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Inproving Current Transformers Transient Response and Saturation Effects Using Air-Gapped Core

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Abstracts: *The work investigates Current Transformers (CTs) transient response and saturation effects on Microprocessor-Based (MPB) relays. The aim is to improve CT transient response and prevent saturation as these leads to relay mal-operation. Magnetic hysteresis loop test setup of conventional CTs core construction using ISA T2000 model and CT Analyzer tests were performed. Design algorithm for proposed Air-gap core CT parameters were presented. Results shows that hysteresis loop of the magnetic circuit is affected by the presence of air gap. Air-gap in the magnetic circuit increase the reluctance of the core from 30315.43 to* $4.54729\ x10^5$ *[A/Wb] and lowered the inductance of the winding from 1.9 to 0.1357 Henry, consequently the secondary time constants is reduced. Remanent flux in the core reduces from 80% of saturation flux to 10% and increases the useful flux density as a result of its lower magnetizing impedance. Errors in current transformation are thereby significantly reduced when compared with conventional close core CTs. CTs operate linearly under transient response without saturation when a given maximum current flows in the winding. Thus air-gap core CT improved transient response and prevent saturation.*

Keywords: *Current transformer, air-gap, magnetic core, hysteresis loop, saturation, transient response, distortion, protective relays.*

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I. INTRODUCTION

The purpose of current transformers is to deliver accurate current reproduction, irrespective of transformer design and characteristics [1].The toroid steel core CTs are widely used throughout the electric power industry for protection schemes; the CT is always expected to deliver accurate secondary current values for protection relays. However, this is not always achieved with conventional current transformers. Under abnormal conditions the CT may deliver incorrect values due to the distortion in CT secondary current waveforms. These incorrect values may cause malfunction of protection relays decreasing its reliability which decrease the system stability [2]. It has been reported that relays act differently during CT saturations and their time-current characteristics do not meet the published characteristics These problems causes severe loss of production to various plants or damages to very critical electrical equipment. [2] [3] [4]. CTs function is to transform power system currents to lower magnitudes, and to provide galvanic isolation between the power network and the relays and other instruments connected to the CT secondary winding [5]. The fault current has a steady state and a transient component. The DC transient part has a major role in the current transformer errors. The error of a conventional current transformer is dependent on, whether the core is saturated or not. When the core is saturated the magnetizing current is large compared to the secondary current and the error is high. This may cause severe distortions in the secondary current supplied to protective relays [6]. Saturation of electromagnetic core significantly influence current transformers transient's response [7], [8]. It is caused by non-linear nature of the electromagnetic core of the current transformer. Saturation can lead to severe signal distortions in the current transformer output. Current transformer saturation can cause both failure to operate and unwanted operation of the protection depending on the measuring principle [9]. Consequently, this may lead to malfunction of microprocessor-based relays (MPBRs). (e.g., under-reach of over-current relays [10], overestimation of fault loop impedance of distancerelays [11] and instability of differential relays [12], and Relays can operate inadequately or delayed; Relays may not be sensitive to the distortions that reduce the root-mean-square value of the secondary current [13].

II. DESCRIPTION

The Conventional Grain Oriented (CGO) closed-steel core current transformers (CTs) are widely used in the Nigerian electric power 330 kV and 132kV Transmission Company's protection schemes for the protections of transmission lines, power transformers and metering purposes. Current transformers must be able to correctly reproduce the current for a minimum time before the CT will begin to saturate in order to guarantee correct operation. There are different types and shapes of magnetic core CTs. These types are related to the design of different materials of CT core. The conventional closed grain oriented CTs are made with high remanence magnetic core and the remanent flux remain for almost infinite time. The conventional core CT retained as high as 80 - 90% of remanent flux in the core on interruption of faults. The primary winding of the CT is connected in series with the network and carries the normal and fault currents while the secondary is connected to the measuring circuits and relays. The primary windings is usually single turn winding and many number of turns on the secondary winding as shows in Figure 1(a), and depend upon the current to be carried by the power circuit while Figure 1 (b) depicts the equivalent circuit of a CT, referred to the transformer secondary side.

