A Novel Inductance-Based Technique for Discrimination of Internal Faults from Magnetizing Inrush Currents in Power Transformers

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Abstract— **This paper presents a new methodology for discrimination between inrush currents and internal faults for a three-phase power transformer. This algorithm is based on instantaneous inductance. First, this method calculates differential inductance of transformer phases from primary side view of transformer by using voltage and current signals. Then, the algorithm compares differential inductance with a threshold value. If the calculated criterion is over than the threshold, disturbance will be inrush current. Otherwise, if the calculated criterion is lower than the threshold, disturbance will be internal fault. The operating time is less than 5 ms, less than 1/4 rd of power frequency cycle. The scheme uses voltage and current signal; hence it can work reliably in the presence of transformer tap variation, fault resistance and as shown later, the criterion works properly in CT saturation or over-flux condition. Simulation studies with respect to different faults and inrush conditions have been conducted and the results proved that the proposed technique is able to offer fast responses in protection and accurately discriminate between inrush currents and internal faults.**

***Keywords-* Equivalent inductance, inrush current, internal fault, transformer protection.**

I. INTRODUCTION

It is obvious that performance of power systems directly relates to the power transformers. In this regard, transformer protection shows itself essential case. The important objective of transformer protection is to detect internal faults from magnetizing inrush currents with a high and also good performance in all condition such as in external fault, in over-flux or CT saturation condition. There are different kinds of inrush current such as sympathetic inrush current or switching inrush current. Nevertheless, in some cases sensitive detection in transformer de-energization enables the faults damage to system and hence it is necessary to be limited. However, it should be able to provide backup protection through faults on the system, as these could lead to deterioration and accelerated aging or failure of the transformer. Winding insulation due to over-heating and high impact forces causes in the windings due to high fault currents. Moreover, abnormal system conditions such as over-flux, over voltage and loss of cooling about internal faults, can lead to deterioration of the transformer. Hence, protection again these failures should be considered as part of the transformer protection scheme. With the advent of electrical system, transformer protections are studied under various situations and conditions. Therefore, their protection can be vastly categorized not only as electrical protection implemented by sensing the current through it, but also voltage and frequency, as mechanical protection implemented by sensing operational parameters like oil pressure, gas evolved and winding temperature. In finance affairs, as every electrical engineer knows, in transformer protection too, the extent of protective devices applied to a particular transformer is dictated by the economics of the protection scheme, and the probability of a particular type of failure and the cost of replacing and repairing the transformer as well the possibility of the failure causing to adjacent equipment damage. Failure costs include all of the direct and indirect costs related to it. Disconnecting device, circuit breaker and other auxiliaries like batteries are necessary infrastructure and costlier protection schemes. Recently, many studies have done in transformer differential protection. An inductance technique for discrimination between inrush currents and internal faults is suggested in [1]. A morphological scheme for inrush identification in transformer protection was presented in [2]. Ref [3] proposed a new method to identify inrush current based on error estimation. In [4] a wavelet based method and in [5, 6], artificial neural network (ANN) was trained to distinguish between inrush and internal fault currents. In [7], a set of developed fuzzy laws based on differential current harmonics has been proposed as differential protection algorithm. Ref [8] proposed a sequential phase energization method for transformer inrush current reduction transient performance and practical considerations. One of the other methods operates via measurement of intervals between two successive peaks of differential current waveform is introduced in [9, 10]. The operation criterion in another method is the duration in which differential current waveform remains near zero. In some of these methods, differential current harmonics are used as inputs to a learned neural network [11]. The output of the neural network indicates transformer situation.

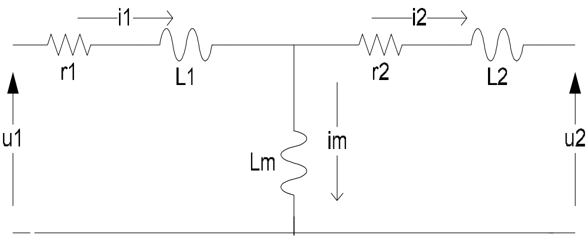

Fig. 2. Transformer model

Moreover, some algorithms based on wavelet analysis are reported in [12]. These approaches are still liable to cause malfunction of relays. In this paper, a novel inductance-based scheme is introduced for power transformer protection. This method calculates differential inductance of every phase of the transformer and by comparing it with a threshold, sent the trip signal.

