Addressing Window Type Transformer Proximity Errors

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1. Abstract

This paper documents the problem of window type current transformer transformation errors in the presence of stray magnetic fields and presents a practical approach to addressing the problem. Specific situations that present a problem for window type current transformers are identified. A method for calculating local saturation will be outlined and validated by test on different field configurations. Alternative methods to address the issues are introduced that can be validated by the model.

2. Introduction

It is known that situations that result in stray magnetic fields can produce window type current transformer (CT) transformation error problems. This is particularly true when primary currents are very large, cores are relatively small. The primary conductor is not centered and the core is oddly shaped, however, the primary current carrying conductors change direction soon after exiting the CT window, or other phase conducts are in close proximity to the outside edge of the CT window. Further, it is worth noting that, not only are these situations possible, they are probable, and exist to some degree in almost every CT installation.

This paper reviews the problems associated with mechanical layout complications. Test data is presented to document the nature of the problem. Several situations are addressed. Test data is presented in a format that leads logically to the problem prediction method suggested in this paper. Next, a method is be defined and verified that allows for the prediction of transformation errors. The error prediction method is independent of the often very complicated magnetic configurations in which window type CTs are expected to operate. The technique in fact, predicts a problem that result from the sum of all of interacting field shaping mechanical layout conditions and the particular characteristics of the CT itself.

Finally, techniques for minimizing errors are presented. Aside from the obvious approach of changing primary conductor routing, which is an expensive or nearly impossible task, techniques are explained that can be performed adjacent to, or even within, the CT housing.

3. CT Saturation Issues

Window type current transformers are almost never installed in a uniform magnetic field. Fortunately, they are resilient passive devices. The end user rarely observes the effects of field non-uniformity. This is primarily because the CT core is not typically saturated. CTs normally operate at relatively low flux density. The stray magnetic fields that should not couple to the core of the CT pass through the CT core, exiting as they entered. The effect is that they do not impact the resulting secondary current signal.

Problems result when the magnetic flux density in the CT core exceeds what the normally very efficient material can support. In this situation, we say that the core is saturating. Universally accepted techniques are practiced which use manufacturer supplied excitation curves for overcurrent analysis. Industry standard methods of overcurrent specification also exist [1] [2]. But all of these only address performance expectations in uniform magnetic fields.

Significant problems can result when the sum of all current carrying conductors cause the magnetic flux density in the CT core to exceed the material capacity in localized regions. In this situation, we usually say that the core is saturating locally. There are no well-defined techniques to address this situation, even though the situation is very common. Some switchgear manufacturers test CTs in standard locations, and some specification engineers ask for cross current compensation, but often fail to specify a complete description of the installation environment that is required to thoroughly define the degree of required compensation.

Until localized core saturation occurs, the metering accuracy is only slightly affected by non-uniform core flux density. Due to the fact that most relay applications do not require high accuracy in overcurrent conditions, the effect of the locally reduced material permeability and the resulting higher magnetizing losses is usually negligible.

Localized core saturation does not necessarily have the catastrophic effects that entire core saturation has on signal loss. It will be later illustrated that local core saturation will cause the CT error to grow significantly, but it does not cause the almost complete loss of signal that results from saturating the entire core. It is not safe to make generalized assumptions about magnitude and wave shape distortion. A well-designed system will avoid this issue by preventing local saturation. This paper offers guidelines on how to design such a system.

4. Localized CT Saturation

Situations that result in localized CT core saturation can be divided into two categories: Lack of concentricity of fields that should couple to the CT core and the presence of fields that are in proximity to the CT that should not couple.

Concentricity problems result when the primary current carrying conductors are not centered in the CT window, or the CT window is irregular in shape. It is common to use bus conductors that are rectangular in shape, which inherently brings the edge of the bus closer to one side of the CT, but more serious problems result when, out of convenience, the CT is allowed to rest on the face or the edge of a bus bar. It is also common to use more than one cable to carry current, and installers are usually content to simply verify that all conductors pass successfully through the CT window. In situations where differential current is to be measured, as in the case of ground fault detection, users often fail to group conductors to cancel magnetic fields that should not couple to the CT core. Finally, and probably the most detrimental situation, is the practice of abruptly turning the primary conductor that passes through a window CT. For example, it is common practice to mount CTs on low voltage bus bars and slide them back against a 90° turn within power handling distribution equipment.

