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Current Transformers' Saturation Detection and Compensation Based on Instantaneous Flux Density Calculations

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Original scientific paper

One of the major problems in power system protection is current transformers saturation and inability of protective relays to recognize and compensate it. In this paper an approach is presented to identify current transformer saturation based on instantaneous flux density calculation. Also the calculated magnetizing current is used to saturation compensation. In the proposed algorithm, the instantaneous flux density and magnetizing current are calculated using Jiles-Atherton method. Using knee point flux density, a criteria is proposed to identify saturation phenomena in the current transformer and finally using calculated instantaneous magnetizing current, secondary current distortion has been compensated. To evaluate efficiency of the proposed algorithm, various types of faults, residual flux, fault occurring angle, CT burdens and DC components have been tested and the results evidence that the proposed algorithm is more accurate and reliable as well as faster than other algorithms and its error is obviously less than them.

Key words: Current Transformer, Modelling, Saturation, Compensation

Detekcija i kompenzacija zasićenja strujnog transformatora zasnovana na trenutnim proračunima gustoće toka. Jedan od najvećih problema zaštite elektroenergetskog sustava je zasićenje strujnih transformatora i nemogućnost zaštitnih releja da to prepoznaju i komenziraju. U ovom radu prikazan je pristup identifikaciji zasićenja strujnog transformatora zasnovan na trenutnim proračunima gustoće toka. Također, za kompenzaciju zasićenja koristi se izračunata struja magnetizacije. U predloženom algoritmu, trenutna gustoća toka i struja magnetizacije izračunati su korištenjem Jiles-Atherton metode. Korištenjem gustoće toka koljena predložen je kriterij za identifikaciju fenomena zasićenja kod strujnih transormatora i konačno, korištenjem izračunate trenutne struje magnetizacije kompenzirana je distorzija struje sekundara. Kako bi se vrednovala učinkovitost predloženog algortima testirane su razne vrste pogrešaka, zaostalih tokova, kutova pogreške, opterećenja strujnog transformatora i istosmjernih komponenata. Dobiveni rezultati su dokaz da je predloženi algoritam točniji, pouzdaniji i brži u odnosu na druge algoritme te da je njegova pogreška očito manja.

Ključne riječi: strujni transfomator, modeliranje, zasićenje, kompenzacija

1 INTRODUCTION

Power system protection becomes more vital when system short circuit capacity increases. One of the most important parts of protection systems is current transformer, which transforms high currents to low currents, usable for protective relays and metering devices. During a fault, high currents can cause CT saturation. Regarding B-H curve of CT core, hence the magnetic flux exceeds the knee point flux, secondary current won't vary proportionally to the primary current variation. This phenomenon causes distortion in secondary current and decreases R.M.S. value of measured current in protective relays, consequently causes delay in relay operation and loss of coordination and finally equipment damages.

Different methods are suggested to detect CT saturation. In [1], second derivative of CT secondary current is used to detect low saturation. This method is very sensitive to noise and its speed is low. In [2], using zero crossing method, CT saturation is detected. Zero crossing method is very sensitive to noise, low saturation, frequency variation and DC offset decline, which can introduce errors in the result of the proposed method.

In [3] sudden changes in secondary current of CT in saturation area are used to detect CT saturation. The proposed method will encounter enormous errors if immediately after saturation, secondary current does not change. Also, elimination of higher order harmonics by the anti-aliasing filter which causes sharp changes in secondary current, are removed and as a result the saturation is not detected.

In [4], secondary current samples and their difference-functions are used to detect CT saturation. This method cannot detect deep saturation. In [5], the difference between the samples exactly before and exactly after a symmetrical variable-length windows have been used in order to detect saturation. The proposed method has immunity against harmonics, noise and possible variations of the power system frequency.

Wavelet method is one of the most powerful methods to extract the fundamental components of distorted signals such as partial discharge signals and saturated CT's secondary current [6]. In [7], wavelet transform method is used to detect CT saturation. The transform is done for a specific frequency band, so the method cannot detect the exact beginning and end of saturation period. In [8], Elman neural network based compensation scheme is presented and the trip decision due to distorted and compensated secondary current is made to have a comparative evaluation of the relay trip decision.

