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Detection, Classification, Protection and Mitigation of Power System Faults and Disturbances Using Wavelets Transform

K. Durga Syam prasad* and Ch. Sai Babu**

Abstract : Fast detection, identification of disturbances, and quick problem salvation are very important features of electrical power generation industries to prevent the consumers from power quality problems. FACTS compensated power transmission line can improve the quality of power, but a Wavelet technique along with compensating device gives more information to the operating engineers by giving time-frequency representation of the faulty signal. FACTS compensated transmission line along with Wavelet entropy algorithm and proposed algorithm can identify, classify, and gives the information about the fault location. Wavelet entropy is used to provide a safe, secure, and accurate algorithm for this concept. Moreover, a comprehensive control strategy is introduced to extract the compensating signals for the control of series and shunt converters of the Unified Power Quality Conditioner. The proposed test system and the results can be obtained using MATLAB/SIMULINK.

Keywords : Wavelet, Distance protection, flat spectrum and Unified Power-Quality Conditioner.

1. INTRODUCTION

Fast protection and fast problem solvation is very important feature in electrical power system. Transmission lines will get so many uncertainties because of temporary and permanent faults. The load variation may also cause voltage fluctuations in the transmission lines. If the voltage fluctuations are not clear within the specified time limit, the electrical appliances may damage. Many protection schemes are used to prevent the transmission line problems. To provide safety to the electrical equipment identification of the fault is very important. Classification and fault section identification is very complicated task. Current and voltage signals are used to determine the resistance of fault and fault location. For the protection of compensated and uncompensated power networks adaptive kalman filtering has been used. But this method finds its limitation that it requires more number of filters to do the task. Neural networks are proposed, but it needs large training set generation, large training time, different methods are applied for fault classification and location, *i.e.*, S-Transform, TT-Transform, fuzzy logic and also support vector machines. The proposed algorithm is more general and uses voltage and current signal which are recorded at one end of the line and no need of synchronization. It is independent of mode of operation of compensating devices. This method is simple and is applied to both unsymmetrical and symmetrical faults and avoids pre-trained neural network.

The algorithm is more common and it uses voltage and current signals. Test system of this paper is built using SIMULINK. The result for different fault types and also position with respect to FACTS devices using wavelet entropy algorithm are analyzed.

* Research Scholar, Department of Electrical & Electronics Engineering, J.N.T University Kakinada, Kakinada – 533003.

** Professor, Department of Electrical & Electronics Engineering, J.N.T University Kakinada, Kakinada – 533003.

2. WAVELET TRANSFORM AND ENTROPY

Transient behavior of waveform includes lot of information regarding the fault and faulty equipments of power systems and it is useful for fault analyzation. Therefore reliability of the power system has been improved. High frequency and instant breaks are the characteristics of transient signals. Information of frequency band contained in component of signal $D_j(k)$ and $A_j(k)$, obtained by reconstruction are as follows.

$$D_j(k) \; : \; [2^{-(j+1)} f_s, 2^{-j} f_s]$$
$$(j = 1, 2, \ldots\ldots m)$$
$$A_j(k) \; : \; [0, 2^{-(j+1)} f_s]$$

f_s – sampling frequency

$A_j(k)$ – low frequency component coefficient. The original signal $x(n)$ is

$$x(n) = D_1(n) + A_1(n) = D_2(n) + A_2(n)$$
$$= \sum_{j=L}^{j} D_j(n) + A_j(n)$$

The definition of non-normalizes Shannon entropy is as

$$E_j = -\sum_k E_{jk} \log E_{jk}$$

$E_{jk} \rightarrow$ wavelet entropy spectrum at scale j

$k \rightarrow$ instant

$$E_{jk} = |D_j(k)|^2$$

First decomposition level of measured signal using mother wavelet to detect the faults. Norm of detailed coefficients for all current signals the phase identified

$$||D_1|| = \left[\sum_{k=1}^{nd} D_1(k)\right]^2$$

If norm D_1 exceeds the threshold level, a disturbance is detected and identified wavelet entropy applied to produce accurate and simple algorithm. With respect to reference sinusoidal signal the magnitude and angle for each measured signal can be estimated band on basic vector mathematical is

$$\text{Magnitude Y} = |1| \frac{|A_{2s}|}{|A_2R_s|}$$

$$\text{Angle } \theta = \cos^{-1} \frac{A_{2R1} \cdot A_{2s}}{|A_{2R1}||A_{2s}|}$$

$A_{2R1.\,A2s} \rightarrow$ dot product of two vectors

$|A_{2R1}|, |A_{2s}| \rightarrow$ norm of the two vectors

3. WAVELET TRANSFORM WITH MRA

In the beginning of 1980’s, the wavelet transform was introduced. Wavelet calculations are based on scaling function $\varphi(t)$, and wavelet function $\psi(t)$.

$$\varphi(t) = \sqrt{2}\sum_k h_k \varphi(2t - k)\ \varphi(t) = \sqrt{2}\sum_k h_k \varphi(2t - k)$$

These functions are two-scale difference equations of properties that satisfy the following conditions.

$$\sum_{k=1}^{N} h_k = \sqrt{2}$$

$$\sum_{k=1}^{N} h_k \cdot h_{k+2l} = 1 \text{ if } l = 0 = 0 \text{ if } l \in z, l \neq 0$$

The scaling and wavelet functions are the prototype of a class of orthonormal basis functions of the form

$$\varphi_{j,k}(t) = 2^{j/2}\,\varphi(2^{j}\,t - k)\ ;\ j, k \in z$$
$$\psi_{j,k}(t) = 2^{j/2}\,\varphi(2^{j}\,t - k)\ ;\ j, k \in z$$

If once a wavelet system created, it is used to expand a function $f(t)$ in terms of the basis functions.

$$f = \sum\nolimits_{l \in z} c(l)\varphi_{l}(t) + \sum\nolimits_{j=0}^{J-1} \sum\nolimits_{k \in z}^{\infty} d(j,k)\Psi_{j}, k$$

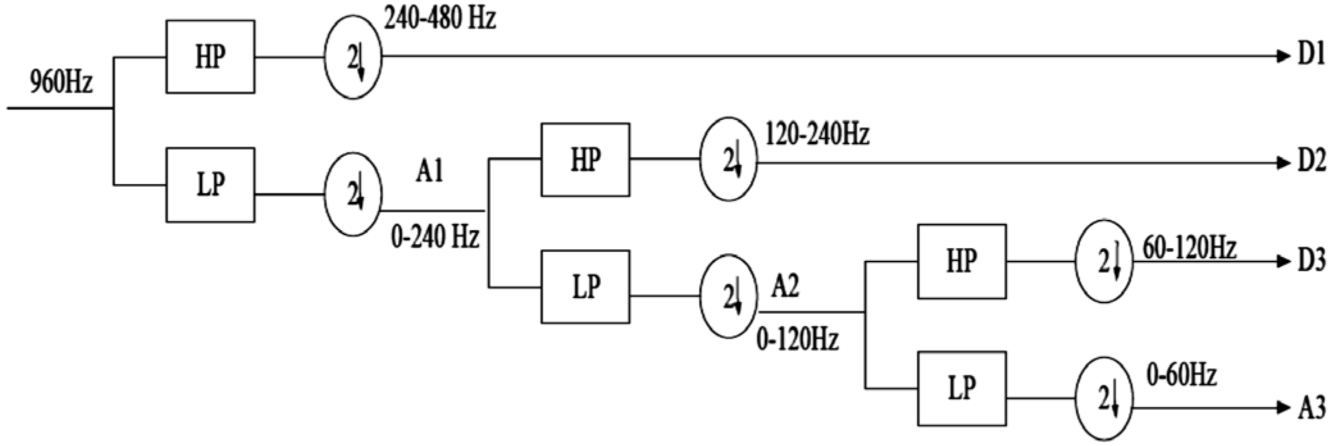


Fig. 1. Wavelet mutiresolution system.