The second, and probably the more difficult issue to address, is the proximity of adjacent conductors. This usually involves the presence of two other phases in a three-phase system or the return conductor of the same phase. Further complicating this situation is that these conductors rarely extend in a straight line and may turn abruptly very near the CT. Interference from the same phase is prevalent in fused switch and circuit breaker applications where bus bars leave riser bus, pass through the circuit protection device and out the back of the gear.

The goal of a switchgear, generator, or control equipment manufacturer to shrink gear and reduce size and losses is a complicating factor for the use of window type CTs.

5. Saturation Phenomena Documentation

The following examples indicate how window current transformers can be saturated by poor concentricity and the presence of a nearby current carrying conductor.

A. Concentricity

A 1000:5, C50, CT was mounted as indicated in Figure 1. Primary current was passed through the window in a 46" x 46"

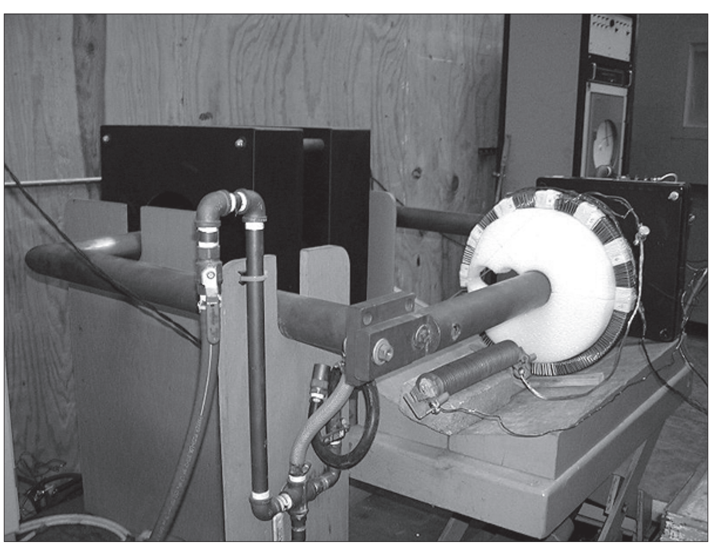

Fig 1.
Concentricity Test Configuration.

square path. This large path was used to ensure that the return conductor had very little influence on the unit under test. In order to measure the flux in the core, search windings were placed at 30° intervals around one hemisphere of the toroidal core.

Knowing the proportional relationship of flux density to induced voltage, it is possible to measure the local flux density in the core with the use of a search winding located over the core in the area of interest.

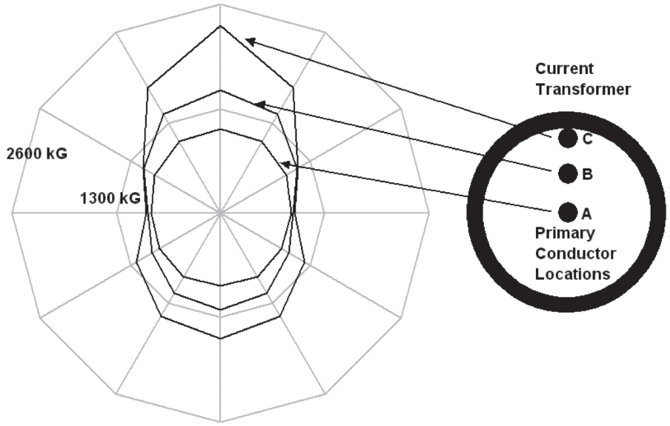

Fig 2.
Core Flux Density Characteristic due to Lack of Concentricity at 1kA.

The relationship of induced voltage to core flux @ 60 Hz:

$$E=1.72 * B * A * T * 10^{-5} \quad (1)$$

Where:

E= Voltage sensed by a search coil

B= Flux in the core (gauss)

A= Area (sq. in.)

T= Number of turns

(This formula will change slightly based on particular assumptions like core material stacking factors, etc.)

