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A Contemporary Discrete Wavelet Transform Based Twelve Phase Series Capacitor Compensated Transmission Line Protection

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***Abstract*— This paper presents a contemporary discrete wavelet transform based relaying scheme for the detection and classification of simultaneous occurring single line to ground fault and one conductor open fault on a twelve phase series capacitor compensated transmission line. MATLAB software is used to simulate a 765 kV, 50 Hz and 200 km long twelve phase series capacitor compensated transmission line. The effect of fault type, fault inception time, fault resistance, ground resistance and fault location deviation has been taken into consideration throughout the simulation study. The test results accomplished by the practice of proposed technique authenticate the appropriateness and dependability of the proposed scheme under a variety of fault circumstances.**

Keywords—Twelve phase series compensated transmission line; discrete wavelet transform; fault detection and classification.

I. INTRODUCTION

To raise the power transfer potential of the power transmission network, the most widespread key is the use of series capacitor compensation which reduces the effective transmission line inductance. Through the transmission line faults, the connection of capacitors in series with transmission line inductance leads to voltage or current inversions. As a result, the performance of the distance relays can break down shielding series compensated transmission line from various types of faults. Over and above, in preference to planning advanced transmission line structure there is an urgency to boost current power transmission system effectiveness of power transfer. Simultaneous single line to ground fault and one conductor open fault which occur at different locations on a twelve phase series capacitor compensated transmission line generates erroneous tripping of the ordinary protective relays. One conductor open fault occurs in series with the transmission line due to breakdown of opening or closing of one phase of a circuit breaker or isolator. On the occurrence of one conductor open fault, the current in the faulted phase collapse to zero [6]. Thus classification of one conductor open fault can be done by evaluating the deviation in the current magnitude from pre-fault to the post fault operating condition. On this subject, G C Sekhar in [1] proposed a logic based scheme for six phase transmission line protection. The proposed scheme exploit negative sequence components of each phase of a six phase transmission line for the detection of fault. A comparative study of electric field calculations beneath six phase and double circuit transmission lines had been described in [2]. By the usage of charge simulation technique, calculation of electric field had been done for both double circuit and six phase transmission line at one meter above the earth level. Ebha Koley, et al. in [3] proposed hybrid WT and modular ANN based scheme for the protection of six phase transmission line which utilized the measured data of single end only. The scheme had been used for the six phase transmission line fault detection, classification and location. [4] Developed an algorithm for the over current protection of six phase transmission line by the help of numerical relay. The testing of numerical relay was done for LG and LLLG faults on six phase transmission line test system. [5] Classified phase to phase faults on six phase transmission line by using Haar WT and ANN. Accurate classification of phase to phase faults was discovered by the usage of proposed technique. [6] Introduced ANN based scheme for the protection of six phase transmission line against one conductor open faults. The proposed scheme correctly detects and classifies all possible types of one open conductor faults within the time of one cycle. A protection scheme which includes backup protection based on logic had been proposed by G C Sekhar in [7] for the six phase power transmission line protection. The proposed scheme had been used against line and bus faults of six phase transmission line. X Q Yan, et al. in [8] proposed fault analysis algorithm in a twelve phase transmission line based on the method of twelve sequence symmetrical components. [9] Proposed ANN based scheme for the six phase transmission line protection against phase to phase faults. ANN based algorithm for the protection of six phase transmission line against six phase to ground faults had been proposed in [10]. In [11] six phase transmission line fault detection and classification scheme by using ANN was reported. In the proposed work, protection from all possible single line to ground had been successfully carried out by the usage of the proposed ANN based protection scheme within one cycle from the starting of the fault point. [12] Introduced a scheme based on negative sequence current detection by using logic for the six phase transmission line protection from unsymmetrical faults. Tuan Mohd., et al. in [13] presented auto-transformer application for three phase to six phase conversion for use in six phase transmission line. A method of six sequence variables for location of fault and selection of faulty phase(s) on a six phase transmission line had been proposed by Yan Wang in [14]. A twelve sequence component method for the location of fault in a jointed twelve phase transmission line had been proposed by Chunju Fan, et al. in [15]. The fault location had been calculated by capturing the inverted sequence component voltages from both buses during the fault occurrence. Investigation had been carried out on voltage stability during conversion of three phase double circuit to a six phase single circuit transmission line by Masoud, et al. in [16]. Excluding exaggerate power relocation effectiveness at the receiving end, multi-phase power transmission lines overture numerous more assets over traditional three phase power transmission lines essentially: six phase transmission lines produces less electric field, less requirement of right of way (ROW) and tower dimensions, increased line capacitance and decreased line inductance, preserved voltage stability, increased reactive power limit at the receiving end voltage point, reduced conductor's surface gradient, reduced effect of corona, audio and radio noise, reduced TV interference, increased power handling capacity, reduced reactive power losses, reactive power requirement for maintaining the stable load voltage is reduced, increased line loading limit in the case of uncompensated and compensated line as described in literatures [2, 16, 17, 19, 23]. In the last decade, protection of multi-phase power transmission lines had engaged much consideration from researchers and much research had been done on six phase transmission line protection without any series compensation device connection. In most of the formerly announced approaches the protection of six phase transmission line had been done with the help of ANN technique which requires lot of test sample data for its scheme verification.