II. METHODOLOGY

The effect of an inductor in a circuit is to oppose changes in current through it by developing a voltage across it proportional to the rate of change of the current. An ideal inductor would offer no resistance to a constant direct current; however, only superconducting inductors have truly zero electrical resistance. The relationship between the time-varying voltage v(t) across an inductor with inductance L and the time-varying current i(t) passing through is described by the differential equation:

$$v(t) = L\frac{di(t)}{dt} \tag{1}$$

When a sinusoidal alternating current (AC) through an inductor is produced, a sinusoidal voltage is induced. The amplitude of the voltage is proportional to the product of the amplitude of the current and the frequency (f) of the current as follows:

$$i(t) = I_p \sin(2\pi f t) \tag{2}$$

$$\frac{di(t)}{dt} = 2\pi f I_p \cos(2\pi f t) \tag{3}$$

$$v(t) = 2\pi f L I_p \cos(2\pi f t) \tag{4}$$

According to KCL and KVL rules and Fig. 2, in a transformer for every phase have:

$$u_1 = r_1 i_1 + L_1\frac{di_1}{dt} + \frac{d}{dt}((L_m)i_m) \tag{5}$$

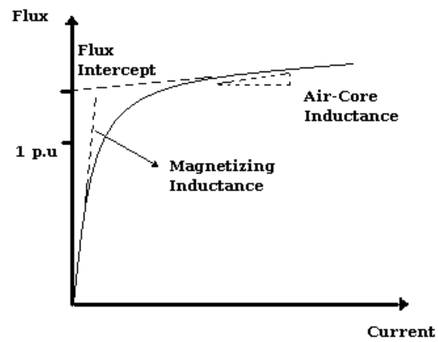

Fig.3. Magnetizing inductance

$$\frac{d}{dt}((L_m)i_m) = L_m\frac{di_m}{dt} \tag{6}$$

$$\Rightarrow L_m = \frac{d\varphi_m}{di_m} \tag{7}$$

$$u_1 - u_2 = (r_1 i_1 - r_2 i_2) + (L_1\frac{di_1}{dt} - L_2\frac{di_2}{dt}) + (\frac{d}{dt}(L_m i_m) - \frac{d}{dt}(L_m i_m)) \tag{8}$$

Then, using (8), the differential inductance from primary and secondary sides of transformer can be calculated. It means that using the differential current and the voltage with regarding the (8) and (9) get (10) and differential inductance (criterion) can be calculated by (11).

$$u = ri + L\frac{di}{dt} \tag{9}$$

$$(1-\frac{n_1}{n_2})u_1 = (r_1 - r_2\frac{n_1}{n_2})i_1 + (L_1 - L_2\frac{n_1}{n_2})\frac{di_1}{dt} \tag{10}$$

Suppose for i=k and i=k+1, it can be written:

$$Criterion = L = k\frac{(u_{(k-2)} \times i_{(k-1)} - u_{(k-2)} \times i_{(k-1)})}{(i^2_{(k-2)} + i^2_{(k-1)} + 2i_{(k-1)} i_{(k-1)} - 2i_{(k-2)} \times i_{(k)})} \tag{11}$$

Where i is differential current in sample k_{th}, u is voltage sample in sample k^{th} and k is a constant. Magnetizing inductance shows itself in Fig. 3. It is found from Fig. 3, magnetizing inductance is an intrinsic feature of an inrush current, but internal fault does not have it. It is relates to this truth, which in internal fault, current does not pass from magnetizing branch, but in inrush it does. According to the results, this criterion strongly differs for internal fault from magnetizing inrush current. Fig.9, 10 and 11 shows the criterion values for inrush current case. After faulty time, the criterion does not have large changes but in internal fault as shown later, criterion changes by step state and will fix in second value as soon as possible.

