

High frequency modeling of protection / measurement current transformers for partial discharge detection

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Abstract—This paper investigates the choice of using preinstalled protection and measurement current transformers (CTs) for the detection of high frequency partial discharge (PD) signals in medium voltage cables by conducting frequency response analysis (FRA) of these CTs and by frequency response modeling. Researchers have developed many high frequency models, mainly for the transient behavior of CTs. While the energy of the high frequency signals in these models is very high, the energy content associated with PDs is very low. The transformer core behavior will be different in both cases and, as far as the authors could ascertain, there is little information on the FRA of such CTs for low energy high frequency input. A high frequency model of the current transformer is presented. The Jiles –Atherton model is used to analyse the behavior of the CT core in a high frequency partial discharge environment. A method for obtaining model parameters such as parasitic capacitances, leakage inductance, winding resistance, and iron loss component is proposed.

Index Terms—Partial Discharges, High Voltage Cables, Current Transformers, Jiles –Atherton model

Introduction

Most of the high voltage system comprising electricity generation, transmission and distribution infrastructure in the UK are approaching the end of its predicted life [1]. Immediate and wholesale replacement of these assets is difficult. In these circumstances informed maintenance planning through on-line condition monitoring can mitigate unplanned outages. High voltage insulation is an important component of power plant that degrades by aging due to mechanical, electrical and thermal stresses. Insulation failure can lead to catastrophic failure of equipment, introducing serious hazards involving health and safety, environmental and economic consequences. It is necessary to continually monitor such systems and detect degradation at an early stage, so that appropriate replacement and repair can be arranged at the appropriate time. Partial discharge (PD) detection is an effective diagnostic tool for insulation degradation in high voltage equipment. Traditionally, cable diagnostics were carried out using offline methods, where the cables are removed from service and tested for PDs.

Alternatively, online PD diagnostics are preferable since no outages are required. This paper focuses on the on-line PD detection in medium voltage cables. PD signals in these

agate via two possible channels namely shield to phase and phase to phase. Traditionally, high frequency current transformers (HFCT), installed in the earth strap of cables, are used to detect these high frequency PD signals. Often earth strap accessibility is limited due to the switch gear and substation design. Moreover PD signals obtained from earth straps are not ideal for signal processing. In this case phase to phase measurement is the other alternative. On-line installation of these sensors is difficult since sensor installation in live phase conductors is not always feasible. In order to overcome this difficulty, it is logical that one should consider using the preinstalled protection and measurement CTs for detecting PD signals. However, the frequency response of such CTs is not quantified by any manufacturer and subsequently not readily available.

II. MOTIVATION

As utilities attempt to comply with regulatory demands while maintaining high standards of service within a competitive market environment, optimizing asset management strategies and maintenance processes have become widely perceived as key business objectives. Effective asset management and maintenance strategies are therefore considered vital aspects in enabling utilities to achieve the best possible return on their ageing asset base. Underpinning these strategies are condition monitoring technologies, used to capture the plant data required to detect, diagnose and locate incipient failures, defects or problems and subsequently inform key asset management and maintenance decisions.

PD detection and location is a valuable tool for the insulation assessment of high voltage equipment. On-line monitoring of PD activity has already been applied to other types of medium voltage and high voltage equipment like transformers, generators etc. where sensors can be placed close to the PD source. On-line PD diagnosis in cables is more complex and hence presents more challenges. One such challenge is deciding the most suitable location for the PD sensors. Shim et al [2] analyzed PD signals that were successfully acquired from High Frequency Current Transformer (HFCTs) installed on the earth straps of 11 KV cables. However, this method proved unsuccessful in 33 KV cables due to the method of cable termination and substation geometry. The only solution to this problem is to make the PD measurement from the phase conductors instead of from the shield conductor. This requires the PD sensors to be clamped around the energized phase conductors, which is

clearly unsafe. Another possibility is to make use of the existing current transformers installed for protection/instrumentation purposes. These transformers are designed for 50 Hz measurements and the frequency response of such devices is unknown, with PD signals often in the tens of Mega-Hertz range.

III. HIGH FREQUENCY MODEL OF CT

Frequency response modelling of CTs is not a new area with many high frequency models readily available. Most of the models are developed for the behaviours of CTs during substation switching which involves high energy signals, however the energy content associated with PD activity is very low.

