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Discrimination Between Inrush and Short Circuit Currents in Differential Protection of Power Transformer Based on Correlation Method Using the Wavelet Transform

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Abstract: This paper presents a novel technique for transformer differential protection to prevent incorrect operation due to inrush current. The proposed method in this paper is based on time-frequency transform known as the Wavelet transform. The discrete Wavelet transform is used for analysis the differential current signals in time and frequency domains. The investigation on the energy distribution of the signal on the discrete Wavelet transform components shows the difference distribution between inrush and internal fault current signals of power transformer. The correlation factor which is a statistical parameter is used here to express the pattern of the energy distribution for different current signals. The proposed algorithm is based on the correlation factors to distinguish between internal fault and inrush currents in the transformer differential protection. The proposed algorithm is tested and simulated for several cases by simulating inrush and internal fault currents. The simulation of inrush and internal fault currents are performed using electromagnetic transient program PSCAD/EMTDC software. Simulation results show that the proposed scheme accurately identifies inrush and fault currents at the distance of the power transformer protection in a time period less than quarter of power frequency cycle. In addition the proposed method has high sensitivity and reliability. The method has low computation work and not requires determining the threshold for each new power system.

Key words: Inrush current · Differential protection · Power transformer · Discrete wavelet transform (DWT) · Internal fault

INTRODUCTION

Differential relays are the initial and principal protective tools for power transformers protection. The essence of operation of differential protection is based on comparing currents flowing into and out of the transformer protected area. There are some cases such as inrush currents, saturation of current transformer and operation of the transformer tap changer that may lead to incorrect operation of the differential relay. Any sudden change in transformer terminals voltage results in a transient current into the power transformer that is called inrush current. One of the important cases of inrush currents is the case that transformer is switching to the power system. Inrush current results in needless action for differential relays.

A common way to detect the inrush current is use of the second harmonic component of current that usually in an inrush current is larger than an internal fault current [1]. The ratio of the second harmonic component to original component of the current signal is compared with a threshold value. This ratio is a measure to distinguish the inrush current from fault current. However, by occurring power system changes and improving in transformer core material and, the level of second harmonic component of the inrush current has been reduced [2]. On the other hand, in some severe faults, the level of second harmonic component in fault currents is higher than inrush currents. Drawbacks of the method in [2] indicate that there is a need for expressing new tools for detecting inrush currents. In one approach namely, differential power method, sum of active power flowing into transformers

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from each terminal is used [3]. The proposed method in [4] is based on the modal transform of voltage and current waveforms. This method needs measuring of the voltage as well as current and, also computations and recognition time are lengthy. In [5], the dead angle method is used which is based on the time at which the current waveform is zero, but it has also long time delay in its detection algorithm. In recent years, some methods such as fuzzy logic and neural network have been proposed for identifying inrush current [6-8]. The fuzzy logic methods have not good performances when there are rapid changes in the power system. Also, these methods use a lot of rules to make a decision and to create these rules, more work should be done. On the other hand, the neural network based techniques require large training patterns which need a lot of computation time. Also, a separate design should be performed for each new network in the power system.

Frequency analysis can be an effective technique to analysis and get features of signals with complicated characteristics. Such effective analysis is achieved by employing new and efficient signal processing tools. The traditional signal processing tools such as Fourier transform are based on the condition of stationarity and alternating of the signals. However, the disturbances in power systems are non periodic, non-stationary, with short duration and abrupt natures [9]. Recently, some new signal processing techniques such as Wavelet analysis have been proposed to solve this. The Wavelet technique can be applied successfully to various signal and image processing methods, especially for the signals with transient natures and variation with time such as some power system disturbances. Useful information in signal usually can be extracted completely when a simultaneous resolution is performed both in time and frequency regions using the Wavelet transform. Therefore, this transform have been used in many study cases for discriminating between fault current and inrush current in power transformer differential protection [10-12].

This paper proposes a new algorithm for identification inrush currents from fault currents. The Wavelet transform is used to decompose the signal into approximation and detail coefficients for this approach. Then, the detection is performed based on a criterion that is formed using these coefficients. The recognition criterion employs a correlation factor. This factor is used to determine the relationship between wavelet coefficients energy at the different levels. The proposed algorithm is evaluated by several simulated inrush currents and internal fault currents on the simulated power system.

This paper is organized as follows: the proposed method is presented in the Section II. In this section brief description about the Wavelet transform and correlation factor is given and then, the use of the Wavelet transform and correlation factor is explained in the proposed method. The proposed algorithm in the differential protection is presented in Section III. Simulating the proposed method on a test system is presented in Section IV.

