Causes and Effects of Overfluxing in Transformers and Comparison of Various Techniques for its Detection

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ABSTRACT
Transformer saturation is an area of major concern as the transformers are designed to run near peak magnetizing flux value and if voltage/frequency (V/f) ratio increases, it may cause the transformer to reach into saturation, which can affect normal operation of the transformer and even cause mal-operation of the protective equipments. This paper explains different techniques of transformer saturation detection and current waveform improvement.

Keywords
Finite Element Method, Transformer, Overfluxing.

1. INTRODUCTION
Transformers are among the most important and expensive equipments that always been used in industry and power system. Transformers are generally designed to work just below peak value of magnetic flux,so proper analysis of transformer behavior under overfluxing condition is necessary. This paper provides information on different type of overfluxing[1-3] conditions that may occur in the transformer and its effects on transformer operation and also explain different techniques to analyze saturation and techniques to reduce its effect.

2. OVERFLUXING
Transformers are designed in such a way that under steady-state operating conditions they can operate near peak magnetizing flux but below the saturation level. When the transformer core is unsaturated, the total exciting current is about 0.1% of the rated current. But, if this operating flux increases above certain value, the core may enter periods of saturation. Under saturation transformer draws very high magnetizing current and significant Ampere-turns imbalance takes place.Overfluxing also causes increase in transformer losses. The core losses typically increase by 40% for a 10% overfluxing in the transformer. In current transformer (CT), it may result in wrong measurements and may even cause mal-functioning of protective relays. So, to compensate effect of saturation in CT it is necessary to identify the overfluxing operating quantities and distinguish them from those for internal faults.In transformer, some or all of the below mentioned conditions [4-7] may take place:

2.1 Energisation
In transformersoverfluxing may occur during energisation which depends onthe value of the source voltage waveform at the time of transformer energisationand also on the magnitudeand polarity of residual flux of transformer core. These factors also affect the nature and peak value of inrush current waveform. As during energisation magnetizing current may be very high and protective relays may misunderstand it as fault hence it is necessary to distinguish it from the fault current. The main difference between magnetizing inrush current and fault current waveforms is the non-sinusoidal nature of inrush current waveforms and presenceof significant amount of second harmonic content. There are two techniques to distinguish between fault current and inrush current. First one is measuring second harmonic content and another technique is based on detection of null periods.

2.2 AC Overfluxing
In transformers V/f ratio is generally maintained constant but if due to any reason voltage is increased above nominal voltage or the frequency is reduced below nominal frequency transformer may experience overfluxing and may also reach under saturation. This type overfluxing may be due to sudden load-rejection overvoltages, or due to the excitation of generator at low frequency. AC overfluxing may also be experienced when transmission line is lightly loaded and proper shunt compensation is not provided.

Transformer protection should be provided in such a way that it should assure the stability of the system under transient overfluxing conditions, but should also be able to trip when duration and severity of the condition crosses safe operation limit.

2.3 DC Overfluxing
DC overfluxing can be experienced when currents of extremely low frequency or DC currents flow at least one set of transformer windings. This situation may occur when transformers are installed adjacent to DC power links and some of the zero potential currents do not return through intended paths. DC overfluxing condition is also seen in the transformers placed in some northern latitudes of the earth due to somegeomagnetic disturbances.

3. EFFECTS OF OVERFLUXING IN TRANSFORMER
The magnetic flux in a transformer, under normal conditions, is limited to the core of transformer because permeability of transformer core is very high as compared to other parts of the transformer. If flux density in the core increases and reaches saturation point, significant amount of flux leaks and gets distracted to structural parts like transformer tank, clamping structure etc. and into the air. Due to these saturation flux densities, transformer will overheat and hot spots will form in the transformer. This Flux not flowing in intended paths may link conducing loops in the windings, loads, tank base and structural parts and these circulating currents in these loops can cause dangerous temperature increase. When transformer working under high flux density condition heating of inner portion of winding may be extremely high as large amount of magnetizing current full of harmonics is flowing in the circuit. This can increase transformer losses to a great extent and can affect transformer performance. Practical evidences show that damage due to over fluxing varies with many factors viz. the

level of over excitation, time period of occurrence and the transformer design. Some of the effects of overfluxing are as follows:

- Significant increase in core losses.
- Formation of hot spots.
- Increased leakage flux and magnetizing current.
- Delayed operation in case of inverse-time-overcurrent relay.
- Over-reach and under-reach problems inimpedance relays.
- Introduction of harmonics.

