# Wavelet Entropy Based Algorithm for Fault Detection and Classification in FACTS Compensated Transmission Line

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*Abstract:* - Distance protection of transmission lines including advanced flexible AC transmission system (FACTS) devices has been a very challenging task. FACTS devices of interest in this paper are static synchronous series compensators (SSSC) and unified power flow controller (UPFC). In this paper, a new and simple algorithm is proposed 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. The algorithm is suitable for the analysis of different types of faults. Discrete wavelet transformation and wavelet entropy calculations are used to analyze during fault current and voltage signals of the compensated transmission line. The proposed algorithm is very simple and accurate in fault detection and classification. A variety of fault cases and simulation results are introduced to show the effectiveness of such algorithm.

*Key-Words:* - Fault detection; Power systems; Wavelet transform; Entropy calculation; FACTS; SSSC; UPFC.

## 1 Introduction

In recent years, it has become more difficult to construct new generation facilities and transmission lines due to energy and environmental problems. Hence, it is required to enhance the power transfer capability of existing transmission lines instead of constructing new ones. On the other hand, FACTS devices have received more attention in transmission system operations as they can be utilized to alter power system parameters in order to control power flow. With FACTS technology, such as Static Var Compensators (SVCs), Static Synchronous Compensators (STATCOMs), Static Synchronous Series Compensators (SSSCs) and Unified Power Flow Controllers (UPFCs), etc., bus voltages, line impedances and phase angles in the power system can be flexibly and rapidly regulated. In addition, the FACTS devices have the capability of increasing transmission capabilities, decrease the generation cost and improve the security and stability of power system [1,2]. During fault, the presence of compensating devices affects steady-state and transient components of current and voltage signals which create problems with relay functionality [3,4].

Fault classification and section identification in a transmission line with FACTS devices is a very challenging task. Different attempts have been made for fault classification using wavelet transform, S-transform along with pattern recognition, the kalman filtering approach, neural network, fuzzy logic systems and support vector machines [3-11]. All these attempts were trying to classify the fault and identify the faulted section in a transmission line compensated either by series capacitor protected by metal-oxide varistor (MOV) or compensated by thyristor-controlled series compensators (TCSCs) protected by MOV or compensated by both. Some other researchers attempted to locate the fault in transmission lines compensated with UPFC using differential equations-based method [12].

In this paper, we are interested in two of the most important FACTS devices; the SSSC and the UPFC. The SSSCs are FACTS devices for power transmission line series compensation. It is a power electronic-based voltage source converter (VSC) that generates a nearly sinusoidal three-phase voltage which is in quadrature with the line current. The SSSC converter block is connected in series with the transmission line by series coupling transformer. The SSSC can provide either capacitive or inductive series compensation independent of the line current [13].

The UPFC, which has been recognized as one of the best featured FACTS devices, is capable of providing simultaneous active and reactive power flow control, as well as, voltage magnitude control. The UPFC is a combination of STATCOM and SSSC which are connected via a common DC link, to allow bidirectional flow of real power between series output terminals of SSSC and the shunt terminals of the STATCOM [2].

For the purpose of fault identification and classification, the wavelet entropy theory is applied to produce a simple and accurate algorithm. Wavelet transform (WT) has good time-frequency localization ability so it particularly adapted to analyze the singular signals caused by fault as such a transformation allows good frequency resolution at low frequencies and good time resolution at high frequencies. Wavelet transform provides theory basis for fault detection. The most effective method for fault detection is using a universal applicable quantity (UAQ) to describe the system and detect the fault. Shannon entropy is such a UAQ, and wavelet entropy (WE) is formed by combining WT and Shannon entropy together [14].

In [17] a simple algorithm was introduced to detect and classify the faults in an uncompensated transmission line based on wavelet entropy calculations. In this paper, further modification of the algorithm in [17] are made to analyze faults in FACT compensated systems. A test system is built using SIMULINK. The resulting data under different fault types and position with respect to the compensating device are analyzed. The test results show the effectiveness of the proposed algorithm.

## 2 Wavelet Transform and Entropy Calculations

Lots of fault information is included in the transient components. So it can be used to identify the fault or abnormity of equipments or power system. It can also be used to deal with the fault and analyze its reason. This way the reliability of the power system will be considerably improved.

