different manufacturers’ probes on this basis.

PEM have developed a simple test to compare the susceptibility of our probes to close coupled voltage fields over a wide frequency range. This is shown below:

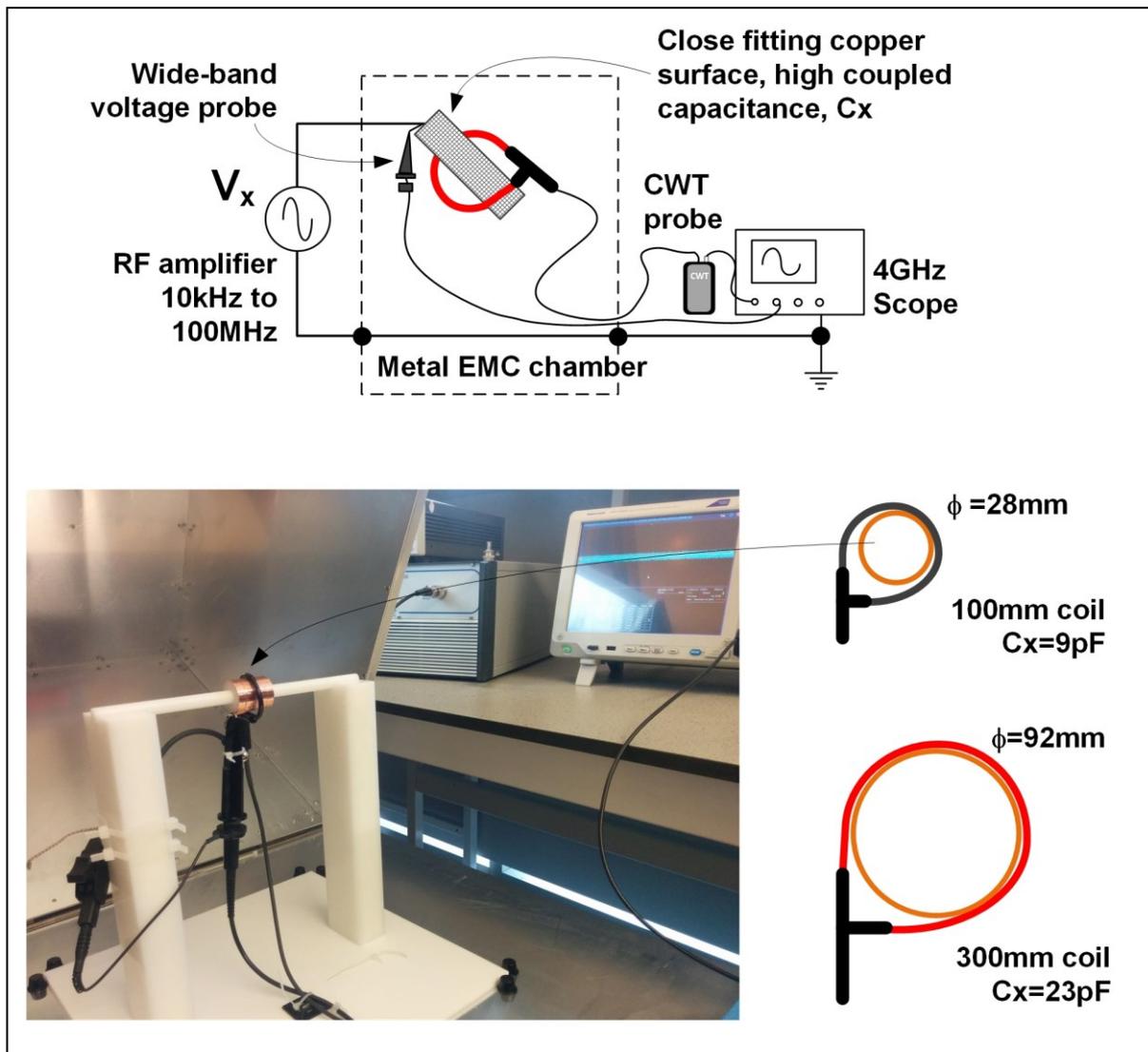


Figure 2. Test set-up for determining voltage immunity

The amplifier is capable of generating 40Vrms, 100kHz to 100MHz, a frequency range that reasonably mimics commonly encountered voltage slew rates in power converters. The Rogowski coil is clipped around the copper conductor which is changed to fit the coil size very closely and maximise the coupled capacitance (a real worst-case scenario).

