Fault Detection of Phase to Phase Fault in Series Capacitor Compensated Six Phase Transmission Line using Wavelet Transform

Gaurav Kapoor

Department of Electrical Engineering, Modi Institute of Technology, Kota, Rajasthan, India
e-mail: gaurav.kapoor019@gmail.com

Received: August 7, 2018 *Accepted: September 8, 2018*

Abstract— This paper proposes a fault detection and faulty phase identification technique based on wavelet transform for series compensated six phase transmission line against phase to phase faults. Six phase current signals are processed using wavelet transform with daubechies-4 wavelet up to level-1. Detail coefficients are reconstructed using wavelet reconstruction process. Different fault parameters such as fault type, fault resistance, fault inception time, and fault location of each phase to phase fault case are varied to evaluate the performance of the proposed scheme. Simulation results exemplify that the proposed technique effectively detects all types of phase to phase faults; and identifies the faulty phase accurately.

Keywords— Fault detection, faulty phase identification, series capacitor compensated six phase transmission line, wavelet transform.

I. INTRODUCTION

Since the electricity requirement is growing endlessly and to congregate the growing electricity requirement, the power transfer capability of transmission lines should be improved constantly. Currently, power transmission companies are looking right of way as the most notable dispute. Six phase power transmission system is examined as a feasible substitute for enhancement in power carrying capacity of current three phase power transmission systems without changing the right of way. In contrast to a three-phase single circuit and three-phase double circuit transmission lines, the probability of faults occurrence is more in six phase transmission lines; this in turn demands the use of a consistent and high-speed protection method against faults. Various schemes to fault detection, classification and location on multi-phase transmission lines have been introduced by numerous researchers till now. Along with the various techniques reported, wavelet transform in combination with artificial neural network was used for fault detection, classification and location in a six-phase transmission line in [1]. A technique based on the combination of discrete wavelet transform and artificial neural network was introduced for the detection, classification and location of faults in parallel transmission lines in [2]. In [3], a fault loop model based on fault location technique was reported for the location of inter-circuit faults in a double circuit transmission line. A combination of Haar wavelet transform and artificial neural network was used for the classification of phase to phase faults in a six-phase transmission line [4]. A logic based protection technique was introduced in [5] for the protection of a six-phase transmission line against line and bus faults. A scheme based on transient current direction for the protection of a series compensated double circuit transmission line was reported in [6]. A fault location technique using a twelve sequence component method for the protection of a twelve-phase transmission line was proposed in [7]. In [8], researchers did fault analysis on a twelve-phase transmission system. A faulty phase selector, based on an adaptive cumulative sum method, was reported in [9] for double circuit transmission lines protection. An artificial neural

Corresponding author's e-mail: gaurav.kapoor019@gmail.com

network was used for the detection and classification of six phases to ground faults in a six-phase transmission line [10]. For the protection of an ultra-high voltage six phase transmission line, a fault location and faulty phase selection technique based on six-sequence variables method was introduced in [11]. In [12], researchers did a voltage stability analysis on a six-phase transmission line. A six-phase transmission line protection technique based on the combination of microprocessor and wavelet transform was introduced in [13]. In [14], researchers did a transient stability analysis on a six-phase transmission line. Fault analysis was made on a double circuit transmission line converted into a six-phase transmission line in [15]. For the protection of a 500 kV ultra-high voltage transmission line, a high speed protection scheme based on a multi-resolution morphological gradient was used in [16]. Wavelet transform was used for a six-phase transmission line fault classification and faulty phase selection [17]. In [18], researchers illustrated the performance of various techniques used for the six-phase transmission system protection. A digital distance relay based on a directional impedance scheme was developed and its performance was checked on a six-phase transmission line in [19]. In [20], a microprocessor based relay was developed and tested on a six-phase transmission line system for various types of shunt faults.

In this paper, a fault detection technique is proposed for the six-phase series capacitor compensated transmission line protection against phase to phase faults by using wavelet transform, bearing in mind the occurrences of various types of phase to phase faults, which have not been proposed or reported yet to the best of the knowledge of author. The paper is prepared as follows. Section 2 discusses simulation studies. Section 3 contains the proposed wavelet transform based fault detection technique. Section 4 contains simulation results; and section 5 contains the conclusions.

II. SIMULATION STUDIES

A single line diagram of a six-phase power transmission network is shown in Fig. 1. The power transmission system consists of a 400 kV, 50 Hz six phase series capacitor compensated transmission line of 200 km length, connected to a source at the sending end and a load at the receiving end. Series capacitors connected at the middle of transmission line supply 40% series compensation to the six phase transmission line. The six phase current signal is obtained from the relay location, i.e. at bus-1. It is processed using wavelet transform to extract various output parameters such as detail coefficients at level-1, wavelet energy, squared detail coefficients and distorted energy of a particular phase for the detection of phase to phase faults. The six phase transmission system model is simulated using Simscape Power System toolbox of MATLAB.

