RCTrms Technical Notes

All measuring instruments are subject to limitations. The purpose of these technical notes is to explain some of those limitations and to help the engineer maximise the many advantages of PEM's Rogowski current transducers.

These technical notes should be read in conjunction with the RCTrms short-form datasheet.

Cosinus Messtechnik GmbH * Rotwandweg 4 * D-82024 Taufkirchen
Tel.: 089-665594-0 * Fax: 089-665594-30 * Web: www.cosinus.de * eMail: office@cosinus.de

Contents

Figures

1. Basic operation

The RCTrms is an ac current sensor. It comprises a thin, flexible, clip-around sense coil (a Rogowski coil), which is connected to an electronic integrator and signal conditioner housed in a DIN rail mount electronics enclosure.

The output from the electronic integrator is an instantaneous voltage, $\mathbf{V_{out}}$, proportional to the measured current. Details of the operation of the Rogowski coil and integrator electronics can be found in the document 'RCTi – technical notes – 001.pdf'.

The output voltage from the integrator is fed into a high accuracy, true rms converter which performs the calculation

$V_{dc\,rms} = \sqrt{Avg(V_{out})^2}$

$\mathbf{V_{dc\ rms}}$ is a dc voltage proportional to the true rms of the integrator output. Lower performance 'average responding' devices simply average the measured waveform and scale according to some pre-determined factor. This gives highly inaccurate measurement with changes in crest factor, for example SCR waveforms or currents with higher order harmonics. The RCTrms converter is capable of accurately calculating the true rms value of complex waveforms with crest factors up to 5.

Finally, a high precision voltage to current converter changes $\mathbf{V_{dc\,rms}}$ to an industry standard 4 to 20mA signal, $\mathbf{I_{out}}$, thus providing a highly noise immune dc current output proportional to the rms of the measured primary current.

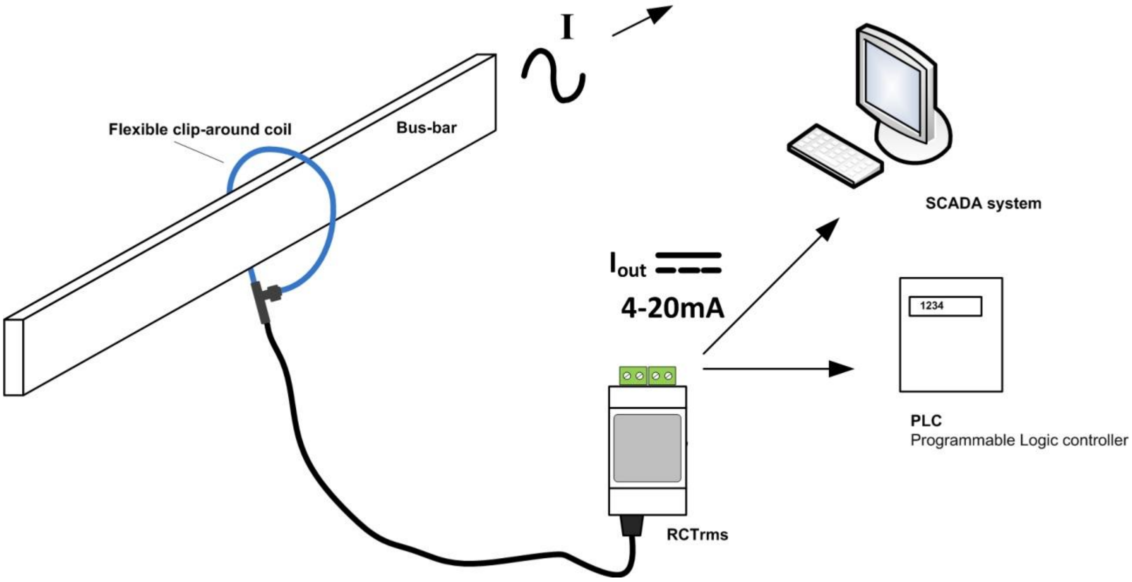


Figure 1. A schematic showing RCTrms operation

The RCTrms is suitable for a number of applications:

- Process control e.g. large pumps, compressors and heaters, arc and ladle furnaces.
- Power utilities, for example monitoring load sharing in various branches of a low voltage network.
- Health monitoring in VSD applications where the wideband and true rms capability of the RCTrms allow accurate measurement of currents containing higher order harmonics.

