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Development of a compensating algorithm for an iron-cored measurement current transformer

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***Abstract*-- This paper describes the design of a compensating algorithm for an iron-cored measurement current transformer (CT) that removes the effects of the hysteresis characteristics of the iron-core. The exciting current resulting from the hysteresis characteristics of the core causes an error between the primary current and the secondary current of the CT. The proposed algorithm decomposes the exciting current into the core loss current and the magnetizing current and each of them is estimated. The core loss current is calculated from the secondary voltage and the voltage-core loss current curve. The core flux linkage is calculated and then inserted into the flux-current curve to estimate the magnetizing current. The exciting current at every sampling interval is obtained by summing the core-loss and magnetizing currents and then added to the measured current to compensate the secondary current. The voltage-core loss current curve and flux-current curves, which are different from the conventional curves, are derived in this paper. The performance of the proposed algorithm is validated under various conditions using EMTP generated data. The experimental test results of an iron-core type electronic CT, which consists of the iron-core and the compensation board, are also included. The results indicate that the proposed algorithm can improve the accuracy of the measurement CT significantly, and thus reduce the size and the cost of the CT.**

***Index Terms*-- Compensating algorithm, Hysteresis characteristic, Measurement current transformer, hardware implement**

I. Introduction

A current transformer (CT) should provide the faithful reproduction of the primary current to the measurement or protection devices. An iron-core has been used to maximize the mutual flux linkage between the primary and the secondary windings. A CT can be divided into the two groups depending on its applications i.e. a measurement CT and a protection CT. The former should reproduce the normal current in the steady state whilst the latter is designed to reproduce the large fault current avoiding saturation during the fault conditions [1].

The measurement CT has an error between the primary and secondary currents due to the hysteresis characteristics of an iron-core. Thus, the core with a high permeability and a large size is necessary to reduce the error. This inevitably results in increase in the cost and core size.

These days, a Rogowski coil and an optical CT that eliminate the nonlinear characteristics of the iron-core have been developed [2]–[5]. The Rogowski coil does not saturate so that it would measure the large fault current correctly. However, the Rogowski coil as a measurement CT might have large errors in measuring a low current due to the weak flux linkages. On the other hand, the optical CT has the small size, and nonconductive characteristic. However, it is expensive because the optical CT has vulnerability against vibrations and thus additional equipments for reducing vibrations are required.

Some compensation algorithms to reduce the error of the measurement CT have been suggested [6]–[8]. In [6], the exciting current, which is an error of a CT, is estimated and an additional analogue circuit for supplying the exciting current is connected to the secondary winding to compensate the secondary current. However, the hysteresis characteristics of the core were not considered.

In [7] and [8], compensation algorithms considering the hysteresis characteristics of the iron-core were proposed in the time domain. In these methods, the compensated current is obtained by adding the exciting current estimated from the hysteresis loop to the measured secondary current. They can enhance the accuracy of the measurement CT because they can reduce the effects of the hysteresis characteristics of the core. However, these methods can have large errors on the low currents because they are based on the major hysteresis loop. Thus, they may also cause large errors if the primary current contains a dc offset and/or some harmonic components.

This paper proposes a compensating algorithm for the secondary current of a measurement CT that removes the effects of the hysteresis characteristics of the iron-core. The proposed algorithm decomposes the exciting current into the core loss current and the magnetizing current. The former is calculated from the voltage and the voltage-core loss current curve (the v-i_c curve). The latter is obtained by inserting the calculated flux linkage into the flux linkage-magnetizing current curve (the λ-i_m curve). The exciting current, i.e. the sum of the core loss current and the magnetizing current, is

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added to the measured secondary current to obtain the correct current. The performance of the proposed algorithm has been investigated through EMTP simulation. In addition, the test results of an iron-core type electronic CT (ECT), where the proposed compensating algorithm is implemented, are also included.

II. Compensating Algorithm for a Measurement CT

In this section, we will describe the proposed algorithm to improve the accuracy based on the equivalent circuit of an iron-cored CT.

