Low Frequency Bandwidth, Noise and Droop

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 defines the terms used to describe the low frequency performance of the CWT ranges of ac current probes and provides practical examples of measurements of low frequency bandwidth, noise, and droop.

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Power Electronic Measurements Ltd
Nottingham ▪ UK
Tel: +44 (0) 115 946 9657
Fax: + 44 (0) 115 946 8515
Email: info@pemuk.com
Web: www.pemuk.com

1. Low Frequency (-3dB) Bandwidth

A Rogowski coil has an output proportional to the di/dt, or rate of change of the current, of the conductor inside the Rogowski loop. The signal from the Rogowski coil is integrated to give an output which is proportional to the measured current (V/A) using an electronic integrator. The integrator gain increases as the frequency is reduced.

In theory, the gain of the integrator becomes infinite as the frequency approaches zero. It is necessary to limit the low frequency bandwidth otherwise the low frequency noise and DC drift of the integrator would be excessive. The low frequency bandwidth is limited using a low pass filter in parallel with the integrating capacitor as illustrated below.

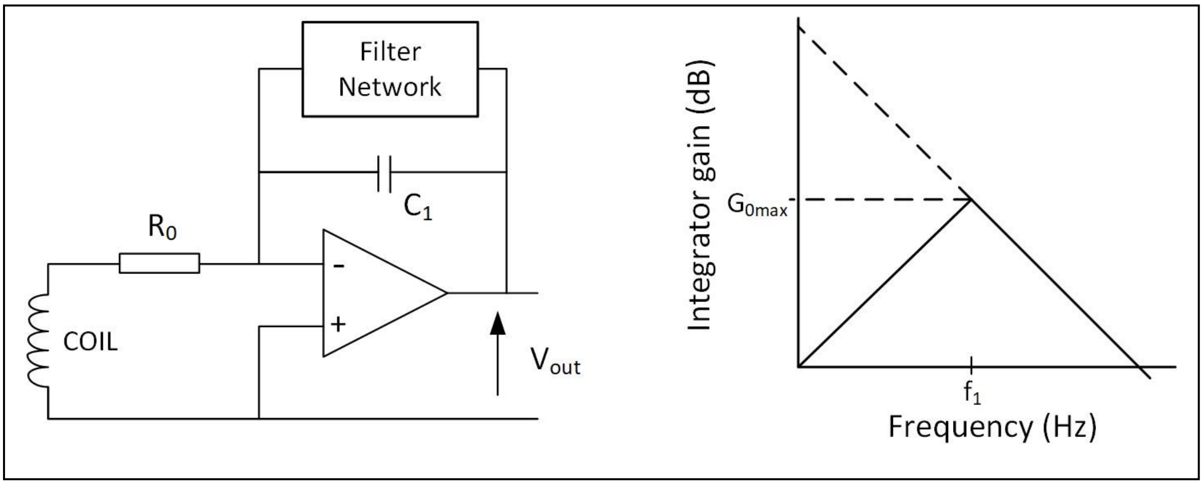


Figure 1. Simplified integrator block diagram and an illustration of the maximum integrator gain and low frequency roll off

Selecting the low frequency bandwidth is a compromise between:

1. The maximum low frequency noise (see Section 2)
2. The droop (see Section 3)
3. The high frequency bandwidth

As the Peak current rating of a given CWT probe increases, the overall sensitivity (V/A) decreases, and the gain of the integrator is reduced. To keep the noise for any given CWT probe below 20mVp-p (which represents <0.1% full-scale output) the low frequency bandwidth reduces as the peak current rating increases. This is illustrated in the theoretical bode plot of Figure 2. which shows the change of low frequency bandwidth for the CWT Ultra-mini (CWTUM) range.

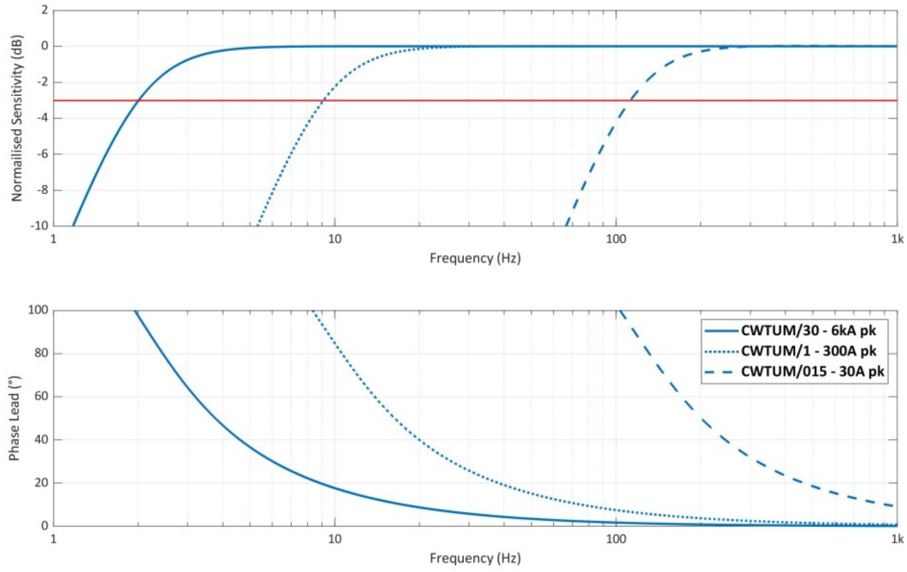


Figure 2. Theoretical Low frequency bandwidth of the CWTUM product range reduces as the current rating increases
*CWTUM/30 (**6kA peak,** LF bandwidth 2Hz)*
*CWTUM/1 (**300A peak,** LF bandwidth 9.2Hz)*
*CWTUM/015 (**30A peak,** LF bandwidth 116Hz)*

The low pass filter is designed using low drift, high tolerance passive components which result in a predictable and repeatable:

- Low frequency bandwidth
- Phase lead in the current measurement at low frequency

Where the phase of the current measurement is important it is possible to compensate for the phase shift by referring to the theoretical bode plot.

