An ANN Based Electromagnetic Transients Identification Technique for Power Transformer Systems

P L Mao, R K Aggarwal, Z Q Bo

Department of Electronic and Electrical Engineering, University of Bath, Claverton Down, Bath BA2, 7AY

Abstract - **Power transformers are subject to transient overvoltages/overcurrents which invariably accompany any disturbance such as a switching operation, internal/external fault, etc. It is imperative to be able to accurately distinguish the various types of disturbances both for correct transformer design (in terms of insulation level specification) and the associated protection technique design. Conventional techniques based on power frequency signals have limitations in distinguishing correctly the different types of disturbances. This paper addresses the problem through the use of an artificial neural network (ANN), which has the ability to map highly complex non-linear input/output patterns and is capable of very effectively dealing with the high frequency transient phenomena associated with any disturbance. The results presented show that the proposed technique is able to not only capture the high frequency current transient signals inside a transformer, but also fast and accurate identification of the cause and nature of the transients.**

Keywords: Power transformer, High frequency signal, Artificial neural network, Transient identification

I. INTRODUCTION

Power transformers are subject to many types of electromagnetic transient disturbances, which result in abnormal voltages and currents. For example, physical phenomena such as fault and lightning may generate transient overcurrents and/or overvoltages. On the other hand, normal operating procedures, such as breaker closing and switching of equipment cause electromagnetic transients. Overcurrents may damage the power transformer due to excessive heat dissipation and the high dynamic mechanical stress. Overvoltages may result in flashovers or insulation deterioration, and eventual breakdown of the power transformer.

Electromagnetic transient analysis of the power transformer plays an important role in the design and operation of the power transformer. It is widely accepted that measurement of transient-induced quantities and determination of the nature of transients would be invaluable. It would not only provide useful information in terms of optimal design and functionality of the power transformer, but also provide information for designing new protection schemes. The signals generated by switching are high frequency transients in nature, a genuine fault on the transformer will also generate high frequency noise signals. They cannot be detected by conventional techniques, which are mainly based on the measurement at power frequency signals. In this respect, recent developments in transient detection and identification techniques[1] make it possible the on-line measurement of switching transients and fault transients. However, distinguishing between the signals generated by the two events cannot be accomplished using the more traditional techniques. In this respect, the advent of ANNs, with their ability to map complex and highly non-linear input/output patterns, provides an attractive solution to the problem of transient identification in the power transformer system.

In recent years, a few studies which investigate the feasibility of using ANNs for transformer protection have been reported[2,3,4]. The work reported in this paper is concerned with designing a novel technique for transient identification in the power transformer system using neural networks. A specially designed transient detector unit is firstly applied to capture the various transient signals. The spectral energies of these captured signals are extracted, and then used to train a neural network in order to determine the source and nature of the transient in terms of the changes in spectral energies. The neural network takes into consideration the various transient events. The results presented demonstrate the feasibility of the new technique. It can be an attractive alternative for distinguishing the magnetising inrush from internal faults in the field of power transformer protection.

II. ELECTROMAGNETIC TRANSIENTS SIMULATION IN POWER TRANSFORMER

2.1 Studied System

Transient simulations in a power transformer are implemented using the electromagnetic transients program *(EMTP)* in a typical 11 kV/132 kV three-phase power transformer connected between an 11kV generator and a 132kV transmission line, which is shown in Figure 1. The current transformer (CT) model and its saturation have also been taken into consideration in the simulations. To evaluate the high frequency transient behaviour of the transformer, particularly under switching operation and internal fault conditions, the winding shunt capacitances were added to the transformer model[5].

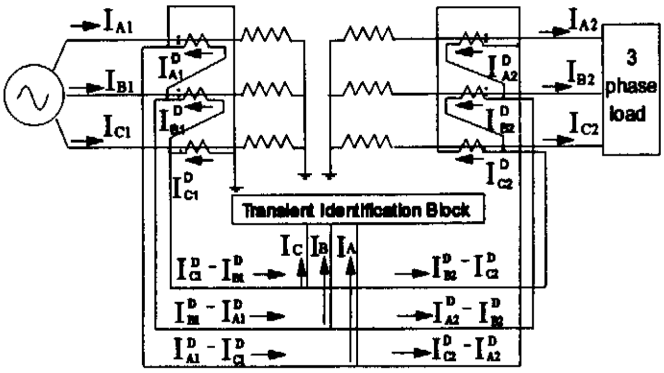


Figure 1: The studied power transformer system

2.2 Simulated Transient Event Types

In this paper, the following electromagnetic transient events of the power transformer have been taken into consideration

