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Traceable electric current clamp meter calibration using current coil

Marcelo Costa[1]

[1] *Eletrobras Eletronorte, Rod. Arthur Bernardes 2172, Belém, Brazil,*
marcelo.melo@eletronorte.gov.br

***Abstract* – This paper presents a procedure for electric current clamp meters calibration in the range of 20 A to 1000 A, DC and low frequency, using a multifunction calibrator as working standard and a current coil for multiplication of the current generated by the calibrator. This procedure is an alternative for calibration techniques that employ high current sources and standard current transformers. Some calibration results are presented and analysed. Measurement uncertainty of about 2 x 10^{-3} at 200 A (60 Hz) for toroidal-wound clamp meter calibration can be obtained.**

I. INTRODUCTION

Current clamp meters are widely used in industry and power plants for current measurements. These instruments commonly measure currents up to 1000 A or higher at line frequency and DC. Other clamps are suitable for measurement of few miliamperes or microamperes at higher frequency – sometimes an harmonic frequency. Fig. 1 shows some clamp meters models.

Fig. 1. Some clamp meter models

There are two main types of clamp meters: toroidal-wound and Hall Effect sensor clamps. Toroidal-wound clamp meters are effectively current transformers with the current carrying conductor to be measured forming the primary and a winding around a jaw and closing mechanism forming a secondary. The jaw is composed of a suitable magnetic core material which completes the magnetic circuit when closed. Toroidal clamps can measure only AC current. Hall Effect based clamps can measure AC and DC current and unlike current transformer clamp meters, the jaws are not wrapped by copper wires. Instead, the magnetic field generated by the conductor is focused across one or more gaps in the core after the jaws are clamped around the conductor [1].

Like all other measurement instruments, clamp meters need to be calibrated and certified in regular intervals. Some clamp meter calibration techniques or procedures use high current sources and standards, like current transformers or shunts [2], [3]. On the other hand, it is a well-established practice in calibration laboratories to use current coils for clamp meter calibrations – there are a small numbers of current sources capable of driving currents from 500 A to 1000 A. Also, using current coils avoid the need of high current standards as current transformers.

This paper presents a procedure for current clamp meters calibration and measurement uncertainy estimation using current coils, with SI traceable results. The calibration procedure uses a multifunction calibrator as current source working standard. Measurement uncertainty and SI traceabilty are presented and discussed.

II. CURRENT COIL

When a current is passed through a single strand of wire, it produces a magnetic field. The force that produces the magnetic field is called magnetomotive force (mmf). The unit of mmf is defined as the ampere-turn (At). One ampere-turn is the amount of force that is generated by a direct current of 1 ampere flowing in a single loop turn in a vacuum. The total mmf that is produced is defined by the product of the number of turns and the current. If a single strand of wire is looped into 50 turns (N), the current in the wire would be multiplied by 50 to obtain the mmf [4].

Many laboratories either build their own coil, or simply make several loops of a test lead for the purpose of increasing the current value sensed by the clamp meter. Some manufacturers provide current coils, capable of clamp meters calibration up to 1000A or 1500A, as an optional of multifunction calibrators. Fig. 2 shows a single set and a multi-set of turns current coils. The single set coil is a Fluke 5500A/Coil with 50 turns, and multi-set is a Transmille model EA002 with sets of 2 turns, 10 turns and 50 turns.

Fig. 2. Multi-set and single set of turns current coils

Toroidal-wound and Hall Effect clamp meters present different loads which the current coils and their source must be designed to cope with. Hall clamps are typically much higher inductance than the toroidal ones and are more sensitive to magnetic field non-uniformity and interference within the clamp area, the result of design differences needed to accommodate the Hall sensor within the jaw magnetic circuit [5].

To evaluate the characteristics of a current coil, it is necessary to calibrate it. This calibration is intended to ensure that there are no manufacturing defects, and that the mmf generated by each coil is equivalent to an ideal conductor. The calibration is performed at a low frequency AC value (50 or 60 Hz) because this is the typical use case for clamp meters.

The reason that instruments are calibrated is because the physical properties of the instrument may drift over time (e.g. electronic components drift, physical standards like weights or gauge blocks wear). This is not the case of current coils, since they do not have components that degrade or drift during the years. For this reason, after initial calibration there is no need to recalibrate a current coil. However, intermediate verifications or checks can be performed to assure that the coil does not have defects due to mishandling or accidents. These verifications can be performed using a clamp meter, and must be able to confirm that the N turn coil remains with the same number of turns since calibration. The frequency of the verifications depends on the risk of damage to the coil, and must be evaluated by the end user. It can be annually, semi-annually or either every time the coil is used in clamp meters calibration [6].

