A METHOD FOR CALIBRATING 10-TURN AND 50-TURN CURRENT COIL USING MULTIPRODUCT CALIBRATOR

Metode Kalibrasi Current Coil 10 Lilitan dan 50 Lilitan Menggunakan Multiproduct Calibrator

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Abstract

This paper presents a traceable measurement method developed in the Laboratory of National Measurement Standards for Electricity and Time (NMS Lab for Electricity and Time) - National Standardization Agency of Indonesia for calibrating current coil in order to obtain correction and uncertainty estimation of the current coil windings number (N). Current coils as objects of this research were 10-turn and 50-turn current coil. Calibration was performed using standard multiproduct calibrator (MPC) and two auxiliary devices, current coil F-5500 and clamp meter F-337. Correction and uncertainty values of N current coil were evaluated for DC and AC supplied current using formulation developed based on principle of current division between current coil output and supplied current from MPC. Based on evaluation result analysis, the expanded uncertainties of this method span from 0.47% to 1.0% (when supplied by DC current) and from 0.57% to 1.1% (when supplied by AC current) for 10-turn current coil, and span from 0.44% to 0.65% (when supplied by DC current) and from 0.54% to 0.96% (when supplied by AC current) for 50-turn current coil. Moreover, it also showed that the largest uncertainty component came from current coil F-5500. Meanwhile, the largest correction for 10-turn current coil was obtained 1.2% at 10 A DC, and for 50-turn current coil was obtained -0.47% at 700 A AC. Verification of the calibration and evaluation methods had also been carried out and it indicated that the calibration and analysis methods developed can be used to examine the performance of the current coil.

Keywords: calibration, current coil, multiproduct calibrator, uncertainty

Abstrak

Paper ini memaparkan tentang metode pengukuran tertelusur yang dikembangkan di Laboratorium Standar Nasional Satuan Ukuran Kelistrikan dan Waktu (Lab SNSU Kelistrikan dan Waktu) Badan Standardisasi Nasional (BSN) untuk mengkalibrasi current coil guna mendapatkan koreksi dan estimasi ketidakpastian jumlah lilitan (N) current coil. Current coil yang menjadi objek penelitian ini adalah current coil 10 lilitan dan 50 lilitan. Kalibrasi dilakukan dengan menggunakan standar multiproduct calibrator (MPC) dan dua perangkat bantu, yaitu current coil F-5500 dan clamp meter F-337. Nilai koreksi dan ketidakpastian N current coil dievaluasi untuk arus suplai DC dan AC dengan formulasi yang dikembangkan berdasarkan prinsip pembagian arus antara arus keluaran currrent coil dengan arus suplai MPC. Berdasarkan analisis hasil evaluasi, ketidakpastian bentangan yang didapatkan menggunakan metode ini terentang dari 0,47% hingga 1,0% (ketika disuplai oleh arus DC) dan dari 0,57% hingga 1,1% (ketika disuplai oleh arus AC) untuk current coil 10 lilitan, dan terentang dari 0,44% hingga 0,65% (ketika disuplai oleh arus DC) dan dari 0,54% hingga 0,96% (ketika disuplai oleh arus AC) untuk current coil 50 lilitan. Selain itu, hasil analisa juga menunjukkan bahwa komponen ketidakpastian terbesar berasal dari current coil F-5500. Sementara itu, koreksi terbesar untuk current coil 10 lilitan didapatkan sebesar 1,2% pada 10 A DC, dan untuk current coil 50 lilitan adalah sebesar -0,47% pada 700 A AC. Verifikasi metode kalibrasi dan evaluasinya juga telah dilakukan dan hasil verifikasi menunjukkan metode kalibrasi dan analisis yang dikembangkan ini dapat digunakan untuk menguji kinerja dari current coil.

Kata kunci: *current coil, kalibrasi, ketidakpastian, multiproduct calibrator*

1. INTRODUCTION

Laboratory of National Measurement Standards for Electricity and Time (NMS Lab for Electricity and Time) in National Standardization Agency of Indonesia has standard namely Multiproduct Calibrator (MPC) which able to generate electrical quantities such as voltage (DC and AC), current (DC and AC), resistance, and capacitance. MPC has played role as working standard for calibration services of meters which have accuracy of 6.5 digit or below (Galliana, Capra & Gasparotto, 2012). During this time, in Lab NMS for Electricity and Time, electrical quantities generated by MPC which have been traceable in metrology were voltage, current, and resistance. The traceability of the quantities were through standard reference multimeter which traceable to system international unit (SI Unit) through Korea Institute of Science and Standard (KRISS) – South Korea and National Measurement Institute of Australia (NMIA) (KRISS, 2014) (NMIA, 2017). In addition to meters, The use of MPC for calibration of other electrical equipment has begun to develop along with many requests from customers, one of which is calibration of current multiplier devices, or commonly called by current coil.

In industrial application or calibration laboratory, current coil has been used to calibrate AC clamp meter as was done by Karel & Renata and to calibrate DC and AC Clamp Meter as was done by Transmille which performed clamp meter calibration using 2-turn, 10-turn, and 50-turn of coil (Transmille, 2008) (Draxler & Styblíková, 2016) . It also can be used to calibrate other meters which uses a clamp for current sensor, as was done by H. Amalia and A. Faisal on the calibration of power quality analyzer (PQA) (Amalia & Faisal, 2017). For the need of traceability to SI unit and to evaluate the caracteristics of values generated by the coil, it should be calibrated using a traceable standard to SI unit (Costa, 2018). Calibration of the current coil has been done by A. Olencki and P. Mróz in the process of power clamp meters calibration in current range up to 1000 A at 50/60 Hz. Their method was conducted in automatic way and allowed to measure two parameter of current coil that are necessary for calibration of power clamp meter - known as amplitude coil effect (ACE) and phase coil effect (PCE). In their research, ACE is defined as coupling error due to coupling between a current clamp meter and a current coil when calibrating a current clamp meter with a current coil. While PCE is a new error parameter which they proposed to be taken into account as an uncertainty source in calibration of power clamp meters (Olencki & Mróz, 2017).

$$I_o = I_i \times N \qquad (1)$$

where:

I_O = output current of current coil

I_i = input current of current coil (supplied current from source)

N = windings number of current coil

Current coil is operated based on the principle of multiplication between input current and windings number of current coil (*N*) by following mathematical equation as indicated by (1). Windings number of current coil (*N*) is a fixed-value, meaning that the coil will never increase or decrease unless changes were made mechanically by adding or subtracting the number of windings. However, an output current measurement of current coil is necessary to be carried out to determine the actual value of *N*. Mathematically based on Eq. 1, the value of *N* can be obtained by dividing the input current and output current of current coil.