4. DIFFERENT TECHNIQUES OF SATURATION DETECTION

4.1 Lumped Parameter Approach

Behavior of transformer under saturation condition is different from normal conditions. When transformer reaches deep saturation condition spilling of the magnetic flux from the core occurs. This leaked flux links to tank, clamping structures and other parts of the transformer and some amount leaks into air. Hence for analyzing transformer performance under overfluxing condition modification to the conventional equivalent magnetic circuit of transformer is necessary.

In this lumped parameter approach [8-11],transformer is replace by its equivalent magnetic circuit. Transformer yoke, limb, air leakage flux, saturation effect etc. are replaced by their equivalent permeances. All the flux linking to transformer tank and clamping structure i.e. all the flux fringing out of the core but not linking to the winding is represented by one parameter: air flux. To take into account the effect of saturation in the limb portion, flux between outer diameter of core and inner diameter of winding is presented by an extra branch parallel to the limb. All these modifications are done in conventional transformer model by representing modified parameters by their respective permeances. The resultant equivalent model of 3-phase 5-limb transformer is shown in the Figure [1]. Now this modifiedequivalent circuit is used to analyze saturation effect.

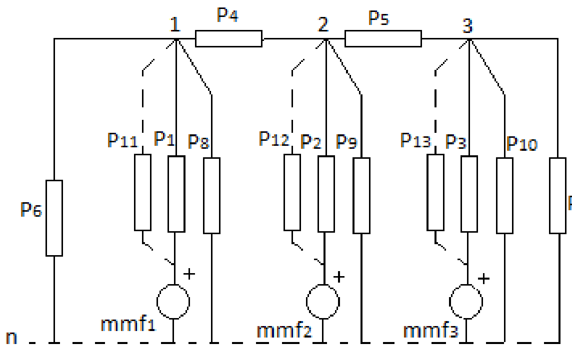

Fig 1: Modified equivalent magnetic circuit

This method can be used to design main limb, yoke and end-limb area of optimum size so that flux density can be maintained within specified limits.

But, main disadvantage of this method is that many essential parameters like remnant flux, DC offset etc. are not considered in the analysis.

4.2 Artificial Neural Network (ANN)

Saturation in current transformers (CT) can cause mal-operation or can prevent tripping of protective relays. During saturation secondary current waveformof CT gets highly distorted. Artificial neural network (ANN) can be used to detect and correct this distorted secondary current [12-16]. Under saturation condition secondary current of CT is distorted which causes decrease in RMS value of current than the normal value. ANN is used to detect distortion in current waveform, for this purpose it is first trained to generate inverse transfer function of transformer core then output of CT is processed to provide an estimate of primary current waveform.For training purpose Feed-forward type of network is selected due to its inherent stability, which consists input layer, hidden layers and output layer. Input layer nodes are selected based on the signal-sampling rate. To improve training, hidden layers are added in between input and output node. Adding hidden layers improve results but system complexity also increases, hence selection of number of hidden layers must be done judiciously.

Behavior of CT during present cyclealso depends on previous cycle hence one node is taken for summating the samples, which are received from the previous cycle. This summation is proportional to the integral of the secondary current of CT and magnetic flux during the last cycle. To train the network many variables such as X/R ratio,fault impedance magnitude, and closing angle etc. are selected. Then ANN is trained through test data and actual CT data. Once the network is trained, it can be used to process the output of CT and can provide an estimate of primary current.

Advantage of this technique is that it can produce sample-by-sample estimate of CT primary current at the output. Also, if proper training is done, this approach can result in calculation of secondary current even under heavy saturation condition. Another advantage is that we can train the network from the output of auxiliary CTs. This avoids the need of taking approximations in the system.

