1. How to test the current clamps and a flexible Rogowski coil?

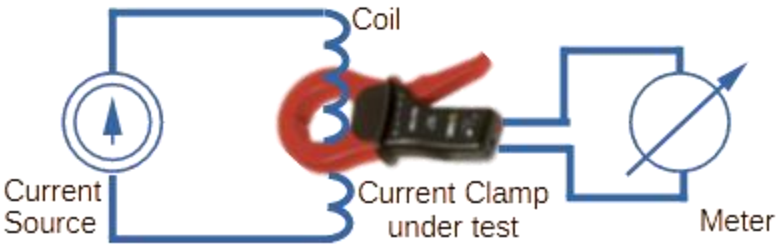
Current clamps and Rogowski (flexible) coils are in wide use as sensors of current in many electronic devices like ammeters, power quality analysers, energy meter testers, and control devices. (see picture below).

The current range of the sensors starts from a few ampers up to 6000A of input current and accuracy starts from 0.1% up to 5% of the mesured value. Testing consists of passing a current of known value through the wire which includes the clamps and measuring the output signal from the sensor. In practice, it's difficult to apply a current with a value of hundreds of amperes, so usually the wire is made in the form of a coil with numerous turns. The current equivalent which is seen by the current clamps is given by by the formula:

$$I_{eq} = N \times I_{cal}$$

where: I_{eq} – the curent equivalent, N – number of coil turns, I_{cal} – current flowing through the coil.

For example, for a coil with 100 turns, the set current of 10A will give 1000A of the current equivalent.

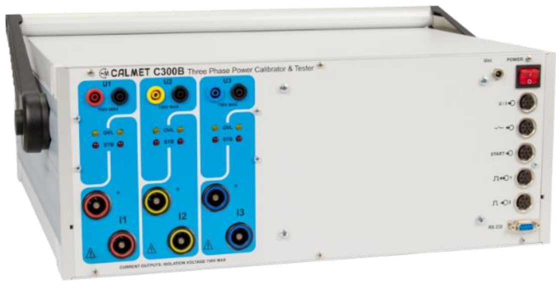


2. Required equipment

2.1. Source of current

As a source for testing, we can use a single or three-phase power calibrator, e.g. the CP11B or C300B type. Both calibrators can generate AC current in range from 1mA to 120A with the output power up to 80VA.

CP11B single-phase calibrator



C300B three-phase calibrator

The uncertainty of the C300B and CP11B calibrators is presented in the table below. It is an absolute extended uncertainty under the confidence level of 95% and covers the reference uncertainty of standards, stability in the span of 12 months, influence quantities (ambient temperature in the range of +20…+26°C, humidity of <90% @ +5...+30°C, and power supply voltage of 90…264V / 47...63Hz, load of < 80VA for frequency in range 45…65Hz) and for settings greater than 10% of range.

Parameter	Range	Settings span	Resolution	Uncertainty		Maximum load
Current I	0.5A	0.001000…0.500000A	0.000001A	±0.02%	±0.05%	17V@0.5A
	6A	0.05000…6.00000A	0.00001A			8.5V@6A
	20A	0.2000…20.0000A	0.0001A			3.3V@20A
	120A	1.000…120.000A	0.001A			0.95V@60A 0.70V@120A

2.2. Coil

Coils can be made individually by repeatedly threading the current-carrying wire through the hole in the clamps. However, this method gives unstable results and requires to be repeated for each current clamp. It's a better solution to use readymade coils with a defined number of turns and different diameters. For instance, Calmet, our company, has two coils showcased below. These coils possess the capability to achieve the current equivalent of > 1000A.

ZW100/10A

ZW10/20A

The uncertainty of ZW100 and ZW10 coils in an interaction with the current clamps is described in the table below.

Parameter / coil type	ZW10/20A	ZW100/10A
Clamp/Coil interaction (uncertainty) for toroidal-type clamps and in frequency range f=45-65Hz	±0.25% ±0.02A	±0.25% ±0.02A

2.3. Meter

Typical current clamps have two types of output: voltage - usually in the range of 1 – 3V AC for the maximum current, or current output from the range of 100mA to 6A for maximum input current. This output signal can be measured by any typical multi-meter. However, the special functionality of CP11B and C300B calibrators allows tests to be performed in a whole range of input currents in an automatic way. Calibrators have an analogue input for voltage in the range of 0…10V AC/DC and current in the range of 0…24mA DC or 0…6A AC. The uncertainty of the analogue module is presented in the table below.

