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Adaptive differential protection of three-phase power transformers based on transient signal analysis

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ABSTRACT

This paper presents a three-phase power transformer percentage differential protection formulation based on transient signal analysis. The proposed formulation uses discrete wavelet transforms (DWT) to extract transitory features of non-stationary signals with fast transition, mapping the signal in time–frequency representation. The proposed formulation was implemented on MATLAB® environment and evaluated through a case study using BPA'S ATP/EMTP software. Comparative test results are presented showing that the proposed formulation is highly reliable, fast, accurate and easy for real-life construction.

1. Introduction

Power Transformers (PT) play an extremely important role on the reliability and energy supply continuity of electric power systems (EPS). The inherent characteristics of power transformers introduce a number of unique problems that are not present in transmission lines, generators and motors protection [1]. When internal faults occur in PT, immediate disconnection of the equipment is necessary to avoid extensive damage and/or preserve power system stability and power quality. Furthermore, the replacement of a faulted transformer is very expensive and time consuming. Therefore, PT protection can prevent great economic losses and also avoid long power outages [2].

Currently, percentage differential protection is a common practice for power transformer protection. However, nonlinearities in the transformer core or in the currents transformers (CTs) core, can generate a substantial differential current causing a percentage differential relay miss-trip [1]. Thus, the differential relays are equipped with harmonic restraint, where magnitudes of the second and fifth harmonic components are compared with the fundamental frequency component magnitude to discriminate internal faults from magnetizing inrush currents and transformer overexcitation, respectively [3].

Aiming to improve the efficiency of PT differential protection a significant number of relaying formulations have been proposed [4–24]. These formulations are based on finite elements, artificial neural networks, fuzzy systems, dynamical principal components analysis, wavelet transforms (WTs), hybrid systems, symmetrical components, space vector and power-based protection methods. In [25] is presented a review on computational intelligence techniques applied on oil-immersed PT conditions evaluation for operating costs reduction, to enhance operational reliability and to improve power supply and customer service. However, all mentioned relaying formulations have hard to design parameters, which make real life construction difficult. Ref. [26] present a Discrete Wavelet Transform (DWT) application for PT differential protection, however the proposed scheme does not have adaptive characteristics. In [27] is proposed an adaptive differential protection scheme, however not all possible PT operational conditions were tested and evaluated.

In this paper, a simple to implement percentage differential relaying algorithm for three-phase power transformers protection based on DWT is proposed. The proposed algorithm formulation uses logical decision criteria based on wavelets coefficient spectral energy variation to identify and discriminate correctly internal and external faults, inrush currents and incipient internal faults all under or not current transformer saturation. In order to analyze the proposed algorithms efficiency, the formulation was built in MATLAB® platform [28] and tested with simulated fault cases under BPA'S ATP/EMTP software [29]. Comparative test results with a traditional percentage differential relaying with harmonic restraint formulation [1] shows the proposed algorithms efficiency and its easiness for real life construction.

The remaining of this paper is divided as follows. Section 2 describes the percentage differential protection formulation. Section 3 describes the DWT used. The proposed algorithm is presented on Section 4, while Section 5 presents the case study. Section 6

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presents the test results and discussions. The conclusions of this work are presented on Section 7.

2. Percentage differential protection

The percentage differential relay can be implemented on PT through overcurrent relays (**R**) with operation (**o**) and restriction coils (**r**), as illustrated in Fig. 1. Here, N1 and N2 are the primary and secondary windings number of turns, respectively.

The differential relay operation is based on two currents [1,2]:

1. *Restraint current* (i_r):

$$i_r = \frac{(i_{2P} + i_{2S})}{2} \tag{1}$$

where i_{2P} is the CT secondary current connected to the power transformer primary winding, and i_{2S} is the CT secondary current connected to the power transformer secondary winding.

2. *Differential current* (i_d):

$$i_d = i_{2P} - i_{2S} \tag{2}$$

In this protection philosophy, CTs transformation errors, CTs mismatch and power transformer variable taps can cause a differential current to flow in the overcurrent relay (**R**). To consider these effects, the differential protection formulation compares the value of *differential current* to a fixed percentage value, named K, of the *restraint current*. This percentage value is the slope of the percentage differential characteristic and determines the relay trip zone [1]. The K value is used as safety margin and is defined by:

$$K = \frac{i_{2P} - i_{2S}}{(i_{2P} + i_{2S})/2} = \frac{i_d}{i_r} \tag{3}$$

Typical values for K are 10%, 20% and 40%. Differential protection relays identify internal faults when the *differential current* exceeds this pre-determinate *restraint current* percentage value, as show by:

$$i_d \geq K \cdot i_r = K \cdot \frac{(i_{2P} + i_{2S})}{2} \tag{4}$$

3. Discrete wavelet transform

EPS fault generated signals are associated with fast electromagnetic transients, are typically non-periodic and with high-frequency oscillations. These characteristics present a problem for traditional Fourier analysis techniques [30]. The wavelet transform (WT) is a powerful tool that can be used in power systems transient phenomena analysis. It has the ability to extract information from transient signals simultaneously in both time and frequency domain and has replaced the Fourier analysis in many applications [31]. This ability can greatly help the detection of signal features which may be useful in characterizing the source of the transient or the state of the post-disturbance system [30].

