CT SATURATION CORRECTION BASED ON THE ESTIMATED CT SATURATION TIME CONSTANT

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Keywords: current transformer, CT saturation correction, CT time constant, EMTP simulations.

Abstract

A new method for CT saturation correction is presented that is based on an on-line estimation of the CT magnetizing inductance. The approach adopted is based on numerical solution of the differential equation, which describes the saturated current transformer. The correction procedure proposed has been tested with EMTP-ATP signals proving to be an effective tool for primary current reconstruction.

1 Introduction

It is obvious that protection criterion values calculated on the basis of saturated CT secondary signal may fall quite distantly from their correct values, which might have been determined if the CT primary unsaturated signal was available. Erroneous measurement may in consequence lead to false decisions (e.g. underreaching of overcurrent relays, erroneous calculation of fault loop impedance in distance relays) and protection maloperation. All those problems are well described e.g. in [7]. Thus it can be stated that CT saturation phenomenon may impair protection system reliability if appropriate algorithms for saturation detection and/or correction are not applied to eliminate the problem.

A large number of papers, which dealt with the CT saturation detection and correction issue, may be grouped into four families:

1 - no CT current correction is performed, but the information on CT saturation is used for other purpose, e.g. for adaptation of protection settings [11] or performing calculations during CT unsaturated periods only [1];

2 - correction performed is based on the information extracted from the secondary current during the saturation interval, with the aim to reproduce the primary current [4, 5, 6];

3 - correction is based on information extracted from the secondary current during the non-saturation interval, which aims at determination of the fundamental and DC components of the primary current [10];

4 - CT saturation detection and/or correction is done with use of Artificial Neural Networks trained with the simulation cases of CT transients [2, 8, 12, 14].

The known in literature methods of reconstruction the current on the ground of the secondary current data during the saturated period (family 3) usually require that the CT magnetizing characteristic and its load are a'priori known, which is not always the case. In this paper a new method is presented, which estimates the magnetizing inductance of the saturated CT and the resulting time constant on-line, on the ground of secondary current and estimated primary current samples. In fact, those parameters do not appear in the final equation, which determines the next unknown sample of the corrected current.

The developed CT saturation correction algorithm has been tested in simulative way with EMTP-ATP generated signals.

2 Idea of the correction method

The basic idea of handling the CT saturation problem adopted here is based on splitting the task into two subtasks, namely saturation detection and correction of the distorted secondary current (Fig. 1). When the CT is not saturated (i.e. the detection block has not detected it) the correction block is not activated. Starting from the point of saturation beginning t_{SB} the procedure of secondary current correction is activated. The procedure is operative until the CT goes out of saturation.

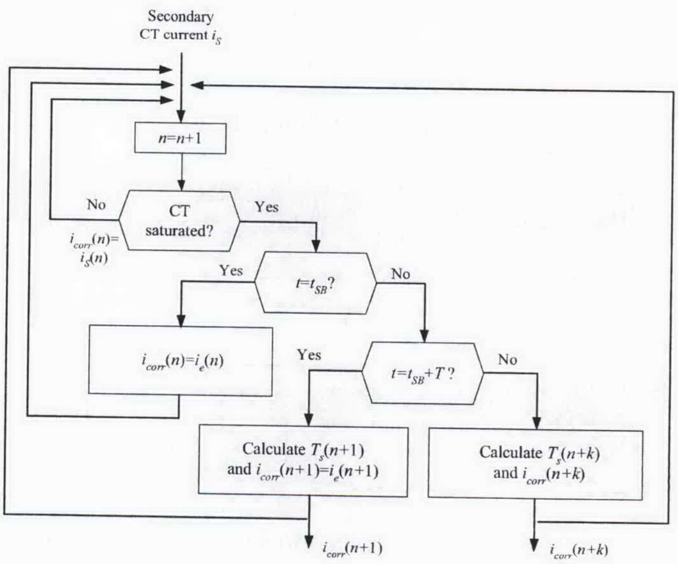

Figure 1: Block scheme of the proposed CT saturation correction procedure.

