Identifying Inrush Currents from Internal Faults using Symmetrical Components in Power Transformers

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Abstract— **This paper presents a novel technique for three phase transformer protection, which the method effectively identify magnetizing inrush currents from internal fault currents. This technique employs symmetrical components. When transformer is switched, inrush current happens. This current have some features, which it is enough for identify itself. In this paper, by extract these features, a new criterion is proposed to discriminate inrush currents from internal faults in power transformers. In faulty time such as switching or short circuit, the value of negative sequence for differential current is different from positive sequence value. Helping this feature, new criterion is introduced. Simulations show this criterion works properly in over-flux and CT saturation condition too. The simulated results presented clearly, the proposed algorithm can accurately discriminate between an internal fault and a magnetizing inrush current in power transformer protection in all cases.**

Keywords- Symmetrical component, inrush current, internal fault, transformer protection

I. INTRODUCTION

Power system protection is one of the electrical engineering fields that relates to the electrical power systems protection and its duty is isolation of faulty parts from the rest of the electrical network. It is necessary to protection schemes to apply a very pragmatic approach to clear system faults. For this reason, the technology utilized in protection schemes can often be old and well-established because they should be very reliable. One of the important issue for protection scheme is to keep the power system stable by isolating only the components that are under fault, whilst leaving as much of the network as possible still in operation. Therefore, there are different types of protection for transforms. The transformer protection provided by multiple function protective relays is appropriate for critical transformers of all applications. In below, some common protection schemes are expressing:

- differential current protection
- over current protection
- over excitation protection
- over voltage protection

Over current protection is commonly used for protection for phase and ground faults [12]. It is used to primary protection where differential protection is not used; it is used to backup protection if differential protection has been used. Over current protection zone is usually more than the transformer. Therefore, they are part of the system protection and need to be coordinated with the other system protection devices. In this paper, it is paid to the differential protection of the transformer. So far, many studied have performed for transformer differential protection. One of those is a method based on desensitizing or delaying the relay to overcome the transients [1]. Ref [2] proposed an equivalent instantaneous inductance-based technique for discrimination between inrush current and internal faults in power transformers. Also, harmonic restraint differential protection is a common method to detect inrush current from magnetizing inrush current. Ref [3] proposed an algorithm for harmonic restraint differential relaying based on the discrete Hartley transform. Ref [4] proposed a method based on the use of one of the primary phase voltage as the control signal. Various artificial intelligent (AI) techniques are introduced to power system protection [5, 6]. Saleh et al. [7] and Eissa [8] proposed a wavelet packet based algorithm for transformer protection. Sheng et al. [9] proposed the use of decision trees and wavelet analysis for the protection of large transformers.

In this paper using the symmetrical component, a new scheme is introduced for transformer protection. This studied simulated by PSCAD/EMTDC in all items such normal situation, inrush condition, internal fault, CT saturation and over-flux condition. Results proved the proposed algorithm works properly in all conditions.

II. DIFFERENTIAL PROTECTION BASIC

A. Differential protection Problems

The philosophy of transformer differential protection is protecting transformer through internal fault from magnetizing inrush current, also, it has different advantages [11]. Internal fault is based on the possibility of mechanical of the windings due to the fault current, rather than on thermal characteristics of the transformer. Generally speaking, differential protection provides the best overall protection for transformer. Also, in some cases, for example ungrounded or high impedance grounding, it cannot provide ground fault protection. Differential protection is normally applied to transformers 10 MVA and above it. Also it depends on its critical protection

item. There are factors affect the differential current in transformers and can be considered due to differential protection. They are as follows [12]:

1. *Magnetizing inrush current*-In magnetizing inrush condition the peak amplitude of current can be as high as 8-30 times the rated current, which is depending upon the transformer and system resistance. Normal magnetizing current is 2-5 times of the rated current.