(a) internal fault transients, these include:
  - (i) terminal three-phase faults without CT saturation and with CT saturation, respectively;
  - (ii) terminal two-phase short-circuits without CT saturation and with CT saturation, respectively;
  - (iii) terminal single-phase-to-earth faults without CT saturation and with CT saturation, respectively;
  - (iv) internal winding turn-to-earth faults without CT saturation and with CT saturation, respectively;
  - (v) internal winding turn-to-turn faults without CT saturation and with CT saturation, respectively.

(b) switch operating transients, such as when the transformer is energised at no-load condition.

(c) external faults with extreme CT saturation.

All the above transient events are simulated via electromagnetic transients program (EMTP). Some typical results of the simulation are given in detail here.

2.3 Transient Simulations of Internal Faults

Figure 2, Figure 3 and Figure 4 respectively show some typical simulation results under different fault conditions. They are *(i)* terminal two-phase (b and c phase) short-circuit occurring on the high voltage side of the transformer as shown in Figure 2; *(ii)*'a'-phase turn-to-earth fault occurring at mid-point of winding on the high voltage side of the transformer as shown in Figure 3; and *(iii)* an 'a'-phase 5% turn-to-turn fault occurring on the high voltage side of the transformer at 50% of voltage winding from the neutral point as shown in Figure 4. For each fault case, the primary currents in CTs on the high voltage side of the transformer as well as the three phase differential currents are given respectively in each figure.

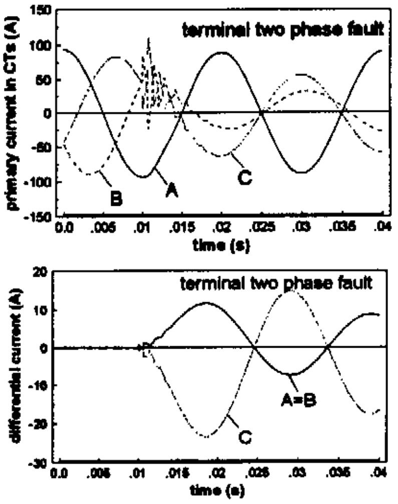


Figure 2: terminal two-phase (b and c) short-circuit fault on the high voltage side of the transformer

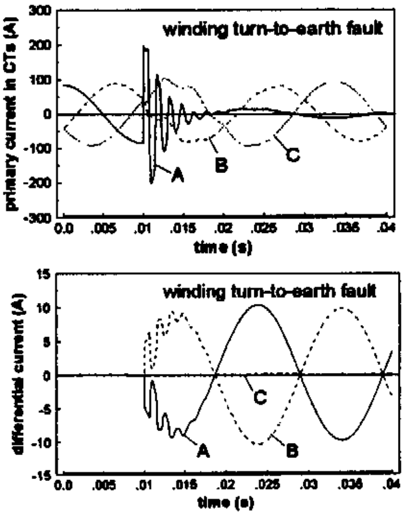


Figure 3: 'a'-phase turn-to-earth fault at mid-point of winding on the high voltage side of the transformer

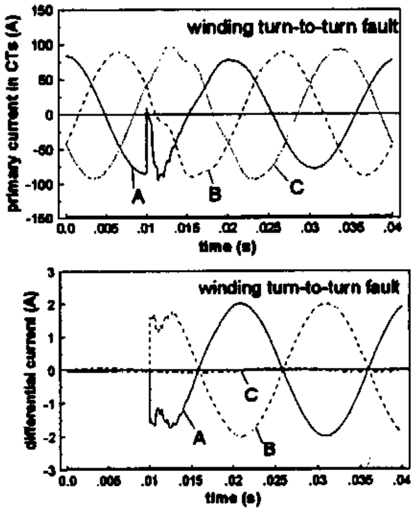


Figure 4: 'a'-phase 5% turn-to-turn fault on the high voltage side of the transformer at 50% of voltage winding from the neutral point

From the above figures it can be clearly seen that the fault generated high frequency current is present in the period at the start of the fault in the current signals. It is a direct result of the interaction between the coupled winding inductance and capacitance of the power transformer and the distributed inductance and capacitance of the transmission line.