Different from what was done by A. Olencki and P. Mróz, in this research, calibration method was developed to determine correction of N current coil and uncertainty estimation which were traceable to SI Unit so that the true value of current coil output can be determined validly. Calibration was conducted manually using calibrator, clamp meter, and 2 (two) current coils, i.e. 50-turn current coil and the switchable 50-turn and 10-turn current coil. Correction and uncertainty were evaluated and presented based on the windings number of current coil (*N*) in term of percent (%). The correction was obtained by comparing the value of *N*, which was obtained through a mathematical calculation based on measurement data of actual output current, and nominal value of *N* current coil. Calibration method and analysis to obtain correction and uncertainty were built based on actual phenomena and mathematical model was developed using the principle of current division based on Eq. 1.

This paper attempts to provide an overview of the developed current coil calibration system which can be applied practically, easily, and traceable validly to SI unit. Equipment set up, data collection methods, evaluation process, and evaluation results in the form of correction and measurement uncertainty values, along with their analysis, which have been verified, are presented in detail so that it is expected to be a guideline and proofing that the method can be applied and has good performance.

2. BASIC THEORY

Working Principle of Current Coil

A Current coil has working principle similar to current transformer which uses the Faraday law to produce an induced current as shown in Figure 1 (Fluke Corporation, 2002) (Ziegler, Woodward, Iu & Borle, 2009).

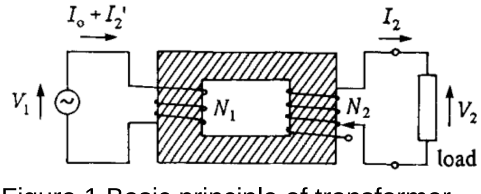


Figure 1 Basic principle of transformer.

When current is driven to the primary winding, the magnetic field is created and attracted into the steel core which is encircled by the secondary winding. On both primary and secondary transformer winding, the actual field strength is common and becomes no important. When secondary winding is loaded, its induce voltage will drive current into the load. The value of secondary winding current and voltage can be obtained based on mathematical expression shown by Eq. 2 and Eq. 3 where N_1 is the primary winding number, N_2 is the secondary winding number, I_1 is current on primary winding, I_2 is current on secondary winding, U_1 is voltage on primary winding, and U_2 is voltage on secondary winding (Ljubljanac, 2018).

$$N_1.I_1 = N_2.I_2 \quad (2)$$

$$U_1.I_1 = U_2.I_2 \quad (3)$$

where :

N_1 = primary winding number
N_2 = secondary winding number
I_1 = current on primary winding
I_2 = current on secondary winding
U_1 = voltage on primary winding
U_2 = voltage on secondary winding

On current coil enclosed by clamp meter shown by Figure 2 is assumed that N_2 is 1 and N_1 is N of current coil, so the output current (I_2) of the clamp meter is formulated by mathematical equation given by Eq. 4 where I_1 in this case is current input of current coil.

$$I_2 = N.I_1 \quad (4)$$

Where:

I_1 = current input of current coil
N = winding number (N) of current coil
I_2 = output current read on the clamp meter

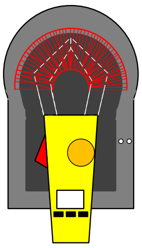


Figure 2 Combination of current coil and clamp meter.

Uncertainty: Definition and Theory

There is always a margin of doubt existed in every measurement, even for the most careful measurement, called by uncertainty of measurement. The term of uncertainty is usually followed by the width of margin, or interval, and a confidence level which states how sure we are that the 'true value' is within that margin. Besides uncertainty, in measurement science, there is also the term of error which is define as difference between measured value and the 'true value' of the thing being measured. The error can be corrected by applying corrections from calibration certificate. But, not all value of error can be known and corrected. This kind of error, then, will become a source of uncertainty. Sources of uncertainty also can come from the measuring instrument, the item being measured, the measurement process, imported uncertainties, operator skill, sampling issues, and the environment (Bell, 2001).

In calculating uncertainties, it is important to know what the probability distribution of the uncertainty is, such as normal distribution, rectangular distribution, triangular distribution, M-shaped distribution, or lop-sided distribution. Moreover, uncertainty can be calculated using 2 ways, i.e. type A evaluation and type B evaluation. Type A evaluation is uncertainty which is evaluated using statistical method and usually comes from repeated readings. While type B evaluation is uncertainty which is estimated from other information such as data from history measurement, calibration certificate, technical specification, other researches, or published information (Farrance & Frenkel, 2012). Statistically, all of sources of uncertainty are assumed to be uncorrelated because each of them are measured and estimated using independent methods. There are generally 5 steps which have to be done to evaluate calibration uncertainty follows:

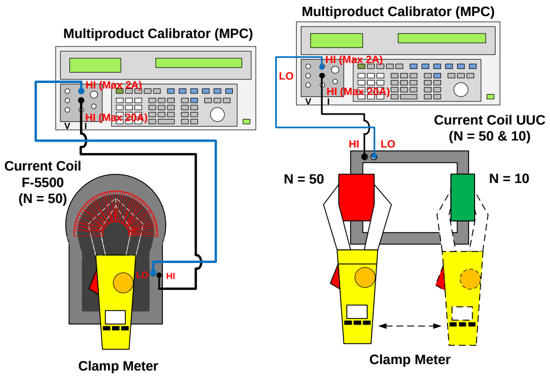
a. Obtained sources of uncertainties from manufactures' specification, previous experience, and/or literature.
b. Calculate standard uncertainty using expanded uncertainty and statistical distribution.
c. Calculate sensitivity coefficient using partial derivative from measurement equation for each variable.
d. Calculate combined uncertainty using the root sum of the squares of the standard uncertainty times the sensitivity coefficient.
e. Calculate expanded uncertainty using combined uncertainty times the coverage factor (k).

(Habte, Sengupta, Reda, & Andreas, 2014) (Hogan, 2015).