The signal is sending through high-pass and low-pass filters. Outputs of the high-pass filters are called as the details (D) and the outputs of low-pass filters are known as approximations (A). These detailed and approximated coefficients are used for further calculations to find out the type of faults and position of the fault and also to find out the disturbances in electrical power transmission lines.

4. TEST SYSTEM PARAMETERS

Base MVA = 100 ,Area 1: Rated voltage: 13.8 KV, Short circuit capacity: 21,000 MVA, Area 2: Rated voltage: 735 kV, Short circuit capacity: 30,000 MVA, Transformer 1 (D/Y): Rated voltage: 13.8/735 kV, Rated power: 2100 MVA, Leakage resistance: 0.002 pu, Leakage reactance: 0.08 pu, Transformer 2 (Y/Y): Rated voltage: 735/230 kV, Rated power: 300 MVA, Leakage resistance: 0.002 pu, Leakage reactance: 0.15 pu, Transmission lines: Resistance: 0.001 pu, Reactance: 0.0195 pu, Loads: Load 1: 100 MW, Loads 2 and 3: 1.32 MW, 330MVAR, Load 4: 250MW, Load 5: 300MW, SSSC: rated power: 100 MVA, Nominal DC voltage: 20 kV, Nominal AC voltage: 138 kV, Number of pulses: 48 pulse, UPFC: SSSC and STATCOM each of, rated power: 100 MVA, Nominal DC voltage: 20 kV, Nominal AC voltage: 138 kV, Number of pulses: 48 pulse, Series coupling, transformer (Y/Y): ,Rated voltage: 138/147 kV,Rated power: 100 MVA, Leakage resistance: 0.002 pu, Leakage reactance: 0.05 pu , Shunt Coupling, Transformer (Y/Y):, Rated voltage: 138/735 kV, Rated power: 100 MVA, Leakage resistance: 0.002 pu ,Leakage reactance: 0.02 pu.

5. RESULTS OF THE SIMULATION

(*a*) Detection and Identification of Power System Faults

Fault detection can be obtained from the details of the first decomposition level of the measured current signals using db1 wavelet. By calculating the norm of the detail coefficients (D1) for all currents, the phase(s) on disturbance can be identified.

$$\|D_1| = \left[\sum_{k=1}^{\ddot{u}\ 1\ 2} D1(k)\right]$$

The norm D1 of one or more current detail coefficients exceeds the threshold (M), a disturbance is detected and identified. The test system was designed using MATLAB/SIMULINK. After applying different kinds of faults, we can observe the performance of the system. Original current wave form and its approximation, dilations during LG fault.

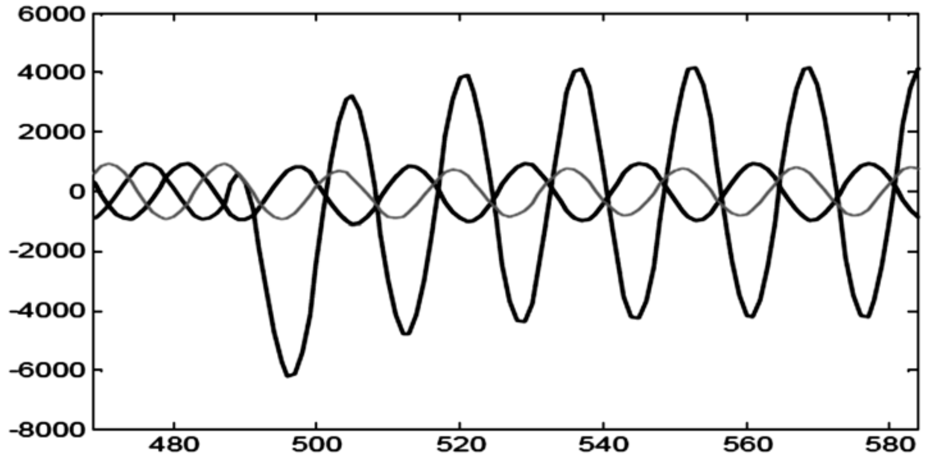
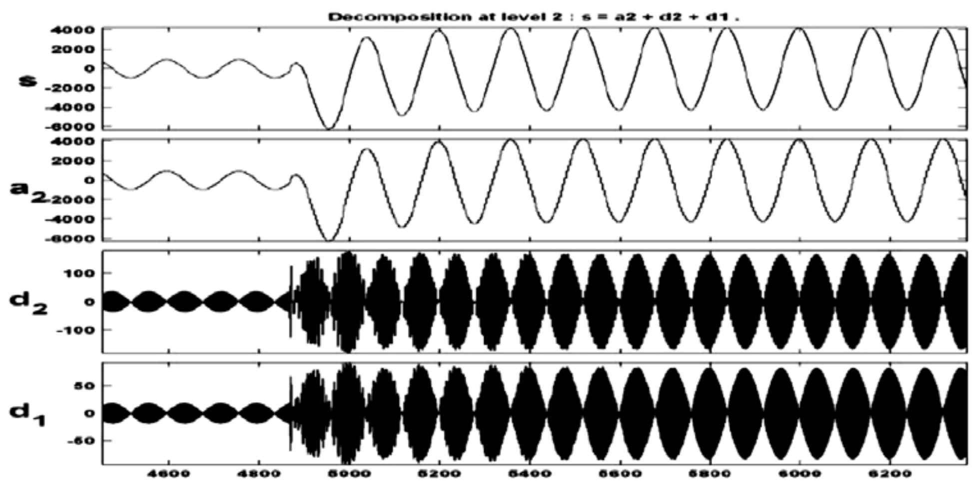
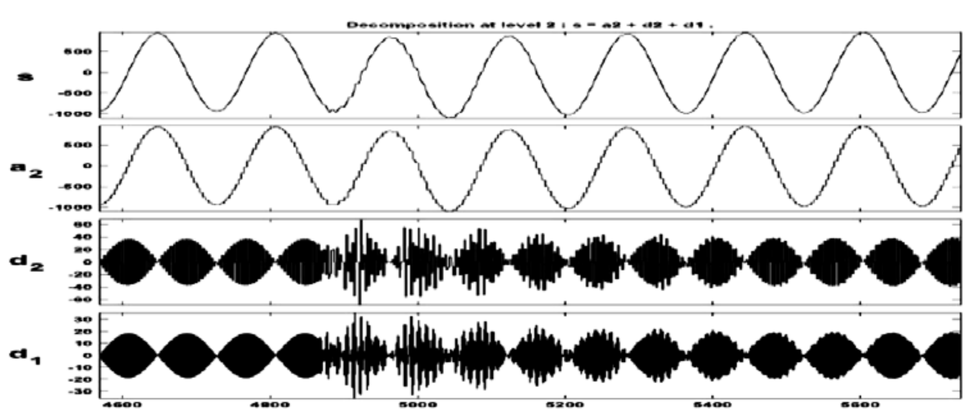


Fig. 3. Current waveform during LG fault.

