A Wavelet Based Approach for Fast Detection of Internal Fault in Power Transformers

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***Abstract*—This paper proposes a wavelet based technique for power transformer internal fault detection and protection. The suggested algorithm consists of two parts, disturbance detection and disturbance discrimination. The three phase differential currents are decomposed up to the second level. Then, spectral energy and standard deviation of the decomposed signals in 2nd level are calculated. The relay scheme issues a trip signal in the case of internal fault, according to spectral energy and standard deviation of the decomposed signal in 2nd level. The operating time of the scheme is less than half of the power frequency cycle (8 ms for 50Hz). The scheme is not affected by Current Transformer (CT) saturation and mismatch error. In order to validate the performance of the proposed scheme, it was implemented in a Matlab environment and tested with several simulated fault cases in EMTP program. Results show the effectiveness of the proposed method.**

Keywords - transformer; differential protection; wavelet; fault.

I. INTRODUCTION

The power transformer is one of the most expensive elements of power system and its protection is an essential part of the overall system protection strategy. The differential protection provides the best protection for power transformer. Its operation principle is based on this point that the differential current during an internal fault is higher than normal conditions. But, a large transient current (inrush current) can cause mal-operation of differential relays. Then, studies for the improvement of the transformer protection have focused on discrimination between internal short circuit faults and inrush currents in transformers [1]. The magnetizing inrush current has a large second order harmonic component in comparison to internal faults. Therefore, some transformer protection systems are designed to halt operating during the inrush current by sensing this large second order harmonic [2]-[4]. The second harmonic component in the magnetizing inrush currents tend to be relatively small in modern large power transformers because of improvements in the power transformer core materials [5]. Also, it has been seen that the fault current can contain higher second order harmonics than the inrush current due to nonlinear fault resistance, CT saturation, the distributed capacitance in the transmission line, which transformer is connected to, or due to the use of extra high voltage underground cables [6]. Various methods have been suggested for overcoming this protection system mal-operation. In [7], a modal analysis has been proposed. In this method, both voltage and current transformers, signals should be used. Therefore, it requires a huge amount of computational burden. In [8, 9], the application of the wavelet packet-based algorithm have been suggested. The algorithm, proposed in [8], requires the measurement of the voltage in addition to current. Hence, it has the same problem of [7]. Recently, some protection methods based on wavelet transform, Artificial Neural Networks [5], [10]-[11] and Fuzzy logic [12]-[13] have been suggested. These algorithms have high dependency to the elements and parameters of the protected system and hence, are greatly system dependent. Also, might need re-configuration for use in other systems. In [14], Discrete Wavelet Transform (DWT) and Correlation factors have been used to discriminate between the inrush currents and the single phase to ground faults.

This paper presents a wavelet based method for discrimination among inrush current, internal short circuit, external short circuit and energizing and it is not affected by CT saturation and it is able to detect internal faults while transformer energization. Unlike Artificial Neural Network and Fuzzy logic based algorithms, this approach is not system dependent. The operating time of the scheme is less than 10ms.The Daubechies mother wavelet is used with a sample rate of 5 kHz. Then, the differential currents of the three phases are decomposed into two details and only the second level will be considered by using db5 mother wavelet.

II. DISCRETE WAVELET TRANSFORM

The wavelet transform is a powerful tool to extract information from the non-stationary signals simultaneously in both time and frequency domains. The ability of the wavelet transform to focus on short time intervals for high-frequency components and long intervals for low-frequency components improves the analysis of transient phenomena signals. Various wavelet functions, such as Symlet, Morlet and Daubechies are used to analyze different power system phenomena [9], [15]. The mother wavelet must be Selected performed based on its application and the features of signal, which should be processed. In this paper, Daubechies wavelet is used. There are three types of wavelet transform, which are Continuous Wavelet Transform (CWT), Discrete Wavelet Transform (DWT) and Wavelet Packet Transform (WPT). The WPT is described in [8]. DWT is derived from CWT. Assume that $x(t)$ is a time variable signal, then the CWT is determined by (1) [15]:

$$CWT(\tau,a) = |a|^{-\frac{1}{2}} \int_{-\infty}^{+\infty} x(t)\, \varphi^{*}(\frac{t-\tau}{a})dt \qquad (1)$$

where, τ and a are translating and scaling parameters, respectively. Also, $\varphi(t)$ is the wavelet function and $\varphi^{*}(t)$ is the complex conjugate of $\varphi(t)$. Wavelet function must satisfy (2) and should have limited energy [16].