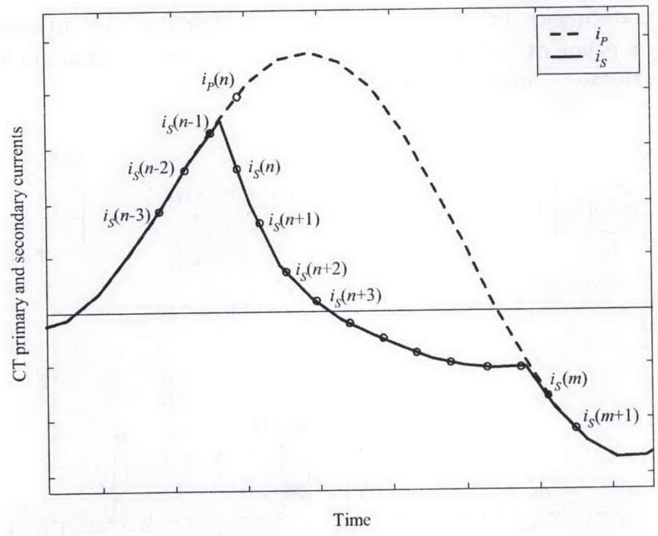

Figure 2: CT currents with marked samples before, during and after saturation time span.

The applied CT saturation detection procedure is based on comparison between the actual level of the secondary current i_S and the estimated level of the current i_e. This difference is close to the actual value of the transformer magnetizing current. Therefore, if it becomes substantial, it shows that the saturation took place. Otherwise this difference is small and i_e is very close to i_P.

To predict the sample $i_e(n)$, which is unknown, one has to use previous samples taken during the undistorted section. The estimation algorithm adopted here was based on an assumption that in the sampling period between the samples $(n-1)$ and (n) the third derivative of the primary current is the same as it was during the previous sampling cycle, which leads to the formula [13]:

$$i_e(n) = 4 i_S(n-1) - 6 i_S(n-2) + 4 i_S(n-3) - i_S(n-4) \tag{1}$$

With eq. (1) four previous samples from the unsaturated time span are to be available. The other algorithms for the estimation of i_e are described in [13].

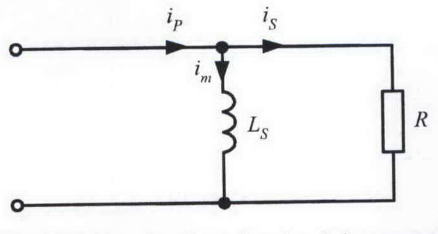

Figure 3: Simplified equivalent circuit of the saturated CT.

The approach adopted for secondary current correction is based on the numerical solution of the differential equation, which describes the saturated current transformer. In the equivalent circuit of the CT with resistive burden (Fig. 3, secondary side reactance neglected) the unknown parameter is the magnetizing inductance L_S, which during saturation becomes very small. The equation describing CT performance after saturation of the core is written in numerical form, and then solved for the unknown sample of the primary current i_P (equal to i_{corr}).

For the equivalent circuit from Fig. 3 one may write:

$$L_S \left(\frac{di_m}{dt} \right) = (i_P - i_m)\, R \tag{2}$$

where: R – secondary resistance of the CT,
i_m – magnetizing current of the CT,
i_P – primary current related to the secondary side.

Substituting $i_m = i_P - i_S$ one gets:

$$L_S \left(\frac{di_S}{dt} \right) + R\, i_S = L_S \left(\frac{di_P}{dt} \right) \tag{3}$$

where: i_S – secondary current of the CT.

In the numerical form the Equation (3) becomes:

$$\begin{aligned} & L_S \frac{i_S(n+2) - i_S(n+1)}{T} + R \frac{i_S(n+2) + i_S(n+1)}{2} \approx \\ & \approx L_S \frac{i_P(n+2) - i_P(n+1)}{T} \end{aligned} \tag{4}$$

where: T – sampling period.