2. What are the advantages of the RCTrms over other current measurement devices?

The RCTrms measures ac current and provides an industry standard 4-20mA dc output proportional to the true rms of the measured current. They have a number of important benefits, they:

- ✓ **…are very easy to use and ideal for retro fit applications**- the coil is thin, flexible and easy to insert around a current carrying device.

- ✓ **… the size of the Rogowski coil can be chosen independently of the current magnitude.** This is unlike other current transducers which become bulkier as the current magnitude increases. For currents of several kA's or more there is really no better alternative than the Rogowski transducer!

- ✓ **…accurately measure the true rms of complex waveforms with crest factors up to 5.** Ideal for measurement of SCR waveforms, non-linear waveforms from variable speed drives or 50/60Hz waveforms with considerable higher order harmonics. The RCTrms has a (3dB) bandwidth from 2Hz to 100kHz.

- ✓ **…have an industry standard 4 to 20mA dc output**. Thus they are simple to interface to SCADA systems for continuous monitoring applications or PLC's in process control applications.

- ✓ **…are intrinsically safe devices.** There is no danger of an open circuit secondary unlike a current transformer (CT).

- ✓ **…provide an isolated measurement at ground potential** similar to other current transducers (except co-axial shunts) i.e. there is no direct electrical connection to the main circuit.

- ✓ **…can measure AC signals superimposed on large DC**. The transducer does not measure direct currents - as a result it can measure small AC currents in the presence of a large DC component

- ✓ **…are non-intrusive**. They draw no power from the main circuit carrying the current to be measured. The impedance injected into the main circuit due to the presence of the transducer is only a few pico-Henrys!

3. Accuracy and Calibration

3.1 Calibration

The primary calibration is at 50Hz. PEM has the capability of generating highly stable sinusoidal currents up to 5000A from 15Hz to 1kHz. The RCTrms Rogowski current transducer is very linear with current magnitude, as shown in Section 3.2, thus a single point calibration for the RCTrms is considered sufficient. Where possible the calibration is performed at full scale current.

Every RCTrms is supplied with a calibration certificate. The certificate contains details of all measurement devices and recording equipment used in the calibration including reference to their traceable United Kingdom Accreditation Service (UKAS) calibration certificates. A copy of our traceability chart is available on request.

3.2 Linearity - Accuracy with current magnitude

Linearity error is the difference ΔI between the rms of the true current value, I, and the measured value I_{out}/R_{SH}, where R_{SH} is the calibrated sensitivity (mA/A). For a fixed frequency, fixed temperature, and fixed current position the linearity error will vary with current magnitude over the rated current of the RCTrms.

A Rogowski current transducer comprising a Rogowski coil and integrator, such as the RCTi or RCTi-3ph, has exceptional linearity better than 0.1% of reading from 5% to 150% of full scale see 'RCTi – Technical notes - 001.pdf' for further details.

Unlike the RCTi, the RCTrms has a signal conditioner to convert the instantaneous voltage output from the integrator to a dc current proportional to the true rms of the measured current. This process contributes small non-linearity errors. The maximum theoretical non-linearity of the RCTrms is ±0.38% of reading.

Figure 2. shows measured linearity results for two different RCTrms models, the RCTrms/250A and the RCTrms/5000A. The linearity was measured by varying a sinusoidal current source from 5% to 100% Rated current. The linearity was measured at a frequency of 50Hz, a temperature of 25°C and with the conductor central in the Rogowski loop.

