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A Novel Method in Differential Protection of Power Transformer Using Wavelet Transform and Correlation Factor Analysis

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Abstract

This paper presents a new online approach for power transformer differential protection. The proposed method is concluded by sampling from differential current product of three phases primary and secondary currents. Recognition of fault type in protection area is based on wavelet transform and correlation factor appointment and eventually correlation factor matrix analysis and determines the size of each dip. Simulations of power system, online relay, and fault applying for relay analysis have been performed by MATLAB/Simulink. Unlike other current proposal methods, the most important advantage of our approach is being online of the performance of its designed relay in each time period that provide to make the industrial sample of that. Simulation results show that the performance of designed relay is remarkable and the performance of this relay is compared to that of other existing offline methods, obtaining considerably better and very promising results.

Keywords : Power Transformer, Differential Protection, Wavelet Transform, Correlation Factor, Online Performance

1. Introduction

Power transformers are very important equipment in the power system that is used for energy transmission. Internal faults that occur every time with different amplitudes damage power transformer windings. Faulted transformer must be isolated from power system very fast because of preventing damages that can be occurred. Moreover, the act of differential protection must be accurate. Hence, differential protection is the most important protection for power transformers. Some disturbances such as inrush current, saturation, and over excitation can result in mal function in differential protection. Correct and fast discrimination between internal fault and inrush current is an important problem about transformers' differential protection. False trip due to incorrect discrimination can have economic burden. All of the transformer disturbances are non-stationary with short duration signals. Recently, because of high ability for transient signal analysis, wavelet transform is the main technique for feature extraction. The wavelet technique can be applied successfully in various signal and image processing methods, especially for the signals with transient natures and variation with time such as some disturbances of the power system [1]. Some methods for power transformer protection have been proposed such as adaptive differential protection [2]. Fuzzy logic is another method that is used for differential protection [3]. An effective way to avoiding malfunction of the differential protection on magnetizing inrush current is phase angle difference (PAD) technique [4]. In this way, at first the relay differential and restraint currents

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are calculated, and the fundamental-frequency components of the two currents are then compared to identify the phase angle difference (PAD) between the primary and secondary currents. Another method is based on wavelet transform and neural network [5], [6] or wavelet transform combined with support vector machine [7]. The method that is based on median absolute deviation (MAD) of wavelet coefficients over a specified frequency band uses wavelet transform as signal-processing step [8]. A new methodology to distinguish between inrush currents and internal faults based on the differential current gradient is proposed in [9]. This 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 [10] is used Clarke's Transform and Discrete Wavelet Transform (DWT) for discrimination between internal fault and other events. Bayesian Classifier (BC) which works based on Bayesian rules in parallel with artificial neural network is a method for power transformer differential protection [11]. Discrete Fourier Transform with Radial Basis Function Neural Network is used for detecting inrush current from internal fault [12]. The concept of differential powers is introduced In [13], [14]. Wavelet transform and adaptive network-based fuzzy inference system (ANFIS) is another way to discriminate internal faults from inrush currents [15]. The [16] Proposed an algorithm based on processing differential current harmonics for differential protection of power transformers. ANN-based method [17], radial basis neural networks [18], and also decision trees [19] are used for power transformer differential protection.
The rest of this paper is organized as follow, Section 2 describes wavelet transform that is used for signal processing stage. In Section 3, correlation coefficient is described. Test system that is used in this study presented in Section 4. Section 5 describes the proposed method. Section 6 presents simulation results and its comparison. The paper is concluded in section 7.

2. Wavelet Transform

The wavelet transform is an efficient tool for signal analysis in time-frequency domain. Wavelet is a waveform which has a limited period of time and possesses zero-average quantity. Continuous wavelet transform is defined as:

$$c(a,b) = \int_R s(t)\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)dt \tag{1}$$

where *S(t)* is the primary signal and $\psi(t)$ is mother wavelet.

$$a = 2^j, b = k2^j, (j,k) \in z^2 \tag{2}$$

where *j* shows the wavelet level and *k* shows the time, discretely. *C(a,b)* is a coefficient which shows similarity level of shifted and scaled mother wavelet with primary signal. At any level of wavelet transform, the coefficients of A_j and D_j are generated as follow:

$$D_j(t) = \sum_{K \in z} c(j,k)\psi_{j,k}(t) \tag{3}$$

$$\psi_{j,k}(t) = 2^{-j/2}\psi(2^{-j}t - k), j \in z, k \in z \tag{4}$$

$$A_j = \sum_{j \succ J} D_j \tag{5}$$

A_j is an approximation of the primary signal, and D_j shows the details of the signal. As shown in Fig. 1. the signal is passed through two complimentary filters, called low-pass decomposition (LD) and high-pass decomposition (HD) filters, and the convolution of the signal is evaluated by filters' coefficients. The low-frequency (LF) and the high-frequency (HF) coefficients of the wavelet transform are then determined by down sampling of the obtained results. In the multilevel wavelet analysis, the above single-stage scheme is repeated, and the low-frequency coefficients are decomposed in any stage such that a signal is decomposed into many low orders of decomposable components [15].

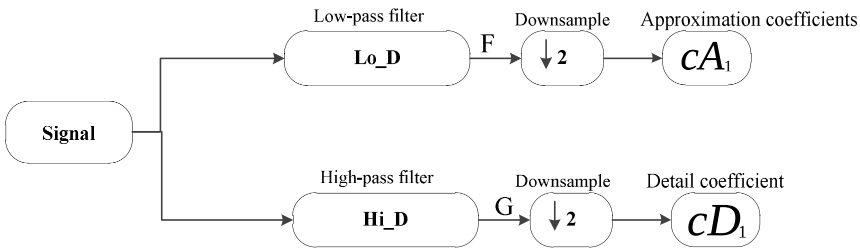


Fig. 1. *Single stage wavelet transform*

The energy of a discrete signal *x(n)* is calculated as follow [10]:

$$E = \sum_{i=1}^{n} X^2[i] \tag{6}$$

where n is the number of signal samples.

