STRAY FLUX AND ITS INFLUENCE ON PROTECTION RELAYS

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Abstarct

Current transformers (CT) normally have excellent performance when applied correctly under conditions for which they were designed. While the common operating conditions affecting CT performance are usually recognized and properly considered, there is one factor, the importance of which is sometimes underestimated or even overlooked entirely. This is the effect of external stray flux produced by:

- abrupt bends of the CT primary conductor at very close distance from the CT location;
- high-current busses adjacent to the CT; and
- other sources of magnetic fields near the CT (e.g. CTs installed within power transformer or shunt reactor tank).

If a CT is applied incorrectly (e.g. without considering the existence of stray fluxes) the secondary CT current can be, under certain circumstances, entirely different from the primary CT current which then can easily cause unwanted operations of sensitive protection relays like for example differential protection.

Introduction

The bar-primary (i.e. ring-core; window type) current transformers are typically designed assuming that the flux in the CT magnetic core is homogeneous and only caused by the current flowing in the CT primary conductor. Thus, this means that:

- the primary CT conductor is ideally centered in the middle of the CT toroidal magnetic core;
- the primary CT conductor is straight and infinitely long; and
- there are not any external magnetic fields which can cause additional flux in any part of the CT core.

However, in practice the primary conductor is never straight and infinitely long and the CTs are commonly installed in a three-phase system. Thus, at least the magnetic fields from the other two phases are present in the vicinity of the CT. These "external magnetic fields" may under certain circumstances produce significant stray flux in the CT magnetic core, which can cause problems for protection systems connected to that CT.

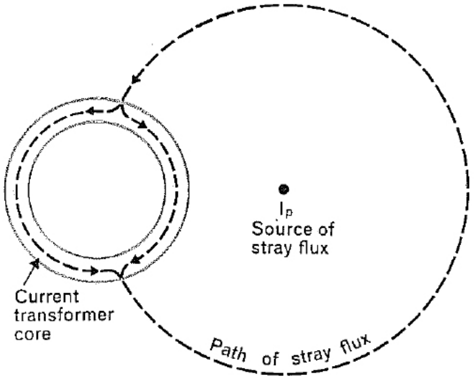


Figure 1 : Stray flux influence on a CT core [9].

As shown in
Figure 1 1, the stray flux will split in two parallel paths inside the CT core. Thus, at one side of the CT core the resultant flux will be equal to the sum of the "usual flux" caused by the CT primary current and the stray flux, while at the other side of the CT core the resultant flux will be equal to the difference between the usual flux and the stray flux. Obviously the resultant flux will have different values in different parts of the CT core and a partial CT saturation may occur.

There are quite a number of papers published regarding CT accuracy under such operating conditions [2,7,8,9,10]. Surprisingly very few papers discuss the influence of the stray flux on the relay protection systems. Even in some of the above mentioned references it is stated that stray flux should not produce big impact on the relay protection. This might be true for the relays with time delayed operation such as phase or ground overcurrent relays. However, stray flux can easily cause unwanted operation of the instantaneous and sensitive relays like differential protection. Note that both high impedance and low impedance differential protection relays can be affected by this phenomenon.

Testing in the laboratory

The laboratory testing was performed on the two CT cores designated CT #1 and CT #2 as shown in Figure 2.

Both CT cores have the ratio 800/1A with a relative small core cross section. The only important difference between the two CT cores is the core cross section area. The core cross section area of the CT #1 is 17.1cm^2 and the core cross section area of the CT #2 is 1.9cm^2.