Protection CTs are normally air gapped to prevent the magnetic core becoming saturated by a dc component in the primary current. Furthermore, it increases the linearity of the magnetic curve [3]. A high frequency model of the protection CT differs from the measurement CT in terms of the inductance of air gap. Measurement CTs are designed in the linear portion of the magnetization curve for metering accuracy while protection CTs are designed in the lower portion of the magnetization curve so that higher fault current does not push those CTs into saturation. Factors which influence the high frequency limitations of the CT are inter winding capacitance, capacitance between primary winding and core, secondary winding turn to turn, secondary winding turn-core, core material permeability and winding resistance variation due to skin effect [3]. A high frequency model of the CT (Protection/measurement) is shown in Figure 1 and Figure 2.

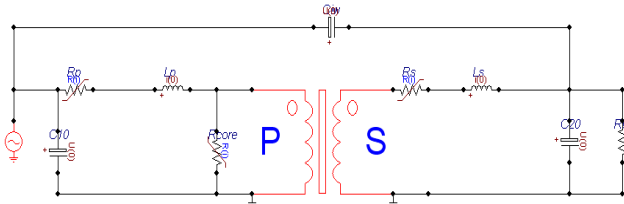


Fig. 1. High frequency model of measurement CT

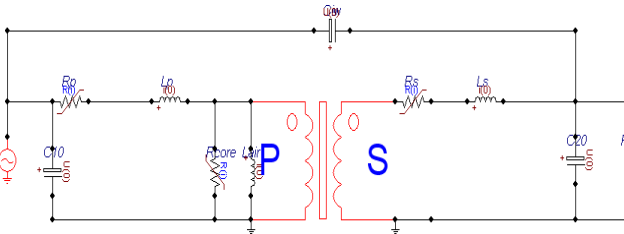


Fig. 2. High frequency model of measurement CT

Where

C_{10}	: Primary winding to core capacitance.
C_{20}	: Secondary winding to core capacitance.
C_{iw}	: Intertwinding capacitance.
R_p	: Primary winding resistance.
R_s	: Secondary winding resistance.
R_w	: Core loss component.
R_b	: Resistive burden.
L_p	: Primary winding Leakage inductance.
L_s	: Secondary winding Leakage inductance.
L_{air}	: Inductance of air gap.

IV. EFFECT OF CORE MATERIAL

The need for magnetic material in a transformer is to provide a flux path in order to facilitate the flux linkage. Metallic and Metallic Oxide or ceramic are the commonly used materials employed in the manufacturing of transformer cores. The most common metallic material is the familiar laminated steel used in power transformers. This material works well at power frequencies, but becomes ineffective at high frequencies [4]. Metallic Oxide materials are called ferrites, which are essentially ceramics, and like all ceramics considered very stable, and exhibit the excellent characteristic of fairly high resistivity. The most common ferrite contains approximately 50% iron oxide. From there, the balance of the remainder of the material classifies the type of grade of ferrite. The most common type is made up of oxides of manganese (Mn) and zinc (Zn). Mn-Zn ferrites are used for lower frequency work. They have high permeability, but their bulk resistivity is relatively low which increases the eddy current loss. The other type of ferrite has nickel and zinc oxide (Ni ZnO) composition. This ferrite has a lower permeability, on average, but will work well at higher frequencies. This material has much higher bulk resistivity. Apart from the material composition the performance of a ferrite has a lot to do with how it is made. [4].

The core of a conventional CT is made up of steel plates which has low initial permeability with high conductivity. The CTs installed in cable networks will see a power frequency signal at the beginning at time, $t=0$ which will magnetise the core and establish the flux path. Later on (at $t>0$), high frequency low magnitude pulses enter the CT. Figure 3 shows the PD signal waveform of a discharge sequence where the higher amplitude 50Hz power frequency waveform is shown alongside the lower amplitude cavity voltage waveform; the PD pulse waveform is also shown. Therefore, the core material will be subjected to both 50 Hz and high frequency signals. The effect of power frequency interference with the PD signal on the transformer core is analyzed by applying Jiles Atherton (J-A) theory of magnetic

properties of materials, expressed using magnetization curves or hysteresis curves. J-A expresses the hysteresis effect in magnetic materials in the form of the energy balance equation. Magnetic energy supplied to an initially demagnetized material, can appear either as a change in total magnetization M (magneto static energy), or be dissipated due to irreversible changes in magnetization M_i , (hysteresis loss) [5].