Numerical methods for modeling of hysteresis curve of CT's core has been addressed in many publications [9-15]. In these studies, impacts of various parameters on modeling issues are discussed. Jiles-Atherton method is one of the most important and reliable methods for modeling of CT's core non-linear behavior. In [15] a combination of regression and wavelet transform is used to detect saturation period and to compensate it. Because of using wavelet, this method cannot compensate all types of saturations. In [16] ANN and inverse function of saturation is used to compensate secondary current of saturated CT. In this method only DC component of secondary current was taken into account and two other main factors of current i.e. time constant and remanent flux are neglected.

In digital compensation proposed in [17], at first remanent flux is calculated. Then using hysteresis curve, exciting current is calculated. Since it is supposed that CT core does not have remanent flux, only for low saturation this method is acceptable. In [18], it is assumed that the behavior of a saturated CT could be approximated by a straight line parallel to the H axis, and then an impedance based technique is proposed to detect saturation period. The proposed algorithm does not respond well for low saturation.

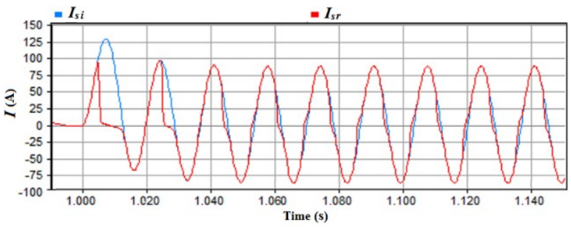
In [19] a partially nonlinear model is used to show CT core nonlinearity and using regression, the saturated area is distinguished from non-saturates area. An equation is introduced to estimate the magnetizing current. Also the magnetizing curve is needed. Since most of parameters of this method, such as initial remanent flux, should be estimated using regression, the method is slow.The presented algorithm in [20] is based on a CT saturation detection index which is obtained by using the derivatives of the current signals and Newton's backward difference formulae. Then the computed index is compared with an adaptive threshold to estimate the CT saturation.

In this paper, a new algorithm has been proposed to detect the CT saturation and compensate it. In this procedure, using the Jiles-Atherton method, all of hysteresis model parameters of CT's core have been accurately calculated. After determination of the core parameters, the instantaneous values of flux density and magnetic branch current have been computed. Then, the CT saturation initiation and termination can be detected by comparison between the obtained instantaneous flux density and flux density in the knee point. Also secondary current distortion has been compensated by using the magnetic branch current. This method is able to detect the deep and partial saturation of CT.

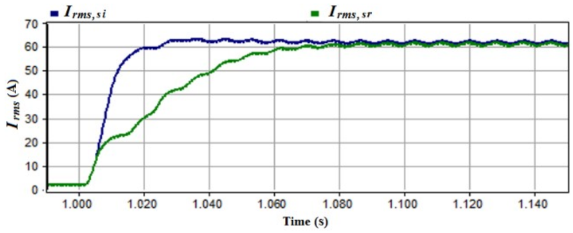
2 PROBLEM DEFINITION

2.1 Saturation and its impacts on over currents relays

In general, the current magnitude increases by the faults occurrence on a power system. This current can cause the CT saturation in the protective gears. Fig. 1(a) shows the secondary currents of ideal CT, I_{si}, and real CT, I_{sr}, when the magnetic core of the CT is saturated. As it is depicted, the secondary current has been distorted by different events as faults occurrence.



(a) Instantaneous value



(b) R.M.S. value

Fig. 1. Primary and secondary current of CT

The secondary current distortion reduces the effective value (rms) of the current, and consequently it can be caused the time delay of a relay operation and incoordination among protective devices. Also Fig. 1(b) shows the effective values of secondary current of ideal CT ($I_{rms,si}$) and real CT ($I_{rms,sr}$). As depicted in Fig. 1(b), the effective secondary current has a time delay and magnitude

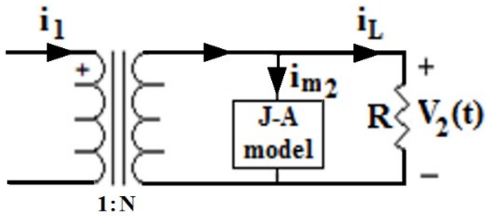


Fig. 2. The current transformer model [14]