If you have a specific requirement and need to know the gain / phase of a certain model over a particular frequency range please contact PEM. Theoretical and measured low frequency bode plots for the CWT range can be supplied upon request.

2. Noise

The CWT generates low levels of internal noise which is listed in the product specification as 'Noise Max'. The noise includes broadband noise, which is typically very small, and the low frequency or 1/f noise which tends to dominate. The low frequency noise is a random noise which is distributed around the low frequency bandwidth where the gain of the integrator is at a maximum.

The 1/f noise for each model is limited by adjusting the low frequency bandwidth of the integrator as described in Section 1. For higher sensitivity models, where the integrator gain is necessarily large, the low frequency bandwidth is increased to maintain an acceptable noise level (typically <20mVp-p, which represents <0.1% full-scale output).

The frequency content of the noise will vary depending upon the model and the low frequency bandwidth. Figure 3. shows an example of the Voltage Noise Spectral Density (V/√Hz) measured at the output of the CWTUM/1 (300Apk). The peak noise density occurs around 9.2Hz which corresponds to the low frequency (-3dB) bandwidth of the CWTUM/1 (see Figure 2).

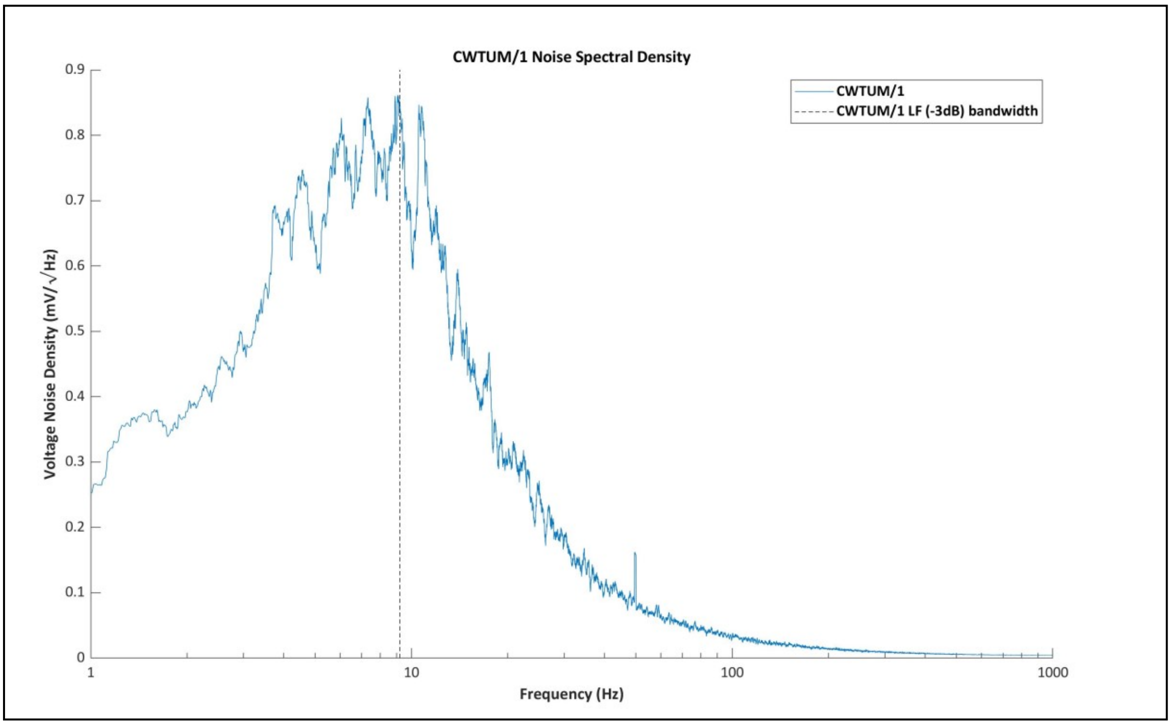


Figure 3. Voltage noise distribution of the CWTUM/1

PEM specifies the maximum low frequency noise on the datasheet as a Peak to Peak voltage because the CWT is mostly used as an oscilloscope probe. The 1/f noise follows a normal (Gaussian) distribution which means that the Peak to Peak noise voltage is typically six times larger than the corresponding RMS noise voltage. Figure 4 shows the measured peak to peak noise for the CWTUM/1 and the corresponding RMS noise for the same measurement.