The electronic integrator is located outside the chamber and next to the oscilloscope. Although the integrator electronics has significant EMC screening, the long cable between the coil and the integrator is intended to keep the electronics positioned away from the very harshest measurement environments.

There is no current flowing in the conductor in Figure 2. A 4 GHz oscilloscope records the integrator output voltage resulting from the coupled voltage V_x . The coupling capacitance is large and shown in the results of Figure 3.

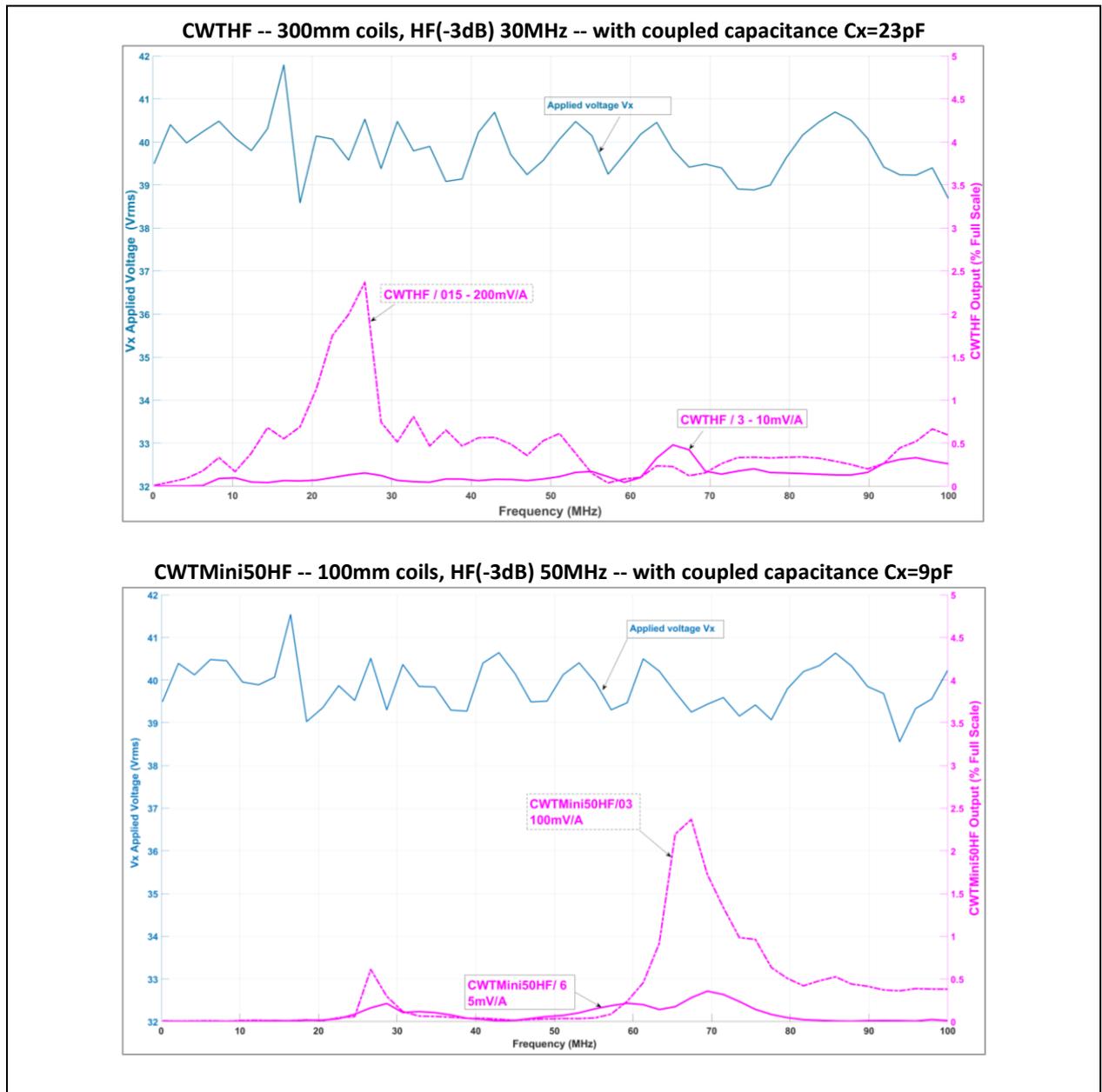


Figure 3. Voltage output from the probe as disturbance voltage V_x sweeps from 80kHz to 100MHz

4. ‘Real-world measurements’ in fast switching power converters