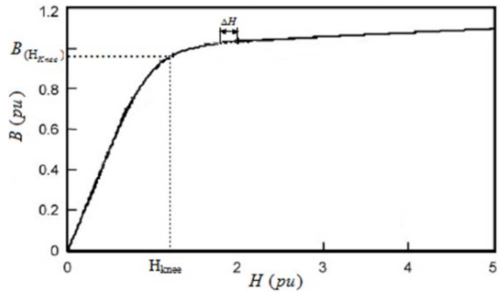


Fig. 3. Typical B-H curve of a magnetic core

drop in a real CT which is saturated. This problem can lead to mal-operation of the protective relays. Therefore, it is necessary to present a methodology for detection and compensation of the CT saturation.

2.2 Analytical definition

Fig. 2 shows the current transformer model by using the Jiles-Atherton hysteresis model instead of the nonlinear core. Also the burden is assumed resistive, firstly [14].

According to Fig. 2, the secondary voltage of the current transformer can be obtained as following:

$$v_2\,(t)=R\,i_L(t) \tag{1}$$

Also using Faraday's law, the secondary voltage of the current transformer can be written as the following equation.

$$v_2\,(t)=N\frac{d\varphi}{dt}=\mu_0 NA\frac{d(H+M)}{dt} \tag{2}$$

where A, N, H and M are the cross sectional area of the core, the number of turns at secondary winding of current transformer, the magnetic field and the total magnetization, respectively. Also $\frac{dM}{dt}$ can be stated as the following relation.

$$\frac{dM}{dt}=\frac{dM}{dH}.\frac{dH}{dt} \tag{3}$$

By substituting Eq. (3) to Eq. (2), the secondary voltage of current transformer can be obtained as following.

$$v_2\,(t)=\mu_0 NA.(1+\frac{dM}{dH})\frac{dH}{dt} \tag{4}$$

According to Ampere's circuital law for a CT with average magnetic length, ***l***, Eq. (5) can be written.

$$H=\frac{N\,i_{m2}}{l} \tag{5}$$

With substituting Eq. (5) to Eq. (4), the below Equation has been achieved.

$$v_2\,(t)=\frac{\mu_0 N^2 A}{l}.(1+\frac{dM}{dH})\frac{di_{m2}}{dt} \tag{6}$$

Also by using Eq. (1) and Eq. (6), the magnetizing current can be obtained.

$$i_{m2}=\int\frac{Rli_L(t)}{\mu_0 N^2 A.(1+\frac{dM}{dH})}dt \tag{7}$$

According to [14] value of $\frac{dM}{dH}$ can be stated by Eq. (8).

$$\frac{dM}{dH}=\frac{1}{1+C}\frac{M_{an}-M_{irr}}{sign\,(H)\,.k-\alpha(M_{an}-M_{irr})}+\frac{C}{1+C}\frac{dM_{an}}{dH} \tag{8}$$

where C is the coefficient of proportionality and α is the inter-domain coupling factor (Jiles-Atherton parameters). Also M_{an} and M_{irr} are anhysteretic and irreversible magnetization, respectively, which have been described in appendix.

Therefore, by using Eq. (8) the total magnetization, M, can be calculated. Then the flux density obtains by Eq. (9).

$$B=\mu_o(H+M) \tag{9}$$

Discrete value of the magnetizing current can be computed by the following equation.

$$\frac{i_{m2}\,(j+1)-i_{m2}(j)}{\Delta t}=\frac{1}{\mu_o N^2 A}\frac{1}{1+\frac{dM}{dH}}\;R\,i_L(j) \tag{10}$$

Hence the magnetizing current can be computed by using the recursive method and the mentioned relations [14].

2.3 Description of the saturation detection algorithm

In this method, CT saturation is detected by using the instantaneous flux density. According to Eqs. (1)- (10), the core parameters are determined. Then using these calculated parameters, the amount of the instantaneous flux density is computed from Eq. (9). The CT saturation is detected by comparison between the instantaneous flux density and flux density in knee point, B_{knee}, as shown in Fig. 3. It is necessary to mention that B_{knee} can be determined by the magnetization curve of the CT.