3. Correlation Factor

Correlation factor is a statistical tool for determining the kind and grade of relation between a quantitative variable with another quantitative variable. The correlation factor shows the severity and the kind of relation (direct or reverse). This factor is between 1 and −1, and if there is no relation between two variables, then it is equal to zero.
Correlation between two random variables *X* and *Y* will be defined as follows:

$$r_{X,Y} = \frac{\operatorname{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{E[(X-\mu_X)(Y-\sigma_Y)]}{\sigma_X \sigma_Y} \tag{7}$$

where *E* is the operator of mathematical expectation, cov is covariance, corr is simple symbol stands for Pearson correlation, and σ is the standard deviation.

$$r_{X,Y} = \frac{E(XY)-E(X)E(Y)}{\sqrt{E(X^2)-E^2(X)-\sqrt{E(Y^2)-E^2(Y)}}} \tag{8}$$

For discrete state, the correlation factor r_k will be defined as follows:

$$r_k = \frac{\sum_{t=1}^{N}(X_t-\bar{x})-(X_{t+k}-\bar{x})}{\sum_{t=1}^{N}(X_t-\bar{x})^2} \tag{9}$$

where N is the number of stages and X_t is the number of data in time period, k is the time delay and $\bar{x}$ is the average amount of data that defined as:

$$\bar{x} = \sum_{t=1}^{N} \frac{X_t}{N} \tag{10}$$

Pearson and Spearman are some kinds of correlation factor, which Pearson correlation factor is a parametric method that used for normal distribution or large number of data. If the amount of data is low, we can use the Spearman correlation.

4. Test System

In this study, for internal fault, external fault, and inrush current simulation, MATLAB Simulink is used. The following power system contains a 3-phase, 230 kV, and 50 Hz power supply and a 20 km transmission line and a 300 MVA, 230 /63 kV power transformers that is connected “Y-Y’’ and an inductive load with 100 MW active power and 500 KVAR reactive power. Single line diagram of this system is shown in Fig. 2.

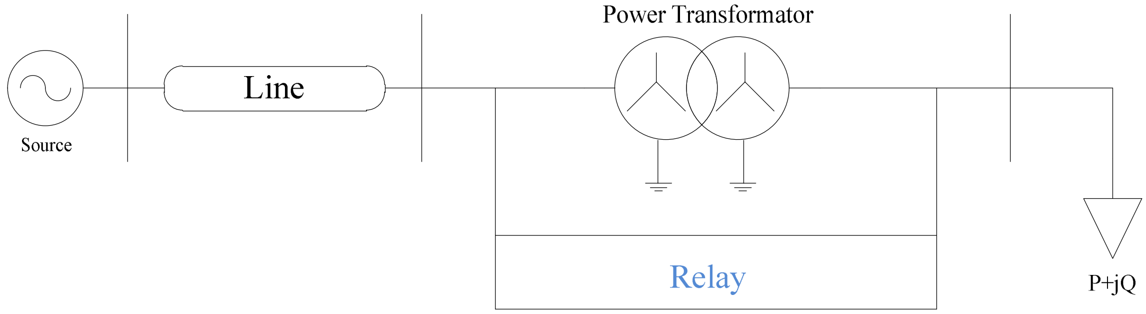


Fig. 2. Test system single line diagram [1]

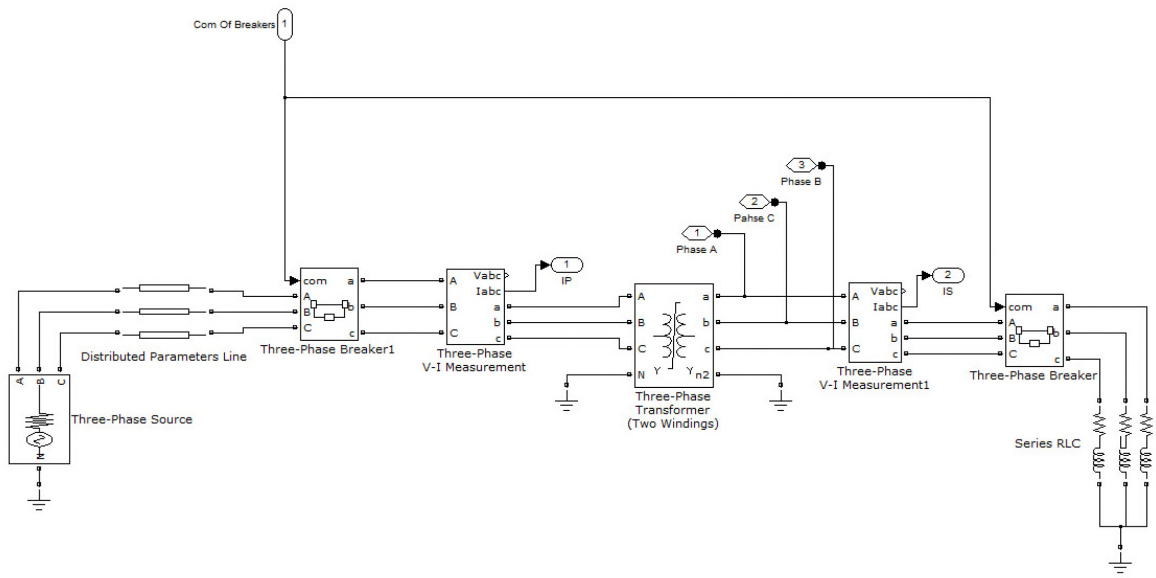


Fig. 3. Simulated test system

Inrush current is simulated by using saturation enabled power transformer. Therefore, a saturation characteristic is defined. More details are shown in Fig. 4.

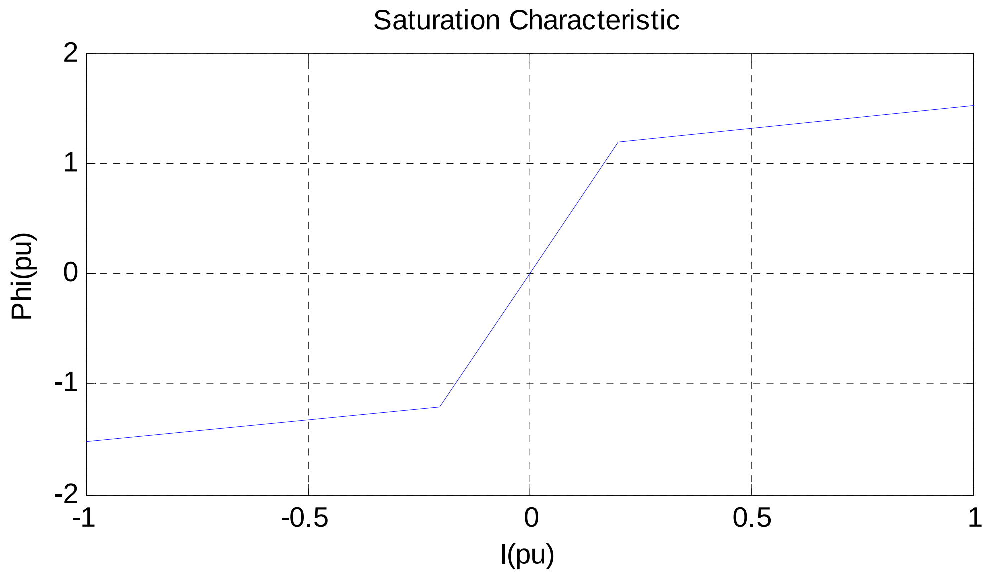


Fig. 4. Saturation characteristic

5. Proposed Method

Power transformer is *Y*-*Y* connected, thus current transformer is connected at Δ-Δ form. Therefore, relay differential currents are calculated as follows [1]:

$$I_1 = (I_{AP} - I_{AS}) - (I_{CP} - I_{CS}) \tag{11}$$

$$I_2 = (I_{BP} - I_{BS}) - (I_{AP} - I_{AS}) \tag{12}$$

$$I_3 = (I_{CP} - I_{CS}) - (I_{BP} - I_{BS}) \tag{13}$$

Fig. 5 shows the differential current block diagram in MATLAB/Simulink.

