Current and Voltage Ratio Method for Power Transformer Differential Protection

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Abstract- In this review paper, a fast and efficient differential relay algorithm that isolates the power transformer from the system causing least damage is proposed. The algorithm must evade mal operation while differentiating between the operating conditions. This paper presents an enhanced differential protection scheme for power transformer. The proposed scheme is based on the ratio of the absolute difference and absolute sum of the primary and secondary currents of each phase, supplemented by the ratio of the absolute difference and absolute sum of the primary and secondary terminal voltages of each phase. The projected algorithm aims at avoiding mal-operation, possible with the conservative three-phase transformers differential protection scheme due to transient phenomena, including the magnetic inrush current, simultaneous inrush with internal fault, and faults with current transformer saturation. Analysis of the proposed differential protection scheme using both current and voltage ratios shows that it can provide fast, accurate, secure and dependable relay for power transformers.

Keywords- CT ratio, PT ratio, differential relay algorithm

I.   INTRODUCTION

The relays used in power system protection are of different types. Proper continuous monitoring of power transformer can provide early warning of electrical failure and can prevent catastrophic losses. It can minimize damages and enhanced the reliability of power supply. Accordingly, high expectations are imposed on power transformer protective relays. Expectations from protective relays include dependability (no missing operations), security (no false tripping), speed of operation (short fault clearing time) and stability. Differential relaying principle is used for protection of medium and large power transformers. Among them differential relay is very commonly used relay for protecting transformers and generators from localized faults. Differential relays are very sensitive to the faults occurred within the zone of protection but they are least sensitive to the faults that occur outside the protected zone. Most of the relays operate when any quantity exceeds beyond a predetermined value for example over current relay operates when current through it exceeds predetermined value. But the principle of differential relay is somewhat different. It operates depending upon the difference between two or more similar electrical quantities. This superior approach compares the currents at all terminals of the protected transformer by computing and monitoring a differential (unbalance) current. When there is large and sudden change in the input terminal voltage of transformer, either due to switching-in or due to recovery from external fault, a large current is drawn by the transformer from supply. Similar condition occurs when transformer is energized in parallel with a transformer that is already in service, known as "*sympathetic inrush*" condition. This results in core of transformer getting saturated. This phenomenon is known as magnetizing inrush or in other words, inrush can be described by a condition of large differential current occurring from either the transformer is just switched-in or the system recovers from an external fault or a transformer in energized in parallel to already operated transformer. Magnetizing inrush current may be as high of the order of 10 times of full load current [1]. This resulting high differential current may cause the relay to operate. To avoid the mal- operation of relay, discrimination between magnetizing inrush current and fault current is required.
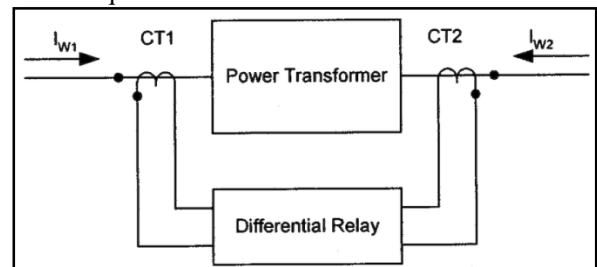

Fig.1: Typical Connection diagram for Differential Relay

II.   LITERATURE REVIEW

Power transformers, one of the most important equipment in power systems, are subject to faults, similar to any other component of the power system. About 10% of the faults take place inside the transformers and 70% of these faults are caused by short circuits in the windings [1]. The choice of protection depends on the criticality of the load, relative size of the transformer compared to the total system load and potential safety concerns. Percentage differential protection is the most widely used scheme for the protection of transformers rated 10 MVA and above [2]. It is, however,

recognized that the percentage differential relay can mal-operate due to various phenomena [2] related to the nonlinearities in the transformer core. The major concern in power transformer protection is to avoid mal-operation of protective relays due to transient phenomena including magnetic inrush current, simultaneous inrush with internal fault, external faults with current transformer (ct) saturation.