2. *Over excitation*- It relates to generator-transformer units (voltage/frequency unit). Also it came back to transmission transformers where line capacitance is more than inductance and some light load conditions can lead to high voltage on the transformer. Transformers are normally designed to operate just below the flux saturation level. Any increase from the max voltage (voltage/frequency ratio), can leads to core saturation.

3. *CT Saturation*- External faults near to transformer often lead to CT saturation. Distortion of the saturated CT current leads to mal-operation of differential relays. Also, values of harmonic current in the saturated CT can cause a delay in the operation of the differential relay during internal faults. A proper CT selection ratio is essential to minimize problems due to the saturation.

Different primary and secondary voltage levels, phase displacement in Δ/Y transformers, control taps of voltage transformer and phase shift in regulating transformers are another factors affect the differential current.

B. Percentage Differential Relay

Differential relays with percentage characteristics in the range of 15 to 60% are applied to transformers to account for the variables less sensitive percentage. Moreover, in numeric relays, harmonic restraints can be used. The second harmonic is the dominant harmonic in the magnetic inrush current. Therefore, a second harmonic restraint is utilized to prevent relay from operating during the inrush condition. Over excitation includes high magnitudes of the odd harmonic, normally 25% of the third component and 11% of the fifth component. In over excitation condition, relay has been used the fifth harmonic signal to block the differential trip signal. Otherwise, it is used to restraint the relay operation. Moreover, to the fixed the percentage differential relays, variable percentage relays are also used [12].

C. Differential Relay Connections

Transformer differential relay have some consideration in connection; one of the basic rules of it is all the currents should be accounted for per unit per phase:

1. The number of restraint windings used should be at least equal to the number of transformer windings.
2. A restraint winding should be used for each fault source.
3. If CTs of the feeder side are paralleled, they should be considered.

The current should be in phase as well as the current difference should be small (ideally zero) for load and through fault conditions. The way to method to achieve this is a two step process as below [11]:

1. *Phasing*- Using suitable Δ/Y CT units to ensure that the primary and secondary currents are in phase.

2. *Ratio Adjustment*- Having decided on the CT connections, the CT ratio and the relay tap is selected so as to have minimum relay operating current.

III. METHODOLOGY

Symmetrical components are commonly used for three-phase electrical power systems analysis [11]. If the phase quantities are expressed in phasor notation using complex numbers, a vector can be formed for the three phase quantities. For example, a vector for three phase voltages can be written as follows:

$$V_{abc} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{1}$$

Therefore, the three symmetrical components phasors arranged into a vector are as follows:

$$V_{012} = \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \tag{2}$$

Where the subscripts 0, 1, and 2 in (2) respectively refer to the zero, positive, and negative sequence components. A phase rotation operator 'a' is defined in (3) to rotate a phasor vector forward by 120 degrees. Matrix A can be defined using this operator to transform the phase vector into symmetrical components:

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \tag{3}$$

The phase voltages are generated by the sequence equation.