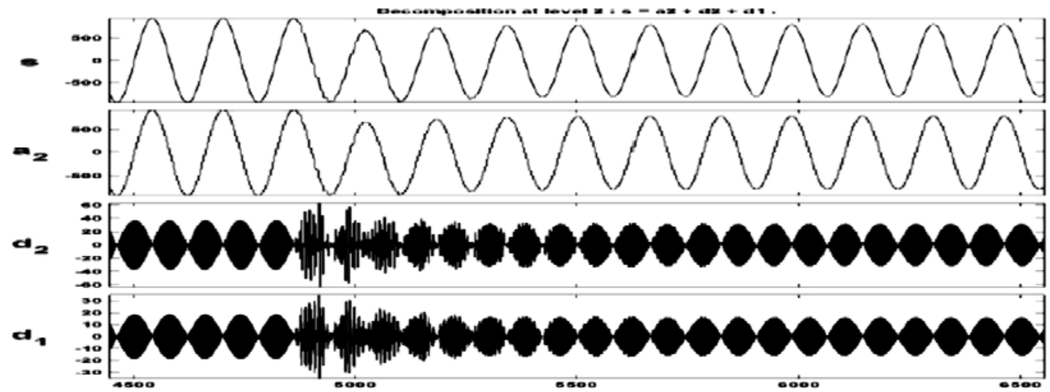
When the fault is happening on the system, all the phases will be effected. And the waveforms of all the phases during the fault are



(a). phase A



(b). phase B



(c). phase C

Fig. 4. Current waveforms of all phases.

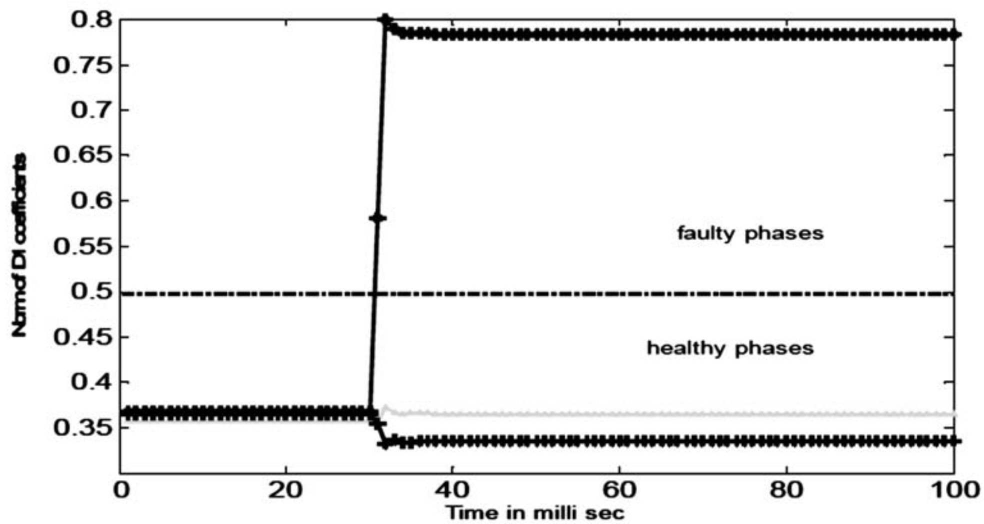


Fig. 5. Norm of D1 coefficients for LG fault.

(*b*) Classification of Power System Faults and Disturbances

Fault identification and classification, the wavelet entropy theory is applied to produce a simple and accurate algorithm. Form this algorithm to detect and classify the fault and identify the fault position in a transmission. Discrete wavelet transformation and wavelet entropy calculations are used to analyze during fault current and voltage signals of the compensated transmission line. The definition of nonnormalized Shannon entropy is as follows,

$$E_j = -\sum E_{jk} \log E_{jk}$$

where E_{jk} is the wavelet energy spectrum at scale *j* and instant *k* and it is defined as follows

$$E_{jk} = |D_j(k)|^2$$

high-frequency component coefficient $D_j(k)$

During fault, the amplitude and frequency of the test signal will change significantly as the system change from normal state to fault. The Shannon entropy will change accordingly. Wavelet becomes incapable of dealing with some abnormal signals therefore Wavelet combined entropy can make full use of localized feature at time–frequency domains.

The algorithm determines the type of fault if it is a single line to ground (SLG) fault, line to line (L–L) fault, double line to ground (DLG) fault or a three line to ground (3LG) fault. Finally, the algorithm selects the phases involved in the fault. The algorithm classifies the type of disturbance and events

Table 1. Wavelet Entropy minimum and maximum values for R, Y, & B .

Fault	Phase-A Wavelet Entropy		Phase-B Wavelet Entropy		Phase-C Wavelet Entropy	
	Min.	Max.	Min.	Max.	Min.	Max.
AG	1.3589 ×10⁵*	-	-	0.5715×10⁵+	-	0.5559×10⁵+
BG	-	0.4988×10⁵	0.7690×10⁵*	-	-	0.4837×10⁵
CG	-	0.5794×10⁵+	-	0.5577×10⁵	0.7393×10⁵*	-
ABG	2.5397×10⁵	-	2.0021×10⁵	-	-	0.4557×10⁵
BCG	-	0.5179×10⁵	1.1915×10⁵	-	0.8084×10⁵	-
CAG	1.9323×10⁵	-	-	0.4447×10⁵	1.6221×10⁵	-
AB	2.3390×10⁵	-	2.3532×10⁵	-	-	0.0253×10⁵
BC	-	0.0548×10⁵	0.8212×10⁵	-	0.8315×10⁵	-
CA	1.8047×10⁵	-	-	0.0405×10⁵	1.8366×10⁵	-
ABCG	2.7743×10⁵	-	1.7837×10⁵	-	1.2769×10⁵	-
ABC	2.7743×10⁵	-	1.7837×10⁵	-	1.2769×10⁵	-

