Electric Power Systems Research 110 (2014) 9–24

Contents lists available at ScienceDirect

Electric Power Systems Research

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

A new algorithm based on Clarke's Transform and Discrete Wavelet Transform for the differential protection of three-phase power transformers considering the ultra-saturation phenomenon

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ARTICLE INFO

Article history:
Received 27 July 2013
Received in revised form 4 December 2013
Accepted 2 January 2014
Available online 29 January 2014

Keywords:
Power transformer
Differential protections
Ultra-saturation phenomenon
Inrush current
Internal and external faults
IEEE 14-bus test system

ABSTRACT

This paper presents, at first, a novel model for investigating the ultra-saturation phenomenon during energization of a loaded three-phase power transformer. Then a new approach is presented to control the unusual false trip of a three-phase power transformer differential protection due to ultra-saturation phenomenon based on Clarke's Transform and Discrete Wavelet Transform (DWT). In this method, the transient phenomena of a power transformer including the magnetic inrush current, the ultra-saturation phenomenon, the external faults, and the internal faults of the power transformer are simulated. To distinguish between these phenomena, appropriate criteria based on Clarke's Transform and DWT are presented using the standard deviation of coefficients and the energy coefficients. The results of this study may be used as notifications by the personnel of substation and relay manufacturers.

1. Introduction

One of the most important parts in power systems is the power transformer whose differential protection is a major concern [1]. The effect of the magnetizing inrush currents has to be considered in the power transformer protective design. The inrush current occurs when a power transformer is switched on, and it can be much higher than its nominal value, hence causing the false trip of the differential protections [2]. Power transformers must act properly with regard to their differential protection when they face different transient signals which are the results of the magnetizing inrush currents, the internal faults, and the external faults. So, the differential protection should operate rapidly during the internal faults of the power transformer and should not have any actions while facing external faults and magnetizing inrush currents. The common technique utilized to prevent the false trip of the differential protection during the energization of the power transformer is the level of harmonic components. The inrush current includes a high level of second harmonic component which is used as a discriminative feature in conventional protective schemes [1,2]. To distinguish between the internal faults, the external faults, and the inrush current in a standard differential protection, an algorithm is used in which the differential protection operates when the amplitude of the basic component of the differential current, which is computed by discrete Fourier transform (DFT), fixes at more than 0.25 p.u. and the level of the second harmonic to the basic harmonic of the differential current, which is computed by DFT, fixes at lower than 15% [3–7]. In the standard differential protection, however, the mal-operation of differential protection in certain conditions under magnetizing inrush current leads to a tripping of healthy transformers [3–5]. Wavelet transform is a powerful and effective tool for processing transient signals [8–16]. The wavelet transform technique is widely utilized in power systems for protection [8], assessment of power quality [9], fault detection [10], solving the power quality problem [11,12], and data compression [13,14]. Wavelet transform, due to its natural ability in adjusting the width of the mother wavelet frequencies [15,16], is more appropriate than other methods of frequency domain such as Fourier window for analyzing transient states. The DWT can process a signal by decomposing it into an approximate and a detail by crossing through low-pass and high-pass filters. The approximate is decomposed to obtain the information of the next level and the process continues. Moreover, the practical implementation of DWT is very simple. Therefore, the DWT is widely used to distinguish between the transient phenomena in the power transformer differential protection. In addition, one of the transient phenomena that leads to the false trip of the power transformer differential protection during the energization of a loaded power transformer is the ultra-saturation phenomenon. The mechanism of unusual false trip of the differential protection resulting from the ultra-saturation

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http://dx.doi.org/10.1016/j.epsr.2014.01.001

