ERROR ANALYSIS FOR INDUCTIVE CURRENT TRANSFORMERS UNDER NON-SINUSOIDAL WAVEFORM CURRENT

ĐÁNH GIÁ SAI SỐ CỦA BIẾN DÒNG ĐIỆN KIỂU CẢM ỨNG TRONG ĐIỀU KIỆN DÒNG ĐIỆN BỊ MÉO DẠNG HÌNH SIN

Anh-Tuan Phung[1,3], Hoang-Phuong Vu[1], Trinh-Tuan Nguyen[1], Dang-Hai Nguyen[1,2]

[1]*Hanoi University of Science and Technology; tuan.phunganh1@hust.edu.vn*

[2]*Hanoi University of Industry; dhai.haui@gmail.com*

[3]*International Research Institute for Computational Science and Engineering; icse@hust.edu.vn*

Abstract - Instrument transformer is a popular electric device which is used in measurement of load current. While dealing with pure sine-wave primary current, these instrument transformers work well with no significant problem. A primary load current which includes high frequency components, the relative error of this device must be reconsidered. This paper presents a research result of the effect of high harmonic ratio primary current on the relative error of instrument transformers. The increasing relative error could be explained by using a first order timed delay element of the current transformer versus the fast-changing load current. The result can be used in either selecting the right instrument transformer for a specific load or defining the requirements for other electric loads to permit a correct measurement.

Key words - current transformer, electrical steel; magnetic core; total harmonic distortion; high frequency harmonic; relative error.

Tóm tắt - Máy biến dòng đo lường là thiết bị điện phổ thông được dùng để đo dòng điện của các phụ tải. Khi dòng điện của các phụ tải này thuần sin, độ chính xác của biến dòng điện này sẽ vẫn được đảm bảo. Khi dòng điện của các phụ tải này không còn dạng thuần sin và chứa các thành phần sóng hài bậc cao, độ chính xác của biến dòng điện đo lường sẽ cần phải được xem xét. Bài báo này nghiên cứu về tác động của dòng điện chứa sóng hài bậc cao lên độ chính xác của biến dòng điện đo lường. Sự gia tăng về sai số của biến dòng điện này đến từ việc lõi sắt từ của biến dòng điện phản ứng như một khâu quán tính bậc nhất có trễ đối với các biến đổi nhanh của dòng điện. Kết quả nghiên cứu này có thể được dùng để tham khảo trong lựa chọn loại máy biến dòng điện hoặc yêu cầu đối với phụ tải điện nhằm đảm bảo độ chính xác của phép đo.

Từ khóa - biến dòng điện; thép kỹ thuật điện; lõi thép; méo dạng sóng tổng hợp; sóng hài bậc cao; sai số tương đối.

1. Introduction

Current transformer is widely used in current measurement and protection of power system. Its working principle is based on the induced electromagnetic phenomena. Its quality is judged on the relative error of current and angle error between primary current and secondary current. Current transformer construction includes magnetic core, coils and insulating media [1]. The magnetic core is manufactured with high grade silicon steel to ensure low measuring error.

In modern power system, there are more and more power electronic devices which participate in power transformation and delivery process. Hence, instrument transformer must be reviewed to respond to this change. Large power electronic devices require a non-sinusoidal current from the grid whose frequency is different from 50Hz (National grid frequency). These currents compose high order frequency which are called harmonics [2]. The main current in that case will be distorted.

To characterize this distortion, the total harmonic distortion [3] is used:

$$THD_i = \sqrt{\frac{\sum_{k=2}^{\infty} I_k^2}{I_1^2}} \quad (1)$$

which: I_k^2 – squared of the RMS value of the current which oscillates k^{th} time the fundamental frequency 50 Hz;

I_1^2 – squared of the RMS value of the fundamental current.

High harmonic-content current will cause some negative effects including divergence on error of current transformer.