Provisions were made to move the primary conductor from the center position to a position midway between the center and the inside edge, and then against the inside edge. At 1000 A, the voltage was measured and plotted in a radar plot to indicate the magnitude of flux in the core around the circumference of the toroidal transformer. The distance from the center represents the magnitude of the flux density and the angular location represents the angular location on the CT core. This flux density is plotted in Figure 2. The inner circle represents the search coil voltage with the primary in the center of the CT window. The shape is round and exactly the magnitude predicted by equation #1 based on the CT core size, winding resistance and a connected 0.5 Ω burden. The highest magnitude of flux density resulted from positioning the primary conductor against the transformer inside wall. Near the bus bar, the flux density was over 2.5 times the calculated density. The curve in between the extremes represents a 50% displacement of the primary conductor.

Figure 3 indicates where problems start to arise. The primary current was raised from 1kA, to 5kA, then to 10kA. This plot has been re-scaled to indicate all three current levels. Additionally, a circle is drawn at 18k gauss - the point at which the core starts

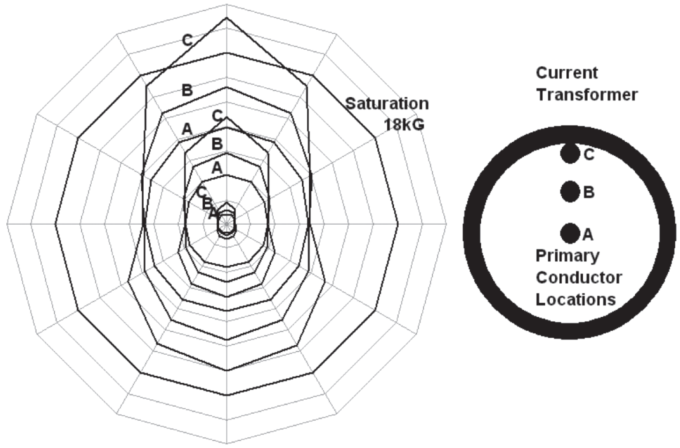

Fig 3.
Core Flux Density Characteristic due to Lack of Concentricity - At 1kA, 5kA, and 10kA.

to saturate and transformation begins to fail. At 10x nominal rating, or 10k amperes, this CT is saturating at maximum primary conductor offset. Notice that the shapes of the curves are identical at each current level and grow in magnitude proportional to the primary current. This fact will be critical in our predictive model to follow.

B. Proximity

The same 1000:5, C50, CT was tested with the primary current routed through the center of the window. This time the return conductor was intentionally passed in close proximity to the outside of the CT window. See Figure 4 for the set-up.

The diameter of the mean magnetic path was 13.75". The center of the return conductor was located first at 6.875", then at 3.375", then at 1.25" from the centerline of the CT wall. Figure 5 represents the voltage measured, which is exactly proportional to the flux density in the core measured at 30° intervals. At 8kA it can be seen that the core starts to saturate locally when the return conductor is closest to the CT wall. Again notice that, as in the cases of poor concentricity, the shapes of the curves are identical at each current level and grow in magnitude proportional to the primary current. Again, this fact will be critical in our predictive model to follow.

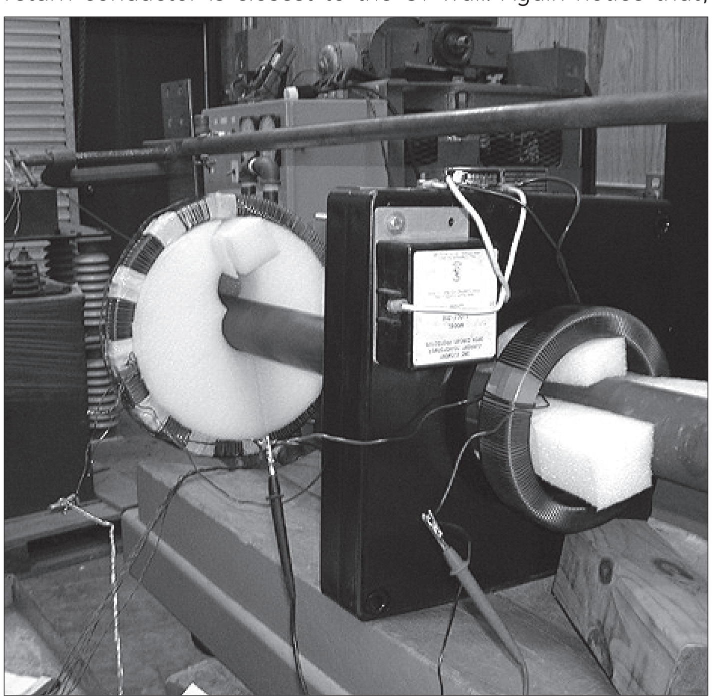

Fig 4.
Proximity Test Configuration.

