Mitigating the negative impact of the stray flux on the current transformers using flux equalizing windings

Hadi Givi¹, Javad Shokrollahi Moghani¹ and Haidar Samet²

Abstract: The accuracy of the current transformers (CTs) supplying the generator differential relay is essential in power plant stations. One important factor which decreases the CT accuracy is the stray flux originated from the adjacent phases. During external fault conditions, the currents of adjacent phases contain a considerable decaying DC component. Thus, corresponding fluxes also contain a decaying DC component which cannot be counteracted by bus bar enclosure and generator shell, completely. Hence, the CT output signal deviates from the correct waveform which may lead to undesirable operation of the differential relay supplied by the CT. In fact, there is no internal fault in the generator but the differential relay trips the breaker due to negative impact of stray flux on CT accuracy. In this paper, a real power plant bus bar is modelled using three-Dimensional (3D) finite element method. Then, the effect of the stray flux on the accuracy of the CTs is studied. Finally, flux equalizing windings are considered on the CT’s secondary winding. According to finite element simulation results, the negative impact of the stray flux on the CT accuracy is decreased considerably by the flux equalizing windings.

Subjects: Instrumentation; Measurement & Testing; Power Engineering; Technology

Keywords: current transformer; finite element method; generator differential protection; stray flux; flux equalizing windings

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PUBLIC INTEREST STATEMENT

Electrical generators are considered as the main source of electrical energy in the world. As a result, different protection devices are utilized to protect them against faults. These devices are supplied by the generators’ voltage and current signals to monitor the generator status. These signals are obtained using sensors. Current transformers are the sensors utilized to measure the currents flowing in the generator conductors. However, their output signal may be affected by the stray flux which is an undesirable factor. This situation may lead to incorrect operation of the protection devices which in turn results in the generator disconnection from the electrical network. This research aims to analyze the performance of the current transformers in the presence of the stray flux. Finite element method is employed for analysis which is an efficient numerical technique. Furthermore, using flux equalizing windings is evaluated to mitigate the negative impact of the stray flux.
1. Introduction

Due to increasing demand for electrical power, the generators in the power plants should be designed for high rates of power. Based on technical limitations, the generators output voltage cannot exceed 25 kV. So the rate of their output currents should be increased (Braun, 1977). These currents are measured using current transformers. The accuracy of the current transformer secondary signal under transient conditions is a challenge for protection schemes. The CT saturation and stray flux threaten correct operation of protective relays.

There have been many papers in the literature regarding transient performance of current transformers. The saturation of CT’s core under fault conditions has been discussed and the techniques for correction of CT transient performance have been listed (Wiszniewski, Rebizant, & Schiel, 2008). The accuracy of transformer differential protection is threatened by CT saturation since discrimination between internal fault currents and inrush current becomes difficult during saturation. An effective compensating algorithm has been proposed to reconstruct the CT distorted current by which discrimination between fault and inrush currents is possible (Hajipour, Vakilian, & Sanaye-Pasand, 2015). The method is simple and independent of power system topology. The effect of CT saturation on transformer differential protection has been investigated (Stanbury & Djekic, 2015). Considering the importance of CT accuracy for protection schemes, a method was proposed to tackle the problems caused by CT excitation current (Telino Meneses & Laurindo Maitelli, 2016). It was shown that the ratio and angle errors could be decreased through compensating the voltage drop in the CT secondary by a simple control circuit. CT saturation leads to nuisance trips and it was shown that harmonic blocking achieves desirable security against these trips. Saturation detection algorithms are sensitive to noises. Employment of Savitzky–Golay (SG) filters was proposed to increase the robustness of saturation detection algorithms while requiring low computational burden (Schettino, Duque, & Silveira, 2016). CT saturation has been detected using multiplication of CT secondary current by its derivative (Esmail, Elkalashy, Kawady, Taalab, & Lehtonen, 2015). In case of saturation, a Kalman filter based approach has been presented to reconstruct the CT secondary current. The CT saturation could be detected by an index extracted from the current derivative signals through Newton’s backward difference formula (Chothani & Bhalja, 2014). The index is compared with an adaptive threshold to detect saturation and appropriate filters are applied to eliminate noises. Furthermore, the secondary current of saturated CT has been reconstructed by a compensating algorithm based on Fourier transform. Two variance functions have been applied to a variable-length window of the CT secondary current (Hooshyar & Sanaye-Pasand, 2015). Using these functions in simulations, the CT saturation has been detected in various operating conditions. The main advantage of this method is its robustness to fault characteristics, CT burden, and core remanence. To avoid malfunction of protective relays in case of CT saturation, a detection algorithm based on first difference of low-noise Lanczos filter has been presented (Schettino, Duque, Silveira, Ribeiro, & Cerqueira, 2014). It was shown that the method achieves high detection capability for different values of CT characteristics, secondary burden, fault currents and several levels of noise. The size of protective CTs utilized in auto-reclosing schemes should be much higher than CTs employed in single-step fault clearing relays to avoid CT saturation. A low-power and cost efficient electronic device has been proposed by which the CT could be demagnetized during the dead time of reclosing scheme (Hajipour, Salehizadeh, Vakilian, & Sanaye-Pasand, 2016). Using this device, the CT size can be reduced up to 40%.

