Traceable Technique to Calibrate Clamp Meters in AC Current From 100 to 1500 A

Flavio Galliana and Pier Paolo Capra

Abstract—A measurement technique to calibrate current clamp meters in ac current in the measurement range from 100 to 1500 A at 50 Hz has been developed at the National Institute of Metrological Research (INRIM) in addition to the primary reference measurement systems for ac current calibrations at INRIM. This technique is traceable to the national standards of dc resistance, dc voltage, and ac current ratio. It is based on a standard current transformer (CT), on a 50-mΩ standard shunt, and on a 61/2-digit digital voltmeter (DVM) that measures the voltage on the standard shunt inserted in a conductor, to which also the clamp meter is applied, whose current is supplied by a CT that can generate currents up to 1500 A. The CT is controlled by a variable transformer. The clamp meter is applied to a copper wire and placed on a tilting support simulating the actual operating mode of the meter. This measurement technique is applicable in industrial metrological laboratories and is an alternative to measurement practices of accredited secondary laboratories involving digital calibrators and turn current coils. This measurement technique was also tested utilizing an 81/2-digit high-accuracy DVM. The results of the evaluation are presented and discussed. The expanded uncertainties of the technique span from \( \frac{1}{10} \) to \( \frac{1}{100} \) at 100 A to \( 2 \times 10^{-3} \) at 1500 A.

Index Terms—Current clamp meter, current gain, current transformer (CT), measurement uncertainties, resistance shunt.

I. INTRODUCTION

In many industrial processes, the measurement of the electrical current is strategic for technical and economic aspects and to realize high levels in production quality. This measurement can be made with different techniques of varying accuracy, application difficulty, and costs. In ac current, accurate measurement methods involve high-performance current comparators, standard current transformers (CTs) (SCTs), and shunts [1]–[7]. These devices are usually permanently fixed in their measurement circuits. An alternative solution is the use of current clamp meters that are handheld electronic transducers. Their use is widespread in industrial and on-site applications as they do not require breaking of the conductor under test.

The high level of insulation between a current clamp meter and the conductor under test assures suitable safety for the operator. Current clamp meters are not generally used in well-defined positions and in environments in which temperature and humidity are not always under control, while they are calibrated in a standard position and in laboratories in which temperature and humidity are under control. This situation should be taken into account with the aim of calibrating clamp meters in conditions under which they will be used. In this paper, a traceable technique for the calibration of current clamp meters from 100 to 1500 A at 50 Hz with a system to simulate their actual operating mode developed at the National Institute of Metrological Research (INRIM) is presented. An uncertainty analysis of the technique and some comments on the calibration results of two typical clamp meters are also added. This technique was developed and tested not as a primary reference system for high-ac-current calibrations but to establish a measurement method also applicable in secondary and industrial laboratories to calibrate ac current clamp meters.

II. CURRENT CLAMP METERS

Current clamp meters (Fig. 1) are measurement devices that can measure dc or ac currents over a wide range, up to 2000 A. Their external measurement circuit is made up of a coil that can be opened with a lever. The two jaws of the clamp can be separated by a few centimeters allowing its application to the conductor under test.

The measured current is converted by an electronic circuit and the output quantity (voltage or current) is measurable by means of two terminals, or the current is directly available as in the clamp meter shown in Fig. 2.

Fig. 1. View of several models of current clamp meters.

1These laboratories are accredited by the National accreditation Service of Calibration Laboratories SIT.

Manuscript received September 23, 2011; revised January 23, 2012; accepted January 25, 2012. Date of publication April 3, 2012; date of current version August 10, 2012. The Associate Editor coordinating the review process for this paper was Thomas Lipe.

F. Galliana is with the National Institute of Metrological Research (INRIM), 10135 Torino, Italy (e-mail: f.galliana@inrim.it).
P. P. Capra is with the Politecnico di Torino, 10129 Torino, Italy, and also with the National Institute of Metrological Research (INRIM), 10135 Torino, Italy (e-mail: p.capra@inrim.it).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIM.2012.2188660
Current clamp meters with a Hall effect transducer can operate in dc current or in ac current at frequencies up to 100 kHz. The stated accuracy of current clamp meters is from 1% to 2% of the measurement range as their performance is affected by significant errors due to position and environment conditions.