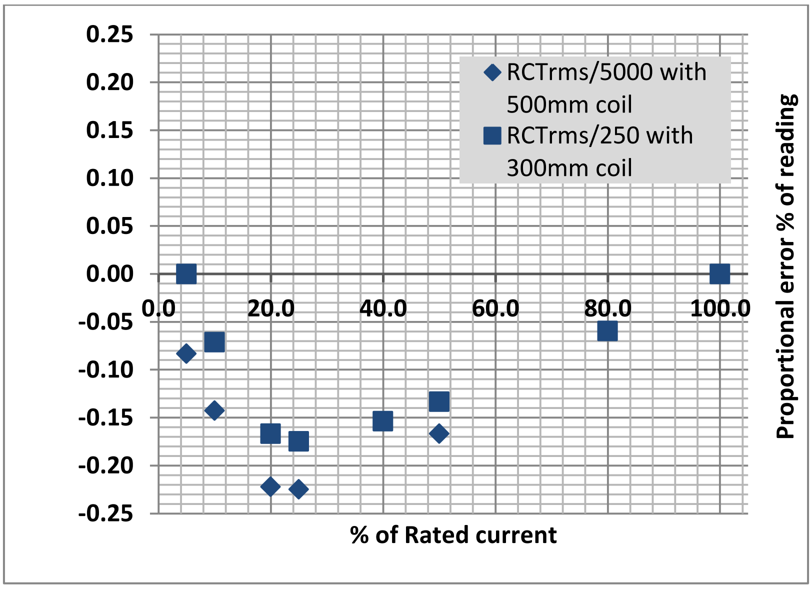


Figure 2. Linearity of the RCTrms

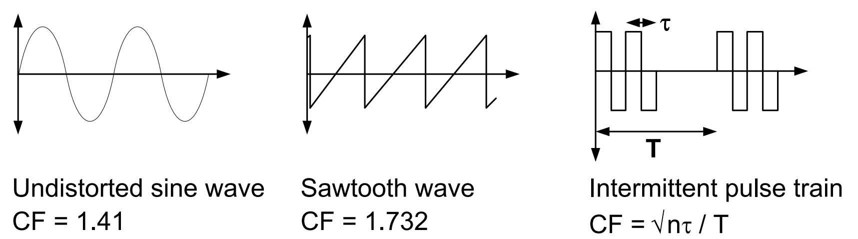
The comparative measurement device is a current transformer having a traceable UKAS calibration certificate across the current range. The measurements are compared on two Keithley model 2000 DMM's, each having a traceable UKAS calibration certificate. The number of ampere turns through the current transformer is arranged such that the DMM is used close to full scale of range to achieve maximum accuracy. The output of the RCTrms is measured across a precision burden resistor to give a dc voltage output for comparison. The uncertainty for each measurement is ±0.18% of reading.

From the results in the scatter graph of Figure 2. the linearity was found to be better than ±0.22% of reading. Even given the measurement uncertainty, the linearity is almost certainly better than ±0.38%, the maximum theoretical value.

3.3 Accuracy with crest factor

Crest factor is defined as the ratio of the peak value of the measured current to the rms value of the measured current.

Figure 3. below shows the crest factors of a few commonly encountered waveforms:



Crest factor	Error (%) of reading
2	0.2
3	0.8
4	1.5
5	2.5

Additional error due to crest factors > 1.41.

Figure 3. Crest factor (CF) of some common waveforms

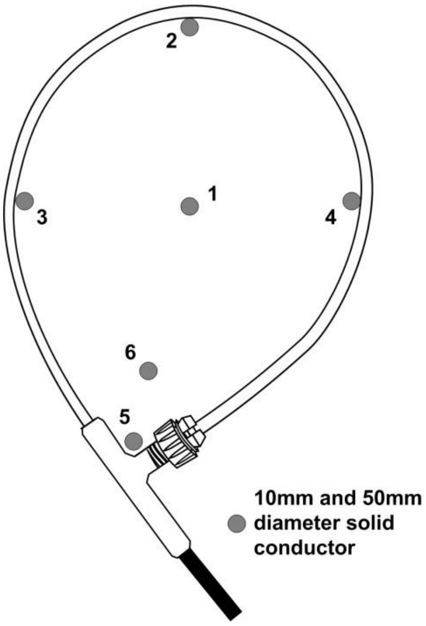
As the crest factor of the measured current increases the accuracy of the measurement is reduced according to the table below. The RCT*rms* is capable of measuring waveforms with crest factors up to 5.

The quoted typical accuracy assumes a crest factor of < 1.41.

3.4 Positional Accuracy

The output of the RCTrms varies slightly depending on the position of the current in the Rogowski coil and also the size of the current conductor relative to the coil. More information about the tests used to quantify the positional accuracy variation can be found in the RCTi technical notes, 'RCTi – Technical notes -001.pdf'.