Figure 6 is a plot of the flux intensity measured in a CT where the primary conductor is routed through the center of a 1000:5, C50 CT, but the bus turns 90° just 3.375" from the center of the current transformer. It can be observed that the shape of the flux plot is quite odd, indicating that the distortion can be either subtractive or additive depending on the actual bus layout. But as before, the shapes of the curves are identical at each current level, and grow in magnitude proportional to the primary current.

Data was taken at other CT ratios, bus configurations and CT shapes to explore the compounding effect of stray field problems. In all cases, the error was noted to track linearly, as in all the configurations illustrated herein.

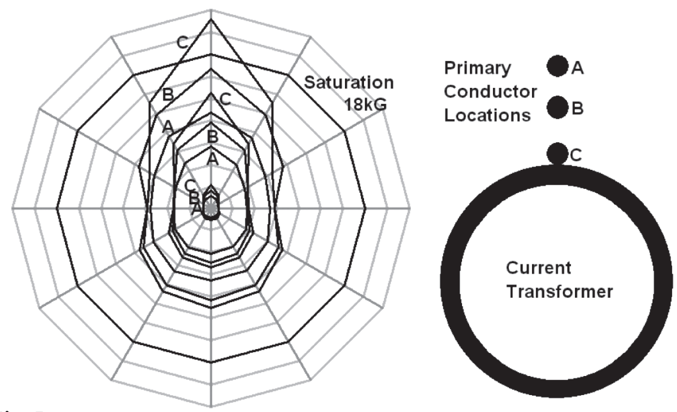

Fig 5.
Core Flux Density Characteristic due to Proximity of a return conductor - At 1kA, 5kA, and 8kA.

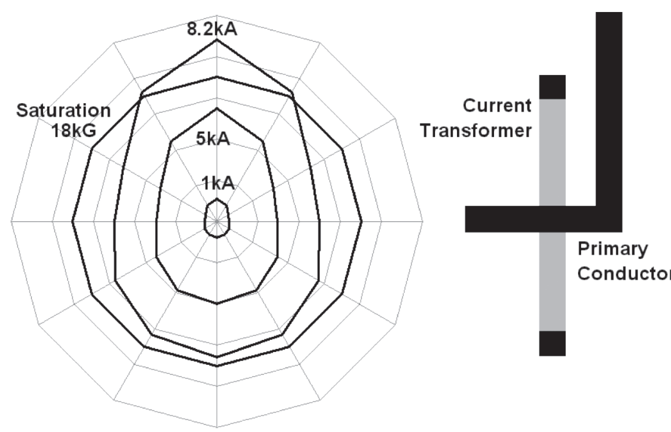

Fig 6.
Core Flux Density Characteristic due to a primary conductor turn of 90° - At 1kA, 5kA, and 8.2kA.

6. Problem Characterization

While attempts have been made to calculate the extent of local CT saturation, they have proven to be both cumbersome and complicated, so that they are virtually ineffective for the practitioner [3]. Further, they are inadequate because the problems that result in local saturation are almost always compounded by the combination of phase shifts and physical layout complexity.

The ultimate solution lies in the scalability of the flux density in the localized region of a core based on a fixed mechanical system by observing small signal phenomena. Then protection, and sometimes even metering, flux density levels can be calculated to see if the CT will experience saturation.

It is very easy to calculate the expected flux density in a CT core based on the internal resistance, the connected burden, the primary to secondary turns ratio, and the magnitude of primary current. CT designers do this routinely and with very high accuracy. If this expected flux density is subtracted from the stray flux density measured by search coils, then an error, or "nuisance" flux level can be determined for any region of a CT core. Further, based on the similarity of curve shapes, it is possible to extrapolate this error to any desired operating level to see if a problem exists in an application.

Returning to our examples, we will plot the following: Stray Voltage/Primary Current vs. Angular Location, where the absolute value of "Stray Voltage/Primary Current" represents the absolute value of a normalized error signal. Angular Location is the position on the core. Figure 7 is a plot of concentricity test data indicated in Figure 3. Figure 8 is a plot of proximity test data indicated in Figure 5, and, Figure 9 is a plot of proximity test data indicated in Figure 6. The magnitude and profile are very hard to predict, but fortunately, once known, the profiles are easily and accurately scalable.