A. Equivalent Circuit of an Iron-cored CT

Basic principles of an iron-cored CT are the same as those of a power transformer. Fig. 1 shows the equivalent circuit of a CT referred to the secondary. The branch currents of the equivalent circuit represent the primary, the secondary, the exciting, the magnetizing and the core loss current (i_1, i_2, i_0, i_m and i_c), respectively. v_2 and R_b represent the secondary voltage and the secondary burden. The circuit accounts for nonlinear hysteresis characteristics. The magnetizing inductance (L_m) represents the nonlinear relationship between the flux linkage and the magnetizing current. The core loss resistance (R_c) represents the core loss composed of the eddy current and hysteresis loss. The exciting current is expressed by:

$$i_0(t) = i_c(t) + i_m(t) \tag{1}$$

The exciting current consists of the core loss and magnetizing currents. Fig. 2 shows that the solid, dotted and dashed lines are the exciting current, the core loss current and the magnetizing current, respectively. The primary current is given by:

$$i_1(t) = i_0(t) + i_2(t) \tag{2}$$

If $i_0(t)$ is estimated and used for compensation of the secondary current, the error of the iron-cored CT can be eliminated.

B. λ-i_m Curves and v-i_c Curves

To obtain the flux linkage-magnetizing current curves and voltage-core loss current curves, accurate information on the transformer's magnetic circuit is required i.e. a functional or empirical relation should be obtained, linking the core flux to the exciting current.

In [7] and [8], the compensated current is obtained by inserting the hysteresis loop (the λ-i_0 curve). However, in this paper, the exciting current is decomposed into the core loss current, which is calculated from the voltage and the v-i_c curve, and the magnetizing current, which is obtained by inserting the calculated flux linkage into the λ-i_m curve. The v-i_c curve and the λ-i_m curve can be obtained from measured hysteresis loops. Fig. 3 shows a measured hysteresis loop at the rated current relating the exciting current to the flux linkage of the iron-core. The hysteresis loop is generated by HYSDAT, an auxiliary program in EMTP.

In Fig. 3, both A (i_A, λ_0) and B (i_B, λ_0) represent points on the hysteresis loop with the same ordinate, λ_0. Points A and B are on the ascending offshoot and descending offshoot, respectively. The abscissa of the midpoint M (i_m, λ_0) can be calculated by:

$$i_m = \frac{i_A + i_B}{2} \tag{3}$$

Varying λ from λ_{min} to λ_{max}, which are the minimum and maximum of the flux linkage in the major hysteresis loop, respectively, the λ-i_m curve can be obtained by connecting all midpoints, which is shown as the dashed line in Fig. 3. Note that the λ-i_m curve described in this manner is different from the conventional magnetization curve in the previous work [9], which is obtained by connecting the tips in the first quadrant of a family of hysteresis loops.

As the exciting current i_0 is the sum of the core loss current i_c and i_m, i_c at a λ can be calculated by subtracting i_m from i_0 i.e.:

$$i_c = i_0 - i_m = i_A - \frac{i_A + i_B}{2} = \frac{i_A - i_B}{2} \tag{4}$$

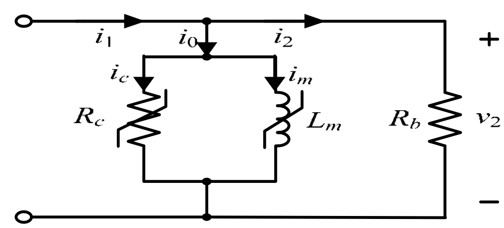


Fig. 1. Equivalent circuit of an iron-cored CT.

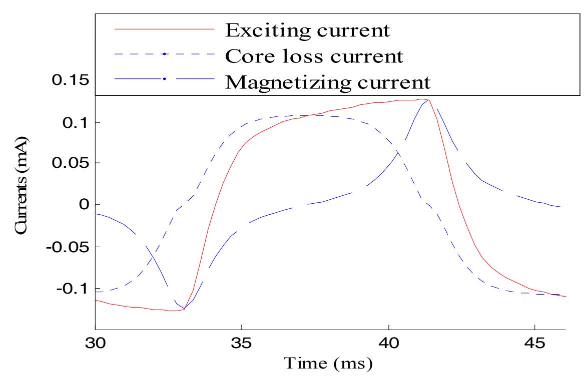


Fig. 2. Exciting, core loss and magnetizing currents.