In the literature, effect of current and voltage harmonics on distribution transformer losses and motors were investigated in many publications [3], [4], [5], [6], [7]. They were mainly interested in monitoring the efficiency degradation of the device. Others tried to compensate the harmonics effect by using various technical solutions much as passive filter or active harmonics filter. A very good reference related to the current transformer model was presented in [8], [9]. This Jiles-Atherton model was widely used to study the current transformer in electrical engineering software because of its demonstrated accuracy. However, implementation of this model is not straightforward while dealing with high harmonics current in finite element modeling software [10], [11]. Hence, direct experiment data handling with simple manipulation will be favored.

In this paper, individual measured data of the silicon steel under different frequency will be merged at different ingredient percentage to study their mixed effect on the current transformer. Simple data filtering technique will be used to extract valuable information from experiment without ignoring the main trend. Authors will evaluate the current transformer by using a dedicated software to figure out changes in terms of relative error and angle error while dealing with high harmonics content primary current.

This paper will be organized as follows: the second section will describe the construction data of the current transformer; current with high harmonics content will be simulated in the third section; recommendations and future work will be presented in the final section.

2. Construction data for current transformer modeling

The device under test (DUT) is a generic current transformer. Declared relative error of the DUT is 0.5%. The current ratio is 50/5 – which means at 50 amps primary current, the secondary current will be 5 amps ± 0.5% [12]. The rated voltage of this DUT is 600 VAC.

2.1. Construction data of the current transformer

2.1.1. Magnetic core

Inner diameter: 40 mm

Outer diameter: 70 mm

Core height: 55 mm

2.1.2. Windings of the current transformer

Primary winding: single turn or multiple turns (external conductive bar or wire);

Secondary windings: 10 turns

Figure 1. *The real current transformer under test*

2.2. Modeling tool

Maxwell 3D software is used for the modeling of the current transformer. This is a part of ANSYS software package. This software is based on the finite element method (FEM). It is widely used in the modeling of continuous media such as Mechanical – Electrical – Heat transfer – Fluid dynamics – Vibration and Structural analysis. This Maxwell 3D software allows a reliable modeling of magneto-static simulation, electric conduction, magneto-transient and multi-physic couplings with other tools [13].

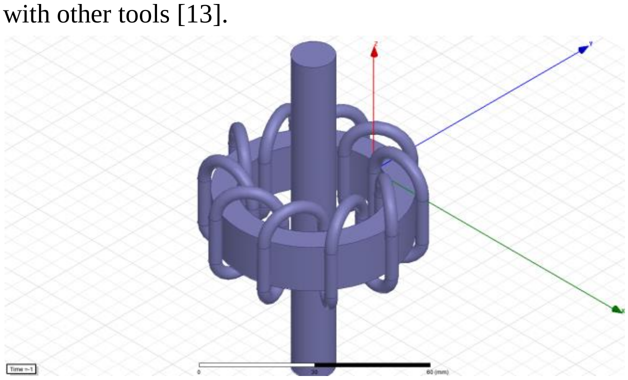

Figure 2. *Geometry of the current transformer under test*

2.3. Electrical and magnetic properties of the current transformer

The core of the current transformer is made of high grade silicon steel with code name 30P120 from POSCO – South Korea with a thickness of 0.3 mm; the specific loss at 1 Tesla for a unit weight is 1.2 W/kg. Its magnetic properties are shown on Fig. 3 Tab. 1.

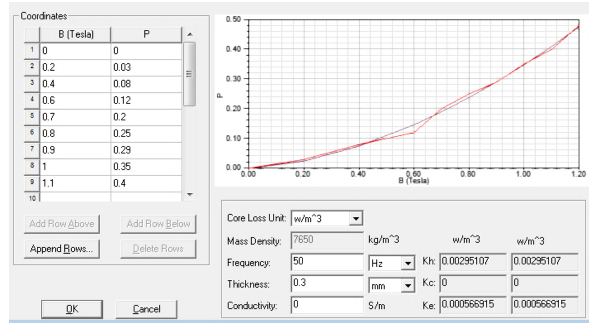

Figure 3. *Loss characteristics of 30P120 at 50 Hz [14], [15]*

Table 1. *Magnetic properties of 30P120-POSCO*

STT	Name	Value
1	Volumic conductivity	769,230 Siemens/m
2	Core loss type	Electrical steel
3	Hyteresis loss factor	0.00295106 W/m3
4	Mass density	7,650 kg/m3

The measured data will be used to properly predict reaction of the current transformer under high harmonic excitation.