The plots serve to verify that the relationship between stray voltage (i.e. stray flux density) and primary current is linear at any particular region of the core. The plots that overlap are actually at different primary currents. The shifts in the clusters of data reflect different bus bar arrangements.

To the casual observer, it is obvious that data need only be gathered from the regions where the flux density peaks because this is where the core will first saturate. Going forward it becomes clear that it is not necessary to plot the data in Figures 7, 8 and 9. The critical information can be gathered from one or two search coils located on the CT where the CT core will be most influenced by a current carrying conductor. Other tests were performed at only the test points of concern to verify that this linearity exists for all CTs.

To the practitioner, the ability to identify a problem can be reduced to a simple process:

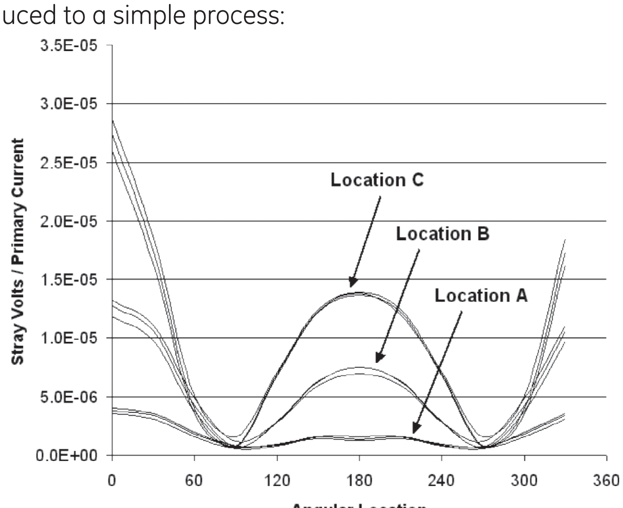

Fig 7.
Normalized error due to Lack of Concentricity - At 1kA, 5kA, & 10kA.

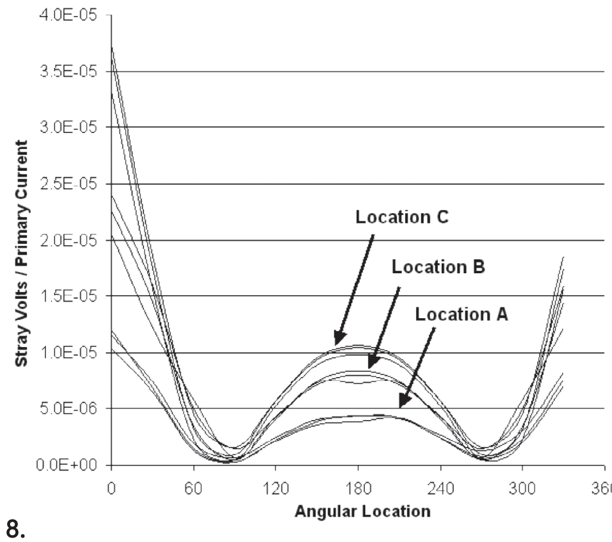

Fig 8.
Normalized error due to Proximity of a Return Conductor - At 1kA, 5kA, & 8kA.

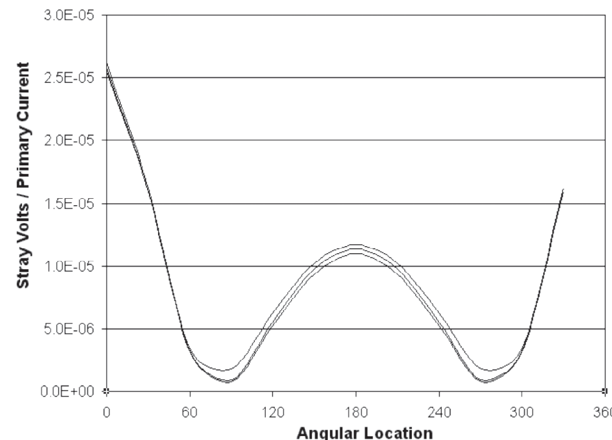

Fig 9.
Normalized error due to a primary conductor turn of 90° - At 1kA, 5kA, & 10kA.

