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A method to identify inrush currents in power transformers protection based on the differential current gradient

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ABSTRACT

This paper presents a new methodology for distinguish between inrush currents and internal faults based on the differential current gradient. The scheme is based on calculating the differential current gradient vector angles in phases A-B-C at all points of the data window. Using statistical calculations, the inrush current is then identified, because its gradient vector behavior will be different in the case of a short circuit occurrence. The method effectiveness has been verified in several computational simulation cases using EMTP/ATP and MATLAB®, analyzing situations of internal faults and inrush currents, including cases of sympathetic inrush in a power transformer, presenting highly satisfactory results.

1. Introduction

Differential protection is the main protection scheme for large transformers, especially those with capacity greater than 10 MVA. These transformers perform a task of fundamental importance in electric power systems operation. Given its importance and its high cost, it is necessary to develop and implement a reliable protection system with the ability to identify internal faults and to disconnect the equipment as fast as possible.

In transformers differential protection, the main difficulty is to distinguish the inrush currents from the internal short circuit currents. Traditionally differential relays perform this task using the harmonic restraint technique, based on the assumption that the inrush currents have high concentrations of second-order harmonic components. However this technique is not always effective.

In the past years, several methods have been presented in order to solve this difficulty. Techniques based on wavelet transform (WT) have been proposed in recent years and demonstrated good results in detecting internal faults in power transformers [1,2]. The use of artificial neural networks (ANN) as a tool to distinguish between inrush currents and internal faults in power transformers has also gained enough popularity with excellent results. References [3,4] are examples of methods based on ANN. Several other authors have proposed alternative methods to distinguish between the inrush currents and internal faults in power transformers. Algorithms based on mathematical morphology [5], time difference method [6], instantaneous frequency of differential current signal [7] and, more recently, the gradient of the differential current method [8] are examples to be highlighted.

In this article, a new methodology is tested based on the differential current gradient to distinguish between inrush currents and internal faults currents in three-phase power transformers. The proposed technique has been evaluated in a test system (three-phase 25MVA, 13.8/138KV power transformer) using EMTP/ATP and MATLAB®, showing promising results.

2. Differential protection

The differential protection philosophy is based on the assumption that the currents flowing in the secondary side of the current transformer (CT) installed in the primary and secondary sides of

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the power transformer are approximately equal [9]. The difference between these currents is called the differential current (I_D), with magnitude approximately null. In practice, a small current is expected, but this current should not be sufficient to activate the differential relay. This situation also occurs when a fault occurs outside the differential relay protection zone. However, for internal faults the difference between these currents becomes significant and differential balance is not maintained, indicating the possible operation of the relay. It is observed that many practical situations may cause the appearance of small differential currents under normal operation, e.g. non-perfect match between primary and secondary CTs, transformer tap changes and CT errors. These three situations must be taken into account in the operation of the differential relay for power transformers. This is done in the percentage differential relays, since the differential current needs to exceed a previously adjusted percentage of the restriction current (I_R) for operation according to bellow equation [9]:

$$I_D \geq K I_R \tag{1}$$

where K is the percentage differential characteristic of the relay. Typical values of K are in the range of 15–40%. The differential relay will be sensitized when the differential current exceeds a previously adjusted percentage value of the restriction current. This concept is derived from electromechanical relays, where this current produces a restriction torque, while the operation current produces an operation torque.

As previously mentioned, during normal operation of the percentage differential relay, a small differential current is expected, however, this current is not sufficient to sensitize the relay. Therefore, considering the electrical and magnetic characteristics of the power transformer and the CT, certain operating situations can cause the appearing of significant differential currents capable of sensitizing the differential relay, causing improper operation, even in situations where there is no fault in the electric power system (EPS) under its protection. The most recurrent situation where this occurs is where there is the occurrence of magnetizing currents in the power transformer primary winding (inrush current). The inrush currents generally occur at transformer energization, removal of external faults or at energization of transformers in parallel (sympathetic inrush). These false differential currents should be identified and blocked because they are potentially able to cause the differential relay activation.