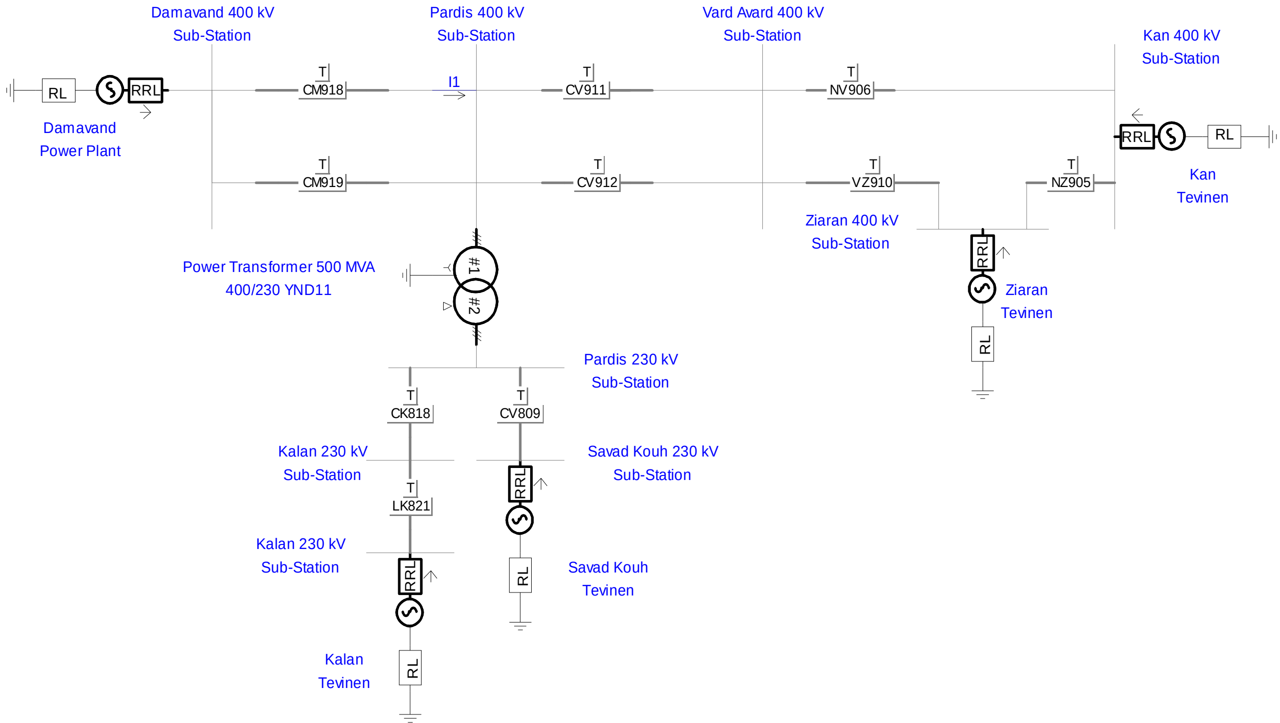

Fig. 4. Power system schematic.

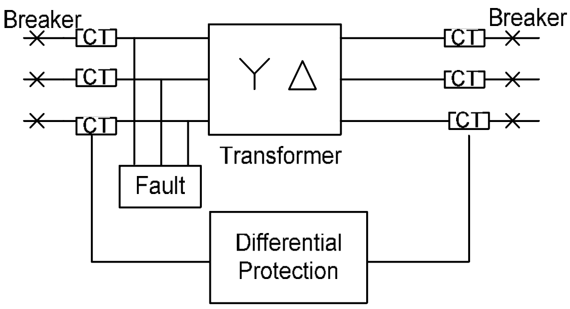

Fig. 5. Three-phase internal fault model.

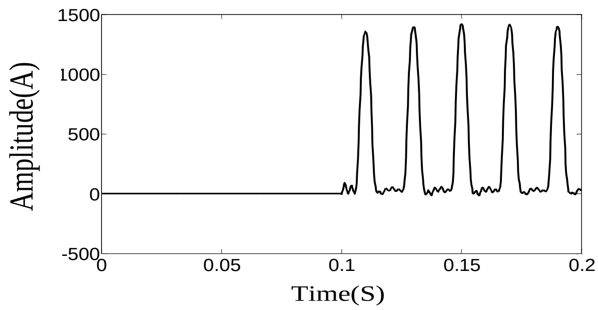

Fig. 6. Typical inrush current.