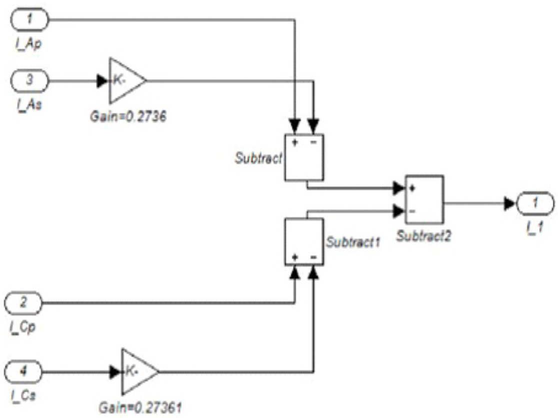


Fig. 5. Differential current block diagram

Differential currents are then compared with a predetermined threshold. 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 to avoid response to heavy external fault condition and steady-state condition. If any of the three differential currents exceeds the threshold, the program starts to run the DWT analysis to the currents. In this method, to get the high accuracy, the wavelet transform is done for each signal period. After the wavelet transform has been done, we can get the wavelet energy which can be seen in Fig. 6.

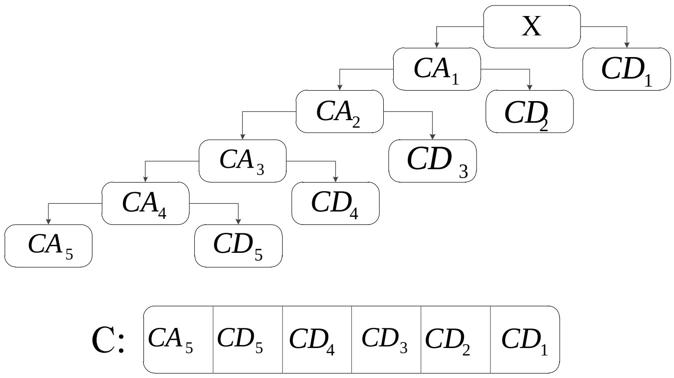


Fig. 6. Five stages wavelet transform

Where Matrix E_a shows the approximation coefficients energy and matrix E_d shows the detail coefficient energy in each level. The energy of detail coefficient produced by wavelet transform at each level will be computed as follows:

$$Ed_i = \sum_{n \in z} s^2 [n_i] \tag{14}$$

where *n* shows the number of existing samples in each level, and *i* shows the considered level. In this study, sampling frequency is 3.2 kHz, thus each period has 64 samples that is divided into eight slide windows with eight samples. Signal energy at j^{th} window can be expressed as follow:

$$E_j = \sum_{k=1}^{8} s^2 [N_k] \quad , j = 1,2,\ldots,8 \tag{15}$$

The proportion of detail coefficient at each level *i* to the total signal energy is defined as:

$$Ed_{i,j} = \frac{Ed_i}{E_j} * 100 \tag{16}$$

therefore, a vector including the percent of detail coefficient energy of wavelet transform created as:

$$Ed_j = [Ed_{1,j}, Ed_{2,j}, Ed_{3,j}, Ed_{4,j}, Ed_{5,j}]^T \tag{17}$$

where Ed_j is equal to the percent of detail coefficients energy to the energy of j^{th} window's signal. Since in this study, the signal analysis will be conducted in five levels, so the introduced vector in equation 17 has five elements.

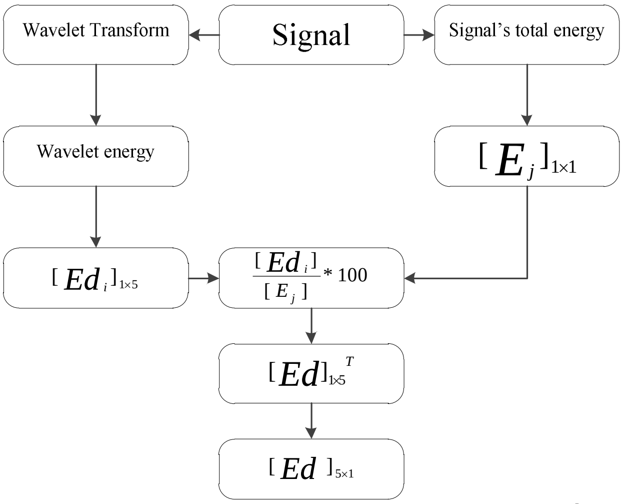


Fig. 7. Ed matrix creation Block diagram at i^th level

In Fig. 7, for an input signal which has *N* discrete samples, the matrix of coefficients energy percent that generated by wavelet transform is defined as:

$$Ed = \begin{bmatrix} E_{11} & E_{12} & E_{13} & E_{14} & E_{15} & E_{16} & E_{17} & E_{18} \\ E_{21} & E_{22} & E_{23} & E_{24} & E_{25} & E_{26} & E_{27} & E_{28} \\ E_{31} & E_{32} & E_{33} & E_{34} & E_{35} & E_{36} & E_{37} & E_{38} \\ E_{41} & E_{42} & E_{43} & E_{44} & E_{45} & E_{46} & E_{47} & E_{48} \\ E_{51} & E_{52} & E_{53} & E_{54} & E_{55} & E_{56} & E_{57} & E_{58} \end{bmatrix} \qquad (18)$$

In this study, for recognizing between inrush current and internal fault after creation of matrix *Ed*, correlation factor is used. As Fig. 8, the matrix of correlation factor is created by correlating j^{th} column of matrix *Ed* with the next column (j+1) that will be formed as:

$$\mathrm{CF} = \lfloor \rho_{1,2}\,\rho_{2,3}\,\rho_{3,4}\,\rho_{4,3} \ldots \rho_{j-1,1} \rfloor \qquad (19)$$