$$\int_{-\infty}^{+\infty} \varphi(t)dt = 0 \qquad (2)$$

Then, the discretized mother wavelet is, as follows [15]:

$$\psi_{m,n}(t) = \frac{1}{\sqrt{a_0^m}} \psi(\frac{t - nb_0 a_0^m}{a_0^m}) \qquad (3)$$

where, $a_0 \rangle 1$ and $b_0 \rangle 0$ and they are fixed real values. Also, m and n are positive integers. DWT is expressed by (4) [15]:

$$DWT_{\psi} f(m,n) = \sum_{k} f(k) \psi_{m,n}^{*}(k) \qquad (4)$$

where, $\psi_{m,n}^{*}(k)$ is the complex conjugate of $\psi_{m,n}(k)$. In (4), the mother wavelet is dilated and translated discretely by selecting a and b [15].

$$a = a_0^m \text{ and } b = nb_0 a_0^m \qquad (5)$$

DWT can be easily and quickly implemented by complementary low pass and high-pass filters.

III. PROPOSED ALGORITHM

In the proposed algorithm, the DWT is applied to the differential currents of three phases. The Daubechies Db-5 type wavelet is used as the mother wavelet and the signals are decomposed up to the second-level. Then, the spectral energy and standard deviation of the decomposed signals in the 2^{nd} level are calculated. The proposed method consists of two steps; detection and discrimination.

A. Disturbance Detection

Under normal conditions and external faults, the differential currents have smaller values than internal faults. However, in some operating conditions, the external faults can result in high differential currents due to ratio mismatch of CTs or tap changes of power transformer. Then, these conditions may cause mal-operation of the relay. Therefore, a threshold current is used in order to prevent malfunctions caused by non-faulty currents. If one of differential currents exceeds this threshold value, it will be identified as a fault. The threshold value is defined, as follows [17]:

$$i_{\det} = k.\frac{(i_{\sec-CT} + i_{per-CT})}{2} \qquad (6)$$

where $i_{\sec-CT}$ and i_{per-CT} are the secondary and primary CT currents, respectively, and k is the slope of the differential relay characteristic. If $i_{\det} \leq i_{dif}$, then the detection algorithm defines it as an internal fault.

B. Disturbance Discrimination

In order to classify disturbances, the differential currents are decomposed up to the second level, using Daubechies Db-5 type wavelet with data window less than the half of the power frequency cycle. A sampling rate of 5 kHz is considered for the algorithm (i.e., 100 samples per power frequency cycle based on 50 Hz). Then, the energy and standard deviation in the second detail are calculated for each differential current. It is seen that the spectral energy as well as the standard deviation in 2^{nd} level tends to have high values in case of internal faults, while they have low values during inrush currents. Then, a discrimination index (D_{ind}) can be calculated by multiplying the spectral energy by standard deviation in the second detail for each differential current, as follows:

$$D_{ind} = STD * E \qquad (7)$$

where, STD is the standard deviation in 2^{nd} detail and E is its spectral energy. The STD can be determined using the following equation:

$$STD = \sqrt{\frac{\sum_{n=1}^{M} (d_{2(n)} - d_{2mean})^2}{M}} \qquad (8)$$

where, $d_{2(n)}$ is n-th coefficient from detail 2, d_{2mean} is its mean value and M is the total number of existed coefficients. Then, the spectral energy of the wavelet signal in the 2^{nd} level is calculated by (9):

$$E = \sum_{n=1}^{M} \left| d_{2(n)} \right|^2 \qquad (9)$$

Then, the discrimination index (D_{ind}) will be compared with a threshold value (D_{Thr}). The relay will be activated, if any one of the three-phase differential currents exceeds this threshold value (D_{Thr}).

IV. SYSTEM UNDER STUDY

In order to study the performance of the proposed algorithm, the system, shown in fig.1, has been simulated by EMTP program. The simulated transformer is a three phase power transformer with the rating of 31.5MVA, 132/33 kV [18]. The primary winding has 10 layers of 98 turns and the secondary winding has 4 layer of 106 turns. The algorithm has been developed in MATLAB and the inputs are differential currents derived from EMTP program. The transmission line has been modeled by two identical π sections.