III. Simulation Results

A. Simulated Network

Power system schematic is shown in Fig. 4. A 500 MVA transformer is used to this study. The transformer is a real power transformer in a real network in Iran. Single transformer model is depicted in Fig. 2. For internal modeling, according to the Fig. 5, fault is located between the CTs and the transformer. Fig. 4 shows the simulated power system schematic. The current and voltage of transformer are generated by PSCAD/EMTDC. Transformer capacity is 500 MVA and its rated voltage U1/U2 is 400kV/230kV. The remnant magnetization is 0% Bm. The sampling frequency is 64 sampling points per cycle, and Butterworth low-pass filter with cutoff frequency 1920 Hz is used for filtering. Also, noise-filtering have done for increasing the accuracy of the inductance calculation.

B. Results

1) Inrush Condition

Fig. 6 shows a typical inrush current. Due to inrush current, differential current have special form and it is cause to such criterion, which differs from internal fault criterion value. According to the Figs. 7, 8 and 9 inrush current, the calculated criterion have no large changes after the fault detection, but in internal fault, which is show later, criterion suddenly dropped. Figs. 7, 8 and 9 show the criterion in transformer energizing. The main flux of the core increases greatly when the transformer switches on without load, which results the saturation of the core and generates the inrush current. This is because the core alternatively operates at the linear area and the saturation area of the excitation curve. The excitation current of this study is derived using CTs of every phase.

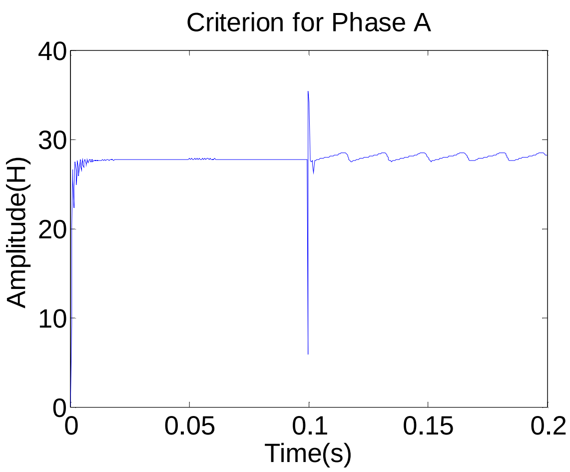

Fig. 7. Criterion value due to inrush current for phase A.

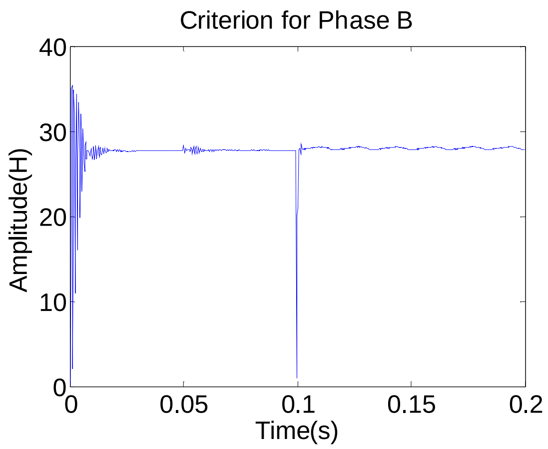

Fig. 8. Criterion value due to inrush current for phase B.

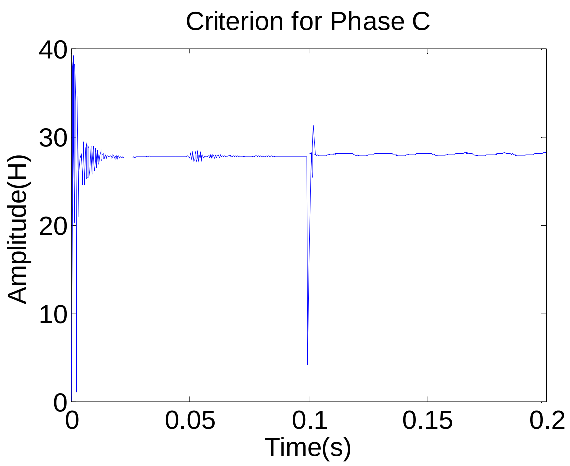

Fig. 9. Criterion value due to inrush current for phase C

2) Internal Fault

As told previously, due to the internal fault, because of the differential current and voltage, calculated criterion differs from magnetizing inrush current case. Also, this change is differed to inrush current case. Nevertheless, this change gives a good criterion, which is introduced previously. Figs. 10, 11 and 12 shows the criterion for internal fault cases, which is strongly different from inrush case. It is found from the Figs.