3. METHODS

Unit which is calibrated in this research was the number of windings, or commonly called by *N*. Based on the formulation in Eq. 1, to obtain the value of *N*, supplied current from MPC and output current of current coil need to be known. The measurement was performed on DC and AC current outputs of the current coil with both of 10 and 50 numbers of windings. Henceforth, this current coil will be called by current coil UUC (Unit Under Calibration). Calibration was carried out indirectly using standard multiproduct calibrator (MPC) and two auxiliary devices, namely current coil F-5500 and clamp meter F-337. Unlike current coil UUC, current coil F-5500 has only one of N, i.e. 50. MPC used in this research is a source which can provide DC and AC supplied currents up to 20 A, while the clamp meter F-337 has measuring capability of DC and AC current up to 999.9 A. Therefore, the point of measurement in this research was adapted to maximum capabilities of MPC and current coil F-337. Moreover, AC current measurement was carried out at frequency of 53 Hz only.

In this calibration method, for both DC and AC current, measurements were performed on two steps. The first step was the output current measurement of current coil F-5500, while the second step was the output current measurement of the current coil UUC. The measurement schemes of each step are presented in Figure 3.



(a) (b)

Figure 3 Schematic diagram of current measurement step 1 (a) and step 2 (b).

In the measurement step 1, as shown in Figure 3(a), the current from MPC was directly transferred to current coil F-5500 by using two (2) wires method. The current that have been enlarge since passed the current coil F-5500 was read using clamp meter F-337 that clamped into current coil F-5500. Similar to the measurement at step 1, at step 2, the current from MPC was directly transferred to current coil UUC using two (2) wires method as shown in Figure 3(b). The current that has passed current coil UUC was read using clamp meter F-337.

Step 1 and 2 measurements were conducted for the current coil UUC with N = 10 and 50, for both DC and AC current. When conducting measurement for N=10, at step 2 measurement, clamp meter F-337 was clamped to the 10-turn coil (N=10). Likewise, when conducting measurement for N=50, at step 2 measurement, clamp meter F-337 was clamped to the 50-turn coil (N=50). While at step 1 measurement, for both current coil UUC with N=10 and N=50, the measurement was performed using the 50-turn current coil F-5500.

In the measurement for 10-turn current coil UUC, level of supplied current from MPC in step 1 was different with level of supplied current from MPC in step 2. That was because the difference in the windings number of current coil F-5500 used in step 1 and current coil UUC used in step 2. Level of MPC supplied current for step 1 and step 2 was calculated using formulation in Eq. 5 and Eq. 6. In Eq. 5 and Eq. 6, I_{MPC1} was supplied current of MPC in step 1, I_{MPC2} was supplied current of MPC in step 2, and I_{nom} was nominal current in output current measurement of 10-turn current coil UUC.

$$I_{MPC1} = \frac{I_{nom}}{50} \quad (5)$$

$$I_{MPC2} = \frac{I_{nom}}{10} \quad (6)$$

I_{MPC1} = supplied current of MPC in step 1
I_{MPC2} = supplied current of MPC in step 2
I_{nom} = nominal current in output current measurement of 10-turn current coil UUC

Table 1 Measurement point of current coil calibration

10-Turn Current Coil UUC			50-Turn Current Coil UUC	
Nom Meas Point [A]	Current Supplied from 5520A [A] Step 1	Step 2	Nom Meas Point [A]	Current Supplied from 5520A [A] Step 1=Step 2
10	0,2	1	50	1
30	0,6	3	100	2
50	1	5	150	3
70	1,4	7	200	4
90	1,8	9	250	5
110	2,2	11	300	6
130	2,6	13	350	7
150	3	15	400	8
170	3,4	17	450	9
200	4	20	500	10
			550	11
			600	12
			650	13
			700	14
			750	15
			800	16
			850	17
			900	18
			950	19

In the measurement of 50-turn current coil UUC, level of supplied current from MPC in step 1 was the same as level of MPC supplied current in step 2. It was because windings number of current coil F-5500 used at step 1 was equal to windings number of current coil UUC used in step 2. Level of supplied current from MPC for step 1 and step 2 measurement was calculated using Eq. 7 where $I_{MPC1,2}$ was supplied current of MPC in step 1 and step 2 measurement and I_{nom} was nominal current in output current measurement of 50-turn current coil UUC.

$$I_{MPC1,2} = \frac{I_{nom}}{50} \quad (7)$$

$I_{MPC1,2}$ = supplied current of MPC in step 1 and step 2 measurement

I_{nom} = nominal current in output current measurement of 50-turn current coil UUC.

By using formulation in Eq. 5, 6, and 7, supplied current from MPC for each step was obtained as shown in Table 1. The value calculated in this research was correction of N and measurement uncertainty. The mathematical model used to get the correction and the uncertainty was obtained through derivation of mathematical model formulated based on system in step 1 and step 2.

Step 1 Measurement

The purpose of measurement in step 1 is to obtain the value of correction and uncertainty of DC and AC current level reading by clamp meter F-337. In this case, MPC serves as standard as well as current source, current coil F-5500 serves as auxiliary device, and clamp meter F-337 serves as instrument under calibration. Mathematical model used to evaluate the correction (C_m) is shown by Eq. 8, where I_{SS} was current generated by combination of MPC and current coil F-5500, and I_{cm1} was average current reading of clamp meter F-337 in step 1. I_{SS} was defined by (1) in mathematics, so the formulation to find correction of clamp meter F-337 can be derived into Eq. 9. N_{f5500} was the windings number of current coil F-5500, i.e. 50.

$$C_m[A] = I_{SS} - I_{cm1} \quad (8)$$

$$C_m[A] = \lfloor I_S * N_{f5500} \rfloor - I_{cm1} \quad (9)$$

$C_m[A]$ = correction of DC and AC current level reading by clamp meter F-337 (in Ampere [A] Unit)

I_{SS} = current generated by combination of MPC and current coil F-5500

I_{cm1} = average current reading of clamp meter F-337 in step 1

I_s = the current value set at standard MPC

N_{f5500} = the windings number of current coil F-5500, i.e. 50.