Various frequencies have been tested and loss curves have been recorded. They are presented on Fig. 4. One could remark that at a higher frequency, higher loss can be observed.

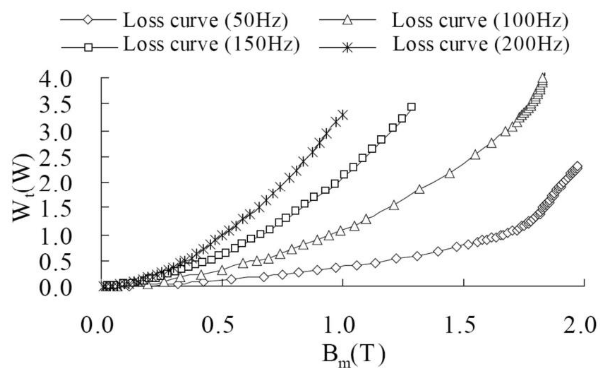

Figure 4. *Measured loss curves at different frequencies [15]*

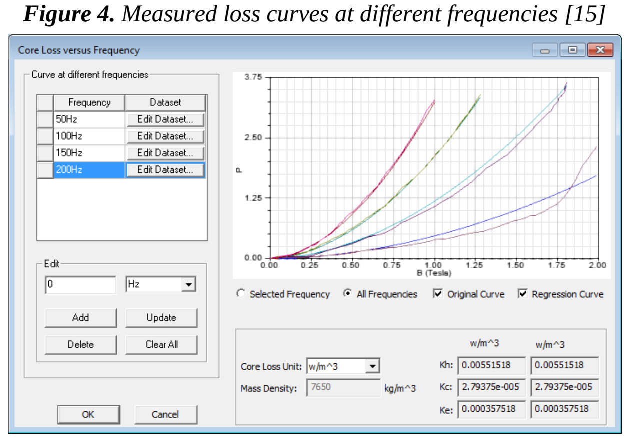

Figure 5. *Regression curves of simulated loss characteristics of silicon steel at different frequencies [15]*

Experimentation data contains lots of measurement errors due to uncertainty. Porting these data into simulation software needs care in order to filter out all the variation

When frequency increases, higher power losses due to friction and hysteresis area increase. Magnetic domains and domain walls in oriented silicon steel or non-oriented steel move against each other to react to the external field. Hence with a quick time-variant applied field, these movements generate heat which induces higher losses.

However, in order to quantify these losses in the current transformer, one should place the magnetic materials into real form of the magnetic core of the concrete current transformer and excites it with a distorted primary current [5].

3. Distorted primary current and its effects one the magnetic core of current transformers

3.1. Fourier analysis of a periodic waveform

Input current of a generic load is considered as a periodic waveform. An arbitrary periodic function *i(t)* can be broken up into a set of simple complete orthogonal terms [2] on an interval $[-\pi, \pi]$:

$$i(t) = \frac{1}{2} i_0 + \sum_{n=1}^{\infty} a_n . \cos(nt) + \sum_{n=1}^{\infty} b_n . \sin(nt) \quad (2)$$

where

$$i_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} i(t).dt$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} i(t).\cos(nt).dt$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} i(t).\sin(nt).dt$$

n = 1, 2, 3…

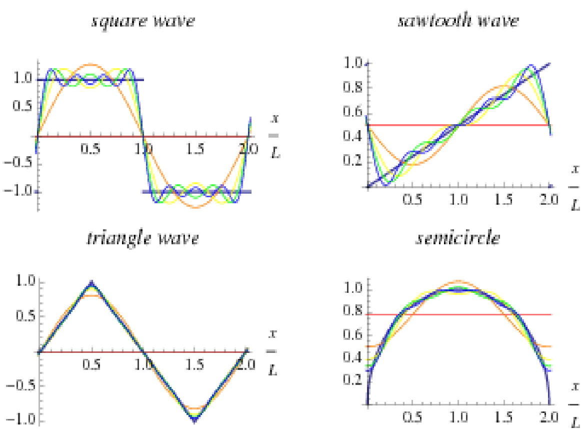

Figure 6. *Fourier analysis of an arbitrary periodic waveform. Images courtesy from Wolfram Inc*