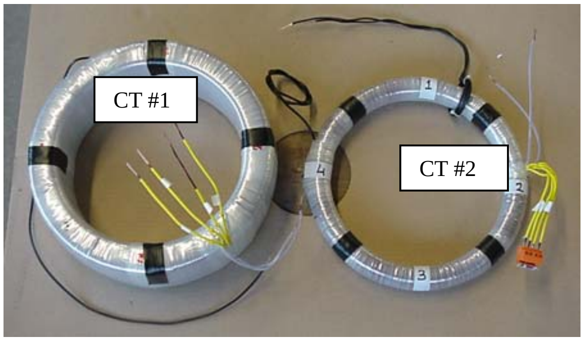
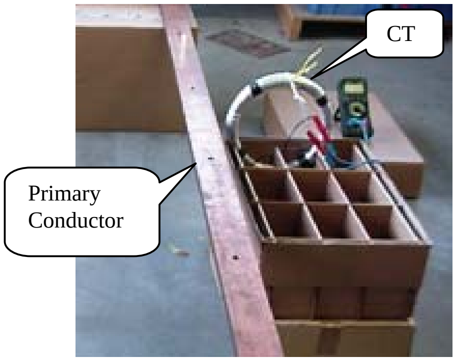


Figure 2 : Tested CT cores in the Laboratory [3].

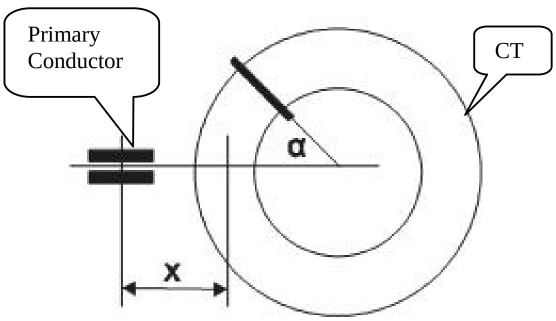
As shown in Figure 3, the stray flux influence is tested by positioning the CT core close to an adjacent primary conductor. Figure 3a was taken by digital camera during laboratory testing, while

Figure 3 3b represents the simplified geometrical view of the test setup. The distance X is 6cm during these tests. The test was done by applying the 50Hz, AC current with the RMS value of 6.5kA. The primary current could be injected with or without a DC offset. The applied current through the primary conductor and the CT secondary current were recorded by an oscilloscope as Channel 1 and Channel 2 respectively. These two waveforms are given in

Figure 4 4 [3]. In the Figure 4a, the two waveforms are given when the DC offset is present in the primary current. The CT secondary current with maximum peak of 1.5A was recorded during this test. In Figure 4b, the two waveforms are given for the symmetrical primary current with AC RMS magnitude of 6.5kA. The recorded peak of the CT secondary current during this test reaches 0.2A. Note that secondary current spikes are only observed during testing of CT #2 and not during testing of CT #1.

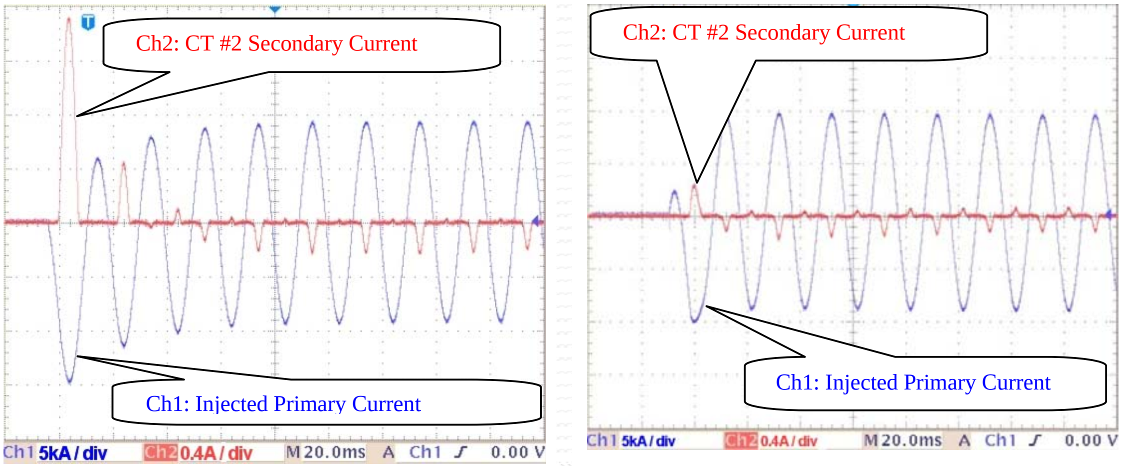


a) Actual test arrangement



b) Principle setup drawing (cross-section)