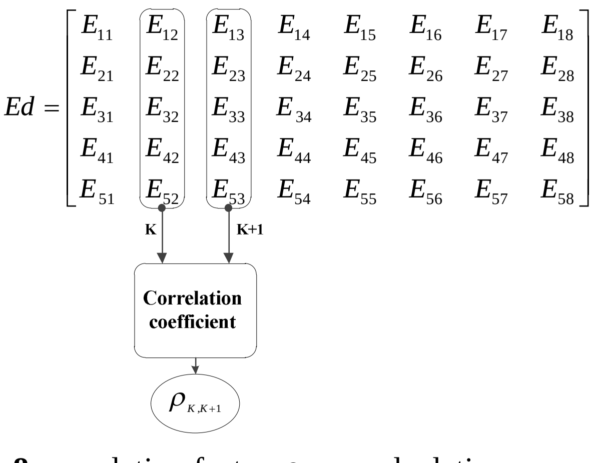


Fig. 8. correlation factor $\rho_{K,K+1}$ calculation procedure

As soon as differential current changes, a change in correlation matrix will occur. In Fig. 9, the differential relay performance flowchart is presented. Based on this flowchart, when the input current is more than the threshold, the process of wavelet transform and correlation factor's creation stats. Fig. 9 shows how we use the correlation factor CF_m for determining fault's kind where elements of m = 1, 2, 3 shows phase number. F_{nm} is a filter where n = 1, 2 is the number of each filter with length of N. N is the number of samples in two periods. Min_{nm} is the minimum amount of each filter F_{nm} which by possessing Min_{nm} the following equations will be defined as:

$$S_1 = abs(abs(Min_{11} - Min_{21}) + abs(Min_{13} - Min_{23})) \quad (20)$$

$$S_2 = abs(abs(Min_{12} - Min_{22}) + abs(Min_{11} - Min_{21})) \quad (21)$$

$$S_3 = abs(abs(Min_{13} - Min_{23}) + abs(Min_{12} - Min_{22})) \quad (22)$$

After that, the upper algorithm has been performed, *Q* parameter is defined as:

$$Q = \text{sum}\ (S_1, S_2, S_3) \quad (23)$$

If the amount of *Q* more than 1, the internal fault will be detected, otherwise the inrush may current may occur

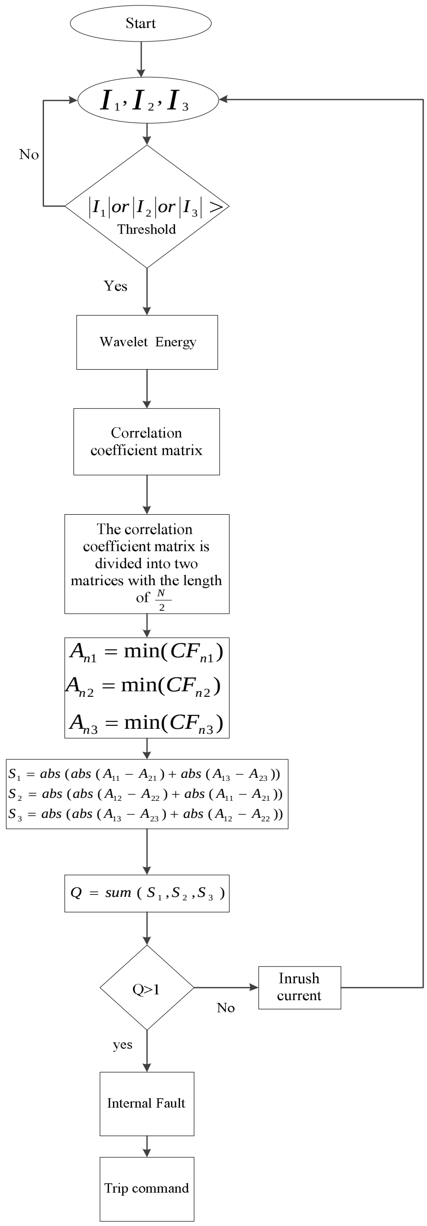
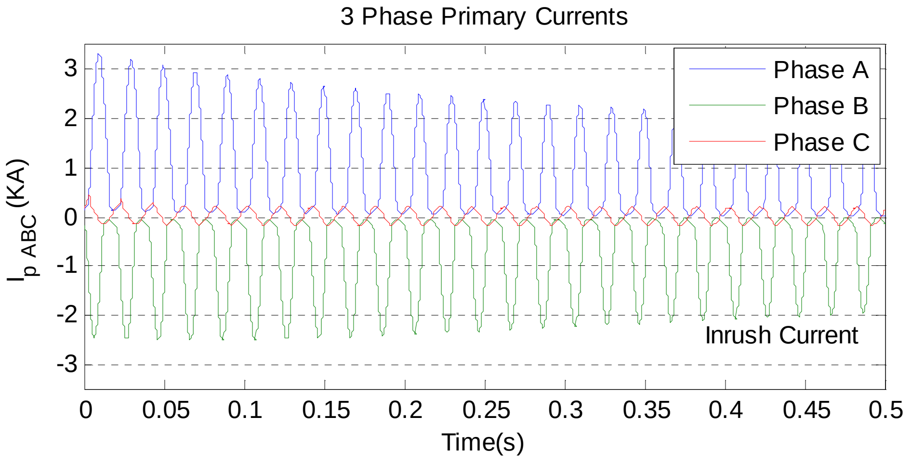