Wavelets are mathematical functions with advantages over Fourier transforms for analysis of signal with transient features. Wavelet analysis is based on decomposition of a signal according to time-scale, rather than frequency, using basis functions with adaptable scaling properties. This method of analysis is generally referred to as multi-resolution analysis. A wavelet transform expands a signal not in terms of trigonometric polynomial but by wavelets, generated using the translation (shift in time) and dilation (compression in time) of a fixed wavelet function. The wavelet function is localized in time and frequency yielding wavelet coefficients at different scales. This gives the wavelet transform much greater compact support for analysis of signals with localized transient components [3].

Transient signals have some characteristics such as high frequency and instant break. Wavelet transform is capable of revealing aspects of data that other signal analysis techniques miss and it satisfies the analysis need of electric transient signals. Usually, wavelet transform of transient signal is expressed by multi-resolution decomposition fast algorithm which utilizes the orthogonal wavelet bases to decompose the signal to components under different scales. The approximations are the high-scale, low-frequency components of the signal produced by filtering the signal by a low-pass filter. The details are the low-scale, high-frequency components of the signal produced by filtering the signal by a high-pass filter. The band width of these two filters is equal. After each level of decomposition, the sampling frequency is reduced by half. Then recursively decompose the low-pass filter outputs (approximations) to produce the components of the next stage [15, 16].

Given a discrete signal x(n), being fast transformed at instant k and scale j, it has a high-frequency component coefficient $D_j(k)$ and a low-frequency component coefficient $A_j(k)$. The frequency band of the information contained in signal components $D_j(k)$ and $A_j(k)$, obtained by reconstruction according to [18] are as follows.

$$\begin{cases} D_j(k):[2^{-(j+1)} f_s , 2^{-j} f_s] \\ A_j(k):[0, 2^{-(j+1)} f_s] \end{cases} (j=1,2,...,m) \quad (1)$$

Where, $f_s$ is the sampling frequency.

The original signal sequence x(n) can be represented by the sum of all components as follows [18].

$$x(n) = D_1(n) + A_1(n) = D_1(n) + D_2(n) + A_2(n) = \sum_{j=1}^{J} D_j(n) + A_J(n) \quad (2)$$

For the purpose of unification, denote $A_J(n)$ by $D_{J+1}(n)$ and we get

$$x(n) = \sum_{j=1}^{J+1} D_j(n) \quad (3)$$

$D_j(n)$ represents the component of transient signal x(n) at each scale (frequency band), it is also the multi-resolution representation of the signal which can act as feature subset of classification.

During fault, the amplitude and frequency of voltage and current signals will change significantly as the system change from normal state to fault. The Shannon entropy will change accordingly but will not be capable of dealing with some abnormal signals while wavelet can. Wavelet combined entropy can make full use of localized features at time-frequency domains [15].

Various wavelet entropy measures were defined in [15] one of them was the nonnormalized Shannon entropy that will be used in this paper. The definition of nonnormalized Shannon entropy is as follows [18].

$$E_j = -\sum_k E_{jk} \log E_{jk} \quad (4)$$

Where $E_{jk}$ is the wavelet energy spectrum at scale j and instant k and it is defined as follows.

$$E_{jk} = \left| D_j(k) \right|^2 \quad (5)$$

## 3 Proposed Algorithm for Transmission Line Fault Detection and Identification

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. It becomes incapable of dealing with some abnormal signals while wavelet can. Wavelet combined entropy can make full use of localized feature at time-frequency domains. Wavelet analysis deals with unsteady signal while information entropy expresses information of the signal. That is why wavelet entropy can analyze fault signals more efficiently [14-16]. For an effective protection requirement, these changes in the signals are to be identified as fast as possible with the least number of false detection.

The proposed algorithm detects if there is a fault or the compensated system is under normal conditions such that the protective devices can operate or not. For post-fault analysis, the algorithm can also determine the position of the fault if it is after or before the compensating device. In addition, the algorithm is suitable for the analysis of both symmetrical and unsymmetrical faults such that it can determine 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, in case of unsymmetrical faults, the algorithm selects the phases involved in the fault.

The transient signals of the three phase currents and voltages are produced using the simulation model built with the power block set of the SIMULINK. A discrete wavelet transformation is performed using two level symmetric wavelet for the three phase current signals ($i_a$, $i_b$ and $i_c$) and the ground current $i_g$, where

$$i_g = i_a + i_b + i_c \quad (6)$$

The entropy of each coefficient of the four currents is then calculated. The sum of absolute entropies of such coefficients for each current is then calculated (suma, sumb, sumc and sumg). The sums related to the three phase currents are then arranged in a descending order such that the first value (maximum sum) is max1, the second value is max2 and the third value (minimum sum) is min1.