Current research has been focused on the protection of twelve phase series capacitor compensated power transmission line from various types of simultaneous occurring single line to ground and one conductor open faults by using discrete wavelet transform based multi resolution analysis approach, which is never done before.

II. PROPOSED TEST SYSTEM

The single line diagram of a twelve phase power transmission system is demonstrated in Fig. 1. Test system consists of a 765 kV; 50 Hz and 200 km long twelve phase series compensated transmission line. The twelve phase series capacitor unit is connected at the mid-point of a twelve phase transmission line as shown in Fig. 1. The series capacitor unit supplies 40% compensation to the line. DWT based fault detection and classification scheme is explored on a twelve phase series compensated transmission line test system. For the confirmation of proposed scheme, data was generated by modeling the particular test system by the usage of MATLAB software. DWT relay is connected at bus-1 as shown in Fig. 1. The current signal at bus-1 is used for verification of the proposed DWT based fault detection and classification scheme. The performance of the proposed schemes was examined with various fault parameters variation.

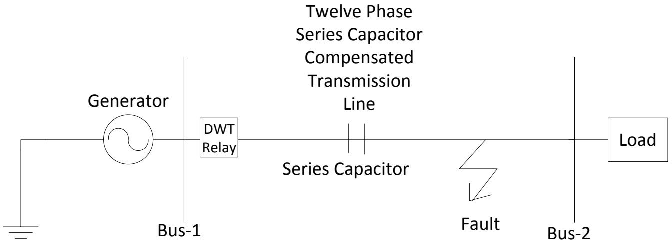


Fig. 1 Proposed test system

III. DISCRETE WAVELET TRANSFORM

Wavelet transform (WT) was developed to rise above the unhelpful aspect linked to short time Fourier transform. WT is a mathematical tool that divides up data, function or operation into unlike frequency components. Wavelet transform [3, 5] is termed as:

$$W(j, k) = \sum_j \sum_k x(k)\, 2^{-j/2}\, \varphi(2^{-j}n-k) \qquad (1)$$

Where a mother wavelet is designated as φ (t) having finite energy.

High pass filter gain after sub-sampling twice is defined as:

$$y_H(k) = \sum_n x(n) g(2k-n) \qquad (2)$$

Low pass filter gain after sub-sampling twice is defined as:

$$y_L(k) = \sum_n x(n) h(2k-n) \qquad (3)$$

The approximate and detailed coefficients can be computed for any function f (t) as: -

$$A_{j,k} = <\int (t), \Phi_{j,k}(t)> = \int f(t)\, \Phi_{j,k}(t)\, dt \qquad (4)$$

$$D_{j,k} = <\int (t), \psi_{j,k}(t)> = \int f(t)\, \psi_{j,k}(t)\, dt \qquad (5)$$

The scale function $\Phi_{j,k}$ (t) and the wavelet function $\psi_{j,k}$ (t) are calculated by selecting the mother wavelet ψ.

IV. PROPOSED SCHEME

In the proposed work, detection of fault has been done by calculating the sum of square of detail coefficient of each phase current at level-1. A fault detector will declare the occurrence of shunt fault when the magnitude of sum of square of detail coefficients of faulted phase is found greater than the magnitude of sum of square of detail-1 coefficient of un-faulted phase. Classification of fault has been done by calculating D1 (detail coefficient at level-1) norm of each phase current for the duration of fault condition. The proposed scheme (as depicted in Fig. 2) detects and classifies one conductor open fault based on the higher magnitude of wavelet energy with lower magnitude of sum of square of detail coefficients of the faulted phase. The wavelet based fault detector will confirm the occurrence of one conductor open fault (series fault) in a system when the magnitude of wavelet energy of faulted phase is found greater than the magnitude of wavelet energy of un-faulted phase and at the same time magnitude of sum of square of detail coefficients of faulted phase should be lower than the magnitude of sum of square of detail coefficients of an un-faulted phase.