To achieve a fast switching time and rate of change of voltage (dV/dt) similar to that encountered in the fastest Si and SiC switches PEM have developed a test rig using a GaN semiconductor switch to generate a 50A peak current with a rise-time of 12ns, see Figure 4.

The CWTMini50HF 3/B/1/100/2 probe (sensitivity 10mV/A, (-3dB) 50MHz) measures the current in the presence of a close coupled voltage transient of 40V/ns. The reference device is a DC to 2GHz shunt at earth potential.

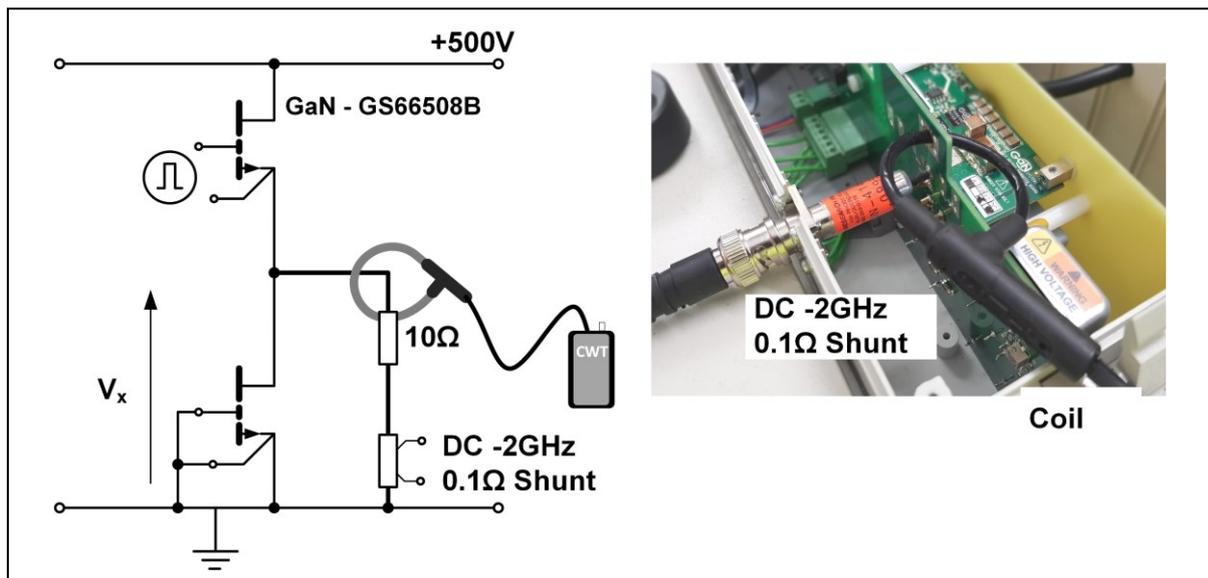


Figure 4. Fast switching circuit

Figure 5. shows the de-skewed (delay compensated) measurement with no noticeable interference from the voltage transient. The scope has an analogue bandwidth of 1 GHz.