The current value set at standard MPC (I_S) was nominal value. This value need to be corrected in advanced to get the value of the actual current supplied to the current coil F-5500. The correction came from standard MPC and correction caused by other factors, such as correction caused by gain and linearity of MPC, correction because of the loading effect, correction caused by drift of MPC, correction due to temperature coefficient, and correction sourced by stability of MPC. Correction and uncertainty of standard MPC were obtained from calibration certificate of MPC. Henceforth, correction and uncertainty taken from MPC's calibration certificate were called by certificate correction (C_{sert}) and certificate uncertainty (u_{sert}). While correction derived from other factors (i.e. gain, linearity, loading effect, drift, temperature coefficient, and stability, notated by C_{spek}) was taken from reference data. In this research, the correction coming from those factors were estimated to be zero. However, the correction factors were compensated in the calculation of uncertainty where their values were taken from the technical specification of MPC (Fluke Corporation, 2003). For the ease of explanation, uncertainty caused by other factors except MPC's certificate was called by uncertainty of MPC's specification (u_{spek}).

Supplied current from MPC (I_S) was passed first to the current coil F-5500 before being transferred to the clamp meter F-337. Output current of current coil F-5500 was also influenced by factors such as linearity, stability, temperature coefficient, and drift. Therefore, correction needs to be added to it. Correction caused by these factors was obtained from reference data and for the next will be called current coil F-5500 correction and notated by C_N. In this calibration method, current coil F-5500 correction was ignored and had zero value in correction calculation. Because the value of uncertainty caused by these factors was not evaluated independently, at uncertainty calculation, its value was taken from technical specification of current coil and for the next will be called by uncertainty of current coil F-5500 (u_N) (Fluke Corporation, 2002).

$$C_m[A] = \left[(I_S + C_{sert} + C_{spek}) * (N_{f5500} + C_N)\right] - \bar{I}_{cm1} \quad (10)$$

$$C_m[A] = \left[(I_S + C_{sert}) * N_{f5500}\right] - \bar{I}_{cm1} \quad (11)$$

$C_m[A]$ = correction of DC and AC current level reading by clamp meter F-337 (in Ampere [A] Unit)

I_s = the current value set at standard MPC

C_{sert} = MPC's certificate correction

C_{spek} = correction derived from other factors (i.e. gain, linearity, loading effect, drift, temperature coefficient, and stability of MPC)

N_{f5500} = the windings number of current coil F-5500, i.e. 50

C_N = current coil F-5500 correction

I_{cm1} = average current reading of clamp meter F-337 in step 1

Based on explanation above, Eq. 9 can be derived to Eq. 10. Because the value of C_{spek} and C_N were considered by zero, Eq. 10 can be derived to Eq. 11 which was the final equation to find clamp meter F-337 correction. Besides correction of current level readings, evaluation in step 1 measurement was also conducted to obtain uncertainty. Uncertainty calculation was carried out based on rules of uncertainty evaluation by using type-A and type-B method (JCGM, 2008). Based on correction equation in Eq. 9, uncertainty budget in the calibration method at step 1 was derived from MPC, current coil F-5500, and clamp meter F-337.

Uncertainty came from MPC (us) was combined uncertainty of certificate uncertainty (u_{sert}) and MPC's specification uncertainty (u_{spek}) which mathematically formulated in Eq. 12. Furthermore, the value of u_s was expressed in relative using Eq. 13 which $I_{setting}$ was nominal current supplied by MPC. Certificate uncertainty (u_{sert}) was evaluated using type-B method by assumed to be normally distributed and mathematically given by : $u_{sert} = U_1/2$. U_1 was the certificate uncertainty of current parameter taken from calibration certificate of MPC (P2M-LIPI, 2017). While MPC's specification uncertainty (u_{spek}) was evaluated using type-B method which assumed to be normally distributed with confidence level of 99% and mathematically expressed by : $u_{spek} = U_2/2$. U_2 was absolute uncertainty obtained from Operating Manual Book of MPC (Fluke Corporation, 2003).

$$u_s\,[A] = \sqrt{u_{sert}^2 + u_{spek}^2} \quad (12)$$

$$u_{s\mathrm{Relatif}}\,[\%] = \frac{u_s}{I_{setting}}.100\% \quad (13)$$

u_s = uncertainty came from standard MPC

u_{sert} = MPC's certificate uncertainty

u_{spek} = MPC's specification uncertainty

$u_{sRelatif}$ = the value of u_s expressed in relative using Eq. 13

$I_{setting}$ = nominal current supplied by MPC

Uncertainty came from current coil F-5500 (u_N) was evaluated using type-B method which assumed to be normally distributed with confidence level of 99%. Mathematical model to evaluate this uncertainty is presented in Eq. 14. U_3 was total specification of the measured effective current output of the current coil. Its value was obtained from instruction sheet of current coil Fluke 5500A (Fluke Corporation, 2002). In this case, the value of U was already in relative.

$$u_N\,[\%] = \frac{U_3}{2.6} \quad (14)$$

u_N = uncertainty came from current coil F-5500

U_3 = total specification of the measured effective current output of the current coil

Uncertainty came from clamp meter F-337 (u_{cm1}) was uncertainty caused by repeatability of clamp meter F-337 readings and evaluated by type-A method using experiment standard deviation of the mean (ESDM) of 5 times data retrieval (JCGM, 2008).

Total uncertainty evaluated in step 1 was combined uncertainty of $u_{sRelatif}$, u_N, and u_{cm1}. To simplify the calculation, relative combined uncertainty ($u_{combRelatif}$) of MPC uncertainty and current coil F-5500 uncertainty was evaluated first by using Eq. 15 and 16. Afterwards, evaluation to find total uncertainty, which was a combination of $u_{combRelatif}$ and ESDM (u_{cm1}), was conducted using Eq. 17. It was based on lesson learned from a study of current measurement done previously by S. K. Jaiswal et al (Jaiswal, Ojha & Singh, 2005).

$$u_{comb\mathrm{Relatif}}\,[\%] = \sqrt{u_{s\mathrm{Relatif}}^2 + u_N^2} \quad (15)$$

$$u_{comb}\,[A] = \frac{u_{comb\mathrm{Relatif}}}{100} \times \left(I_{setting} \times 50\right) \quad (16)$$

$$u_m[A] = \sqrt{u_{comb}^2 + u_{cm1}^2} \quad (17)$$

$u_{combRelatif}$ = relative combined uncertainty of MPC uncertainty and current coil F-5500 uncertainty

$u_{sRelatif}$ = the value of u_s expressed in relative using Eq. 13

u_N = uncertainty came from current coil F-5500

u_{comb} = combined uncertainty of MPC uncertainty and current coil F-5500 uncertainty

$I_{setting}$ = nominal current supplied by MPC

u_{cm1} = uncertainty came from repeatability clamp meter F-337 reading

u_m = total combined uncertainty of clamp meter F-337 evaluated in step 1

The final uncertainty in step 1 was expanded uncertainty (U_m) with confidence level of 95%. Coverage factor and expanded uncertainty calculation were refers to guidelines of GUM (JCGM, 2008).