Hence, a generic load current could be decomposed into fundamental component and higher frequency components. These higher frequency components are called harmonics for ease of use. The total harmonic distortion (THD) is the measurement of the harmonic distortion present in a signal. This is defined as the ratio of the RMS amplitude of a set of higher harmonic frequencies to the RMS amplitude of the first harmonic, or fundamental, frequency. The higher the percentage, the more distortion that is present on the mains current.

3.2. Regulations on the THD of load current

International standards have a strict regulation on the current distortion. IEC 61000-3-2 and IEEE 519 are the most cited regulations on this area. In these standards, the percentage of the harmonic components or absolute value of harmonic contents is defined with respect of the fundamental component. In Vietnam, IEC 61000-3-2 is widely accepted as a standard for harmonic regulation. On the other hand, circular number 39 TT/BCT-2015 [16] issued by Ministry of Industry and Trade mentioned the interface between sources and loads (which is described as the point of common coupling – PCC) with strict regulation.

Practical application of these standards and regulations is not the subject of this paper. However, it is meaningful to remark that harmonic pollution in Vietnam in recent years is a matter of concern.

3.3. Effect of distorted current on relative error of current transformer

Primary current will be simulated to be distorted at a certain level to evaluate its effect on the current transformer.

3.3.1. Pure sinusoidal primary current

On Figure 7, magnetic flux density on the magnetic core of the current transformer is presented. The excitation primary current is pure sinusoidal at fundamental frequency – 50Hz. Maximum flux density is recorded at 3mT, average flux density is about 1mT. These values correspond to a normal operation of the said current transformer. The maximum flux density is located at the proximity of secondary windings.

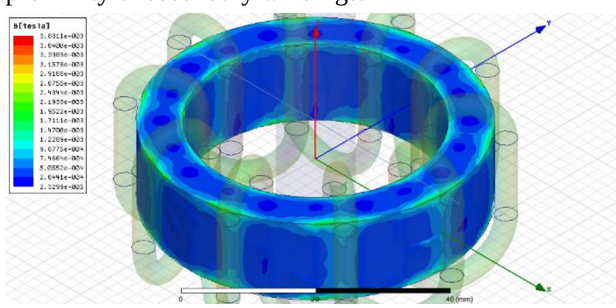

Figure 7. *Induction distribution on the magnetic core 30P120 with pure sine excitation*

Relative error between scaled secondary current to the primary current is presented on Figure 8. When observing the error of the current ratio and phase error for the pure primary sinusoidal current, it is possible to see that angular error and relative error are within the allowable range of the precision (under 0.5%, see Figure 8). The secondary current which is converted into primary level almost coincides with that of the primary current. Average current error is below 0.4%.

Thus, for current transformers using this type of 30P120 material, the standards for error rate and current deviation of primary and secondary currents are in line with the actual test standards. This accuracy allows the use of this model in further studies of the effect of current distortion on the inductive current transformer.

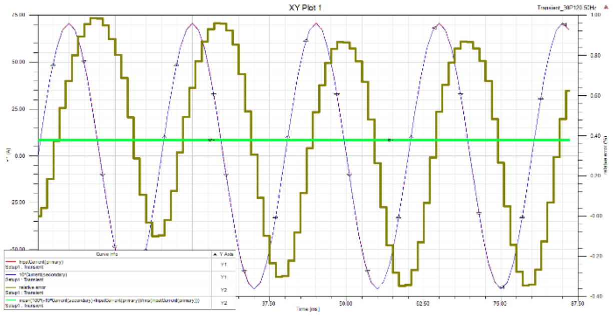

Figure 8. *Current superposition of primary and secondary current (pure sine wave). Angular error (stepped curve) and relative error (green curve)*

Error curve tends to decrease versus time toward a regular manner. The step representation is used to visualize more easily the trend of the error evolution. The maximum recorded value of the relative error is around the moment when the current cancels out. This is coherent with the experiment data.