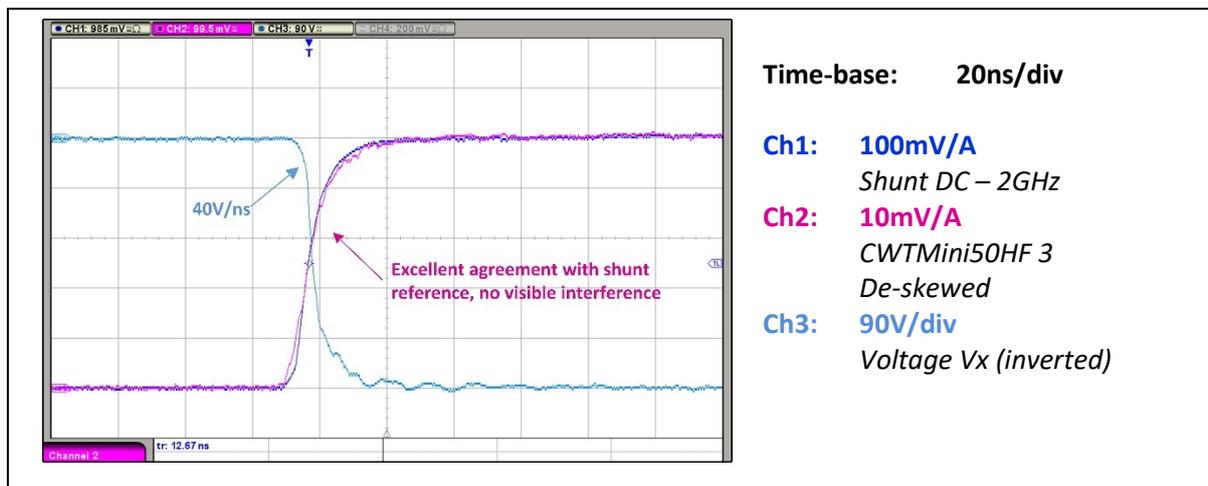


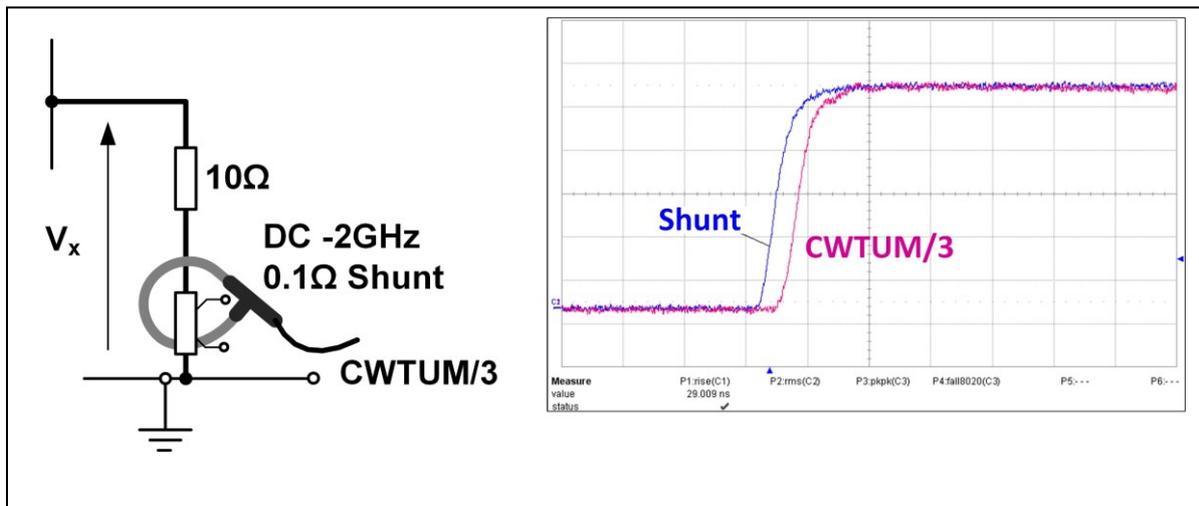
Figure 5. Measurement of 12ns / 50A current transient with local dV/dt 40V/ns