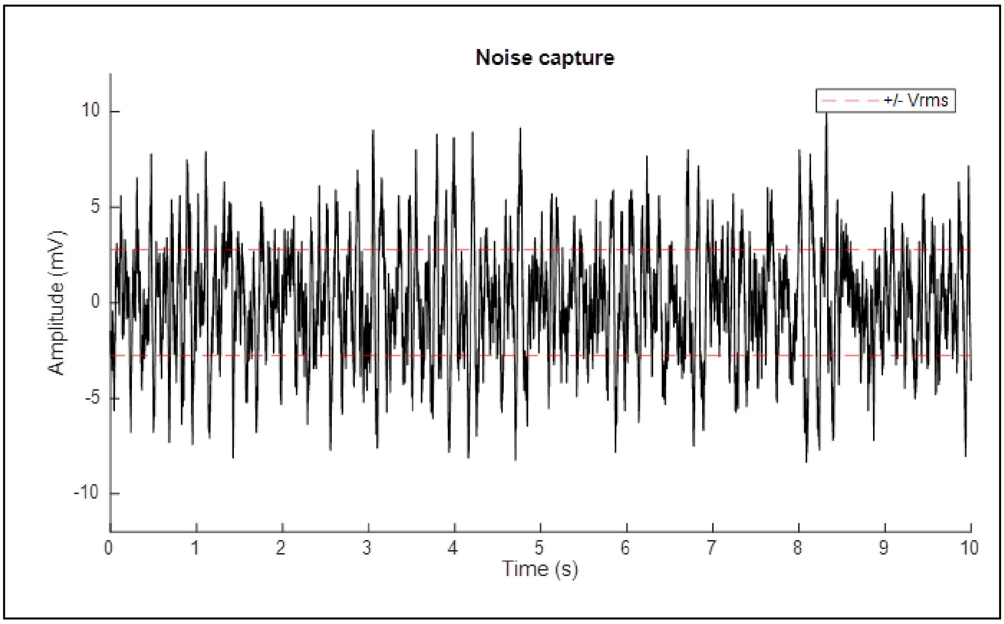


Figure 4. Noise capture of the CWTUM/1 (RMS = 2.4mV)

As a general rule, for customers using the CWT probes with an oscilloscope, we advise the dynamic range of the CWT is approximately 100:1. This ensures that the minimum current is at least five times greater than the 'Noise Max' quoted for the probe.

Using the CWTUM/1 as our example; the CWTUM/1 has a 'Peak Current' rating ±300Apk, and so the recommended minimum current would be +/-3Apk based on a 100:1 dynamic range. This is more than five times the 'Noise max' of 15mVp-p (±0.38Apk) quoted on the datasheet.

The recommended minimum current is selected to ensure the best accuracy across the full bandwidth of the probe. However, with the noise predominantly centred around the low frequency (-3dB) bandwidth it is possible to resolve even smaller currents at higher frequency. More detailed information on this is supplied in the Technical notes relating to Accuracy.

It is possible to reduce the 1/f noise of a design by increasing the Rogowski coil sensitivity (Vs/A) which results in a lower integrator gain. However, the consequence of increasing the coil sensitivity is usually a reduction in the high frequency bandwidth or an increase in the cross-sectional area of the coil (or both).

Noise measurements for a variety of CWT models can be found in the Appendix.

3. Droop

3.1 Droop of a Single Pulse

For non-sinusoidal current waveforms (such as PWM or rectified current) the effect of the phase displacement at low frequencies can cause some distortion of the measured waveform. This also applies for pulses of relatively long duration. This distortion is termed droop, the droop for a rectangular pulse is quoted on the datasheet for every CWT. The droop distortion is illustrated in Figure 5.

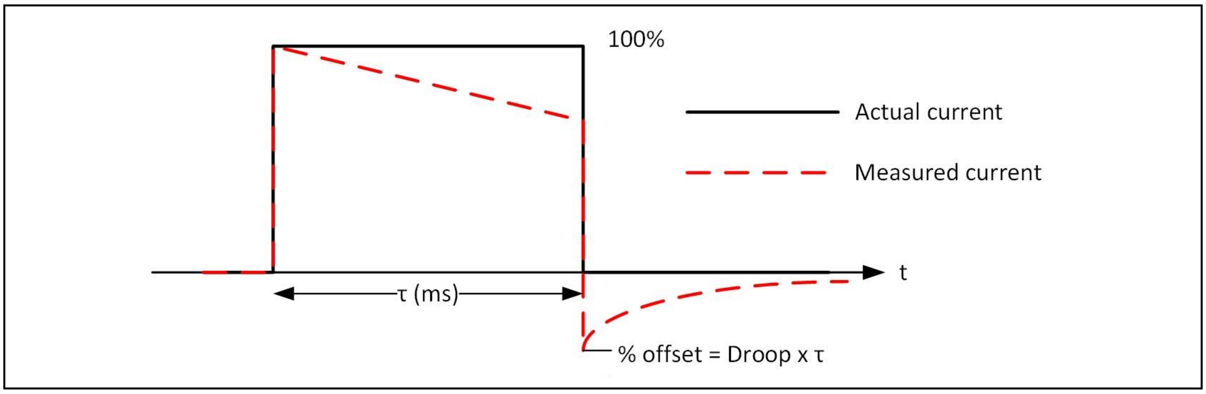


Figure 5. Droop definition - based on a rectangular pulse

The droop rate for a rectangular pulse is the worst case and in general

$$\% \text{ offset} = \tau(ms) * \text{Droop } (\%/ms)$$

The calculation of droop assumes that the measured pulse duration $\tau << T$, where T is related to the low frequency bandwidth by approximately $T \approx 1/(2\pi f_L)$.

The droop figure can also be used to calculate the offset for a general waveform using the following adjustment:

$$\% \text{ offset} = \tau(ms) * (\text{mean value / peak value}) * \text{Droop } (\%/ms)$$

For the ½ sine waveform this is

$$\% \text{ offset} = \tau(ms) * (2/\pi) * \text{Droop } (\%/ms)$$

The calculated offset is illustrated in Figure 6.