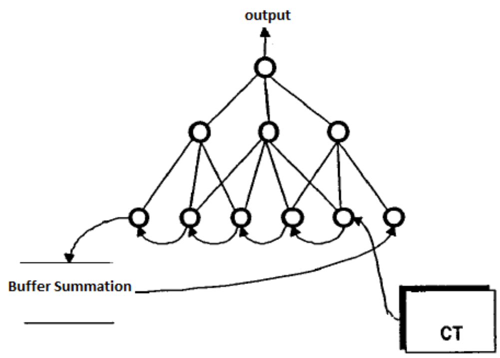

Fig 2: Operation of ANN

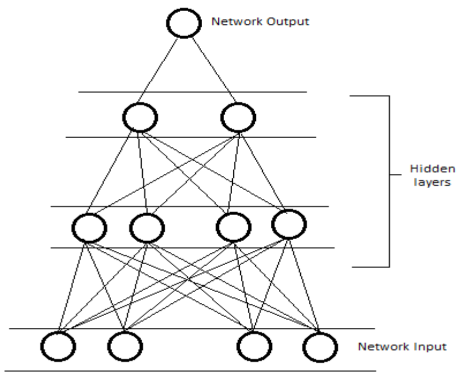

Fig 3: ANN structure

Limitation of this method is that an artificial neural network learns transformer magnetization characteristics and restructuring of distorted waveform through the characteristics learned by it during training. However, as CT saturation characteristics and secondary burdens can be different for different transformers this method cannot be applied universally in various situations.

4.3 Morphological Lifting Scheme

This technique uses morphological waveletsto extract important features from secondary current distorted by saturation by detecting points of inflection in the distorted current waveform. Then a compensation algorithm is used to reconstruct healthy secondary current using features extracted through morphological lifting scheme [17-21].

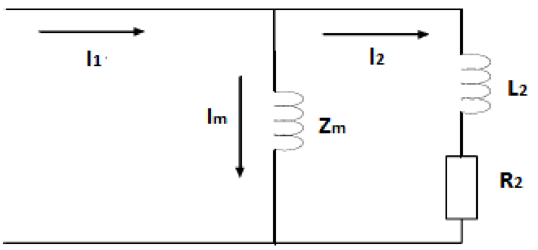

Fig 4: Simplified equivalent circuit of a CT

Figure [4] shows an equivalent circuit of a Current Transformer for transient analysis. Here Zm represents excitation impedance, L2 is the secondary inductance and R2 is secondary resistance.

When CT is running at low values of flux densitiesZm is very large, hence secondary current waveform of CT is sinusoidal in nature and replica of primary current referred to secondary side.

But when fault occurs, the fault current through the primary circuit increases and becomes equal to the superposition of a sinusoidal component and an exponential component, which is given by

$$i_1(t) = Ae^{-\propto t} + B\sin\emptyset_t(1)$$

Where, A, α,$\emptyset_t$ B, are the initial values of the exponential component, decaying coefficient, fault inception angle and amplitude of the sinusoidal component, respectively.

As exponential component is large, the magnetic density enters saturation level and results in decrease of Zm value, now large amount of magnetizing current Imflows through Zm branch and causes the secondary current to be distorted. When the system is running under heavy saturation conditions Zmreduces to zero and whole current starts flowing through the excitation coil, which causes the secondary current to reduce to almost zero, which induces high measurement errors or may cause mal-operation of protective relays during tripping.

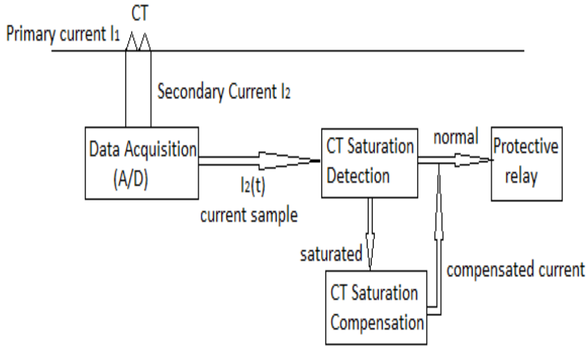

Fig 5: Real time detection and compensation of current transformer saturation

Figure [5] shows real time detection and compensation of distorted secondary current using morphological lifting technique. In this technique secondary current $I_2$of CT is sampled into discrete-time sequence values$i_2(t)$, using data-acquisition module. If CT saturation detection scheme find this sampled current value$i_2(t)$ within saturation range, compensation algorithm constructs a compensated sample of the current and these compensated currents values are supplied to protective relays.

Morphological operations convert a signal into a quantitative description of its geometrical structure. By using proper operation, noise or irregularities present in a signal can be detected and removed while healthy characteristics and details can be preserved.

Main advantage of this method is its capability to extract important features from the distorted signal during CT saturation. After detecting CT saturation characteristics real-time compensated secondary current can be achieved.

But, this scheme has a weakness that when the secondary current of CT is extremely distorted, it becomes difficult for this technique to distinguish saturation periods from the signal.