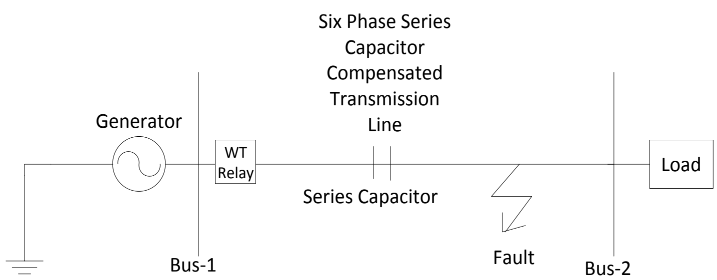


Fig. 1. Single line diagram of six phase power transmission network

III. PROPOSED WT BASED FAULT DETECTION SCHEME

In the area of digital signal processing, the techniques based on wavelet transform have become one of the most powerful mathematical tools. These techniques have become trendier since 1980s. As an alternative to short time Fourier Transform (STFT), the wavelet transform (WT) was developed to rise above the drawbacks related to its resolution problem. More exclusively, if a window of infinite length is selected, one can obtain perfect frequency resolution but without time information. WT is a recently developed mathematical tool that divides up data, function or operation into different frequency components. Fourier analysis splits up a signal into a wave of various frequencies, whereas wavelet analysis breaks up a signal into a shifted and scale version of the original signal. Multi-resolution analysis (MRA) is an alternative approach which is used to analyse a signal to overcome time and frequency resolution problems.

$$DWT\psi f(m.k) = \frac{1}{\sqrt{a_0^m}} \sum_n x(n)\, \psi[\frac{k-n_0 b_0 a^m}{a_0^m}] \tag{1}$$

where the mother wavelet is represented by Ψ; the scale parameter is expressed as a_0^m; and the parameters of translation are designated as a^m, n_0 and b_0 [1].
The subsequent equation also defines DWT:

$$W(j, k) = \sum_j \sum_k x(k) 2^{-\frac{j}{2}} \varphi(2^{-j} n - k) \tag{2}$$

where a mother wavelet is designated as $\varphi(t)$. It has a finite energy and it is a function of time. Associated to a bank of filters with multi-rates, the discrete wavelet analysis can be implemented by employing a high-speed algorithm. A DWT bank of filters with multi-rates is perceived as a filter bank having octave spacing amid filter centres. Each sub band is accommodated with the neighbouring enormous frequency sub band half of the samples.

$$y\,H\,[k] = \sum_n x[n] g[2k-n] \tag{3}$$

$$y\,L\,[k] = \sum_n x[n] h[2k-n] \tag{4}$$

where $y_H[k]$ and $y_L[k]$ are the high pass (g) and low pass (h) filters gain [4].
In the proposed work, 'daubechies-4' mother wavelet is used for the detection of fault and identification of a faulty phase of a six phase series capacitor compensated transmission line by the wavelet decomposition of the six phase fault current measured by the relay located at bus-1. For this purpose, detail coefficients of each phase current are extracted at level-1 followed by the wavelet decomposition of each phase current signal. Then the reconstruction of detail coefficients has been made. After that the wavelet energy of each phase current signal has been calculated. The detection of fault is made by calculating the square of detail coefficients of each phase current at level-1. The relay will declare the incidence of a fault on a six-phase transmission line when the magnitude of a square of detail coefficients of a faulted phase is found greater than the magnitude of a square of detail coefficients of a healthy phase. Fig. 2 shows the flow chart of the proposed wavelet transform based on a fault detection technique. The proposed fault detection technique is tested for numerous types of phase to phase faults with various fault parameters variation; a general threshold value is chosen.

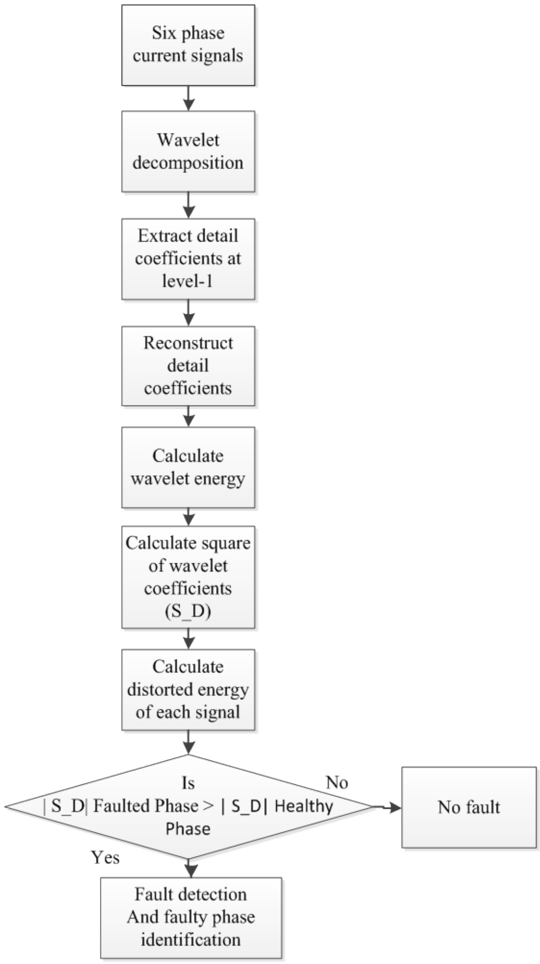


Fig. 2. Proposed wavelet transform based on fault detection scheme

IV. Simulation Results And Discussions

To inspect the accuracy of the proposed wavelet transform based fault detection technique, comprehensive simulation studies have been carried out for numerous types of phase to phase faults with variation in different parameters of fault like fault type, fault location, fault resistance and fault inception time. The results are discussed in the subsequent sub-sections.

A) Performance During No-Fault

The proposed technique is tested for a no-fault condition. Fig. 3 demonstrates the six phase current of a series capacitor compensated six phase transmission line during no-fault. The six phase voltage of a six phase series capacitor compensated transmission line during no-fault has been shown in Fig. 4. The magnitude of detail-1 coefficients of six phases for no-fault is illustrated graphically in Fig. 5. It can be observed from Fig. 5 that the magnitudes of detail coefficients of all six phases are below the threshold value. This clearly shows that a six-phase transmission line has no-fault. Table 1 illustrates the test results of fault detection in case of no-fault. Table 1 indicates that the magnitudes of output parameters viz. detail coefficients, wavelet energy, squared detail coefficients and distorted energy of each phase of a six-phase transmission line are within the threshold limit. This exemplifies that the six phase transmission line has no-fault.