III. CLAMP METER CALIBRATION PROCEDURE

The clamp meter calibration procedure demonstrated in this paper uses a standard current source (usually a multifunction calibrator) and a multi-turn current coil. The multifunction calibrator generates a current that is passed by the N number of turns of the current coil, so clamp meter indication is the about N-turn times the generated current. Fig. 3 shows the setup for a current clamp meter calibration. Clamp meter should be flat and in the middle for better accuracy. On the other side, measurement can be performed in different clamp positions, in order to evalute the position dependance. Clamp position can be modified at three dimensions, as can be seen in Fig. 4.

Fig. 3. Clamp meter calibration with 50-turn current

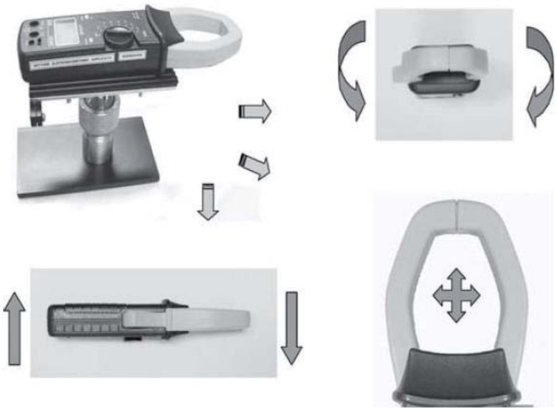

Fig. 4. Possible variations of clamp meter positon related to the current conductor (current coil) [2]

Before measurements, some steps have to be performed: batteries check, cleaning of the jaw contacts and temperature stabilization with the room temperature [7]. Measurements should be done at least in three points in one range and at least in one point in the other ranges, from 50% to 99% full scale [8]. All measurements should be performed with controlled enviroment conditions: temperature should be between 18ºC and 28ºC and relative humidity between 30% and 70%, so a thermo-hygrometer should be used for enviroment conditions measurement.

The mathematical model for a clamp meter calibration can be found in Eq. 1:

$$E_X = I_{iX} - N.(I_S + \delta I_S + \delta I_{S.C}) + \delta I_{iX} \quad (1)$$

where:

E_X	Error of the indication of the clamp meter under calibration
I_{iX}	Indication of the clamp meter under calibration
δI_{iX}	Correction due to finite resolution of the clamp meter under calibration
I_S	Current driven by the calibrator
δI_S	Correction of the calibrator based on accuracy specification given by its manufacturer
$\delta I_{S.C}$	Correction of the calibrator based on its last calibration report
N	Number of turns of the coil (its uncertainty is related to the coil / clamp interaction)

In clamp meters calibration, there is no uncertainty due to the number of turns, e.g., the N number of turns is an exact number. But there is an uncertainty due to the interaction between the coil and the clamp meter. This uncertainty depends on the type of the clamp meter being calibrated, current transformer (toroidal-wound) or Hall sensor types. Typical values for this uncertainty, stated by current coil manufacturers, vary from about 0.2% (current transformer) to 0.5% or higher (Hall sensor) at DC or line frequency. For example, for Transmille model EA002 current coil, uncertainty at full scale is assumed to be 0.24% for its use with current transformer clamp meters and 0.48% for Hall sensor clamps [9], assuming rectangular probability distribution.

The current sourced by the multifunction calibrator is a fixed value, adjusted using its front panel keys or remotelly by means of a communication interface (usually GPIB). As the current is fixed, no variations can be seen.

The correction based on accuracy specification of the calibrator comes from its operator manual. Depending on the manufacturer, probability distribution can usually be uniform or normal, with 95% or 99% confidence.

The correction based on the last calibation report of the calibrator if often a non zero value associated with a 95% confidence uncertainty (k=2).

IV. UNCERTAINTY ANALYSIS

Some calibration results are presented below for calibration procedure evaluation and measurement uncertainty analysis. Standard measurement uncertainty was evaluated according to [10]. All examples employ Fluke 5522A multifunction calibrator [11] as standard current source and Transmille EA002 current coil at 50-turns set. Standard uncertainty presented is relative to the measured current by the clamp meter under calibration. For TUR calculations, i.e., the ratio between the error limit of the clamp meter and the measurement uncertainty, standard uncertainty was multiplied by 2 (95% confidence).

First, Table 1 shows the uncertainty budget for a low resolution toroidal wound clamp meter calibration, at 200 A (60 Hz), 400 A range. Error limit at this calibration point is about 2 x 10^{-2}. In this case, clamp meter readings were taken in a single clamp position, centered related to the coil. As it can be seen, major uncertainty contribution comes from clamp / coil interaction, so it clearly dominates standard measurement uncertainty.

The same calibration than previous one was performed, but clamp meters readings were taken at different clamp positions. In this case, $u\ (I_{iX})$ became greater than zero, and also measurement uncertainty became greater. This uncertainty budget can be seen in Table 2.