u_{pa}, u_{pb}, u_{pc}, u_{sab}, u_{sbc}, and u_{sca} the voltages of primary and secondary windings of the power transformer
i_{pa}, i_{pb}, i_{pc}, i_a, i_b, and i_c the currents of primary and secondary windings of the power transformer
R_p, R_s, L_{dp}, and L_{ds} the resistances and the inductances of the primary and secondary windings of the power transformer
φ_a, φ_b, φ_c, and φ_d the flux of the core magnetic through the windings legs and air branch of the power transformer
N_P the number of the primary turns of the power transformer
N_S the number of the secondary turns of the power transformer
e_{pa}, e_{pb}, e_{pc}, e_{sa}, e_{sb}, and e_{sc} the inducted primary and secondary voltages of winding legs of the power transformer
f_a, f_b, f_c, and f_d the magnetic potential through the three-legged and air branch of the power transformer
p_a, p_b, p_c, k_{1a}, k_{1b}, k_{1c}, k_{2a}, k_{2b}, k_{2c}, f_{0a}, f_{0b}, and f_{0c} related to power transformer saturation curve
R_b and L_b the resistive and the inductive load of the power transformer
Ψ_μ the flux linkages of the current transformers
Ψ_s the flux linkages at the saturation knee point of the magnetization curve of the current transformers
$i_{\mu 0}$ the magnetization current at the saturation knee point of the magnetization curve of the current transformers
L_s the slope of the saturation zone of the current transformers
i_{ps} the primary current referring to the secondary side of the current transformers
i_μ the magnetizing current of the current transformers
i_s the secondary current of the current transformers
e_s the induced voltage in the secondary winding of the current transformers
x_i, $\bar{x}$, n and σ coefficients, the mean of coefficients, the number of coefficients, and the standard deviation, respectively
$I_{d\,set\,point}$ the activation current of the differential protection
k the percentage value of the restrain current of the differential protection
i_r the value of the restraint current of the differential protection
i_{2p} and i_{2s} the secondary currents of the current transformers on the primary and secondary side of the power transformer
I_0 the ground mode current component
I_1 and I_2 the aerial mode current components
$D_1 I_0$ the detail coefficients vector at the first level of the ground mode
σD_{inter}, $\sigma D_{inter\text{-}min}$ and $\sigma D_{inter\text{-}max}$ the standard deviation of D vector at the first level in various test signals of different transient phenomena, the minimum, and the maximum of the standard deviation of D vector at the first level related to the internal faults.
ED_1, ED_{1min} and ED_{1max} the energy coefficients at the first level in various test signals of different transient phenomena, the minimum, and maximum of energy coefficients at the first level related to the internal faults, respectively

phenomenon is related to the saturation of the magnetic core of the power transformer, which occurs during a rapid jump of the terminal voltages and is a widely occurring phenomenon. This happens when a power transformer is switched on or when a short circuit fault that occurred near a power transformer is removed. In these situations, slow and high decaying inrush currents may be created which may well be much higher than the full load value. Consequently, even in conditions where saturation is very heavy, there is always a considerable second harmonic in the current in the state of having the same polarity for the residual flux in the magnetic core of the power transformer as the DC flux which results from the voltage jump and does not reach below 15% of the basic one. Thus, the ratio of the second harmonic is an appropriate criterion for preventing an unusual mal-operation in differential protections. If the differential protection discovers the second harmonic that is higher than 15% of the basic component, the operation of the differential protection will be blocked. But the mal-operation of the differential protection in certain conditions under magnetizing inrush current has led to the tripping of healthy transformers [3–5]. In this case, the inrush current during the period of the ultra-saturation will miss some specifications such as the high ratio of the second harmonic and the dead angle. Also, the DC flux in the magnetic core of the power transformer in the primary stage of the process tends to increase rather than decrease, resulting in the ultra-saturation phenomenon [3–5]. Hence, the amplitude of the basic component of the differential current gets higher, and the level of the second harmonic decreases under that of relay restrain [3–5]. So, the standard differential protection is not able to identify the ultra-saturation phenomenon and the description and control of the ultra-saturation phenomenon is necessary for preventing the false trip of the differential protection. In all previous studies of ultra-saturation phenomenon, the model of a loaded power transformer was considered as single-phase [3–5]. Also, several studies have been done to distinguish between the inrush current, the internal and the external faults by various algorithms [8–16], but none has taken the ultra-saturation phenomenon into account.

This paper presents a novel model for investigating the ultra-saturation phenomenon during energization of a loaded three-phase power transformer. It also presents a new approach for a three-phase power transformer differential protection, considering the effect of ultra-saturation phenomenon based on Clarke's Transform and DWT. To model the ultra-saturation phenomenon, the nonlinear specification of the transformer core and the saturation effect of current transformers are taken into account. It is assumed that the load of the transformer is a resistive and inductive load. In this algorithm, the ultra-saturation phenomenon, the external and internal faults of the power transformer (including the three-phase fault (ABC fault), the three-phase-to-ground fault (ABCG fault), the phase-to-ground fault (AG fault), the phase-to-phase fault (AB fault), the phase-to-phase-to-ground fault (ABG fault)) and the magnetic inrush current are simulated. Also, the turn-to-turn and turn-to-ground internal faults are simulated. To distinguish between these phenomena, appropriate criteria are presented using Clarke's Transform and DWT by the use of energy coefficients and the standard deviation of coefficients. In this paper, the DWT is utilized since it provides enough information for the analysis of the main signal in a considerably short computation time. Moreover, the practical implementation of DWT is very simple. To distinguish between transient phenomena in the power transformer, energy coefficients and the standard deviation of coefficients at the first level in a time window involving transient states are used. Since the criteria are defined at the first level, the proposed algorithm is totally appropriate in terms of speed, accuracy and computational cost. Practically, the algorithm is also very easy to implement. To verify the results of the proposed algorithm, the ultra-saturation phenomenon in IEEE 14-bus test