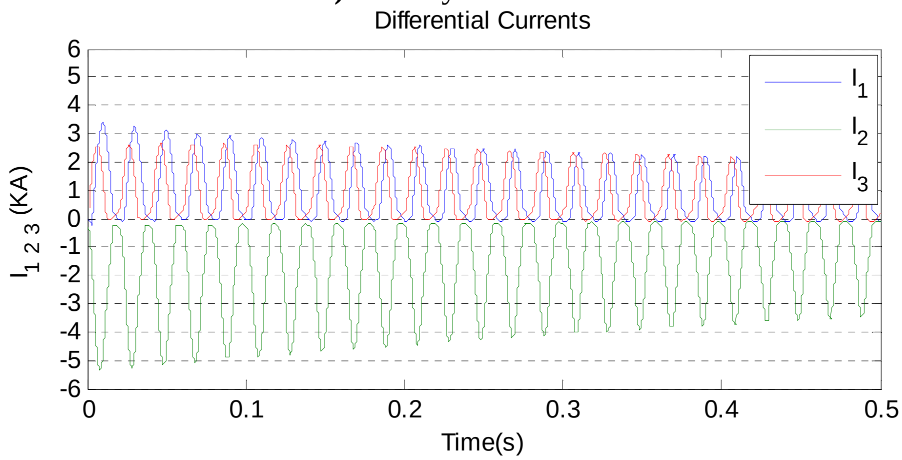
Fig. 9. Relay operation flowchart

6. Simulation Results

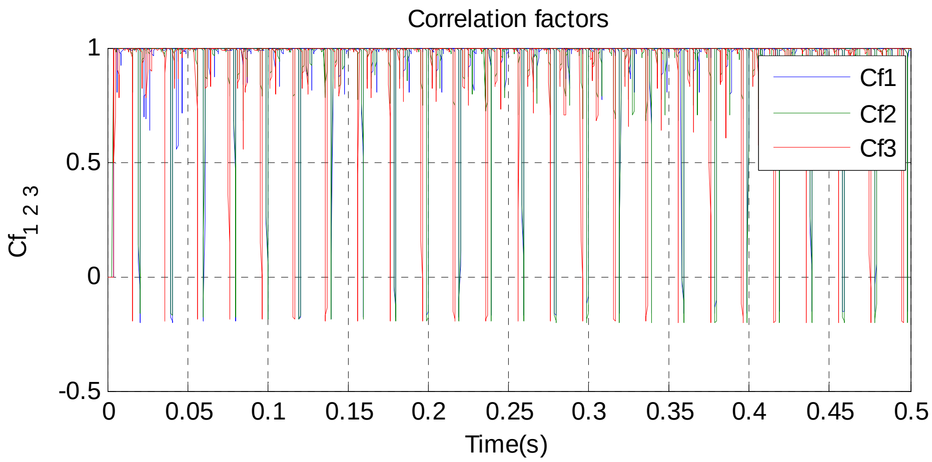
At energizing time inrush current occurs as shown in Fig. 10. Fig. 10.3 shows the correlation factors of inrush current have many dips where their negative picks are different with internal fault. The differential relay take no reaction by correct determination of inrush current based on Fig. 10.4.