This enables to calculate the unknown sample of the current $i_P(n+2)$:

$$\begin{aligned} i_P(n+2) = i_P(n+1) + i_S(n+2) \left[\frac{T + 0.5\, T_S}{T} \right] - \\ - i_S(n+1) \left[\frac{T - 0.5\, T_S}{T} \right] \end{aligned} \tag{5}$$

where T_S is the time constant of the saturated transformer and becomes $T_S = \dfrac{L_S}{R}$.

However, to calculate $i_P(n+1)$ one must know the value of the saturated core magnetizing inductance L_S. If the magnetizing characteristic of the CT is given, then the inductance is known for any value of the magnetizing current i_m. However, it is not always the case, and the inductance is to be calculated in the process of current estimation.

The magnetizing inductance, which corresponds to the sampling step between two consecutive samples n and n+1, is proposed to be estimated by means of the formula that is expressed as a ratio of the flux increase to the magnetizing current increase:

$$\begin{aligned} & L_S(n+1) \approx \frac{\Delta\Psi(n+1)}{\Delta i_m(n+1)} \approx \\ & \approx 0.5\, R\, T \frac{i_S(n+1) + i_S(n)}{[i_P(n+1) - i_S(n+1)] - [i_P(n) - i_S(n)]} \end{aligned} \tag{6}$$

where: $\Delta\Psi$ - increase of the magnetic flux in the core.

Therefore the time constant T_S becomes:

$$T_S(n+1) \approx 0.5\,T \frac{i_S(n+1)+i_S(n)}{i_P(n+1)-i_P(n)+i_S(n)-i_S(n+1)} \tag{7}$$

Since the inductance L_S (same for T_S) may vary with the variation of i_m the above calculation may be repeated for the next sampling periods as long as the CT remains saturated.

Knowing T_S one may now calculate the value of the unknown sample $i_P(n+2)$. Combining (5) and (6) one may write:

$$i_P(n+2) \approx i_P(n+1) + [i_S(n+2) - i_S(n+1)] + \frac{[i_S(n+2)+i_S(n+1)]\,T}{2\,T_S} \tag{8a}$$

or

$$i_P(n+2) \approx i_P(n+1) + [i_S(n+2) - i_S(n+1)] + \frac{[i_S(n+2)+i_S(n+1)]\,[i_P(n+1)-i_P(n)+i_S(n)-i_S(n+1)]}{i_S(n+1)+i_S(n)} \tag{8b}$$

One may observe, that the values of the saturated magnetizing inductance L_S and the time constant T_S of the saturated CT are estimated by means of sample processing, and eventually they do not enter into the final expression used to evaluate the unknown sample of the current.

The calculation of samples of the current i_P ought to continue until the sample m, which is the last sample of the interval during which the CT is saturated. After that the unsaturated time span follows - samples $m+1$, $m+2$ etc. (see Fig. 2), where the secondary current is undistorted.

3 Algorithm testing with EMTP signals

3.1 Test system and CT model in EMTP-ATP standard

The testing of developed method for CT saturation correction was performed with EMTP-ATP generated signals [3]. Simple 110kV transmission system fed from one side was modeled, as shown in Fig. 4a. It comprises the equivalent of feeding system represented by an electromotive source behind appropriate impedance (positive and zero sequence values, $X_0/X_1=1.5$) and transmission line transferring power to the end user (load). Phase-to-ground or phase-to-phase faults in the middle or at the end of transmission line were simulated with the arrangement of switches as shown in the Fig. 4b.

The system model shown in Fig. 4 included also appropriately designed elements of the current and voltage measurement chain. In case of the current it consisted of Current Transformer models (saturable elements) as well as analogue low-pass antialiazing filters realized as double RC circuits. The R and C values have been selected so that the filter cut-off frequency was equal to f_c=350 Hz, which is around 1/3 of the sampling frequency f_s=1000 Hz. The transformation ratio of CTs under study was 500:1 A/A. The CT model developed was an equivalent of standard current transformer type 5P20. Its magnetizing characteristic is shown in Fig. 5. The last point of the flux-current curve was set at various levels (flux coordinate) to obtain CTs with a number of different inductances and time constants of the secondary circuit under saturation, from 0.3 ms up to 5 ms.