Table 1. Uncertainty budget for toroidal wound clamp meter calibration at 200 A (60 Hz) - clamp readings at the same position.

Quantity X_i	Estimate x_i	Standard uncertainty $u\ (x_i)$	Probability distribution	Sensitivity coefficient c_i	Contribution to the Standard Uncertainty $u_i\ (y)$	Degrees of freedom ν_i
I_{iX}	201.1 A	0 A	Normal	1	0 A	2
δI_{iX}	0 A	2.9 x 10^{-2} A	Rectangular	1	1.4 x 10^{-4}	∞
I_S	4 A	0 A	Normal	-50	0 A	2
δI_S	0 A	3.4 x 10^{-3} A	Normal	-50	8.5 x 10^{-4}	∞
$\delta I_{S.C}$	0 A	6.6 x 10^{-4} A	Normal	-50	1.6 x 10^{-4}	∞
N	50 A/A	7.5 x 10^{-2} A/A	Rectangular	-4 A	1.5 x 10^{-3}	∞
			Standard uncertainty $u\ (y)$		1.7 x 10^{-3}	

Table 2. Uncertainty budget for toroidal wound clamp meter calibration at 200 A (60 Hz) – clamp readings at different positions.

Quantity X_i	Estimate x_i	Standard uncertainty $u\ (x_i)$	Probability distribution	Sensitivity coefficient c_i	Contribution to the Standard Uncertainty $u_i\ (y)$	Degrees of freedom ν_i
I_{iX}	201.1 A	0.27 A	Normal	1	1.3 x 10^{-3}	2
δI_{iX}	0 A	2.9 x 10^{-2} A	Rectangular	1	1.4 x 10^{-4}	∞
I_S	4 A	0 A	Normal	-50	0 A	2
δI_S	0 A	3.4 x 10^{-3} A	Normal	-50	8.5 x 10^{-4}	∞
$\delta I_{S.C}$	0 A	6.6 x 10^{-4} A	Normal	-50	1.6 x 10^{-4}	∞
N	50 A/A	7.5 x 10^{-2} A/A	Rectangular	-4 A	1.5 x 10^{-3}	∞
			Standard uncertainty $u\ (y)$		2.2 x 10^{-3}	

As it can be seen, standard measurement uncertainty ranges from 1.7 x 10^{-3} to 2.2 x 10^{-3}. These values are very similar to those found when calibration procedure employs high current sources and standard current transformers. In both cases, TUR was greater than 3, therefore, adequate.

Table 3 shows uncertainty budget for a hall sensor clamp meter calibration at 200 A (60 Hz), 1 kA range. In this calibration point, clamp meter error limit is about 2.8 x 10^{-2}. Readings were also taken in different clamp positions. In this case, uncertainty due to clamp / coil interaction is much higher than other uncertainty contributions, even than the uncertainty contribution due to clamp meter readings variation, so it clearly dominates. Standard uncertainty was higher than uncertainty found in calibrations performed with high current sources and standard current transformers, but it had enough TUR for this clamp meter calibration (TUR >3).

Table 3. Uncertainty budget for hall sensor clamp meter calibration at 200 A (60 Hz) – clamp readings at different positions.

Quantity X_i	Estimate x_i	Standard uncertainty $u\ (x_i)$	Probability distribution	Sensitivity coefficient c_i	Contribution to the Standard Uncertainty $u_i\ (y)$	Degrees of freedom ν_i
I_{iX}	201.1 A	0.27 A	Normal	1	1.3 x 10^{-3}	2
δI_{iX}	0 A	2.9 x 10^{-2} A	Rectangular	1	1.4 x 10^{-4}	∞
I_S	4 A	0 A	Normal	-50	0 A	2
δI_S	0 A	3.4 x 10^{-3} A	Normal	-50	8.5 x 10^{-4}	∞
$\delta I_{S.C}$	0 A	6.6 x 10^{-4} A	Normal	-50	1.6 x 10^{-4}	∞
N	50 A/A	0.19 A/A	Rectangular	-4 A	3.8 x 10^{-3}	∞
			Standard uncertainty $u\ (y)$		4.1 x 10^{-3}	

V. CONCLUSIONS

This paper presented a procedure for electrical current clamp calibration, using a stable current source (a multifunction calibrator) and a current coil. Some calibration results were presented. Measurement uncertainty of toroidal-wound clamp meter calibration was very similar to those estimated when calibrations are performed with high current sources and standard current transformers. Measurement uncertainty of hall sensor clamp meter calibration was higher, but had enough test uncertainty ratio (TUR). Position variation of the clamp meter in relation to the current coil caused variations on its readings, and in some cases increased measurement uncertainty.

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