Figure 3 : Laboratory test setup [3].



a) With DC offset in the primary current

b) Without DC offset in the primary current

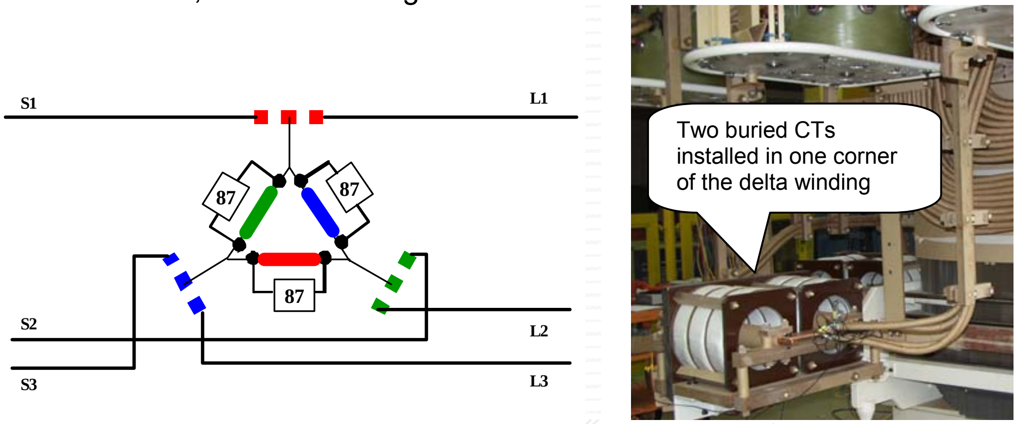
Figure 4 : Captured waveforms for CT #2 in the laboratory [3].

Field recordings

The authors have observed and recorded this phenomenon in the field mostly in installations of phase shifting transformers (PST) [6] and power transformers [5]. As described in reference [4] protection schemes for such special transformers often require buried CTs within the transformer tank.

First recording from the field

Within a symmetrical, single-core PST [6] with rating data 450MVA, 138/138kV, ±58°, 60Hz, six buried CTs, with ratio 3000/5 and class C800, are installed. Two CTs, one at each side of every phase of the delta winding are used for the differential protection scheme, as shown in Figure 5a.



a) Principle drawing for symmetrical, single-core PST.

b) Two buried CTs installed next to each other in one corner of the delta winding.

Figure 5 : Application information for the first field case.

The two recorded currents should have the same waveforms with opposite polarity (e.g. their sum shall be zero). However, it is clear that one of the two currents (i.e. red trace in

Figure 6 6) is distorted for a part of the power system cycle. Actually, its peak value is almost completely reversed. Later it was concluded that this waveform distortion was caused by stray flux from the primary current in the neighboring phase (see Figure 5b).