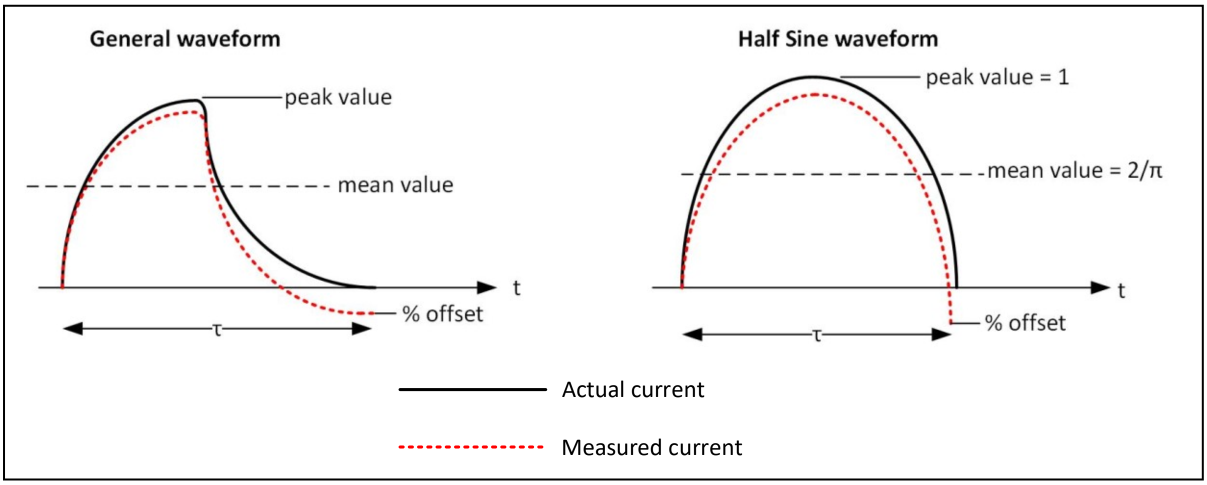


Figure 6. Droop calculation for any pulse where τ<<T

Table 1 provides the calculation for the ratio of mean current to peak current for some common current waveshapes found in power electronics.

Waveform shape	Mean value/Peak value
Square pulse	1
Ramp	1/2
Half sine wave	$2/\pi$
1st order exponential decay $(1-e^{\lambda/t})$	λ

Table 1. Ratio of Mean value to peak value for some common waveforms

3.2 Droop and Offset Distortion for a Unipolar Pulse-train

A unipolar pulse train contains a continuous DC offset which the Rogowski coil cannot measure. In the same way that the CWT can measure a short rectangular pulse with a DC offset, the CWT initially measures the DC component of the pulse-train. The DC offset slowly decays to zero at a rate determined by the droop and the low frequency bandwidth as described in Section 3.1. The time taken for the DC offset to decay to zero can be approximated using the following formula:

$T_{settling} \approx 5 * T \quad \text{where } T \approx 1/(2\pi f_L)$

The initial settling period is illustrated in Figure 7. The distortion of each individual pulse is determined by the droop rate.

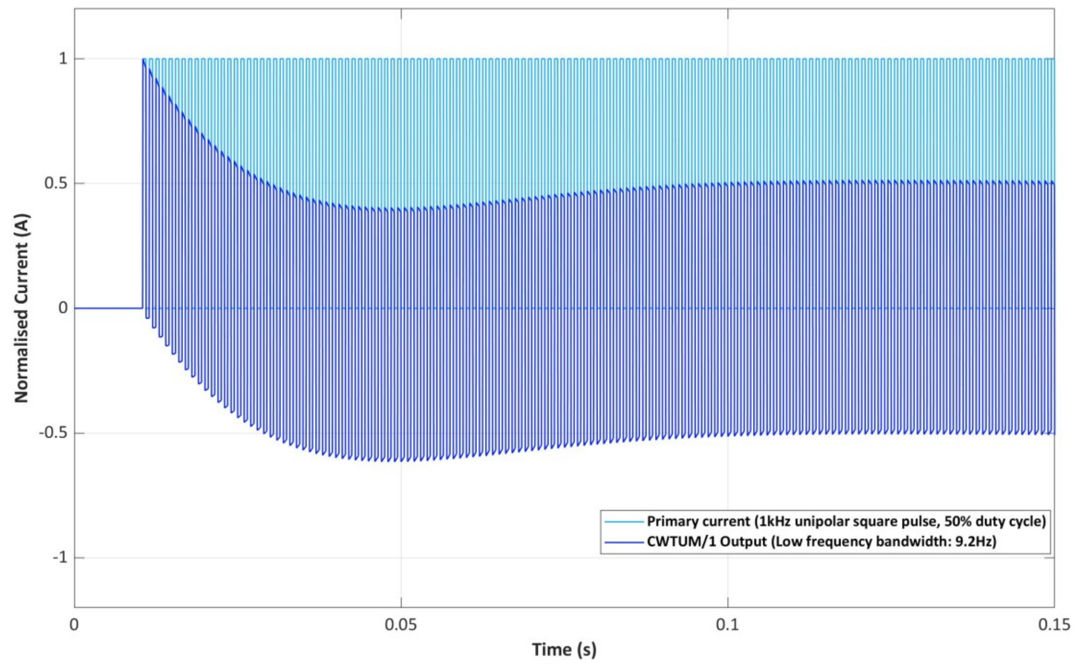


Figure 7. Typical settling period for a unipolar pulse-train

After the initial settling period, the pulse-train will be offset so that the mean output of the CWT is zero. In Figure. 8, it can be seen that the measured current has a zero level which will vary depending upon the duty cycle (%) of the pulses.