Proposed Approach Based on Wavelet Transform and Correlation Factor

Discrete Wavelet Transform: The Wavelet Transform provides an efficient tool for signal processing in time and frequency domains. Investigation on the signal energy components within the lower frequency levels reveals that it is possible to use the information of this energy for discriminating inrush from short circuit current. Also the sub-band filtering of the signal leads naturally to multi-resolution signal decomposition [13]. As the input signals in our study are non stationary signals that their statistical properties change with time. For such signals, ordinary Fourier analysis is not adequate for extracting proper features. For this purpose, it is necessary to express the signal both in time and frequency domains. The short-time Fourier transform (STFT) and the Wavelet transform have are potent for analysis the signals. The STFT has a fixed-duration window that makes a fixed frequency resolution and thus allows only a fixed time-frequency resolution. On the other hand, the wavelet transform is obtained by dilation (or contraction) and translation of the primary band pass function. The Wavelets are used to transform the under investigation signals into another representation which shows the information of the signals in a more useful form. It is worthwhile to note that the wavelet transform is a convolution of the wavelet function with the original signal. In this paper, the wavelet transform is implemented in its digital format, Discrete Wavelet transform (DWT). The complexity of DWT is very low in compared to the continuous Wavelet transform (CWT). Also, performing coefficients analysis of DWT is easier than many coefficients of CWT. Pattern recognition of the signal manner is more accurate using DWT. The continuous wavelet function is defined as follows [14]:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi(\frac{t-b}{a}) \quad (1)$$

The dilation and contraction of the wavelet is established by the dilation parameter "a". The movement of the wavelet along the time axis is established by the translation parameter "b". The wavelet described by Eq. 1 is known as the mother wavelet or analyzing wavelet. For DWT, wavelet function is defined by sampling from these parameters (a, b). This wavelet has the form as:

$$\psi_{m,n}(t) = \frac{1}{\sqrt{a_0^m}}\psi(\frac{t - b_0 a_0^m}{a_0^m}) \qquad (2)$$

Where, the integers 'm' and 'n' control the wavelet dilation and translation, respectively. The parameter of 'a_0' is a specified fixed dilation step parameter and 'b_0' is the location parameter. Common choices for discrete wavelet parameters 'a_0' and 'b_0' are 2 and 1, respectively which is known as the Dyadic grid arrangement. The Dyadic grid is the simplest and most efficient choice for practical purposes [14]. Dyadic wavelet (mother wavelet) can be written as (n is an integer number):

$$\psi_{m,n}(t) = 2^{-m/2}\, \psi(2^{-m}\, t - n) \qquad (3)$$

The orthonormal dyadic discrete wavelets are associated with scaling function and their dilation equation. The scaling function is given by:

$$\phi_{m,n}(t) = 2^{-m/2}\, \phi(2^{-m}\, t - n) \qquad (4)$$

Let $f(1)$ be a discrete input signal and it is a signal with a finite length of $N = 2^M$. Thus, the range of scales can be investigate is 0<m<M. The input signal can be expressed in terms of its discrete wavelet equation as follows:

$$f(t) = \sum_{n=0}^{2^{M-m}-1} S_{m,n}\phi_{m,n}(t) + \sum_{m=1}^{M}\sum_{n=0}^{2^{M-m}-1} T_{m,n}\psi_{m,n}(t) \qquad (5)$$

Where, $T_{m,n}$ and $S_{m,n}$ are known as detail and approximation coefficients, respectively. Detail and approximation coefficients are correspond with filtering plus down sampling of the original signal $f(t)$ as shown in Fig. 1.

Fig. 1 shows the decomposing the signal into detail and approximation coefficients. In this figure, LP and HP are high pass and low pass filters, respectively. According to this figure, in discrete wavelet analysis, the signal is first divided into low and high frequency components at the first level. This first low frequency sub-band, containing most of the signal energy, is the approximation coefficients in the first level. These approximation coefficients are convolved with the low pass filter and then down sampled to give the approximation signal coefficients at the next level. On the other hand, the approximation coefficients are convolved with the high pass filter and down sampled to give the detail signal coefficients at the next level. The detail components are kept and the approximation components are again passed through the low pass and high pass filters to give coefficients at the subsequent level and process is be continued. Eventually, the signal can be represented by a low-pass at a certain scale, plus sum of detail signals at different resolutions.

It should be noted that the frequency band presented by each level is directly related to the sampling frequency and it is used to determine the frequency band for the wavelet analysis. According to the Nyquist criterion, the highest frequency component found in a signal is the half of the sampling frequency [15]. In this study, the chosen sampling frequency is 20 kHz which is corresponds to 400 samples at the power frequency cycle of 50 Hz.

It is worthwhile to note that there are different mother wavelet functions for different applications. On the other hand, choosing the mother wavelet plays an important role in the success and efficiency of the analysis and detecting signal events. The mother wavelet should be chosen based on the nature of the under study signal as well as the shape of signal transient being detected. This paper includes analyzing short duration, fast decaying and oscillation type of high frequency current signals. For these signals, Daubechies mother wavelet is an appropriate choice as reported in [16]. In the proposed method, Daubechies with two coefficients 'db2' is introduced as the mother wavelet.

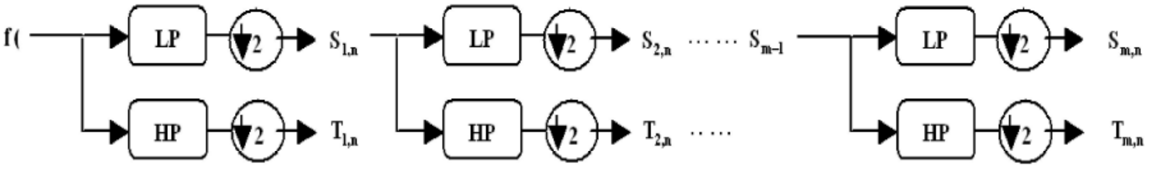

Fig. 1: m-level signal decomposition

The next step is to determine the number of decomposition levels. Since the data window has 64 samples, utmost of decomposition level can be six. For our purpose five levels is sufficient and signal features are specified for using in the discriminative algorithm by these numbers of levels. A sliding window of 64 samples is used in this paper that results in five level of resolution with five details plus an approximation.