$$\mu_0 \int Man(dH) = \mu_0 \int M(dH) + \mu_0 \int \left(\frac{n\epsilon_\pi}{2Ms} \right) \left[\frac{dM}{dH} \right] (dH) \quad \text{----- (i)}$$

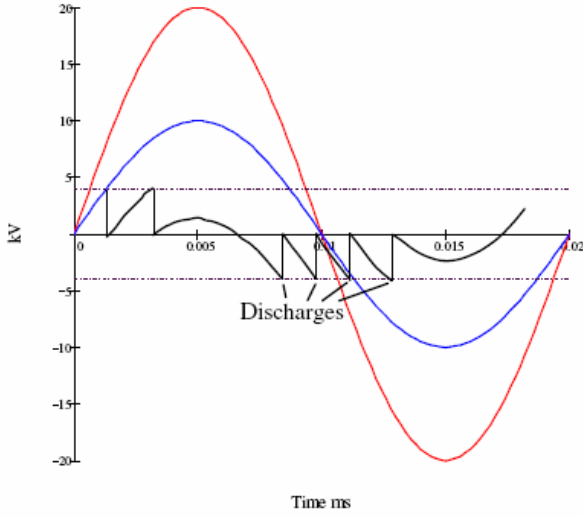


Fig. 3. PD signal from a discharge sequence

Where Man is Anhysteretic magnetization defined by the modified Langevin function given as follows

$$M_{an} = Ms * \left[\text{Cot}(He/a) + \left(\frac{a}{He} \right) \right] \quad \text{----- (ii)}$$

Where He is the effective field given by

$$H_e = H + \alpha * M$$

α : Mean field parameter

M : Magnetization vector

Ms : Saturation Magnetization

a : Shape parameter

μ_0 : Permeability of free space

n : Number of pinning sites

ϵ_π : Domain wall pinning in 180°

In the absence of dissipation (hysteresis) then, by definition, the magnetization must follow the anhysteretic (hysteresis-free) curve as shown in figure 4.

The J-A hysteresis model decomposes the magnetization M into its reversible component M_{rev} , which corresponds to domain bending during the magnetization process, and its irreversible component M_{irr} , which corresponds to domain wall displacement against the pinning effect given in equation [6].

$$M = M_{irr} + M_{rev}$$

$$M_{an} = M_{irr} + M_{rev} + k\delta(1-c) \left(\frac{dM_{irr}}{dH_e} \right) \quad \text{----- (iii)}$$

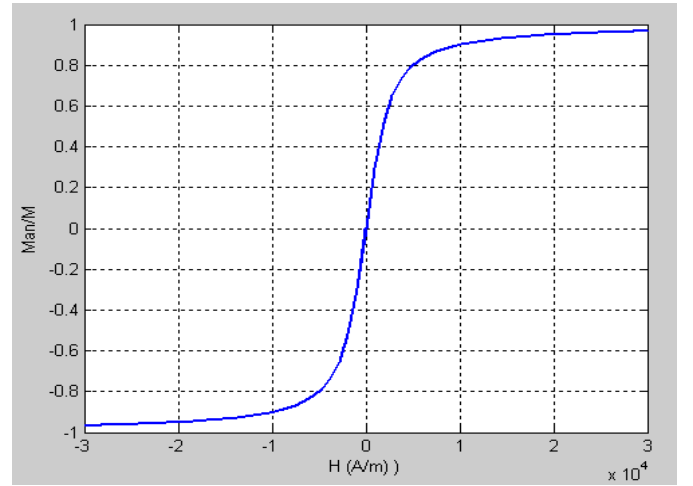


Figure 4. Anhysteretic magnetization

$$M_{rev} = c(M_{an} - M_{irr})$$

The final equation of J-A model is

$$\left(\frac{dM}{dH} \right) = (1-c) \left\{ \frac{Man - M_{irr}}{k\delta - \alpha(Man - M_{irr})} \right\} + c \left(\frac{dMan}{dH} \right) \quad \text{----- (iv)}$$

k is coercivity

The numerical solution of the above equation will give the quasi-state time independent magnetization characteristics. Equation (iv) is solved by using Matlab with parameters values such as $Ms = 16M$, $a = 1000$, $\alpha = 0.001$, $c = 0.1$, $k = 3000$, $H = 10k$ the sample result is shown in figure 5. J-A parameters can be empirically.