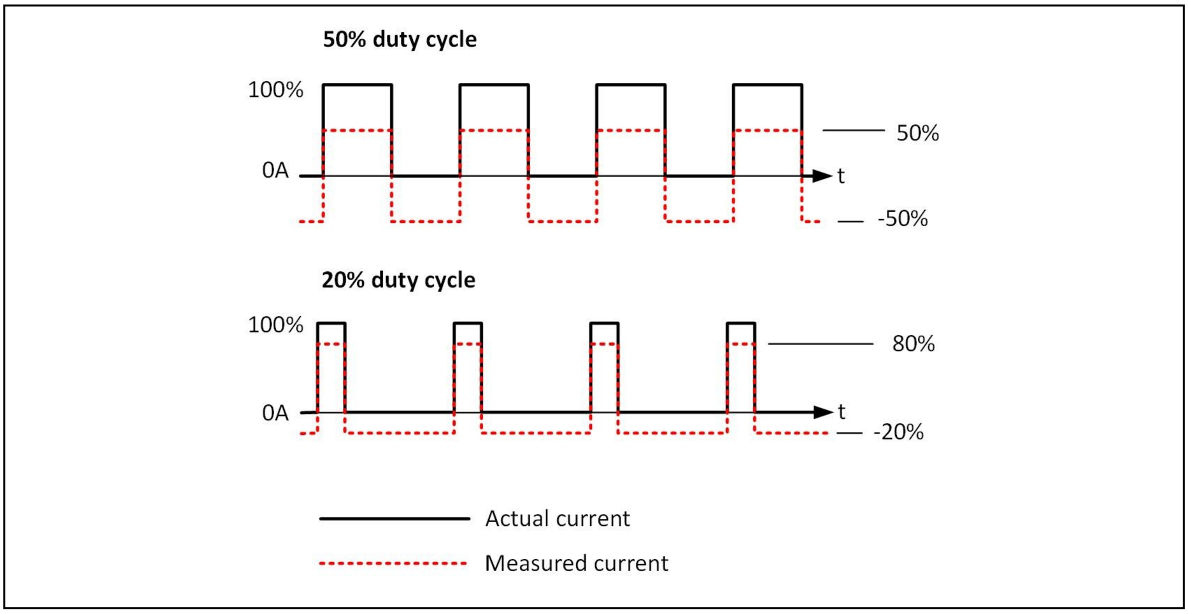
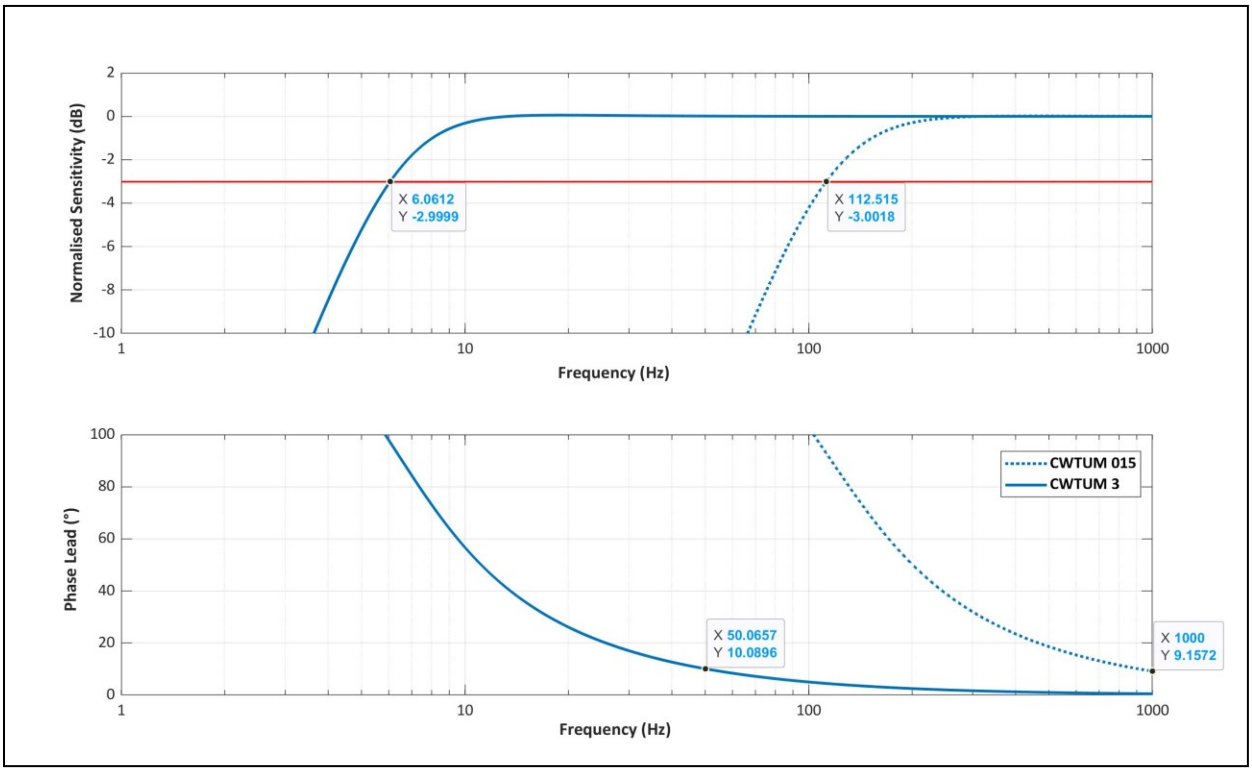


Figure 8. Measured offset of a unipolar pulse-train (after settling)