Step 2 Measurement

Step 2 Measurement was performed after correction and uncertainty of AC and DC current level reading by clamp meter F-337 were obtained in step 1. The final value evaluated in step 2 was correction of windings number of current coil UUC (C_{NX}) and its uncertainty. In the schematic of measurement system presented in Figure 3(b), MPC serves as standard as well as current source, clamp meter F-337 serves as auxiliary device, and current coil UUC was instrument under calibration. The mathematical model used was developped based on (1) and mathematically expressed in Eq. 18 which N_X was obtained by using the principle of current division between output current of current coil UUC read by clamp meter F-337 (i_{cm2}) and supplied current from standard MPC (I_S). Therefore, Eq. 18 can be derived to Eq. 19.

$$C_{NX} = N_x - N_{nom} \quad (18)$$

$$C_{NX} = \frac{I_{cm2}}{I_S} - N_{nom} \quad (19)$$

C_{NX} = correction of windings number of current coil UUC

I_{cm2} = output current of current coil UUC read by clamp meter F-337 in step 2 measurement

I_S = nominal supplied current set at standard MPC

N_X = current division between I_{cm2} and I_S

N_{nom} = nominal windings number of current coil UUC (10 or 50)

Similar to the measurement performed in step 1, nominal value of the supplied current set at standard (I_S) had two kinds of correction and uncertainty, which were correction and uncertainty from standard's calibration certificate (called by standard correction which notated by C_{sert} and standard uncertainty which notated as u_{sert}), and correction and uncertainty due to others factor which the value taken from technical specification of MPC (called by specification correction which notated by C_{spek} and specification uncertainty which notated by u_{spek}) (Fluke Corporation, 2003). Clamp meter F-337 used to read output current of current coil UUC also had correction (C_m) and uncertainty (U_m) which has been obtained on the step 1 measurement. Accordingly, Eq. 19 can be derived to Eq 20 which was the final equation to evaluate correction and uncertainty. N_{nom} represents nominal windings number of current coil UUC (10 or 50) and the value of C_{spek} was ignored to be compensated in the calculation of uncertainty.

$$C_{NX} = \frac{(I_{cm2} + C_m)}{(I_S + C_{sert} + C_{spek})} - N_{nom} \quad (20)$$

C_{NX} = correction of windings number of current coil UUC

I_{cm2} = output current of current coil UUC read by clamp meter F-337 in step 2 measurement

C_m = correction of DC and AC current level reading by clamp meter F-337

I_S = nominal value of the supplied current set at standard

C_{sert} = MPC's certificate correction

C_{spek} = correction derived from other factors (i.e. gain, linearity, loading effect, drift, temperature coefficient, and stability of MPC)

N_{nom} = nominal windings number of current coil UUC (10 or 50)

Based on the mathematical model in Eq. 20, budget uncertainty in step 2 measurement came from MPC and clamp meter F-337. Similar to the step 1 measurement, uncertainty came from MPC (u_S) was combined uncertainty of certificate uncertainty (u_{sert}) and MPC's specification uncertainty (u_{spek}) which their values were calculated using Eq. 12 and 13. While uncertainty came from clamp meter F-337 (u_{cm2}) was combined uncertainty of ESDM and clamp meter F-337 uncertainty obtained from step 1 measurement (u_m), which mathematically presented by Eq. 21. The value of u_{cm2} was then expressed as relative using Eq. 22 (Horálek, 2013).

$$u_{cm2} = \sqrt{u_{ESDM}^2 + u_m^2} \quad (21)$$

$$u_{cm2\,Relatif} = \frac{u_{cm2}}{I_S \times N_{nom}} \times 100\% \quad (22)$$

u_{cm2} = uncertainty came from clamp meter F-337

u_{ESDM} = uncertainty came from repeatability of clamp meter F-337 reading

u_m = clamp meter F-337 uncertainty obtained from step 1 measurement

$u_{cm2Relatif}$ = u_{cm2} expressed in relative

I_S = nominal supplied current set at

standard MPC

N_{nom} = nominal windings number of current coil UUC (10 or 50)

Research conducted by S. K. Jaiswal et al stated that if there was a division in mathematical model used to calculate correction, then the calculation of combined uncertainty was more easily done if each uncertainty component expressed in relative (Jaiswal et al., 2005). Therefore, combined uncertainty in step 2, as shown by mathematical model at Eq. 20, can be formulated as Eq. 23.

$$u_{NX\,\mathrm{Re}latif}\,[\%] = \sqrt{{u_{S\,\mathrm{Re}latif}}^{2} + {u_{cm2\,\mathrm{Re}latif}}^{2}} \quad (23)$$

$U_{NXRelatif}$ = final combined uncertainty in the relative form

$u_{sRelatif}$ = the value of u_s expressed in relative using Eq. 13

$u_{cm2Relatif}$ = uncertainty came from clamp meter F-337 expressed in relative

The final uncertainty was expanded uncertainty (U_{NX}) which the value evaluated based on guidelines of GUM (JCGM, 2008) with confidence level of 95% and expressed in relative (%) of the N nominal value (Jornada, Caten & Pizzolato, 2016).

4. **RESULTS AND DISCUSSIONS**

Data of measurement result in step 1, which were the average of 5 times of data reading, can be seen in “Clamp meter reading” column at Table 2. “Nominal operating current” was measurement point based on Table 1, while “Setting current of MPC” was nominal supplied current from MPC obtained by using Eq. 5, 6, and 7. By using Eq. 11, correction of AC and DC current level indication by clamp meter F-337 is obtained and presented in “Correction of clamp meter” column at Table 2. Evaluation result showed that the largest correction for DC current occurred at the nominal operating current of 700 A in the amount of -6.9 A or in relative was -0.98 %. While the largest correction for AC current occurred at nominal operating current of 550 A in the amount of -5.3 A or in the relative was -0.97 %. Measurement uncertainty of DC and AC current level obtained in step 1 using Eq. 17 is presented at Table 2 in “Unc of clamp meter” column. Evaluation result showed that uncertainties of DC current measurement by clamp meter F-337 span from 0.44% to 0.77% with the largest uncertainty occurred at nominal operating current of 30 A. While for AC current, uncertainties span from 0.52% to 1.1% with the largest uncertainty also occurred at nominal operating current of 30 A.