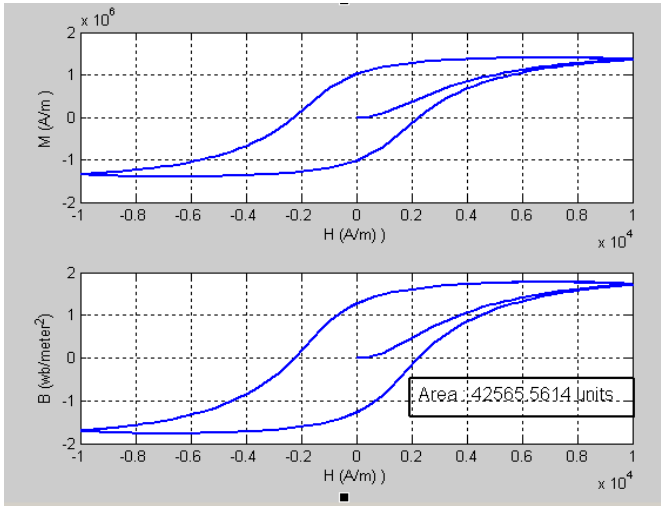


Figure 5. Solution of J-A equations without eddy current loss

Eddy current loss is not considered in the above J-A model. Steel plates are used as core material in conventional current transformers. Due to the low resistivity of that material, eddy current loss cannot be ignored, moreover eddy current loss is frequency dependent. The new energy balance equations including eddy current loss given by J-A is .[7]

$$\mu_0 \int Man(dH) = \mu_0 \int M(dH) + \mu_0 \int \left(\frac{n\epsilon_\pi}{2Ms} \right) \left[\frac{dM}{dH} \right] (dH) + \int \frac{\mu_0 d^2}{2\rho\beta} \left(\frac{dM}{dT} \right)^2 dt \quad \text{-----(v)}$$

Where ρ is the resistivity in ohm-meter.[7]

β is geometry factor for laminations. [7]

The final equation of the J-A model for low resistivity core materials is,

$$\left(\frac{dM}{dH} \right) = \left(\frac{Man - M - k\delta(1-c) \frac{dM_{irr}}{dHe}}{k' - \alpha \left(Man - M - k\delta(1-c) \frac{dM_{irr}}{dHe} \right)} \right) \quad \text{-----(vi)}$$

The equation is solved in Matlab. Due to the inclusion of eddy current losses, there is a 15 % increase in the loop area as shown in Figure 6.

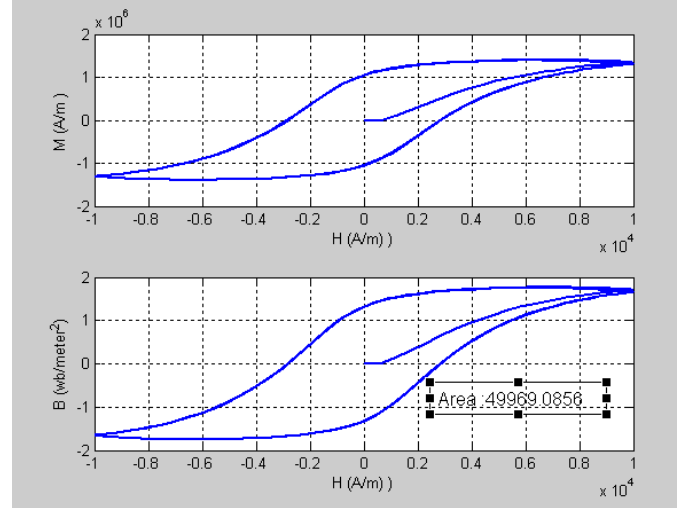


Figure 6. Solution of J-A equations with eddy current loss included

Using the same values of M_s , α , a , c , k , a simulated PD pulse as shown in figure 7 is injected into the model to view the its effect. The effects of the simulated PD pulse on the BH characteristic model output is shown in Figure 9.