A CT saturation detector has been proposed (Rebizant & Bejmert, 2007) based on artificial neural network (ANN). This saturation detector is then optimized using genetic algorithm. The use of an ANNs scheme has been proposed (Khorashadi-Zadeh & Sanaye–Pasand, 2006) to correct the CT secondary waveform distortions, where the proposed module uses samples of current signals to achieve the inverse transfer function of the CT. In order to compensate a sampled current waveform that is distorted due to CT saturation, an adaptive network-based fuzzy inference system was proposed (Erenturk, 2009). This compensation algorithm is simple, quick, and independent of
CT's parameters and characteristics. An effective method was presented to compensate distorted secondary current of measurement type CTs (Ozgonenel, 2013). The proposed method estimates the magnetizing current through Fröhlich hysteresis approach. A new and accurate current transformer model has been proposed using the Preisach theory (Rezaei-Zare, Iravani, Sanaye-Pasand, Mohseni, & Farhangi, 2008). This model is appropriate for analysis of electromagnetic transients based on representation of core magnetization characteristics. The main advantage of this model over existing models is determination of hysteresis minor loops independent of hysteresis major loop which results in higher precision in modeling of core hysteresis loop. A digital simulation technique was presented to compute the current wave shapes and flux excursions for a wide range of fault current parameters which represents both hysteresis and eddy current actions for steel cores (O'Kelly, 1992).

Conductors of a power plant bus bar are connected to generator windings through terminal box of the generator. A specified number of current transformers are located on the line side and neutral side of the bus bar to supply different protection schemes. For each phase, two CTs, one in the line side and the other in the neutral side are utilized for supplying the generator differential relay. The accuracy of CTs is affected by the stray flux of adjacent phases especially in gas power plants, where the CTs are set up in the vicinity of each other (Kaifeng, Wei, Peng, Songling, & Bo, 2009; Pfuntner, 1951; Seely, 1970). Different solutions have been proposed to tackle this problem such as employing aluminum or copper shielding as well as utilization of shield winding (Haiyu, Yuan, & Zou, 2006).

In this paper, the conductors of a real power plant bus bar and the CTs installed on these conductors are modelled using 3D finite element method (FEM). In the next step, the effect of the stray flux on the accuracy of the CTs is analyzed especially during fault conditions where the currents contain a considerable DC component. Finally, flux equalizing windings are considered on the secondary winding of the CTs. Using simulation results, it is confirmed that the negative impact of the stray flux on the CT accuracy is decreased noticeably.

2. Fault analysis on the power plant station
In order to determine the fault currents flowing in the bus bar conductors, the proposed power plant station is simulated in PSCAD software. The configuration of the proposed substation is illustrated in Figure 1.

To obtain fault currents, it is assumed that the fault is occurred in the generator bus. This is the worst case since the fault currents in the bus bar conductors will contain the most possible DC component. The input data utilized for components of the power plant station are presented in Tables 1–4 which belong to a real power plant station.