In Fig. 3, an arrangement of a clamp meter in a laboratory undergoing calibration is shown. In this situation, the temperature and humidity are under control, and the position of the clamp meter is fixed.

Tests were conducted to evaluate the changes in the clamp meter reading with changes in its orientation. The results are shown in Figs. 4 and 5. The inclination of the tilting platform was measured with a mechanical goniometer with an uncertainty of ±3° while the horizontal level was defined with an air bubble device.

Fig. 6 shows the reading changes of a current clamp meter moving the conductor under test in the indicated positions.

### III. DESCRIPTION OF THE MEASUREMENT CIRCUIT

The measurement setup of the technique is shown in Fig. 7. The current in the conductor $C$ is obtained by a CT capable of supplying 15 kW controllable by a variable transformer (VT). The secondary circuit of the CT is connected to a 0.01-class SCT with a ratio of 1000:5. A 30-mm-diameter copper rod allows the application of the current clamp meter under calibration. This rod can be easily removed, allowing also the calibration of toroidal transducers and CTs. The secondary circuit of the SCT is closed on a 0.05-Ω Tinsley 1682 standard shunt with $L/R \approx 1 \times 10^{-6}$ at 1 kHz. As the measurement system works at 50 Hz, $L/R$ at this frequency is smaller. Nevertheless, this value was used as a conservative estimate in the uncertainty analysis. The evaluated temperature and power coefficients are $-1.8 \times 10^{-6}/°C$ and $4.0 \times 10^{-6}/W$, respectively. The voltage drop on the standard shunt is measured by a digital voltmeter (DVM) working on the 100-mV or 1-V ranges [8], [9]. The standard shunt is traceable to the dc resistance national standard as it is calibrated by the Low Resistances Laboratory of INRIM with a measurement method involving a high-performance current comparator bridge. The SCT and the DVM are traceable to the ac current ratio and dc voltage national standards, respectively, as they are calibrated by the High Voltage and Current Laboratory and the Laboratory for Calibration of High Precision Multifunction Instruments of INRIM, respectively [10].

The measurement setup is inserted in a rack (Fig. 8). The current is generated in the lower part of the rack, while the instruments to measure the current are in the upper part. The current clamp meter under calibration is placed on a tilting platform (Figs. 9 and 10) that allows movement in five degrees of freedom to better characterize it and to simulate its actual operating mode.

A small camera was integrated in the platform to visualize the indication of the current clamp meter on its display for further convenience for the operator (Fig. 11). The system works in semiautomated mode with a Visual Basic control program as the settings of the VT are made manually by the operator. The values of the current clamp meter under calibration are also recorded by the operator. The DVM control is performed by a General Purpose Interface Bus 488 interface.

### IV. ANALYSIS OF MEASUREMENT UNCERTAINTIES

According to [11] and to the scheme in Fig. 7, the gain $G$ at a current $I$, expressed as the ratio of the standard current to the current read by a current clamp meter, is given by

$$
G = \frac{I_{\text{appl}}}{I_{\text{meas}}} = \frac{V}{R_s(D + d)} \left( V + v + k_v \right) \times \left( R_s + \delta R_s + \delta R_{sac/dc} + \delta R_{T} + \delta R_P \right) \times \frac{1}{(D + d)I_c} 
$$

(1)
Fig. 4. (a) Reading change of a current clamp meter according to the degree of freedom in (b). (b) Tilt degree of freedom on the longitudinal axis.

Fig. 5. (a) Reading change of a current clamp meter according to the degree of freedom in (b). (b) Tilt degree of freedom on the cross axis.