4.4 Partial Non-Linear Model Technique

When transformer comes under the effect of saturation it experiences large number of non-linearities. In this method Partial nonlinear model [22-23]is used to represent nonlinear characteristic of a current transformer (CT) under saturation conditions. Both unsaturated and saturated portion of the distorted secondary current are used for conducting nonlinear regression, and even a short section of current waveform is enough for estimation of current waveform parameters and these estimated parameters are used to recover improved secondary current waveform. To improve output resultsremnant flux, DC offset, inception angle etc. are also included in the study. Therefore it gives more accurate results of the estimated parameters. This technique is also capable of calculatingphasor of the fault current without reconstruction of current waveform.

General expression of the current can be given as,

$$i_p(t) = i_s(t) + i_m(t) \qquad (2)$$

Where,$i_p(t)$ is the primary current$i_s(t)$ is secondary current, $i_m(t)$magnetizing current.

The above function is transformed to a regression model where primary fault current is the superposition of sinusoidal waveform and exponentially decaying DC-offset which can be expressed as

$$i_p(t) = A\sin(\omega t + \theta) + Be^{-\tau t} \quad (3)$$

Where, A is the amplitude, ω is the angular speed, θ is the inception angle, B is the initial value and τ is the time constant of the DC-offset. Then, first-order Taylor series expansion is applied on the above mentioned equation and resulting expression is:

$$i_p(t) = A\cos\theta\sin(\omega t) + A\sin\theta\cos(\omega t) + Be^{-\tau t}$$

$$= a_1\sin(\omega t) + a_2\cos(\omega t) + a_3 + a_4 t (4)$$

Where, a_1-$a_4$are unknown parameters.

Then, magnetizing current $i_m(t)$is expressed as a function of core flux ϕ(t) and these values are put in equation(2) and solved for calculating secondary current value by calculating unknown parameters. In this technique combination of single dimension non-linear regression and multi-dimensional non-linear regression using Separable Non Linear Least Squares(SNLLS) method is used, this makes realization of non-linear regression easier.

Drawback of this method is that as supply voltage non-linearity increases excitation waveform becomes peakierin nature and third harmonic component increases, which makes calculation more complex.

4.5 Compensation Algorithm

When saturation occur RMS value of current becomes lower due to distortion by saturation. Hence, relay may fail to sense fault. This technique is able to recover compensated current waveform from samples of current waveform that is distorted by CT saturation. For this it consist a compensation algorithm[24-27] which can convert sampled current waveform which is distorted due to saturation, to a compensated current waveform.

Which is based on the conditions that distorted current waveform will contain two distinguished portion in every cycle- a saturated portion and an unsaturated portion. Also, for about 1/6 cycle there will be no saturated portion in the first saturated waveform and about 1/4 cycle between two successive saturated portions. Also, in unsaturated portion of the waveform there are unsaturated points that repeat exactly one cycle later. These unsaturated portions can be determined using a Reference Point (RP). This Reference Point can be determined after fault occurrence and is taken as first sample of fault current. After setting reference point (RP), samples of distorted current waveform are separated into saturated and unsaturated portion. Then compensation algorithm and a function with CT parameters are applied to reconstruct secondary current through the information received from sampled data. This function represents the nonlinear core characteristics of a specific model of CT.

Advantages of this method are quick response time, independence from CT parameters and secondary burdens, free from cumulative estimation errors and capability of online implementation.

Drawback of this technique is that it includes some assumptions such as when CT saturates the current collapse to zero and there is no initial residual flux. These assumptions are not always satisfied in practical conditions which make applicability of the method limited.

Another limitation is, unsaturated portion of sufficient length is necessary to obtain accurate results. If the current waveform is saturated severely and has only small unsaturated section in each cycle, more number of cycles of current is needed to get enough unsaturated sections.

4.6 Finite Element Method

Finite element method is another technique being used to study transformer under saturation condition. It is a numerical technique and can be applied effectively even with complex system geometries are non-linear material properties. Another advantage of using this method is its capability to work in both 2D and 3D work-space.

This technique [28-31] is inspired from variational approach technique which tries to find a function whose task is to minimize an energy function but, unlike variational approach it can be used for non-linear cases and it has no topological restriction. In actual, it tries to search for the function that minimizes the functional instead of trying to solve it. And, for effective searching problem is first discretized which is done by sub-dividing entire region under consideration into small triangles. These triangles can be of any size and can be arranged in any desired manner in such a way that it includes all regions under consideration.