Base of Proposed Method: The proposed method is based on a statistical criterion that is used to extract specification of differential currents components. To illustrate the discriminating criterion, the covariance is firstly described. The covariance function tries to capture a sense of joint dependence between two real valued random variables. A correlation coefficient; however, is an appropriately scaled version of a covariance. The correlation coefficient between two random variables x_1 and x_2, denotes by ρ_{x_1,x_2} is defined as follows [17]:

$$\rho_{x_1,x_2} = \frac{\operatorname{cov} ariance(x_1,x_2)}{\sigma_1\sigma_2} \tag{6}$$

Where, $\sigma_i^2 = \operatorname{var} iance, i = 1,2.$

Two random variables, x_1 and x_2 are called negatively correlated, uncorrelated, or positively correlated, respectively if and only if ρ_{x_1,x_2} is negative, zero or positive, respectively.

Assume that the two random variables are two matrices or vectors with the same size. Thus, the resulted equation for the correlation factor between x_1, x_2 is as follows:

$$\rho_{x_1,x_2} = \frac{\sum_m\sum_n (x_{1_{mn}} - \overline{x_1})(x_{2_{mn}} - \overline{x_2})}{(\sum_m\sum_n (x_{1_{mn}} - \overline{x_1})^2)(\sum_m\sum_n (x_{2_{mn}} - \overline{x_2})^2)} \tag{7}$$

Where, *m,n* are dimension of vectors and $\overline{x_i} = mean(x_i), i = 1,2$.

From above explanation, this statistic coefficient and Wavelet transform is used to produce discriminative criterion to distinguish between inrush and fault currents in power transformer. In order to create the discriminative criterion, at first energies of detail components from wavelet transform in each level are computed as:

$$Ed_i = \sum_{n=0}^{2^{M-i}-1} (d_{i,n})^2 \tag{8}$$

Where, $d_{i,n}$ are the components of detail coefficients, 'M' is the all number of Wavelet decomposition levels and 'i' is a certain level that the detail components energy is computed at its level.

Also, the total energy of signal at each sliding window is computed as:

$$E_j = \sum_{n=0}^{k-1} (I_j(n))^2 \tag{9}$$

At the above equation 'k' is the amount of samples at each sliding window and 'j' is the number of sliding window. From Eqs. 8 and 9, the energy percentage of detail coefficients to the total energy of signal is computed:

$$Ed_{i,j} = \frac{Ed_i}{E_j} \times 100 \tag{10}$$

Therefore, a vector of energy percentage of DWT coefficient for each of the five levels and in any sliding window is obtained from:

$$Ed_{i,j} = [Ed_{1,j}, Ed_{2,j}, Ed_{3,j}, Ed_{4,j}, Ed_{5,j}] \tag{11}$$

Where, Ed_i = Wavelet detail coefficients energy percentage to total signal energy at the level, (i=1, 2, 3, 4, 5) and j is the number of sliding window. Therefore, for the input signal with N discrete samples, the energy vectors matrix of all samples is constituted as below:

$$Ed = \begin{bmatrix} E_{11} & E_{12} & E_{13} & \cdots & E_{1,j} \\ E_{21} & E_{22} & E_{23} & \cdots & E_{2,j} \\ E_{31} & E_{32} & E_{33} & \cdots & E_{3,j} \\ E_{41} & E_{42} & E_{43} & \cdots & E_{4,j} \\ E_{51} & E_{52} & E_{53} & \cdots & E_{5,j} \end{bmatrix}_{5,j} \tag{12}$$

As there are 64 samples at each sliding window, the number of all windows at the signal with N samples is j=N-64. Therefore, the *Ed* matrix has the dimension of 5×N-64. It means that the resolutions are performed for the signal with N samples at the sliding windows with 64 samples at five levels of wavelet transform decomposition. After that the correlation factor between two continuous vectors is calculated as below (j is the number of the sliding window):

$$Ed_j = [Ed_{1,j}, Ed_{2,j}, Ed_{3,j}, Ed_{4,j}, Ed_{5,j}]^T \tag{13}$$

$$Ed_{j+1} = [Ed_{1,j+1}, Ed_{2,j+1}, Ed_{3,j+1}, Ed_{4,j+1}, Ed_{5,j+1}]^T \tag{14}$$

$$\rho_{j,j+1} = correlation(Ed_j, Ed_{j+1}) \tag{15}$$

The $\rho_{j,j+1}$ is the correlation factor between the energy vectors at the j and j+1 numbers of sliding windows. Thus, the correlation factors for the matrix of the (12) that are named Cf are as below:

$$Cf = [\rho_{1,2} \;\; \rho_{2,3} \;\; \rho_{3,4} \;\; \cdots \;\; \rho_{j-1,j}] \tag{16}$$

In this study, the values of Cf factors are used in the discriminative method. It is expected that the values of Cf to be near the value of "1" (highly correlated signals) for the steady state condition. It is because of fact that the normal current has smooth condition and the energy of the signal has not a noticeable change and energy percentage between two sliding windows are highly correlated. On the other hand, with a sudden change in the current magnitude and power system disturbances, the energy of signal has a rapid change in the DWT components and with change in the condition of the power system the signal energy should be greater than the normal condition. In the case of inrush current because of oscillatory nature of the current and having a different energy spectrum at different frequency levels, the energy percentage at the high frequency level will be changed approximately with an oscillatory shape.