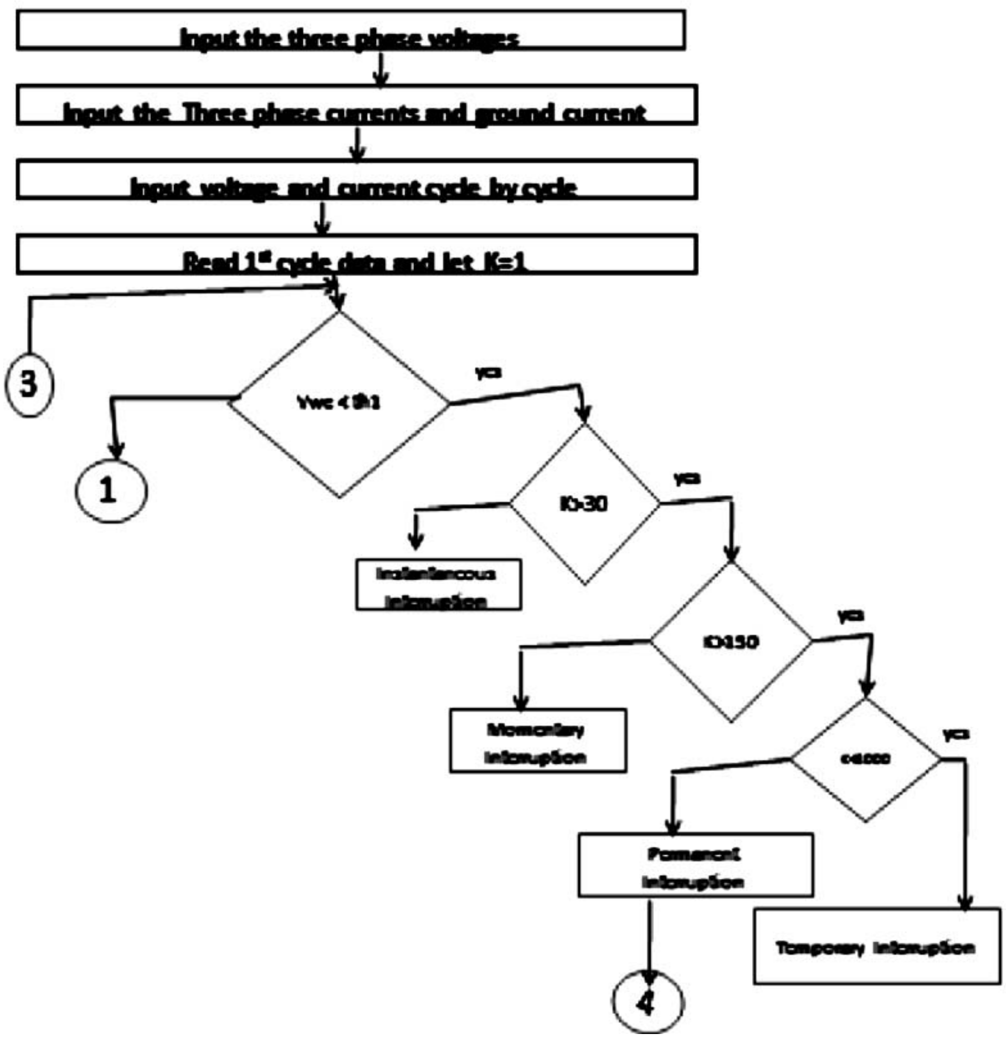


Fig. 6.

From table Minimum fault Wavelet Entropy in phase A (*Vfva_min*) is 1.3589 $\times 10^5$ which is obtained considering for all possible faults with phase A involved i.e., AG fault, ABG fault, CAG fault, AB fault, CA fault, ABCG fault and ABC fault. Maximum fault Wavelet Entropy in phase A (*Vfva_max*) is 0.5794 $\times 10^5$ .Which is obtained for faults with healthy phase A *i.e*., BG fault, CG fault, BCG fault and BC fault.

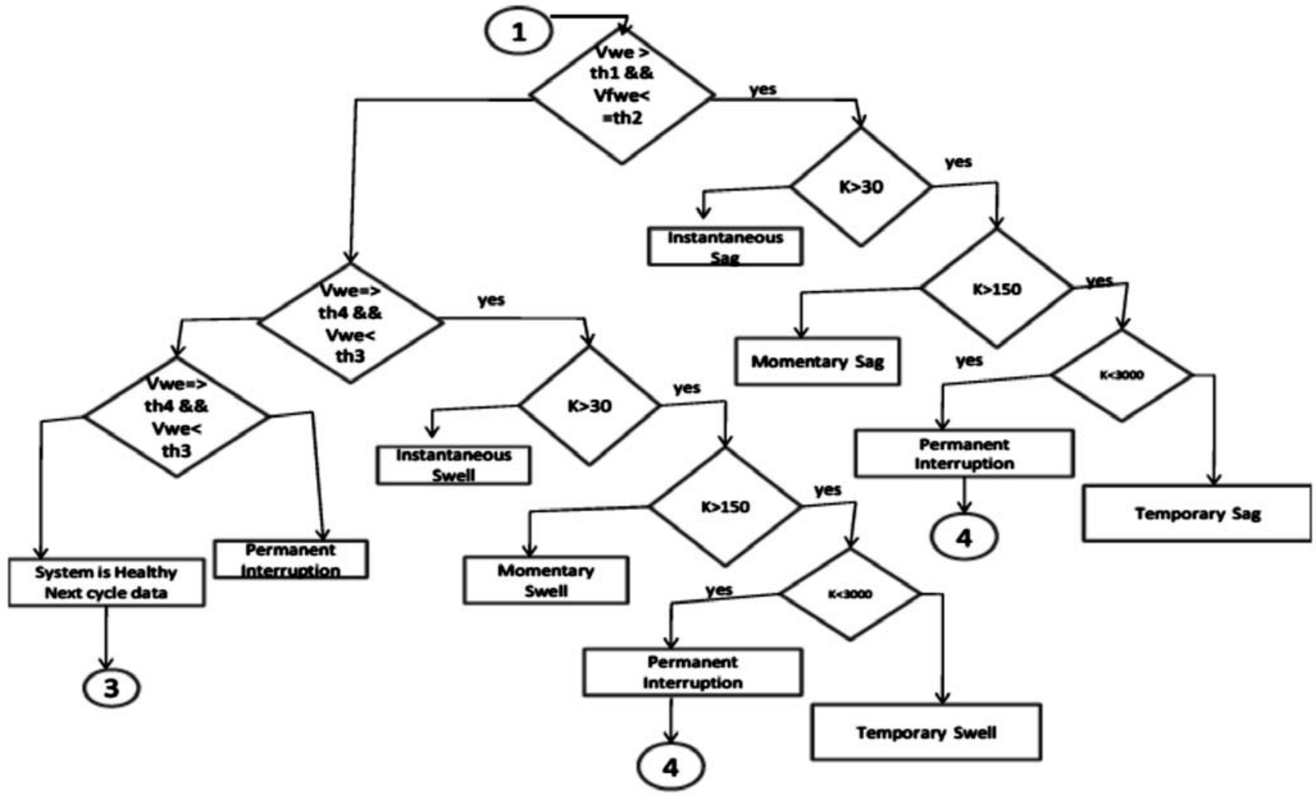


Fig. 7.