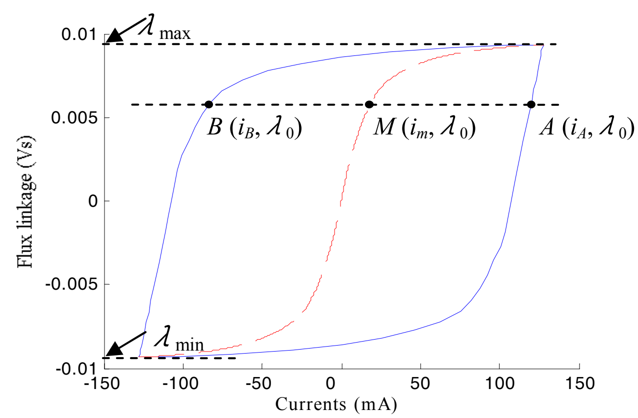


Fig. 3. Measured hysteresis loop (λ-i_0 curve) and λ-i_m curve.

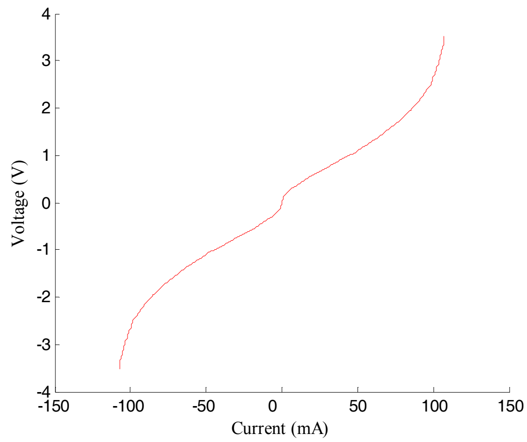


Fig. 4. v-i_c curve.

Geometrically, i_c can be interpreted as the horizontal distance from the edge to the midpoint of the hysteresis loop in Fig. 3. Varying λ from λ_{min} to λ_{max} along the ascending offshoot and the descending offshoot obtains the λ-i_c curve. However, λ-i_c curve obtained in this way, i_c corresponding to each λ has two values whilst the λ-i_m curve is the one-to-one function. Thus, in this paper, the secondary voltage-core loss current v-i_c curve, which is converted from the λ-i_c curve, is used. The voltage corresponding to the flux can be obtained by the secondary current and the burden of a CT. The v-i_c curve is the one-to-one function as shown in Fig. 4.

C. Proposed Compensating Algorithm of an Iron-cored CT

The compensated current (i_2^*) is calculated by adding i_0 to i_2. i_0 is obtained by adding i_c to i_m.

i_c is obtained by inserting v_2 into the v-i_c curve, where v_2 is estimated by:

$$v_2(t) = R_b i_2(t) \qquad (5)$$

i_m is obtained by inserting λ into the λ-i_m curve, where λ is calculated by the integration of v_2 by using:

$$\lambda(t) = R_b \int_{t_0}^{t} i_2(t)dt + \lambda(t_0) \qquad (6)$$

where $\lambda(t_0)$ is an initial flux linkage, which can be obtained by the method in [10].

Consequently, the correct current is obtained by summing i_0 and i_2, i.e.:

$$i_2^*(t) = i_0(t) + i_2(t) \qquad (7)$$

III. Case Studies

Fig. 5 shows a single-line diagram of a typical Korean 154kV transmission system. A sampling rate is 64 samples per cycle and all the currents are passed through the first-order low-pass resistance-capacitance (RC) filters with a cutoff frequency of 1,920 Hz (i.e., half the sampling frequency) at 60 Hz.