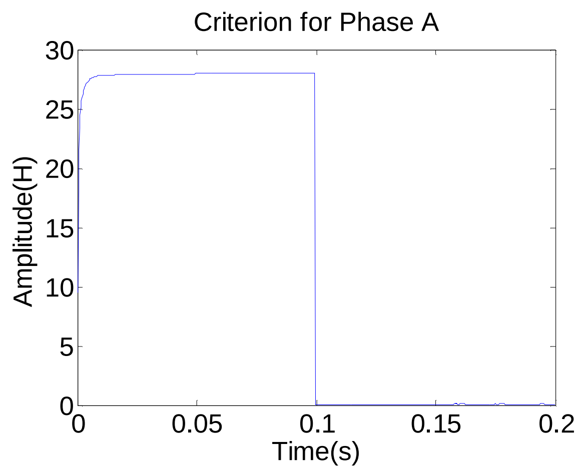

Fig.10. Criterion value due to internal fault for phase B (A-B-fault).

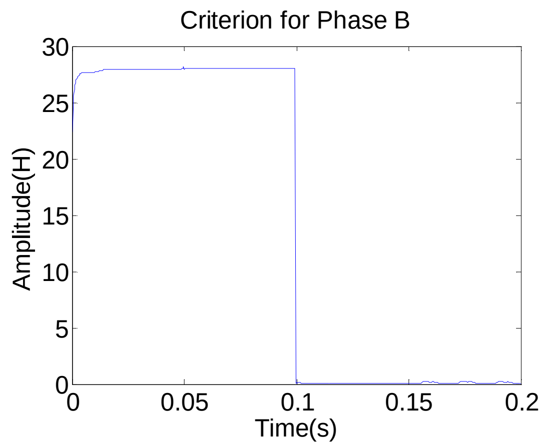

Fig. 11. Criterion value due to internal fault for phase A (A-B-fault).

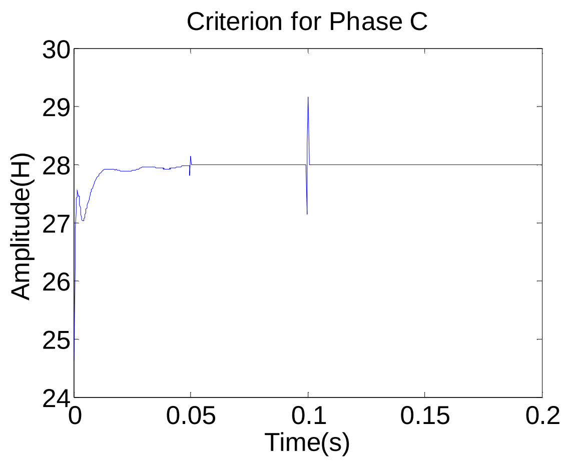

Fig. 12. Criterion value due to internal fault for phase C (A-B-fault).

10 to 12 that in internal fault, criterion value changes in step state, which it is significantly different from inrush current.

3) External Fault with CT Saturation

Current Transformers (CT) are transformer instruments that are used to supply a reduced value of current to meters, protective relays, and other instruments. CT provides isolation