Similarly minimum and maximum fault Wavelet Entropy for Phase B and C (V*fvb_min*, V*fvc_min*, V*fvb_max*, V*fvc_max*) are identified. Proper threshold Wavelet Entropy (VTH) is then set between minimum fault Wavelet Entropy (V*fV_min*) and maximum fault Wavelet Entropy (V*fV_max*) of all faults as

$$\text{VTH} < \text{V}fV\_min \text{ and VTH} > \text{V}fV\_max$$

$$\text{V}fV\_min = \min(\text{V}fva\_min, \text{V}fvb\_min, \text{V}fvc\_min)$$

$$\text{V}fV\_max = \max(\text{V}fva\_max, \text{V}fvb\_max, \text{V}fvc\_max)$$

Table 2. Classification of Faults comparison by using Different methods

Sl.no	*FFT*	*STFT*	*WET*
1	LL	LG	LG
2	LLL	LL	LL
3	---	LLG	LLG
4	----	LLL	LLL
5	----	LLLG	LLLG
6	----	-----	ARC
7	---	-----	HIF

$$Vfv\_min = 0.5794 \times 10^5 \text{ and } Vfv\_max$$

$$= 0.7393 \times 10^5 \text{ without STATCOM (from Table 1) and}$$

$$Vfv\_min = 0.5548 \times 10^5 \text{ and } vf\_max$$

$$= 0.8229 \times 10^5 \text{ with STATCOM (from Table 2).}$$

Table 3. Classification of Disturbances comparison by using Different methods.

Sl.no	*FFT*	*STFT*	*WET*
1.	Sag	Sag	Sag
2.	Swell	Swell	Swell
3.	--------	Interruption	Interruption
4.	---------	Capacitor Switching	Capacitor Switching
5.	--------	--------	Transformer Energizing
6.	---------	-------	Load Switchig Eevents

A common threshold Wavelet Entropy TH = 0.65×10^5 is best suitable to lie between V*fv_min* and V*fv_max* for both without and with STATCOM in the system. The feature of this algorithm is that transients are easily extractable using wavelet analysis and provides a common setting of threshold Wavelet Entropy. The STATCOM in the system does not require any change in the fault Wavelet Entrop. Fault Wavelet Entropy calculation is based on sum of detail-1 coefficients of currents at both ends of the line with measurements on either side of STATCOM.

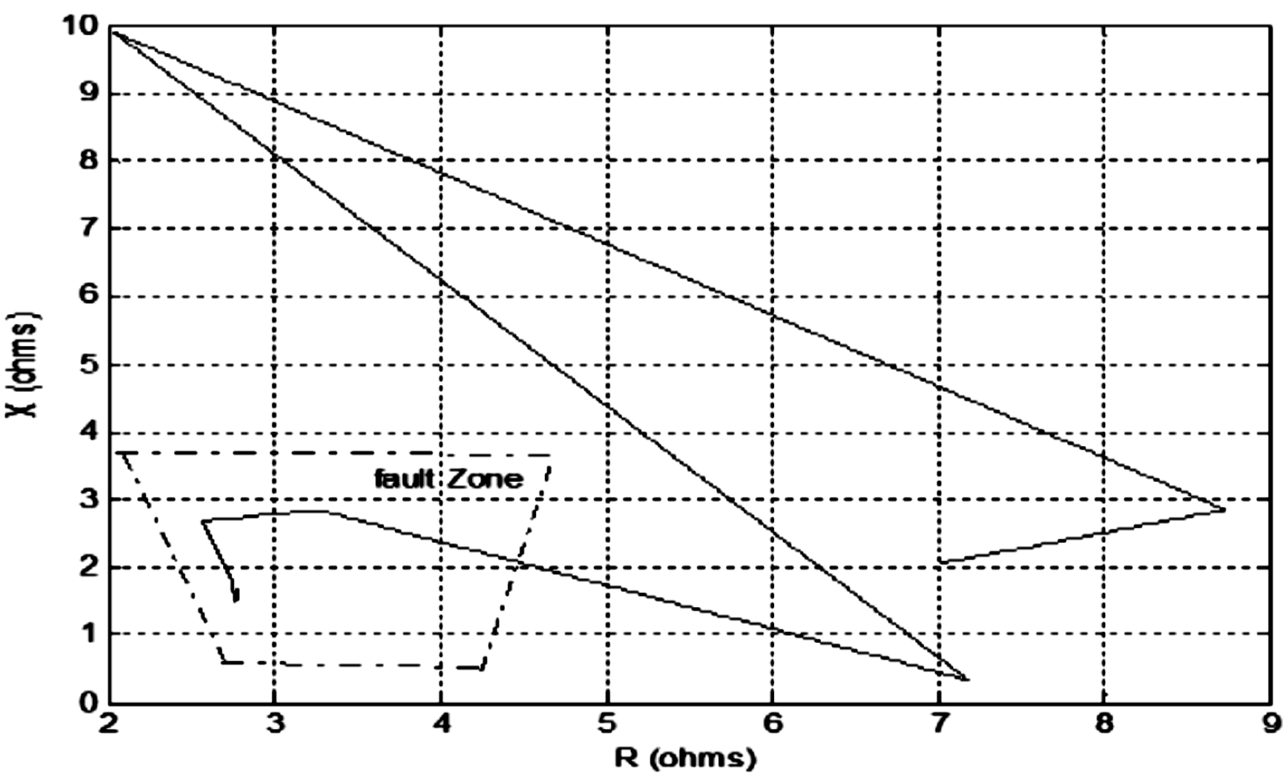


Fig. 8. Fault trajectory for 3LG solid fault at 300 km.

This algorithm provides Classification of Faults comparison by using Different methods and Classification of Disturbances comparison by using Different methods. The overall accuracy of classification which reflects the extrapolating capability of proposed method is 99.71%.

Table 4. Actual location of fault = 300 km.

Fault Type	***Estimated Length (KM)***	***%Error***
LG fault	299.92	-0.079
LL fault	299.82	-0.173
Three phase fault	300.134	0.103477
High impedance Fault	299.33	-0.67
Arc fault	301.73	1.73

Seven classes of PQ events are considered as the classification problem. These events are normal class (C1) , phaseto- ground fault (C2), phase-to-phase fault (C3) and three-phase fault (C4) , load switching event (C5), capacitor switching event (C6) and the transformer energizing event (C7) are selected for switching events.

Table 5. Classification of power quality disturbances with different classes.

True class	***C1***	***C2***	***C3***	***C4***	***C5***	***C6***	***C7***	
C1	100	0	0	0	0	0	0	100
C2	0	98	2	0	0	0	0	98
C3	0	0	100	0	0	0	0	100
C4	0	0	0	100	0	0	0	100
C5	0	0	0	0	100	0	0	100
C6	0	0	0	0	0	100	0	100
C7	0	0	0	0	0	0	100	100
								99.71

(*c*) Fault location calculation

Fault identification and classification, the wavelet entropy theory is applied to produce a simple and accurate algorithm form this algorithm to classify the fault and identify the fault position in a transmission line with respect to a FACTS device placed in the midpoint of the transmission line. By using the fundamental voltage and current information, location of fault is identified by using

$$L = V \times \Delta t \text{ relation.}$$

$$L = \text{distance in Km.}$$

$$V = \text{velocity of wave}$$

$$= 299750 \text{ km/s.}$$

The velocity of propagation of the travelling waves over the overhead transmission lines equals the velocity of light. In actual practice because of the resistance and leakage reactance of the lines, the velocity of travelling wave is slightly less (250km/sec assumed) than the velocity of the light.