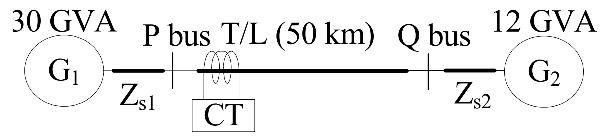


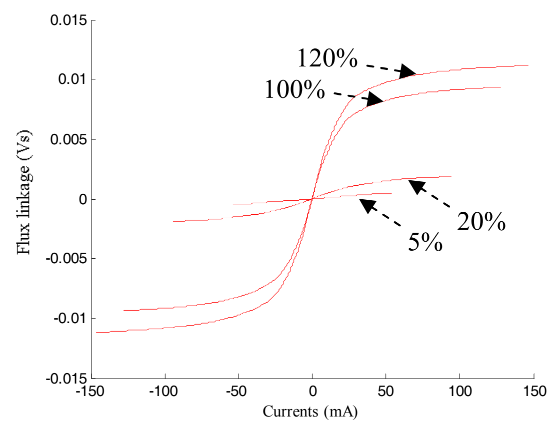
Fig. 5. Single-line diagram of model system.

TABLE I
Limits of Error for Measurement CT

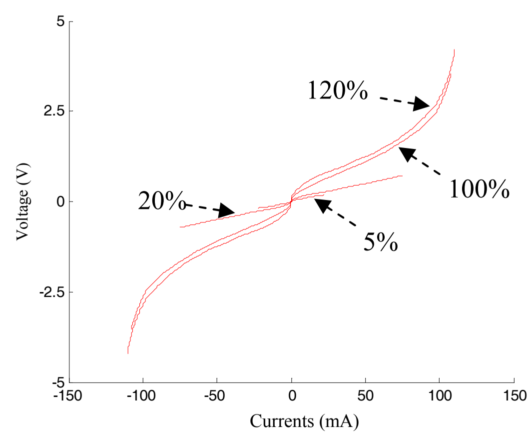
Accuracy class	± percentage current (ratio) error at percentage of rated current shown below				± phase error at percentage of rated current shown below (minutes)			
	5	20	100	120	5	20	100	120
0.1	0.4	0.2	0.1	0.1	15	8	5	5
0.2	0.75	0.35	0.2	0.2	30	15	10	10
0.5	1.5	0.75	0.5	0.5	90	45	30	30
1.0	3.0	1.5	1.0	1.0	180	90	60	60

TABLE II
Results of Case Study

Case	1.0C		0.1C		Uncompensated		Compensated	
	Current Error (%)	Phase Error (min)	Current Error (%)	Phase Error (min)	Current Error (%)	Phase Error (min)	Current Error (%)	Phase Error (min)
Case 1	±1.0	±60	±0.1	±5	–1.49	30.31	–0.012	–0.11
Case 2	±1.0	±60	±0.1	±5	–1.71	33.42	–0.003	–0.24
Case 3	±1.5	±90	±0.2	±8	–4.95	167.98	–0.021	–1.85
Case 4	±3.0	±180	±0.4	±15	–6.12	456.02	–0.034	–1.32



(a) λ-i_m curves



(b) v-i_c curves

Fig. 6. λ-i_m curves and v-i_c curves.

The measurement CT is modeled using a type-96 element [11]. The hysteresis characteristic curve is obtained using the HYSDAT, an auxiliary program in EMTP/ATP. We set the saturation point of the CT as (0.02 Vs and 2.047 A). The current ratio is 100/5 A and the burden is modeled with pure resistance, 12.5 VA (0.5 Ω).

Table I shows the limits of the error for the measurement CT on IEC standard [12]. The performance of the proposed algorithm was tested and compared with Table I for 120%, 100%, 20% and 5% of the rated current. Fig. 6a and Fig. 6b shows the λ-i_m curves and the v-i_c curves for 120%, 100%, 20% and 5% of the rated current. They are obtained using the same method as explained in II. B from the hysteresis curves at 120%, 100%, 20% and 5% of the rated current.