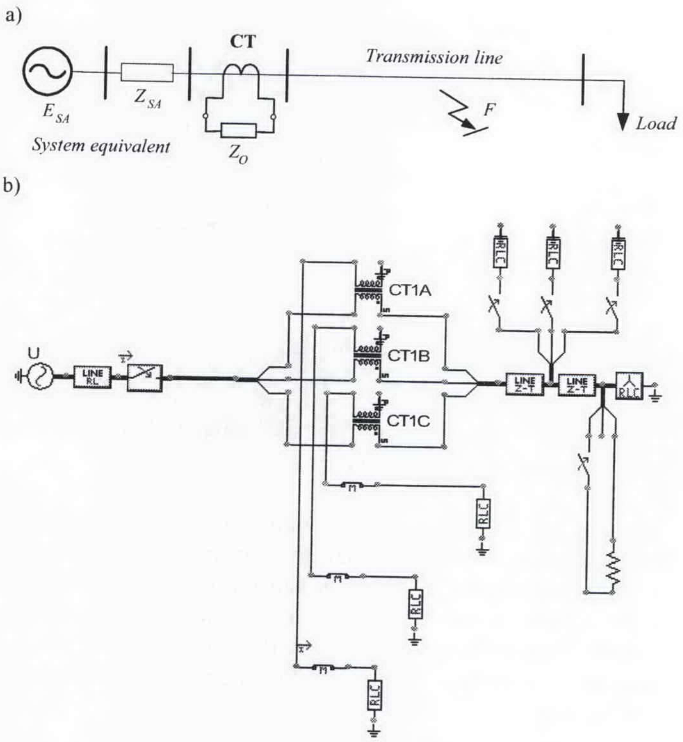

Figure 4: Schematic diagram of the system with CTs under study: a) system structure, b) EMTP-ATP model.

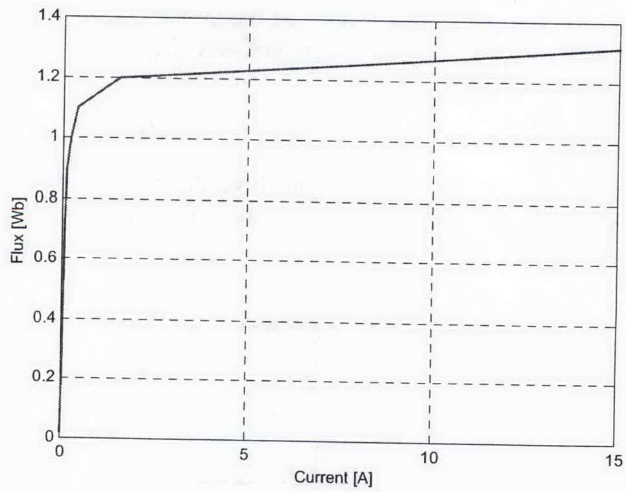

Figure 5: Magnetizing characteristic of the CTs.

3.2 Scope of simulation analyses and statistical overview

Thorough simulation study of the current transformer operation under various conditions has been performed. To obtain a wide variety of CT operation the following parameters of the system and transient conditions were being changed in each simulation run:

- level of the primary current during fault (resulting from the strength of the supplying system): [4.8, 5.2, 5.7, 6.2, 6.9, 7.7, 8.8, 10.2, 12.2, 15.0, 19.7, 28.5] x I_n,
- fault instant: 20:2:40 ms (various angles of fault inception),
- R/X ratio of the primary system: [0.07, 0.08, 0.09, 0.1],
- time constant of the CT secondary side during saturation: [0.3, 0.5, 1, 1.5, 2, 3, 4, 5] ms.

With the abovementioned options a number of 4224 simulation cases have been generated and stored in *.pl4 files. The primary and secondary CT current signals were next transformed to the Matlab-compatible format, since further signal processing and testing of the CT detection and correction methods was performed in Matlab environment.

The method's reconstruction abilities were examined with an assumption that the periods of CT saturation (beginnings and ends) are known precisely. This information was available since the CT secondary current could be compared with the primary current that was taken from simulation files. The CT was considered to be saturated when the following condition was satisfied.

$$\text{CT saturated when } \left| i_p(n)/\upsilon_{CT} - i_s(n) \right| > 0.5\text{A} \quad (8)$$

where i_p, i_s are primary and secondary currents, and υ_{CT} is CT transformation ratio.