Many approaches to distinguish between inrush and internal fault currents have been proposed. Harmonic restraint is one of the simplest and most widely used approaches [3–7]. This approach has limitations with new low-loss amorphous core materials in modern transformers. These materials produce low harmonic content during magnetizing inrush current. Also, internal faults might contain sufficient amount of second and fifth harmonics like inrush current. So, it is hard to distinguish between internal fault and energization.

Other approaches have been developed to overcome the above limitations. These approaches include voltage and flux restraints [8–10] and inductance based methods [11–14]. These approaches have high dependence on transformer parameters. Digital signal processing approaches also have been proposed to avoid maloperation of transformer differential protection. Among these approaches are pattern recognition based on neural networks [15–18] and fuzzy logic [19–24]. Their main drawbacks include the need for more training, complex computation, large memory and complex setup of experimental work [25].

Recently, wavelet transforms have been used with transformer differential protection [25–28]. Studies report that this approach has better ability of time-frequency location. Their shortcomings are that they need long data window and are also sensitive to noise and unpredicted disturbances, which limit their application in relaying [29]. The approaches mentioned above have limitations especially when the internal fault includes fault resistance and during transformer energization with internal fault that may affect their speed and security.
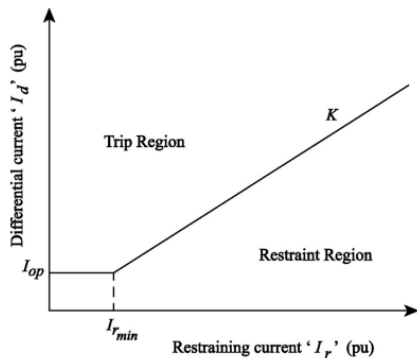

Fig.2: Characteristic of Percentage differential relay

An approach using current and voltage ratios to address the challenges faced by the differential protection scheme for power three-phase transformers is proposed in this paper. The current ratio is used to discriminate between fault current and inrush current during no-load energization, and the voltage ratio is used to detect transformer energization on internal fault. Also, current direction criterion is used to discriminate between internal faults and external faults or loaded energization.

III.   PROPOSED METHDOLOGY

The proposed scheme is evaluated by studies such as inrush conditions, internal fault, external fault combined with ct saturation and simultaneous inrush with internal fault. The results demonstrate that the proposed discrimination scheme is fast, accurate, simple and robust to settings that improves the security and dependability of the power transformer protection.

A.   Percentage Differential Relay

The basis of the conventional percentage differential relay is that the differential current (Id) is more than a predetermined percentage of the restraint current (Ir). Characteristic of the percentage relay is shown in Fig. 2 . Magnitude of the fundamental component of the difference between the sampled values of the primary (i1) and secondary (i2) currents in per unit of each phase of the transformer, as measured by cts' secondary, is obtained using one cycle Discrete Fourier Transform (DFT). The differential current may be expressed as [30],

$$Id = Fundamental\ of\ (|i1(k) − i2(k)|) \qquad (1)$$

Likewise, the restraining current is calculated as;

$$Ir = Fundamental\ of\ (|i1(k) + i2(k)|)/2 \qquad (2)$$

The operating characteristic of percentage differential relay is calculated as;

$$\{Id \geq Iop\}\&\{Id \geq K\ (Ir − Irmin) + Iop\} \qquad (3)$$

where, I_{op} is the minimum operating current (0.2 pu), I_{rmin} is the minimum restraining current (0.6 pu) and K is the restraint coefficient (20%). The relay is biased for tap-changing, ct saturation and ct mismatch during external fault.

B.   Current and voltage ratios based scheme

To overcome the possibility of mal-operation using the operating criterion in Eq. (3), the following approach is proposed. On receipt of a positive (logic '1') signal based on the criterion in Eq. (4), check the current ratio, ε, calculated as:

$$ε = \big||I1| − |I2|\big|/(|I1| + |I2|) \qquad (4)$$

where, |I1 | and |I2| are the magnitudes in per unit of the fundamental components of the primary and secondary currents obtained by DFT.