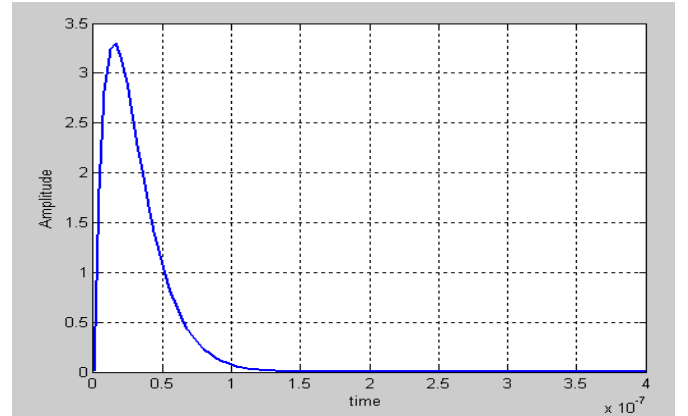


Figure 7. Simulated PD pulse

This PD pulse is injected into the power frequency waveform. The real PD is simulated using matlab and is input to the J-A model. Results are as shown in figure 8 and figure 9. From the results it is evident that there is a 33% increase in the BH loop area due to the injection of the high frequency PD pulse which will alter the frequency response of the CT. In reality PD pulses are often corrupted with noise, which will again degrade the core performance. In wide band current transformers non conductive ferrites are used . As a

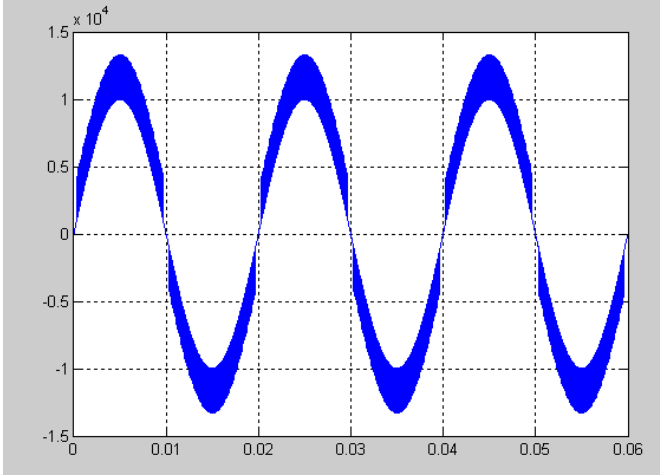


Figure 8. Power Frequency with PD pulse

result eddy current effects are nullified. Moreover these materials have high initial permeability which will set up the flux path in high frequency mode. Hence transformer action will not be lost. Stray capacitance is the other factor which affects the transformer action at high frequencies. Stray capacitance depends upon the clearance between the primary and secondary windings. When conventional CTs are installed for measurement and protection purposes, the primary conductor dimension is chosen in such away that air breakdown and corona inception is not allowed [8].

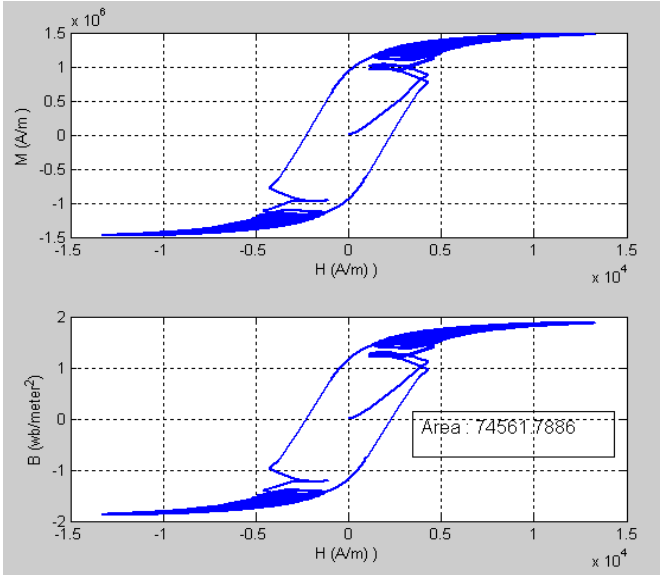


Figure 9. BH loop during partial discharge

Hence the compromise in conductor dimension to minimize stray capacitance is difficult, resulting in increases in stray capacitance and degrading high frequency performance. Since the high frequency CT is normally used in earth straps

there is a high degree of control over the stray capacitance which gives a flat frequency response over a wide range of frequencies.