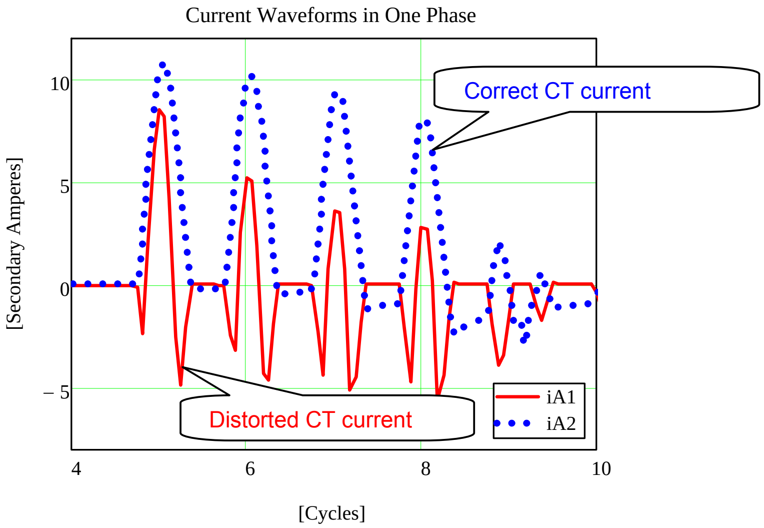
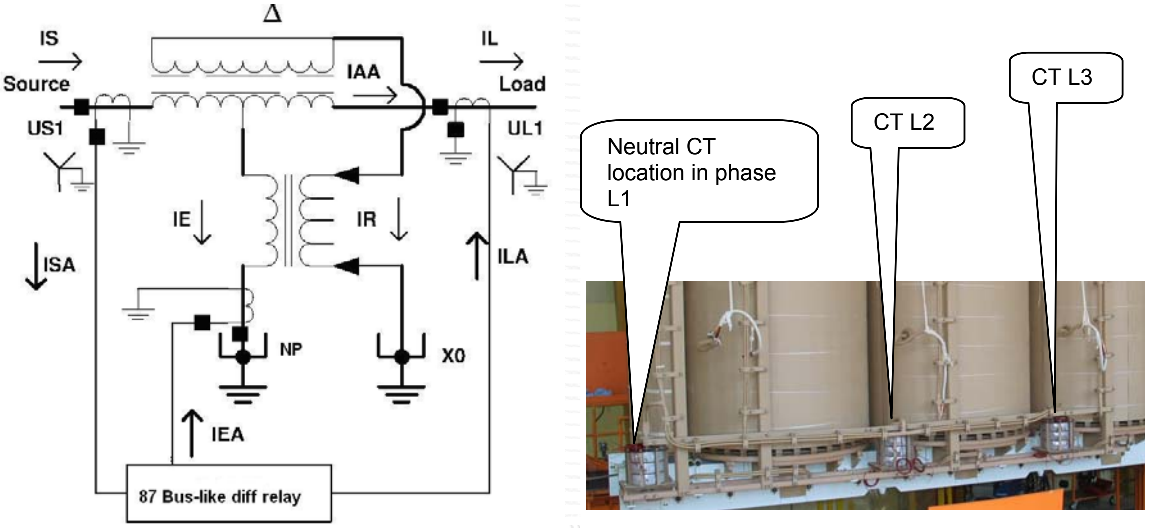


Figure 6 : Recorded currents at the two ends of the delta winding in phase L1.

Second recording from the field

Within a symmetrical, dual-core PST [6] with rating data 600MVA, 232/232kV, ±35^o, 50Hz, buried CTs (with rated data 1200/1A; 10P20; 60VA) are installed. CTs are located at the neutral point of the PST primary exciter winding in each phase, in accordance with main differential protection scheme recommended [5] and shown in Figure 7a. Due to space limitations within the tank, neutral point CTs used for this differential protection are located next to the yoke of the magnetic core of the excitation transformer (see Figure 7b). Unwanted operation of the differential protection has spuriously occurred during PST energizing.



a) Principle drawing for symmetrical, dual-core PST.

b) Buried CTs installed close to the transformer yoke.

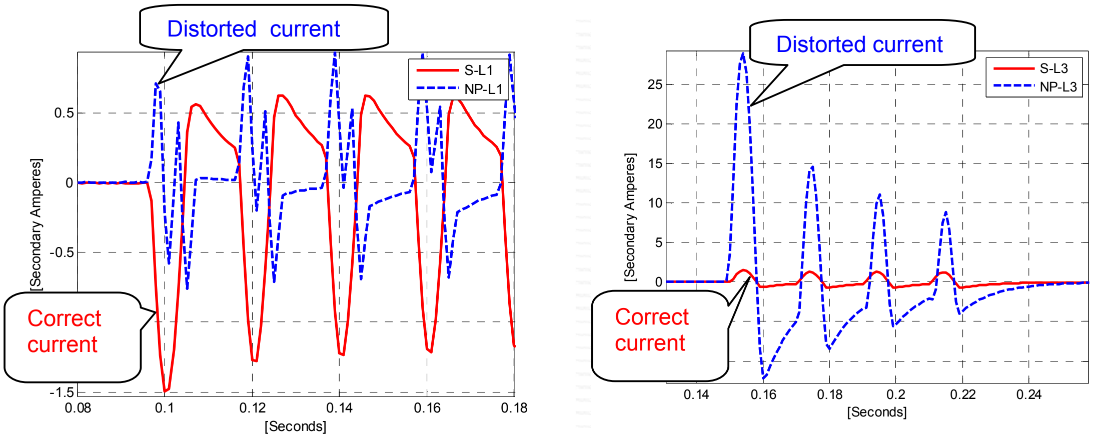
Figure 7 : Application information for the second field case.