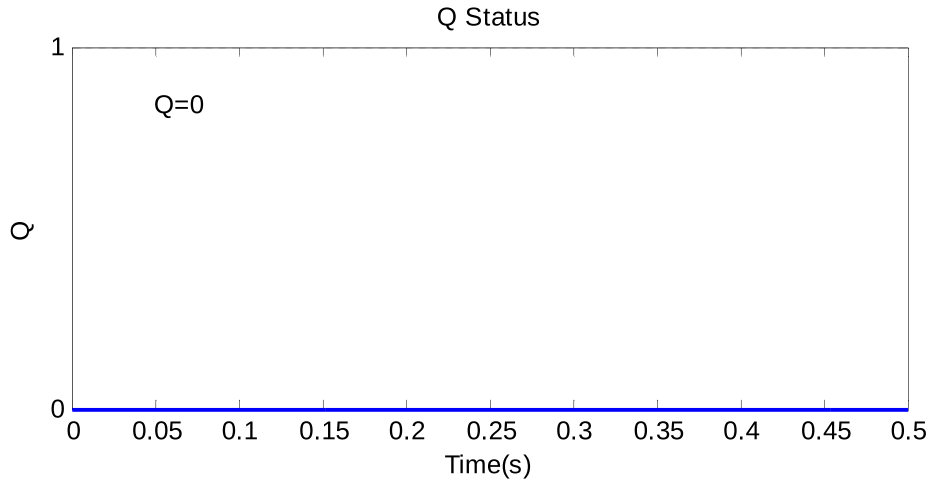
10.1) Primary inrush currents



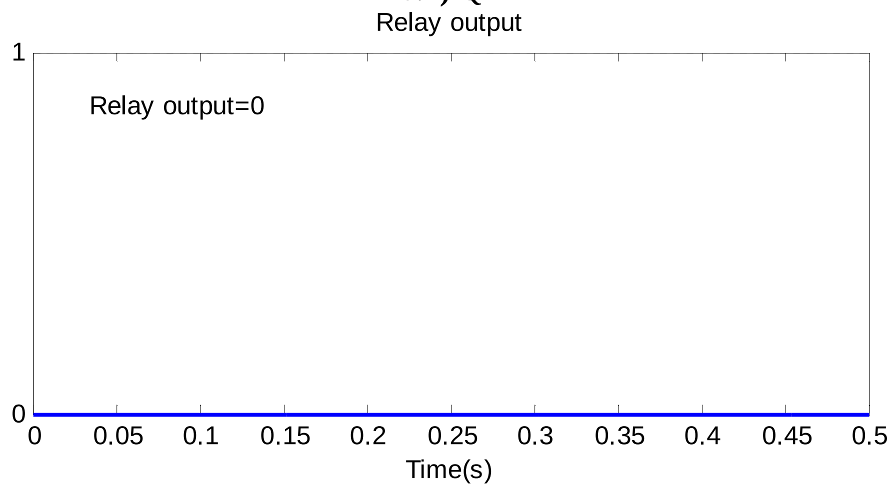
10.2) Differential currents



10.3) Correlation factors for inrush current



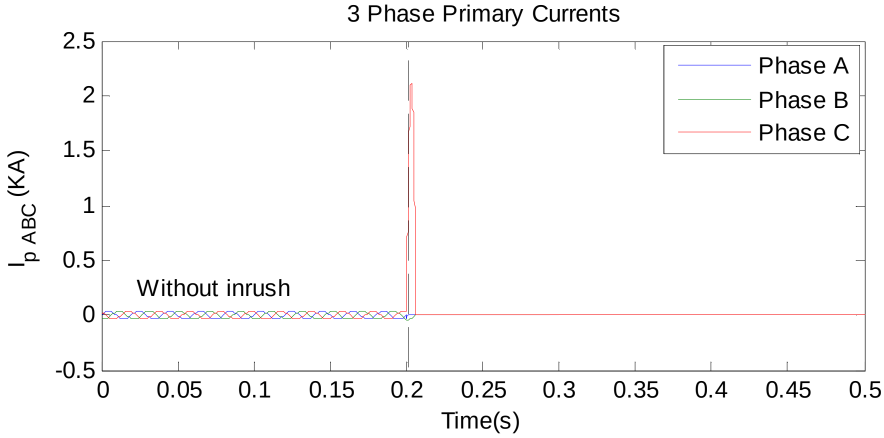
10.4) Q



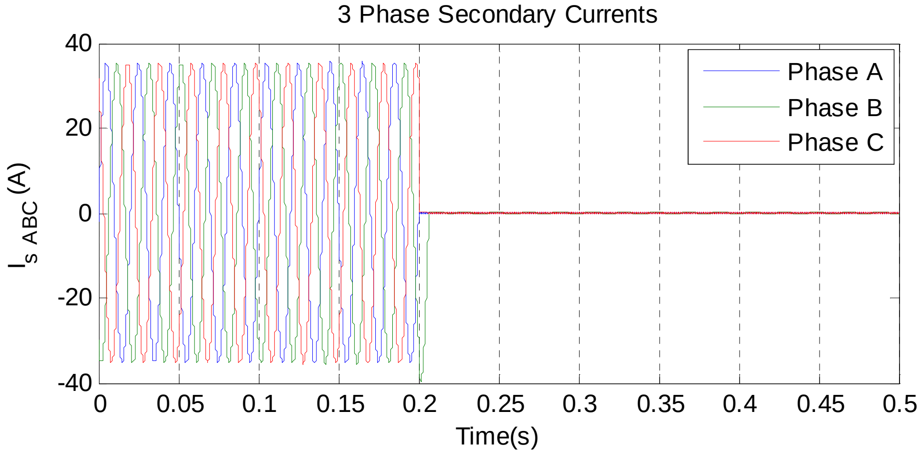
10.5) Relay output against inrush current

Fig. 10. inrush current

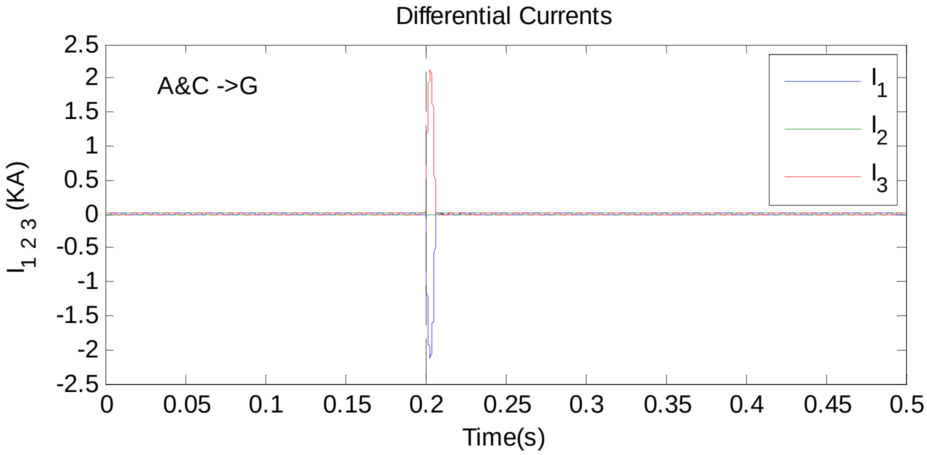
For relay test against internal fault, at T = 0.2 s the two phases to earth fault has been applied on phases A and C. As seen in Fig. 11.1, A and C primary currents at the fault time has increased to around 2000 A and as the time passes $\Delta t = 0.000124$ s, this current will reach to zero. This shows that relay has opened the breakers correctly at less than *0.2 millisecond*. The differential currents including A, B and C phases passes from its threshold. In Fig. 11.3, at first, relay takes action to determine the kind of fault by using correlation factor matrix and analyzing this matrix from aspect of size and number of dips (Fig. 11.4) and then gives open command to breakers and final performance of relay is shown in Fig. 11.6.