1) Case 1: 120% of the rated current

Fig. 7 shows the results for Case 1. Fig. 7a shows the primary and secondary current, where solid and dashed lines mean the primary and measured secondary current, respectively. To see the results clearly, a portion of the Fig. 7a is expanded. The measured secondary current is significantly different from the primary current due to the exciting current. Fig. 7b shows the secondary current i_2, the calculated core loss current i_c, and the calculated magnetizing current i_m. The compensated primary current is obtained by adding i_c and i_m to i_2, and shown in Fig. 7c in dotted lines. Comparing the primary current shown in solid lines and compensated current in Fig. 7c, the compensated current is very similar as the primary current. The current error is reduced from −1.49% to −0.012% and the phase error from 30.31 min to −0.11 min. Table II shows comparison between uncompensated and compensated currents. The result for Case 1 indicates the algorithm can improve the accuracy up to the 0.1C from 1.5C.

2) Case 2: the rated current

As in the previous case, the measured secondary current is different from the primary current due to the large exciting current. The current and phase errors of the measured secondary current are –1.71% and 33.42 min, respectively. However, the current and phase errors of the compensated current are −0.003% and −0.24 min, respectively. This result meets the accuracy for 0.1C.

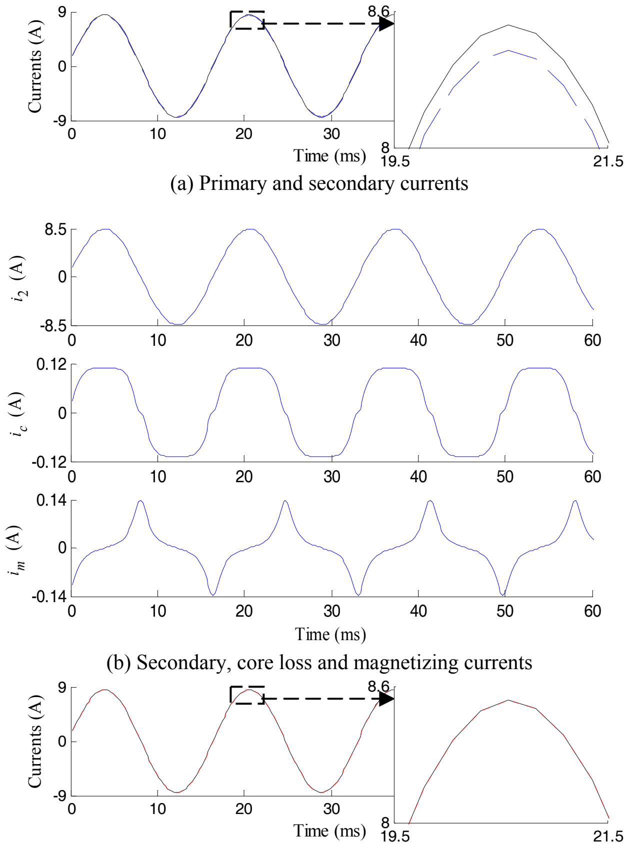
3) Case 3: 20% of the rated current

In this case, the current error is decreased from –4.95% to –0.021%. The phase error is decreased from 167.98 min to –1.85 min. These errors meet the limits of the error of IEC Standard.