$$V_{abc} = A V_{012} \tag{4}$$

Conversely, the sequence components are generated from the analysis equations.
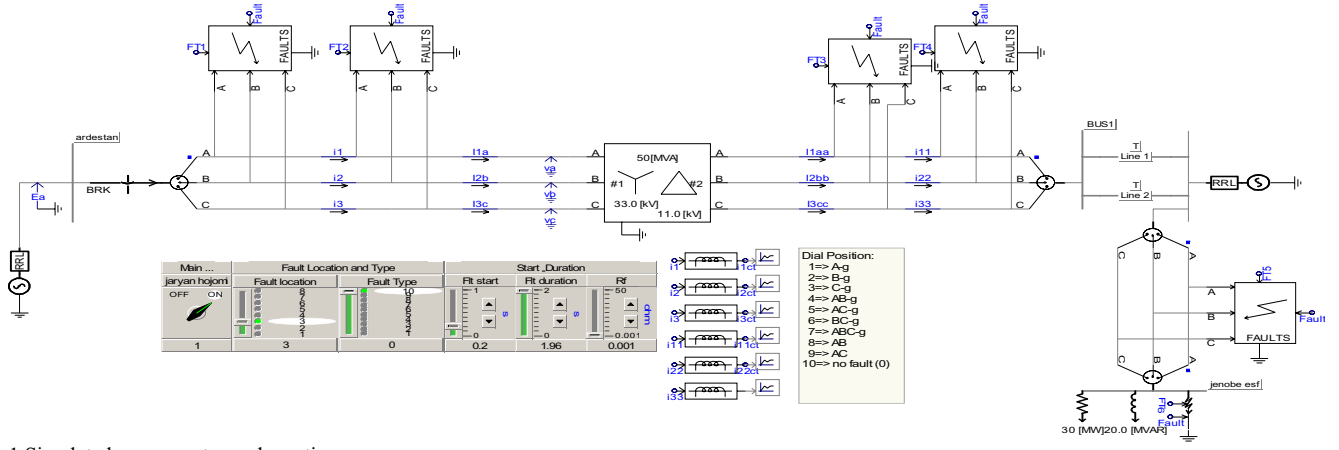
$$V_{012} = A^{-1} V_{abc} \tag{5}$$

Fig. 1.Simulated power system schematic.

where:

$$A^{-1} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \quad (6)$$

When transformer is switched, inrush current will happen. This current have some features, which it is enough for identify itself. In this paper, with extract these features, a new criterion is proposed to discriminate inrush currents from internal faults in power transformers. The point is the value of negative sequence is different from positive sequence in faulty conditions. Helping this rule, the criterion is introduced. Every voltage and current can be written as follows:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \times \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \quad (7)$$

$$\alpha = \alpha\angle 120 \Rightarrow I_a = 1\angle 0, \ I_b = 1\angle +120, \ I_c = 1\angle -120 \quad (8)$$

In faulty condition, it is obvious that the value of I_2 (negative current) is larger than I_1 (positive current) in normal condition [10]. Using this feature, define new below criterion:

$$Criterion = \frac{I_1^2 - I_2^2}{I_1^2 + I_2^2} \quad (9)$$

This criterion has some advantages from other criterion, see [10]. For example defined criterion in (9) works properly in over-flux condition or in CT saturation due to inrush or internal fault condition but introduced criterion in [10] cannot. In phase to ground fault, have:

$$I_2 = I_1 = \frac{v_f}{Z_0 + Z_1 + Z_2 + 3Z_f} \quad (10)$$

Where Z_f is impedance between phase and ground, Z_0 is zero sequence impedance, Z_1 is positive sequence impedance and Z_2 is negative sequence impedance. In phase to phase to ground fault have:
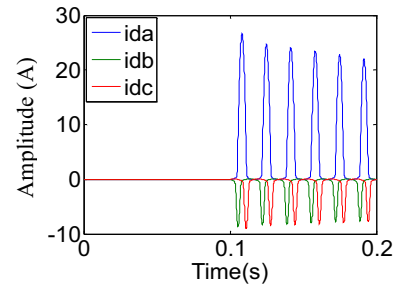

Fig. 2. Typical inrush current.

$$I_2 = (-I_1) \times \frac{Z_0 + 3Z_f}{Z_0 + Z_2 + 3Z_f} \quad (11)$$

Replacement (10) to (9), threshold of phase to ground fault, the criterion will be almost zero, and for the threshold of phase to phase to ground have:

$$Criterion_{threshold} = \frac{2Z_2(Z_2 + 3Z_f)}{(Z_0 + Z_2 + 3Z_f)^2 + (Z_0 + 3Z_f)^2} \quad (12)$$

IV. SIMULATION RESULTS

A. Simulated Network

Using PSCAD/EMTDC, a real network in Iran is simulated. Transformer capacity is 30 MVA in rate 33kV/11kV. The transformer is a real power transformer. Fig. 1 shows the simulated power system schematic. Also, a typical inrush current is shown in Fig. 2.