The wavelet and entropy calculation are performed also for the three phase voltages in case the algorithm detected a single line to ground fault after the compensating device. The entropy sums of the three phase voltages are used to determine which phase is included in the fault.

The proposed algorithm is applied in three main steps. First, the fault is detected then its type and position with respect to the compensating device are determined. Finally, the phases included in the fault are identified. A detailed flow chart of the proposed algorithm is shown in Fig.1.

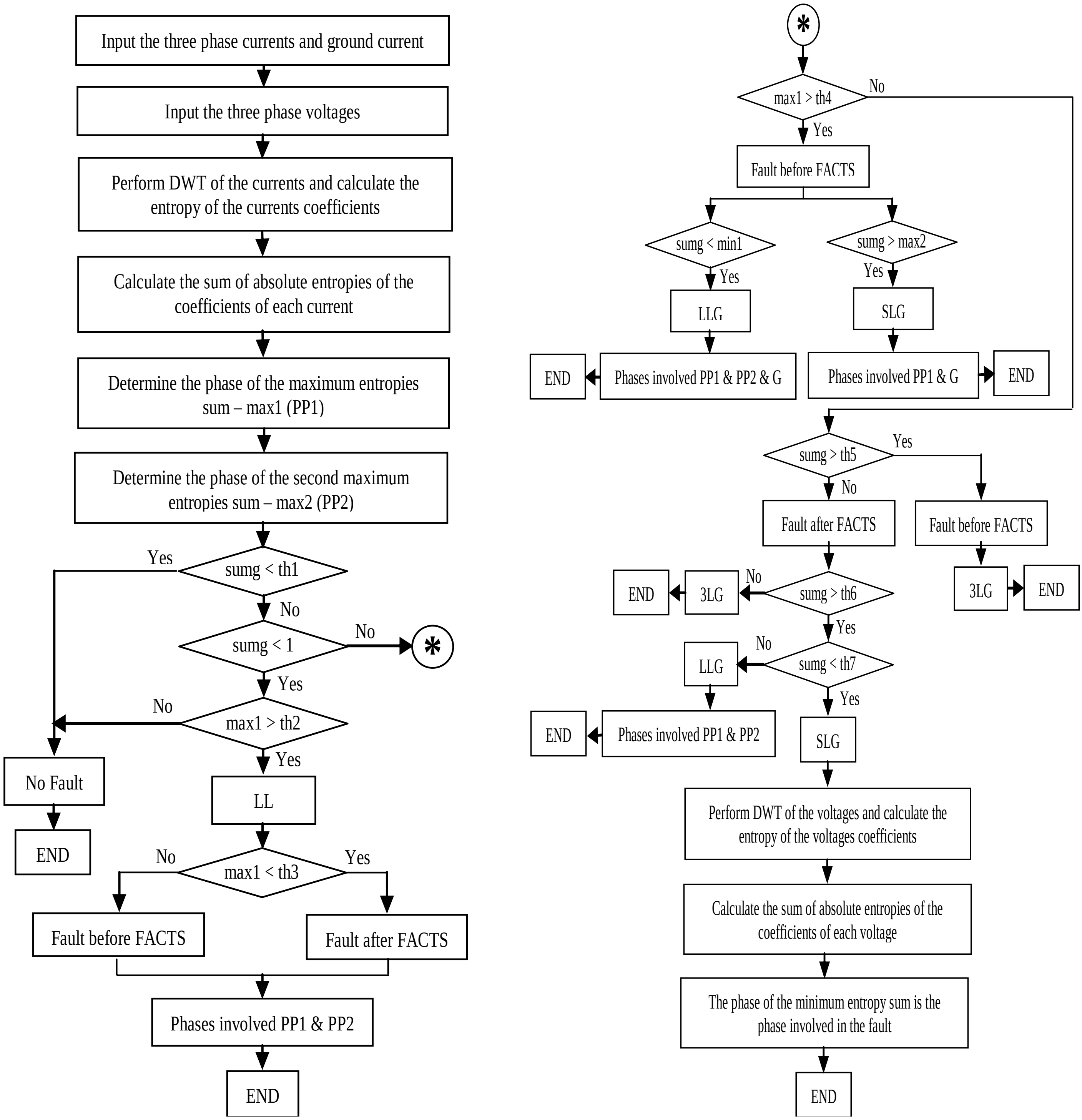


Fig.1 Flow chart of the proposed algorithm

# 4 Test System

Using the power system blockset (PSB) and the SIMULINK software, the test system is simulated. The test system is shown in Fig.2 and its data are listed in the APPENDIX.