The primary current reconstruction with the above-described procedure was started at t=t_{SB} (Fig. 1) and stopped at the points where the CT was going out of saturation.

Statistical analysis of the algorithm performance showed that:

- the algorithm performs worse for CTs with very small saturation time constants (below 1.5 ms); this is, however, understandable since by 1kHz sampling rate it is quite difficult to obtained accurate estimates when the CT secondary signal changes with high derivatives;
- the accuracy of secondary current reconstruction is to some extent dependent on the R/X ratio of supplying system (time constant of decaying DC in the primary current signal); the higher the ratio the better performance of the algorithm;
- the algorithm operates with higher accuracy when the CT primary current contains significant amount of decaying DC component;
- the results obtained are dependent on the accuracy of time constant T_S estimation; since the values calculated at the beginning of each saturation fragment were kept constant in the respective period (algorithm version with equations (7) and (8a)), certain correction errors could appear if the value of Ts was determined with poor accuracy; better results are expected if the CT saturation time constant is calculated continually, i.e. when the equation (8b) instead of (8a) is used;
- it was observed that the method usually overestimates the first peak of the corrected current; however, the difference is not big (a few percent on average).

3.3 Results of testing for selected EMTP-ATP cases

Operation of the CT correction method presented can be assessed while looking at the selected cases from simulation runs generated with EMTP-ATP.

As one can see in Fig. 6, the correction of CT secondary current is not perfect; however, it is more than good for calculation of most current-related protection criteria. The reconstruction quality is dependent on the CT saturation time constant; better results are obtained for longer values of T_S. In the case of T_S smaller than sampling period T the accuracy of T_S estimation with eq. (7) is rather poor; to improve it - application of higher sampling rate is recommended.

For both cases shown in Fig. 6 certain "overshoot" of the estimation is seen, especially for the initial period of saturation. It can be explained by the fact that at the very first moment after CT saturation beginning the time constant T_S is usually slightly underestimated, which in turn results in overestimated current sample values.

a)

b)