Proposed Discriminative Algorithm: The algorithm of the proposed approach is illustrated in this section. In order to clarify the proposed method, the diagram of the test system is depicted in Fig. 2. This test system will be used later in the simulation section.

At first, relay differential currents are calculated from the currents that are measured at two sides of protected transformer. These currents are calculated as follows [15]:

$$I_1 = (I_A - I_a) - (I_C - I_c) \tag{17}$$

$$I_2 = (I_B - I_b) - (I_A - I_a) \tag{18}$$

$$I_3 = (I_C - I_c) - (I_B - I_b) \tag{19}$$

Where, I_A, I_B, I_C are the primary side currents and I_a I_b I_c are secondary side currents of power transformer (Fig. 2) and I_1, I_2, I_3 are the differential currents and input currents for the differential relay. In the proposed algorithm I_1, I_2, I_3 are the input signals which are employed by the proposed method. Differential currents are then compared with a predetermined threshold to uses in the proposed algorithm. The value of the threshold current is determined based on the specifications of power system, power transformer and performance characteristics of differential relay, which is set such that to avoid responding to heavy external fault and steady state conditions. If any of the differential currents exceeds this threshold, the program starts to apply the DWT analysis to the currents signals. As a result, the signals are decomposed into detail and approximation coefficients. Then, the energy percentage of detail coefficients is calculated for any of the five levels. After this step, a vector is organized from the calculated energy percentages for each sliding window (Eqs. 11 and 12). In the next step, the correlation factor ($\rho_{j,j+1}$) is calculated between two consecutive vectors that are organized from two consecutive sliding windows (Eqs. 15 and 16). The values of the correlation factors versus the samples number for each of the three differential currents in the proposed algorithm is computed in the next step. The values of correlation factors are labeled by 'Cf 1', 'Cf 2' and 'CF 3' respectively, for I_1, I_2 and I_3 in the simulation results part of the study.

Simulation results verify that the correlation factors for inrush current have oscillation nature and for fault current these factors have smooth nature after transient state. By the use of the waveforms of Cf factors, a criterion is defined for the discriminative algorithm. The proposed criterion is based on the number of dips in the shape of the Cf factors. As the simulation results shows later, the fault currents have only one dip and sudden descent at the start instance of the fault. However in the case of inrush current the number of dips are more

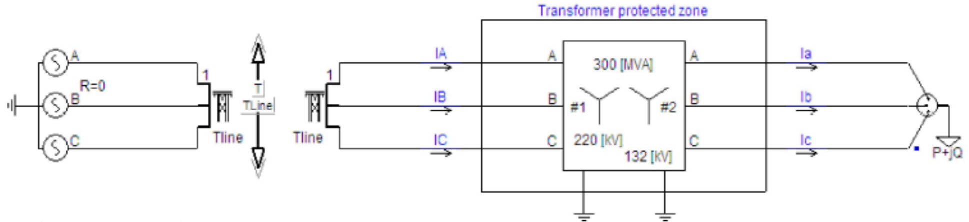

Fig. 2: Simulated power transformer

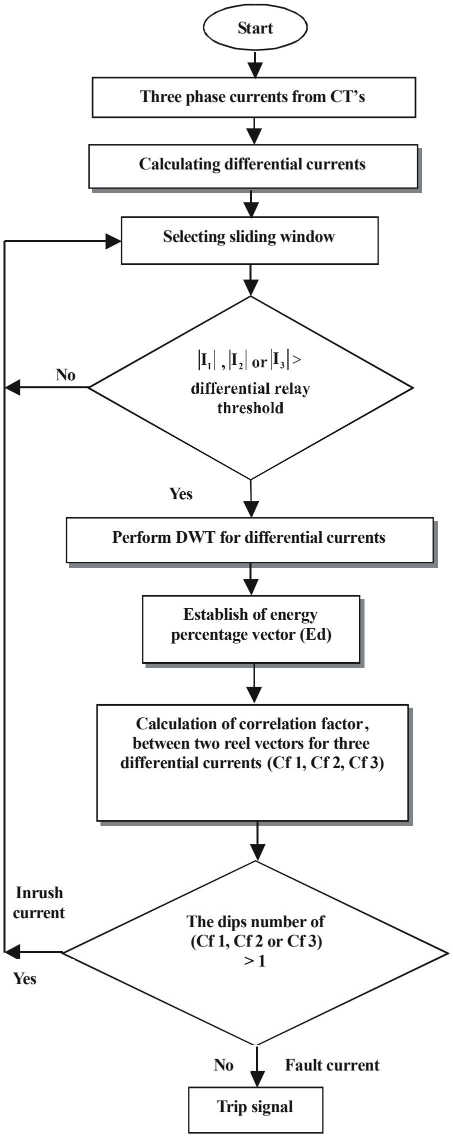

Fig. 3: Protection flowchart in the proposed method

than one and the dips repeat for next times until the inrush current is settled. In counting the number of dips, those dips are smaller than 0.9 are considered. The chosen magnitude of 0.9 is because of the correlation factors that are very near to the value of one and having more reliability at the algorithm and on the other hand simulation results show that the correlation factors for fault current are smaller than 0.9 after removing the transient state. Thus, number of dips in the correlation factors in the proposed algorithm is considered as:

$$\begin{cases} \rho_{j-1,j} > \rho_{j,j+1} < \rho_{j+1,j+2} \\ and \quad \rho_{j,j+1} < 0.9 \end{cases} \Rightarrow \rho_{j,j+1} \leftrightarrow One\, dip\, at\, Cf \qquad (20)$$

The interpretation for the above equation which is in the calculation of number of dips, the values of correlation factors ($\rho_{j,j+1}$) which are smaller than the previous and next values and also is smaller than the value of 0.9 are considered as a dip.