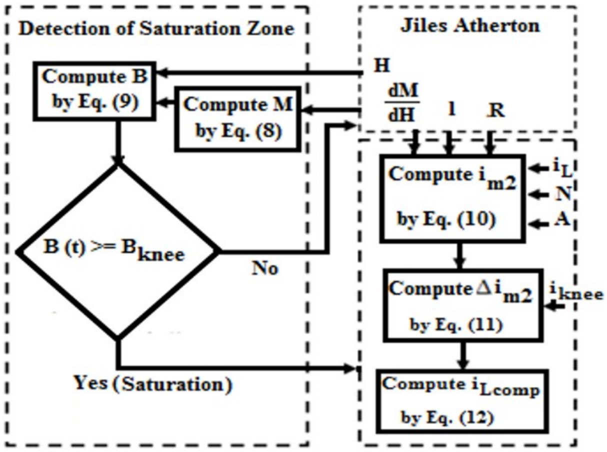


Fig. 4. Flowchart of the proposed algorithm

2.4 Saturation compensation algorithm

According to the recursive method and the mentioned relations in section A, the secondary current of CT is consisting of the burden current and the magnetizing current. When the CT core runs heavily saturated, the magnetizing current will increase and the secondary current decrease. Therefore, for compensation of the CT saturation, the variation of magnetizing current is added to the secondary current, as shown in Eq. (11).

$$\Delta i_{m2}\left(t\right)=i_{m2}\left(t\right)-i_{knee} \tag{11}$$

where Δi_{m2} is the variation of the magnetizing current when the CT saturation occurs. Finally, the compensated secondary current in a saturated CT can be yielded as the following relation.

$$i_{Lcomp}\left(t\right)=i_{L}\left(t\right)+\Delta i_{m2}\left(t\right) \tag{12}$$

Fig. 4 represents the flowchart of the proposed method. In this flowchart, the Jiles-Atherton section has been carried out by [14]. Also in detection of saturation zone, instantaneous flux density is compared to a threshold value, B_{knee}. According to the flowchart, the core saturation of the current transformer can be detected if the value of instantaneous flux density was further than the calculated threshold value in knee point. In this stage the compensated secondary current is calculated by Eq. (12).

3 IMPLEMENTATION OF THE PROPOSED METHOD

Fig. 5 shows a sample power system to demonstrate the effectiveness of the proposed procedure. The power system under consideration consists of two sources and a single line. The equivalent impedances are Z_{s1} and Z_{s2}. The

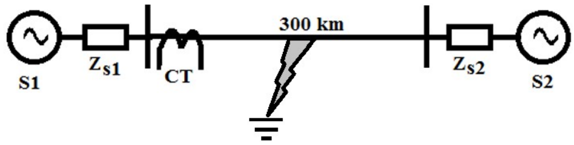


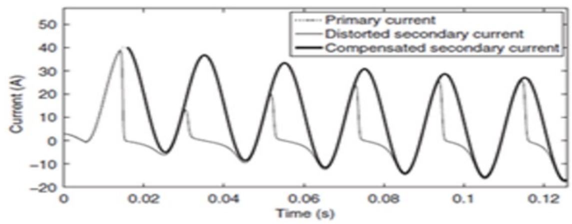
Fig. 5. Power system under study

line voltages of the sources are 240kV. Also the total length of the transmission line is 300 km. This network has been developed using EMTP-RV, PSCAD/EMTDC and Matlab software.

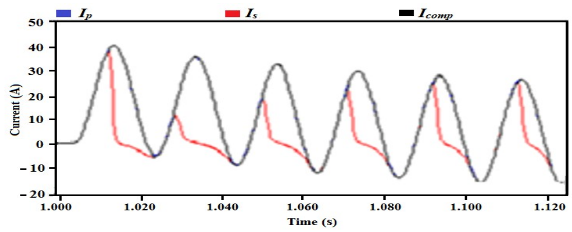
Table (1) shows the simulated cases. Since to validate the simulation result, they have been compared with the results presented in [19], the simulation cases and related data have been selected as cases used in [19].