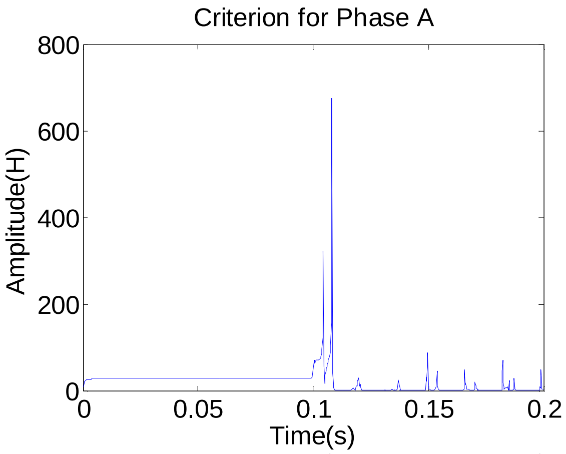

Fig. 13. Criterion value due to external fault with CT saturation for phase A

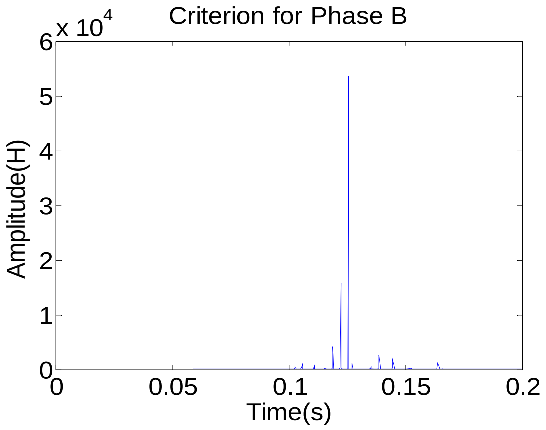

Fig. 14. Criterion value due to external fault with CT saturation for phase B

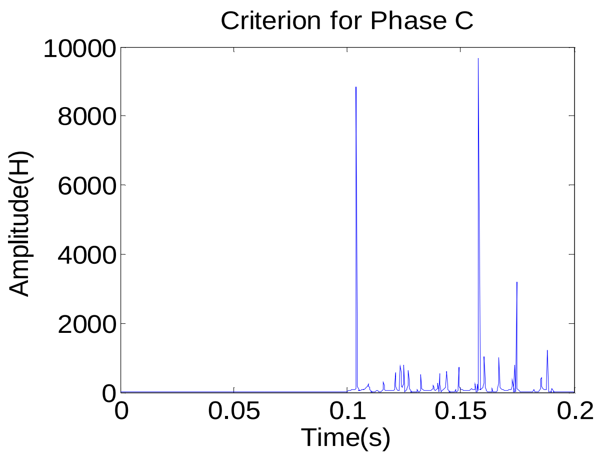

Fig. 15. Criterion value due to external fault with CT saturation for phase C

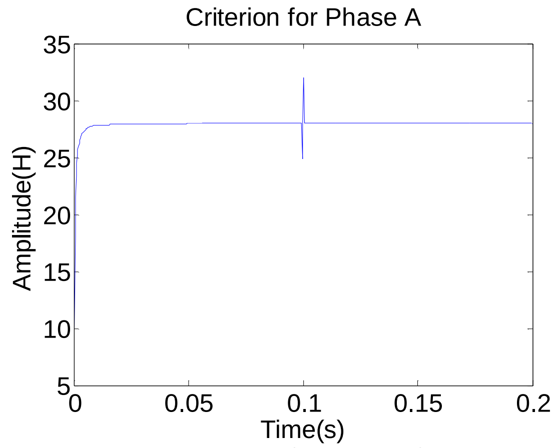

Fig. 16. Criterion value due to over-flux condition for phase A.

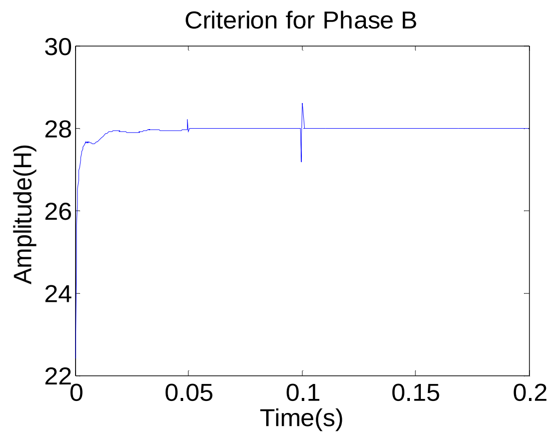

Fig. 17. Criterion value due to over-flux condition for phase A.