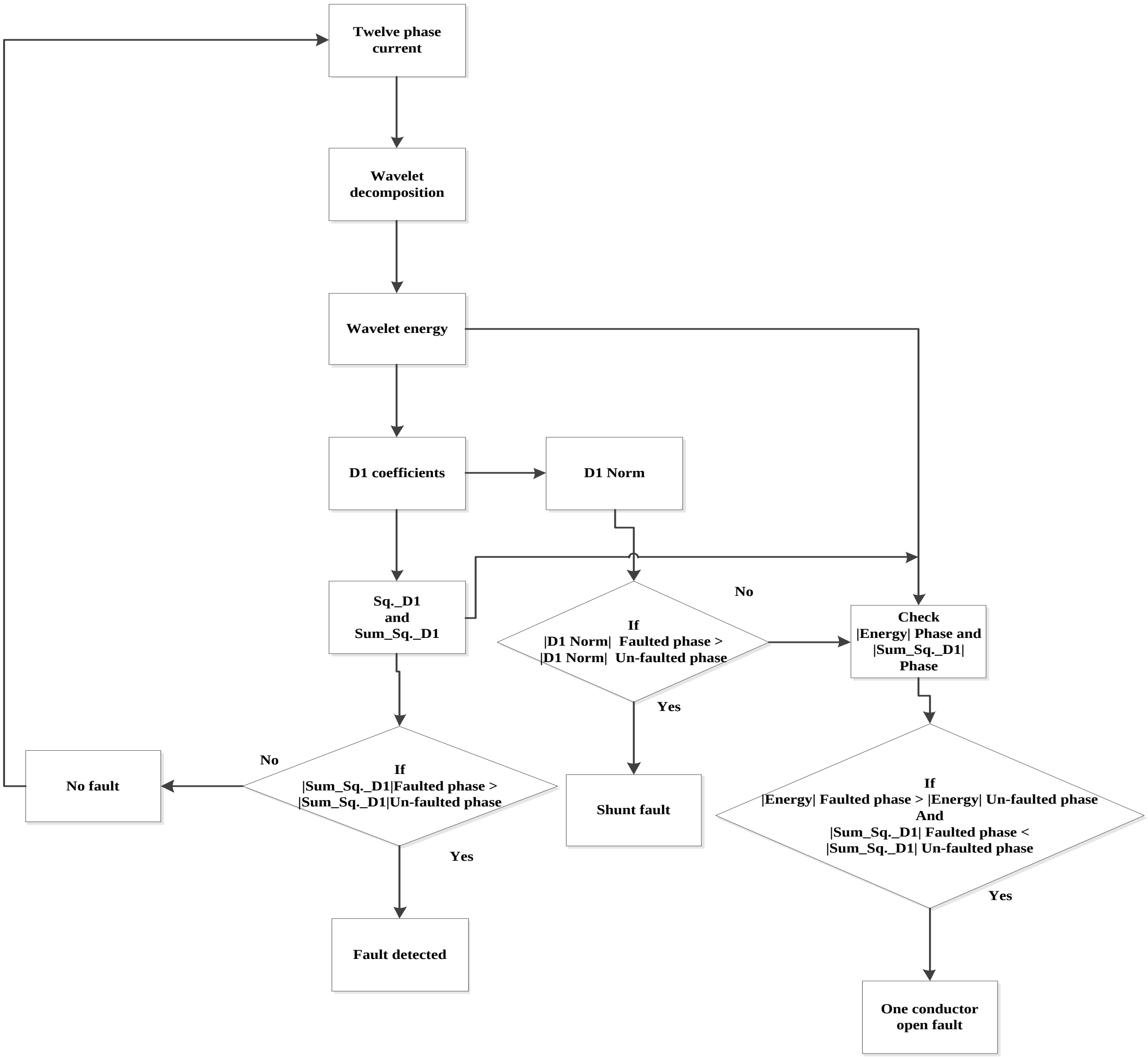


Fig.2 Proposed DWT based fault detection and classification scheme

V. TEST RESULTS AND DISCUSSIONS

The twelve phase current I_A, I_B, I_C, I_P, I_Q, I_R, I_U, I_V, I_W, I_X, I_Y, and I_Z waveforms of the interrelated phases during no-fault is illustrated in Fig. 3.

To evaluate the performance of wavelet transform based fault detector and classifier, the proposed scheme is comprehensively tested for a variety of single line to ground and one conductor open faults occurring simultaneously at different locations, at different fault inception time and with different values of R_F and R_G.

For authenticating the appropriateness of any fault detection and classification scheme, it is very important to check for one conductor open fault because on the occurrence of one conductor open fault the current in the faulted phase immediately falls to zero and it is very difficult to detect such type of fault with the help of usual over current relays. Thus the proposed scheme is tested for together occurring single line to ground fault and one conductor open fault. Table I depicts the test results of wavelet transform for no-fault condition.