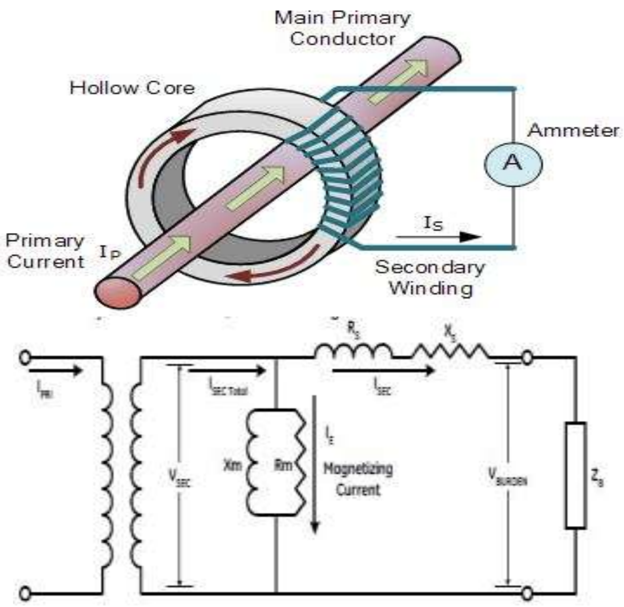
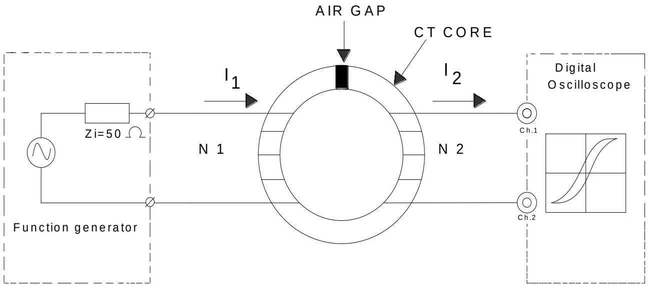


Figure 1(a) Current Transformer Circuit(b) Equivalent circuit of a Current Transformer

The primary winding of a CT is in series with the line and, therefore, carries the current that flows in the line. Ideally, the secondary current is proportional to the primary current. The CT will develop sufficient voltage (Es) to make this current to flow in the secondary circuit. The nonlinear excitation reactance Xm, and resistance Rm, represents the CT magnetization. The magnetizing current I_E flowing through the excitation impedance has two components. The magnetizing current flowing through the inductive component of Z_E, is needed to generate the flux in the CT core.I_E, represent the magnetizing current, which mainly results from the core hysteresis and eddy losses. The diagram shows that not all the primary current passes through the secondary circuit. Part of it is consumed by the core, which means that the primary current is not reproduced exactly. The secondary excitation voltage E_S is the voltage induced in the secondary winding. Impedance Z_B represents the total load connected to the CT secondary winding. This impedance is referred to as the CT burden. The CT secondary terminal voltage V_S appears across the CT burden [14].

III. MATERIAL AND PROPOSED METHOD

The use of Air-gap core current transformers is proposed. A set of devices and software tools using primary injection test equipment (CT Analyzer) with oscilloscope feature and a measured frequency of 100 Hz were used to carry out measurement of the CTs core materials and to examine the transient behavior. In the measurement setup, the oscilloscope feature is utilized to trace and capture the magnetic hysteresis loop of the CT core.Figure 1 shows the schematic diagram of the test set-up of "cutting" (slotted) small air gap on the closed silicon iron core CTs. A single air-gap was slotted in the design of the magnetic component, using leather-rod as the gapping material. Air-gap is a non-magnetic part of a magnetic circuit inserted in series with the magnetic part, so that substantial part of the magnetic flux flows through the gap. Placement of the gapping material is critical in keeping the core structurally balanced. This technique virtually eliminate errors due to leakage inductance. Figures 2 (a) shows a toroid air-gap iron core and (b) its equivalent magnetic circuit.