1. Lay out a simple simulation test at a low current level.
2. Using one or more search coils, measure the total local Voltage (V_{TL}) in any area of concern (most probably where conductors are closest).
3. Calculate the voltage that corresponds to the "expected" low level flux in the test (V_L).
4. Subtract the calculated "expected" low level voltage (V_L) from the voltage measured by the search coil (V_{TL}), and multiply this difference by the ratio of the "expected" final primary current (I_H) divided by the primary test current level (I_L). This will yield the expected high current voltage due to stray flux (V_{EH}).
5. Finally add to this expected stray flux voltage (V_{EH}) the calculated "expected" core flux voltage (V_H) for the final high primary current.
6. Calculate the voltage that corresponds to saturation flux density for the CT construction in question (V_{SAT}).
7. If the extrapolated stray flux voltage (V_{EH}) plus the calculated expected final flux voltage (V_H) is greater than the saturation point voltage (V_{SAT}), then the CT will not perform accurately because this section will be in saturation.

The following must be true to ensure no local saturation:

$V_{SAT} \geq V_{EH} + V_H$ (2)

Where

V_{SAT} = Volts/Turn from a core at saturation

V_{EH} = Volts/Turn in a region of a core due to stray fields at maximum current

V_H = Volts/Turn requirement at the application high current level in an ideal magnetic field condition necessary to support the connected burden

V_{EH} is derived from linear extrapolation from a test set-up data as follows:

$V_{EH} = (V_{TL} - V_L) * (I_H / I_L)$ (3)

Where

V_{TL} = Volts/Turn measured at the test level

V_L = Volts/Turn requirement at the test level in an ideal magnetic field condition necessary to support the connected burden

I_H = Actual in-service maximum current

I_L = Test set-up current

It is recognized that interference can be difficult to model. Some sources will be out of phase and others will have a magnitude that is not proportional to the primary signal. Metering simulations will usually be balanced three phase currents, while circuit protection simulations will typically be unbalanced, based on various fault conditions. It is incumbent on the simulation designer to address these permutations by defining proper boundary conditions. As an aid to the designer it is worth observing that in-phase opposing flux will be more detrimental than phase shifted flux. Therefore, it may be possible to envelop three-phase problem situations with single-phase test configurations. Scaling of primary conductors, transformer cores, wire resistance and burdens is not recommended without further investigation. This model is intended only for the identification of local core saturation due to increases in current magnitude.

7. Model Verification

Use this technique to analyze two transformers.

Case Study #1

A toroidal 5000:5 CT of mean diameter 9.34" is mounted on a centered primary bus bar. A return conductor is routed 2.875" from the centerline of the mean diameter. Will this CT saturate at the nominal current of 5kA?

The unit was tested at 1250 amps to predict performance at 5000 amps.

Based on the transformer design and connected burden the following was calculated:

$V_{SAT} = 0.0463$ Volts/Turn

$V_L = 0.00265$ Volts/Turn

$V_H = 0.0106$ Volts/Turn

Using the equation:

$V_{EH} = (V_{TL} - V_L) * (I_H / I_L)$

Then

$V_{EH} = (0.0196 - 0.00265) * (5000 / 1250) = 0.0678$

Next we must satisfy this condition:

$V_{SAT} \geq V_{EH} + V_H$

Since $0.0463 \geq 0.0678 + 0.0106$ is not true, the CT will be in local saturation.

By calculation, the total search coil voltage should have been 0.0678 + 0.0106= 0.0784 volts. The voltage measured was 0.0686, indicating saturation. And indeed, the ratio error of the CT was measured at -4.8%.

Case Study #2

A rectangular 1000:5 CT with nominal core dimensions of 4.875" by 10.625" is mounted on a bus bar offset 2.44" from the short leg of the core. See Figure 10 for a picture of the set-up. A return conductor is routed 2.44" from the centerline of the long leg. This test represents an offset primary, nearby return conductor and a less than ideal core shape. Will this CT saturate at the nominal current of 1kA? Will this CT saturate at the nominal current of 3kA?

The unit was tested at 500 amps to predict performance at 1000 and 3000 amps. The local saturation voltage was measured at the point closest to the return conductor.