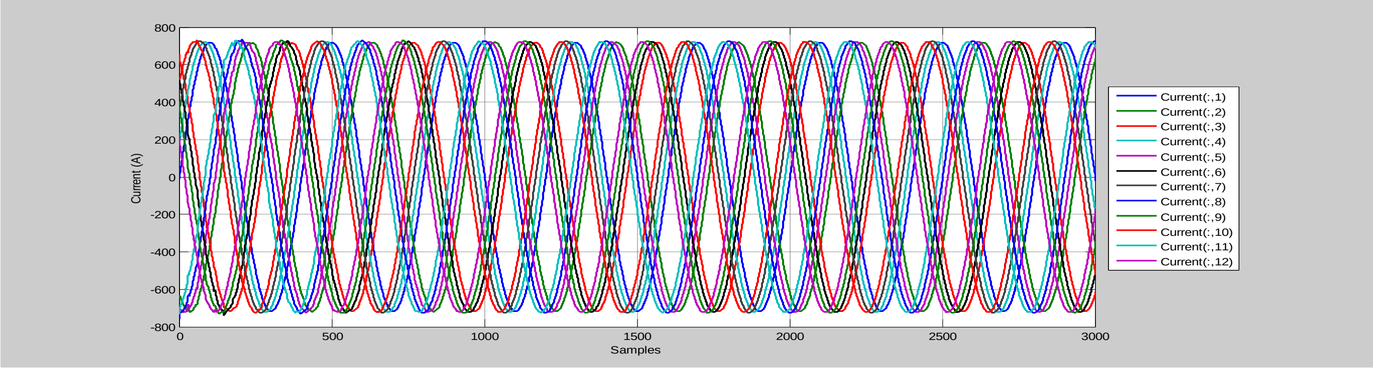


Fig. 3 Twelve phase current during no-fault

TABLE I. TEST RESULT FOR NO-FAULT

OUTPUT					
Phase	**D1 coefficient**	**Energy**	**Sum_S_D1**	**D1 Norm**	**Relay output**
A	16.46	99.60	4.6463*10^4	84.0711	Transmission line has no fault
B	17.45	99.60	4.4662*10^4	83.6141	
C	17.96	99.63	4.7885*10^4	84.6088	
P	17.67	99.59	4.6235*10^4	84.9926	
Q	19.07	99.60	4.6255*10^4	85.2154	
R	19.09	99.63	4.9298*10^4	85.6529	
U	19.24	99.65	5.0913*10^4	85.4796	
V	20.30	99.65	5.0584*10^4	86.1910	
W	19.42	99.59	5.1863*10^4	86.3351	
X	17.88	99.66	4.8977*10^4	84.0178	
Y	21.70	99.63	5.0068*10^4	85.2354	
Z	17.74	99.59	5.0781*10^4	84.8554	

5.1 Case-1 test result

The proposed scheme is tested for phase-‘A-g’ fault at 25%, phase-‘Q-g’ fault at 50%, phase-‘W-g’ fault at 75% and phase-‘X’ open conductor fault at 100% happening simultaneously from the relay position at FIT=0.1 seconds with $R_F = R_G = 0.001\Omega$. The twelve phase current for the duration of phase-‘A-g’, ‘Q-g’, ‘W-g’ and ‘X’ simultaneous faults is demonstrated in Fig. 4. Fig. 6 demonstrates the magnitude of detail-1 coefficients of twelve phase current during phase-‘A-g’, ‘Q-g’, ‘W-g’ and ‘X’ simultaneous faults and it is clearly observed from Fig. 6 that the magnitude of detail-1 coefficient of phase-‘A-g’, ‘Q-g’ and ‘W-g’ is more than the magnitude of detail-1 coefficient of un-faulted phase.

Table II summarizes the performance of the proposed scheme for phase-‘A-g’, ‘Q-g’, ‘W-g’ and ‘X’ simultaneous faults occurring concurrently at different locations from the relay position at equivalent time. It is evident from Table II, that the magnitude of sum of square of detail coefficients of phase-‘A’, ‘Q’ and ‘W’ is greater than the magnitude of sum of square of detail coefficients of un-faulted phase. Fig. 5 demonstrates the procedure of fault classification using wavelet transform. Fig. 5 depicts the magnitude of D1-norm of twelve phase current for the duration of phase-‘A-g’, ‘Q-g’, ‘W-g’ and ‘X’ faults. It can be clearly seen from Fig. 5, that the magnitude of D1-norm of phase-A, Q and W is greater than the magnitude of D1-norm of other phases. Because an open conductor fault is applied on phase-‘X’ so the magnitude of sum of square of detail coefficient of phase-‘X’ is lower than the magnitude of sum of square of detail coefficient of un-faulted phase but with higher magnitude of wavelet energy in comparison to the magnitude of wavelet energy of un-faulted phase (s) hence phase-‘X’ is an open-conductor fault.

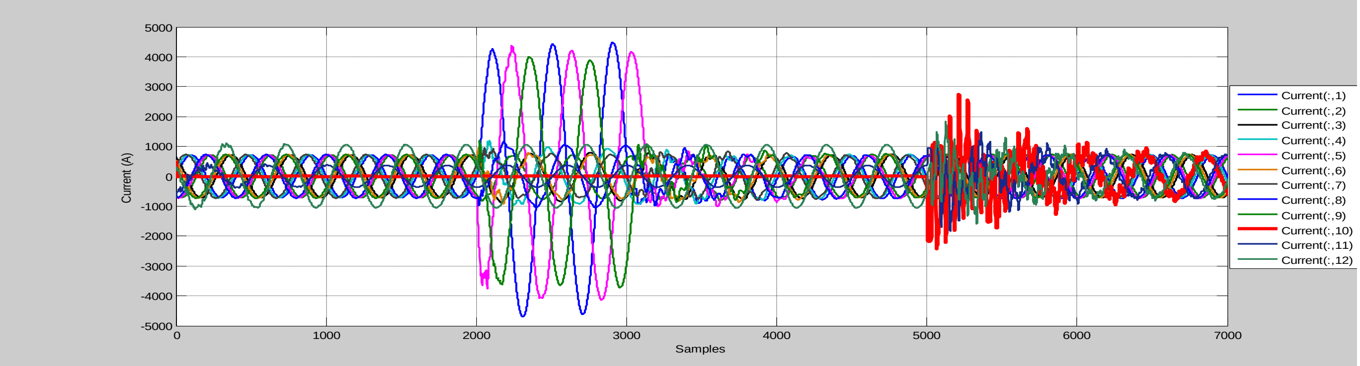


Fig. 4 Twelve phase current during phase ‘A-g’ fault at 25%, phase ‘Q-g’ fault at 50%, phase ‘W-g’ fault at 75% and phase ‘X’ open conductor fault at 100% from bus-1 with $R_F = R_G = 0.001\ \Omega$ having FIT = 0.1 seconds