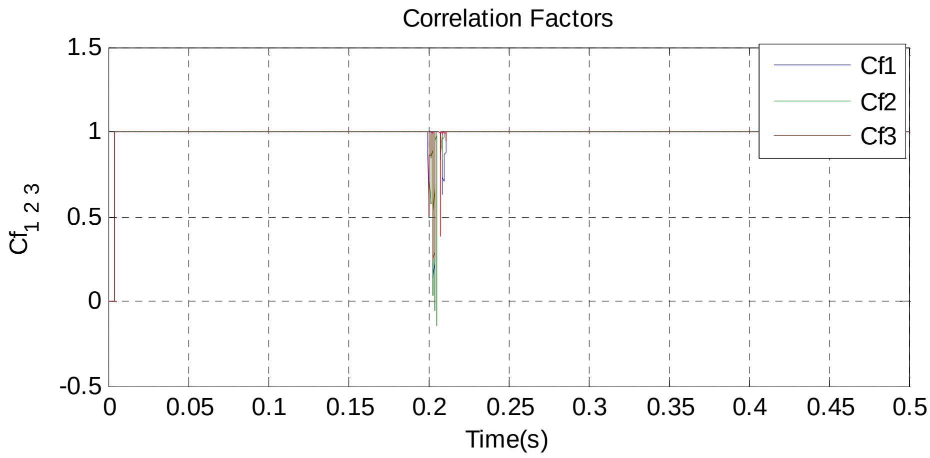
11.1) Primary internal fault currents



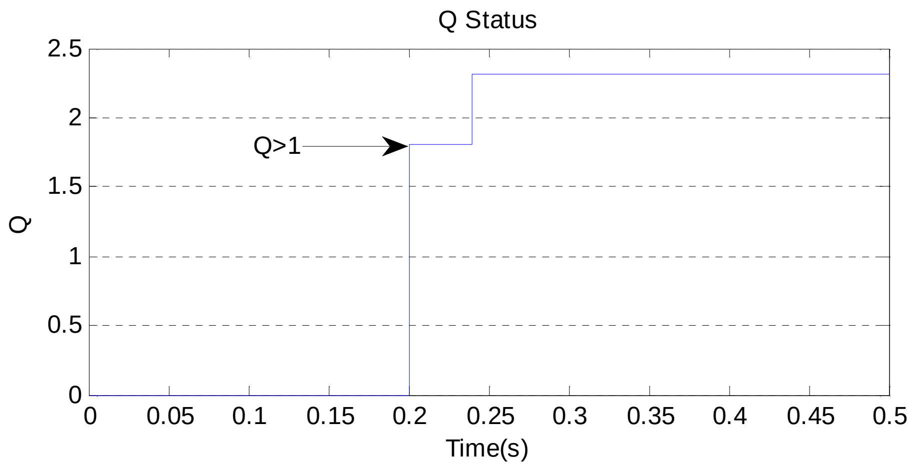
11.2) Secondary internal fault currents



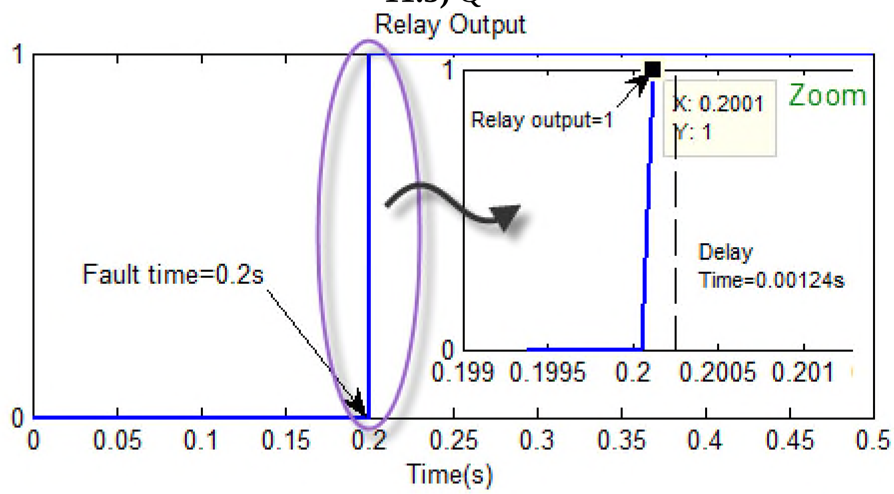
11.3) Differential currents



11.4) Correlation factors for internal



11.5) Q



11.6) Relay output for internal fault

Fig. 11. Internal fault

In external fault condition The differential relay must not work, which Fig. 12 shows the external fault appliance at time of T = 0.2s

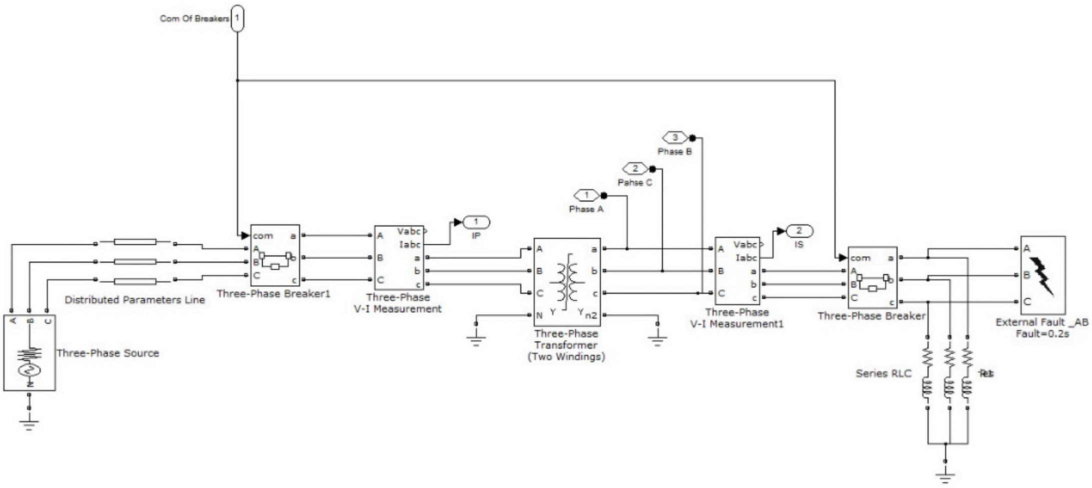
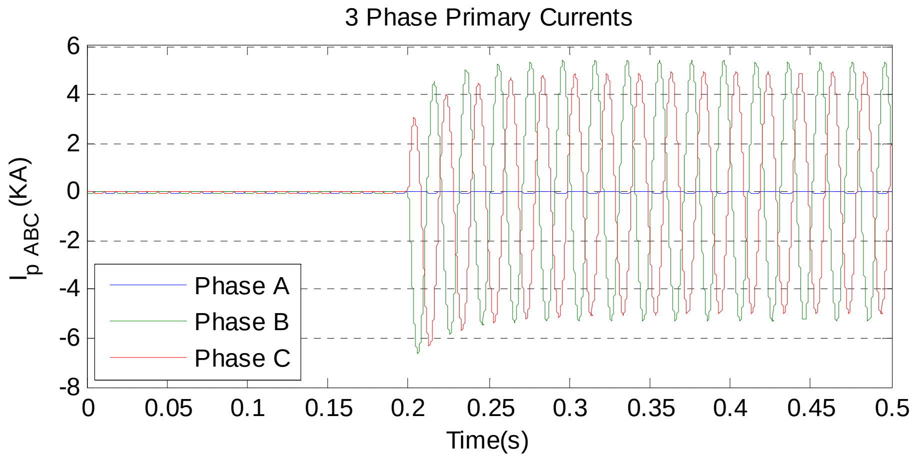
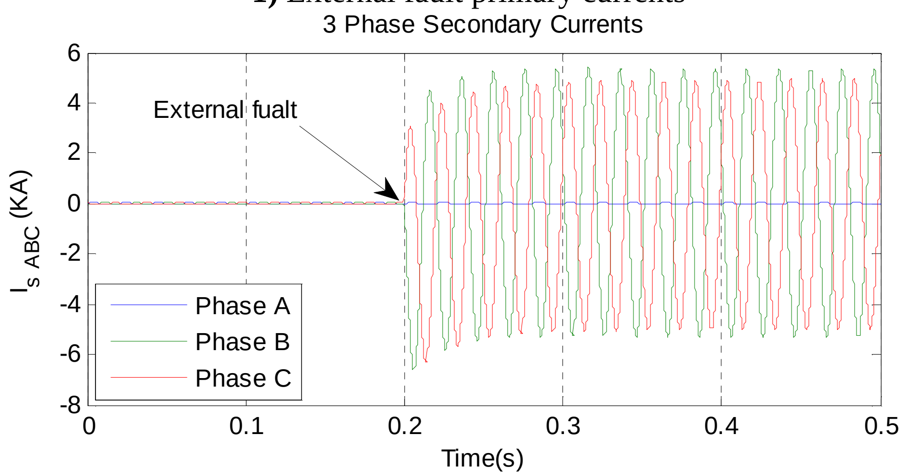


Fig. 12. Simulated test system by applying the external fault

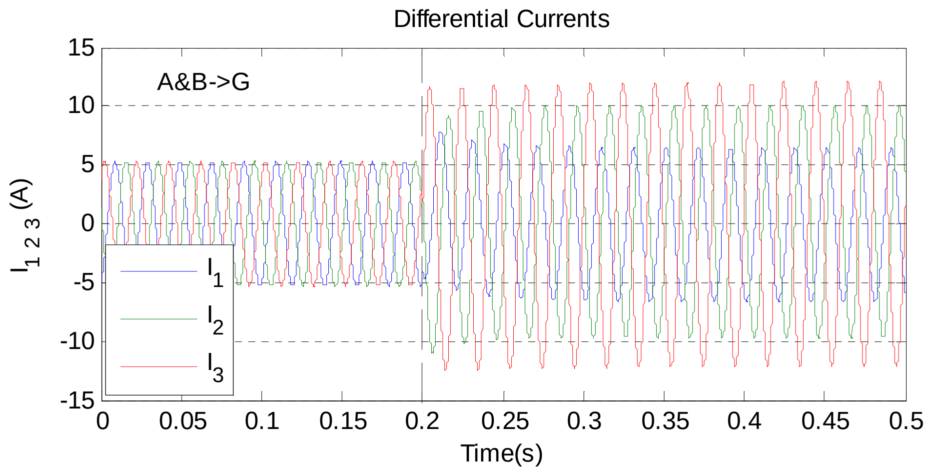
Fig. 13.1 shows that the relay output in external fault condition is zero. As seen in Fig. 13.3, amplitude of differential current is less than defined threshold for relay. This means it is <20 A and so relay takes no reaction. (Fig. 13.4)