For normal operation the absolute values of I1 and I2 are almost equal and the value of current ratio, ε, is almost equal to zero. During energization, with the circuit breaker on the transformer secondary side open, inrush current flows on the

primary side but no current flows on the secondary side. So, the value of the current ratio will be equal to one.

If an internal or external fault or loaded energization occurs, ε will be greater than zero and less than one depending on the value ofI1 and I2. To discriminate between internal and external faults or loaded energization, the direction of instantaneous currents, i1 and i 2, is checked. Direction of one of these currents reverses for internal faults but not for an external fault or loaded energization. The magnitude of the fundamental component of(i1 − i2) being less than the magnitude of the fundamental component of (i1 + i2) indicates an external fault or loaded energization.

When an internal fault takes place simultaneously with transformer energization with secondary open, the current ratio will be also almost one. Moreover, if there exists an internal fault with loaded transformer energization, the current flow to the load will be a small value and the current ratio will be close to one. Therefore, current ratio scheme will mal-operate. So, it needs another discrimination criterion.

An internal fault not only affects the currents seen at the transformer terminals, but also the terminal voltages. Subject to the availability of the voltages on both sides of the transformer, it is proposed to use voltage ratio to detect the internal fault during transformer energization with or without load. Voltage ratio, λ, is the ratio between the absolute difference and absolute sum of primary and secondary voltages of the transformer and is calculated as:

$$\lambda = ||V1| - |V2||/(|V1| + |V2|) \qquad (5)$$

where, |V1 | and |V2| are the magnitudes in per unit of the fundamental components of the primary and secondary voltages obtained by DFT.

During inrush current without fault this value is almost zero. When an internal fault exists during transformer energization, this value will be greater than zero. The decision making logic is shown in Fig. 2. As indicated in the flowchart, the differential and restraint currents are calculated using Eqs. (1) and (2).

Magnitudes of the fundamental components of the currents I1 and I2, and terminal voltages V1 and V2 of the power transformer are extracted using one cycle DFT. Subsequently, the percentage differential relay criterion in Eq. (3) is checked to ensure the operating conditions of the relay.

If the percentage criterion is satisfied, a condition of inrush and/or fault either internal or external exists. Otherwise, the condition is normal. Then, the current ratio is evaluated to discriminate between fault and inrush current. If the current ratio is greater than a threshold value (Thi) and less than 0.9, a condition of loaded energization and/or fault, either internal or external, exists. The value of 0.9 is chosen to detect simultaneous fault with loaded energization. This value will avoid the error due to ct saturation. Then the direction of two currents is checked. If the direction of one current is reversed a trip signal is sent to the circuit breaker (CB) to isolate the

faulted transformer. The value of Thi chosen in this work is 0.05 based on normal operating conditions till 10% mismatch between the cts'. This leaves sufficient margin above zero for normal operation.

As long as the output of current ratio is equal to or higher than 0.9, the inrush condition and/or internal fault have taken place. After that, the voltage ratio is calculated to discriminate between the inrush and simultaneous inrush with internal fault. If the voltage ratio is greater than the voltage threshold (Thv), the relay declares an internal fault and issues a trip signal to the CB.

The inrush condition is assigned when voltage ratio is less than *Thv*. Because of high current during energization there may be a voltage drop. So, the value of *Thv* is selected equal to 0.025 taking the voltage drop into consideration.

The classification trip logic of internal fault is shown in Fig. 3. Using four inputs, the output logic of ε, current direction check and relay criterion in Eq. (3) for each phase, the relay can detect and classify the faulty phase, as shown in Fig. 3.
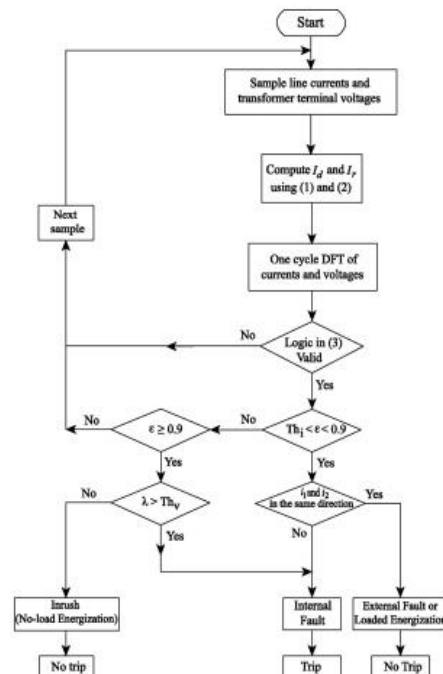