The current waveforms in phase L1, captured by the built-in disturbance recorder within differential relay, during one PST inrush case, are shown in Figure 8a. Because the Load-side circuit breaker was open during PST energizing, the two recorded currents should have the same waveforms with opposite polarity (e.g. their sum shall be zero). However, it is clear that the neutral point current is distorted for a part of the power system cycle. Actually, its peak value is reversed. Later it was concluded that this waveform distortion was caused by stray flux coming from the PST excitation transformer.

Several unwanted operations of the differential relay were recorded. During an another inrush cases the distorted CT current reached more than 25A secondary in peak current value in phase L3, as shown in

Figure 8 8b. Such big current caused unwanted operation even of the unrestrained differential protection element.

Finite element magnetic field calculations were performed for this PST in order to check the stray magnetic field during inrush and during external fault. During external faults there is ampere-turn balance between excitation transformer primary and secondary windings and the stray flux is essentially contained in the main ducts between the two windings. During inrush the secondary winding is open circuited and the magnetic field caused by the inrush current spreads out in the entire transformer tank. From these calculations it can be concluded that much bigger stray flux is present at the CT location during inrush condition then during an external fault. Such theoretical calculations were confirmed by primary full scale testing. Different types of external faults were applied on the PST Load-side and stability of the differential protection was verified.



a) Phase L1 Source- and NP-side currents for the first inrush.

a) Phase L3 Source- and NP-side currents for the second inrush.

Figure 8 : Examples of captured recordings in second installations.

Third recording from the field

Within an auto-transformer with rating data 500MVA, 400/132kV, 50Hz [5] common neutral point CT (with ratio 2400/1A) is installed within the tank. Several unwanted operations of the low impedance restricted earth-fault (REF) relay were recorded. Figure 9 shows one of captured inrushes when low impedance REF relay operated. From the recording it is clear that auto-transformer neutral point current is distorted. Its peaks are much bigger then corresponding 3Io current at 400kV side. This neutral point current distortion is caused by the stray flux from the auto-transformer main magnetic core.

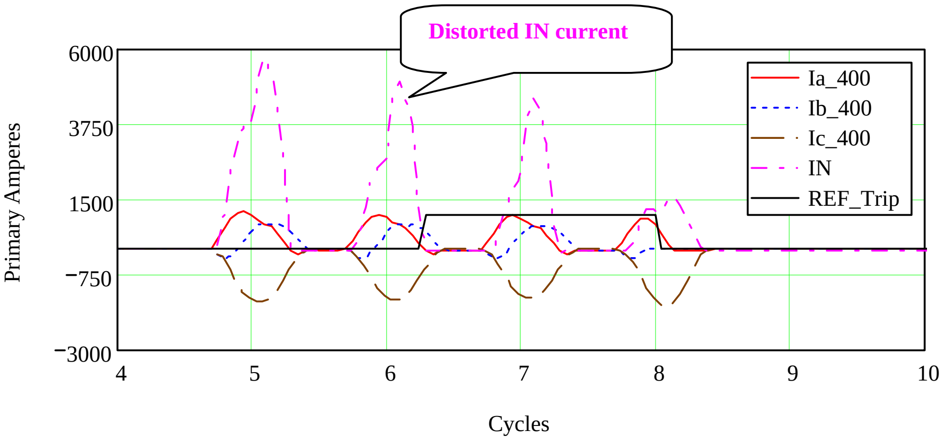


Figure 9 : Recorded currents during auto-transformer energizing from 400kV side.