For all possible faults in the generator bus, the power plant station has been simulated and the currents in the bus bar conductors are extracted. An example of the fault current's waveforms is shown in Figure 2 where it is assumed that the phase A of the generator is connected to the ground denoted by G, so a single phase to ground fault is occurred, shown by A→G fault.
Figure 1. The diagram of the power plant station in PSCAD.

Table 1. Generator input data for short circuit calculation

| Parameter       | Value | Parameter       | Value |
|-----------------|-------|-----------------|-------|
| kV Nominal      | 15.75 | Winding connection | YG    |
| Rated S [MVA]   | 200   | $R''$ [p. u.]   | 0.009 |
| Type            | Fixed Generator | $X''$ [p. u.] | 0.179 |
| $P$ [MW]        | 160   | $R'$ [p. u.]    | 0.005 |
| $Q$ [MVAR]      | 120   | $X'$ [p. u.]    | 0.234 |
| Angle           | 0     | Internal $R$ [p. u.] | 0.00238 |
| Power factor    | 0.8   | Internal $X$ [p. u.] | 2.38  |
3. Finite element modeling of the generator bus bar and its current transformers

The 3D model of the CT in finite element software is shown in Figure 3. As seen in Figure 3, the secondary winding is composed of 16 parts where each part consists of 500 turns. These parts are connected in series. Consequently, the total turns of the secondary winding will be 8,000. Ansoft Maxwell software is utilized for simulations.

In Figure 3, the CT’s core is made of M110-23S alloy with nonlinear B-H characteristic presented in Table 5. This characteristic is defined in the finite element software as illustrated in Figure 4. The current transformer specifications are presented in Table 6.
Figure 3. 3D finite element model of the CT.

Figure 4. Defining the B-H characteristic of the core in the finite element software.

Table 5. B-H characteristic of M110-23S

| $H$ (A/m) | $B$ (T) | $H$ (A/m) | $B$ (T) |
|----------|--------|----------|--------|
| 0        | 0      | 22.96    | 1.2    |
| 5.06     | 0.1    | 28.35    | 1.4    |
| 11.04    | 0.3    | 48.14    | 1.6    |
| 16.44    | 0.6    | 88.2     | 1.7    |
| 18.65    | 0.8    | 274.7    | 1.8    |
| 20.76    | 1      | 1418     | 1.9    |
The model of the power plant bus bar with the current transformers installed on the conductors is illustrated in Figure 5. The primary conductor’s inner diameter is 138 mm while their outer diameter is 150 mm and they are made of Al-1350 alloy. The distance between the axis of two adjacent conductors is 100 cm.

In Figure 5, three current transformers are installed on each of the three phases in the generator line side (vertical cylindrical conductors) and three current transformers are installed on the generator neutral side (horizontal cylindrical conductors). Each of these CTs is used for a special protection purpose. For example, three CTs from the generator line side and three from the generator neutral side are utilized for generator differential protection.

In order to minimize the negative impact of the stray flux originated from the adjacent phases, each of the conductors should be surrounded by an aluminum enclosure. Based on eddy effects, this enclosure decreases the effect of the stray flux on the CT accuracy. The bus bar model with the enclosure is illustrated in Figure 6 where the red parts represent the bus bar enclosures.

| Parameter                  | Value               |
|----------------------------|---------------------|
| Insulation level           | 0.72–3 kV           |
| Allowed thermal range      | −22.8–50 °C         |
| Primary nominal current    | 8,000 A             |
| Secondary nominal current  | 1 A                 |
| Thermal current            | 80.1 kA/s           |
| Dynamic current            | 200 kA              |
| Nominal frequency          | 50 Hz               |
| Standard                   | IEC 60044–1         |
| Nominal burden             | 30 VA               |
| Accuracy class             | 5P20                |
| Core material              | M110–23 S           |

Table 6. Current transformer characteristics

Figure 5. The model of the bus bar and its protective CTs in finite element software.
4. Analyzing the current transformers performance under fault conditions

For analyzing the performance of the current transformers under fault conditions, the conductors should be excited in the finite element software with the fault currents extracted from PSCAD. As an example, the conductors are excited with the currents achieved by PSCAD for single phase fault as illustrated in Figure 7.