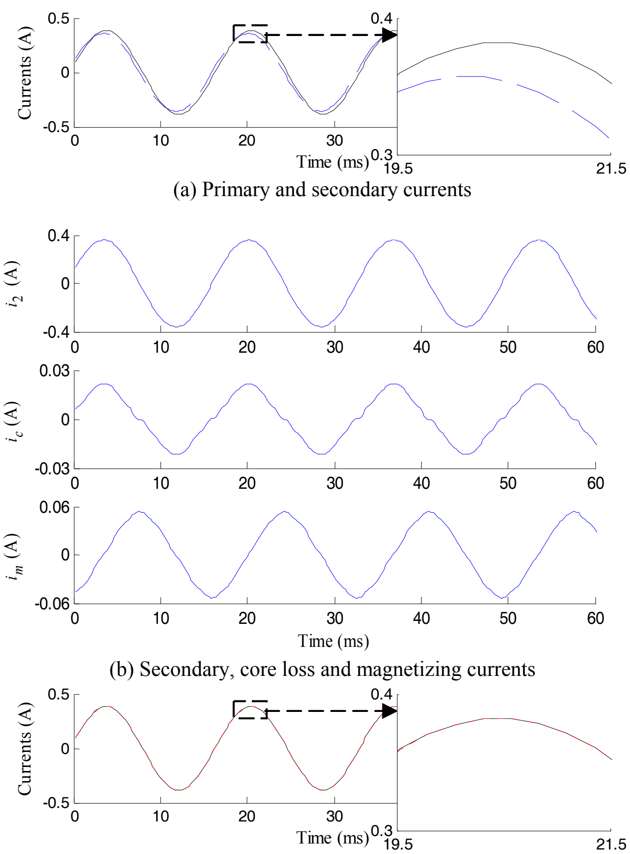
4) Case 4: 5% of the rated current

Fig. 8 shows the results for Case 4. In this case, the current and phase errors of the measured secondary current exceed the limits of IEC Standard significantly. The measured secondary current leads the primary current by 456.02 min and current error is –6.12%. However, the compensated current is very similar to the primary current as shown in Fig. 8c. The current error and phase error are reduced to –0.034% and –1.32 min, respectively, which meets the IEC standard.

The above results clearly indicate that the algorithm can improve the accuracy of the measurement CT significantly.



(a) Primary and secondary currents
(b) Secondary, core loss and magnetizing currents
(c) Primary and compensated currents
Fig. 7. Results for case 1.



(a) Primary and secondary currents
(b) Secondary, core loss and magnetizing currents
(c) Primary and compensated currents
Fig. 8. Results for case 4.

IV. Experimental Test on Real CT

This section describes a series of the experimental tests for an iron-core type electronic current transformer (ECT), where the algorithm implemented. The ECT was tested in the Korea Electrotechnology Research Institute (KERI), the officially recognized organ. KERI signs Mutual Recognition Arrangement of the International Laboratory Accreditation Cooperation as one of the Korea Laboratory Accreditation Scheme.

A. Experimental Tests

An iron-core type ECT for 100A of the rated current was tested. Fig. 9 shows the configuration of the tested ECT. The ECT consists of an iron-cored CT and a compensation board, where the proposed algorithm is implemented. The output of the ECT can be digital or analog. Analogue output signal is used for test because digital output signal cannot be tested in Korea yet. The rated delay time is –648 min. A sampling rate of 64 samples/cycle was used and the first-order low-pass RC filter with a cutoff frequency of 1,920 Hz was used.

Table III shows the test results for 4 cases, i.e. 120%, 100%, 20% and 5% of the rated current at 60 Hz. The rated primary current is 100 A. The test results meet the limits of error for 0.2 C on IEC standard [12].

1) Case 8: 5% of the rated current

Fig. 10 shows the results for Case 8. Fig. 10a shows the primary and secondary current, where solid and dashed lines mean the primary and measured secondary current, respectively. Due to the exciting current the measured secondary current is significantly different from the primary current. Fig. 10b shows the secondary current i_2, the calculated core loss current i_c, and the calculated magnetizing current i_m. The compensated primary current is obtained by adding i_c and i_m to i_2, and shown in Fig. 10c in dotted lines. Comparing the primary current shown in solid lines and compensated current in Fig. 10c, the compensated current is very similar as the primary current. The current error is reduced from −4.44% to 0.26% and the phase error from 35.17 min to -8.47 min. The result for Case 8 indicates the algorithm can improve the accuracy up to the 0.2C from 2.0C.

The above results clearly indicate that the algorithm can improve the accuracy of the real measurement CT significantly. However, due to the errors caused by the noise, D/A and A/D conversions, the accuracy of compensated error of the ECT is larger than EMTP simulation results as shown in Table III. However, the current errors and angle errors meet the accuracy limits of 0.2C on the IEC standard.

The cost of the CT depends on the permeability and the size of the core. Table IV shows the production cost and core size for 100/5A measurement CT in Korea. The size of the iron-core is larger than that of the Ni core due to the poorer permeability whilst the price of the iron-core is smaller than that of the Ni core. In the case of 0.2C Ni core, its size is four times bigger than the size of 1.0C Ni core. It is possible to make 1.0C iron-core CT, whereas it is practically impossible to make 0.2C iron-core due to the too big size.