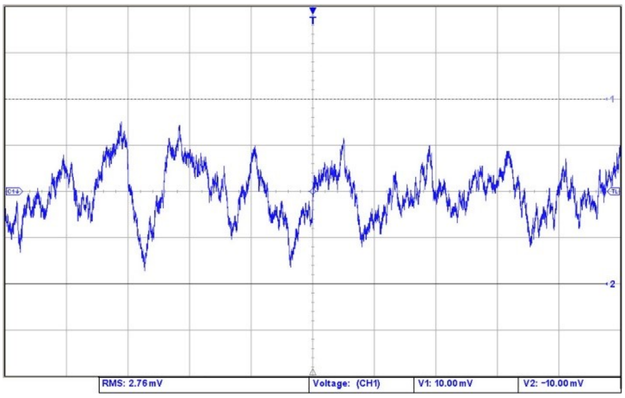
PEM offer a range of products with an extended low frequency performance which are suitable for measuring very long current pulses including short circuit asymmetrical fault currents. Please contact PEM or visit the website www.pemuk.com for more details about these products.

Appendix 1 – CWT Ultra-mini

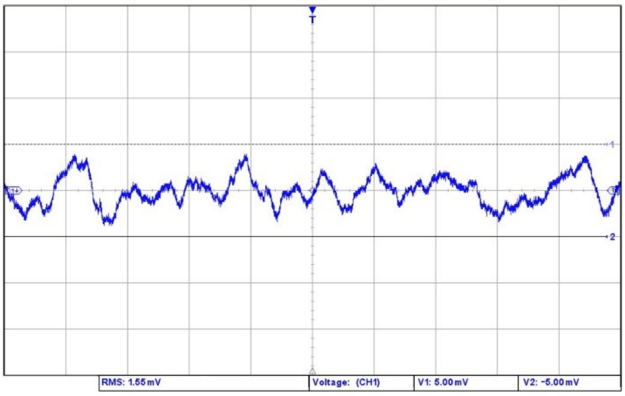
Features:- Very thin 1.7mm thick Rogowski coil, 1.2kV peak insulated, full datasheet for CWT Ultra mini



Appendix 1a. CWTUM/015 (30A Peak) vs CWTUM/3 (600A Peak)
Simulated low frequency response

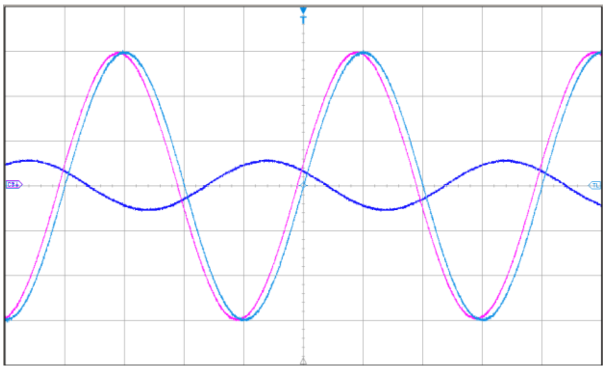


Ch 1: CWTUM/015 - 5mV/div (25mA/div)
Time base: **5ms/div**
Cursors: 20mVp-p (Max noise)
RMS Noise: 2.76mV

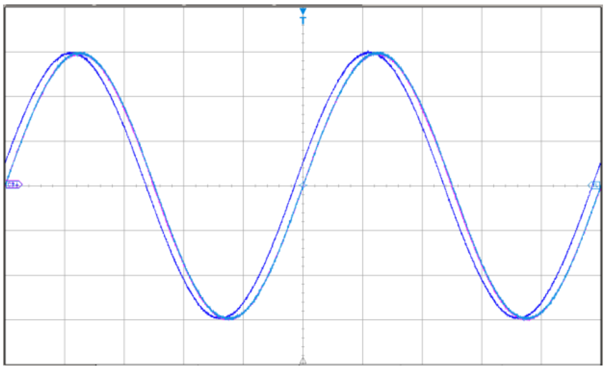


Ch1: CWTUM/3 – 5mV/div (0.5A/div)
Time: **100ms/div**
Cursors: 10mVp-p (Max noise)
RMS Noise: 1.55mV

Appendix 1b. CWTUM/015 & CWTUM/3 Noise

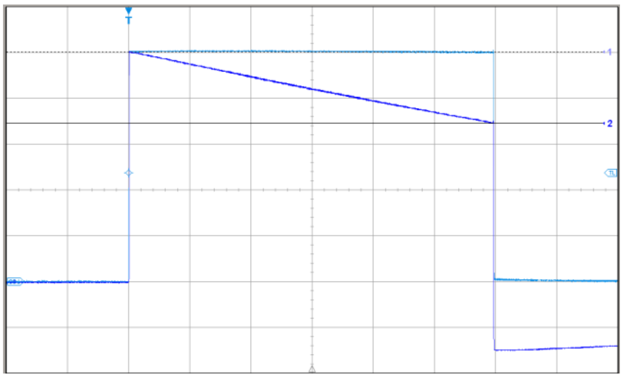


Ch 1: **Co-axial shunt** - DC-2GHz – 1A/div
Ch 2: CWTUM/015 – 4A/div
(attenuation: -14dB, phase lead at 50Hz: 145deg)
Ch 3: **CWTUM/3 – 4A/div**
(attenuation: negligible, phase lead at 50Hz: 10deg)
Time base: 5ms/div