5. CWT Ultra-mini – voltage immunity

In some applications in power electronics a coil which is smaller and thinner than the CWTMini50HF is required to get around very small conductors. The CWT Ultra-Mini, with a coil thickness of 1.7mm and circumference of 80mm, is often used in these instances. Although the CWT Ultra-Mini has a high bandwidth, of 30MHz (-3dB), it does not have a shielded coil.

Although the CWTMini50HF, with a superior 50MHz bandwidth and screened coil, will always produce a better measurement there are a couple of techniques that can be used to avoid excessive interference from fast voltage transients when using an unshielded coil.

The first technique is simple; with reference to Figure 4. if the coil can be placed in the same position as the DC shunt, away from the dV/dt interference, near the ground plane, this will certainly improve the measurement though typically not as effective as a screen. The measurement can be seen in Figure 6.



**Figure 6. Measurement of 30ns rise-time 50A at the 'quiet' earthed end of the circuit
Time-base 50ns**

If the coil cannot be placed away from a high dV/dt then a second suggested technique requires use of the MATH function on a digital storage oscilloscope or software to post process the measurement.

The three steps required to achieve such a measurement are explained graphically in Figure 7.

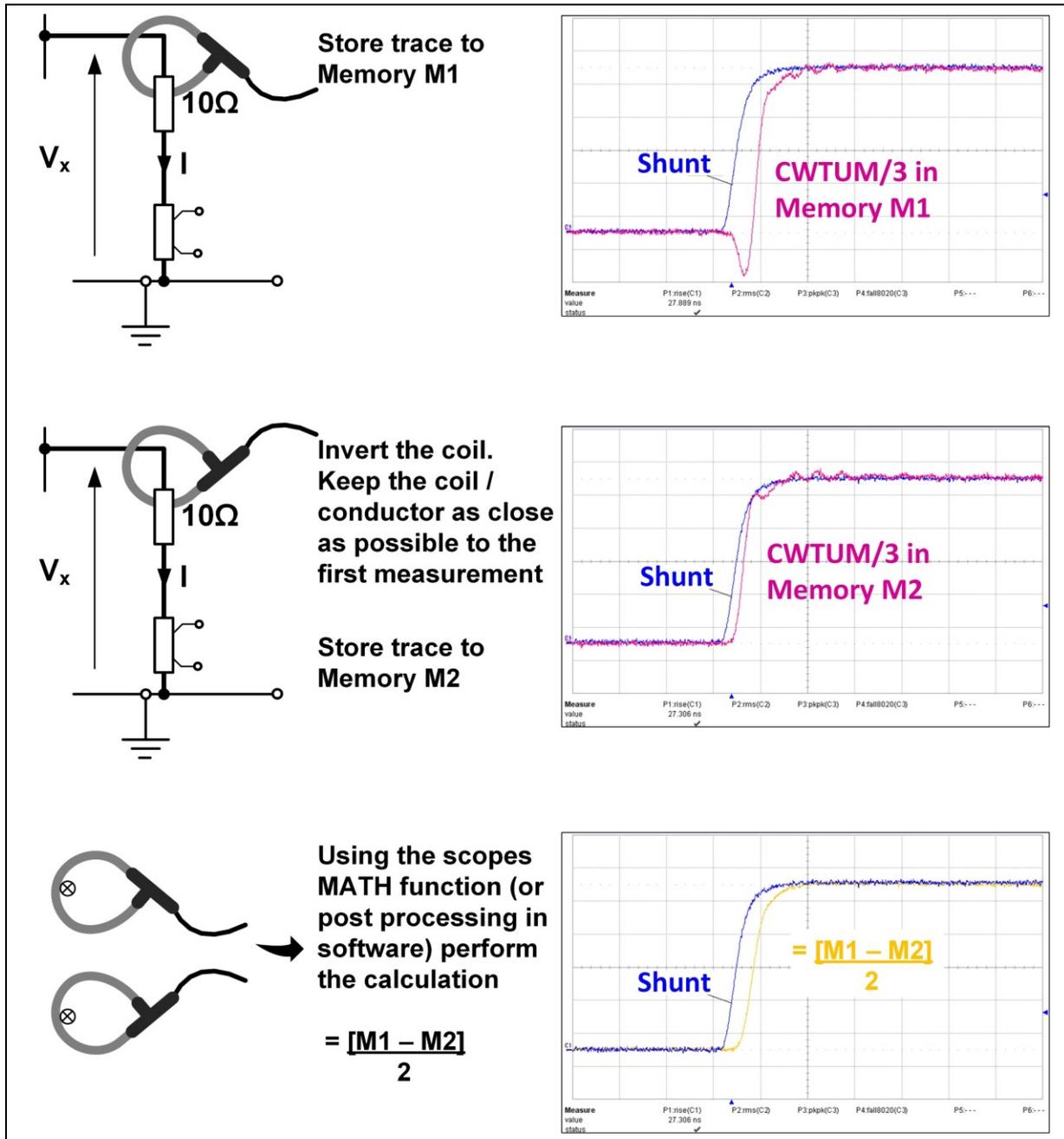


Figure 7. A technique for reducing voltage interference on the CWT UM
Time-base 50ns/div

If the last trace of Figure 7. and the measurement of Figure 6. are compared it is clear that these two techniques offer a way of reducing the effect of voltage interference when using PEM’s thin, unshielded, CWT Ultra-mini coil.

6. Large magnitude 50/60Hz fields

Rogowski probes are often used for measuring power frequency currents or small magnitude high frequency harmonics in the presence of large 50/60Hz voltages.

The CWT can be supplied with a Rogowski coil insulation of up to 10kV peak.

Therefore, it is instructive to quantify how well Rogowski coils reject interference from 50/60Hz voltages when there is no current in the conductor.