Fig. 6. Reading change of a current clamp meter due to the movement of the conductor according to the indicated degree of freedom. The size of the circles is proportional to the reading change.

where

- \( V \) term due to the repeatability of the readings of the DVM;
- \( v \) correction due to the calibration of the DVM;
- \( k_V \) correction due to the accuracy of the DVM;
- \( R_s \) calibration value of the standard shunt;
- \( \delta R_{\text{ad}} \) correction due to the drift of the standard shunt;
- \( \delta R_{\text{vac}/dc} \) correction due to the variation of the value of the standard shunt from dc to ac current;
- \( \delta R_{\text{ssh}} \) correction due to the variation of the value of the standard shunt due to self-heating, which can be considered negligible as the application time of the current is too short to lead to heating of the shunt;
- \( \delta R_{\text{sh}} \) correction due to the overall contribution from different temperatures and to the different current.
application times to the standard shunt between its calibration and its use in this setup;
\( \delta R_{sP} \) correction due to the power coefficient of the standard shunt;
\( D \) calibration value of the SCT ratio;
\( d \) correction due to the drift of the SCT ratio;
\( I_c \) reading, including its resolution, of the current clamp meter under calibration.

In Tables I and II, the uncertainty budgets of the measurement technique for the calibration of a specific current clamp meter utilizing as a standard DVM the 61/2-digit Agilent 34401 DVM or the high-accuracy 81/2-digit Agilent 3458 DVM at a current of 500 A are reported. All input quantities are considered independent.

The expanded uncertainties \( (k = 2) \) of the current gain at 500 A are then \( 4.4 \times 10^{-3} \) and \( 2.2 \times 10^{-3} \) depending upon
the used DVM. To make the type-A evaluation of the uncertainty, 20 readings on the clamp meter varying its position on the tilting platform for each measurement current were made. These measurements were performed in a laboratory at $23 \pm 2 ^\circ C$ and at a humidity of $40\% \pm 15\%$. In Table III, typical calibration expanded uncertainties ($k = 2$) in the range $2\delta$ were $2.2 \times 10^{-3}$.

### Table I

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Estimate $x_i$</th>
<th>$u(x_i)$</th>
<th>Probab. distr.</th>
<th>$c_i$</th>
<th>$u(G)$</th>
<th>Degrees freed. $v_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V'$</td>
<td>$125 \text{ mV}$</td>
<td>$4.6 \times 10^{-3} \text{ V}$</td>
<td>Normal</td>
<td>$8.0 \text{ V}^{-1}$</td>
<td>$3.6 \times 10^{-4}$</td>
<td>19</td>
</tr>
</tbody>
</table>

#### Type A uncertainty components

| $R_i$ | $50 \text{ m}\Omega$ | $5.0 \times 10^{-7} \text{ } $Ω | Normal | $20 \text{ } $Ω$^{-1}$ | $1.0 \times 10^{-5}$ | $\infty$ |
| $n$ | $0 \text{ V}$ | $2.9 \times 10^{-4} \text{ V}$ | Rect. | $8.0 \text{ V}^{-1}$ | $2.3 \times 10^{-4}$ | $\infty$ |
| $k_v$ | $0 \text{ V}$ | $2.3 \times 10^{-4} \text{ V}$ | Rect. | $8.0 \text{ V}^{-1}$ | $1.8 \times 10^{-3}$ | $\infty$ |
| $\delta R_{ad}$ | $0 \text{ } $Ω | $2.9 \times 10^{-3} \text{ } $Ω | Rect. | $20 \text{ } $Ω$^{-1}$ | $5.8 \times 10^{-6}$ | $\infty$ |
| $\delta R_{ac/dc}$ | $0 \text{ } $Ω | $1.4 \times 10^{-4} \text{ } $Ω | Rect. | $20 \text{ } $Ω$^{-1}$ | $2.9 \times 10^{-7}$ | $\infty$ |
| $\delta R_{a}$ | $0 \text{ V}$ | negl. | Rect. | $20 \text{ } $Ω$^{-1}$ | negl | $\infty$ |
| $\delta R_{d}$ | $0 \text{ Ω}$ | $1.8 \times 10^{-5} \text{ } $Ω | Rect. | $20 \text{ } $Ω$^{-1}$ | $3.6 \times 10^{-4}$ | $\infty$ |
| $D$ | $500 \text{ A}$ | $0.5 \text{ A}$ | Rect. | $2.0 \times 10^{-4} \text{ A}^{-1}$ | $1.0 \times 10^{-3}$ | $\infty$ |
| $u(G)$ | combined | Standard uncertainty | $2.2 \times 10^{-3}$ | $k = 2$ |