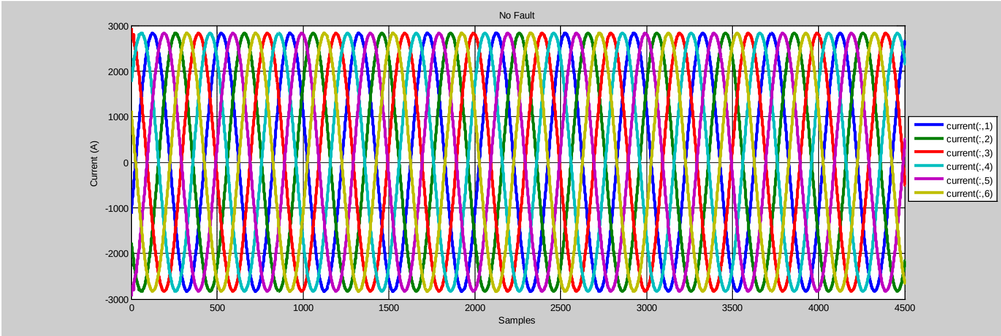


Fig. 3. Six phase current during no-fault

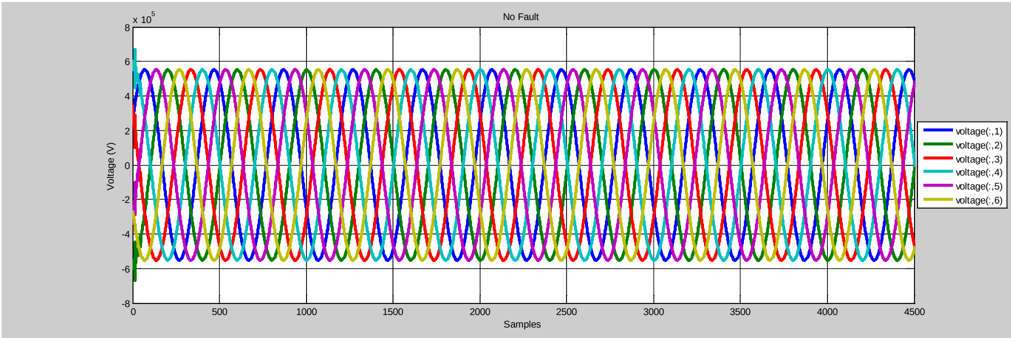


Fig. 4. Six phase voltage during no-fault

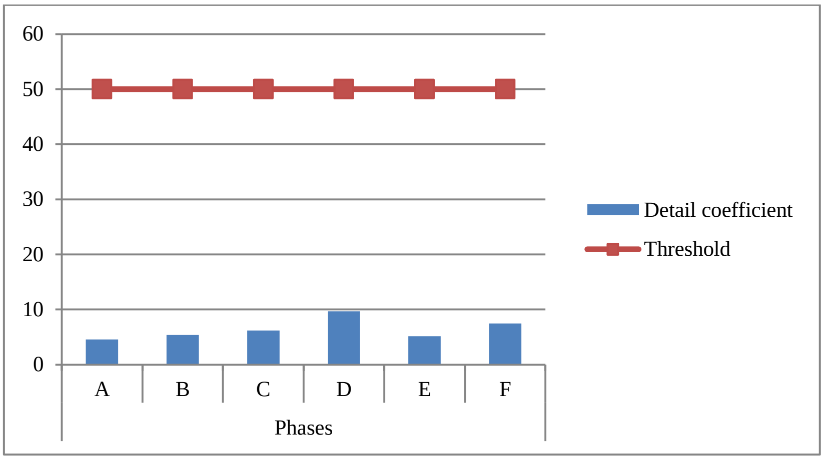


Fig. 5. Detail-1 coefficients of six phases during no-fault

TABLE 1
WAVELET PERFORMANCE IN CASE OF NO-FAULT

Outputs	Phases					
	A	***B***	***C***	***D***	***E***	***F***
CD_1	4.5391	5.3637	6.1588	9.6658	5.1425	7.4860
E_a	98.2350	98.2993	98.1340	98.2993	98.1340	98.2350
S_D_1	29.7960	50.5774	20.2733	50.5774	20.2733	29.7960
d_1	1.0733*10^3	1.1194*10^3	1.2324*10^3	1.1194*10^3	1.2324*10^3	1.0733*10^3

where A, B, C, D, E and F are the phases of a six-phase series compensated transmission line; CD1 is the level-1 detail coefficient; Ea is the wavelet energy of a particular phase; S_D1 is the squared detail coefficient; and d_1 is the distorted energy of a particular phase.

B) Performance During Phase-'AB' Fault

The performance of the proposed technique is examined for phase-'AB' fault. The six phase current and voltage during phase-'AB' fault occurring at 50 km away from bus-1 or at 50 km before the location of series capacitors at FIT=0.017 seconds with R_f = 20 Ω are shown in Fig. 6 and Fig. 7. The magnitude of detail-1 coefficients of a six-phase current for the period of phase-'AB' fault is shown in Fig. 8. The magnitude of detail-1 coefficients of six phases for phase-'AB' fault is demonstrated graphically in Fig. 9. It can be observed from Fig. 9 that the magnitude of detail coefficients of phase 'A' and 'B' is greater than the threshold limit while the magnitudes of detail coefficients of other phases are below the threshold line. Thus, the performance of the proposed scheme is tested for phase-'AB' fault; and the test results are depicted in Table 2. From Table 2, it is observed that the magnitude of a square of detail-1 coefficients of the faulted phases-'A' and 'B' is greater than the magnitude of a square of detail-1 coefficients of healthy phases-'C, D, E and F'. This exemplifies that the proposed wavelet transform based fault detection technique effectively detects phase-'AB' fault; and it efficiently discriminates between the faulty and healthy phases.