Parameters of Inputs for automatic tests functions					
Input		Range	Uncertainty 1)	Number of inputs	Conditions
Multimeter Input	DC Voltage	0…±14.0000V	0.02% + 0.5mV	1	
	DC Current	0… ±24.0000mA	0.02% + 1μA		
	AC Voltage	0…10.0000V	0.05% + 0.5mV		In the 45…65Hz range
	AC Current	0…16.0000mA	0.05% + 1.6μA		
		0…200.000mA	0.05% + 10μA		
		0…6.0000A	0.05% + 300μA		
	Phase shift	0…360.00° ref. to I1	0.1° 2)		
1) absolute extended uncertainty under confidence level of 95%, including stability in 12 months 2) from 5% of current and voltage range					

3. Measurement uncertainty calculation

3.1. Uncertainty of C300B calibrator with current coil ZW

The uncertainty of current clamp testing by means of C300B calibrator and ZW coils can be expressed by the equation below.

$$U_{intcal} = \sqrt{U_{int}^2 + U_{cal}^2}$$

where: U_{intcal} – measurement uncertainty;
U_{int} – uncertainty of interaction between coil and clamps;
U_{cal} – uncertainty of current set on the calibrator;

The uncertainty of C300B calibrator is a constant value of 0.02% or 0.05% (depending on the calibrator class) in the output current range from 50mA to 20A. The uncertainty of coil-clamp interaction depends on the value of the current and equals to 0.25%+0.02A of equivalent current. For that reason the uncertainty is described by the equation below:

$$U_{intcal} = \sqrt{U_{int}^2 + U_{cal}^2} = \sqrt{\left(0.25\% + \frac{0.02A}{I_{cal} \times N} \times 100\%\right)^2 + U_{cal}^2}$$

where: U_{intcal} – measurement uncertainty;

U_{int} – interaction coil – clamp uncertainty;

I_{cal} – value of current set in calibrator [A];

N – number of coil turns;

U_{cal} – uncertainty of current set on the calibrator: 0.02% or 0.05%.

Example values of calculated uncertainty for two C300B calibrator classes – the 0.02% and the 0.05% together with two current coils ZW100 and ZW10 are presented below.

	Calibrator accuracy class							
	0.02%				0.05%			
	ZW100		ZW10		ZW100		ZW10	
I_{cal} [A]	I_{eq} [A]	U_{incal}[%]	I_{eq} [A]	U_{intcal}[%]	I_{eq} [A]	U_{intcal}[%]	I_{eq} [A]	U_{intcal}[%]
0,05	5	0,650	0,5	4,250	5	0,652	0,5	4,250
0,1	10	0,450	1	2,250	10	0,453	1	2,251
0,2	20	0,351	2	1,250	20	0,354	2	1,251
0,5	50	0,291	5	0,650	50	0,294	5	0,652
1	100	0,271	10	0,450	100	0,275	10	0,453
2	200	0,261	20	0,351	200	0,265	20	0,354
5	500	0,255	50	0,291	500	0,259	50	0,294
10	1000	0,253	100	0,271	1000	0,257	100	0,275

Where:

I_{cal} – value of the current set in the C300B calibrator;

I_{eq} – value of I_{cal} multiplied by the number of coil turns;

U_{intcal} – uncertainty of the calibrator interacting with the coil.

