Electric Power Systems Research 154 (2018) 140–150

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Power transformer differential protection using current and voltage ratios

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ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form 12 July 2017
Accepted 21 August 2017

Keywords:
Differential relay
Current and voltage ratios
Inrush current
Internal fault

ABSTRACT

The main challenge in transformer protection is to find a fast and efficient differential relay algorithm that isolates the transformer from the system causing least damage. Algorithm should also avoid mal-operation while differentiating between the operating conditions. This paper presents an improved 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 proposed algorithm aims at avoiding mal-operation, possible with the conventional 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. Investigation 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.

1. Introduction

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]. Transformer protection is of vital significance to provide reliable operation of power systems.

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 mal-operation 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 dur-

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http://dx.doi.org/10.1016/j.epsr.2017.08.026
0378-7796/

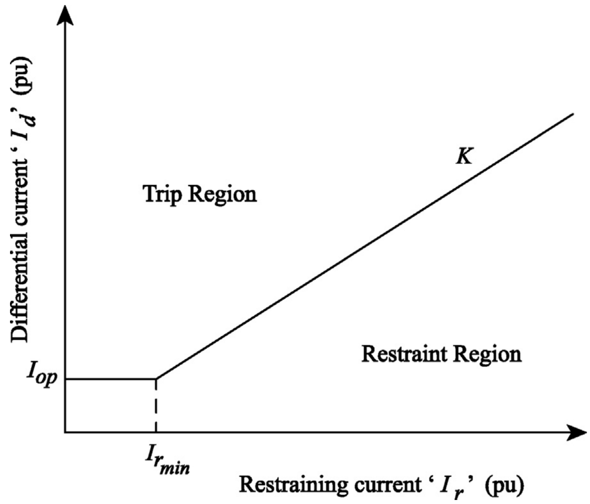

Fig. 1. Percentage differential relay characteristic.

ing transformer energization with internal fault that may affect their speed and security.

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.

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.

2. Methodology of the proposed method

2.1. Percentage differential protection

Basis of the conventional percentage differential relay is that the differential current (I_d) is more than a predetermined percentage of the restraint current (I_r). Characteristic of the percentage relay is shown in Fig. 1. Magnitude of the fundamental component of the difference between the sampled values of the primary (i_1) and secondary (i_2) 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],

$$I_d = \text{Fundamental of } (|i_1(k) - i_2(k)|) \quad (1)$$

Likewise, the restraining current is calculated as [30]:

$$I_r = \text{Fundamental of } (|i_1(k) + i_2(k)|)/2 \quad (2)$$

The operating characteristic of percentage differential relay is calculated as [31]:

$$\left\{I_d \geq I_{op}\right\} \& \left\{I_d \geq K\left(I_r - I_{r_{\min}}\right) + I_{op}\right\} \quad (3)$$

where, I_{op} is the minimum operating current (0.2 pu), $I_{r_{\min}}$ 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.

2.2. 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. (3), check the current ratio, ε, calculated as:

$$\varepsilon = ||I_1| - |I_2||/(|I_1| + |I_2|) \quad (4)$$

where, $|I_1|$ and $|I_2|$ 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 I_1 and I_2 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 of I_1 and I_2. To discriminate between internal, and external faults or loaded energization, the direction of instantaneous currents, i_1 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 $(i_1 - i_2)$ being less than the magnitude of the fundamental component of $(i_1 + i_2)$ 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:

$$\lambda = ||V_1| - |V_2||/(|V_1| + |V_2|) \quad (5)$$

where, $|V_1|$ and $|V_2|$ 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 I_1 and I_2, and terminal voltages V_1 and V_2 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 (Th_i) 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