B. Results

1) Normal Condition

In normal condition, differential current is near to zero. So, the values of the positive, negative and zero sequence do not strongly change. Fig 3 shows the sequence current in nominal condition.
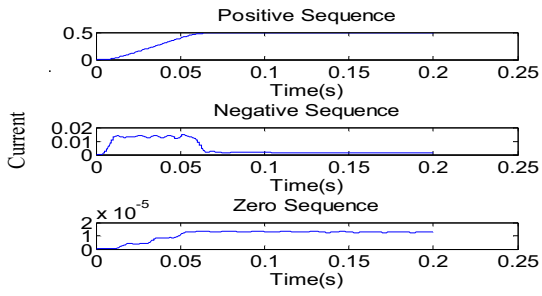
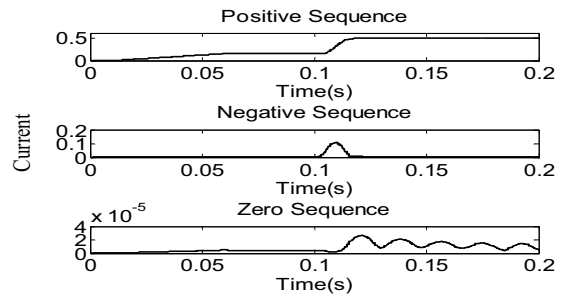Fig. 3.   Sequence currents for I_{diff} in normal condition.

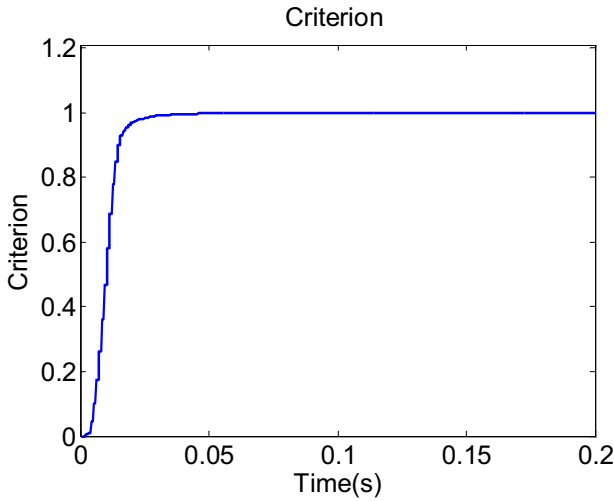Fig. 4.   Criterion value for I_{diff} in normal condition.

Fig. 5.   Sequence currents for I_{diff} for inrush condition.
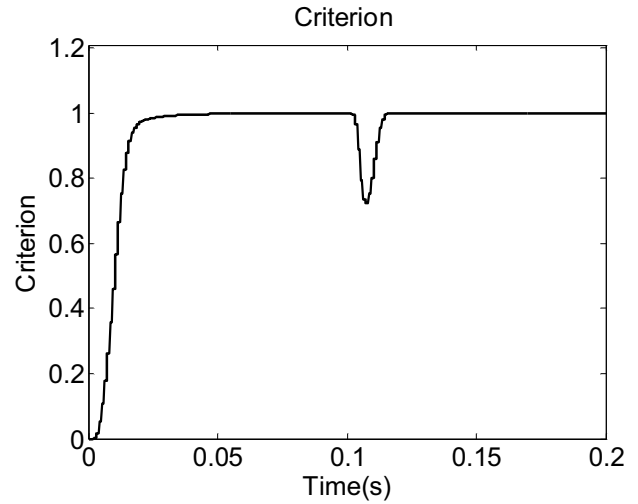

Fig. 6.   Criterion value for I_{diff} for inrush condition.

Fig. 7.   Sequence currents for I_{diff} for internal fault (AB).

Fig. 8.   Criterion value for I_{diff} for internal fault (AB).