Δt is time delay between the oppositely polared samples

$$\Delta t = (N2-N1)/N$$

N1 is the positive coefficient (positive WMM) and

N2 is the negative coefficient (negative WMM)

Where (N2-N1) is the difference between the oppositely polared samples.

$$N = \text{Total number of samples..}$$

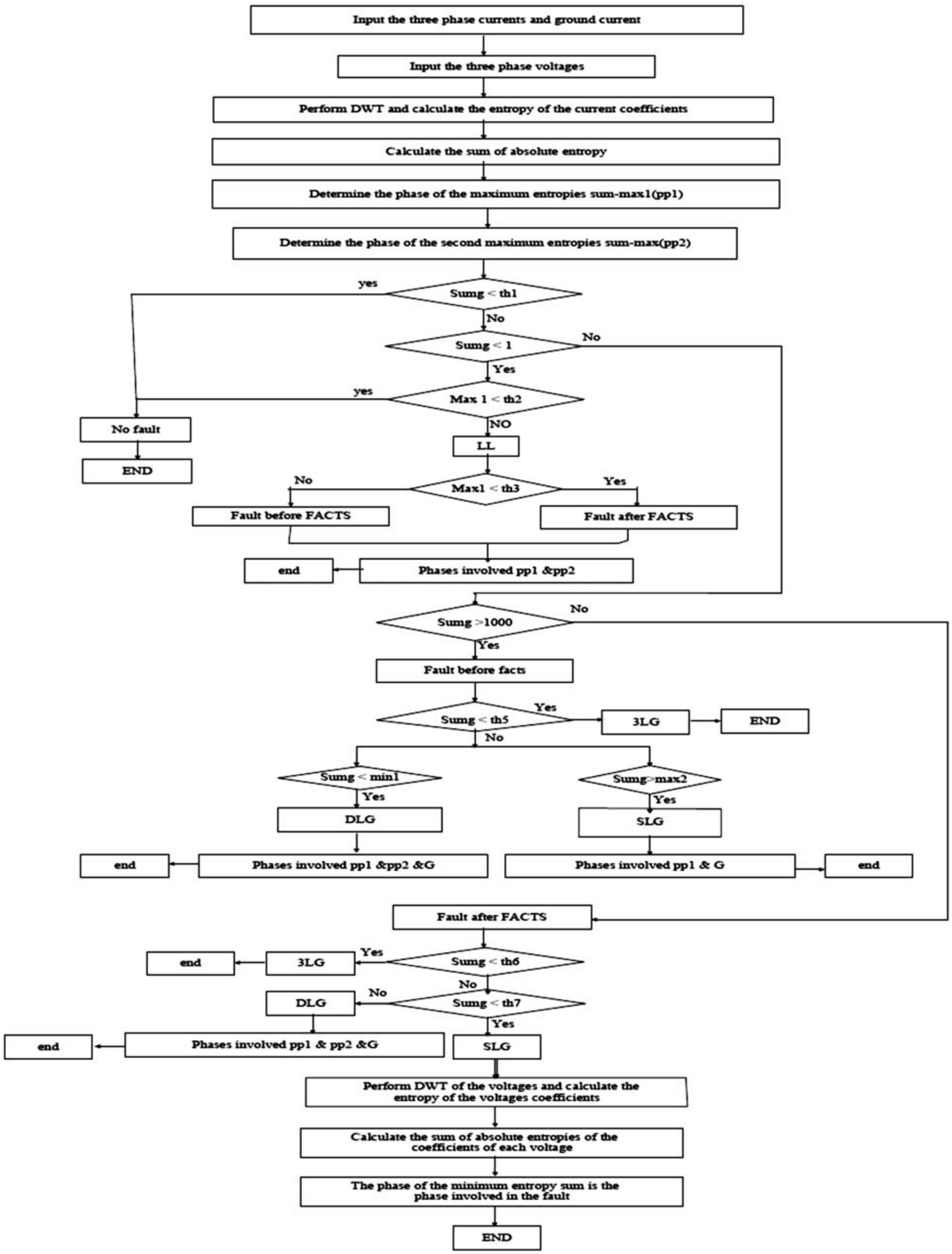

Input the three phase currents and ground current
Input the three phase voltages
Perform DWT and calculate the entropy of the current coefficients
Calculate the sum of absolute entropy
Determine the phase of the maximum entropies sum-max1(pp1)
Determine the phase of the second maximum entropies sum-max(pp2)
yes
Sumg < th1
No
Sumg < 1
No
Yes
yes
Max 1 < th2
NO
No fault
END
LL
No
Max1 < th3
Yes
Fault before FACTS
Fault after FACTS
end
Phases involved pp1 &pp2
No
Sumg >1000
Yes
Fault before facts
Yes
Sumg < th5
3LG
END
No
Sumg < min1
Sumg>max2
Yes
Yes
DLG
SLG
end
Phases involved pp1 &pp2 &G
Phases involved pp1 & G
end
Fault after FACTS
end
3LG
Yes
Sumg < th6
No
DLG
No
Sumg < th7
Yes
end
Phases involved pp1 & pp2 &G
SLG
Perform DWT of the voltages and calculate the entropy of the voltages coefficients
Calculate the sum of absolute entropies of the coefficients of each voltage
The phase of the minimum entropy sum is the phase involved in the fault
END

Fig. 9.

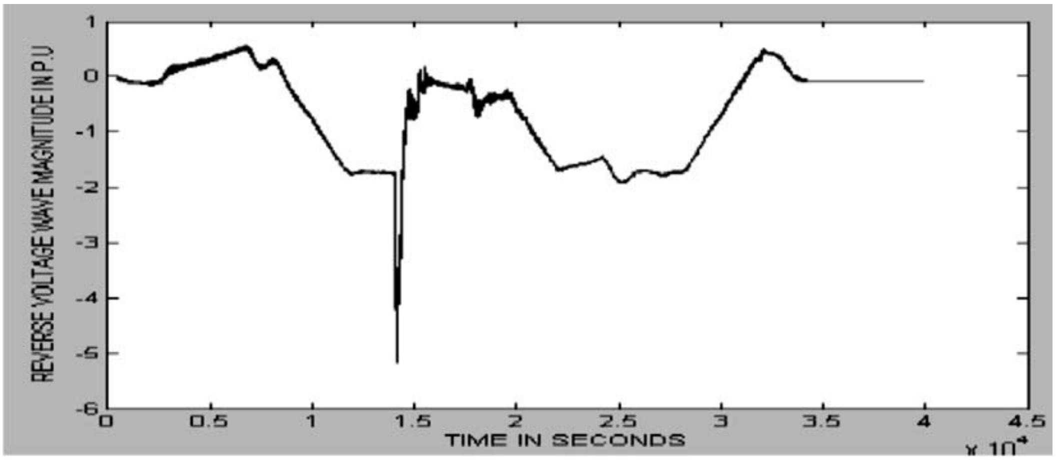


Fig. 10. Reverse voltage signal.