Therefore, the number of dips at any of the 'Cf 1', 'Cf 2' or 'Cf 3' exceeds one, it means that occurrence the inrush current otherwise it consider as a fault current. Reorganization criterion in the proposed algorithm is defined as below:

$$\begin{cases} Number\ of\ dips > 1 & Inrush\ current \\ \quad Otherwise & Fault\ current \end{cases} \qquad (21)$$

If the recognition factors indicate a certain internal fault in the differential current, a trip signal is issued to the power transformer circuit breakers to isolate the transformer from the healthy system. The flowchart of this algorithm is shown in Fig. 3.

RESULTS

In this section effectiveness of the proposed algorithm is evaluated for different types of faults, inrush currents and simultaneous occurrence of internal fault and inrush currents.

Power System Model: In order to generate the current signals for investigation of the performance of the proposed algorithm, a power system is simulated using PSCAD/EMTDC simulation package. The single line diagram for the power system is shown in Fig. 4. It consists of a three phase 220 kV source connected to a three phase, two winding, power transformer (300 MVA, YY 220/132kV) via a 20 km transmission line. The neutral point of the Y connection is grounded. The transformer secondary is connected to a three phase load (44Ω, 0.068H). Different cases of power system condition such as energizing condition, internal faults (on 100% of transformer winding) and simultaneous internal fault and inrush current are carried out in this study.