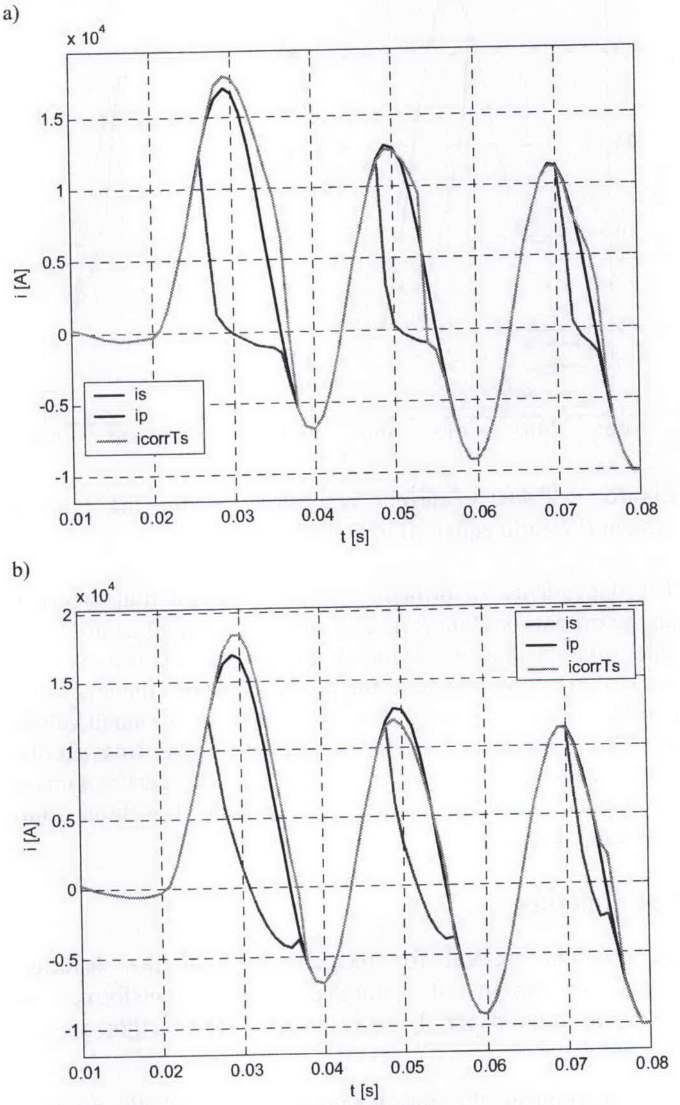

Figure 6: Primary current reconstruction for CT saturation time constant equal: a) 0.5 ms, b) 1.5 ms.

a)

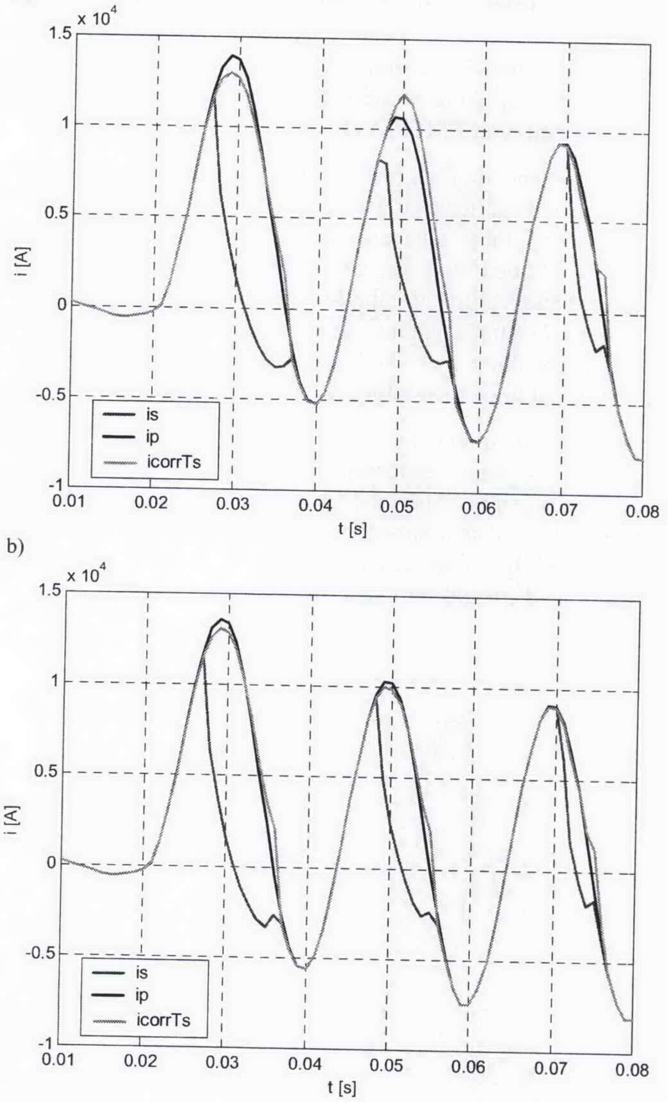

Figure 7: Primary current reconstruction for the primary system R/X ratio equal: a) 0.07, b) 0.1.

The dependence of primary current reconstruction accuracy on the primary system R/X ratio can be evaluated from Fig. 7. One can notice that for higher R/X (lower time constant of the decaying DC component in the primary current) the algorithm performance is very good (Fig. 7b). Contrary, for small values of R/X the results are worse, with higher under-/overshoots, which also depends on the way the CT gets saturated (immediate current change or smooth transition into saturation, Fig. 7a).

Conclusions

An efficient method for reconstruction of the distorted secondary current of saturated current transformer is described in the paper. The advantages of the method are the following:

- it reproduces the instantaneous values of the primary current, thus enabling to calculate the spectrum of it (all the needed higher harmonics, the orthogonal components of the fundamental harmonic etc...);
- the method does not require a'priori known data about the CT magnetizing characteristic, the assumption of resistive load, etc.;
- the proposed CT correction procedure has been tested with EMTP-ATP generated signals proving to be a very effective tool for primary current reconstruction;
- the errors of the method are acceptable, if the time constant T_S is at least two times larger than the sampling interval T.