3.2. Uncertainty of C300B calibrator with ZW coil and C300B meter module

The uncertainty of current clamp testing by means of the C300B calibrator, ZW coils, and the meter module of the C300B calibrator can be expressed by the equation below:

$$U_{intcalmet} = \sqrt{U_{int}^2 + U_{cal}^2 + U_{meter}^2}$$

where: $U_{intcalmet}$ – measurement uncertainty;

U_{meter} – meter uncertainty;

The uncertainty of a meter depends on the value of measured voltage or current, and consists of two components: one proportional to the measured value expressed in % and a second constant value. So the uncertainty is given by the equation below:

$$U_{intcalmet} = \sqrt{U_{int}^2 + U_{cal}^2 + U_{meter}^2} = \sqrt{\left(0.25\% + \frac{0.02A}{I_{cal} \times N} \times 100\%\right)^2 + U_{cal}^2 + \left(\partial_{\%} + \frac{\Delta_{||}}{X_{out}} \times 100\%\right)^2}$$

where: $U_{intcalmet}$ – measurement uncertainty;

$\delta_{\%}$ – proportional meter uncertainty expressed in [%];

$\Delta_{||}$ – absolute part of meter uncertainty expressed in [V] or[A];

X_{out} – value measured by meter expressed in [V] or[A];

As an example, we can calculate the uncertainty for a C300B class 0.05 calibrator, with a ZW100/10A coil with 100 turns, and a C107 Chauvin Arnoux 1000A AC / 1V AC current clamp by using the C300B meter with a voltage range of 10V on the meter input. The test is performed for I_{cal}=10A, so the equivalent current equals Ieq= 10A x 100 = 1000A and expected voltage is 1V AC with uncertainty 0.05%±0.5mV. So, the total uncertainty of the test set is:

$$U_{intcalmet} = \sqrt{U_{int}^2 + U_{cal}^2 + U_{meter}^2} = \sqrt{\left(0.25\% + \frac{0.02A}{10A \times 100} \times 100\%\right)^2 + 0.05\%^2 + \left(0.05\% + \frac{0.0005V}{1V} \times 100\%\right)^2}$$

$$= \sqrt{0.064\% + 0.0025\% + 0.01\%} = \sqrt{0.0765\%} = \mathbf{0.277}\%$$

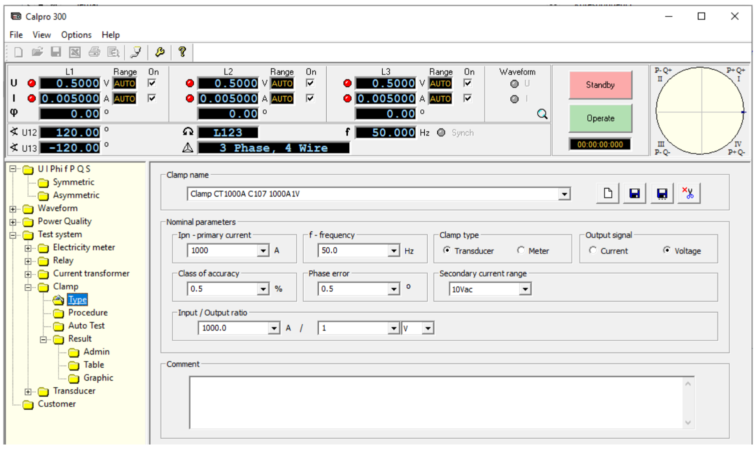
4. Current clamp automatic testing example

4.1. Setting the testing equipment

As an example, we're using: the C300B class 0.05 calibrator, a ZW100/10A coil with 100 turns, a C107 Chauvin Arnoux 1000A AC / 1V AC current clamps, and a C300B meter with a 10V input. The test is performed for the full range of current from 5A to 1000A. The current from the calibrator output is connected to the ZW100/10A terminals, and the current clamp C107 is closed on the coil. The output voltage signal from the current clamps is connected back to the calibrator by means of the AD300 adapter (4mm safety banana sockets or screw connectors plugged to the Amphenol C091A plug suitable for the C300B calibrator). See picture on left.