2.4 *Transient Simulations of Switching Operations*

The various types of switching operation transients were also simulated. Figure 5 illustrates a typical simulation result of the switching operation condition (magnetising inrush case). It is observed that under such a condition, a large differential current is produced.

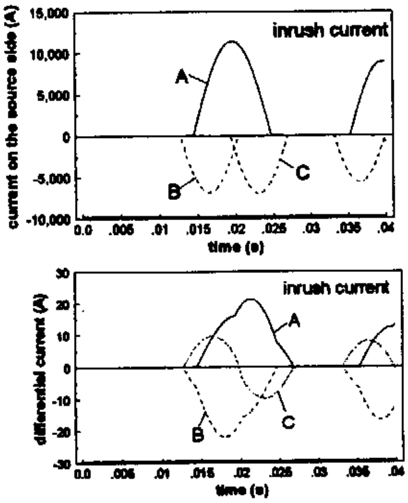


Figure 5: magnetising inrush current in the transformer

2.5 *Transient Simulations Under CT Saturation*

Figure 6 shows the differential currents for an 'a'-phase to earth fault occurring on the high voltage side of the power transformer with CT saturation. For clarity, this figure has presented the secondary currents in CTs on the high and low voltage sides in the transformer as well as the differential currents. It is apparent that the differential currents are severely distorted due to CT saturation. In practice, this may cause mal-operation of the conventional differential protection which is based on second harmonic restraint. This is so because a large second harmonic also exists in the internal fault current, and not just in the magnetising inrush current. A spectral analysis of this differential current has shown that there is around 25% second harmonic component present in the fault current under CT saturation.

Figure 7 shows the differential currents for an external three-phase fault occurring on the high voltage busbar connected to the high voltage side of the power transformer under CT saturation. In this case, the transient unbalance currents are very large due to the saturation on one side CTs of the power transformer.

It can be seen from Fig.6 and Fig.7 that the high frequency current transients are also present in the current signals.

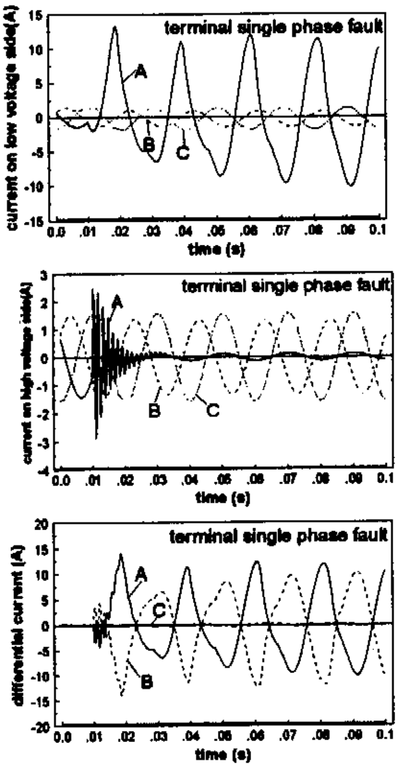
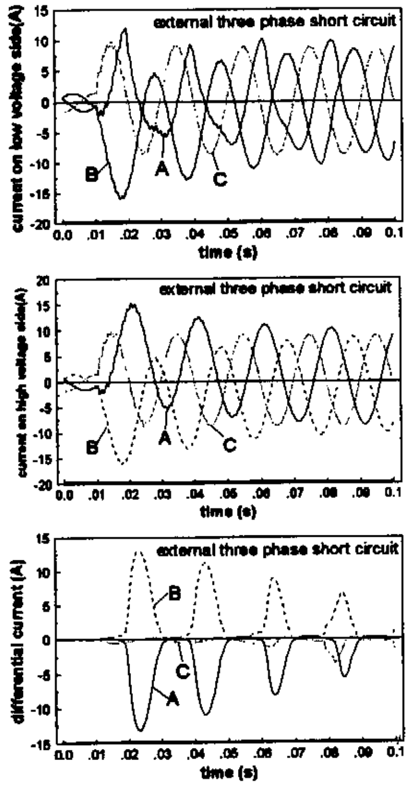


Figure 6: 'a'-phase to earth fault under CT saturation



Figur7: external three-phase short circuit with CT saturation on low voltage side only

III. DETECTION OF HIGH FREQUENCY CURRENT TRANSIENT SIGNALS

When a fault occurs on a power transformer, DC offset, fundamental frequency and non-fundamental frequency components are produced. The non-fundamental frequency components change according to the power transformer operating conditions, such as variations in the internal faults and switching operation conditions. This can be clearly seen through the spectrum analyses of their differential current signals.