A. *Power Transformer Model*

The power transformer is modeled by using 8×8 RL matrices obtained from the subroutine BCTRAN of EMTP software. If a transformer terminal model are known in terms of winding resistance, self and mutual inductances, then, 6×6 RL matrices from BCTRAN routine (for a three phase two winding transformer) can be formed, and also 7×7 and 8×8 matrices can be derived for turn to ground and turn to turn fault studies in a three phase two winding transformer, respectively[19]-[20]. The phase of primary winding is divided into three parts (with 637, 49 and 294 turns), in order to simulate turn to turn fault. Therefore, 8×8 matrices are modeled for the modeled transformer.

B. *CT Modeling*

The current transformers are important part of differential protection system. Hence, the differential protection system requires precise representation of the CT model. In this paper, the current transformers are modeled according to [21]-[23]. The subroutines hysteresis and saturation in EMTP have been used to obtain CT characteristics. Then, this model is capable of simulating hysteresis and saturation characteristics during the fault. A non-ideal transformer coupled with a non-linear hysteretic reactor (type 96) has been used for modeling the CT [18]. Three identical current transformers have been connected in Y on the primary side, and another three CTs are connected in Δ on the secondary side of the power transformer.

V. SIMULATION RESULTS

The differential current signals are obtained from secondary of CTs under various operating conditions (normal, inrush current, CT saturation, energizing while the internal fault, internal turn to turn and turn to ground faults), disturbance inception angles and fault resistances. Figs.2-5 show typical 2 level wavelet analysis of differential currents during different fault conditions using wavelet function db5. Fig.2 shows differential current and it's DWT up to 2nd level for transformer energizing while turn to turn fault occurs between turns 294 and 343. As it is shown the peaks occur at the energizing time. Fig.3 illustrates DWT for turn to turn fault. Fault resistance is 0.6 ohm. Peaks occur at the fault instance. Fig.4 shows DWT results for a single phase to ground fault at transformer terminals through 1ohm resistance. The results are same as fig.2 and fig.3. Fig.5 illustrates DWT of differential current for inrush current. It can be seen that the peaks continue during several cycles. But DWT amplitude in 2nd level is smaller than fault cases.

Fig.1 Simulated power transformer system

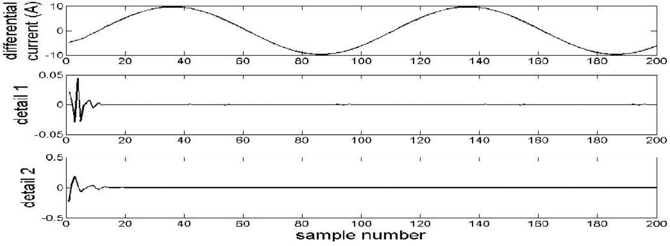

Fig.2 DWT of b-phase differential inrush current for turn to turn fault between turns 294 and 343 in primary winding

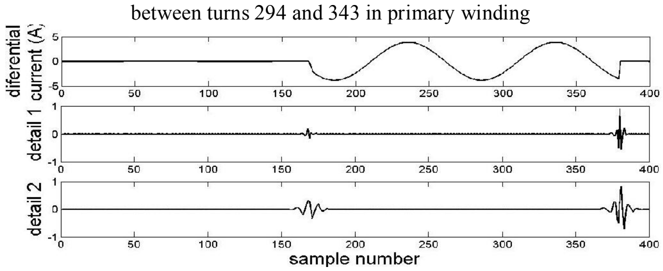

Fig.3 DWT of b-phase differential current for turn to turn resistive fault between turns 294 and 343 in primary winding, R=0.6 ohm

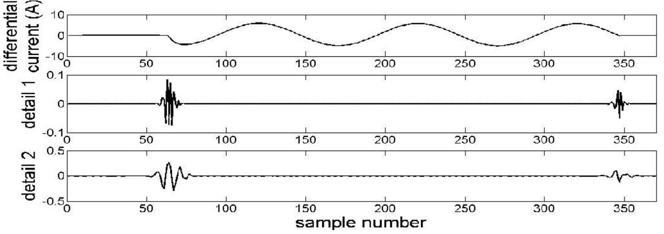

Fig.4 DWT of a-phase differential current for terminal a-phase to ground fault in secondary through 1ohm resistance