Fourth recording from the field

Within a SVC transformer with rating data 100MVA, 220/19kV, YNd11, 50Hz [5]; LV side CTs (with ratio 6000/1A) are installed as bushing CTs. However due to space limitations they were physically installed just under the LV bushings within the transformer tank. Several unwanted operations of the high impedance bus differential protection relay for the 19kV SVC bus were recorded during SVC energizing (i.e. SVC transformer together with SVC filter branches on the LV side were energized) from the 220kV side. Figure 10 shows recorded transformer LV side currents while the Figure 11 shows recorded resultant differential currents seen by the numerical high impedance bus differential relay during one such incident. Note that the high impedance differential relay stabilizing resistor had value of 1500Ω and that the relay pickup was set at 130V.

Investigation has shown that these unwanted operations were caused by the stray flux from the power transformer core during inrush conditions.

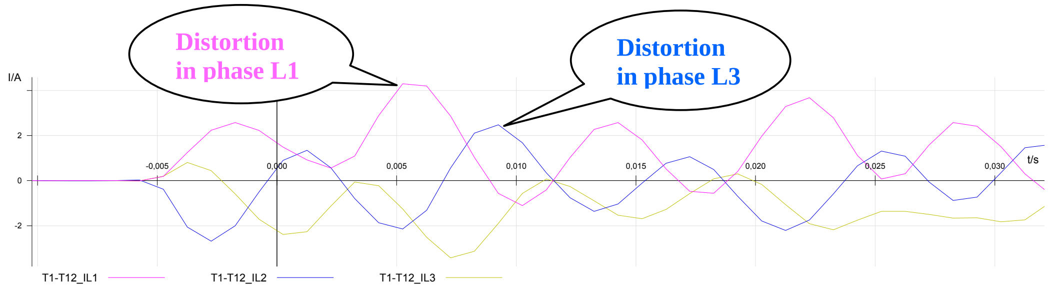


Figure 10 : Recorded secondary currents from the transformer LV CTs during SVC energizing

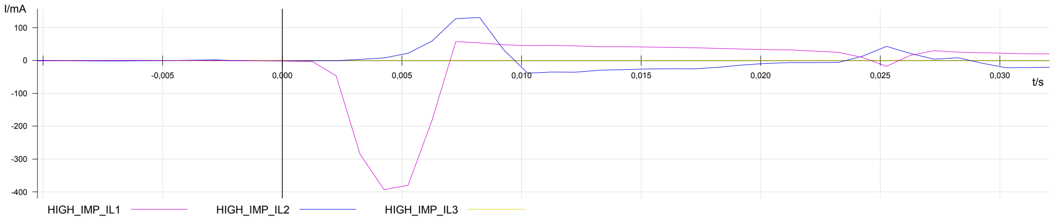


Figure 11 : Currents seen by the numerical high impedance differential relay during this incident

Stray flux influence on protection relays

As shown in the previous sections, consequences of the magnetic stray flux existence at the CT location are current pulses on the CT secondary side. Such pulses have varying magnitude and they are only present for a part of a power system cycle. These current pulses will be measured by the protection relay(s) connected to that CT. As already mentioned, their main influence will be possible unwanted operation of the protection relays. Typically, the differential relays are mostly affected. Such unwanted relay operations often cause confusion and require special investigations in order to understand and rectify the problem. Thus, the protective relaying community shall be aware of possible problems caused by stray flux, because unwanted operations of this nature can be quite costly and may require lengthy investigations.

Note that problems with stray flux can occur in applications where strong external magnetic fields are present at the CT location. Such installations are typically characterized by high phase current magnitudes and small distances between phases or sharp bends of the primary conductor close to the CT location. Installations where this problem may occur more frequently are:

- CTs within LV and MV metal-clad switchgear;
- CTs within HV GIS switchgear;
- CTs at the generator terminals;

- CTs in the generator bus ducts; and
- CTs buried within power transformer, phase shifting transformer or shunt reactor tanks.

When such problems are encountered in practice the following possible actions may be taken:

- increase relay pickup settings;
- add intentional time delay for relay operation;
- use second harmonic blocking for bus-like differential protection;
- use differential protection principle which do not require buried CTs [4];
- change the CT location (if possible); and
- replace the existing CT with a CT equipped with a flux equalizing winding.