Table 2 Measurement data, correction, and uncertainty of clamp meter F-337 obtained through evaluation at step 1.

N current coil UUC (Nx)	Nominal operating current [A]	Setting current of MPC (Nominal Operating Current/50) [A]	DC Current					AC Current (at frequency of 53 Hz)				
			Clamp meter reading [A]	Correction of clamp meter		Unc of clamp meter		Clamp meter reading [A]	Correction of clamp meter		Unc of clamp meter	
				[A]	[%]	[A]	[%]		[A]	[%]	[A]	[%]
10	10	0,2	10,0	0,0	0,39	0,1	0,73	10,1	-0,1	-0,97	0,1	0,66
	30	0,6	30,1	-0,1	-0,31	0,2	0,77	30,2	-0,2	-0,68	0,3	1,08
	50	1	50,3	-0,2	-0,50	0,3	0,61	50,3	-0,3	-0,58	0,4	0,82
	70	1,4	70,3	-0,3	-0,44	0,4	0,55	70,6	-0,5	-0,75	0,5	0,71
	90	1,8	90,4	-0,4	-0,48	0,5	0,51	90,7	-0,6	-0,70	0,6	0,65
	110	2,2	110,5	-0,4	-0,41	0,5	0,49	110,9	-0,9	-0,78	0,7	0,61
	130	2,6	130,6	-0,6	-0,48	0,6	0,47	131,1	-1,0	-0,80	0,8	0,58
	150	3	150,9	-0,8	-0,56	1,0	0,65	151,3	-1,2	-0,83	1,3	0,89
	170	3,4	171,1	-1,1	-0,65	1,0	0,62	171,5	-1,4	-0,82	1,4	0,84
	200	4	201,1	-1,1	-0,54	1,2	0,58	201,8	-1,8	-0,88	1,6	0,78
50	50	1	50,3	-0,3	-0,58	0,3	0,60	50,3	-0,3	-0,58	0,4	0,83
	100	2	100,4	-0,3	-0,35	0,5	0,50	100,8	-0,7	-0,74	0,7	0,71
	150	3	150,9	-0,9	-0,61	1,0	0,65	151,3	-1,2	-0,82	1,4	0,93
	200	4	201,4	-1,3	-0,66	1,2	0,58	201,8	-1,7	-0,85	1,6	0,81
	250	5	251,8	-1,8	-0,72	1,4	0,54	252,3	-2,2	-0,86	1,8	0,74
	300	6	302,4	-2,4	-0,79	1,6	0,52	302,7	-2,6	-0,87	2,1	0,70
	350	7	352,9	-2,8	-0,81	1,7	0,50	353,4	-3,2	-0,92	2,3	0,66
	400	8	403,2	-3,2	-0,79	1,9	0,48	404,0	-3,8	-0,96	2,5	0,63
	450	9	453,8	-3,8	-0,84	2,1	0,47	454,6	-4,4	-0,97	2,7	0,61

N current coil UUC (Nx)	Nominal operating current [A]	Setting current of MPC (Nominal Operating Current/50) [A]	DC Current					AC Current (at frequency of 53 Hz)				
			Clamp meter reading [A]	Correction of clamp meter		Unc of clamp meter		Clamp meter reading [A]	Correction of clamp meter		Unc of clamp meter	
				[A]	[%]	[A]	[%]		[A]	[%]	[A]	[%]
	500	10	504,1	-4,2	-0,83	2,3	0,47	505,1	-4,8	-0,97	3,0	0,59
	550	11	554,8	-4,8	-0,87	2,6	0,47	555,6	-5,3	-0,97	3,2	0,59
	600	12	605,5	-5,5	-0,91	2,8	0,46	606,1	-5,7	-0,95	3,5	0,58
	650	13	656,4	-6,3	-0,97	3,0	0,45	656,5	-6,1	-0,93	3,7	0,57
	700	14	707,0	-6,9	-0,98	3,1	0,45	706,9	-6,4	-0,91	3,9	0,56
	750	15	757,0	-6,9	-0,92	3,3	0,45	757,2	-6,5	-0,87	4,1	0,55
	800	16	807,4	-7,3	-0,91	3,5	0,44	807,4	-6,7	-0,83	4,3	0,54
	850	17	858,1	-7,9	-0,93	3,7	0,44	857,2	-6,4	-0,75	4,5	0,53
	900	18	908,2	-8,0	-0,89	3,9	0,44	906,6	-5,8	-0,64	4,8	0,53
	950	19	958,5	-8,3	-0,87	4,1	0,44	954,9	-3,9	-0,41	5,0	0,52

The value of correction and uncertainty of DC and AC current level measurement using clamp meter F-337 that has been obtained in step 1 was used to evaluate correction and uncertainty of N current coil UUC in step 2. Based on evaluation result in step 2, it can be said that output current from current coil UUC with certain N (N=10 and N=50) were not exactly same as the formulation at (1). As it can be seen in Table 3, the readings of clamp meter F-337 after being corrected by clamp meter F-337 correction (which obtained in step 1) had different values with the results of multiplication of corrected supplied current from MPC and N current coil based on (1). It was indicated that multiplication factor of N current coil UUC was not always appropriate to the value of 10 or 50. There was correction of the value N causing the readings of clamp meter F-337 were not appropriate to the value of calculation results using (1). Furthermore, results presented at Table 3 also showed that the value of correction and uncertainty of N current coil UUC for each nominal operating current were different. It was due to correction and uncertainty of supplied current of MPC and correction and uncertainty of clamp meter F-337 reading also had different values for each nominal operating current. This phenomenon occurred at 10-turn and 50-turn current coil UUC, both when they were supplied by DC and AC current.

Table 3 Measurement data, correction, and uncertainty of N current coil obtained through evaluation at Step 2.