As seen in Figure 7, the currents of the phases A and B both contain considerable positive DC components. Hence, one expects the values of the magnetic flux density in the cores to be considerable in this case. The magnetic flux density distribution of the cores (for $t = 30$ ms which corresponds to the peak value of the phase A current) is depicted in Figure 8 which confirms the mentioned point.
As seen in Figure 8(a) and (b), the magnetic flux densities of the cores have reached to 1.6 Tesla due to the DC components of the fault currents. Based on the knee point of the magnetic curve of M110-23S, (which is at \( B = 1.7 \) Tesla according to Table 5), the cores are not saturated. So one expects the CTs to have correct operation in transferring their primary currents to the secondary. Figure 9 illustrates the performance of the CTs under single phase fault (A→G fault).

The differences in the CTs secondary currents are due to the effect of the stray flux generated by adjacent phases because the enclosure could not nullify this effect completely especially when there is a DC component in the currents. This is shown in Figure 9(a) and (b) for the CTs of the phases B and C under A→G fault.
The same simulations have been done for phase to phase fault (e.g. AB fault), two phases to ground fault (e.g. AB→G fault) and three phases to ground fault (namely ABC→G fault). The results of such simulations confirm that under all of these faults, due to the DC component of the fault currents, the enclosure could not nullify the effect of the stray flux completely and thus, the secondary current waveforms of the CTs located on the same phase are not coincided. So the difference between the secondary waveforms of the CTs feeding the generator differential relay may lead to the maloperation of this relay. As a result, a suitable strategy must be utilized to decrease the effect of the stray flux on the CTs secondary currents.

Figure 9. Secondary current waveforms of the current transformers installed on the same phase for single phase fault (A→G): (a) Phase B and (b) Phase C.
5. Decreasing the stray flux impact on the CT by using flux equalizing winding

5.1. Effect of the stray flux on the CT accuracy

As seen in the previous part, due to the effect of the stray flux, the secondary currents of the CTs located on the same phase are not coincided. This phenomenon is also illustrated in Figure 10(a) and (b) where the secondary currents of the CTs located on the phase A conductor are shown in the first pick of the fault current under phase to phase and three phases to ground faults respectively. It is
observed that the difference between the secondary currents of the CTs feeding the generator differential relay may lead to the undesirable operation of this relay.

5.2. Using flux equalizing winding for the CT

Figure 11 illustrates two possible configurations for the flux equalizing winding (Gajic, Hoist, Bonmann, & Baars, 2008). This winding always has an even number of segments. In Figure 11, it consists of four segments which have the same number of turns and are uniformly distributed around the CT core.

In the first topology shown in Figure 11(a), each two segments located on diametrically opposite sides of the core (1 and 3 or 2 and 4) are cross-connected so as to prepare a path for the circulating current. This current counteracts the effect of its source namely the stray flux according to the Lenz law. Under normal operation, namely when there is no stray flux, no current flows in the winding.

In the second configuration as illustrated in Figure 11(b), all the segments are connected in parallel and they prepare the path for the circulating current. During the stray flux existence, this current generates a magnetic field which is opposed to the magnetic field of the stray flux. So the effect of the stray flux is diminished.

Figure 11. Two possible configurations for the flux equalizing winding.
In this paper, the first configuration is utilized for the CTs. The turn number of each segment of the flux equalizing winding is equal to 10. By increasing the turn number, the stray flux effect could be more decreased but this is in the expense of increasing the CT cost and weight. The modified CT with flux equalizing winding is depicted in Figure 12 where the violet parts are the four segments of the flux equalizing winding.