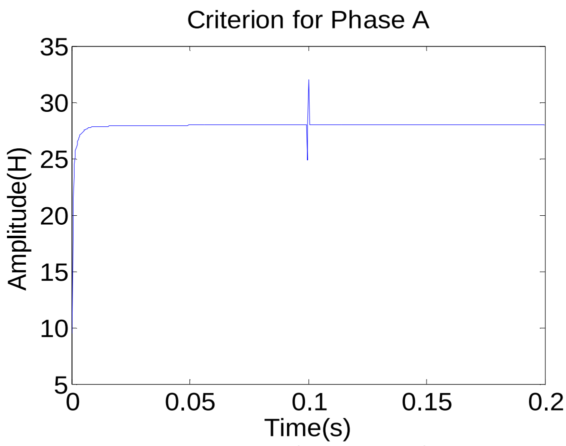

Fig. 18. Criterion value due to over-flux condition for phase A.

from the high voltage primary, permit grounding of the secondary for safety, and step-down the magnitude of the measured current to a value that can be safely handled by the instruments. Due to the CT saturation condition, formation of the current are changed, as a results, current estimation goes to wrong and this cause to mal-operation of some relay such as differential or distance relays. Some external fault leads to CT saturation, which are near to transformer. In this regard Figs 13, 14 and 15 show the results for CT saturation condition. Results show the introduced criterion has the ability to identify inrush current from internal fault in this situation too. Because of current formation in criterion calculation, there are some high peaks.

4) Over-Flux Condition

There are several reasons for over-flux condition. Transformers over voltage or frequency dropt are some of that reasons. Protection against over-flux conditions does not require high

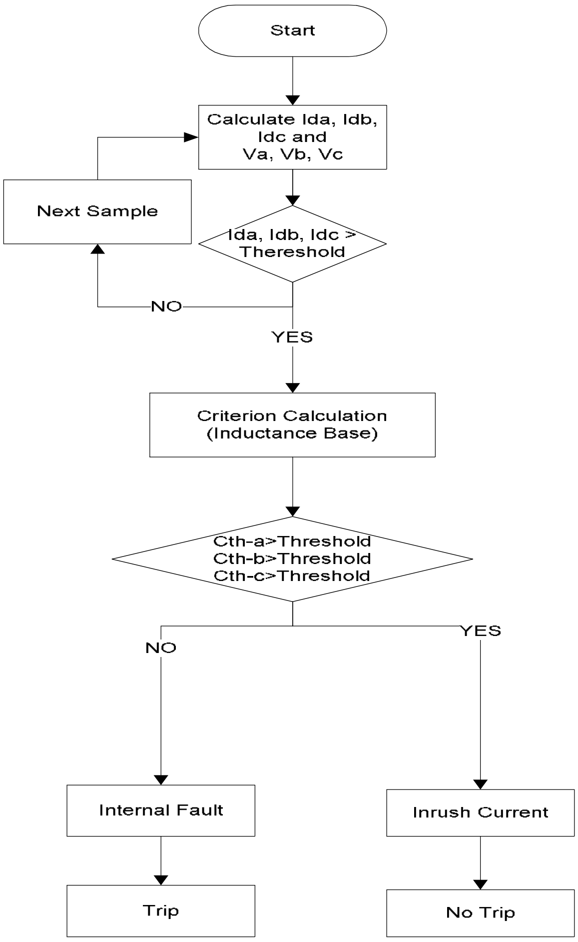

Fig. 19. Proposed flowchart

speed tripping. In fact, instantaneous tripping is undesirable, as it would cause tripping for transient system disturbances, which are not damaging to the transformer. Figs. 16, 17 and18 show the results for over-flux condition. It is obvious in this case, relay does not act because the criterion outlet is not similar to internal fault case and this is desirable.

It is found from various simulations and tests, the criterion have the ability to identify inrush currents from internal currents in power system. Therefore, flowchart Fig. 23 is introduced to discriminate inrush from internal fault current. A good C_{th}(Criterion Threshold) can be about 0.1-0.2.

IV. CONCLUSION

In this paper, a new inductance based-algorithm introduced for discrimination between inrush currents and internal faults. This method calculates the instantaneous differential inductance from primary view of the transformer sides. The validity of the proposed criterion was exhaustively tested by simulating various types of internal faults, external faults and energization conditions in PSCAD/EMTDC with a 500 MVA, 400kV/230kV, Y–Delta transformer. The proposed algorithm is able to properly discriminate between internal faults, external faults and non-fault disturbances for almost cases such as CT saturation and over-flux condition.

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