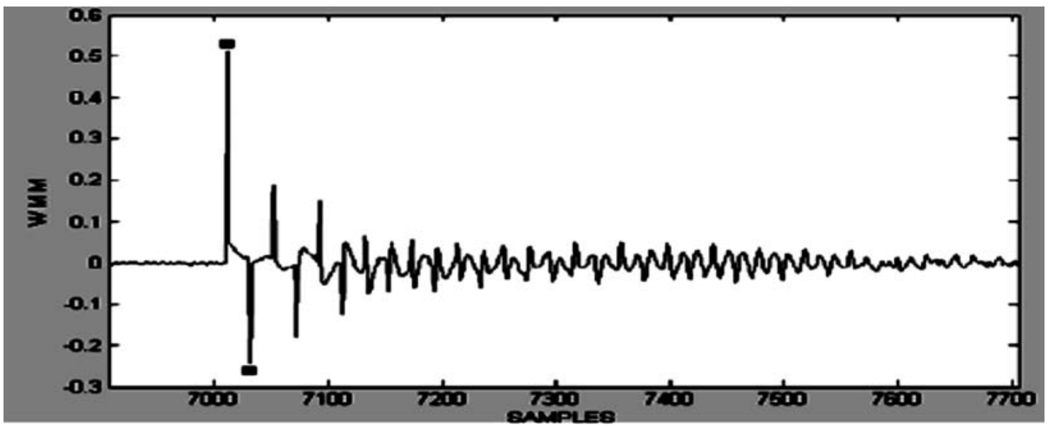


Fig. 11. Wavelet modulus maxima.

The distance of the fault location is calculated by the following equation

N1 = 7011, N2 = 7021, N = 10,000, Dt = (N2 – N1)/ N = 0.001, and V = velocity of wave = 299750 Km/s. The fault distance is computed and is obtained as 299.75.

Table 6. Distance calculation at 300Km for different faults.

Fault type	*Estimated length (km)*	*%error*
LG fault	299.92	–0.079
LL fault	299.82	–0.173
Three phase fault	300.134	0.103477
High impedance fault	299.33	–0.67
Arc fault	301.73	1.73

(*d*) Protection from Power System Faults

Distance protection is used to protect transmission lines. The main target of this technique is to calculate impedance at the fundamental frequency between the relay and the fault point. From the calculated impedance, the impedance trajectory is drawn to identify the fault whether it is external or internal. If it is internal trip signal is generated. The magnitude and angle with respect to the reference sinusoidal signal for each measured signal can be estimated using the basic vector mathematics. Each time a new sample enters the window, the phasors of the signals are estimated and the impedance(s) of the faulty phase(s) are calculated and compared with the line protection zone. If the impedance(s) enter the tripping zone, a tripping signal should be sent to the circuit breaker.

Table 7. Distance calculation for 300Km at different faults and methods.

Fault type	*FFT*		*STFT*		*WT*	
	Estimated length (km)	*% error*	*Estimated length (km)*	*% error*	*Estimated length (km)*	*% error*
LG fault	....		298.1	–1.9	299.92	–0.079
LL fault	297.7	–2.3	298.3	–1.7	299.82	–0.173
Three phase fault	302.1	2.1	301.4	1.4	300.134	0.103477
High impedance fault					299.33	–0.67
Arc fault					301.73	1.73

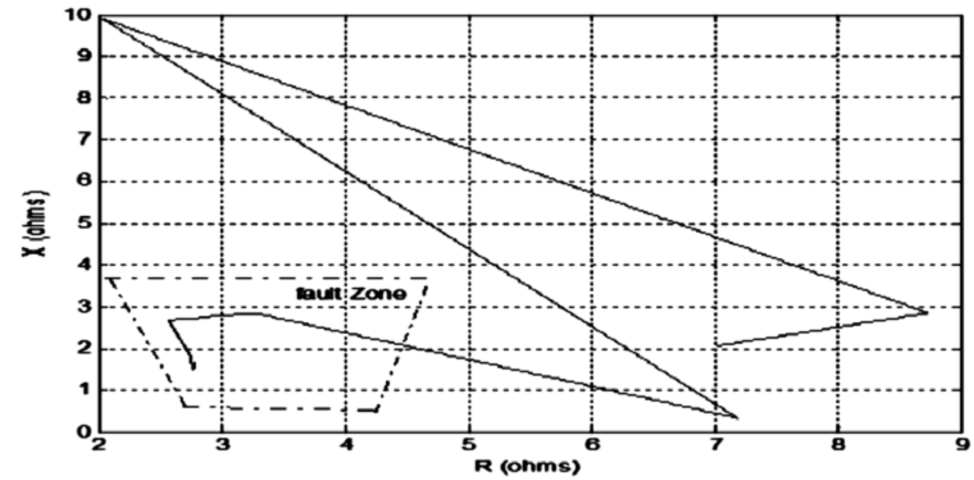


Fig. 12. Fault trajectory for 3LG solid fault at 300 km.

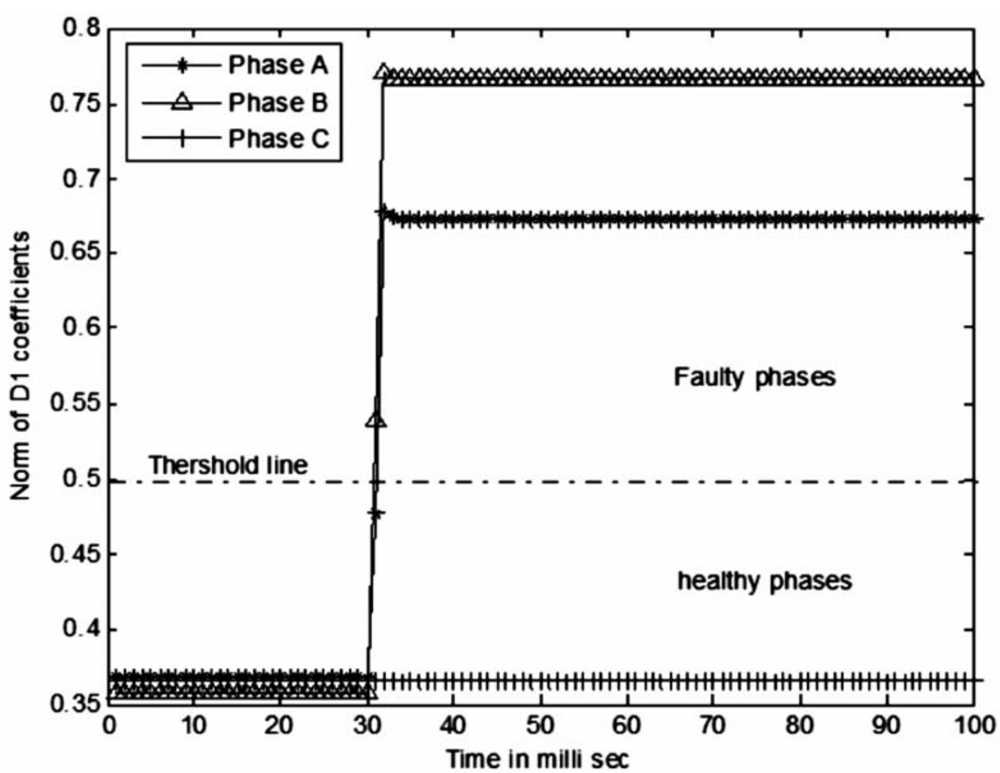


Fig. 13. Norm of high impedance coefficients for phase A and B.