Fig. 4 shows the calculated criterion for I_{diff} in normal condition for phase A.

2)   Inrush Condition

During switching, inrush current happens, and current are produced like Fig. 5. This Fig shows the typical inrush current. But the values of the positive, negative and zero sequence for inrush current are different from normal operation (Figs. 5). It is because of this truth that a disturbance is imposed to network. Anyway, the criterion will be like Fig. 6. But threshold value of it is like equation (12). It calculated in this network and is 0.256. Then, if the criterion is more than 0.256, disturbance will be inrush current. In general condition, the criterion can be varied due to 0.15 to 0.25.

3)   Internal Fault Condition

Modeling of the internal fault is a complex simulation, so, we put faults between the CTs and transformer for internal fault modeling. Fig. 7 shows the sequence currents for AB internal fault. Fig. 8 shows the criterion, which it is lower than 0.15, therefore, it is an internal fault. It is obvious the criterion is lower than 0.15, so it is an internal fault.
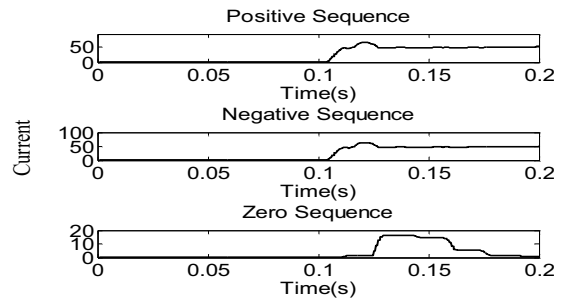
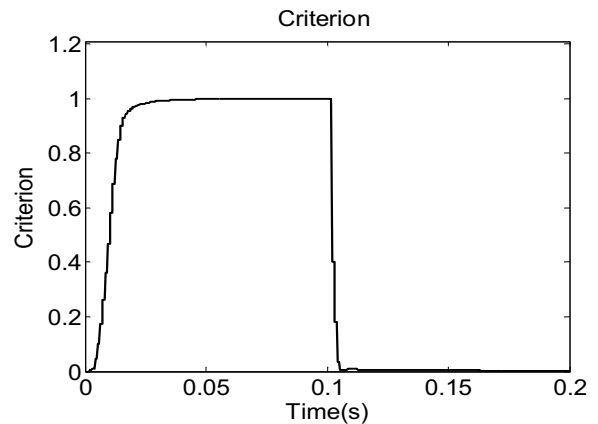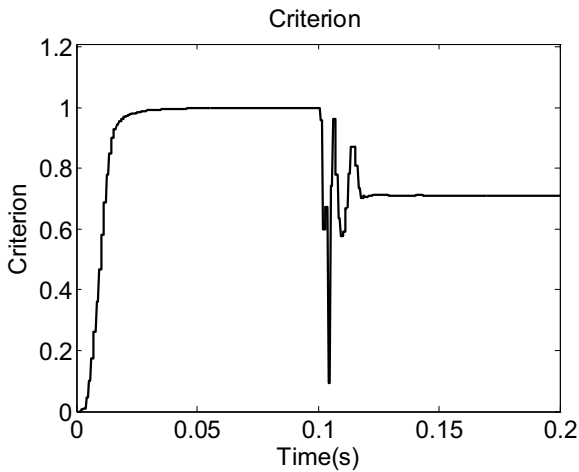Fig. 9. Criterion value for I_{diff} for external fault with CT saturation condition.

4) External Fault Condition

Some extreme external faults near to transformer cause to CT saturation. During the CT saturation, currents are not in common formation, so the rms value of them changes. Moreover, introduced harmonics cause mal-operation of relays. Fig. 9 shows the result for external fault with CT saturation. It can be found from Fig. 9 that the criterion value in CT saturation condition is different in compare to internal fault. Using the introduced criterion in saturation condition, relays can work more reliable with more accuracy.