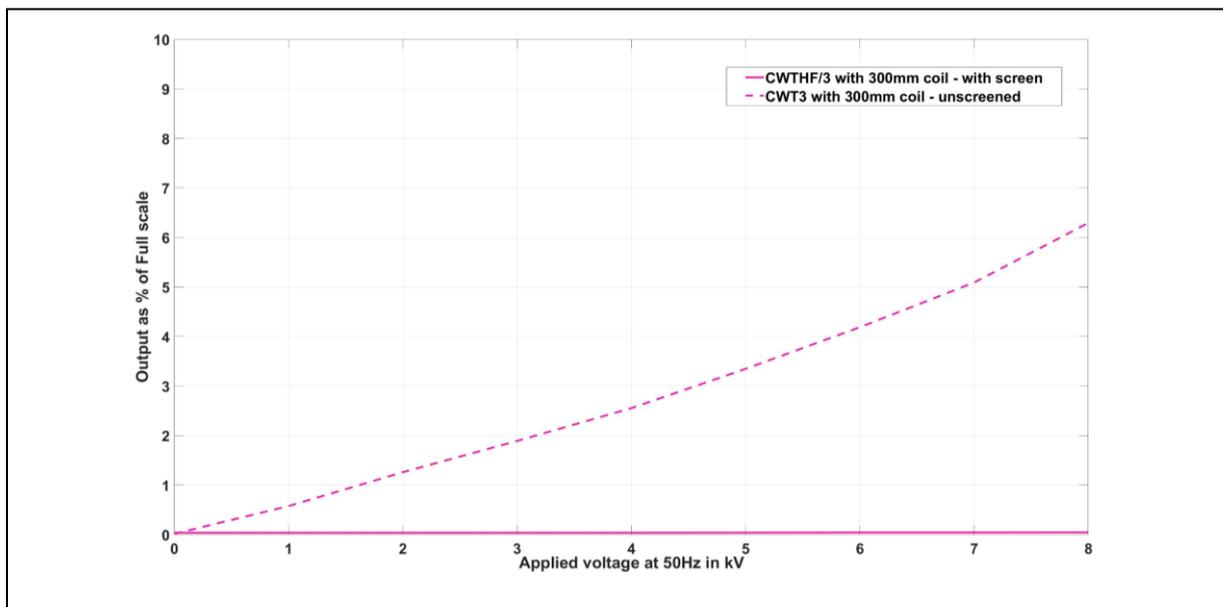


Figure 8. Applying 0 to 8kVrms on a close coupled surface to the Rogowski coil, Coupled capacitance $C_x = 23pF$

Figure 8. shows the difference between a CWTHF 3 (Low frequency (-3dB) 12Hz) and a CWT3 (low frequency 1Hz). Both probes have a sensitivity of 10mV/A.

The coils use a close fitting, high coupled capacitance conductor as shown in Figure 2. on which the 50Hz voltage is applied.

The graph shows the significant improvement of the screen on the CWTHF 3 measurement. Even at 8kVrms the pick-up remains less than the quoted datasheet 'Noise max'. In contrast, the standard CWT3 gives an error of around 6% full-scale when an 8kVrms source is very closely coupled to the coil.

7. Peak voltage coil insulation ratings

The various CWT ranges of Rogowski current probes are intended for instrumentation use and not for permanent installation on equipment. The Peak Voltage Insulation ratings for these probes reflect the fact the transducers are not to be used continuously at high voltages.

- The CWT Rogowski coil supplied by PEM meets the insulation requirements detailed in EN61010-2-032:2012 regarding the safety of current probes and is third party assessed to this standard.
- **EVERY** CWT Rogowski coil supplied by PEM is tested to establish the peak voltage insulation rating. The rating is derived from exposure of the coil to the following test voltage:

AC test voltage (kV) = (2 x Peak Voltage Rating + 1) / $\sqrt{2}$ (kV), for 60 seconds at 50Hz.

For safe operation the user should visually inspect the Rogowski coil and cable for insulation damage each time the probe is used. Typically the Rogowski coil has at least two layers of insulation. These are different colours making visual inspection of the integrity of the insulation easier.

It is imperative that the user grounds the output BNC connector from a safety viewpoint so that in the event of an insulation breakdown at the coil (due to exceeding the voltage rating or due to mechanical damage), a fault current path exists via the co-axial cables to the grounded BNC connector. The practice of “floating the oscilloscope” which results in the BNC connections being isolated from ground is strongly deprecated.

PEM’s Rogowski coils can be damaged by exposure to corona over a reasonably long period of time. The Rogowski coils for the CWT have been designed for intermittent use at voltages no greater than the peak voltage to ground specified by PEM. For these conditions the effects of corona are small and the degradation of coil insulation is negligible.

For CWT coils that have an insulation rating of 5kV peak or 10kV peak:

- ***For voltages to ground of less than 3kV peak (i.e. 2kVrms for a sinusoidal voltage)***

Corona effects will be negligible, and continuous operation is permitted.

- ***For voltages to ground of more than 3kV peak***

The coil must be sufficiently distanced from the high voltage conductor or device, using air and / or insulating materials such that corona does not occur in the vicinity of the coil. Sharp corners should be avoided on the high voltage structures near the Rogowski coil as they lower the voltage at which corona begins. PEM has no control over how its customers install Rogowski coils, and hence the responsibility for long continuous life when operating in a HV environment lies with the customer.

- ***DC voltage and the coil peak insulation rating***

In most cases the equivalent **DC voltage insulation** rating can be derived from the **AC rms** insulation rating (for a sinusoidal waveform). For example, for a CWTMini50HF coil with a 2kV peak rating of the coil the DC equivalent rating would be $2\text{kV}/\sqrt{2} = 1400\text{V DC}$.