Referring to Figure 4., the RCTrms is calibrated with the conductor central in the coil, position 1. The values shown in Figure 4. show how the accuracy varies with both conductor position within the Rogowski coil loop and conductor size relative to the size of the Rogowski loop.



	Positional error % of reading -10mm conductor				
Coil length (mm)	Touching the edge of the coil			Ferrule	3cm from ferrule
	2	3	4	5	6
300	±1	±1	±1	-3.5	-0.75
700	±1.5	±2.0	±2.0	-3.5	-1
700 (x2)	±0.5	±0.5	±0.5	-1.5	-0.5

	Positional error % of reading – 50mm conductor			
Coil length (mm)	Touching the edge of the coil			Ferrule
	2	3	4	5
300	±0.5	±0.5	±0.5	-0.5
700	±1	±1	±1	-1
700 (x2)	±0.3	±0.3	±0.3	-0.3

Figure 4. Positional accuracy variation

From these results, and the additional uncertainty resulting from the true rms conversions, we derive the typical accuracy of ±1.5% of reading quoted on the short-form datasheet.

3.5 Rejecting external currents and voltages

Currents external to the Rogowski coil can cause measurement interference. Once again, full details can be found in the RCTi technical notes, 'RCTi – Technical notes – 001.pdf'. As a 'worst case' indication a conductor external to the Rogowski coil, but touching the coil, will produce a measurement error of 2%, e.g. a 100A current touching, but outside the Rogowski loop will give a 2A error measurement. This reduces significantly as the conductor is moved away from the coil such that when the conductor is one Rogowski coil radius away from the coil edge the interference is negligible.

Rogowski coils can be susceptible to electrostatic interference through capacitive coupling onto the Rogowski coil winding. PEM have published significant research into resolving this problem and the RCT range of Rogowski coils have been optimised to attenuate any voltage interference. However if there is a surface with a high ac voltage very close to the coil then a measurement error can arise. If the voltage is subject to high rates of change (e.g. several 100 V/µs) or high frequency oscillations in the MHz range, the interference will be worse.

3.6 Temperature

The variation in accuracy of the RCTrms with temperature results from:

1. Expansion of the plastic former onto which the Rogowski coil is wound. This reduces the sensitivity of the Rogowski coil.
2. Drift with temperature of the passive component values that set the integrator time constant and the signal conditioner offset and gain.

To overcome these problems the Rogowski coil is wound onto a plastic former with a very low co-efficient of expansion. High stability resistors and capacitors set the integrator time constant.

Rogowski coil temperature coefficient

The temperature coefficient of the Rogowski coil varies with coil length. Two example temperature coefficients are given in the table below:

	Temperature Coefficient (ppm/°C)	
	-40 to +20°C	**+20 to +80°C**
300mm coil, 1m cable	-90	-150
700mm coil, 1m cable	-110	-210

The temperature coefficient will vary with coil and cable length, please contact PEM for more information about longer coils and cables.

Temperature coefficient of integrator and signal conditioner

The integrator, true RMS converter and the 4-20mA converter each have an output which varies with temperature. These temperature coefficients are combined to give a worst case measurement error over the operating temperature range for the RCTrms. The values are shown in the table below:

	Temperature Coefficient (ppm/°C) -5 to +65°C	
RCTrms electronics	±0.11%/°C	±0.11%/°C

The overall measurement uncertainty can thus be calculated from the sum of the 'Rogowski coil and cable' and 'RCTrms electronics' temperature coefficients.

4. Rated Current, overloads and saturation

4.1 Rated Current

The RCTrms has an output of 20mA corresponding to the rated current.

If the peak current exceeds 150% of this rating (28mA output) the signal conditioning circuit on the RCTrms may be damaged.