3.3.2. Distorted primary current, the higher harmonic components involved in the primary current

For the same current transformer, the primary current flowing into the study is described below:

$$i(t) = 50\sqrt{2}.\sin(2\pi 50t) + 15\sqrt{2}.\sin(2\pi 150t) \quad (3)$$

This is an electric current containing the third order component whose effective value is 15 Ampere. The fundamental component of the 50 Hz frequency has an effective value of 50 Ampere. Hence corresponding distortion value is THDi = 30%. The overlapping primary current pattern is shown on Figure 9.

3.3.3. Error analysis with high THD percentage of primary current

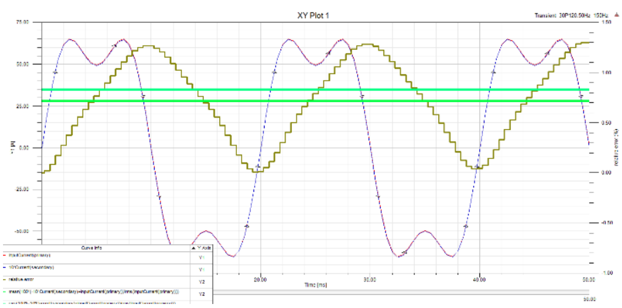

Figure 9. *Synthetic primary current contains 30% of the third harmonic. Effective value and mean value of the error*

Observing the value of the current error, it can be seen that high harmonics current affects the accuracy of the ferromagnetic core current transformer. Here, compared to the error of 0.4% for the pure primary sinusoidal current, the error has increased. The mean error value here is 0.75%, which is higher than the permitted level for the current transformer for measurement [12].

The variation of the error over time is also recorded at a higher level than in the case of pure sinusoidal currents.

The occurrence of large errors for high harmonic currents can be explained by considering the inductive current transformer as a delayed inertia. As the rate of time variation of the current increases (with high harmonics), the frequency response of the current transformer will not react fast enough to keep up with that variable speed.

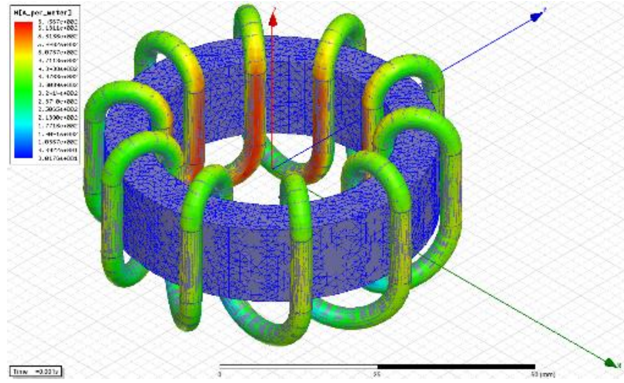

Figure 10. *Magnetic field intensity with non-sinusoidal primary current. Mesh density on magnetic core*

Figure 10 shows the distribution of the magnetic field intensity on the secondary winding and the mesh density on the magnetic core. Mesh density is sufficiently fine (0.2 mm grid) to accurately consider eddy current effect or the delayed loss that may occur in the steel core of the current transformer. The implementation of a finer mesh has yielded comparable results, but the computational time increases drastically, which is not suitable for evaluating more configurations or higher frequencies.

4. Conclusions

Current transformers are very popular in the industrial electrical appliance market today. This article has investigated the effect of currents containing high harmonic components on the accuracy of the 50/5 inductive current transformer. Modeling results show that error of the current transformer with distorted waveform primary current is higher than the allowed standard (greater than 0.5%). It also demonstrates that mixing different frequencies with different percentages is also possible within the modeling software. Hence, various configurations could be carried out to take into account the most significant configuration of the inductive current transformer.

The results of this study suggest that current distortion evaluation of inductive current transformer error is necessary. In the coming time, studies related to the level of waveform distortion and different ratios of involvement of high-level harmonics components that affect the accuracy of the current transformer will be made.