Which action shall be taken in a particular installation depends heavily on the extent of the problem and cost involved. In applications where second harmonic blocking is utilized, in order to stabilize the bus-like differential relays, it is advisable to check whether that decreases the dependability of the differential relay for internal faults. Alternatively, a differential relay capable to bypass the second harmonic blocking criterion for internal faults [1] can be used.

CT with a flux equalizing winding

Current transformers can be protected from the stray flux by shielding. The first solution was to utilize separate solid copper shields as suggested in reference [2]. Later the use of a flux equalizing winding was suggested (see Discussions in reference [8]). The principles of operation of the flux equalizing winding are explained in references [7, 8, 9 & 10].

When the flux equalizing winding is not combined with the usual secondary CT winding it can be represented as a separate winding divided for example into four segments, equally distributed around the CT core circumference as shown in

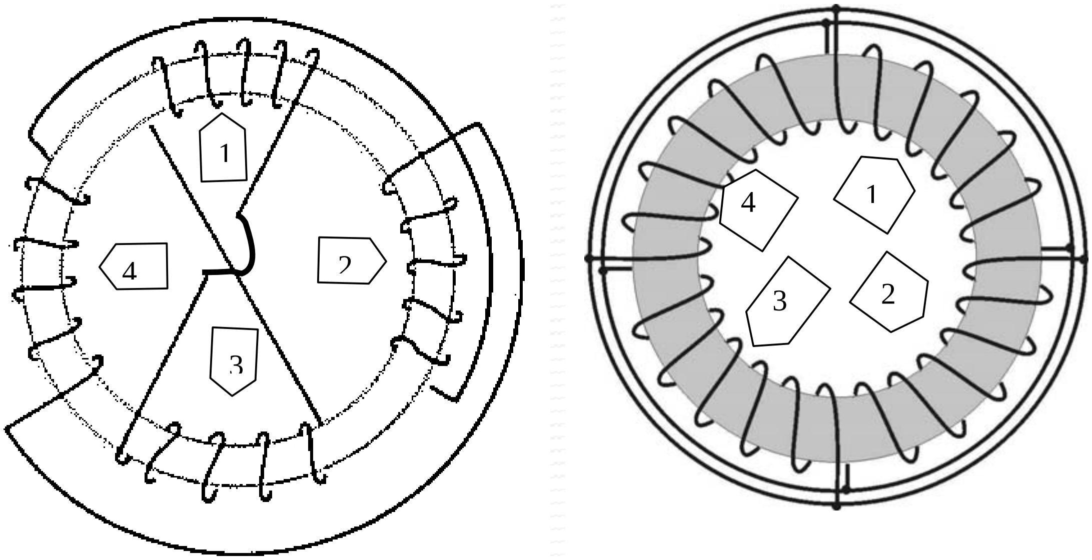
Figure 12. Note that each winding segment is marked with a number in this figure which corresponds to winding marking visible for CT #2 in Figure 2. Sometimes in practice this winding might have a higher, but most often even number of segments. All segments should have equal numbers of turns.

In the first solution, by cross-connecting the two segments located on diametrically opposite parts of the CT core (i.e. 1&3 and 2&4 in

Figure 12 12a), a path for flow of a circulating current between each pair of the flux equalizing winding segments, during stray flux condition, is achieved. These circulating currents will produce a magnetic field in the CT core with an opposite direction to the stray flux diminishing its influence on the CT. Note that these circulating currents will not exist during normal operation of the CT when the stray flux is not present.

In the second solution, shown in

Figure 12 12b, all flux equalizing winding segments are connected in parallel. This connection enables path for flow of circulating currents between all segments of the winding, during stray flux condition. These circulating currents will produce a magnetic field in the CT core with an opposite direction to the stray flux diminishing its influence on the CT. Note that these circulating currents will not exist during normal operation of the CT when the stray flux is not present.