3.1 Behaviour of High Frequency Signals

In order to confirm the existence of the high frequency current transients in the differential currents, figure 8 presents the frequency spectra for the differential currents under the internal fault case shown in Figure 3 and switching operation (magnetising inrush) case shown in Figure 5, over a small range of frequencies. It is important to note that in Figure 8, non-fundamental frequency components exist under both internal fault and magnetising inrush condition. In this paper, the high frequency current transients with a centre frequency around 1kHz has been captured and employed to implement the transient identification.

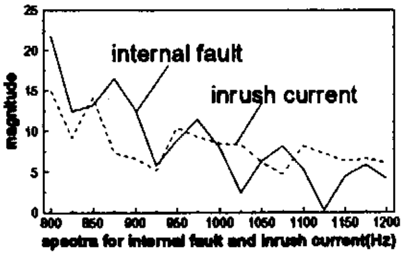


Figure 8: Spectra of differential currents

3.2 Detection and Feature Extraction of High Frequency Current Transient Signals

The high frequency current signals generated under both switching operations and internal faults are captured through a specially designed relay hardware/software. The spectral energies of the captured signals are extracted and then utilised to identify fault transients and switching operations by using the artificial neural network. The diagram of transient identification logic block is shown in Figure 9. A differential current threshold is set and a starting instruction will be issued to enable transient identifications when the differential current exceeds this threshold.

As shown in Figure 9, three phase differential current signals I_A, I_B and I_C are first converted into one modal signal I_{mode} by the modal mixing circuit using the following transformation:

$$I_{mode} = I_A + 2I_B - I_C \qquad (1)$$

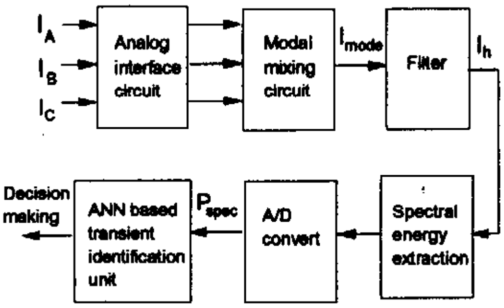


Figure 9: Transient identification block

A 4th order Butterworth band-pass filter is then applied to the modal signal I_{mode} to extract the high frequency current transient signal I_h, which is around a centre frequency of 1kHz, the sampling frequency is 10kHz. Figures 10-15 show the filter outputs corresponding to the typical signal waves shown in Figures 2-7.

From these figures it is worth noting that the features of the high frequency current transient signals between the internal faults and switching operations are significantly different. In the two cases, for example, in the internal fault case (Fig10-12) the high frequency components generated on fault inception rapidly ring down to a near zero value due to losses. However, in the case of magnetising inrush current (Fig 13, resulting from a switching operation) there are burst of high frequency signals (these are as a direct consequence of the transformer core and/or CT saturation). These thus produce the different spectral energy features between internal faults and switching operations, and can be used as the main signature to identify the transients between the internal faults and switching operations via a neural network.

The spectral energies of the high frequency transient current I_h in each sampled window are extracted by the following equation

$$P_{spec} = \sum_{k=1}^{N} I_h^2(k)\Delta t \qquad (2)$$

where Δt= time step length; N = No. of samples in the window.