Fig.3: Flow chart of Proposed Algorithm

C.   Simulated system

Single line diagram of the electrical power system used to evaluate the proposed differential protection scheme is shown in Fig. 5. It consists of a transmission grid with a 138 kV equivalent source, 25 MVA 138/13.8 kV 60 Hz star–star three-phase power transformer, 5 km transmission line connected to a 13.8 kV equivalent source.

The system is simulated using MATLAB/Simulink software. The sampling frequency is 2 kHz. The three-phase transformer has been modeled using MATLAB multi-winding transformer

(see block diagram in Appendix A) where the low voltage (LV) winding is divided into sub-windings. The magnetizing characteristic of the power transformer is shown in Fig. 6. The current transformers, connected in each phase of the high voltage (HV) and LV sides as shown in Fig. 5, are 1200/5 and 100/5 for the LV and HV sides, respectively, and are modeled using saturated transformer model. Also, the magnetizing characteristics are taken into account to simulate the cts' saturation [32].
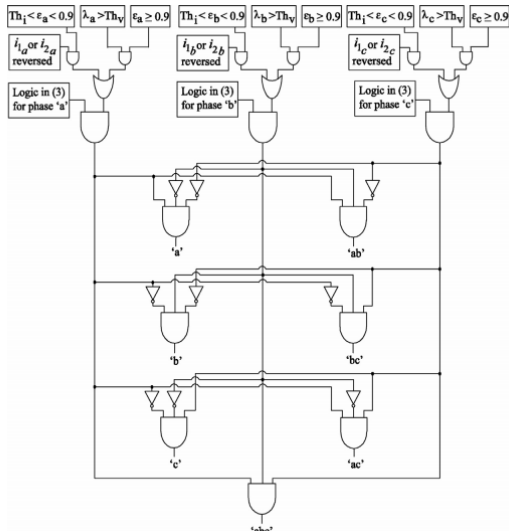
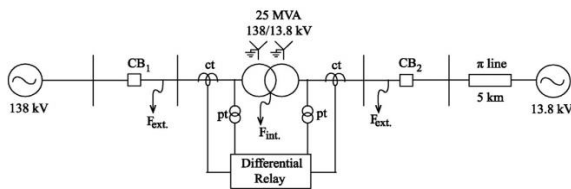Fig.4: Trip Logic classification of internal fault

Fig.5: Single line diagram of simulated system

IV.   SIMULATION RESULT AND ANALYSIS

A large number of studies have been performed on the simulated system for the normal conditions and the following fault cases at different switching angles (0◦, 30◦, 60◦ and 90◦):

- Energization with and without load.
- External faults on both primary and secondary sides with fault resistance.
- External faults with ct saturation.
- Internal fault in both primary and secondary windings of the transformer simulated with different percentage winding and different fault resistance.
- Simultaneous energization with internal fault at different per centage winding and fault resistance.
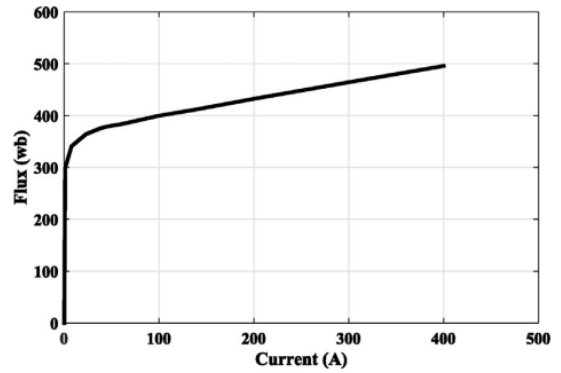
Fig.6: Power transformer magnetizing characteristic

To keep the paper length within limits, only a limited number of cases are described in detail and a summary of others is given in a table to illustrate the results and the performance of the proposed technique.