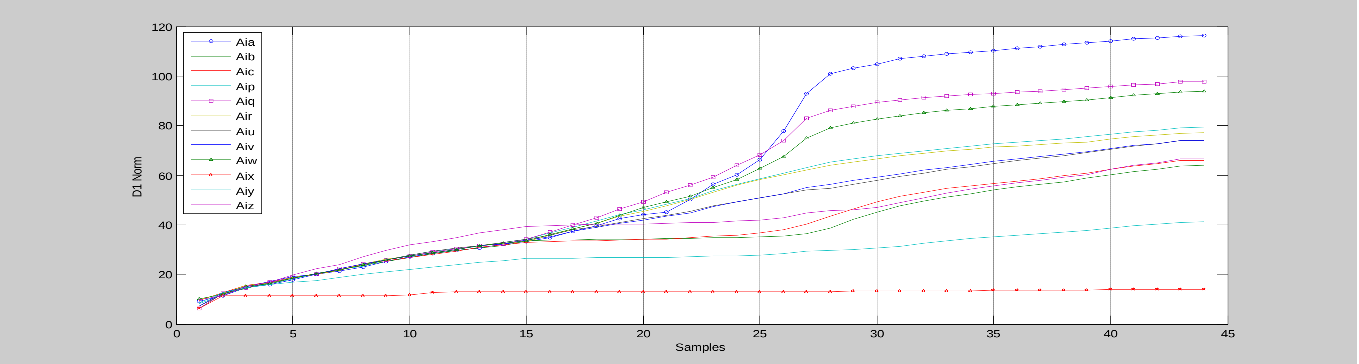
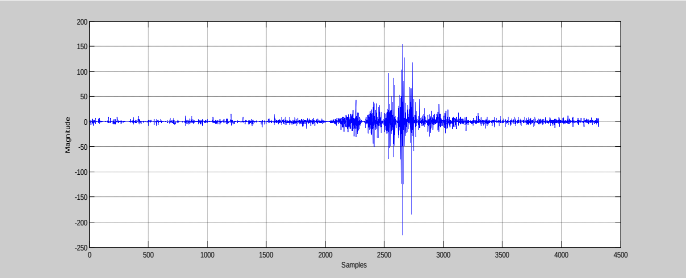
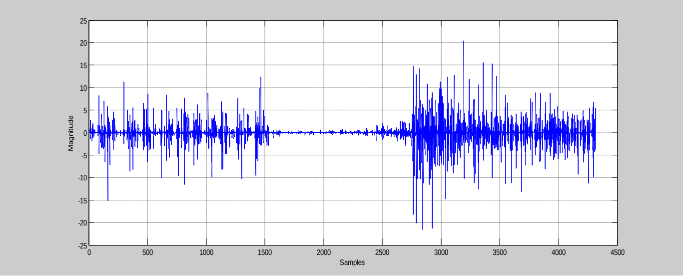


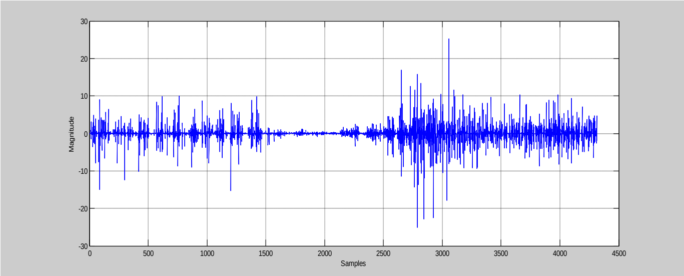
Fig. 5 D1-Norm of twelve phase current during phase ‘A-g’ fault at 25%, phase ‘Q-g’ fault at 50%, phase ‘W-g’ fault at 75% and phase ‘X’ open conductor fault at 100% from bus-1