#### Type B uncertainty components

| $U(G)$ | Expanded | Uncertainty | $2\delta$ | $4.4 \times 10^{-3}$ |

### Table II

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Estimate $x_i$</th>
<th>$u(x_i)$</th>
<th>Probab. distr.</th>
<th>$c_i$</th>
<th>$u(G)$</th>
<th>Degrees freed. $v_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V'$</td>
<td>$125 \text{ mV}$</td>
<td>$1.2 \times 10^{-5} \text{ V}$</td>
<td>Normal</td>
<td>$8.0 \text{ V}^{-1}$</td>
<td>$9.6 \times 10^{-5}$</td>
<td>19</td>
</tr>
</tbody>
</table>

#### Type A uncertainty components

| $R_i$ | $50 \text{ m}\Omega$ | $5.0 \times 10^{-7} \text{ } $Ω | Normal | $20 \text{ } $Ω$^{-1}$ | $1.0 \times 10^{-5}$ | $\infty$ |
| $n$ | $0 \text{ V}$ | $2.9 \times 10^{-4} \text{ V}$ | Rect. | $8.0 \text{ V}^{-1}$ | $2.3 \times 10^{-4}$ | $\infty$ |
| $k_v$ | $0 \text{ V}$ | $2.3 \times 10^{-4} \text{ V}$ | Rect. | $8.0 \text{ V}^{-1}$ | $1.8 \times 10^{-3}$ | $\infty$ |
| $\delta R_{ad}$ | $0 \text{ } $Ω | $2.9 \times 10^{-3} \text{ } $Ω | Rect. | $20 \text{ } $Ω$^{-1}$ | $5.8 \times 10^{-6}$ | $\infty$ |
| $\delta R_{ac/dc}$ | $0 \text{ } $Ω | $1.4 \times 10^{-4} \text{ } $Ω | Rect. | $20 \text{ } $Ω$^{-1}$ | $2.9 \times 10^{-7}$ | $\infty$ |
| $\delta R_{a}$ | $0 \text{ V}$ | negl. | Rect. | $20 \text{ } $Ω$^{-1}$ | negl | $\infty$ |
| $\delta R_{d}$ | $0 \text{ Ω}$ | $1.8 \times 10^{-5} \text{ } $Ω | Rect. | $20 \text{ } $Ω$^{-1}$ | $3.6 \times 10^{-4}$ | $\infty$ |
| $D$ | $500 \text{ A}$ | $0.5 \text{ A}$ | Rect. | $2.0 \times 10^{-4} \text{ A}^{-1}$ | $1.0 \times 10^{-3}$ | $\infty$ |
| $u(G)$ | combined | Standard uncertainty | $1.1 \times 10^{-3}$ | $V_{eff} > 30$ |

| $U(G)$ | Expanded | Uncertainty | $2\delta$ | $2.2 \times 10^{-3}$ | $k = 2$ |
from 100 to 1500 A with the measurement setup utilizing the Agilent 34401 DVM and the Agilent 3458 DVM are reported.

In order to make a complete uncertainty analysis, other uncertainty components should be taken into account due to the following:

1) possible hysteresis effect of the current clamp meter;
2) effect due to the harmonic distortion of the standard current;
3) possible heating of the current clamp meter during its calibration;
4) effects of deviation from true RMS current for clamp meters that are not directly RMS responding instruments.

A full evaluation of the uncertainty would then require accounting for these components, which is beyond the aim of this paper as this measurement system is particularly oriented toward the application in secondary and industrial laboratories and as the accuracies of current clamp meters are not particularly high. For these reasons, to take into account all these small uncertainty components could be an excessive burden in terms of management and economical aspects for a secondary or industrial laboratory. For further details about the calibration procedure and uncertainty analysis for current clamp meters, see [12].