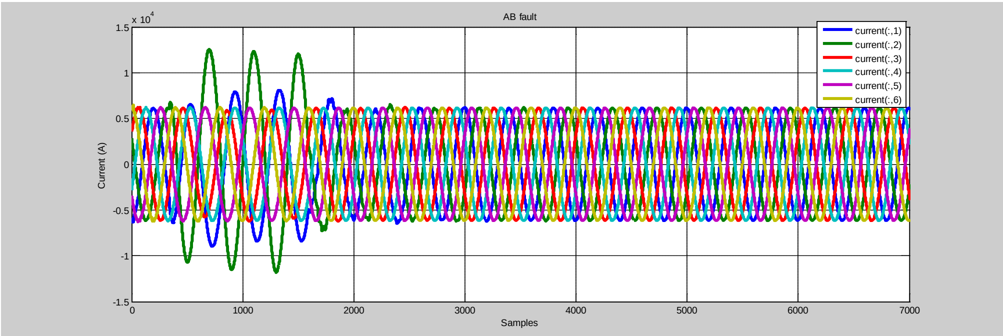


Fig. 6. Six phase current during phase-'AB' fault at 50 km away from bus-1

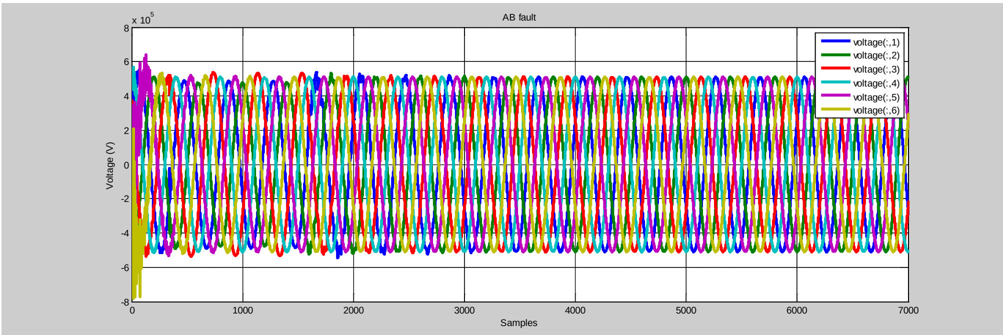
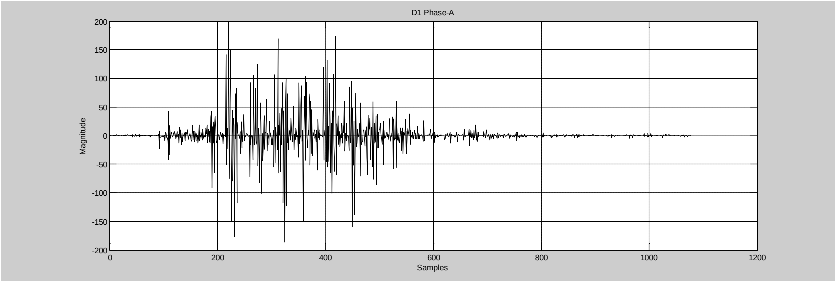


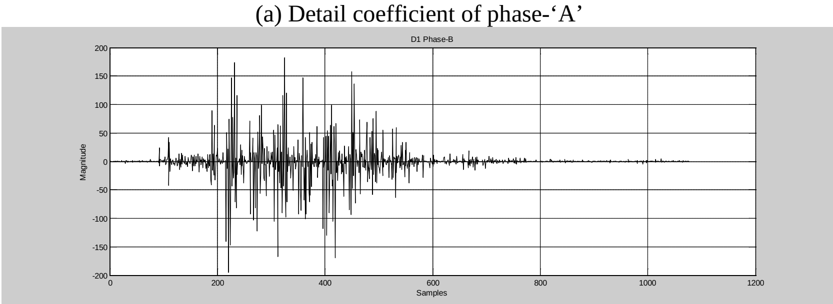
Fig. 7. Six phase voltage during phase-'AB' fault at 50 km away from bus-1

TABLE 2
WAVELET PERFORMANCE IN CASE OF PHASE-'AB' FAULT

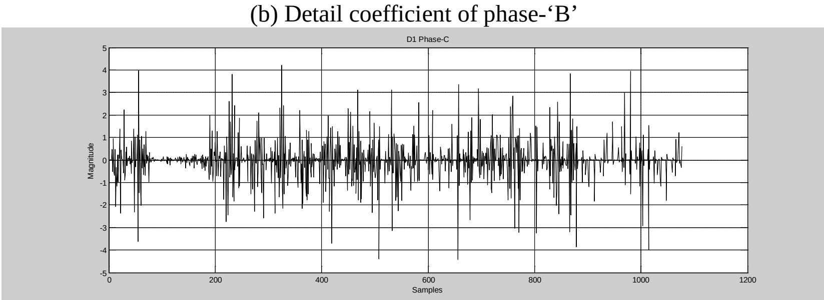
Outputs	**Phases**					
	A	***B***	***C***	***D***	***E***	***F***
CD_1	198.5612	182.5738	4.2104	4.4685	4.4621	4.3516
E_a	99.57	99.56	99.50	99.55	99.50	99.38
S_D_1	2.0448*10^4	1.9852*10^4	10.9180	10.6166	11.0128	11.8433
d_1	8.3637*10^5	8.1361*10^5	853.3039	872.85	823.20	999.63