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REFERENCES

[1] F. das Guerra Fernandes Guerra and W. Santos Mota, “Current transformer model”, *IEEE Trans. Power Deliv.*, Vol. 22, No. 1,

2007, pp. 187–194.

[2] J.-M. Bony, *Cours d'Analyse: Théorie des Distributions et Analyse de Fourier*, 2001.

[3] C. Lee, W. Lee, Y. Wang, and J. Gu, *Effects of voltage harmonics on the electrical and mechanical performance of a three-phase induction motor*, Industrial and Commercial Power Systems Technical Conference, 1998 IEEE, 1998, pp. 88-94.

[4] M. Yazdani-Asrami, M. Mirzaie, and A. A. S. Akmal, *Investigation on impact of current harmonic contents on the distribution transformer losses and remaining life*, in PECon2010 - 2010 IEEE International Conference on Power and Energy, 2010, pp. 689-694.

[5] B. Singh and V. Verma, "An improved hybrid filter for compensation of current and voltage harmonics for varying rectifier loads", *Int. J. Electr. Power Energy Syst.*, Vol. 29, No. 4, 2007, pp. 312-321.

[6] M. Shareghi, B. T. Phung, M. S. Naderi, T. R. Blackburn, and E. Ambikairajah, *Effects of current and voltage harmonics on distribution transformer losses*, in Proceedings of 2012 IEEE International Conference on Condition Monitoring and Diagnosis, CMD 2012, 2012, pp. 633-636.

[7] R. Ghosh, B. Chatterjee, and S. Chakravorti, *Investigations on the effect of voltage harmonics on leakage current for condition monitoring in insulators*, in 2016 IEEE 6th International Conference on Power Systems, ICPS 2016, 2016.

[8] U. D. Annakkage, P. G. McLaren, E. Dirks, R. P. Jayasinghe, and A. D. Parker, "A current transformer model based on the Jiles-Atherton theory of ferromagnetic hysteresis", *IEEE Trans. Power Deliv.*, Vol. 15, No. 1, 2000, pp. 57-61.

[9] J. V. Leite, K. Hoffmann, F. B. R. Mendes, N. Sadowski, J. P. A. Bastos, and N. J. Batistela, *Performance comparison between Jiles-Atherton and play vector hysteresis models on field calculation*, in IEEE CEFC 2016 - 17th Biennial Conference on Electromagnetic Field Computation, 2017.

[10] S. Rosenbaum, M. Ruderman, T. Strohla, and T. Bertram, "Use of Jiles-Atherton and preisach hysteresis models for inverse feed-forward control", *IEEE Trans. Magn.*, Vol. 46, No. 12, 2010, pp. 3984-3989.

[11] A. Benabou, S. Clénet, and F. Piriou, "Comparison of the Preisach and Jiles-Atherton models to take hysteresis phenomenon into account in finite element analysis", *COMPEL - Int. J. Comput. Math. Electr. Electron. Eng.*, Vol. 23, No. 3, 2004, pp. 825-834.

[12] Tổng cục Tiêu chuẩn Đo lường Chất lượng, *Tiêu chuẩn Việt Nam TCVN 7697-1:2007 (IEC 60044-1:2003) về máy biến đổi đo lường - Phần 1: Máy biến dòng*, Tiêu chuẩn Việt Nam, 2007.

[13] S. Moaveni, *Finite Element Analysis Theory and Application with ANSYS*, Odontology the Society of the Nippon Dental University, Vol. 12, No. 8. 1999, pp. 992-993.

[14] POSCO, *Electrical Steel Product Catalog*, 2014.

[15] Z. Cheng et al., "Modeling of magnetic properties of GO electrical steel based on Epstein combination and loss data weighted processing", *IEEE Trans. Magn.*, Vol. 50, No. 1, 2014, pp. 1-9.

[16] Hoàng Quốc Vượng, *Thông tư 39/2015/TT-BCT Quy định hệ thống điện phân phối - Cơ sở dữ liệu quốc gia về VBQPPL - Bộ Công thương*, Bộ Công thương, 2015.

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