A.   No-load energization

This test is carried out when CB1 is closed at 50 ms and zero angle of phase 'a' voltage waveform with CB2 open. Simulation results are shown in Fig. 6. Behavior of the three phase differential currents of three phases is shown in Fig. 7(a). The differential current is greater than the criterion logic in Eq. (3), Fig. 7(b). It means that the conventional percentage differential relay will mal-operate with transformer energization and send a trip signal.

With the proposed algorithm, although the current ratio value is one, Fig. 7(c), the voltage ratio in each phase is less than Thv, Fig. 7(d), confirming that energization occurred and will restrain the relay. Subsequently, the trip logic output is zero which means normal operation and no trip signal is issued as shown in Fig. 7(e).

Accordingly, the proposed scheme avoids the mal-operation of percentage differential relay with transformer energization. Voltage With the proposed algorithm, although the current ratio value is one, Fig. 7(c), the voltage ratio in each phase is less than Thv, Fig. 7(d), confirming that energization occurred and will restrain the relay.
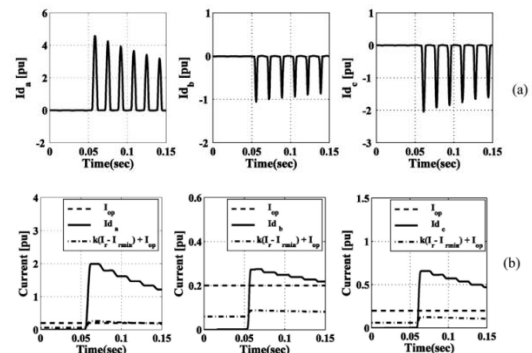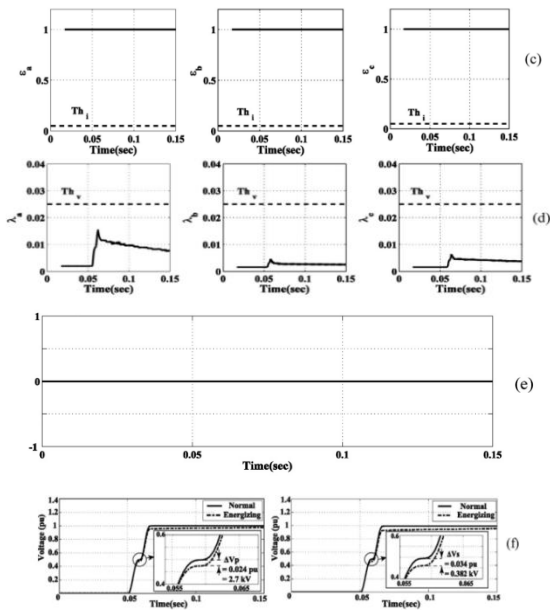
Fig.7: Three differential currents and relay response during no-load transformer energization. (a) Three phase differential currents, (b) percentage differential operation, (c) current ratio, (d) voltage ratio, (e) output logic to CB, and (f) voltage behavior during normal and energizing on primary (left) and secondary (right).