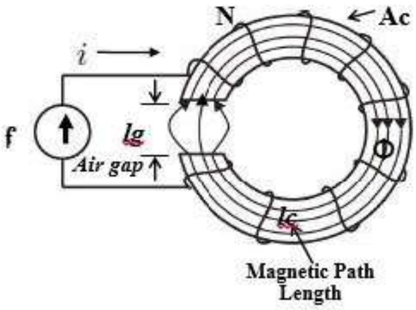


Figure 1: Hysteresis loop circuit set-up with Air-gap core CT Figure 2: (a) Coil on a Toroid Air-gap iron core and digital oscilloscope

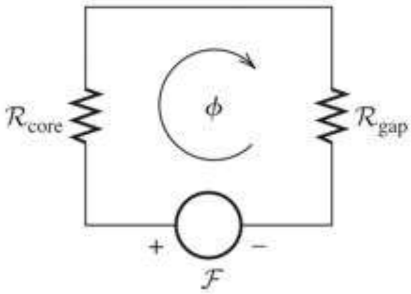


Figure 2 (b) Equivalent magnetic circuitFigure 3: Photograph of "cut" CT core with distributed winding around the core

The distributed secondary winding form a toroid which occupy the whole perimeter of the core.Figure 3 shows photograph of the physically "cut" air-gap core CT wound on toroid core with winding uniformly distributed around the magnetic core The effects of saturation and transient's response on relays is prevented by slotting small air gap into the magnetic core while retaining the properties of the materials. The air gap has the effect of shearing over (slanting) the B-H loop of the material such that the residual flux is reduced and the margin between operating flux density and saturation flux density become high. This increases the reluctance of the magnetic circuit, and enables it to store more energy before core saturation. WithAir gap slotted in a magnetic circuit, almost all of the reluctance in the circuit will be at the gap, because the reluctivity of air is much greater than that of a magnetic material. For all practical purposes, controlling the size of the air gap controls the reluctance.

From the magnetic circuit, the magneto motive force$F = NI = \Phi(R_c + R_g)$A-t(1).

With air-gap placed in the core, the flux flow through the core and across the gap to the other end to complete the cycle. The magnetic circuit consists of two reluctances; the series reluctance of the core R_C, and that of the gap Rg. Thus the total reluctance of the core is the sum of the core reluctance and the air gap reluctance is given in equation (2) as

Thus total reluctance$R_m = R_c + R_g = \frac{l}{\mu Ac} + \frac{lg}{\mu o Ag}$ (2)

Where$R_c = \frac{l}{\mu Ac}$for the ferromagnetic core material; (3a)

and$Rg = \frac{lg}{\mu o Ag}$ for air gap portion, (3b)

The magnetic reluctance of the core with a large relative permeability μ_r is so much smaller than that of the air, that all of the magnetic flux tends to stay within the core; hence the air-gap reluctance dominates. The reluctance of the gap is higher than that of the iron even when the gap is small. The reason is because the magnetic material has a relatively high permeability ranging from 4000 to 7000 as against the permeability of air that is 1.0 [15].

Therefore, inductance L is calculated from equation (4) as

$$L = \frac{\mu_o N^2 A_c}{l_g} \text{Henrys} \quad (4)$$

Where l_g = the gap length,

Ac = cross sectional area of the core,

μ_o = permeability of free space,
N = Number of turns.
The permeability of free space μ_o of the magnetic core is $4\pi * 10^{-7}$.