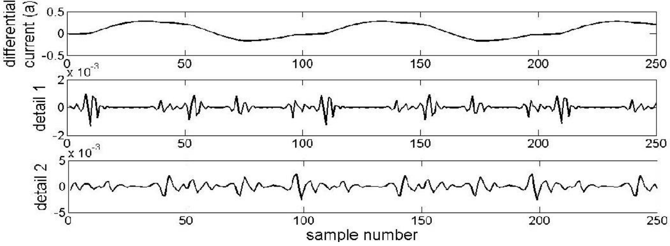

Fig.5 DWT of a-phase differential current for inrush current

Various types of fault with different resistances and fault angles as well as various energizations with different switching angles were simulated. The results for some cases are given in table (1). The D_{ind} values in the internal fault cases are between 0.149 and 4.67, in the faulty phases in presented cases. While it ranges approximately between 1.63E-8 and 1.44E-6 in the inrush current cases. In both internal faults during energization and the internal faults with CTs saturation, the D_{ind} values are higher than the D_{ind} values of the energization cases. It can be seen that at least one of the D_{ind} s calculated for the three phases in fault conditions is higher than the highest D_{ind} computed for the inrush current. Therefore, if any of the D_{ind} s calculated for the three phases exceeds the D_{Thr} value, internal fault is detected and protective relaying system must be activated. It can be seen that it is easy to distinguish between the internal faults and the inrush currents by simply comparing two derived numeric values. Since the primary windings of the power transformer are connected as delta, a fault in the phase B, results in high values of D_{ind} in phases B and C. If the disturbance is an external fault, then the i_{det} is larger than the i_{dif} and the disturbance discrimination process is not performed.

TABLE (1) – SIMULATION RESULTS

Disturbance type	fault resistance (ohm)	b-phase angle at fault (dig)	CT saturation	phase	energy of detail 2	STD of 2th detail	Dind×E+3
inrush	not fault	0	no	a	4.68E-05	1.24E-03	5.81E-05
				b	6.41E-05	1.58E-03	1.01E-04
				c	1.39E-05	1.17E-03	1.63E-05
inrush	not fault	145	no	a	2.56E-05	1.23E-03	3.14E-05
				b	1.51E-04	1.71E-03	2.59E-04
				c	8.78E-04	1.64E-03	1.44E-03
terminal acg	10	0	no	a	1.54E+00	4.43E-01	6.83E+02
				b	1.53E-06	2.21E-04	3.38E-07
				c	9.07E-01	3.39E-01	3.08E+02
turn 294 to ground	1	45	no	a	2.45E-06	4.00E-04	9.80E-07
				b	5.21E+00	8.25E-01	4.30E+03
				c	5.22E+00	8.25E-01	4.31E+03
turn 343 to ground	5	150	no	a	1.35E-06	5.20E-04	7.02E-07
				b	1.14E+00	3.86E-01	4.38E+02
				c	1.13E+00	3.86E-01	4.37E+02
turns 294 and 343	0.01	60	no	a	1.75E-06	2.77E-04	4.83E-07
				b	5.41E+00	8.63E-01	4.67E+03
				c	5.42E+00	5.85E-04	3.17E+00
turns 294 and 343	1	145	no	a	1.14E-06	4.96E-04	5.66E-07
				b	5.48E-01	2.72E-01	1.49E+02
				c	5.47E-01	2.72E-01	1.49E+02
inrush+turns 294 and 343	0.1	0	no	a	3.84E-05	1.70E-03	6.50E-05
				b	4.29E-01	2.59E-01	1.11E+02
				c	4.33E-01	2.59E-01	1.12E+02
inrush+turns 294 and 343	1	20	no	a	1.01E-04	1.38E-03	1.39E-04
				b	1.28E-02	3.76E-02	4.82E-01
				c	1.43E-02	3.80E-02	5.43E-01
turns 294 and 343	0.01	0	yes	a	8.45E-02	6.91E-02	5.84E+00
				b	7.50E+00	8.88E-01	6.66E+03
				c	6.50E+00	8.58E-01	5.58E+03
terminal abcg	0.01	160	yes	a	4.41E+00	6.40E-01	2.82E+03
				b	1.94E+00	4.01E-01	7.79E+02
				c	3.07E+00	5.74E-01	1.76E+03

VI. CONCLUSION

A new method for discriminating different types of transient currents for power transformers protection focused on inrush current and internal fault current is developed. A criterion factor was defined using the standard deviation and the spectral energy of the 2nd detail of the wavelet transform due to a fault or inrush current. Consequently, internal fault conditions can be detected by evaluation and comparison of the criterion factors of all three phases with threshold values. The proposed technique was tested using simulation result from the EMTP. Subroutine BCTRAN in EMTP was used to obtain transformer model. Several cases have been studied to test the effectiveness of the procedure. Simulation results validate the successful operation of the proposed method even in the presence of CT saturation and turn ratio mismatch.

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