Under fault conditions, the stray flux originated from the adjacent phases decreases the CT accuracy. In this part, the effectiveness of the flux equalizing windings is evaluated for different types of the fault currents. For the single phase fault namely A→G fault as depicted in Figure 13, only the phase A of the conductors is excited by the corresponding fault current in the finite element software, namely no currents flow in the conductors of the phases B and C. It is obvious that under this
Figure 14. Secondary currents of the two CTs of the Phase B that feed the differential relay during the phase A excitation with its current for A→G fault: (a) Without flux equalizing winding and (b) With flux equalizing winding.
Figure 15. Secondary currents of the two CTs of the Phase C that feed the differential relay during the phase A excitation with its current for A–G fault: (a) Without flux equalizing winding and (b) With flux equalizing winding.
condition, the currents induced in the CTs of the phases B and C are just due to the stray flux originated from the phase A current. Then the induced currents in the CTs of the phases B and C are extracted for two statues: first when these CTs are without flux equalizing winding and second when they are prepared with this winding. The results are presented in Figure 14(a) and (b). For two phases fault (like AB fault), the primary conductors of the phases A and B are excited with their corresponding currents as illustrated in Figure 16. Namely, no current flows in the phase C primary conductor. Under these circumstances, the currents induced in the CTs located on the Phase C conductors are only due to the stray flux originated from the phases A and B currents. The current waveforms of these CTs are also presented for two conditions: when these CTs are without flux equalizing winding and when they are prepared with this winding. The results are given in the Figure 17(a) and (b). For more clarity, only the waveforms of the secondary currents of the CTs feeding the generator differential relay are shown.

The differential relay responses to the differential current of the CTs feeding it, namely, if the difference between the currents of the CTs feeding this relay exceeds the relay set point, it will operate. As summarized in Table 7, the maximum differential current between the two CTs feeding the differential relay is decreased considerably due to the flux equalizing winding utilization.
Table 7. Decreasing the negative impact of the stray flux on the CT using the flux equalizing winding

| Fault type | Percentage of decrease in the maximum secondary current difference between the CTs of the phase B | Percentage of decrease in the maximum secondary current difference between the CTs of the phase C |
|------------|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| A→G        | 91.67                                                                                             | 97.47                                                                                             |
| AB         | -                                                                                                 | 98.71                                                                                             |
| AB→G       | -                                                                                                 | 98.67                                                                                             |
6. Discussion

The accuracy of output signal of the CTs utilized for differential protection may be affected by two main factors: saturation of the core and stray flux. In case of CT saturation, discrimination between internal fault currents and magnetizing inrush currents becomes difficult. On the other hand, stray flux deviates the output of the CTs from the correct waveform. Hence, the differential relay may consider this case as an internal fault and trip the breaker. The results in Section 5.1 prove that the difference between the currents of the CTs installed on the same phase of the generator may exceed the differential relay set point due to the stray flux impact. This results in the malfunction of this relay and disconnection of the generator from the power grid. To avoid this problem, one effective solution is to employ flux equalizing windings on the CT secondary to counteract the impact of the stray flux. The results presented in Section 5.2 confirm that this winding increases the CT accuracy in different fault conditions and thus improves the reliability of the differential protection scheme.

7. Conclusion

This paper is focused on modeling a typical power plant bus bar using FEM and analyzing the performance of protective current transformers installed on the conductors under fault conditions. The results confirm that during fault condition, the secondary currents of the CTs feeding the generator differential relays deviate from the correct waveforms due to the stray flux effect. This may lead to undesirable operation of this relay. In other words, the relay trips the breaker while no fault has occurred. To tackle this challenge, application of flux equalizing windings on the CT secondary is proposed to mitigate the stray flux impact. The results confirm the considerable effectiveness of this winding for reducing the negative impact of the stray flux during different fault conditions.