3.1 Case 1: the normal saturation consideration

Fig.6(a) shows the primary, secondary and compensated currents at the secondary side of CT for case1 that is presented in [19] and Fig. 6(b) shows the same results that are obtained by proposed method of this paper.



(a) Primary, secondary and compensated currents [19]



(b) Primary (I_p), secondary (I_s) and compensated (I_{comp}) currents for proposed method

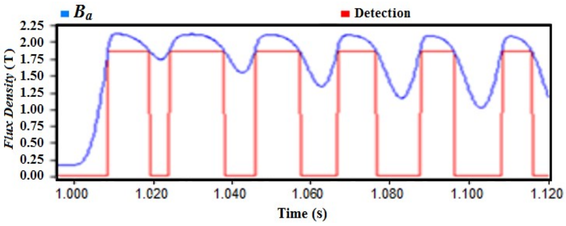
Fig. 6. Results of Case 1

As shown in Fig. 6(a, b), the results of the proposed method have good agreement with the results of [19]. Since the obtained normalized root mean square error of the results in [19] is 1.36%, and this value is 0.07% for the results of this paper, it shows the accuracy of the proposed method. This accuracy is due to accurate calculation of instantaneous flux density in this algorithm, while in [19], the relation between magnetic flux and current has been approximately considered. Also the primary current should be estimated using regression in [19].

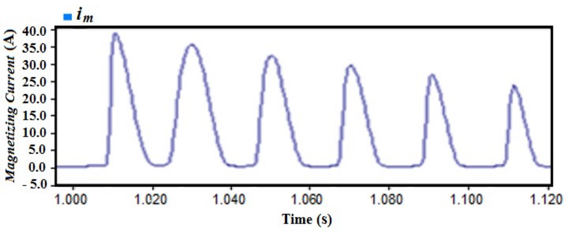
Table 1. Simulation cases and related data

	X/R ratio	Remanent flux	Fault inception angle	Fault location	Fault resistance	Secondary burden
Case1	30	0%	0^o	80 km	0.1Ω	25Ω
Case2	40	80%	45^o	100 km	0.1Ω	25Ω
Case3	20	0%	180^o	80 km	2Ω	30Ω , 0.5pf
Case4	60	80%	45^o	10 km	0.1Ω	1.5Ω
Case5	20	0%	90^o	30 km	0.1Ω	50Ω

The instantaneous flux density and CT saturation zones calculated by the proposed method have been illustrated in Fig. 7(a). As shown in Fig. 7 (a), the CT is saturated when the instantaneous flux density exceeds the knee point flux density. Therefore, this procedure is able to detect partial saturation. Also Fig. 7 (b) shows the variation of instantaneous flux current. It is necessary to mention that this should be added to the secondary current to calculate the compensated secondary current.



(a) Flux density



(b) Magnetic current

Fig. 7. Results of the proposed method in case 1

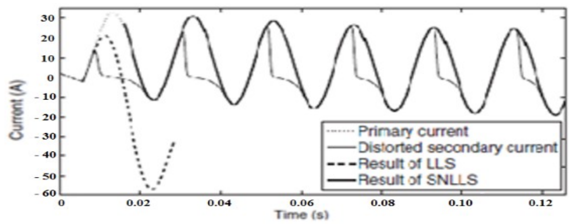
3.2 Case 2: heavy remanent flux

In general, the first half cycle of the secondary fault current has been affected by the remanent flux. Therefore, in this case a deep saturation is caused by the same polarity remanent flux [19]. Fig. 8 shows the effect of large remanent flux on the CT saturation by the proposed method and [19]. According to the obtained results, the normalized root mean square error of the described algorithm in [19] is 1.98%, while this error is 0.78% for the presented procedure in this paper. According to the achieved results, it can be seen that the proposed procedure used in this paper is more accurate.