N current coil UUC (Nx)	Nominal Operating Current [A]	Setting Current of MPC (Nominal Operating Current/ Nx) [A]	DC Current				AC Current (at frequency of 53 Hz)			
			Multiplication of Corrected Current from MPC and Nx	Clamp Meter Reading after Correction (A)	Correction of Nx (%)	Unc of Nx (%)	Multiplication of Corrected Current from MPC and Nx	Clamp Meter Reading after Correction (A)	Correction of Nx (%)	Unc of Nx (%)
10	10	1,00	10,00	10,12	1,2	1,0	10,01	10,00	-0,02	0,65
	30	3,00	30,01	30,01	0,00	0,76	30,01	30,10	0,28	1,1
	50	5,00	50,01	50,01	0,01	0,61	50,02	50,11	0,18	0,80
	70	7,00	70,01	69,99	-0,03	0,56	70,03	70,07	0,06	0,70
	90	9,00	90,01	90,01	0,00	0,52	90,04	90,17	0,14	0,63
	110	11,00	110,00	110,15	0,14	0,49	110,06	110,20	0,13	0,60
	130	13,00	130,01	130,21	0,15	0,47	130,09	130,20	0,08	0,57
	150	15,00	150,02	150,27	0,16	0,64	150,13	150,23	0,07	0,88
	170	17,00	170,04	170,21	0,10	0,61	170,16	170,28	0,07	0,82
	200	20,00	200,04	200,56	0,26	0,58	200,20	200,28	0,04	0,76

N current coil UUC (Nx)	Nominal Operating Current [A]	Setting Current of MPC (Nominal Operating Current/ Nx) [A]	DC Current				AC Current (at frequency of 53 Hz)			
			Multiplication of Corrected Current from MPC and Nx	Clamp Meter Reading after Correction (A)	Correction of Nx (%)	Unc of Nx (%)	Multiplication of Corrected Current from MPC and Nx	Clamp Meter Reading after Correction (A)	Correction of Nx (%)	Unc of Nx (%)
50	50	1,00	50,01	50,05	0,08	0,61	50,03	49,87	-0,32	0,83
	100	2,00	100,01	100,13	0,12	0,50	100,08	99,66	-0,42	0,77
	150	3,00	150,03	150,23	0,13	0,65	150,05	149,39	-0,44	0,96
	200	4,00	200,04	200,24	0,10	0,58	200,08	199,26	-0,41	0,84
	250	5,00	250,04	250,12	0,03	0,54	250,10	249,04	-0,42	0,76
	300	6,00	300,05	300,11	0,02	0,52	300,13	298,91	-0,41	0,73
	350	7,00	350,06	350,08	0,01	0,50	350,15	348,65	-0,43	0,68
	400	8,00	400,06	400,06	0,00	0,48	400,18	398,42	-0,44	0,65
	450	9,00	450,05	450,03	0,00	0,47	450,20	448,18	-0,45	0,63
	500	10,00	499,99	500,01	0,00	0,46	500,23	498,11	-0,42	0,61
	550	11,00	550,02	550,06	0,01	0,47	550,31	547,85	-0,45	0,62
	600	12,00	600,06	600,08	0,00	0,46	600,39	597,75	-0,44	0,61
	650	13,00	650,07	649,97	-0,02	0,46	650,47	647,51	-0,46	0,59
	700	14,00	700,07	699,99	-0,01	0,46	700,55	697,23	-0,47	0,58
	750	15,00	750,10	749,90	-0,03	0,45	750,63	747,23	-0,45	0,57
	800	16,00	800,13	800,09	0,00	0,45	800,71	797,05	-0,46	0,56
	850	17,00	850,19	850,11	-0,01	0,44	850,79	847,13	-0,43	0,55
	900	18,00	900,26	900,24	0,00	0,44	900,86	897,28	-0,40	0,55
	950	19,00	950,23	950,17	-0,01	0,44	950,94	947,86	-0,32	0,54

For 10-turn current coil UUC, when supplied by DC current, uncertainties span from 0.47% to 1.0% with the largest uncertainty occurred at nominal operating current of 10 A. The largest correction also occurred at this nominal operating current in the value of 1.2%. While when supplied by AC current, uncertainties span from 0.57% to 1.1% with the largest uncertainty occurred at nominal operating current of 30 A. The largest correction also occurred at this nominal operating current in the value of 0.28%.

For 50-turn current coil UUC, when supplied by DC current, uncertainties span from 0.44% to 0.65% with the largest uncertainty occurred at nominal operating current of 150 A. The largest correction also occurred at this nominal operating current in the value of 0.13%. While when supplied by AC current, uncertainties span from 0.54% to 0.96% with the largest uncertainty occurred at nominal operating current of 150 A. The largest correction occurred at the nominal operating current of 700 A in the value of -0.47%.

In the step 1 measurement, uncertainty component which serves as major uncertainty was came from coil current F-5500 specification which represents linearity, stability, temperature coefficient, and drift of the current coil F-5500. While at step 2 measurement, uncertainty component that contribute the largest uncertainty value came from uncertainty of clamp meter F-337. Because the values of clamp meter F-337 uncertainty were obtained from step 1, it can be said that the largest uncertainty component which serves as major uncertainty in this calibration method was uncertainty of current coil F-5500 specification.

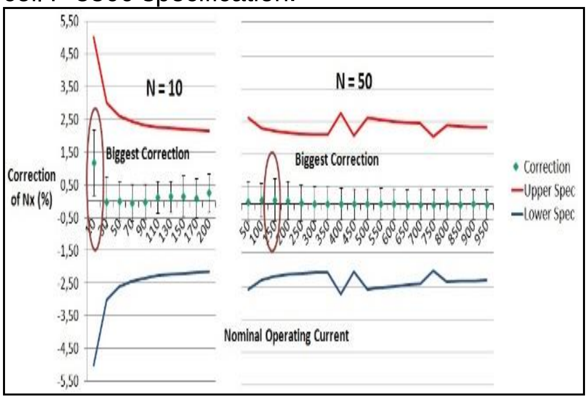


Figure 4 The graph of current coil UUC correction and uncertainty for all measurement points when supplied by DC current.