4.2 Absolute maximum (rms) di/dt

The RCTrms can be damaged by repetitive di/dt due to the RMS voltage generated by the coil. Excessive rms di/dt can result in voltages which exceed the power rating of the coil termination resistors. For sinusoidal waveforms the calculation of rms di/dt is:

di/dt rms = $2\pi f I_{rms}$ (where f is the measured frequency and I_{rms} the rms value of the measured current)

For the RCTrms the **absolute maximum rms di/dt is 240A/μs.**

For a sinusoidal current the safe operating area for the RCTrms is defined in Figure 5. It must be noted that this is for the standard product with less than 4m of cable between coil and integrator and cable and a Rogowski coil circumference of 300 to 700mm. Where different coil and cable lengths are specified the absolute maximum rms di/dt may be different.

It is possible to customise the operating region to allow the measurement of large, high frequency sinusoidal waveforms. For more information, please contact PEM.

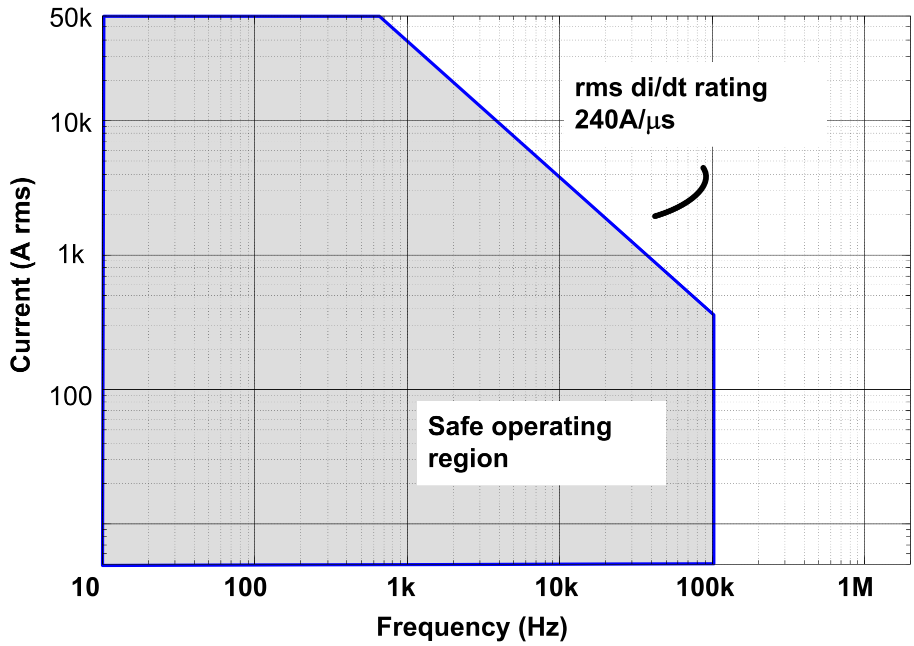


Figure 5. Safe operating area for the RCTrms for a sinusoidal current

5. Frequency response

5.1 Bandwidth

The bandwidth is defined as the range of frequencies for which the measurement of a steady state sinusoidal current will remain within 3dB of its specified sensitivity (mA/A).

The bandwidth varies with measured current magnitude. For example the frequency response in Figure 6. shows the bandwidth for both a measured current of 10% full scale, and a measured current of 100% full scale.

The value for high frequency (3dB) bandwidth quoted on the short-form datasheet is based on the worst case i.e. 10% full scale.