(a) **Required Gap Length**
Due to the remanent flux, the CT can saturate before operation of high-speed protective relays. Air-gap length is calculated as given in equation (5) [16],

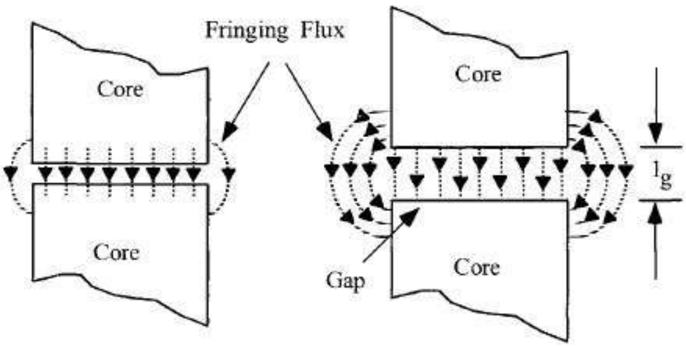
$$l_g = \frac{0.4\,\pi N I x\, 10^{-4}}{B} \text{ cm} \quad (5)$$

Where N = Number of secondary turns,
I = Secondary current flowing through the coil,
B = Magnetic flux density.

3.1 Fringing Flux in Magnetic Circuit with Air-gap

The presence of air-gap causes fringing flux phenomenon. When magnetic lines of force across air gap in the magnetic circuit, they try to bulge out in the air gap. As a result the flux density inside the air gap is more than that inside the magnetic core. This tendency of reducing flux density inside the air gap in a magnetic circuit is known as magnetic fringing. This magnetic fringing phenomenon increases with increase in the mean length of the air gap.The effects of fringing flux is demonstrated in Figure 4(a) and (b) in which magnetic flux flowing in a magnetic core spreads out into the surrounding medium, for example in the vicinity of an air gap. The larger the air gap, the more is the flux fringing and vice versa [14].It is a function of gap dimension, the shape of the pole faces, and the size and location of the winding. With air gap inserted into the magnetic path, there is an induced fringing flux at the gap which reduce the efficiency of the CT core by generating eddy currents that cause localized heating in the windings.

The effective flux 'area' is increased at the gap, lowering flux density in the air gap and increased the magnetic reluctance of the gap which changes the B-H hysteresis curve, decreasing inductance and increase magnetizing current of magnetic core. The 'effective' air gap length is thus less than the physical gap length. Thus the phenomenon of magnetic saturation must be taken into account during design process because saturation of magnetic core causes loss of inductance, increase of magnetizing current in the circuit and increase of power losses [15][16].



(a) Small Gap (b) Large Gap
Figure 4. Fringing Flux at the Gap.

IV. ANALYSIS AND RESULTS

CASE STUDY:

The proposed CT rated power of 25VA, C400, 1200:5 rating under consideration is made of silicon iron core material with a cross sectional area of 18.75 cm^2, mean length path of 50cm and relative permeability μ_r of silicon iron core material is 7000. The coil is wound with 240 turns and secondary burden of 0.6Ω. The magnetic equivalent circuit core, with air gap reluctances and a source representing the winding MMF shown in figure 2 can be analyzed using magnetic circuit analysisas follow,Calculating the required gap length, substitute values of secondary turn ratio of 1200:5 = 240, and measured maximum flux density of 1.5 (T).
The gap length is determine by substituting values into equation (5),

Air-gap length $l_g = \frac{0.4\,\pi * 240 * 5 * 10^{-4}}{1.5}$ = 0.1005 cm or 1.0 mm.
The core permeability is $\mu_{core} = \mu_r \mu_o$ = 7000 x $4\pi\, x 10^{-7}$ = 8.7964 x 10^{-3} [Wb/Am]
Mean length of the magnetic path in the core is 50 cm = 50cm x $\left[\frac{1_m}{100_{cm}}\right]$ = 0.5m.