5) Over-Flux Condition

In over-flux condition, values of the positive, negative and zero sequence for differential have sudden changes. So, it can help us to detect this situation. In this case, criterion value is over 0.15 and cannot lead to signal trip. Figs. 10 show sequence currents and Fig. 11 shows the calculated criterion for over-flux condition.

As discussed, in all cases, this criterion can discriminate inrush currents from internal faults. Therefore, flowchart in Fig. 12 proposed to this algorithm. This algorithm reduces the time of blocking transformer in inrush current due to switching time in power system. If the calculated criterion is less than 0.256, disturbance will be internal fault and relay will trip.
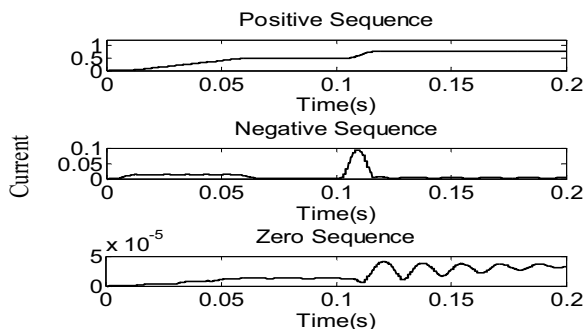

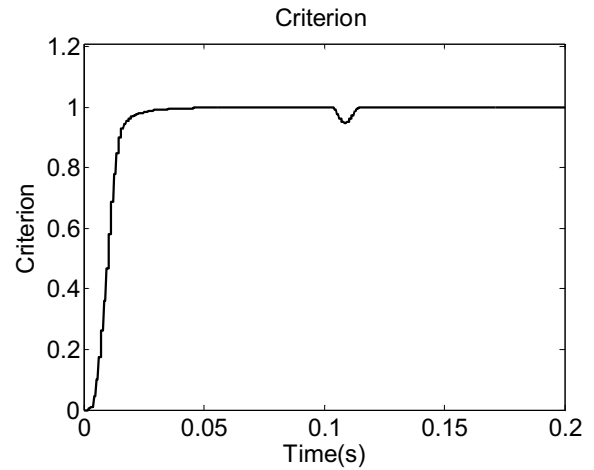Fig. 10. Sequence currents for I_{diff} in over-flux condition.

Fig. 11. Criterion value for I_{diff} for over-flux condition.
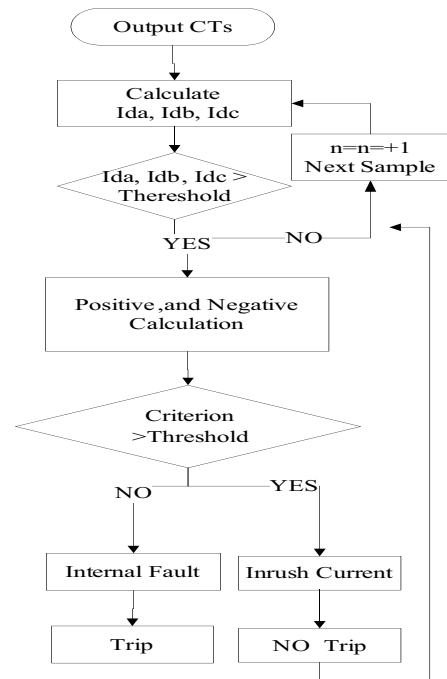

Fig. 12. Proposed algorithm flowchart.

V. CONCLUSION

Transformer switching can cause some problems because mal-operation of power system relays. In this paper, a novel methodology is presented to identify inrush currents from internal fault currents. First, symmetrical component of inrush current or internal fault current extracted. Then, a new criterion introduced to discriminate inrush currents from internal faults. Power system simulated is a real network. Moreover, it was shown that, this criterion have the ability to work properly in CT saturation or over-flux condition. Simulation results obtained with the developed models were presented and it is found almost in all cases, new criterion works well.

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