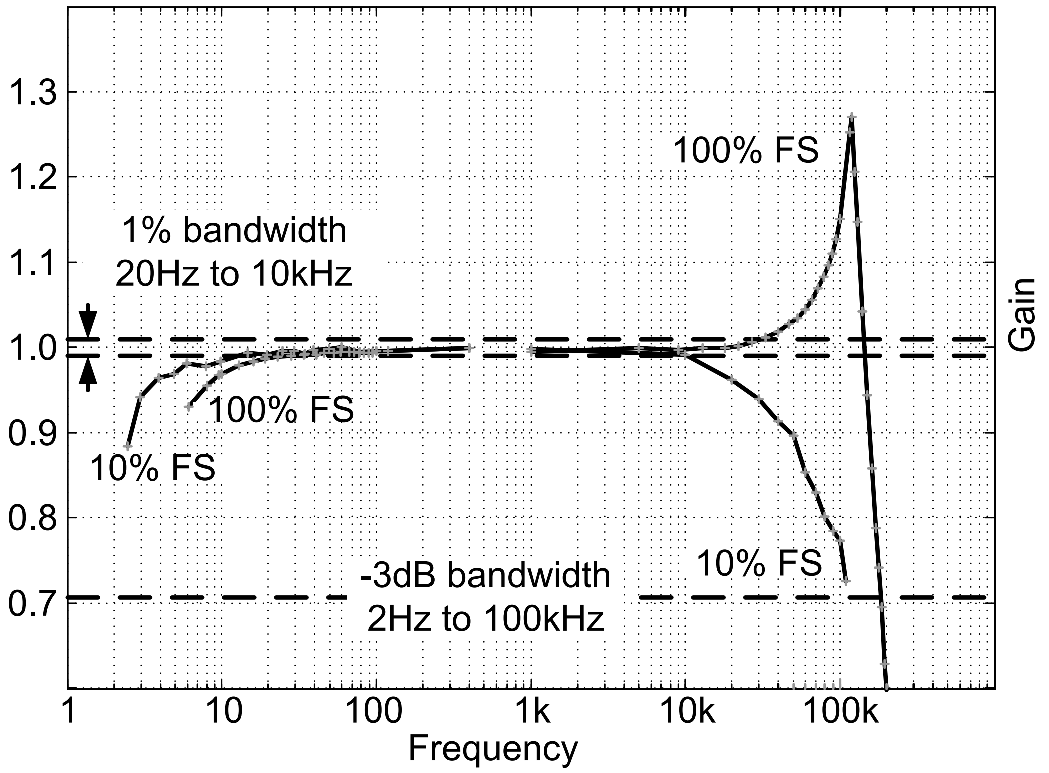


Figure 6. Measured frequency response of the transducer showing (3dB) frequencies, for both a 10% full scale and 100% full scale measured current

It is possible to customise the bandwidth to enable the measurement of

- **higher frequency sinusoidal waveforms (over a limited dynamic range)**
- **or frequencies <1Hz (but with a longer response time).**

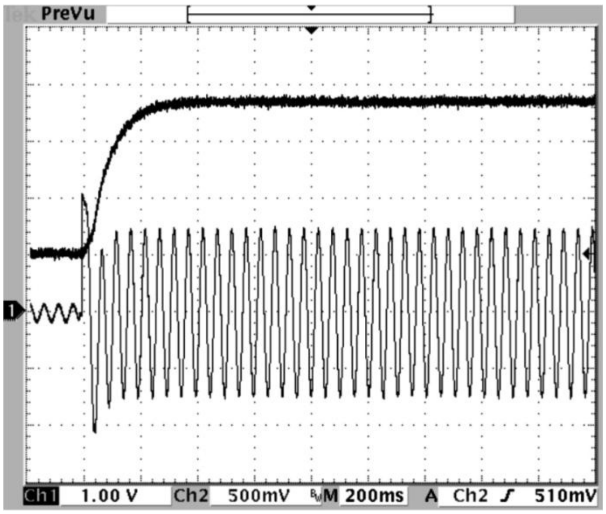
For more information, please contact PEM.

5.2 Response time

The response time of the RCT*rms* is the time it takes the output of the transducer to settle given a change in magnitude of the measured current.

Figures 7. and Figure 8. show the response time of an RCTrms with a rated current of 250Arms.

In Figure 7. the RCT*rms* is measuring a 20Hz, 25Arms (10% full-scale) sinusoidal current, this is 'instantaneously' increased to 250Arms (100% full-scale) and the response of the transducer is recorded. The response time for this rising edge to settle within 1% of the measured current is 400ms.