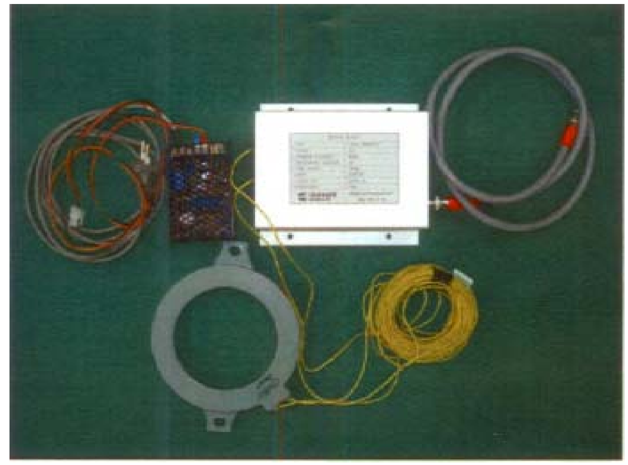


Fig. 9. Electronic current transformer (ECT).

TABLE III
Results of Test

Case	1.0C		0.2C		Uncompensated		Compensated	
	Current Error (%)	Phase Error (min)	Current Error (%)	Phase Error (min)	Current Error (%)	Phase Error (min)	Current Error (%)	Phase Error (min)
Case 5	±1.0	±60	±0.2	±10	–1.92	–24.87	–0.15	0.26
Case 6	±1.0	±60	±0.2	±10	–2.16	–27.03	–0.1	0.86
Case 7	±1.5	±90	±0.35	±15	–4.74	–25.67	0.0013	–0.67
Case 8	±3.0	±180	±0.75	±30	–4.44	35.17	0.26	–8.47

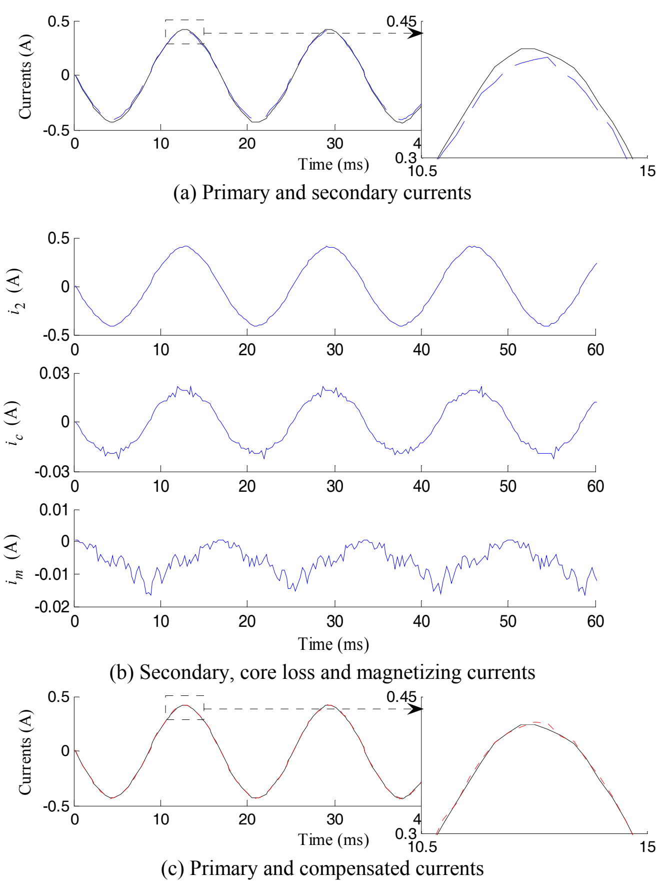


Fig. 10. Results for case 8.