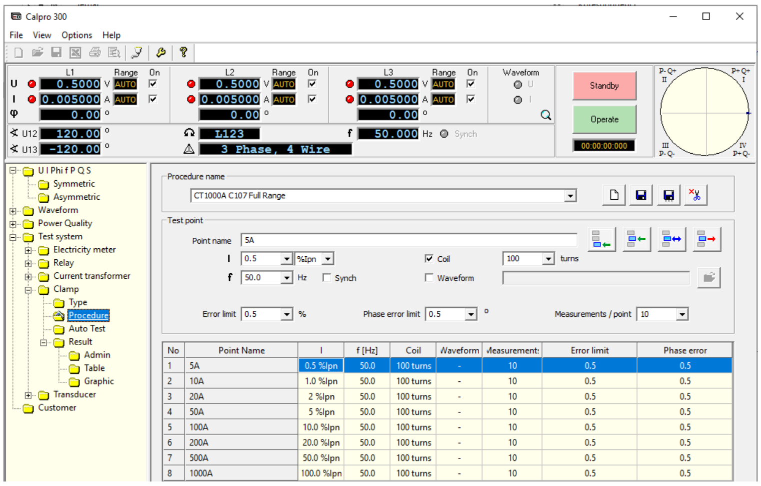
4.2. Automatic procedure preparation in the C300B calibrator

Before starting, check if the C300B calibrator is connected to the PC with the RS232 interface cable, after which the Calpro300 PC Software will be ready for work. As the next step, the appropriate COM port should be selected to enable the C300B remote control. To prepare the test, first we should define the current clamp *Type* as seen in the picture below:



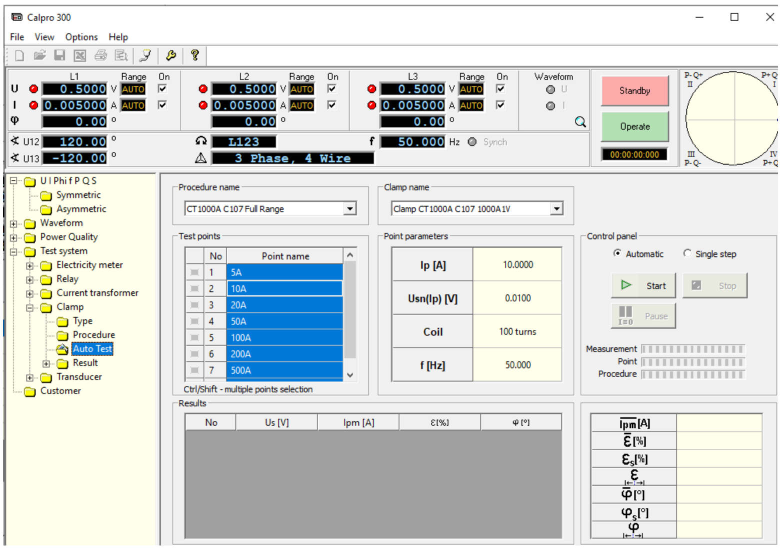
The definition consists of picking the *Clamp name* (Clamp CT1000A C107 1000A1V), *Ipn* – primary nominal current (1000A), *class of accuracy* (0.5), and *phase shift error* (0.5°), *secondary current* / voltage *range* (10Vac), and *input/output ratio* (1000A/1V). The *Type* can be saved in a file, creating a database for future use.

The next step is to prepare the testing procedure , which is the sequence of current values that will be applied to the coil during testing, as seen in the picture below. The procedure consists of *Procedure name* and then the test *Point Name*. Next, the testing current *I* should be set as a percent of the primary nominal current *Ipn*. Coil usage should be selected by check box and entered as the number of coil *turns*. The measurements/point entry is used to define the number of measurements needed for averaging the results and calculating the standard deviation. The *Procedure* can be saved in a file creating a database for the future use.