The traditional differential protection algorithms generally solve this problem by analyzing the harmonic components of the differential current. It is a fact that the inrush currents have significant amounts of second order harmonic component [9,10]. On the other hand, fault currents have low percentages of harmonic components. However, these methods do not satisfactorily respond to situations of internal faults, where the differential current has significant percentages of harmonic components, as well as in situations where inrush currents have low magnitudes of second order components.

3. Proposed algorithm for differential protection

The correct distinction between inrush currents and internal faults to the transformer is, therefore, a great challenge to be overcome. The methods proposed in this paper are based on the fact that the inrush currents present waveforms with very peculiar characteristics. It is a method for waveform recognition which is not based on the harmonic components of the current signal. Correct identification of the waveform will indicate if the transformer is at fault condition.

3.1. The differential current gradient

Applying the concepts of gradient vector to differential current, it is obtained the gradient of the differential current with respect to time $\boldsymbol{t}$, given by [11]:

$$\nabla I_D = \frac{\partial I_D}{\partial t}\vec{i} \quad (\mathrm{A/s}) \tag{2}$$

where $\vec{i}$ is unit vector in the direction of the orthogonal axis $\boldsymbol{t}$ (horizontal); $(\partial I_D/\partial t)$ is first-order time derivative of differential current.

The angle of the gradient vector with respect to the unit vector $\vec{i}$, is given by:

$$\theta_{\vec{i}} = \tan^{-1}\left(\frac{\partial I_D}{\partial t}\right) \qquad (\mathrm{Rad}) \tag{3}$$

With these equations is possible to calculate the magnitude and angle of the gradient vector of the differential current in the three phases of the power transformer.

3.2. Waveform recognition

The inrush currents present a typical waveform, with asymmetric arrangement with respect to the time axis, with only one half-cycle and with slow signal attenuation. The use of the differential current gradient for correct distinction between short-circuit currents and inrush currents in differential protection will be given initially calculating the gradient vector angle of differential current for the phases A-B-C, point by point throughout the data window, using the following equation:

$$\theta_{\vec{i}} = \begin{bmatrix} \theta_{\vec{i}}^{A} \\ \theta_{\vec{i}}^{B} \\ \theta_{\vec{i}}^{C} \end{bmatrix} = \begin{bmatrix} \tan^{-1}\left(\left|\dfrac{\partial I_D^A}{\partial T}\right|\right) \\ \tan^{-1}\left(\left|\dfrac{\partial I_D^B}{\partial T}\right|\right) \\ \tan^{-1}\left(\left|\dfrac{\partial I_D^C}{\partial T}\right|\right) \end{bmatrix} \tag{4}$$

where $\theta_{\vec{i}}^{A}$, $\theta_{\vec{i}}^{B}$ and $\theta_{\vec{i}}^{C}$ are the angles of the gradient of the differential current in phases A, B and C, respectively.

In the internal faults currents, the gradient magnitudes have very high values in almost all time interval of the data window, and, consequently, their angles absolute value are close to 90°, indicating that the gradient vector is almost perpendicular to the unit vector $\vec{i}$, as shown in Fig. 1(a). In the case of inrush currents that situation does not occur, given that, due to the asymmetry of this current over the time axis due to missing half cycles, $\theta_{\vec{i}}$ present reduced values or sometimes almost null, with gradient vector almost parallel to the time axis, as illustrated in Fig. 1(b). The behavior of the gradient vector, established through the angle variation to the horizontal reference will then be used to identify inrush currents in the differential protection of power transformers.

There are two alternatives indicated to extract the behavior of the gradient vector based on their angle variation: the standard deviation (σ) and the median absolute deviation (μ) [12]. The standard deviation is the most commonly used measure of dispersion and measures the variability of values around the average. On the other hand, the median absolute deviation is considered a more robust measure of dispersion, since it is more immune to influence points out the average [2].

Therefore, this paper main objective is to assess the proposed method performance using the standard deviation (Gradient-σ method) and the median absolute deviation (Gradient-μ method).