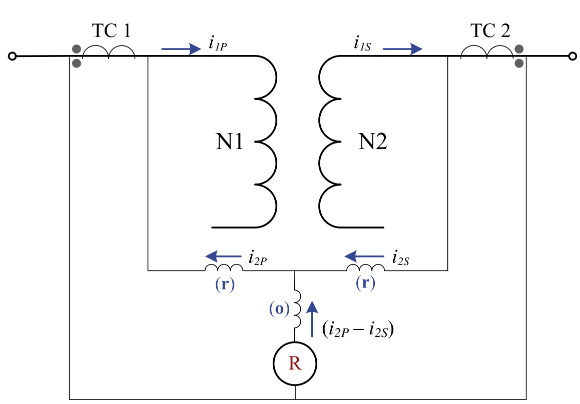

Fig. 1. Schemes of a single-phase transformer using a percentage differential protection relay.

Discrete wavelet transform (DWT) is derived from a continuous wavelet transform and is defined as:

$$DWT[m,n] = \frac{1}{\sqrt{a_0^m}} \sum_{k=-\infty}^{+\infty} x[k]\psi\left(k - \frac{a_0^m n b_0}{a_0^m}\right) \tag{5}$$

where ψ is the mother wavelet and, $x[k]$ is the discretized signal function. The mother wavelets may be dilated and translated discretely by selecting the scaling and translation parameters $a = a_0^m$ and $b = nb_0a_0^m$ respectively (with fixed constants $a_0 > 1$, $b_0 > 1$, m and n belonging the set of positive integers) [32].

3.1. DWT and filters bank

Since the purpose of the discretization process is to eliminate the redundancy of the continuous form and to ensure inversion, the choice of a_0 and b_0 must be made so that mother wavelets form an orthonormal basis. This condition originates a signal processing technique named multi-resolution analysis of Mallat (MRA) [33]. DWT can be implemented by a multistage filter bank, as illustrated in Fig. 2.

The Mallat algorithm consists of series of high-pass (HP) and the low-pass (LP) filters that decompose the original signal $\boldsymbol{x[k]}$ into approximation $\mathbf{a}(\boldsymbol{k})$ and detail $\mathbf{d}(\boldsymbol{k})$ coefficient each one corresponding to a frequency bandwidth. The first detail has $n/2$ samples and the dth detail has $n/2^d$ samples, since for each frequency scale that the DWT is computed, the original signal is decimated leaving a total of n points of the signal in the wavelet domain.

3.2. Detail coefficient energy

The wavelet coefficient energy, named detail-spectrum-energy (DSE), can be calculated by means of a moving data window that goes through the detail coefficients shifting one coefficient at a time [16]. Thus, the DSE is expressed as:

$$\varepsilon_w(k) = \sum_{n=k}^{k+N_\omega/2^j} d_j^2(n) \tag{6}$$

where j is the scale factor, N_w is the number of samples contained in one cycle of the fundamental frequency of the original signal, N_s is the total number of samples of the original signal, n is the sample number and $k = \{1, 2, \ldots, (N_s - N_\omega)/2^j\}$.

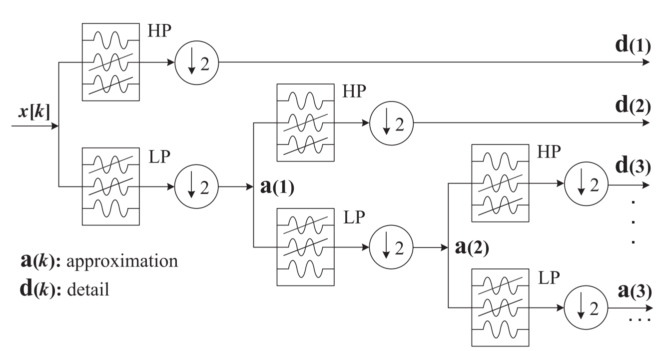

Fig. 2. DWT filter bank framework.