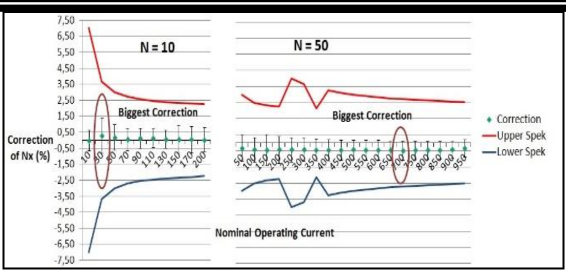


Figure 5 The graph of current coil UUC correction and uncertainty for all measurement points when supplied by AC current.

The value of correction and uncertainty obtained from step 2 were then verified using current coil UUC accuracy specifications. The graph in Figure 4 and Figure 5 showed the value of correction and uncertainty for all measuring points, whether supplied by DC or AC currents, were not exceeding the upper and lower limit of current coil UUC accuracy specifications. All corrections and uncertainties, including the biggest correction and the largest measurement uncertainty were within the range of current coil UUC accuracy specification. Therefore, the calibration system and evaluation method that have been done in this research can be used to examine the performance of the current coil.

5. CONCLUSION

Calibration of windings number of current coil (N) using standard Multiproduct Calibrator (MPC) and 2 auxiliary devices, i.e. current coil F-5500 and clamp meter F-337, had been conducted in this research. The calibration was carried out using indirect method and utilized the current division principle between output current of current coil and supplied current from MPC. The method consisted of 2 steps of measurement in which each step has their own purpose, mathematical model, and equipment set up. Evaluation result showed that there was different correction and uncertainty of N for each output nominal operating current from current coil UUC, both for nominal of 10-turn and 50-turn current coil. Calibration results show that, for 10-turn current coil, uncertainties span from 0.47% to 1.0% with the largest correction of 1.2% when supplied by DC current, and span from 0.57% to 1.1% with the largest correction of 0.28% when supplied by AC current. For 50-turn current coil, uncertainties span from 0.44% to 0.65% with the largest correction of 0.13% when supplied by DC current, and span from 0.54% to 0.96% with the largest correction of -0.47% when supplied by AC current. Uncertainty component that serves as major uncertainty in this calibration method came from the current coil F-5500. Verification was carried out using current coil UUC accuracy specifications and found that values of correction and measurement uncertainties for all measuring points were within upper limit and lower limit of current coil UUC specifications. Therefore, it can be said that calibration system and analysis method performed in this research can be used to examine the performance of the current coil.

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REFERENCES

Amalia, H., & Faisal, A. (2017). Kalibrasi daya ac pada power quality analyzer dengan menggunakan multiproduct calibrator. *widyariset*, *3*(1), 67–80. https://doi.org/http://dx.doi.org/10.14203/widyariset.3.1.2017.67-80

Bell, S. (2001). *A Beginner 's Guide to Uncertainty of Measurement* (11th ed.). United Kingdom: National Physical Laboratory.

Costa, M. (2018). Electrical current coil metrological confirmation for current clamp meters calibration Electrical current coil metrological confirmation for current clamp meters calibration.*XXII World Congress of the International Measurement Confederation (IMEKO 2018)* (p. 4). https://doi.org/10.1088/1742-6596/1065/5/052014

Draxler, K., & Styblíková, R. (2016). Calibration of AC Clamp Meters. *IEEE Transactions on Instrumentation and Measurement*, *65*(5), 1156–1162. https://doi.org/10.1109/TIM.2015.2507413

Farrance, I., & Frenkel, R. (2012). Uncertainty of Measurement : A Review of the Rules for Calculating Uncertainty Components through Functional Relationships. *Clin Biochem*, *33*(May), 49–75.

Fluke Corporation. (2002). *Instruction Sheet, Model 5500A / COIL, 50-Turn Current Coil*. United State of America.

Fluke Corporation. (2003). *Operators Manual 5520A Multi-Product Calibrator*. United State of America.

Galliana, F., Capra, P. P., & Gasparotto, E. (2012). Inter-laboratories comparison at 100 G X and 1 T X level to evaluate the traceability transfer from INRIM in the field of high dc resistance SET OF PRIMARY. *Measurement*, *45*(3), 615–621. https://doi.org/10.1016/j.measurement.2011.10.028

Habte, A., Sengupta, M., Reda, I., & Andreas, A. (2014). Calibration and measurement uncertainty estimation of radiometric data preprint. in *solar 2014*. National Renewable Energy Laboratory (NREL).

Hogan, R. (2015). *7 steps to calculate measurement uncertainty*. United State of America: ISOBudgets LLC.

Horálek, V. (2013). Analysis of basic probability distributions , their properties and use in determining type B evaluation of measurement uncertainties. *Measurement*, *46*, 16–23. https://doi.org/10.1016/j.measurement.2012.09.006

Jaiswal, S. K., Ojha, V. N., & Singh, A. (2005). Estimation of uncertainty in measurement in precision calibration of DC high current source up to 100 A. *Journal of Scientific and Industrial Research*, *64*(9), 666–673.

JCGM. (2008). *JCGM 100 : 2008, Evaluation of measurement data: Guide to the expression of uncertainty in measurement* (1st ed.). JCGM. https://doi.org/10.1373/clinchem.2003.030528

Jornada, D. H. da, Caten, C. ten, & Pizzolato, M. (2016). Guidance Documents on Measurement Uncertainty : An Overview and Critical Analysis. *NCSLI Measure, The Journal of Measurement Science*, *5:1*(May), 68–76. https://doi.org/10.1080/19315775.2010.11721507

KRISS. (2014). *Certificate of calibration*. Daejeon, Republic of Korea.

Ljubljanac, A. (2018). *Basic principles and operation of a transformer networks*. https://doi.org/10.1016/0003-9861(69)90264-1

NMIA. (2017). *Measurement Report on Reference Multimeter*. West Lindfield, Australia.

Olencki, A., & Mróz, P. (2017). Traceable technique to calibrate current coils for calibration of the power clamp meters in AC current range up to 1000 A. *Measurement*, *109*, 366–372. https://doi.org/10.1016/j.measurement.2017.05.024

P2M-LIPI. (2017). *Sertifikat kalibrasi multifunction calibrator fluke 5520A*. Tangerang Selatan, Indonesia.

Transmille. (2008). *Certificate of calibration*. United Kingdom.

Ziegler, S., Woodward, R. C., Iu, H. H., & Borle, L. J. (2009). Current sensing techniques : A review. *IEEE SENSORS JOURNAL*, *9*(4), 354–376.