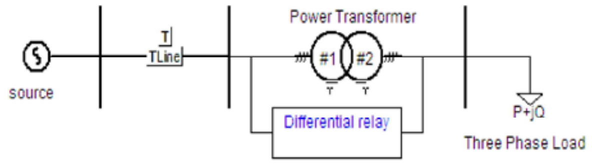

Fig. 4: Simulated power system model

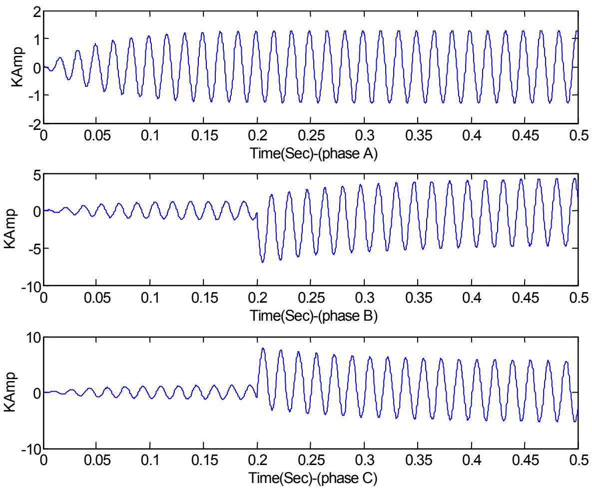

Fig. 5: Internal single line-to-ground fault current

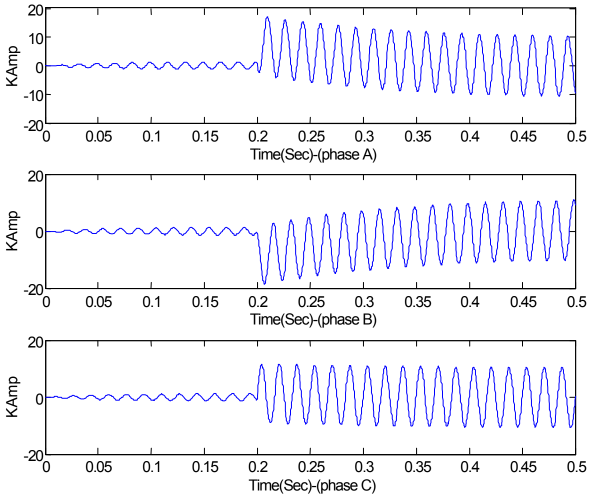

Fig. 7: Internal three line-to-ground fault current

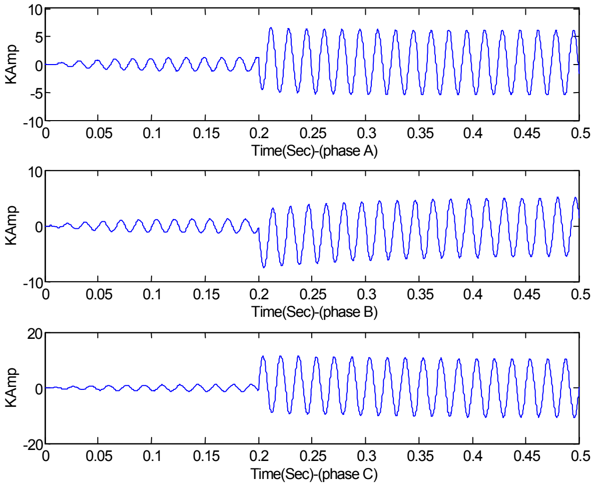

Fig. 6: Internal double line-to-ground fault current

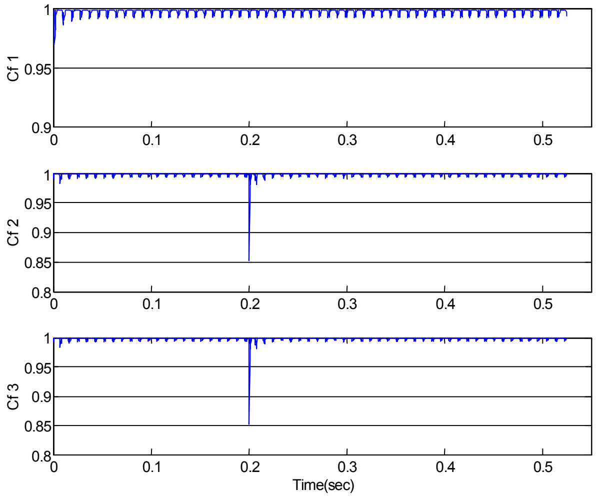

Fig. 8: The Cf factors in case of internal single line-to-ground fault

Fault Current: To obtain the simulation data for internal fault, different faults are simulated inside protective zone of the transformer. These faults consist of phase to ground fault (single phase B to ground), double phase to ground fault (fault between two phases B, C to ground) and three phase to ground fault on the secondary side of the power transformer. The starting time of faults is at 0.2 s and duration time of fault is 0.3 s. Figs. 5-7 show the differential fault current that are simulated at the PSCAD software.

Fig. 8 shows the Cf factors for three differential currents (Cf 1, Cf 2, Cf 3) for single phase internal fault (fault B-G). As can be seen from this figure, the values of Cf are approximately "1" for steady state until the time that the fault is occurs, then a rapid change and descent is appeared in these Cf values, then again come back to the value of "1". The waveform for I_1 is not the similar to other waveforms, because it depends on the currents of the healthy phases. Therefore, its value is always approximately "1" similar to the normal condition and there is no change in the Cf factor.

Fig. 9 shows the case of an internal fault (double phase to ground). In Fig. 9 the values of Cf factors are approximately "1" for normal condition. After occurrence the fault a rapid change is seen in the factors. Then, similar to the previous case, the values of Cf reach close to the value of "1". In this figure, all differential currents depend on the faulty phases, so all of plots have almost the same shape.

Another case of an internal fault (three phase to ground) is shown in Fig. 10. In this figure all differential currents are related to the faulty phases; therefore, the values of Cf factors are approximately "1"