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References

Braun, A. (1977). Determination of current transformer errors at primary currents up to 100,000 A. IEEE Transactions on Instrumentation and Measurement, 26, 263–267. doi:10.1109/tim.1977.4314550
Chothani, N. G., & Bhalja, B. R. (2014). New algorithm for current transformer saturation detection and compensation based on derivatives of secondary currents and Newton’s backward difference formulae. IET Generation, Transmission & Distribution, 8, 841–850. doi:10.1049/iet-gtd.2013.0324
Erenturk, K. (2009). ANFIS-based compensation algorithm for current-transformer saturation effects. IEEE Transactions Power Delivery, 24, 195–201. doi:10.1109/tpwrd.2008.2005882
Esmail, E. M., Elkaloghny, N. I., Kowady, T. A., Taalab, A.-M. I., & Lehtonen, M. (2015). Detection of partial saturation and waveform compensation of current transformers. IEEE Transactions Power Delivery, 30, 1620–1622. doi:10.1109/tpwrd.2014.2361032
Gojic, Z., Hoist, S., Bonmann, D., & Baars, D. A. W. (2008). Influence of stray flux on protection systems. IET 9th International Conference on Developments in Power Systems Protection (DPSP 2008). doi:10.1049/cp:20080075
Haiyu, Yu, Yuan, Jiasheng, & Zou, Jun (2006). Design of novel structure current transformer with shielding coils for overcoming the saturation of core. IEEE Transactions on Magnetics, 42, 1431–1434. doi:10.1109/tmag.2006.872478
Hojjipour, E., Vakilian, M., & Sanaye-Pasand, M. (2015). Current-transformer saturation compensation for transformer differential relays. IEEE Transactions Power Delivery, 30, 2293–2302. doi:10.1109/tpwrd.2015.2411736
Hojjipour, E., Salehizadeh, M., Vakilian, M., & Sanaye-Pasand, M. (2015). Residual flux mitigation of protective current transformers used in an autoreclosing scheme. IEEE Transactions Power Delivery, 31, 1636–1644. doi:10.1109/tpwrd.2015.2480773
Hooshayar, A., & Sanaye-Pasand, M. (2015). Waveshape recognition technique to detect current transformer saturation. IET Generation, Transmission & Distribution, 9, 1430–1438. doi:10.1049/iet-gtd.2014.1147
Khorashadi-Zadeh, H., & Sanaye-Pasand, M. (2006). Correction of saturated current transformers secondary current using ANNs. IEEE Transactions Power Delivery, 21, 73–79. doi:10.1109/tpwrd.2005.858799
O’Kelly, D. (1992). Calculation of the transient performance of protective current transformers including core hysteresis. IEEE Proceedings C Generation, Transmission and Distribution, 139, 455–460. doi:10.1049/ip-c.1992.0063
Ozgonenel, O. (2013). Correction of saturated current from measurement current transformer. *IET Electric Power Applications*, 7, 580–585. doi:10.1049/iet-epa.2013.0105

Pflünter, R. A. (1951). The accuracy of current transformers adjacent to heavy current buses. *AIEE Transactions*, 70, 1656–1661.

Qu, K., Zhao, W., Yang, P., Huang, S., & Jiang, B. (2009). Interference mechanism of external current on heavy current transformer. 2009 IEEE Instrumentation and Measurement Technology Conference. doi:10.1109/imtc.2009.5168647

Rebizant, W., & Bejmert, D. (2007). Current-transformer saturation detection with genetically optimized neural networks. *IEEE Transactions Power Delivery*, 22, 820–827. doi:10.1109/tpwrd.2007.933363

Rezai-Zare, A., Irvani, R., Sanaye-Pasand, M., Mohseni, H., & Forhangi, S. (2008). An accurate current transformer model based on Preisach theory for the analysis of electromagnetic transients. *IEEE Transactions Power Delivery*, 23, 233–242. doi:10.1109/tpwrd.2007.905416

Schettino, B. M., Duque, C. A., Silveira, P. M., Ribeiro, P. F., & Cerqueira, A. S. (2014). A new method of current-transformer saturation detection in the presence of noise. *IEEE Transactions Power Delivery*, 29, 1760–1767. doi:10.1109/tpwrd.2013.2294079

Schettino, B. M., Duque, C. A., & Silveira, P. M. (2016). Current-transformer saturation detection using Savitzky-Golay filter. *IEEE Transactions Power Delivery*, 31, 1400–1401. doi:10.1109/tpwrd.2016.2521327

Seely, S. (1970). Effect of stray flux on current transformers. *Journal of Science & Technology*, 37, 115–120.

Stanbury, M., & Djekic, Z. (2015). The Impact of current-transformer saturation on transformer differential protection. *IEEE Transactions Power Delivery*, 30, 1278–1287. doi:10.1109/tpwrd.2014.2372794

Telino Meneses, L., & Laurindo Maitelli, A. (2016). A proposal for improving the current transformers accuracy. *IEEE Latin America Transactions*, 14, 430–436. doi:10.1109/tla.2016.7437176

Wiszniewski, A., Rebizant, W., & Schiel, L. (2008). Correction of current transformer transient performance. *IEEE Transactions Power Delivery*, 23, 624–632. doi:10.1109/tpwrd.2008.915832