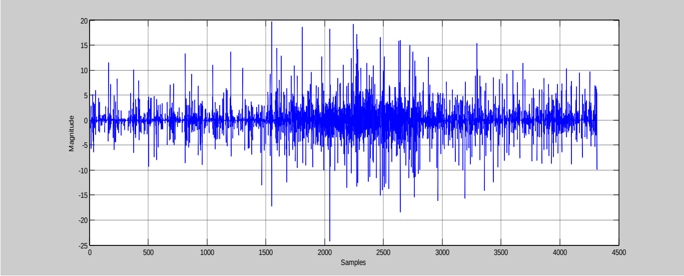
(a) Phase-A



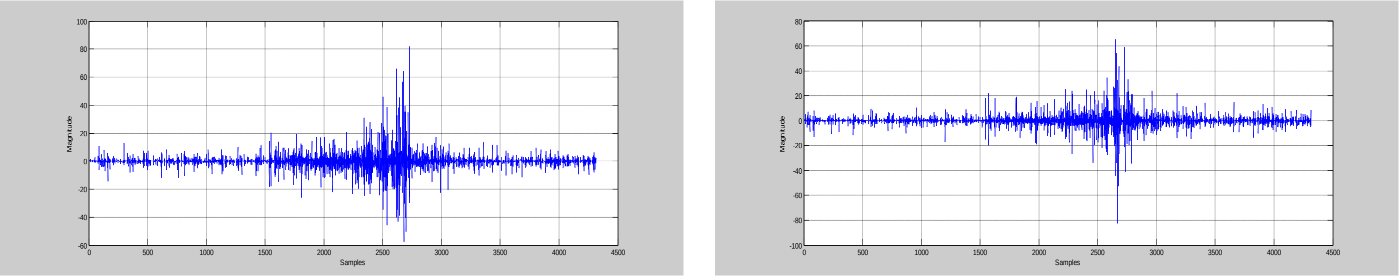
(b) Phase-B



(c) Phase-C

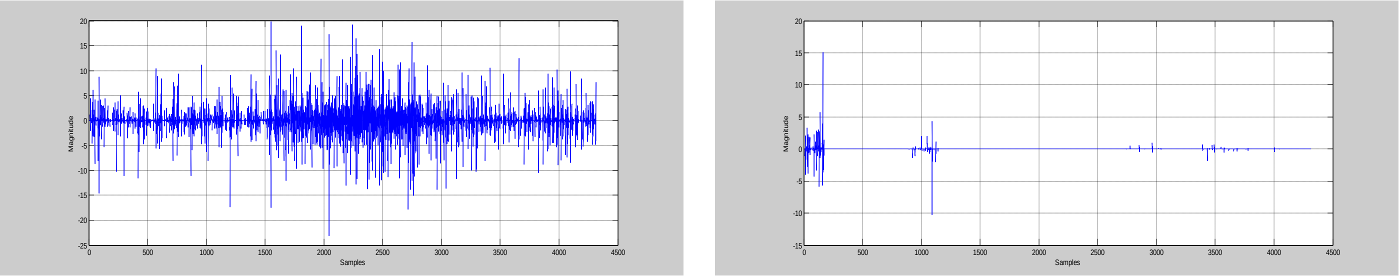


(d) Phase-P



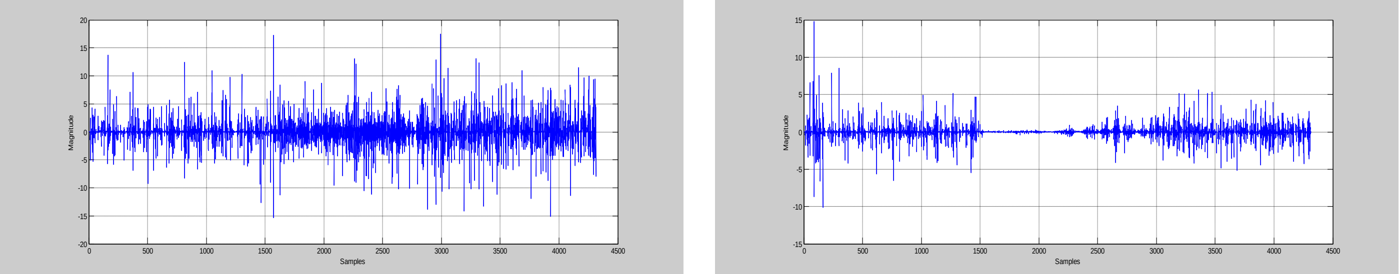
(e) Phase-Q

(i) Phase-W



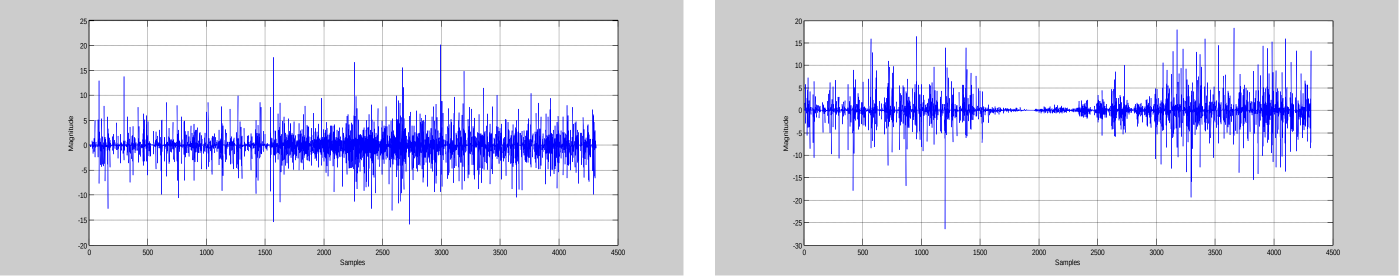
(f) Phase-R

(j) Phase-X



(g) Phase-U

(k) Phase-Y



(h) Phase-V

(l) Phase-Z

Fig. 6 Detail-1 coefficients of twelve phase current during phase-‘A-g’ fault at 25%, phase ‘Q-g’ fault at 50%, phase ‘W-g’ fault at 75% and phase ‘X’ open conductor fault at 100% from bus-1