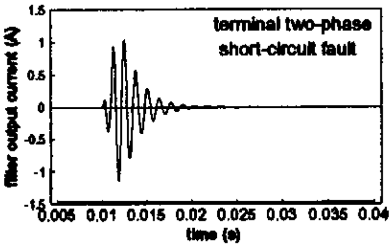


Figure 10: filter output current for two phase short-circuit fault

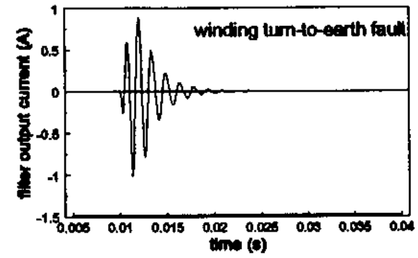


Figure 11: filter output current for winding turn-to-earth fault

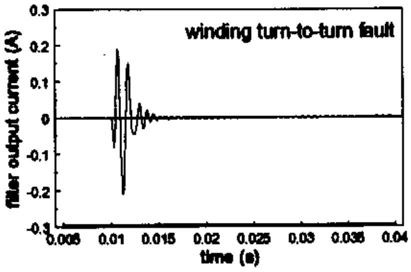


Figure 12: filter output current for winding turn-to-turn fault

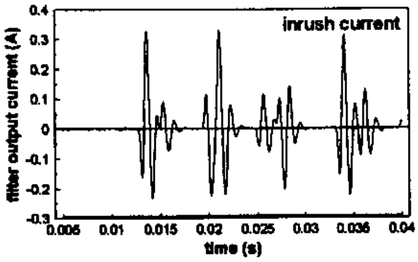


Figure 13: filter output current for inrush current

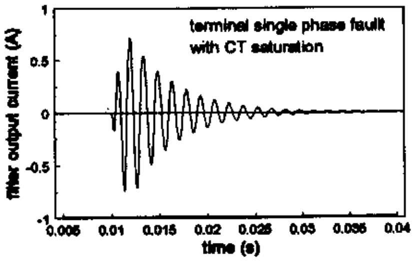


Figure 14: filter output current for internal fault with CT saturation

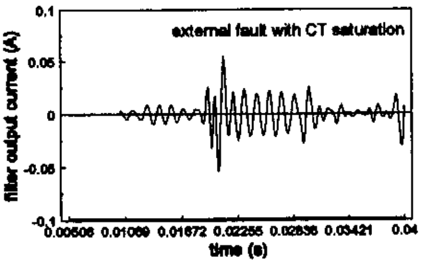


Figure 15: filter output current for external fault with CT saturation

IV. ARTIFICIAL NEURAL NETWORK BASED TRANSIENT IDENTIFICATION

One of the most difficult tasks in applying ANN technique to a particular power system protection is to formulate the problem that needs to be solved. The most important step to formulate the problem is to select the best input and output features that must correctly represent the problem. The vast majority of studies carried out hitherto involving ANN based power transformer protection have been based on the fundamental power frequency signals, which have been sampled over a window length of one power frequency cycle[2,3,4]. Furthermore, some of them have used the moving window principle to sample the signal over a period of several cycles. Both these approaches suffer from drawbacks; the first approach leads to prolonged fault detection times, the second approach can result in very long training times. And also, for certain fault conditions, the ANN may not converge to the required RMS error.

The work presented herein is based on employing the spectral energies of the high frequency current transient signals for the implementation of the transient identification through using the ANN for the power transformer. By detecting the changes of the spectral energies of the high frequency signals in a given observation window, the transient identifications are achieved. The diagram of transient identification logic block has been shown in Figure 9.

4.1 Input selection to the neural network

As shown above, the high frequency transient signals generated by a fault and switching operations mainly exist within a short period of time following a fault or a switching operation; this means that the decision about the nature of transient must be made within this period. Therefore, in this paper, the observation window of the high frequency current transient signals associated with each transient event has been constrained to a time window length of ½ cycle, which in turn is divided into 10 equal time periods, as shown in Figure 16.

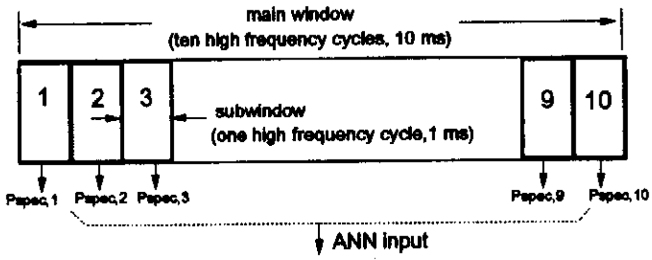


Figure16: Representation of feature extraction

The waveform associated with each subwindow is effectively sampled into ten samples (this is at 10kHz sampling frequency), and the spectral energy of the signal in each subwindow is then calculated by equation (2). Thus, the ten subwindows produce the 10 integrated spectral energies, which represent the main features of the signals for each given case; they are then used as input data to the ANN.

4.2 Network structure and training

A total of 10 sampled signals are employed as inputs to the ANN. The target output of the ANN was built in such way that the value [1, 0] represents the transient caused by an internal fault; the value [0, 1] represents the transient caused by the switching operation; and the value [0, 0] represents the transients caused by the external fault.