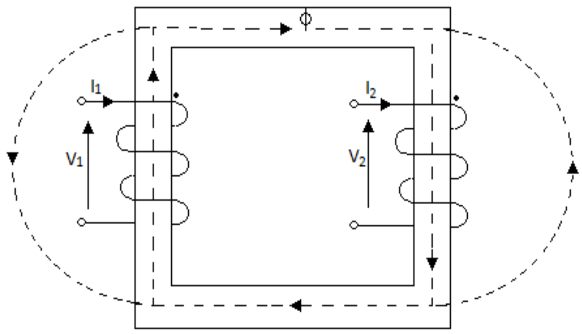

Fig 6: Flux and magnetic paths of single phase transformer

Now for each triangle, an approximation to the function is assumed. Then this function is varied until functional reaches a minimum. In the similar way values are calculated for other triangles also. As during calculation many vertices are common, this reduces the number of calculation required. The main advantage of this technique is its capability to get results equal or almost equal for most of the test results under saturation condition.

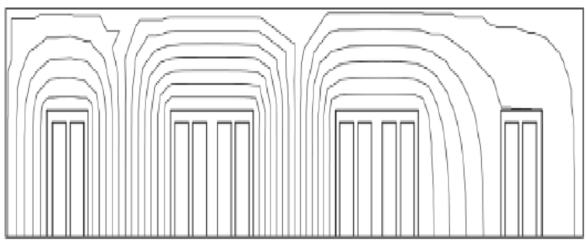

Fig 7: FEM model for flux distribution

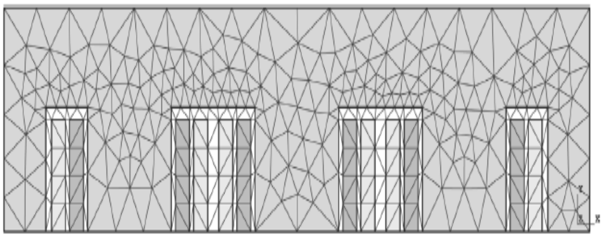

Fig 8: FEM model for overfluxing calculation

Hence, finite element method holds considerable promise for the solution of saturable magnetic field problems, especially when many iron-air interfaces of complicated shape are encountered and can be used as an efficient tool for analysis under saturated conditions.

5. CONCLUSION

Under saturation condition system properties are highly non-linear hence general methods cannot be applied directly. This paper presents effective and practical solutions for transformer saturation detection and compensation. Different techniques were presented and compared. Out of these, Finite Element Method is emerging as an efficient technique due to its wide applicability and flexibility. Its capability to work with both 2D and 3D work space and with system non-linearity and complexity makes it best suited for magnetic field related problems. Results have also shown that FE model is more accurate and reliable for highly non-linear overfluxing calculations.

In future FEM can also be used is different magnetic field related problems and can find its applicability not only in transformers but in various electrical machines also. And can be used in other analysis like heat analysis, electrostatic analysis etc.

6. REFERENCES

[1] Magdalena Puskarczyk1, Brice Jamieson1, WojciechJurczak “The influence of core shape and material nonlinearities to corner losses of inductive element” ABB Corporate Research Centre, Kraków, Poland.

[2] S.V.Kulkarni, S.A.Khaparde Transformer Engineering Design and Practice.

[3] G.Sybille, M.M.Gavrilovic, J.Belanger, 1985 “Transformer saturation effect on EHV system overvoltages” IEEE Transaction on Power Apparatus and System, Vol-PAS-104, No.3.

[4] Manpreet S Manna, Sanjay Marwaha, Gurmeet S Grewal, SarpreetKaur, Sept 2006 “3D FEM analysis for overfluxing in power transformer”, National Conference on Computational Intelligence for Emerging Electrical Power System(CIEEPS06), 255-258.

[5] Hindle P J, Robinson N., March 1997 “Coping with abnormal flux conditions when applying transformer protection”. IEE Conference Publication.

[6] Sonnemann W, Wanger C, Rockerfeller G., 1958 “Magnetizing inrush phenomena in transformer banks”. AIEE Tranc. Part111. Vol.77, 884-92.

[7] T. R. Specht, 1951 “Transformer magnetizing inrush current”,AIEE Trans. pt. I, vol. 70, 323–328

[8] D.A.Koppikar, S.V.Kulkarni, S.A.Khaparde,B.Arora 1998, “A modified approach to overfluxing analysis of transformer” Electrical Power And Energy Systems, Elsevier Science Ltd,Vol-20,No.-4,235-239.