Table II. Test Result for Phase ‘A-g’ Fault at 25%, Phase ‘Q-g’ Fault at 50%, Phase ‘W-g’ Fault at 75% and Phase ‘X’ Open Conductor Fault at 100% from Bus-1 with $R_F = R_G = 0.001\ \Omega$ at Fit = 0.1 Seconds

OUTPUT					
Phase	**D1 coefficient**	**Energy**	**Sum_S_D1**	**D1 Norm**	**Relay output**
A	**153.3**	**99.96**	**4.1745*10^5**	**116.18**	**Ph. ‘A-g’ fault**
B	20.43	97.77	2.0478*10^4	63.97	No fault
C	25.30	98.48	2.0521*10^4	65.91	No fault
P	19.67	97.66	3.5478*10^4	72.3281	No fault
Q	**81.81**	**99.86**	**1.2860*10^5**	**97.7526**	**Ph. ‘Q-g’ fault**
R	19.84	95.72	3.2594*10^4	77.0345	No fault
U	17.50	97.58	2.4220*10^4	74.0849	No fault
V	20.10	98.68	2.4272*10^4	74.0008	No fault
W	**65.53**	**99.77**	**9.6893*10^4**	**93.7666**	**Ph. ‘W-g’ fault**
X	**15.05**	**99.87**	**687.2842**	**13.8542**	**Open conductor**
Y	14.79	98.94	3.6518*10^3	41.1472	No fault
Z	18.32	98.64	2.4464*10^4	66.7284	No fault

5.2 Case-II test result

The proposed scheme is also tested for phase-‘B-g’ fault at 30% with $R_F = 5\Omega$ and $R_G = 10\Omega$, phase-‘R-g’ fault at 55% with $R_F = 10\Omega$ and $R_G = 15\Omega$, phase- ‘V-g’ fault at 80% with $R_F = 15\Omega$ and $R_G = 20\Omega$ and phase-‘Y’ open conductor fault at 100% with $R_F = 0.001\Omega$ occurring simultaneously from the location of the relay at FIT = 0.2 seconds. The twelve phase current during phase-‘B-g’ fault, phase-‘R-g’ fault, phase- ‘V-g’ fault and phase-‘Y’ open conductor fault is illustrated in Fig. 7.

Table III recapitulates the performance of the proposed scheme for phase-‘B-g’, ‘R-g’, ‘V-g’ and ‘Y’ faults occurring at once at different locations from the relay position. It is evident from Table III, that the magnitude of sum of square of detail coefficients of phase-‘B’, ‘R’ and ‘V’ is greater than the magnitude of sum of square of detail coefficients of un-faulted phase. Fig. 8 demonstrates the procedure of fault classification using wavelet transform. Fig. 8 depicts the magnitude of D1-norm of twelve phase current for the duration of phase-‘B-g’, ‘R-g’, ‘V-g’ and ‘Y’ faults. It can be clearly seen from Fig. 8 that the magnitude of D1-norm of phase-B, R and V is greater than the magnitude of D1-norm of other phases. As open conductor fault is applied on phase-‘Y’, therefore the magnitude of sum of square of detail coefficient of phase-‘Y’ is lower than the magnitude of sum of square of detail coefficient of un-faulted phase having higher magnitude of wavelet energy in comparison to the magnitude of wavelet energy of un-faulted phase hence phase-‘Y’ is an open-conductor fault.