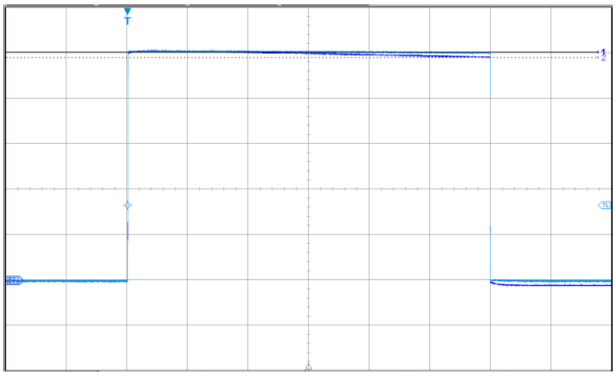


Ch 1: **Co-axial shunt** - DC-2GHz – 1A/div
Ch 2: CWTUM/015 – 4A/div
(attenuation: negligible, phase lead at 1kHz: 9deg)
Ch 3: **CWTUM/3 – 4A/div**
(attenuation: negligible, phase lead at 1kHz: negligible)
Time base: 0.2ms/div

Appendix 1c. CWTUM/015/B/1/80 & CWTUM/3/B/1/80 phase shift at 50Hz and 1kHz



Ch 1: Co-axial shunt - DC-2GHz
Ch 2: CWTUM/015 (1.5A/div)
Droop = 80%/ms (see datasheet)
Pulse duration = 0.3ms
Offset = Droop x 0.3ms = 24% (approx. as measured)



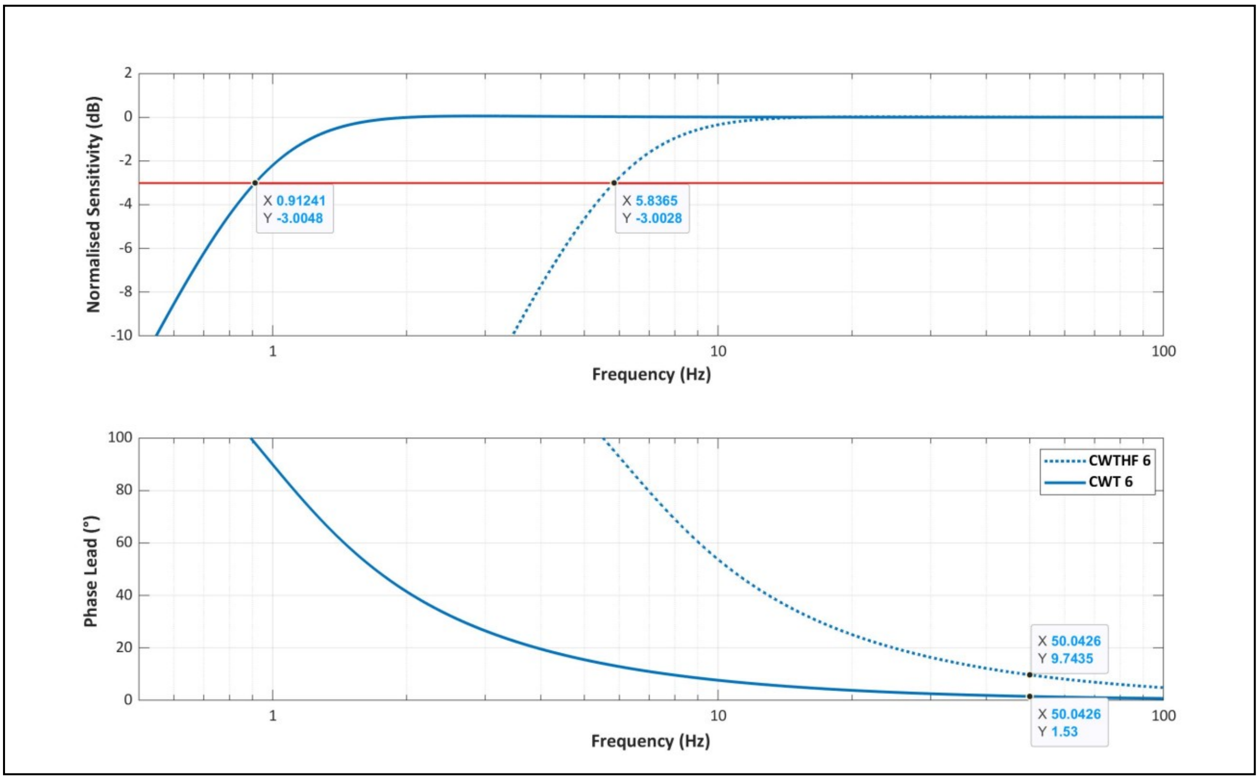
Ch 1: Co-axial shunt - DC-2GHz
Ch 2: **CWTUM/3 (15A/div)**
Droop = 6%/ms (see datasheet)
Pulse duration = 0.3ms
Offset = Droop x 0.3ms = 1.8% (approx. as measured)

Appendix 1d. Examples of the droop distortion of the CWTUM/015 and CWTUM/3 for a 0.3ms rectangular pulse

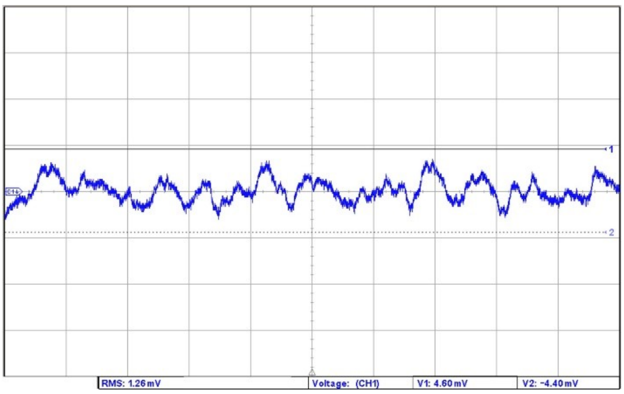
Appendix 2 – CWT & CWTHF

Features:- Flexible, robust 8.5mm thick Rogowski coil, 10kV peak insulated, [full datasheet for CWT and CWTHF.]