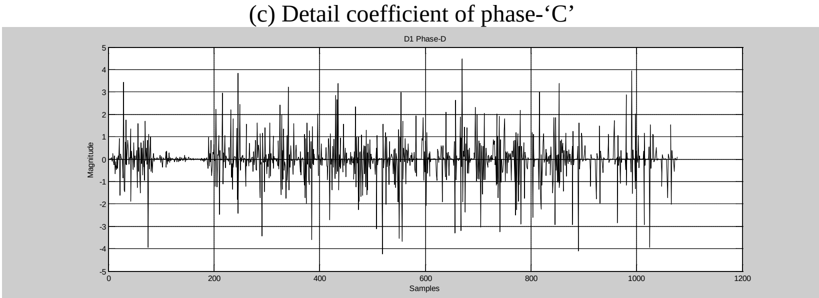
(a) Detail coefficient of phase-‘A’



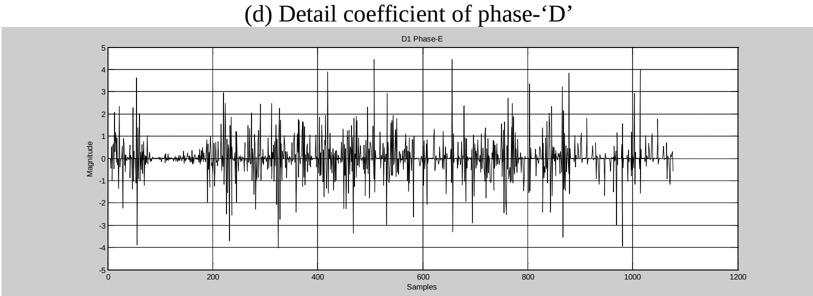
(b) Detail coefficient of phase-‘B’



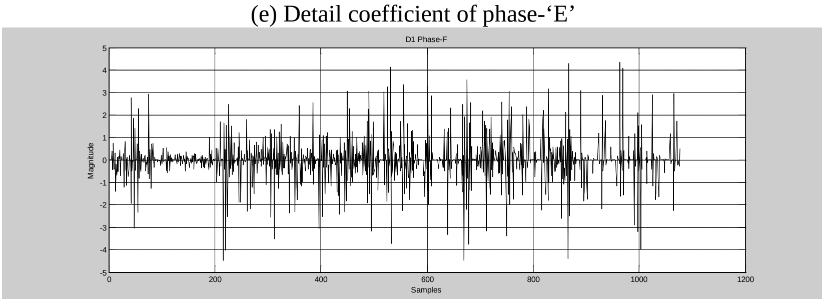
(c) Detail coefficient of phase-‘C’



(d) Detail coefficient of phase-‘D’



(e) Detail coefficient of phase-‘E’



(f) Detail coefficient of phase-‘F’

Fig. 8. Magnitude of level-1 detail coefficients of a six-phase current during phase-‘AB’ fault

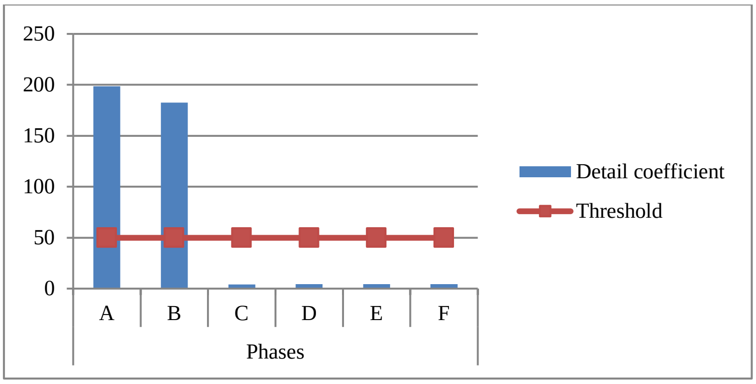


Fig. 9. Detail-1 coefficients of six phases during phase-‘AB’ fault

C) Performance During Phase-‘AC’ Fault

The performance of the proposed technique is examined for phase-‘AC’ fault. The six phase current and voltage during phase-‘AC’ fault occurring at 60 km away from bus-1 or at 40 km before the location of series capacitors at FIT=0.025 seconds with R_f = 25 Ω are shown in Fig. 10 and Fig. 11. The magnitude of detail-1 coefficients of six phases during phase-‘AC’ fault is shown graphically in Fig. 12. It can be observed from Fig. 12 that the magnitude of detail coefficients of phase ‘A’ and ‘C’ is greater than the threshold limit while the magnitudes of detail coefficients of other phases are below the threshold line. Thus, the performance of the proposed scheme is tested for phase-‘AC’ fault; and the test results are depicted in Table 3. From Table 3, it is observed that the magnitude of a square of detail-1 coefficients of the faulted phases- ‘A’ and ‘C’ is greater than the magnitude of a square of detail-1 coefficients of healthy phases-‘B, D, E and F’. This exemplifies that the proposed wavelet transform based fault detection technique effectively detects phase-‘AC’ fault. It efficiently discriminates between the faulty and healthy phases.