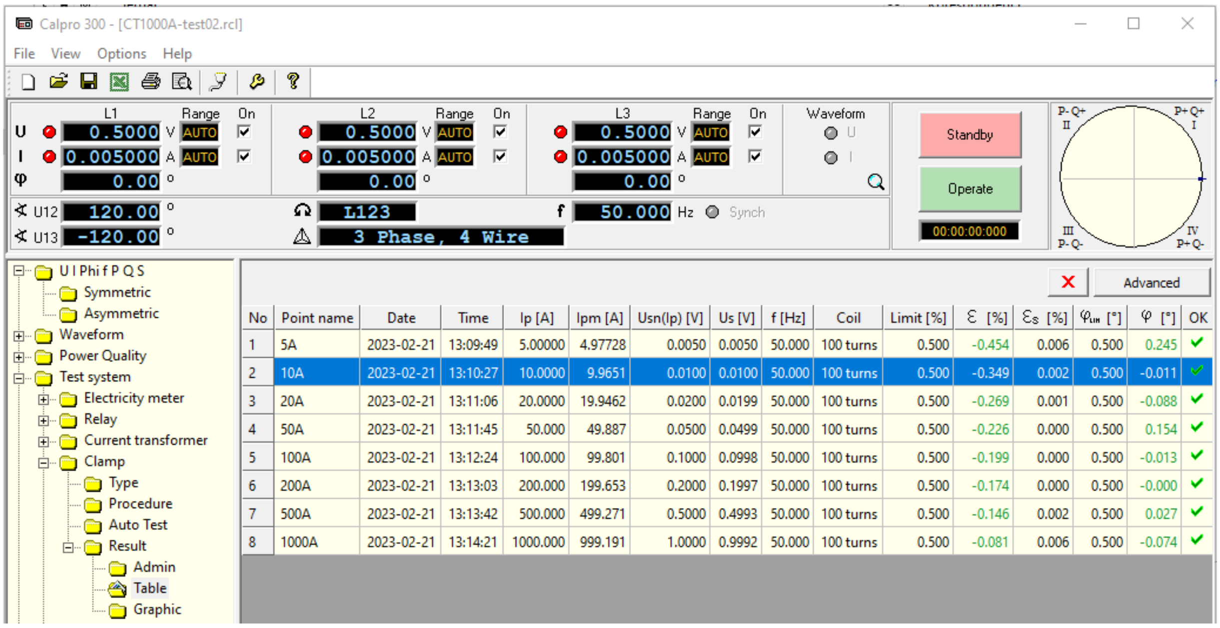
No	Point Name	I	f [Hz]	Coil	Waveform	Measurements	Error limit	Phase error
1	5A	0.5 %Ipn	50.0	100 turns	-	10	0.5	0.5
2	10A	1.0 %Ipn	50.0	100 turns	-	10	0.5	0.5
3	20A	2 %Ipn	50.0	100 turns	-	10	0.5	0.5
4	50A	5 %Ipn	50.0	100 turns	-	10	0.5	0.5
5	100A	10.0 %Ipn	50.0	100 turns	-	10	0.5	0.5
6	200A	20.0 %Ipn	50.0	100 turns	-	10	0.5	0.5
7	500A	50.0 %Ipn	50.0	100 turns	-	10	0.5	0.5
8	1000A	100.0 %Ipn	50.0	100 turns	-	10	0.5	0.5

Depending on the set *Type* of clamps and testing *Procedure,* it is possible to perform an *Auto Test* on all selected test points in the whole range of current clamp characteristics.



4.3. Results of the test

The observed final results can be viewed in many forms, e.g. a table with the results, which can be then printed out or exported to an Excel sheet.



Result exported directly to an Excel sheet.

No	Point name	*Ip* [A]	*Ipm* [A]	*Usn(Ip)* [V]	*Us* [V]	Coil	Limit [%]	ε [%]	εs [%]	Phase Limit [°]	Phase [°]	OK
1	5A	5	4,977	0,005	0,005	100 turns	0,5	-0,454	0,006	0,5	0,245	+
2	10A	10	9,965	0,01	0,01	100 turns	0,5	-0,349	0,002	0,5	-0,011	+
3	20A	20	19,946	0,02	0,0199	100 turns	0,5	-0,269	0,001	0,5	-0,088	+
4	50A	50	49,887	0,05	0,0499	100 turns	0,5	-0,226	0	0,5	0,154	+
5	100A	100	99,801	0,1	0,0998	100 turns	0,5	-0,199	0	0,5	-0,013	+
6	200A	200	199,653	0,2	0,1997	100 turns	0,5	-0,174	0	0,5	0	+
7	500A	500	499,271	0,5	0,4993	100 turns	0,5	-0,146	0,002	0,5	0,027	+
8	1000A	1000	999,191	1	0,9992	100 turns	0,5	-0,081	0,006	0,5	-0,074	+

Where:

- Ip=Ieq – primary (equivalent) current;
- Ipm – measured primary current, based on the output voltage measurement;
- Usn(Ip) – secondary nominal voltage expected for primary current;
- Us – real measured secondary voltage;
- ε - average error of measurement;
- εs – standard deviation of measurement taken from 10 measurements.
- Phase [°] – phase shift error in degrees.