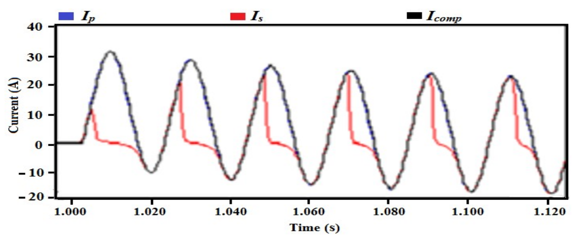
Fig. 9 depicts the instantaneous flux density and variation of the magnetic current for the heavy remanent flux scenario (i.e. case 2). As observed in Fig 9 (a), the initial flux density has a great value which causes deep saturation in the first half cycle. As a result, the secondary current will be distorted, also the CT is saturated in the positive half cycle.

3.3 Case 3: 0.5 pf burden in the CT secondary

Fig. 10 depicts the simulated results of the proposed algorithm when there is no remanent flux and CT burden contains of 0.5pf capacitive load. The obtained normalized root mean square error is 0.43% for the presented procedure in [19], while it is 0.071% with using the proposed method in this paper. In general, if burden impedance of the CT increases then the deeper saturation of a CT will be created.



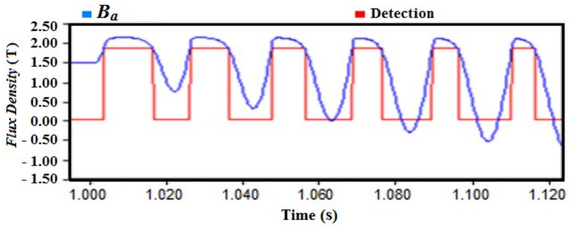
(a) Primary, secondary and compensated currents [19]



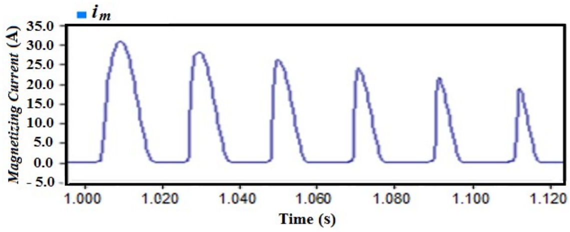
(b) Primary (I_p), secondary (I_s) and compensated (I_{comp}) currents for proposed method

Fig. 8. Results of Case 2

Fig. 11 illustrates the instantaneous flux density and variation of the magnetic current for a CT without remanent flux and 0.5 pf secondary burden. As shown in Fig 11 (a), since the fault inception angle in this case is 180^o so the CT saturation happens on the negative half cycle of the flux density.