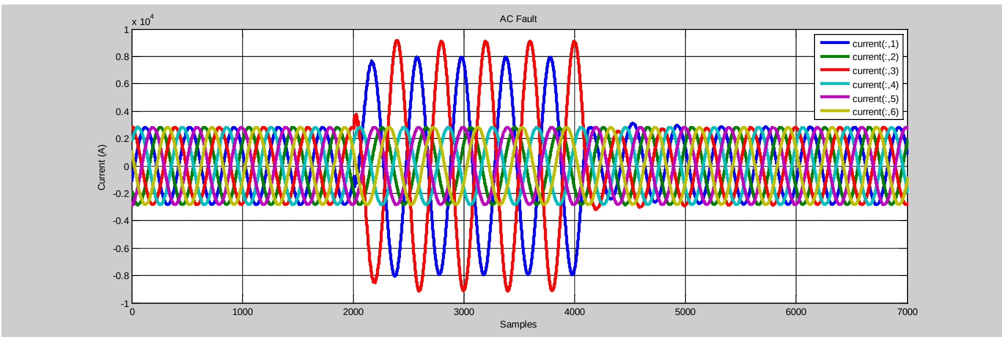


Fig. 10. Six phase current during phase-‘AC’ fault at 60 km away from bus-1

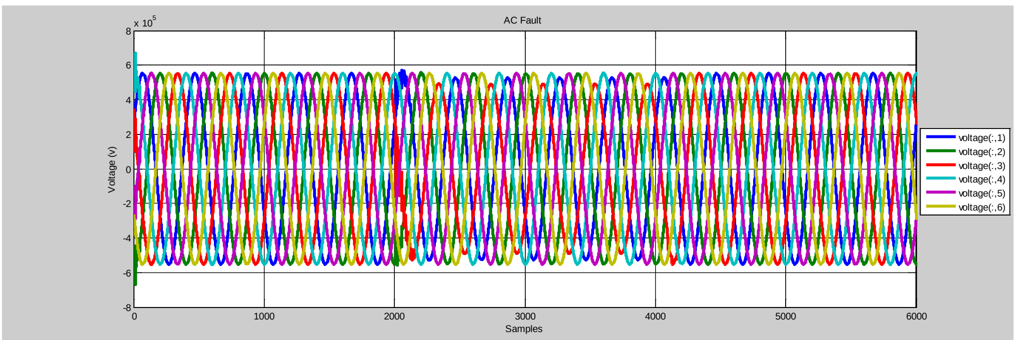


Fig. 11. Six phase voltage during phase-‘AC’ fault at 60 km away from bus-1

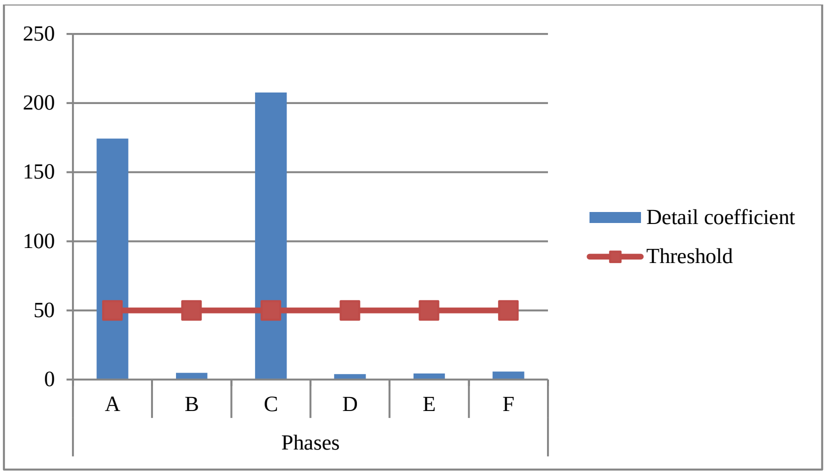


Fig. 12. Detail-1 coefficients of six phases during phase-'AC' fault

TABLE 3
WAVELET PERFORMANCE IN CASE OF PHASE-'AC' FAULT

Outputs	Phases					
	A	***B***	***C***	***D***	***E***	***F***
$\mathbf{CD_1}$	174.2676	5.0113	207.5088	4.0058	4.4006	5.9129
$\mathbf{E_a}$	99.1398	99.45	99.15	99.46	99.43	99.39
$\mathbf{S\_D_1}$	2.1163*10^4	13.0487	2.1877*10^4	12.6471	11.0829	19.6910
$\mathbf{d_1}$	6.2661*10^5	808.79	6.4795*10^5	800.72	942.0044	899.96

D) Performance During Phase-'BC' Fault

The performance of the proposed technique is examined for phase-'BC' fault occurring at 70 km away from bus-1 or at 30 km before the location of series capacitors at FIT=0.033 seconds with R_f = 30 Ω. The magnitude of detail-1 coefficients of six phases during phase-'BC' fault is demonstrated graphically in Fig. 13. It can be observed from Fig. 13 that the magnitude of detail coefficients of phase 'B' and 'C' is larger than the threshold limit while the magnitudes of detail coefficients of other phases are below the threshold line. Thus, the performance of the proposed scheme is tested for phase-'BC' fault; and the test results are summarized in Table 4. From Table 4, it is observed that the magnitude of a square of detail-1 coefficients of the faulted phases- 'B' and 'C' is greater than the magnitude of a square of detail-1 coefficients of healthy phases-'A, D, E and F'. This exemplifies that the proposed wavelet transform based fault detection technique effectively detects phase-'BC' fault; and it efficiently discriminates between the faulty and healthy phases.