V. EXPERIMENTAL RESULTS

Fig. 12 shows a graph of the comparison of the current gain of two current clamp meters, both calibrated in the measurement range from 100 to 1000 A using the Agilent 34401 DVM.

The current gain of the LEM HEME mod LH2015 meter is less dependent on the applied current than the gain of the LEM HEME mod LH1040 meter. At higher currents, the behavior of this meter is presumably due to a vibration of the jaws and to a partial opening of the clamp which leads to an increase of the measurement error. Another hypothesis could be an increase in noise due to the saturation condition of the magnetic material of the jaws of the clamp. This effect might have caused an increase in the harmonic content and a consequent further increase of the response by the meter. Moreover, a temperature effect at higher currents, for example, on the Hall chip or in the electronics due to the heat of the core, could also be another cause of the behavior of the LEM HEME mod LH1040 meter.

A calibration of the YOKOGAWA mod N200 no. JKK8192 current clamp meter utilizing in the measurement setup the Agilent 34401 DVM and the Agilent 3458 DVM was also made. The results are shown in Fig. 13.

From the results shown in Fig. 13 and applying the uncertainties presented in Table III, it is clear that using the Agilent 3458A DVM instead of the Agilent 34401 DVM does not significantly improve the results.

VI. CONCLUSION

In this paper, a description of a measurement technique for the calibration of current clamp meters in the range from 100 to 1500 A at 50 Hz, traceable to the national standards of dc resistance, dc voltage, and ac current ratio, has been given. This technique allows a characterization of clamp meters simulating their actual use conditions during their calibration, making it more useful for the customer. On the other hand, the limits of this technique are the complex power generation system and the
only semiautomated operating mode. The implementation of this setup is feasible, particularly in laboratories that have CTs, shunts, and VTs, may be utilized also for other applications, and can be developed also when necessary with these instruments. The investigation of the setup replacing the normally used 61/2-digit DVM with a higher performance one showed that this could improve the uncertainties and the performance of the technique but not at a significant level. As a matter of fact, the main uncertainty component is due to the reading of the current clamp meter under calibration. This confirms that the original choice of the DVM was appropriate for the calibration of this type of instrument. Future aims of this work will be an evaluation of the dependence of the setup versus environment parameters, the replacement of the SCT with an electronically compensated or a multistage SCT with a secondary current of the CT. All these modifications could further improve the uncertainties and the management of the technique.

ACKNOWLEDGMENT

The authors would like to thank G. La Paglia of the National Institute of Metrological Research (INRIM) and Ing. G. Pellicci, head of a secondary accredited laboratory, for their kind advice during the preparation of this paper.

REFERENCES


Flavio Galliana was born in Pinerolo, Italy, in 1966. He received the M.Sc. degree in physics from the Università degli Studi di Torino, Torino, Italy, in 1991. In 1993, he joined the Istituto Elettrotecnico Nazionale “Galileo Ferraris” (IEN), Torino, where he was involved in precision high-resistance measurements with the development and characterization of some measurement methods. He also joined the “Accreditation of Laboratories” Department, IEN, with particular attention in the evaluation of the quality systems of the applicant laboratories and Servizio di Tratura in Italia calibration centers. From 2001 to 2005, he was responsible of the “Accreditation of Laboratories” Department, IEN. Since 2006, IEN has been part of the National Institute of Metrolgical Research (INRIM), Torino, where he has been involved in precision resistance measurements.

Pier Paolo Capra was born in Torino, Italy, in 1965. He received the Technical High-School degree in chemistry from Istituto Tecnico Industriale Statale L. Casale, Torino, in 1984 and the M.Sc. degree in physics from the Università degli Studi di Torino, Torino, in 1996. He is currently working toward the Ph.D. degree in metrology at the Politecnico di Torino, Torino.

In 1987, he joined the Istituto Elettrotecnico Nazionale “Galileo Ferraris,” Torino, where he was involved in dc voltage and resistance precision measurement. In 1997, he was involved in the realization and maintenance of the national standard of dc electrical resistance at the National Institute of Metrolgical Research (INRIM), Torino, where he became a Researcher in 2001 and is currently responsible for the national resistance standard and for the dissemination of the resistance unit.