(*e*) Mitigation of power quality disturbance

Mitigation of Power Quality Disturbances using Online Wavelet Transform-Based Control Strategy for UPQC Control System. New algorithm is proposed to estimate amplitude and phase angle of load currents and source voltages in the presence of harmonics and frequency oscillation. Moreover, a comprehensive control strategy is introduced to extract the compensating signals for the control of series and shunt converters of the Unified Power-Quality Conditioner (UPQC).

In this paper for mitigation power quality disturbances by using 84 pulses UPQC, assembled by combining one twelve pulse VSC, in Conjunction with an asymmetric single phase seven level converter plus an injection transformer with this arrangement, the VSC outputs total harmonic distortion in voltage is reduced. The proposed strategy allows saving in the number of employed switches .

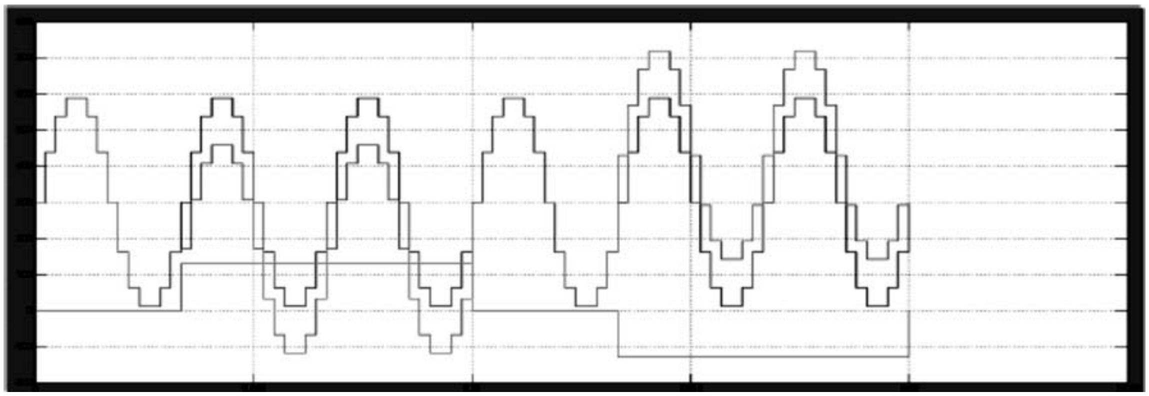


Fig. 14. Mixing of seven level six level signal at reinjection Transformer in UPQC

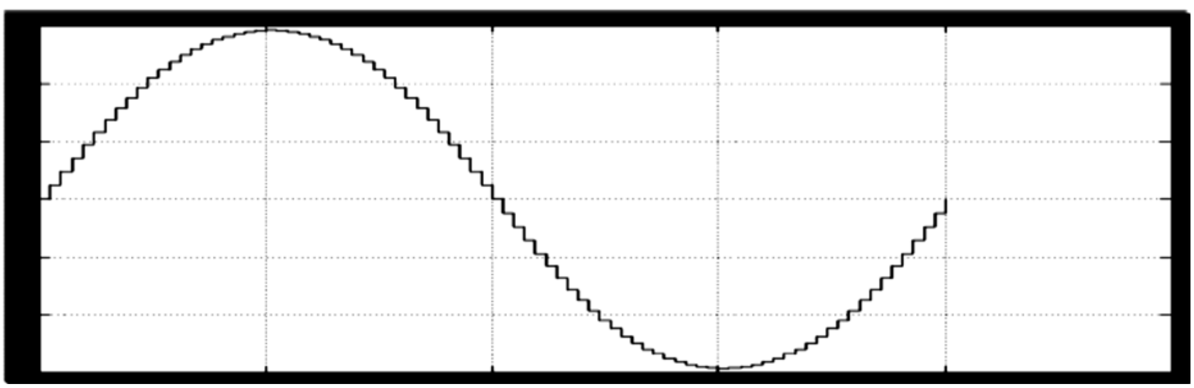


Fig. 15. Line to neutral 84 pulse output voltage of UPQC

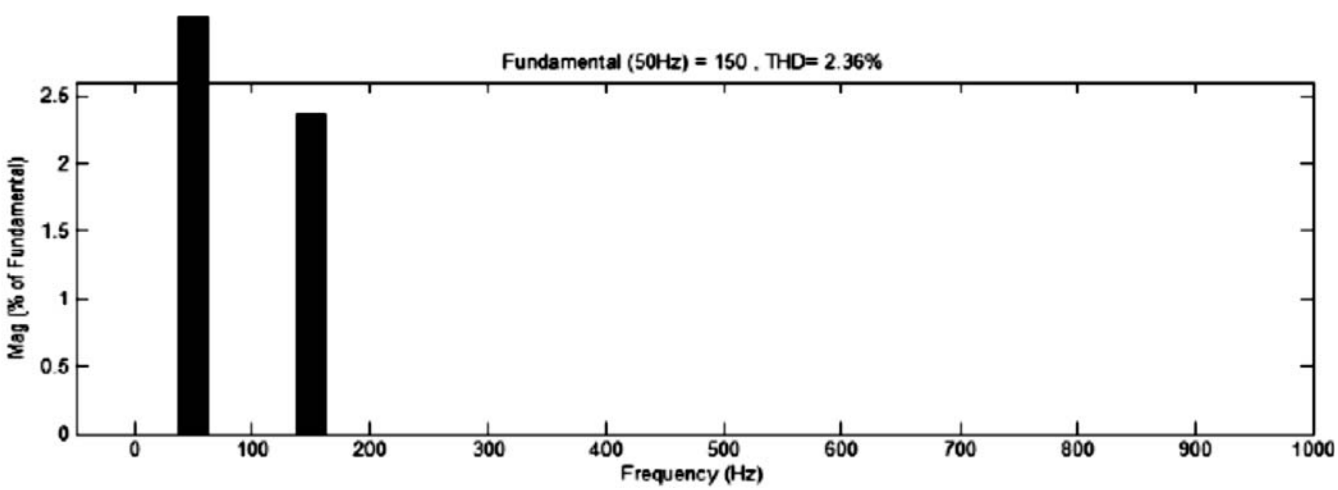


Fig. 16. THD value reduced up to 2.36.

Table 8. Reduction THD Values of system by using 84 pulse UPQC.

Number of pulses	*THD*
12	15.22
24	7.38
48	3.8
60	3.159
84	2.36

6. CONCLUSIONS

Classification of faults and identification in a transmission line with FACTS devices is a very challenging task. the proposed a new algorithm to detect and classify the fault and identify the fault position in a transmission line with respect to a FACTS device placed in the midpoint of the transmission line. Discrete wavelet transformation and wavelet entropy calculations are used to analyze during fault current and voltage signals of the compensated transmission line. Fault classification and disturbance classification once at a time. The automated noise-suppression algorithm makes the use of the DWT techniques in PQ monitoring easy. Location of fault occurred in transmission line at which bus at what distance the fault occurred is also calculated very accurately by using wavelet technique. Disturbance identification and classification by wavelet entropy technique with accuracy of 99.7% by wavelet entropy technique. Mitigation of disturbances with less total harmonic distortion and less number of switches with Online Wavelet Transform-Based Control Strategy in UPQC and The performance of the UPQC has been evaluated under various disturbance conditions such as voltage sag in either feeder, fault in one of the feeders and load change.

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