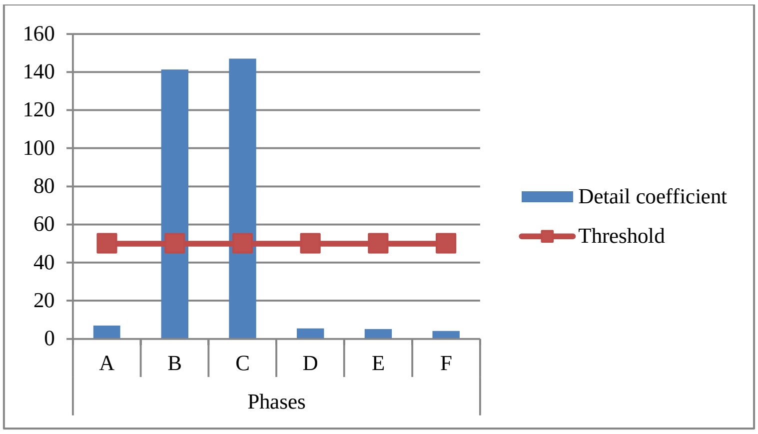


Fig. 13. Detail-1 coefficients of six phases during phase-'BC' fault

TABLE 4
WAVELET PERFORMANCE IN CASE OF PHASE-'BC' FAULT

Outputs	Phases					
	A	***B***	***C***	***D***	***E***	***F***
CD_1	7.0289	141.2742	147.0114	5.488	5.1260	4.1877
E_a	99.5061	99.08	99.04	99.47	99.36	99.50
S_D_1	25.7892	1.2972*10^4	1.2229*10^4	15.94	15.77	26.15
d_1	899.3242	3.3524*10^5	3.2306*10^5	1.1236*10^3	925.67	891.43

E) Performance During Phase-'DE' Fault

The performance of the proposed technique is examined for phase-'DE' fault occurring at 80 km away from bus-1 or at 20 km before the location of series capacitors at FIT=0.0417 seconds with R_f = 35 Ω. The magnitude of detail-1 coefficients of six phases during phase-'DE' fault is demonstrated graphically in Fig. 14. It can be observed from Fig. 14 that the magnitude of detail coefficients of phase 'D' and 'E' is greater than the threshold limit while the magnitudes of detail coefficients of other phases are below the threshold line. Thus, the performance of the proposed scheme is tested for phase-'DE' fault; and the test results are demonstrated in Table 5. From Table 5, it is observed that the magnitude of a square of detail-1 coefficients of the faulted phases- 'D' and 'E' is greater than the magnitude of a square of detail-1 coefficients of healthy phases-'A, B, C and F'. This exemplifies that the proposed wavelet transform based fault detection technique effectively detects phase-'DE' fault; and it successfully discriminates between the faulty and healthy phases.

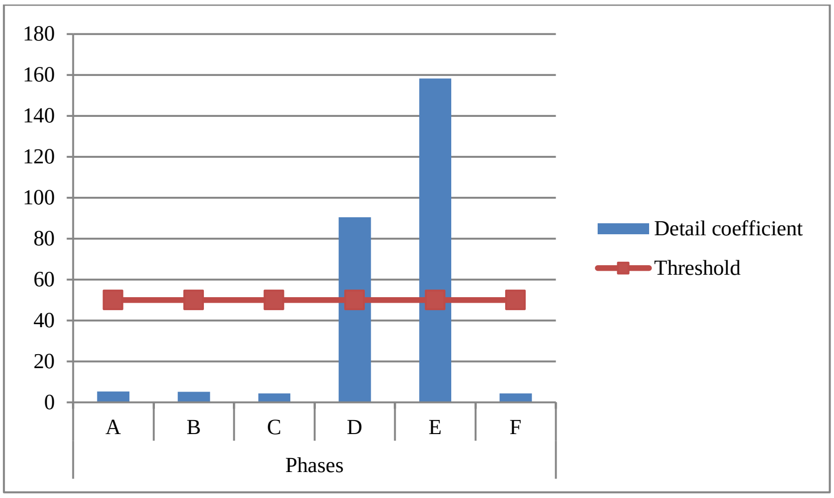


Fig. 14. Detail-1 coefficients of six phases during phase-'DE' fault

TABLE 5
WAVELET PERFORMANCE IN CASE OF PHASE-'DE' FAULT

Outputs	Phases					
	A	***B***	***C***	***D***	***E***	***F***
CD_1	5.3063	5.1423	4.4169	90.4775	158.2825	4.2894
E_a	99.2623	99.4311	99.2772	98.7268	98.6753	99.2643
S_D_1	15.4571	20.5569	17.8065	1.3119*10^4	1.2650*10^4	17.7855
d_1	937.84	1.1000*10^3	963.8930	2.5834*10^5	2.5067*10^5	943.8136

F) Performance During Phase-'DF' Fault

The performance of the proposed technique is examined for phase-'DF' fault occurring at 90 km away from bus-1 or at 10 km before the location of series capacitors at FIT=0.05 seconds with R_f = 40 Ω. The magnitude of detail-1 coefficients of six phases during phase-'DF' fault is shown graphically in Fig. 15. It can be observed from Fig. 15 that the magnitude of detail coefficients of phase 'D' and 'F' is greater than the threshold value while the magnitudes of detail coefficients of other phases are below the threshold limit. Thus, the performance of the proposed scheme is tested for phase-‘DF’ fault; and the test results are exemplified in Table 6. From Table 6, it is observed that the magnitude of a square of detail-1 coefficients of the faulted phases- ‘D’ and ‘F’ is greater than the magnitude of a square of detail-1 coefficients of healthy phases-‘A, B, C and E’. This proves that the proposed wavelet transform based fault detection technique effectively detects phase-‘DF’ fault; and it effectively discriminates between the faulty and healthy phases.