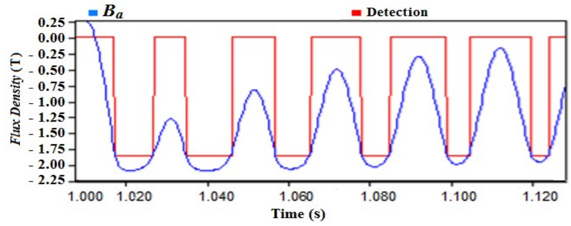


(a) Flux density

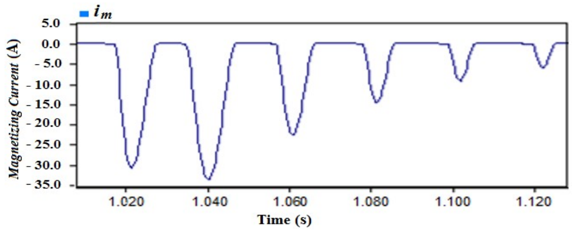


(b) Magnetic current

Fig. 9. Results of the proposed method in case 2

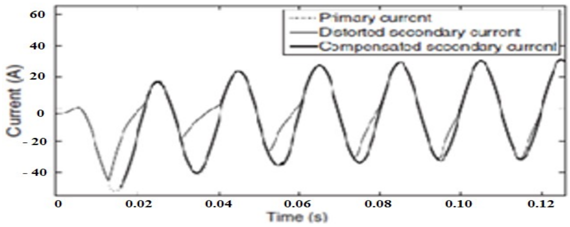


(a) Flux density

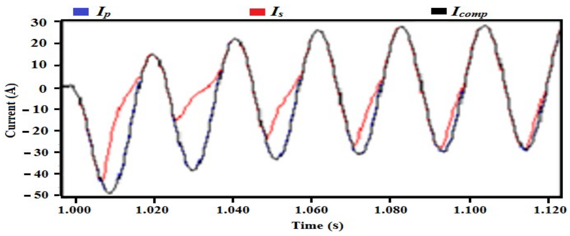


(b) Magnetic current

Fig. 11. Results of the proposed method in case 3

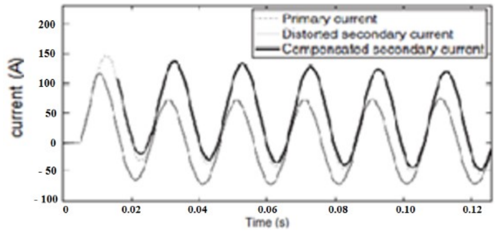


(a) Primary, secondary and compensated currents [19]

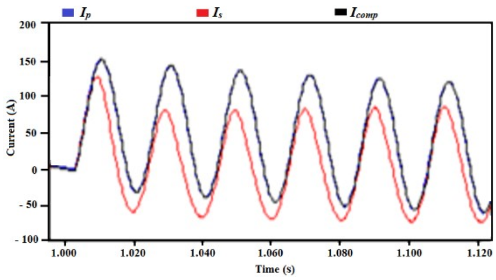


(b) Primary (I_p), secondary (I_s) and compensated (I_{comp}) currents for proposed method

Fig. 10. Results of Case 3



(a) Primary, secondary and compensated currents [19]



(b) Primary (I_p), secondary(I_s) and compensated(I_{comp}) currents for proposed method

Fig. 12. Results of Case 4

3.4 Case 4: small burden and heavy remanent flux

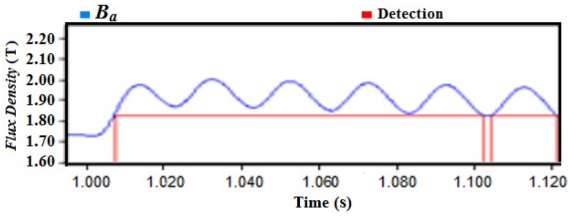
Fig. 12 shows the primary, secondary and compensated currents for the proposed method and the presented algorithm in [19] for a small CT burden and heavy remanent flux. This case occurs for a CT with digital protection relays in its secondary. According to the results in Fig. 12(a, b), the normalized root mean square error of the presented algorithm in [19] is 3.92%, while this value is 0.87% for the presented method in this paper. Therefore, in case 4, which the saturation current waveform is close to sinusoidal, this procedure can detect the saturation of the CT more correct.

The instantaneous flux density and magnetic current variation of the CT in case 4 have been shown in Fig. 13.

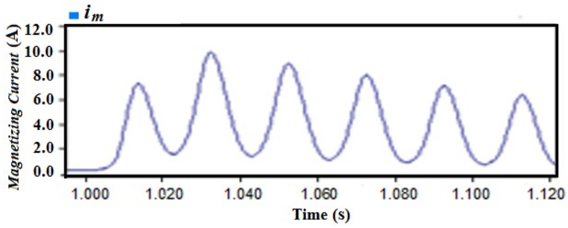
According to Fig. 13(a), exiting of instantaneous saturation can be demonstrated by this procedure.

3.5 Case 5: AC saturation

AC saturation of a CT can be caused by high symmetrical fault current and large burdens of CT. In this case, as shown in Fig. 14, the CT saturation can be created in positive and negative polarities of each cycle. Fig. 14(a,



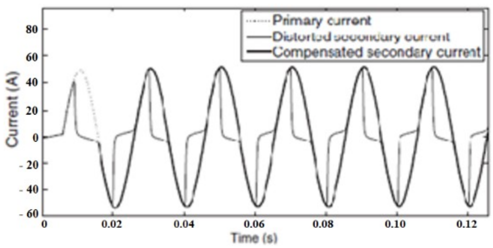
(a) Flux density



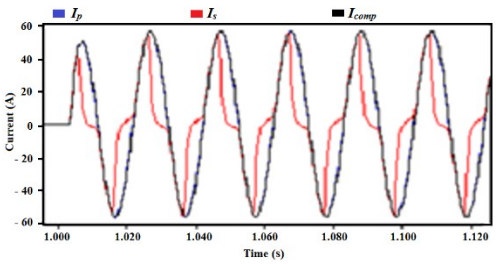
(b) Magnetic current

Fig. 13. Results of the proposed method in case 4

b) exhibit the obtained results for the presented method in [19] and this paper. According to these results, the normalized root mean square error of the presented method in [19] is 0.2%, while it is 0.057% for the proposed procedure in this paper. Therefore, according to the achieved results, it can be seen that the proposed procedure has very high speed and accuracy.