a) Parallel connected winding segments on opposite sides

a) Parallel connection of all winding segments

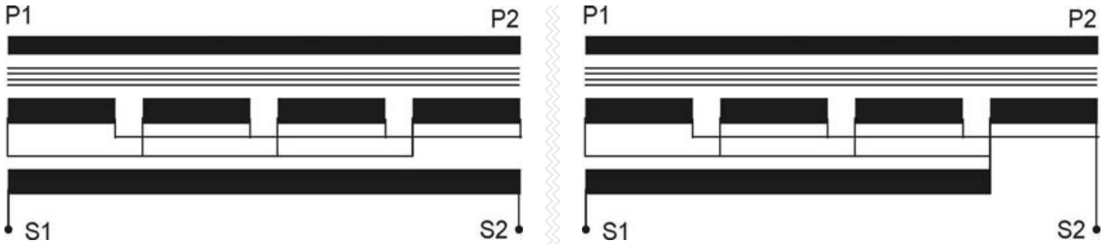
Figure 12 : Possible solutions to shield a CT from stray flux

Note that on both CT cores, shown in Figure 2, an additional secondary flux equalizing winding is already wound. This flux equalizing winding is divided in four equal sections, evenly distributed around the core circumference (see black markings on the two CTs in Figure 2). Note that its influence can be enabled or disabled by changing externally available connections of the four segments ends. Thus presented results from the laboratory testing were shown with disabled flux equalizing winding influence.

When the laboratory testing of CT #2 (see Figure 2) was repeated with the flux compensation winding enabled by connecting its four segments in accordance with the second solution shown in
Figure 12 12b, no secondary current spikes were observed when current was injected through the primary conductor adjacent to the CT core (see
Figure 4 4).

In practice, the flux equalizing winding can be either a standalone winding or combined with the main CT secondary winding as described in references [8, 9] and shown in

Figure 13 13.



a) Flux equalizing winding separate from the main CT secondary winding

b) Flux equalizing winding combined with the main CT secondary winding

Figure 13 : Possibility for practical realization of flux equalizing winding

In order to mitigate the problem of unwanted operation of protection relays for the new installations where there is a risk of the stray flux, it may be advisable to always order and use specially made CTs with flux equalizing winding.

Conclusion

The protective relaying community should be aware of possible influence of the stray flux on protection relays, which is described in this paper. The stray flux will cause current pulses on the CT secondary side which in turn can cause unwanted operation of the relays connected to that CT. Investigations of such problems are typically troublesome and time consuming. Thus, at least for new installations, it might be advisable to always specify and use the specially made CTs with a flux equalizing winding if there is any risk that stray flux might be present during equipment operation. This relatively small investment can be worthwhile!

References

[1] ABB Document 1MRK 504 086-UEN, "Technical reference manual, Transformer Protection IED RET 670", Product version: 1.1, ABB Power Technologies AB, Västerås, Sweden, (2007).

[2] A. H. M. Arnold. “Leakage Phenomena in Ring-Type Current Transformers”, Transactions IEE, 74, pp. 413-423, (1934).

[3] D. A. W. Baars. “Invloed van een uitwending magnetisch veld op een ringkernstroomtransformator”, ELEQ Report FR405R04a, (2005).

[4] Z. Gajić. “Differential Protection Solution for Arbitrary Phase Shifting Transformer”, International Conference on Relay Protection and Substation Automation of Modern EHV Power Systems, Moscow – Cheboksary, Russia, (2007).

[5] Power transformers – International Standard IEC 60076, Edition 2.1.

[6] International Standard IEC 62032/IEEE C57.135. “Guide for the application, specification, and testing of phase-shifting transformers”, First edition (2005).

[7] K. W. Jones. “Addressing Window Type Transformer Proximity Errors”, 59th Annual Conference for Protective Engineers, Texas A&M, College Station, USA (2006).

[8] R. A. Pfuntner. “The Accuracy of Current Transformers Adjacent to High-Current Busses”, AIEE. Transactions, 70, pp. 1656-1661, (1951).

[9] S. Seely. “Effect of Stray Flux on Current Transformers”, IEE Journal of Science & Technology, 37, pp. 115-120, (1970).

[10] H. Yu, J. Yuan, J. Zou. “Design of Novel Structure Current Transformer with Shielding Coils for Overcoming the Saturation of Core”, IEEE Transactions on Magnetics, volume 42, pp. 1431-1434, (2006).