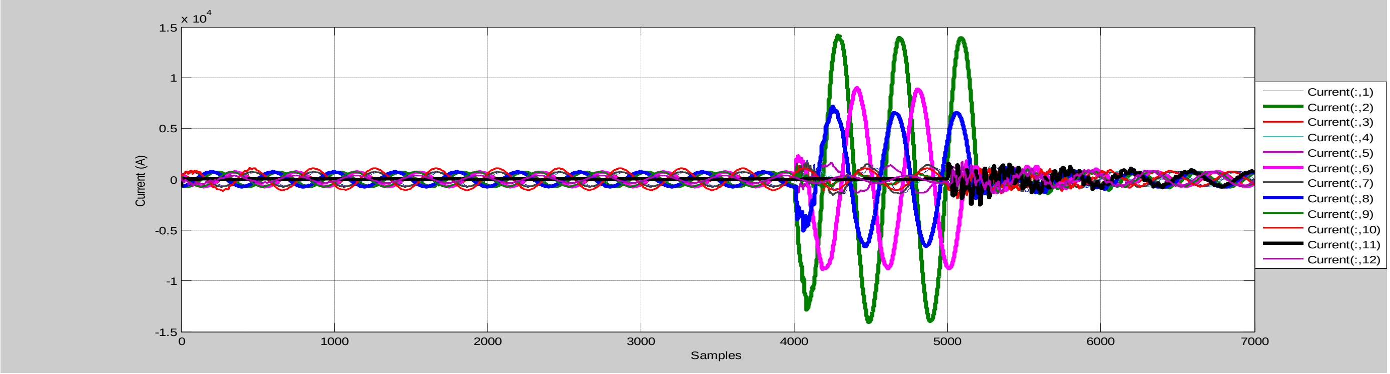


Fig. 7 Twelve phase current during phase-‘B-g’ fault at 30% with $R_F = 5\Omega$ and $R_G = 10\Omega$, phase-‘R-g’ fault at 55% with $R_F = 10\Omega$ and $R_G = 15\Omega$, phase- ‘V-g’ fault at 80% with $R_F = 15\Omega$ and $R_G = 20\Omega$ and phase-‘Y’ open conductor fault at 100% from bus-1 with $R_F = 0.001\Omega$ having FIT = 0.2 seconds

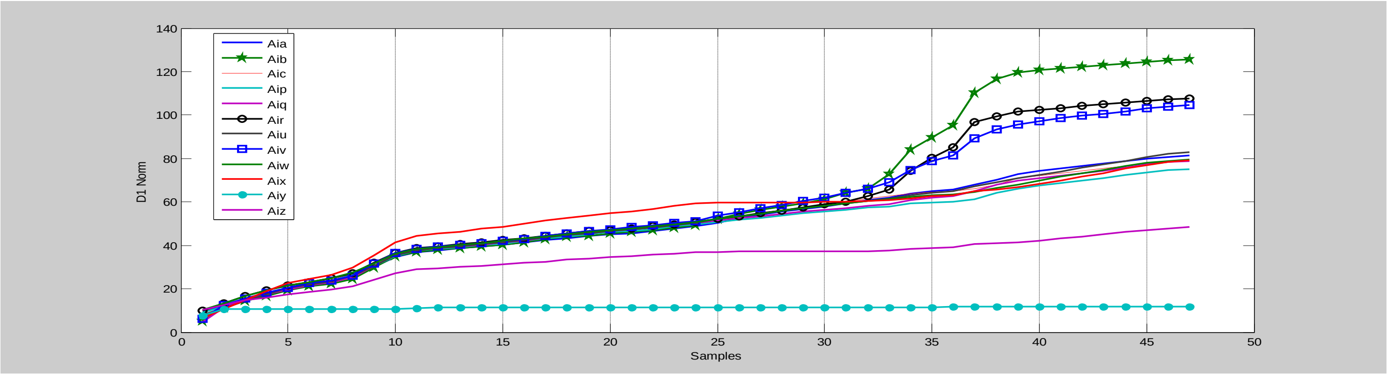


Fig. 8 D1-Norm of twelve phase current during phase-‘B-g’ fault at 30%, phase-‘R-g’ fault at 55%, phase-‘V-g’ fault at 80% and phase-‘Y’ open conductor fault at 100% from bus-1

TABLE III. TEST RESULT FOR PHASE-‘B-G’ FAULT AT 30%, PHASE-‘R-G’ FAULT AT 55%, PHASE-‘V-G’ FAULT AT 80% AND PHASE-‘Y’ OPEN CONDUCTOR FAULT AT 100% FROM BUS-1 AT FIT=0.2 SECONDS

OUTPUT					
Phase	**D1 coefficient**	**Energy**	**Sum_S_D1**	**D1 Norm**	**Relay output**
A	40.70	98.36	3.8129*10^4	81.3191	No fault
B	**257.68**	**99.85**	**7.8617*10^5**	**125.5878**	**Ph. ‘B-g’ fault**
C	39.93	97.50	3.4511*10^4	79.2617	No fault
P	20.54	98.54	2.4397*10^4	75.1511	No fault
Q	20.49	99.04	3.1207*10^4	78.7899	No fault
R	**119.97**	**99.77**	**2.9356*10^5**	**107.6515**	**Ph. ‘R-g’ fault**
U	25.36	98.78	3.5950*10^4	82.9752	No fault
V	**103.03**	**99.73**	**1.7801*10^5**	**104.5469**	**Ph. ‘V-g’ fault**
W	25.61	97.74	2.8842*10^4	79.5680	No fault
X	30.53	99.36	3.7196*10^4	79.2377	No fault
Y	**4.72**	**99.90**	**437.03**	**11.9093**	**Open conductor**
Z	11.61	99.37	5.2138*10^3	48.3416	No fault

VI. CONCLUSION

This paper presents scheme of twelve phase series capacitor compensated transmission line fault detection and classification using wavelet transform. A 765 kV, 50 Hz, twelve phase series capacitor compensated transmission line of 200 km length is simulated by using MATLAB software. Extensive test studies are performed to check the impact of deviation in fault parameters like fault type, fault location, fault resistance, ground resistance, and fault inception time. The proposed scheme makes use of the fault data collected at bus-1 only; exclusive of any information about the transmission line condition at the other side. Test results reveal that simultaneously occurring single line to ground fault and one conductor open fault are correctly detected and classified by using DWT technique.

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