Subsequently, the trip logic output is zero which means normal operation and no trip signal is issued as shown in Fig. 7(e). Accordingly, the proposed scheme avoids the mal-operation of percentage differential relay with transformer energization. Voltage differential between the normal and energizing operation on primary and secondary sides is seen in Fig. 7(f) left side and right side, respectively. It can be seen that on energization there is a voltage drop on both sides compared to the normal condition. Also, the voltage drop in V1 and V2 during energization is different. This voltage drop is taken into account when using the voltage ratio criterion.
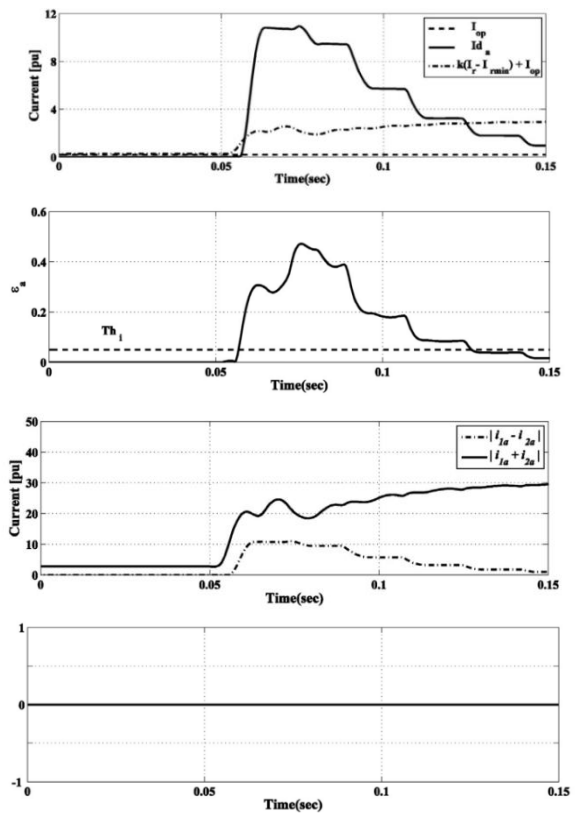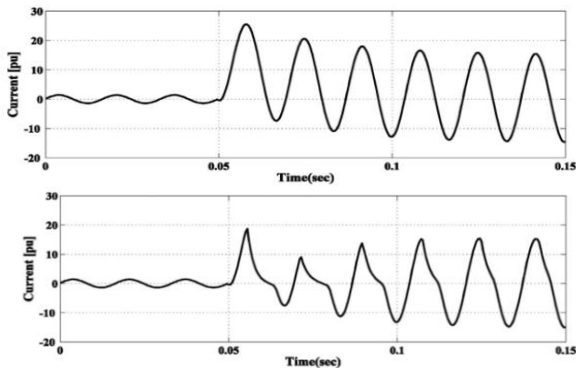

Fig.8: Relay response during external fault on LV side. (a) Primary current, (b) secondary current, (c) percentage differential operation, (d) current ratio, (e) current direction check, and (f) output logic to CB.

B. External fault with ct saturation

In order to test the proposed scheme during ct saturation, a phase "a" to ground external fault at the beginning of the transmission line with ct saturation is presented in Fig. 8. The simulation of this case is done using PSCAD software. As seen from Fig. 8(a) and (b), the direction of i1 and i2 is the same. Also, the differential current is greater than the criterion logic in Eq. (3) as seen in Fig. 8(c). So, the percentage differential relay will mal-operate during external fault with ct saturation.

In Fig. 8(d), value of the current ratio is higher than Thi. The direction check of the ct secondary currents for primary and secondary sides, Fig. 8(e), shows that the magnitude of fundamental component of (i1 − i2) is less than the magnitude of fundamental component of (i1 + i2) indicating an external fault. So, the final logic of the relay is no-trip, which indicates the security of the proposed scheme during external faults.

All studies reported here are with the nominal tap ratio. Additional studies performed, however, showed that the algorithm performs correctly within a range of± 5% tap.

V.   CONCLUSION

A transformer differential protection scheme based on current ratio and voltage ratio between difference and sum of fundamental components of line currents and power transformer terminal voltages, respectively, is proposed in this paper. The current ratio is used to discriminate between inrush and fault conditions. However, voltage ratio is used to detect transformer energization on internal fault. Also, the current direction criterion is used to restrain the proposed relay during external faults and loaded energization.

Many scenarios of fault and non-fault conditions have been simulated. It is demonstrated in this paper that the proposed algorithm successfully differentiates between magnetizing inrush and fault conditions in almost one half power frequency cycle. Also, the presence of fault resistance and ct saturation are evaluated for many cases. The results show that the proposed technique can detect and classify fault cases from 3% of windings and above from neutral end within a short time depending on the fault case. It is found that this technique is simple, dependable, secure and reliable in discriminating the inrush currents from the fault currents. It is simple to implement and is proposed to be tested on a physical transformer as the next step.

VI.   REFERENCES

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