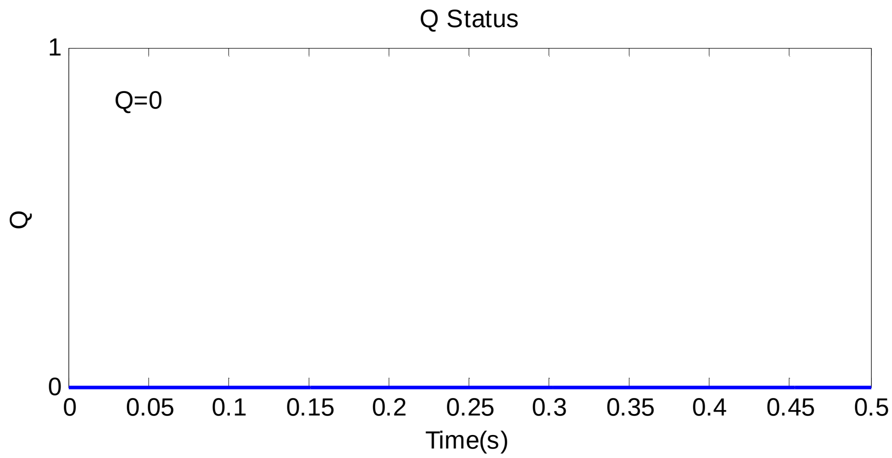
1) External fault primary currents



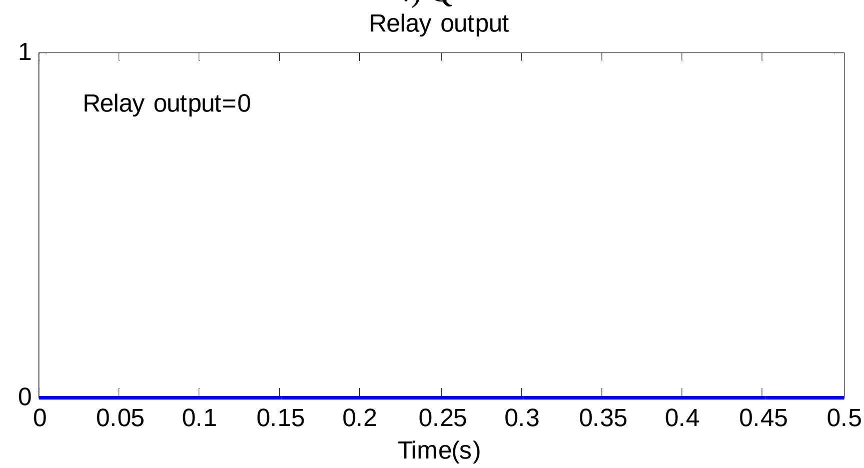
2) External fault secondary currents



3) External fault differential currents



4) Q



5) Relay output at the external fault

Fig. 13. External Fault

When the outcome of Q in equation 27 is <1, relay recognizes the inrush current. If internal fault occurs, the amount of Q would be >1, which relay recognizes as the internal fault. For online relay performance's analysis at different situations are shown in Tables 1 and Table 2.

Table 1: Internal fault appliance after external fault's incidence

	Internal Fault time (s)	Phase (s)	External fault time (s)	Phase (s)	Action time (s)	Delay time (s)	Relay status
No load system	0	-	0	0	0	0	0
	0.1	A	0.009	A	0.100164	164 μs	1
	0.12	A,C	0.115	B,C	0.120088	88 μs	1
	0.13	B,C	0.128	A,B,C	0.14	10 ms	1
	0.143	A,C	0.142	B,C	0.143072	72 μs	1
	0.59	B,C	0.588	A,B,C	0.6	10 ms	1
	1.256	A,B,C	1.255	B	1.26	4 ms	1
	0.2	A,C	0.19	B	0.200124	124 μs	1
	0.3	B,C	0.28	C	0.300084	84 μs	1

Table 2: Apply internal fault

	Fault time (s)	Faulted phase (s)	Relay action time (s)	Delay time (s)	Relay status
No load system	0	0	0	0	0
	0.1	A,C	0.100096	96 μs	1
	0.12	B	0.120088	88 μs	1
	0.13	C	0.14	0.01	1
	1.25	A,C	1.26	0.01	1
	2.9	B,C	2.900132	132 μs	1
	4.13	A,B,C	4.14	0.01	1
On load system	0	—	0	0	0
	0.12	B	0.120088	88 μs	1
	0.13	B	0.14	0.01	1
	0.135	B	0.14	5 ms	1
	0.2	A,C	0.200124	124 μs	1
	0.3	B,C	0.300084	84 μs	1
	1.254	A,C	1.26	6 ms	1
	2.438	A,B,C	2.44	2 ms	1
	2.9	B,C	2.900132	132 μs	1

6.1 Results comparison

This method for power transformer differential protection that is presented in this study has some advantages when compared with existing methods. This study has presented an online differential protection method that in other researches online relay is not presented. Because of power quality events such as harmonic, this method has more reliability rather than phase angle difference method [4]. For this way, it is faster than neural network and support vector machine methods [5]–[7]. Because of using wavelet transform, the method in this study is better than discrete Fourier transform [12].

7. Conclusion

This study presented a novel method to avoid malfunction of transformer's differential protection relays on magnetizing inrush currents. Being online of most clear performance property of relay was designed. Also regarding the relay which is considered that has showed good performance in MATLAB/ Simulink on test system, that it could be used as a suitable relay in industrial applications. Various current waveforms for inrush and internal fault cases are presented to the proposed approach, and its performance is analyzed. The designed relay has great performance speed for power transformer protection that this is so important. The minimum time of fault's recognition is about 1 µs and maximum of that is < 10 ms and is adaptive for different kinds of power transformers, and updating this online relay is regarding to its work situation.

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