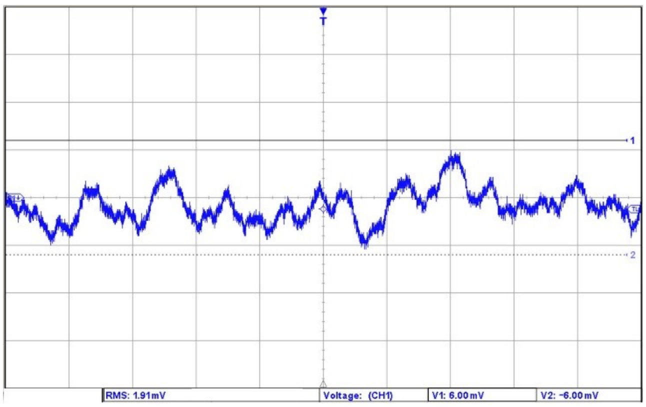
The CWT has improved low frequency performance compared with the CWTHF which is optimised for high frequency measurements. The appendix shows the difference between the CWT6 and the CWTHF6 to illustrate the difference in low frequency performance.



Appendix 2a. CWT6 (unscreened coil) & CWTHF6 (screened coil)
Simulated low frequency response

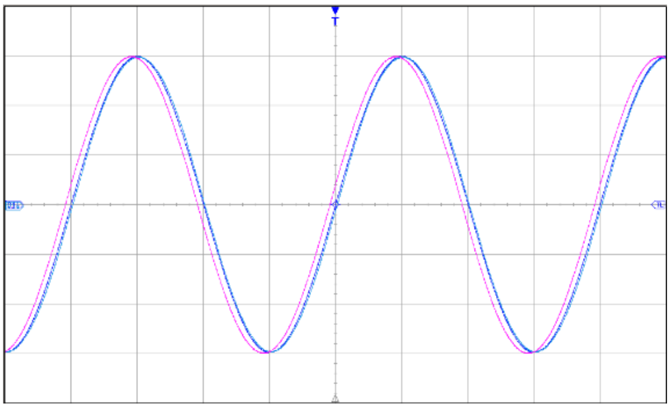


Ch 1: CWT6 - 5mV/div (1A/div)
Time base: **1s/div**
Cursors: 9mVp-p (Max noise)
RMS Noise: 1.26mV



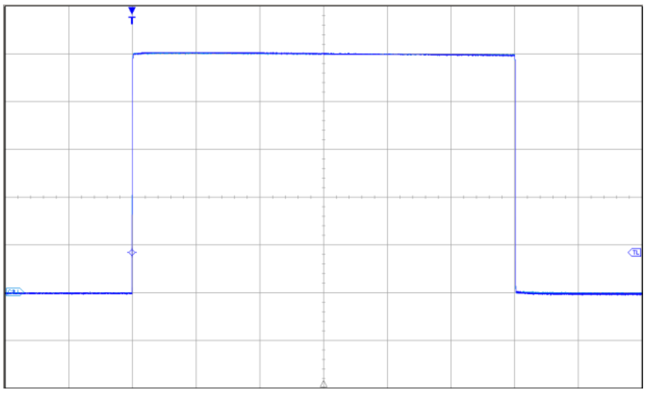
Ch1: CWTHF6 – 5mV/div (1A/div)
Time: **100ms/div**
Cursors: 12mVp-p (Max noise)
RMS Noise: 1.91mV

Appendix 2b. CWT6 & CWTHF6 Noise

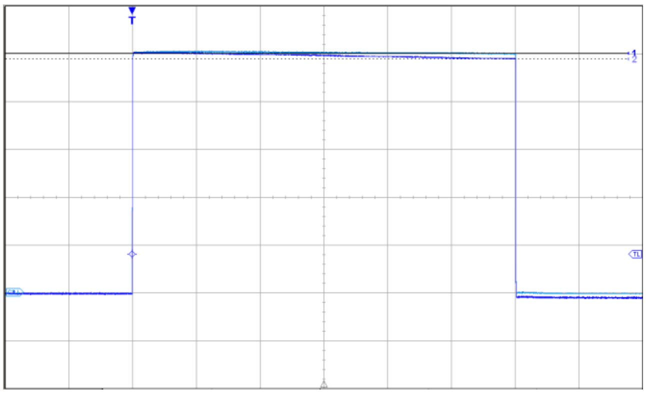


Ch 1: **Co-axial shunt** - DC-2GHz – 1A/div
Ch 2: CWT6 – 40A/div (1.53 degrees phase lead at 50Hz)
Ch 3: CWTHF6 – 40A/div (9.7 degrees phase lead at 50Hz)
Time base: 5ms/div

Appendix 2c. CWT6/B/2.5/300 & CWTHF6/B/2.5/300 phase shift at 50Hz (CWT sees x40 the current in the shunt)



Ch 1: Co-axial shunt - DC-2GHz
Ch 2: CWT6 – 25A/div
Droop = 0.9%/ms (see datasheet)
Pulse duration = 0.3ms
Offset = Droop x 0.3ms = 0.27% (negligible)



Ch 1: Co-axial shunt - DC-2GHz
Ch 2: CWTHF6 – 50A/div
Droop = 5.5%/ms (see datasheet)
Pulse duration = 0.3ms
Offset = Droop x 0.3ms = 1.67% (approx. as measured)

Appendix 2d. Examples of the droop distortion of the CWT6 and CWTHF6 for a 0.3ms rectangular pulse