[9] Stuehm, D.L, Mork, B.A. and Mairs, D.D., 1989, “Five-legged core transformer equivalent circuit”. IEEE Tranc. on Power Delivery. Vol-4, No.-3,1786-1790.

[10] Mairs,D.D,Stuehm,D.L and Mork,B.A. 1989, “Over-voltages on five-legged core transformer on rural electric systems” IEEE Tranc. On power delivery, Vol-25 no.-2, 366-370.

[11] Arthuri, C.M. 1991 “Transient simulation and analysis of three phase five limb step-up transformer” IEEE Tranc. on Power Delivery. Vol-6, No.-1, 196-203.

[12] David C.Yu,James, C.Cummins, Zhuding Wang, Hong-Jun Yoon,LjubomirA.kojovic, , 2001, “Correction of current transformer distorted secondary currents due to saturation using artificial neural network” IEEE Transactions on Power Delivery, Vol-16,No-2.

[13] S.Haykin, 1994 “Neural networks-A comprehensive foundation” IEEE Press. 181.

[14] Rebizant W, 2000, “ANN based detection of OS conditions in power systems”,12th Int. Conf. on Power System Protection, 51-56.

[15] D.C.Yu, Z.Wang, J.C.Cummins, H.J.Yoon, L.A.Kojovic and D.Stone, 1999, “Neural network for current transformer saturation correction”, IEEE Transm. Distrib. Conference, New Orleans, L.A.

[16] K.W.Chen and S.T.Glad, 1991, “Estimation of the primary current in a saturated transformer”, Proceedings of IEEE Conference on Decision and Control, 116-124.

[17] Z. Lu, J. S. Smith, and Q. H. Wu, 2008 “Morphological lifting scheme for current transformer saturation detection and compensation” IEEE Transactions on Circuits And Systems—I: Regular Papers,Vol- 55,No.-10.

[18] P.K.Gangadharan, T.S.Sindhu and A.Klimek, Mar 2007 “Influence of current transformer saturation on on-line current differential protection algorithm”. IET Generat. Tranc, Distrib.Vol- 1,No.-2, 270-277.

[19] W.Sweldens,1998, “The lifting scheme:Aconstruction of second generation wavelets,” SIAM J. Math. Anal., Vol-29, No-2, 511–546.

[20] K.Vu and A.Khan, 1999, Waveform reconstruction from distorted (saturated) currents”, U.S Patent(#5974361).

[21] J. Serra, 1982 “Image analysis and mathematical morphology” London U.K. Academic.

[22] D.Shi, J.Buse, Q.H.Wu, C.X.Guo., 2013 “Current transformer saturation compensation based on a partial non-linear model” Elsevier Electrical Power System Research, 34-40.

[23] Louie J.Powell, J.R.,1979, “Current transformer burden and saturation” IEEE Transaction on Industry Application, Vol IA-15, No.3.

[24] David C.Yu,James, C.Cummins, Zhuding Wang, Hong-Jun Yoon,LjubomirA.kojovic, , 2001, “Correction of current transformer distorted secondary currents due to saturation using artificial neural network” IEEE Transactions on Power Delivery, Vol-16,No-2.

[25] Jiuping Pan, Khoi Vu And Yi Hu, 2004"An efficient compensation algorithm for current transformer saturation effects" IEEE Transactions on Power Delivery, Vol. 19, No. 4, 1623.

[26] B.Kasztenny, E.Rosolowski, M.Lukowicsz and J.Izykowski, 1997, "Current related relaying algorithms immune to saturation of current transformers", Conf. Developments in Power System Protection.

[27] T.Bunyagul, P.Crossley and P.Gale, 2001, "Overcurrent protection using signals derived from saturated measurement CTs", IEEE Summer Meeting, Canada.

[28] P. Silveste and Madabushi V. K. Chari, 1970 "Finite element solution of saturable magnetic field problems" IEEE Transactions on Power Apparatus and Systems, Vol.-89, No. 7.

[29] A. M. Winslow,1965, "Magnetic field calculation in an irregular triangle mesh," Proc. Internatl. Symp. on Magnet Technology, 170-181.

[30] Z.H. Shaikh, H. Yamashita, E. Nakamae, 1988 "A three dimensional magnetic field analysis by a novel finite element method using magnetic flux density directly as an unknown variable" IEEE Transactions on Power Delivery, Vol. 3, No. 1.

[31] P. Concus, 1965, "On the calculation of nonlinear magnetostatic fields," Proc. Internatl.Symp. on Magnet Technology, 164-169.