Subtracting the gap length of 1mm from the mean length = 500 – 1.0 = 499mm = 0.499m,

Core cross sectional area = 18.75cm^2 = 18.75cm x$\left[\frac{1m^2}{10000\,cm}\right]$ = 1.875 $10^{-3}m^2$

Substituting values in to equations (3a) for close core (without gap) gives

Core reluctance $R_c = \frac{0.5}{8.7964\ x\ 10^{-3}\ x\ 1.875\ x 10^{-3}}$ = 30315.43 [Am/Wb].

From figure 3, the measured remanent flux density Br, of a close core material is 1.2Wb.

The magnetic flux $\emptyset = B_r A_c$ = 1.2 x 1.875 x 10^{-3}
= 2.25 x 10^{-3} Wb.

From equation (1) Magneto motive force

F = $\emptyset R_c$ = 2.25 X 10^{-3} x 30315.43
= 68.21 Amps.

Magnetizing current I = $\frac{\emptyset R_c}{N} = \frac{68.21}{240}$ = 0.2842 Amps

And the core inductance L is calculated from equation (4) as

$$L = \frac{\mu N^2 A_c}{l} = \frac{8.7964\ x\ 10^{-3}\ x\ 240^2\ x\ 1.875\ x\ 10^{-3}}{0.5}$$
= 1.9 Henry

Similarly for Air-gap core, substituting values in to equations (3b) gives

Air gap reluctance$R_g = \frac{1.0\ x\ 10^{-3}}{4\pi\ x\ 10^{-7}\ x\ 1.875\ x\ 10^{-3}}$= 424413.18 [Am/Wb].

Results of equations (3a and 3b) are combine in series in equation (2) to give the total reluctance of the core as

Total reluctance $R_{tot} = R_c + R_g$ = 30315.43 + 424413.18 = 454728.61,
= 4.54729 $x10^5$ [Am/Wb].

Increasing the gap length, increases the reluctance. For a given magneto motive force, the flux density is controlled by the gap.

Because air has very low permeability than ferromagnetic material, the gap often accounts for almost all the reluctance seen by the magnetic field. Evaluation shows that the reluctance R of a magnetic path depends on the mean length l, the cross sectional area A, and the permeability μ of the core material.

From figure 4, the measured remanent flux density Br, with air-gap core is 0.15Wb.

The magnetic flux $\emptyset = B_g A_c$ = 0.15 x 1.875 x 10^{-3}
= 2.8125 x 10^{-4} Wb.

Magneto motive force F = $\emptyset R_g$ = 2.8125 X 10^{-4} x 424413.18
= 119.366 Amps.

Magnetizing current I =$\frac{\emptyset R_g}{N} = \frac{119.366}{240}$ = 0.4973 Amps

And the core inductance L is calculated from equation (4) substituting core length l_c with gap l_g,

Hence $$L = \frac{\mu_o N^2 A_c}{l_g} = \frac{4\pi\ x\ 10^{-7}\ x\ 240^2\ x\ 1.875\ x\ 10^{-3}}{1\ x\ 10^{-3}}$$
= 0.1357 H.

Also from figure 4, the measured flux density at saturation pointB_{sat} and remanence flux Br, with air-gap length of 1.0 mm were 1.5Wb and 0.15Wb respectively. Thus percentage remanence flux is given as

Air-gap core, % Krem = $\frac{B_r}{B_{sat}} = \frac{0.15}{1.5}$ x 100 = 10%.

Comparison of calculated close core and Proposed Air-gapped core CTs results are tabulated in Table 1.

Table1: Comparison of calculated close and Air-gapped cores CT Parameters

Materials (Sheet steel)	Flux (mWb)	Flux Density (T)	M.M.F (A)	Reluct-ance (A/Wb)	Magnetizing current (Amps)	Inductance (H)	Remanence %
Close core	2.25	1.2	68.21	30315	0.2842	1.9	80
Air-gapped	0.28125	0.15	119.366	424413	0.4973	0.1357	10

Figures 4(a and b) depicts simulation plots showing comparison of B-H hysteresiscurves for a magnetic core of a conventional 1200:5 CTs cores without and with air-gap.