Based on the transformer design and connected burden the following was calculated:

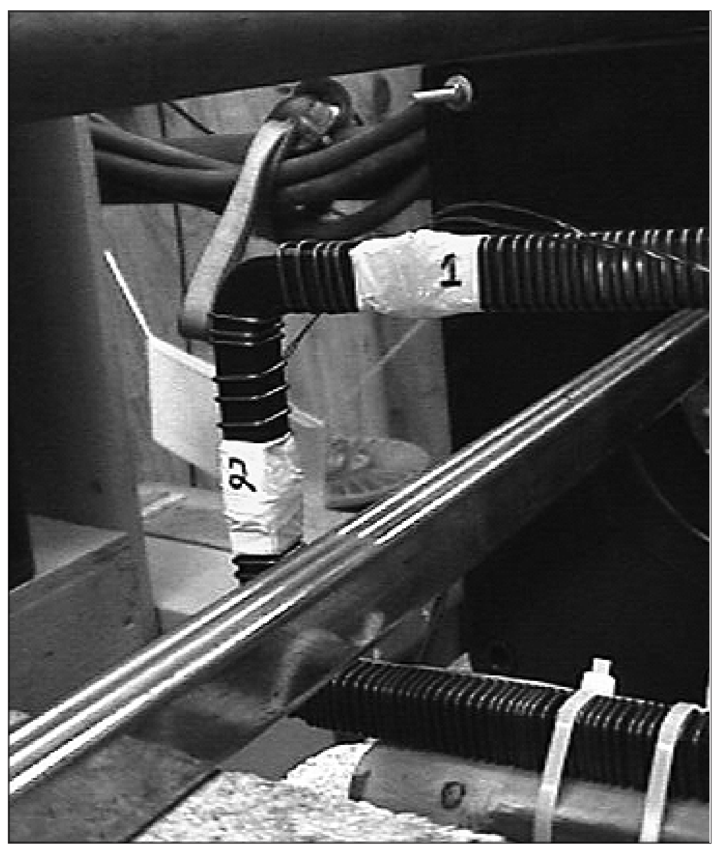

Fig 10.
Rectangular CT Proximity Test Configuration.

$V_{SAT} = 0.0735$ Volts/Turn

$V_L = 0.00273$ Volts/Turn

$V_H = 0.00545$ Volts/Turn

Using the equation:

$V_{EH} = (V_{TL} - V_L) * (I_H / I_L)$

Then

$V_{EH} = (0.0160 - 0.0.00273) * (1000 / 500) = 0.0265$

We must satisfy this condition:

$V_{SAT} \geq V_{EH} + V_H$

Since $0.0.0735 \geq 0.0265 + 0.00545$, the CT will not be in local saturation. The unit was found to be accurate at 1kA by test.

To verify the model, the predicted voltage of $0.0265 + 0.00545 = 0.031$ volts/turn was compared to the measured voltage of 0.032 volts/turn.

This calculation was repeated for a 3000 amp primary, using the same relationship of:

$V_{SAT} \geq V_{EH} + V_H$

Now, since $0.0735 \geq 0.0795 + 0.016$ is not true, then the CT should be in gross local saturation. The unit was tested and found to be 8.8% in error.

8. Addressing Local Saturation

At least four methods can be employed to address local saturation: Magnetic shielding, core size increase, transformer redesign with larger secondary wire, and cross current compensation.

Magnetic shielding is usually accomplished with a stack of laminations within the housing of a CT case or between the CT and the problem source of flux. The size of the shield may sometimes be a problem, and tests must be performed at maximum current levels to verify that the shield works as intended. Care must be taken to secure the shield to reduce noise and to make sure that it will remain in place due to magnetic forces. Do not use the modeling method of section 5 to scale the effectiveness of this technique.

A brute force method of solving the problem of localized core saturation is to increase the cross sectional area of the core. It is a straightforward exercise to return to section 6 of this paper and see that by increasing the capacity of the core to handle more voltage, saturation can be avoided.

Another simple method that can be employed, when the CT has many turns and is not in gross saturation is to increase the secondary magnet wire gage. Remember that the flux in the core is proportional to the required voltage to drive the secondary current. In many cases, the resistance of the wire in a high ratio CT may be greater than the connected "burden". Most CT designers are well aware of the fact that a larger magnet wire used for the secondary winding construction may reduce the voltage demand to a level where the CT will come out of saturation. It is often possible to reduce the sum of the stray and required flux in a local region of a core by reducing the required flux.