4.4. Presentation of results for the test with uncertainty

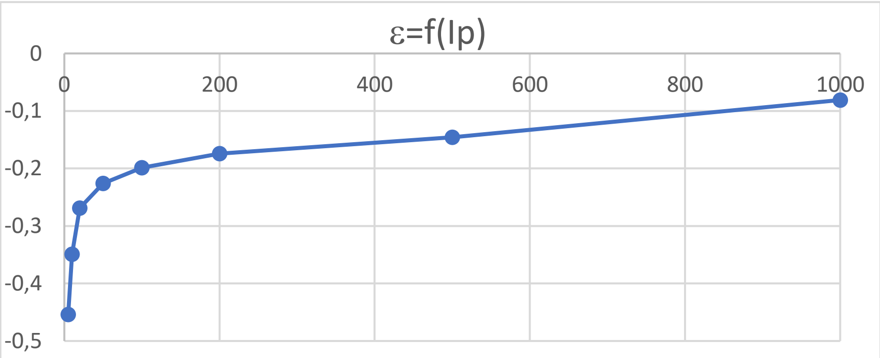
Uncertainty of measurement is the doubt that exists about the result of any measurement. There are two types of uncertainty: Type A (statistical - U_A) and Type B - U_B (e.g. taken from device data sheet or calibration certificate). The uncertainty can be calculated by the following formulas:

$$U_A = \frac{\varepsilon s}{\sqrt{N}} \qquad U_B = \frac{U_{intcalmet}}{\sqrt{3}}.$$

Combined standard uncertainty is given by the equation: $U_C = \sqrt{{U_A}^2 + {U_B}^2}$ and by the expanded uncertainty $U = k \times U_C$ where k is the coverage factor, which tell us (k=2), that 95% of the results are in the spread of $\pm 2 \times \varepsilon s$, N is the number of measurements and $U_{intcalmet}$ is the uncertainty of the whole testing set including the C300B calibrator, the ZW coils, and the C300B meter module.

Complete results of C107 current clamp testing are presented in the table below, together with the calculated uncertainties and a diagram.

No	Point name	Ip [A]	Ipm [A]	ε [%]	εs [%]	U_A	U_B	U_C	U	$U_{intcalmet}$
1	5A	5	4,977	**-0,454**	0,006	0,002	0,381	0,381	**0,762**	0,660
2	10A	10	9,965	**-0,349**	0,002	0,001	0,268	0,268	**0,535**	0,464
3	20A	20	19,946	**-0,269**	0,001	0,000	0,212	0,212	**0,424**	0,367
4	50A	50	49,887	**-0,226**	0	0,000	0,179	0,179	**0,359**	0,311
5	100A	100	99,801	**-0,199**	0	0,000	0,169	0,169	**0,337**	0,292
6	200A	200	199,653	**-0,174**	0	0,000	0,163	0,163	**0,327**	0,283
7	500A	500	499,270	**-0,146**	0,002	0,001	0,160	0,160	**0,320**	0,278
8	1000A	1000	999,191	**-0,081**	0,006	0,002	0,159	0,159	**0,318**	0,276



For example, we can write that the current clamp C107 has error in testing point 1000A as follows: ε = -0.081% ± 0.318% (error equals -0.081% with an expanded uncertainty of ±0.318% under the confidence level of 95%).

5. Conclusions

The current clamps, Rogowski coils (flexible clamps) and other current sensors are very often used in modern measurement installations and require verification of their accuracy. The C300B 3-phase power calibrator as a current source with built-in voltage & current meter together with ZW coils serves as an Automatic Test System for current sensors. The accuracy can be checked in a whole range of input currents from 0 to 1000A AC (or 3000A with three ZW coils in parallel powered from each of the C300B phases) and phase shift error. The test is performed in a fully automatic way, and results can be transferred to the Excel sheet for further calculation and results evaluation and their presentation. The uncertainty of measurement can be calculated in an easy way, by the means of an Excel sheet, based on the presented equations.