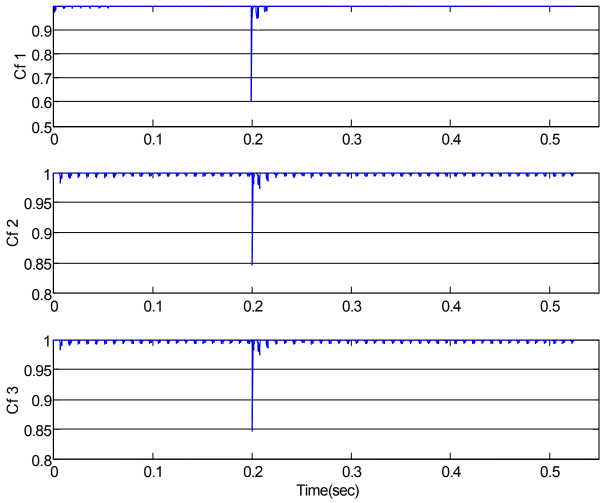

Fig. 9: The Cf factors in case of internal double line-to-ground fault

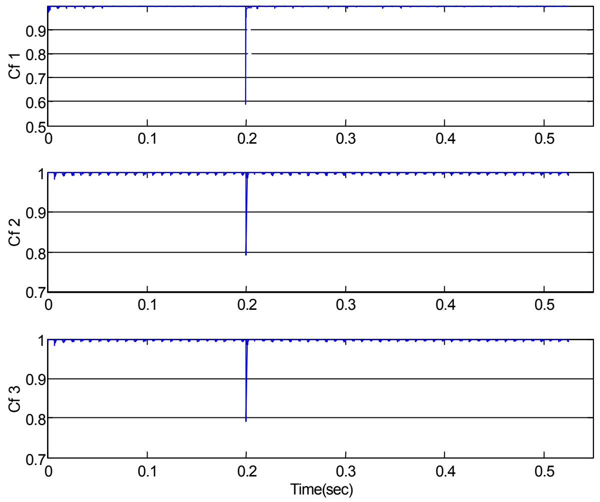

Fig. 10: The Cf factors in case of internal three line-to-ground fault

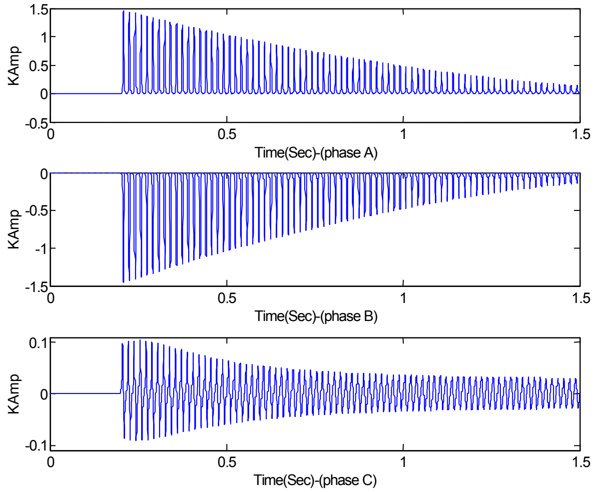

Fig. 11: Inrush current without residual magnetism

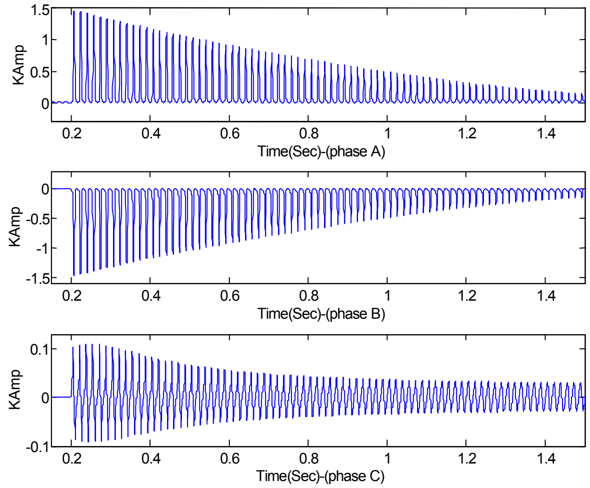

Fig. 12: Inrush current with residual magnetism

for the normal condition. After occurrence the fault a fast change in the factors is observed and then each of the Cf factors returns to "1" value. It comes back to previous value shows occurrence an internal fault current.

At all cases for fault currents the correlation factor becomes smaller than 0.9 at the start time of fault and transient state, after that it becomes approximately "1" and there is only one dip with the magnitude smaller than 0.9 in the Cf values.

Inrush Current: In the case of magnetizing inrush current that is created from transformer switching; two major factors affect the dip value of the magnetizing inrush current [15]. The first factor is the energizing time instant, which can be controlled through controlling the time at which the circuit breaker is closed and transformer is connected to the power system. The second factor is the amount of the residual magnetism in the transformer core, which may exists due to previous switching operations of the transformer. If the polarity of the residual flux value be opposite of the steady state condition polarity, the dip value of the inrush current can increases. On the other hand, the residual magnetism can be considered by switching the transformer for several times or the desired remnant magnetism can be set in unenergized transformer with controlled dc current sources in PSCAD/EMTDC simulation model [18]. Differential magnetizing inrush current is collected while the transformer is unloaded and the transformer is switched to the power system with the circuit breakers on the primary side of the transformer. Several cases of inrush current with variable time switching and different value of residual magnetism were

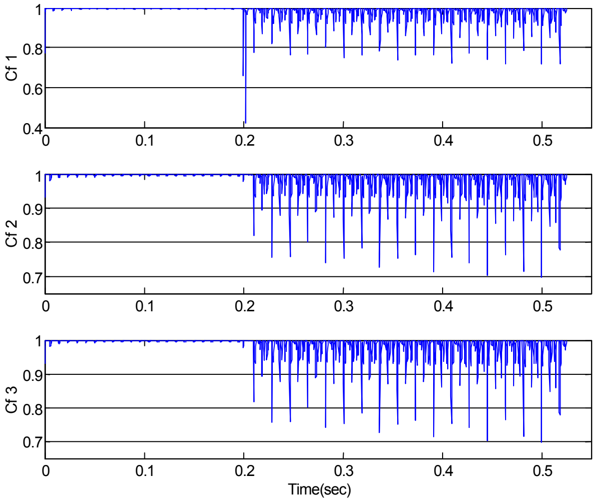

Fig. 13: The Cf factors in case of inrush current without residual magnetism

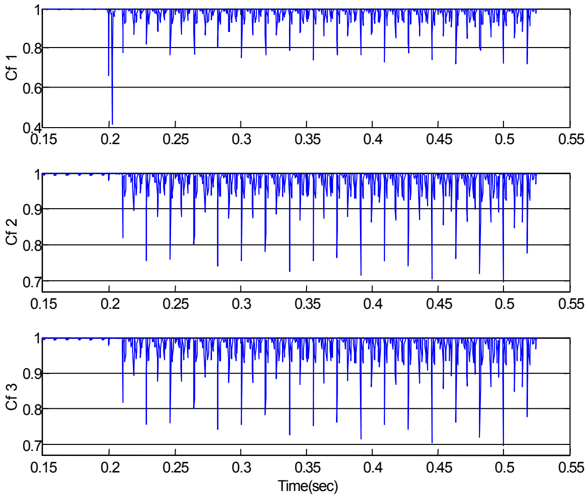

Fig. 14: The Cf factors in case of inrush current with residual magnetism

simulated. In this paper switching time at 0.2 s, is shown. Fig. 11 shows the differential inrush current without the residual magnetism and Fig. 12 shows the differential inrush current for two times switching of transformer and therefore existence of residual magnetism.