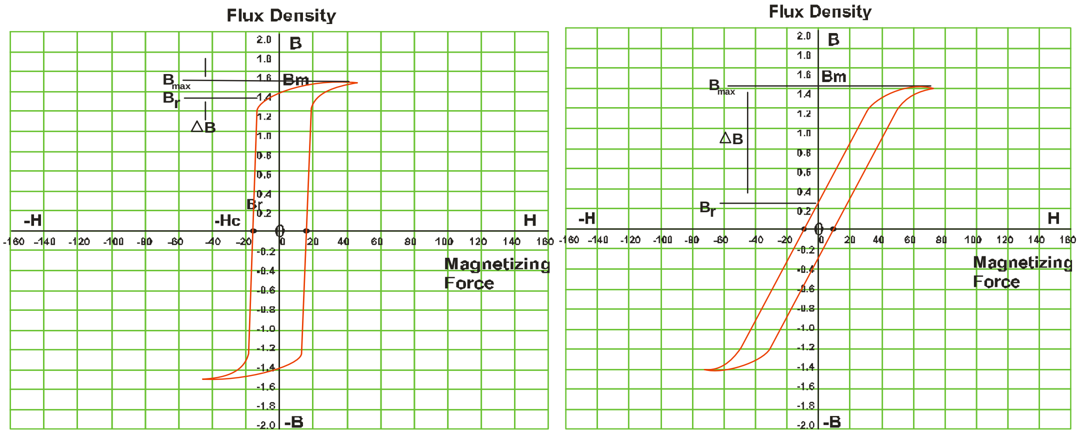


Figure 4(a): Convectional close steel core CT with 80%(b): Proposed Air-Gap CT with Remanence flux at 10%.

(A) RESULTS:

The results shows that hysteresis loop of the magnetic circuit is affected by the presence of air gap.Air-gap in the magnetic circuit increase the reluctance of the core,reduces the secondary time constant and lowered the inductance of the winding. The air-gap in CT core drastically reduces the remanent flux presence in the core from approximately 80% of saturation flux to 10%, and increases the useful flux density as a result of its lower magnetizing impedance.This eliminate the ability of the core to remain saturated after interruption of faults. CTs operate linearly to reduce the time constant and remanence in iron core. This types of current transformers will be used to protect objects of major importance that require a short tripping time. Errors in current transformation are thereby significantly reduced when compared with those with the close core type. It alsohas a powerful demagnetizing effect resulting in slanting “shearing over” of the hysteresis loop, i.e. the value of its slope proportional to the effective permeability is reduced.The amount of “shearing” is proportional to the length of the air gap, the larger the air gap the lower the slope. The magnitude of the air gap effect also depends on the length of the mean magnetic path and on the characteristics of the close CT core materials. Consequently, CTs transient response improves and prevent saturation when a given maximum current flows in the CT winding.

(B) **Advantages of air gaps in current transformers cores includes:**

1) Reduction of the CT secondary time constant, implies a reduction of the core cross section area to the same operating conditions compared to the time constants with closed core;
2) Air-gap CTs operate linearly due to reduced time constant and remanence in iron core.
3) Air-gap core CTs will operate under transient response without saturation when a given maximum current flows in the winding. These types of CTs will be used to protect equipment that require a short tripping time.
4) Air-gap decreases the remanent magnetism by shearing over the hysteresis loop.

V. CONCLUSIONS

The use of Air-gapped core CTs to improve transient performance, reducesinfluence of DC-offset component and the remanent flux of the CT core is presented. The transient response of the air-gapped CTs used in power grid protection is analyzed. It is also presented a method of correcting the distortion of the current transformer secondary current which has a negligible value of remanent flux. This method eliminate the ability of the core to remain saturated after interruption of faults, thus improved CT transient’s response and prevent saturation of protection schemes.

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