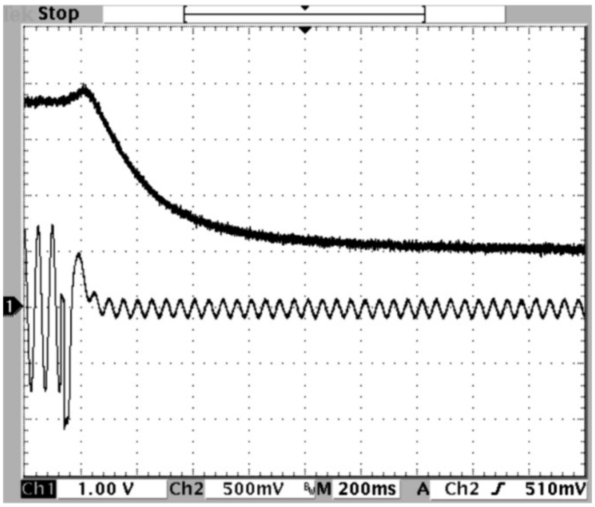


RCT*rms* 4-20mA output driving R_L=90 ohm

Frequency = 20Hz

Figure 7. Response time of 400ms to 10% to 100% rising edge

Figure 8. shows the response of the same unit to a current decreased from 250Arms (100% full-scale) to 25Arms (10% full-scale). The response time for this falling edge to settle within 1% of the measured current is 1000ms. **This represents the 'worst case' for response time and is the value quoted on the datasheet. For smaller changes in current the response will be faster.**



RCT*rms* 4-20mA output driving R_L=90 ohm

Frequency = 20Hz

Figure 8. Response time of 1000ms to 100% to 10% falling edge

It is possible to program the RCT*rms* to have a significantly faster response time than that quoted on the datasheet. There is a compromise between the response time, the low frequency bandwidth and the error when measuring waveforms with a high crest factor.

If you are interested in the RCT*rms* but require a faster response time please contact PEM to discuss your requirement. PEM has supplied units with a response times as fast as 50ms.

6. Output cabling and loading

The RCTrms must be terminated with a burden resistance of less than 300Ω for rated accuracy, the cable resistance must be taken into account when calculating the maximum burden resistance.

Third party EMC tests for the RCTrms have been carried out (see Section 7.2), these tests assume an output cable length of up to 3m.

Output cables longer than 3m have not been included in the EMC immunity tests and may decrease RF noise immunity. However PEM does not consider the use of extension cables to be problematic from the noise viewpoint provided the recommended cable types are used and care is taken to provide additional screening from noise sources.

The specified performance of the RCTrms will be unaffected by longer cable runs, however, the cable resistance must be taken into account when calculating the maximum burden resistance.

7. Product safety and standards

7.1 How does PEM rate the voltage insulation of its Rogowski coils?

The RCTrms is intended for permanent installation on equipment.

Every Rogowski coil supplied by PEM is given a peak voltage insulation rating. The rating is derived from the following test:

The coil is exposed to an ***AC test voltage = (2 x Peak voltage rating (kV) + 1)/√2 (kV rms)****, for 60 seconds at 50Hz. The RCTrms is rated at 2kV peak and will be flash tested at 4kVrms (11kV peak to peak), 50Hz, for 1 minute.*

The user should visually inspect the Rogowski coil and cable for insulation damage each time the transducer is used. Every Rogowski coil has at least two layers of insulation covering the winding. These are always different colours making visual inspection of the integrity of the insulation easier.

From a safety viewpoint it is advisable that the user grounds the output 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 cable connecting the S2 terminal to ground on the subsequent recording equipment.

As for the majority of plastics, the material used for insulating PEM's Rogowski coils can be damaged by exposure to corona over a reasonably long period of time.

The RCT has been designed for permanent installation and hence continuous exposure to nearby voltages. For voltages to ground of less than 2kV peak (i.e. 1.41kVrms for a sinusoidal voltage), corona effects will be negligible, and continuous operation is permitted.

For voltages to ground of more than 2kV 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 sharp corners 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.

7.2 Product safety and EMC compliance

The RCT range of current transducers has been designed, assessed and third party tested to ensure they comply with relevant EU standards and all products carry the CE mark of conformity. In addition, the range has been assessed and tested against the relevant FCC CFR regulations. The CE Declaration of Conformity can be found on our website.

All RCT products comply with:

EMC: IEC 61326-1:2006
EMC: CFR47 Part 15 Class A
Safety: IEC 61010-1:2001; Pollution Degree 2

Refer to the' Instructions for use' document before use.

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COSINUS Messtechnik GmbH
Rotwandweg 4
82024 Taufkirchen
Tel.: 089 / 66 55 94 - 0
Fax: 089 / 66 55 94 - 30

office@cosinus.de
www.cosinus.de