The selection of the number of hidden layers and the number of neurons required in each hidden layer is determined by experimentation involving training and testing various network configurations. The process is terminated when a suitable network with a satisfactory performance is established. In this work, it was found that one hidden layer with 6 hidden neurons gave a satisfactory performance.

The training and testing date sets of the ANN consist of 120 cases, comprising of various internal faults and switching operation transients, with and without taking CT saturation into consideration, as well as the external fault transients again with and without CT saturation.

V. RESPONSE EVALUATION

The ANN was extensively tested and was then embedded into the structure shown in Fig 1 to evaluate the performance and ability of the transient identification. The value of 0.1 is set as the tolerate RMS error of the ANN output. Table 1 shows the performance obtained from the trained ANN when it is subjected to 'unseen' fault/switching operation data. It is apparent from the results presented that the ANN-based technique gives the correct results for all the test cases presented to it.

Table 1: Performance of the ANN based transient identification technique

Type*		Desired output		Actual output	
Internal fault	①	1	0	1.007	0.065
	②	1	0	0.978	-0.005
	③	1	0	1.006	0.003
	④	1	0	0.996	-0.010
	⑤	1	0	1.005	0.025
	⑥	1	0	0.901	-0.031
	⑦	1	0	1.008	0.010
	⑧	1	0	1.004	-0.058
inrush	①	0	1	-0.042	0.932
	②	0	1	0.009	1.007
external fault	①	0	0	0.021	0.002
	②	0	0	0.026	-0.004

type*

Internal fault:

①: 'b'-phase turn-to-earth faults occuring on the low voltage side of the transformer at mid-point of winding winding.

②: 'a'-phase turn-to-turn faults occuring on the high voltage side of the transformer at 20% of voltage winding from the neutral point.

③: terminal two-phase(a and b) fault on the high voltage side of the transformer.

④: terminal two-phase(a and b) fault on the low voltage side of the transformer.

⑤: terminal two-phase(a and c) fault on the low voltage side of the transformer.

⑥: terminal 'a'-phase to earth fault on the low voltage side of the transformer.

⑦: terminal 'b'-phase to earth fault on the low voltage side of the transformer.

⑧: terminal 'c'-phase to earth fault on the low voltage side of the transformer.

Inrush:

①: inrush when a fault inception time is at 13ms.

②: inrush when a fault inception time is at 15ms.

External fault:

①: an external three phase fault occuring on the high voltage busbar connected to the load.

②:an external two phase fault occuring on the high voltage busbar connected to the high voltage side of transformers.

VI. CONCLUSIONS

This paper presents a novel technique for transient identification based on the detection of changes of spectral energies of high frequency current transient signals in the power transformer using the artificial neural network. The various transient events have been taken into consideration. The results show that the proposed technique is able not only to capture the high frequency current transient signals inside a transformer, but also accurately identify the cause and nature of a transient. It is an attractive alternative method to distinguish the magnetising inrush from internal faults in the power transformer protection, compared to the more traditional methods.

VII. REFERENCES

[1]. Z Q Bo, R K Aggarwal, A T Johns, "A New Measurement Technique for Power Transformer Faults", the 30th University Power Engineering Conference, University of Greenwich, 5-7 Sept. 1995

[2]. G Perez, A J Flechsig, J L Meador and Z Obradovic, "Training an Artificial Neural Network to Discriminate Between Magnetizing Inrush and Internal Fault", IEEE Trans. On Power Delivery, Vol. 9, No. 1, January 1994, pp.434~441.

[3]. J Pihler, B Grcar and D Dolinar, "Improved Operation of Power Transformer Protection Using Artificial Neural Network", IEEE Trans. On Power Delivery, Vol. 12, No. 3, July 1997, pp.1128~1136, pp.510-517.

[4]. B.Kasztenny, M.Lukowicz, E.Rosolowski, "Selecting Type of a Neural Network, Pre- and Post-processing Algorithms for Power Transformer Relaying" 32th University Power Engineering Conference, Vol.2, pp.708-712. Sept. 1997, UMIST, UK.

[5]. Walter A. Elmore , "Protective Relaying Theory and Application", ABB Power T&D Company Inc, Relay Division, Coral Springs, Florida, 1995