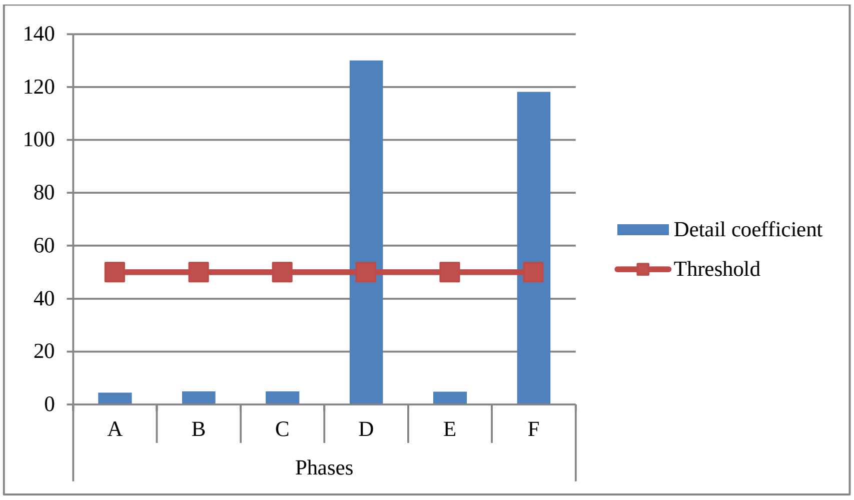


Fig. 15. Detail-1 coefficients of six phases during phase-‘DF’ fault

TABLE 6
WAVELET PERFORMANCE IN CASE OF PHASE-‘DF’ FAULT

Outputs	Phases					
	A	***B***	***C***	***D***	***E***	***F***
CD_1	4.5181	4.9719	4.9187	130.0786	4.8195	118.1751
E_a	99.6251	99.6147	99.5424	98.7568	99.5406	98.8141
S_D_1	10.7954	13.3394	13.6325	8.7160*10^3	12.9236	9.0890*10^3
d_1	755.99	638.70	633.83	1.4904*10^5	629.68	1.5431*10^5

G) Performance During Phase-‘EF’ Fault

The performance of the proposed technique is examined for phase-‘EF’ fault occurring at 100 km away from bus-1 or at the point, where the series capacitors are connected at FIT=0.058 seconds with R_f = 45 Ω. The magnitude of detail-1 coefficients of six phases during phase-‘EF’ fault is verified graphically in Fig. 16. It can be observed from Fig. 16 that the magnitude of detail coefficients of phase ‘E’ and ‘F’ is crossing the threshold value while the magnitudes of detail coefficients of other phases are below the threshold line. Thus, the performance of the proposed scheme is tested for phase-‘EF’ fault; and the test results are tabulated in Table 7. From Table 7, it is observed that the magnitude of a square of detail-1 coefficients of the faulted phases- ‘E’ and ‘F’ is greater than the magnitude of a square of detail-1 coefficients of healthy phases-‘A, B, C and D’. This shows that the proposed wavelet transform based fault detection technique effectively detects phase-‘EF’ fault; and it successfully discriminates between the faulty and healthy phases.

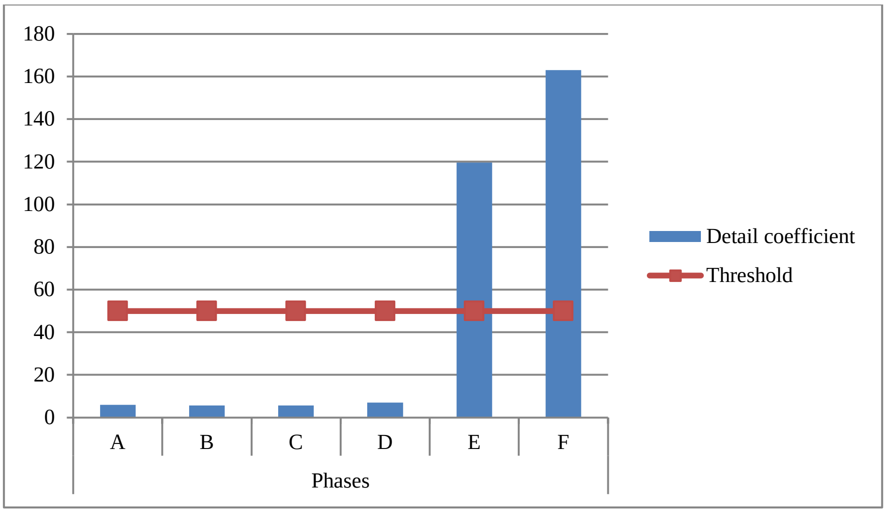


Fig. 16. Detail-1 coefficients of six phases during phase-'EF' fault

TABLE 7
WAVELET PERFORMANCE IN CASE OF PHASE-'EF' FAULT

Outputs	**Phases**					
	A	***B***	***C***	***D***	***E***	***F***
CD_1	5.9796	5.6627	5.6582	7.0690	119.6032	162.9779
E_a	98.9519	98.9697	98.5148	98.9646	98.1162	98.0017
S_D_1	23.2288	26.5140	22.3272	27.1635	1.5679*10^4	1.4390*10^4
d_1	1.2550*10^3	1.1086*10^3	1.0652*10^3	1.1082*10^3	1.5438*10^5	1.4794*10^5

V. CONCLUSIONS

This paper presents the wavelet transform based fault detection technique for the protection of a series capacitor compensated six phase transmission line against different types of phase to phase faults. The performance of the proposed technique is authenticated by a number of simulations, considering the variation in various parameters of faults such as fault location, fault inception time, fault type and fault resistance. The simulation results demonstrate that all the phase to phase faults are accurately detected; and faulty phases are correctly identified. The proposed technique has been found resistant to the effects of different fault parameters variations.

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