Figs. 13 and 14 illustrate the Cf factors in the case of an inrush current (without and with residual magnetism, respectively). According to Figs. 13 and 14, it is obvious that the Cf factors for two cases is approximately "1", similar to previous cases in about faults, for normal condition. After switching the transformer a sudden change in detection criterion (Cf) value is appeared, but waveforms do not come back to the previous values, close to the value of "1" and have an oscilatory nature. Therefore, Cf factors go away from the value of "1" and become lower than the defined threshold (0.9). As a result, there are many dips for correlation factor and in the proposed algorithm the number of dips for the correlation factors (Cf 1, Cf 2, Cf 3) becomes greater than one and differential relay is blocked.

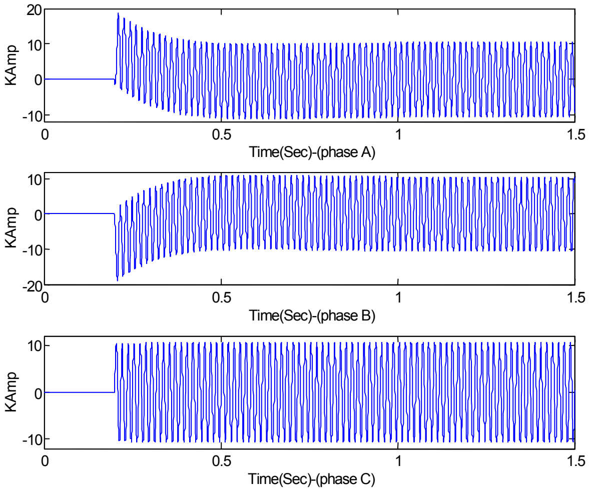

Fig. 15: Simultaneous internal fault and inrush current

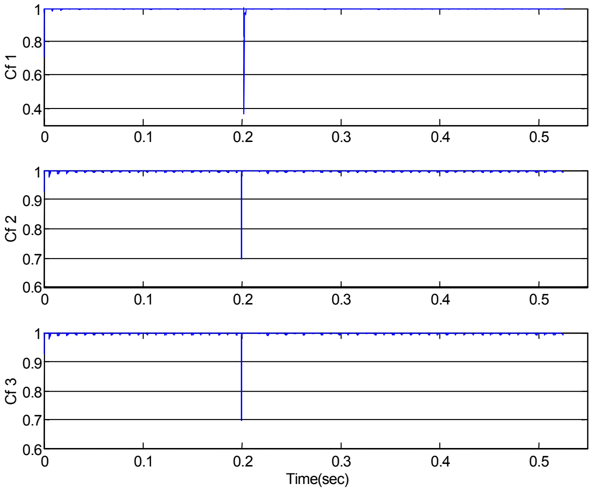

Fig. 16: The Cf factors in case of simultaneous internal fault and inrush current

Simultaneous Internal Fault and Inrush Current: After studying fault and inrush currents cases separately, some more complicated cases (simultaneous internal fault and inrush current) are examined. Fig. 15 shows the differential current signal for the case of simultaneous internal fault and inrush current, whereas switching is at the primary side and fault (three phases to ground) is on the secondary side of the transformer and starting time of fault and transformer switching is at 0.2 s. Fig. 16 shows the Cf factor for three differential currents

(I_1,I_2, I_3) for simultaneous inrush and fault current. The values of Cf factors for these shapes are approximately "1" for normal operation until the time of occurrence the simultaneous fault and inrush, that shows a sudden change in the Cf factor value for the differential currents, then it comes back to "1" value, similar to fault cases. Therefore, there is only one dip at any of the Cf factors and the fault is identified fast and reliably and do not make a mistake in detection algorithm.

According to represented cases, the discrimination between inrush and fault current is performed accurately with considering the Cf 1, Cf 2 and Cf 3 versus the time axis. After the desired signal decomposition in to five levels by using the DWT, the energy percentage vectors are established, as it was explained before. Then, correlation factors are plotted for each current signal (Cf 1, Cf 2, Cf 3). The simulation results depict that a sudden change in waveform of Cf factor shows the occurrence of a disturbance. Then, the algorithm computes the number of dips for Cf values for each three phase differential currents. The exceed of dips number shows inrush current; otherwise, it is considered as fault current and a trip signal is sent to the power transformer circuit breakers. Therefore, the fault and inrush currents can be detected less than time of 3 ms that is a good time for detection of fault.

CONCLUSION

In this study a new algorithm for discrimination between inrush and internal fault currents is proposed using the DWT. The differential currents of the power transformer are decomposed into five levels. The algorithm is based on the energy percentage of the DWT coefficients. The correlation factor between energy percentage vectors of the detail coefficients is calculated at each sliding window. Detection process is then performed by determining the Cf factors versus the time and computing the dips number of them. The proposed algorithm is tested on a power system model. Several cases of the inrush currents, internal faults and also simultaneous inrush and fault currents are simulated and some of them are represented in this paper. The waveshapes from the simulated cases show that the Cf factors for inrush currents have oscillatory nature but for internal fault currents they settle near the one value. By use of this property a threshold is determined that is the dips number of Cf. For an inrush current, number of dips for the correlation factors goes away from one dip and an internal fault current that has a smooth nature, the dips number is one and there is only at the start time of fault. The simulation results show fast and reliable capabilities of the proposed algorithm in identifying the different types of currents flowing in a power transformer under various conditions.

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