(a) Primary, secondary and compensated currents [19]



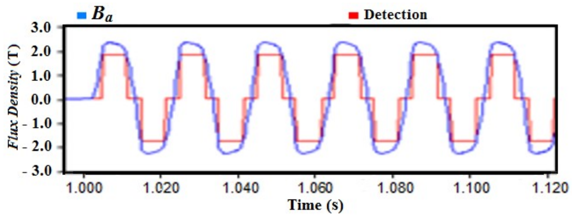
(b) Primary (I_p), secondary(I_s) and compensated(I_{comp}) currents for proposed method

Fig. 14. Results of Case 5

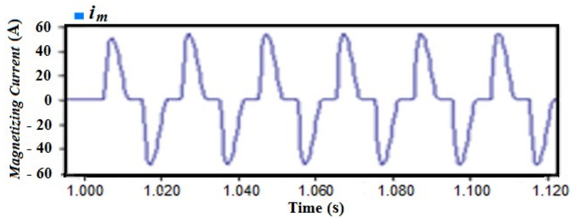
As shown in Fig. 15(a, b), the calculated instantaneous flux density and variation of the magnetic current have positive and negative half cycle. So the detected zone of CT saturation contains both positive and negative polarities of each cycle.

4 CONCLUSION

This paper proposed a novel procedure based on the Jiles-Atherton method for detection and compensation of CT saturation. In this method, amount of the instantaneous parameters such as the flux density and the magnetic flux of the CT core have been calculated by the hysteresis model of Jiles-Atherton. Then the CT saturation initiation and termination have detected by comparison between the calculated instantaneous flux density and flux density in the knee point.



(a) Flux density



(b) Magnetic current

Fig. 15. Results of the proposed method in case 5

According to the obtained results, the secondary current distortion has been compensated by using the magnetizing current. Also, the proposed method is able to detect the deep and partial saturation of CT. Meanwhile, to evaluate the efficiency of the presented algorithm, the impact of faults types, remanent flux, fault inception angle, CT secondary burden and DC offset have been considered and the results showed that the accuracy, speed and reliability of the proposed algorithm is better than the presented algorithm in [19] and the corresponding error is obviously less than the one in [19].

APPENDIX

According to [14] value of $\frac{dM_{irr}}{dH}$ can be stated by Eq. (A.1).

$$\frac{dM_{irr}}{dH}=\frac{M_{an}(H_e)-M_{irr}}{k.sign\left(\frac{dH}{dt}\right)-\alpha[M_{an}(H_e)-M_{irr}]} \quad \text{(A.1)}$$

where $sign(x)$ can be defined by:

$$sign\,(x)=\begin{cases} 1 & x\geq 0 \\ -1 & x<0 \end{cases} \quad \text{(A.2)}$$

The reversible magnetization, M_{rev} can be written as follow:

$\frac{dM_{rev}}{dH}=c\left[\frac{dM_{an}}{dH}-\frac{dM}{dH}\right]$ (A.3)

Then the total magnetization can be written by:

$M=M_{irr}+M_{rev}$ (A.4)

Also the effective magnetic field, H_e, can be presented by:

$H_e=H+\alpha.M$ (A.5)

The anhysteretic magnetization M_{an} is obtained using the following relation.

$M_{an}=M_s\left[coth\frac{H_e}{a}-\frac{a}{H_e}\right]$ (A.6)

and

$\frac{dM_{an}}{aH}=\frac{M_s}{a}\left[1-coth^2\frac{H_e}{a}+\left(\frac{a}{H_e}\right)^2\right]$ (A.7)

where M_s is the saturation magnetic moment of the core material and a is a shape parameter, both Jiles-Atherton parameters [14].

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