Cross current compensation, sometimes called "core balance compensation", has become the shielding method of choice by many who do not have the option to increase the core size or wire size due to weight, size, or cost constraints. The practice is usually to involve some portion of the secondary turns in parallel compensation, then to wind the balance of the secondary turns over the compensation windings in series with the compensation windings. These parallel windings are located in quadrants, or sections. If a major problem is being addressed, several layers of windings may be connected in parallel before the balance of the CT winding is series-connected. See Figure 11 for a typical winding configuration. The function of these parallel windings is to allow current to flow between them to counter the unbalanced flux in the core. Only the number of sections wound and the wire resistance in the sections limit the effectiveness of parallel winding. As the resistance in the paralleled wire sections approaches zero, then the voltage (and flux) in the core approaches a balance.

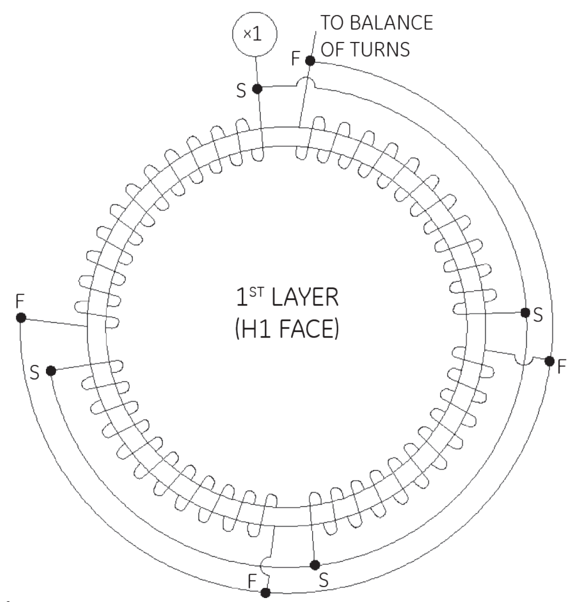

Fig 11.
Windings on a Cross Current Compensation Transformer.

Figure 12 indicates how the addition of cross current compensation vastly improves flux unbalance in the transformer used for the proximity error example in Figure 4. The small inner circle represents ideal balanced flux density. The outer circle represents saturation flux density. Note how much better that CT performs with the addition of 8 sections of core balance windings.

It is important to note that if cross current core balance compensation is used to eliminate a local core saturation problem, then the fix can be verified using the scaling technique of section 5.

9. Conclusions

The identification of probable CT saturation problems is simple in an ideal situation where concentricity with primary conductors is

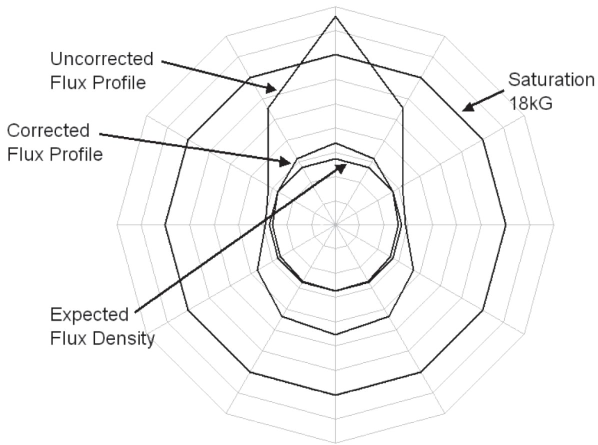

Fig 12.
Core flux density due to proximity of a return conductor before and after the addition of core balance windings at 8kA primary current.

ensured and the influence of other current carrying conductors is not an issue. This "ideal" situation is rarely the case, so caution should be observed under the following conditions, particularly when they are compounded: Primary conductors are not centered in a window, the core is not toroidal, the CT is expected to operate at very high current levels momentarily, other current carrying conductors are in very close proximity to a CT, a current carrying conductor turns abruptly very near the CT, the core cross section is small compared to the diameter of the CT.

11. References

Standards:

[1] IEEE Std. C57.13-1993, "IEEE Standard Requirements for Instrument Transformers"

[2] IEC60044-1: 1997, "Instrument Transformers- Part 1: Current Transformers")