V. EXPERIMENTAL SETUP

A CT is modeled as a bilateral two-port network as shown in figure 10. Circuit parameters can be obtained from open and short circuit tests thereby solving network equations expressed in the form of admittance and impedance parameters and providing the transfer function of the CT. Frequency response can be obtained from the transfer function by using Matlab. The calculation of the network parameters remain ongoing.

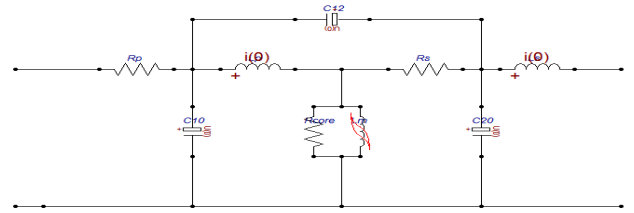


Figure 10. CT two port network

VI. CONCLUSION

At present, protection and measurement transformers are used exclusively for protection and measurement functionality. This paper discusses the suitability of extending their functionality towards the detection of high frequency PD signals. Core material permeability plays a key role in determining the high frequency performance of conventional CTs. Apart from the material resistivity, stray capacitance leakage inductance also contributes to performance degradation. The Jiles - Atherton model is used to test the effect of high frequency signals on the core material. It was shown that the area of the BH loop increased to 33% compared with the power frequency signal. This shows that losses have increased which will eventually degrade the high frequency performance. Moreover, steel plates with low initial permeability will again reduce the bandwidth of those CTs. Apart from core permeability and conductivity, stray capacitance, calculated by solving network equations, will also play a substantial role in reducing the high frequency performance. An examination of the effect of stray capacitance on frequency response of transformer is currently work in progress.

VII. REFERENCES

- [1]. Xiaodi Song, Chengke Zhou, Donald M. Hepburn, Guobin Zhang Second Generation Wavelet Transform for Data denoising in PD Measurement *IEEE Transactions on Dielectrics and Electrical Insulation* Vol. 14, No. 6; December 2007
- [2]. Shim, Ivy A.F.; "Signal processing techniques of partial discharge mapping in high voltage cables"; PhD Thesis; 2000; University of Strathclyde, Glasgow, UK.
- [3]. Faisal P. Mohamed, W. H. Siew, J. J. Soraghan , On-line Partial Discharge detection in Medium voltage cables using protection/Instrument Current Transformers Second UHV net Colloquium, Glasgow Caledonian University, 21 st January 2009
- [4]. Electus Distribution Reference Data Sheet: FERRITES.PDF http://www.jaycar.com.au/images_uploaded/ferrites.pdf
- [5]. D. C. Jiles and D.L. Atherton ,Ferromagnetic hysteresis, *IEEE Transactions on Magnetics*, vol. mag-19, no. 5, September 1983
- [6]. Shun-Tsai Liu, Sy-Ruen Huang, Member, IEEE, Hung-Wei Chen, Ting-Yen Hsien. Current Transformer Module Basing the Jiles-Atherton Hysteresis Model in EMTP/ATP Simulation.
- [7]. D. C. Jiles Ames Laboratory, Iowa State University, Ames, Iowa 50011 ,Frequency dependence of magnetic hysteresis curves in conducting magnetic materials. *Journal of applied physics* Vol. 76, No. 10, 15 November 1994
- [8]. Faisal Peer Mohamed Dr. W. H. Siew Professor QM Li , Online Partial Discharge Detection in HV cables using Conventional Current Transformers 2008 International Conference on Condition Monitoring and Diagnosis, Beijing, China, April 21-24, 2008