TABLE IV
EXPECTED PRODUCTION COSTS OF CT

Rated voltage	Accuracy class	Core	Expected value ($)	Core size (mm) (I×E×W)	Burden (VA)
22.9kV	1.0	Ni	2,700	170×225×80	15
		Iron	1,000	170×225×350	15
	0.2	Ni	10,200	170×225×330	15
		Iron	—	Impossible	15

If we obtain the accuracy of 0.2C using the algorithm for 1.0C iron-core CT, the size of iron-core CT can be decreased. Thus, the proposed algorithm can reduce the size and cost of the measurement CT significantly.

V. CONCLUSIONS

This paper proposes a compensating algorithm for the secondary current of the measurement CT that removes the effects of the hysteresis characteristics of the iron-core. The proposed algorithm decomposes the exciting current into the magnetizing current and the core loss current. The proposed algorithm calculates the flux linkage by integrating the secondary current, and then estimates the magnetizing current in accordance with the λ-i_m curve. The core loss current is obtained by inserting the voltage into the v-i_c curve. The core loss current and the magnetizing current are added to the measured secondary current to obtain the correct current.

The performance of the proposed algorithm is investigated with EMTP generated data. The test results of an ECT, where the proposed algorithm is implemented in the prototype of the compensation board, are also included. The results show that the measured secondary current of the iron-cored CT is compensated with the magnetizing and core loss current. The proposed algorithm can reduce both the current errors and the angle errors of the CT error even in 5% of the rated current, in which the errors of the CT is significant.

The proposed algorithm can reduce the core size and improve the accuracy of the measurement CT significantly and thus make it possible to use the core with low permeability and small size.

VI. ACKNOWLEDGMENT

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VII. REFERENCES

[1] S. H. Horowitz, and A. G. Phadke, *Power system Relaying*, Research Studies Press Ltd, 1992.
[2] D. A. Ward, and J. La T. Exon, "Using Rogowski coils for transient current measurements," *IEE Engineering Science and Education Journal*, Vol. 2, No. 3, pp. 105–113, June 1993.
[3] D. A. Ward, and J. La T. Exon, "Using Rogowski coils for transient current measurements," *IEE Engineering Science and Education Journal*, Vol. 2, No. 3, pp. 105–113, June 1993.
[4] M. Rigoni, J. S. D. Garcia, A. P. Garcia, P. A. Da Silva, N. J. Batistela and P. Kuo-Peng, "Rogowski coil current meters", *IEEE Potentials*, Vol. 27, No. 4, pp. 40–45, 2008.
[5] Y. Hasegawa, Y. Ichikawa, H. Kastsukawa, N. Tanaka, and Y. Sakurai, "Development of a new type of optical transducer for measuring fault current," *IEEE Trans. Power Delivery*, Vol. 9, No. 3, pp. 1245–1252, July 1994.
[6] D. Slomovitz, "Electronic system for increasing the accuracy of in-service instrument-current transformers," *IEEE Trans. Instrumentation and measurement*, Vol. 52, No. 2, pp. 408–410, April 2003.
[7] N. Locci, and C. Muscas, "A digital compensation method for improving current transformer accuracy," *IEEE Trans. Power Delivery*, Vol. 15, No. 4, pp. 1104–1109, October 2000.
[8] N. Locci, and C. Muscas, "Hysteresis and eddy currents compensation in current transformer," *IEEE Trans. Power Delivery*, Vol. 16, No. 2, pp. 154–159, April 2001.
[9] G. R. Slemon, *Electric Machines and Drives*, Addison-wesley publishing company, INC, 1992.
[10] Y. C. Kang, J. K. Park, S. H. Kang, A. T. Johns, and R. K. Aggarwal, "An algorithm for compensating secondary currents of current transformers," *IEEE Trans. Power Delivery*, Vol. 12, No. 1, pp. 116–124, January 1997.
[11] S. N. Talukdar, and J. R. Bailey, " Hysteresis Model for System Studies" IEEE Transactions on Power Apparatus and Systems, Vol. PAS-95, July/August 1976, pp. 1429-1434.
[12] International standard IEC 60044-8, "instrument transformers - part 8: Electronic current transformers," *IEC Std.*, July 2002.

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