The main disadvantage of the method is its sensitivity to the errors in detecting the beginning and the end of saturated regions. When the beginning of saturation is determined with some delay (e.g. for cases of saturation due to decaying DC component rather than high AC current values), the corrected secondary current may be calculated with significant error.

References

[1] T. Bunyagul, P. Crossley, P. Galac, "Overcurrent Protection Using Signals Derived from Saturated Measurement CTs", *PES Summer Meeting*, Vancouver 2001, Vol. 1, pp. 103-108.

[2] K.W. Chen, S.T. Glad, "Estimation of the Primary Current in a Saturated Transformer", *Proceedings of the 30th Conference on Decision and Control*, Brighton, England, December 1991, Vol. 3, pp. 2363-2365.

[3] EMTP-ATP Manuals, EEUG, 2001.

[4] Y.C. Kang, U.J. Lim, S.H. Kang, "Compensating Algorithm for the Secondary Current for Use with Measuring Type Current Transformers", *Proc. of the Int. Conference "Advanced Power System Automation and Protection"*, October 2004, Jeju, Korea, pp. 3-8.

[5] Y.C. Kang, J.K. Park, S.H. Kang, A.T. Johns, R.K. Aggarwal, "An algorithm for compensating secondary current of current transformers", *IEEE Transaction on Power Delivery*, Vol. 12, No. 1, Jan. 1997, pp. 116-122.

[6] Y. C. Kang, J. K. Park, S. H. Kang, A. T. Johns, R. K. Aggarwal, "Development and Hardware Implementation of a Compensating Algorithm for the Secondary Current of Current Transformers", *IEE Proceedings Electric Power Applications*, Vol. 243, No. 1, January 1996, pp. 41-49.

[7] B. Kasztenny, J. Mazereeuw, K. Jones, "CT Saturation in Industrial Applications – Analysis and Application Guidelines", GE Multilin, publication GET-8501.

[8] B. Kasztenny, E. Rosołowski, M. Łukowicz, J. Iżykowski, "Current Related Relaying Algorithm Immune to Saturation of Current Transformers", *Developments in Power System Protection*, Conference Publication No. 434, March 1997, pp. 365-368.

[9] M. Kuzenovic, C.W. Fromen, F. Phillips, "Experimental Evaluation of EMTP-Based Current Transformer Models for Protective Relay Transient Study", IEEE *Transactions on Power Delivery*, Vol. 9, No. 1, April 1994, pp. 405-413.

[10] F. Li, Y. Li, R.K. Aggarwal, "Combined Wavelet Transform and Regression Technique for Secondary Current Compensation of Current Transformer", *IEE Proceedings Generation, Transmission & Distribution*, Vol. 149, No. 4, July 2002, pp. 497-503.

[11] W. Rebizant, T. Hayder, L. Schiel, "Prediction of CT Saturation Period for Differential Relay Adaptation Purposes". *Proc. of the Int. Conference "Advanced Power System Automation and Protection"*, October 2004, Jeju, Korea, pp. 17-22.

[12] M.M. Saha, J. Iżykowski, M. Łukowicz, E. Rosołowski, "Application of ANN Method for Instrument Transformer Correction in Transmission Line Protection", *IEE Developments in Power System Protection*, Conference Publication No. 479, April 2001, pp. 303-306.

[13] A. Wiszniewski, W. Rebizant, L. Schiel, "Correction of Current Transformer Transient Performance", paper accepted for publication in IEEE Transactions on Power Delivery (Paper TPWRD-00832-2006.R1).

[14] D.C. Yu, J.C. Cummins, Z. Wang, H.J. Yoon, L.A. Kojovic, "Correction of Current Transformer Distorted Secondary Current Due to Saturation Using Artificial Neural Networks", *IEEE Transactions on Power Delivery*, Vol. 16, No. 2, April 2001, pp. 189-194.