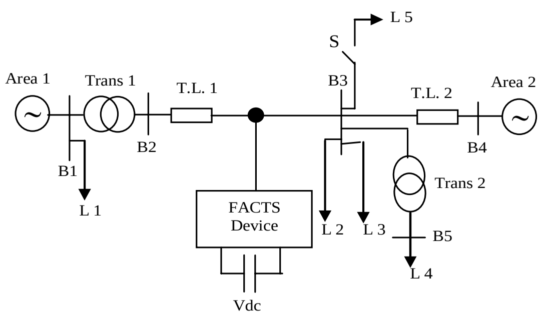


Fig.2 Power System Model

# 5 Simulation Results

As mentioned before the test system was compensated by two different FACTS devices, SSSC and UPFC. In the following the simulation results of the system with the SSSC are given first then the results with the UPFC are given next. The discrete signals of currents and voltages during fault are produced with simulation frequency was 10 kHz.

## 5.1 System Compensated with SSSC

For different fault types before and after the SSSC the sum of absolute entropies of the coefficients of each current is given in Table 1.

It was noticed that in case of SLG fault after the SSSC the selection of the phase included in fault was not possible using sum of currents entropies where sumI of the faulted phase was supposed to be the higher sum. As shown in Table 1, for an AG fault, sumc is greater than suma. Therefore, the sum of entropies of the coefficients of each of the phase voltages were calculated and the phase with the minimum sum was considered as the faulted phase. The sum of entropies of the coefficients of the phase voltages in case of a SLG fault after SSSC are given in Table 2. As shown in Table 2, suma is the smallest sum for an AG fault.

Table 1
The sum of absolute entropies of the coefficients of each current before and after SSSC

| Fault Type | Before x $10^6$ | | | | After x $10^6$ | | | |
|---|---|---|---|---|---|---|---|---|
| | suma | sumb | sumc | sumg | suma | sumb | sumc | sumg x $10^{-6}$ |
| AG | 1.48 | 1.18 | 1.06 | 2.09 | 1.05 | 0.94 | 1.15 | 26.2 |
| BG | 0.98 | 1.34 | 1.24 | 1.75 | 1.04 | 1.03 | 0.99 | 22.34 |
| CG | 1.15 | 1.02 | 1.45 | 1.88 | 0.89 | 1.08 | 1.09 | 24.57 |
| AB | 5.5 | 4.86 | 0.99 | 0.04 | 2.29 | 1.94 | 0.93 | 0.17 |
| BC | 0.91 | 3.6 | 2.96 | 0.05 | 0.88 | 1.88 | 1.54 | 0.13 |
| CA | 5.27 | 0.94 | 6.04 | 0.04 | 2.01 | 0.85 | 2.48 | 0.14 |
| ABG | 5.91 | 4.61 | 1.06 | 0.59 | 2.24 | 1.84 | 0.89 | 20.73 |
| BCG | 0.98 | 3.77 | 2.99 | 0.74 | 0.86 | 1.72 | 1.43 | 21.77 |
| CAG | 5.39 | 1.01 | 6.03 | 0.60 | 1.95 | 0.78 | 2.33 | 21.67 |
| 3LG | 8.20 | 4.64 | 5.3 | 0.33 | 2.93 | 3.17 | 2.18 | 9.78 |
| Load-ing | 0.99 | 1.02 | 1.08 | 0 | 0.99 | 1.03 | 1.08 | 0 |
| No Fault | 0.98 | 1.02 | 1.07 | 0 | 0.98 | 1.02 | 1.07 | 0 |

Table 2
The sum of entropies of the coefficients of the phase voltages in case of a SLG fault after SSSC

| Fault Type | sum a | Sum b | sum c |
|---|---|---|---|
| AG | $3.4885 x 10^3$ | $3.5568 x 10^3$ | $3.5539 x 10^3$ |
| BG | $3.5476 x 10^3$ | $3.5149 x 10^3$ | $3.5551 x 10^3$ |
| CG | $3.5418 x 10^3$ | $3.5631 x 10^3$ | $3.5022 x 10^3$ |

As a sample, the waveforms of the three phase currents in case of 3LG fault before the SSSC are shown in Fig.3. The wavelet coefficients (approximate A2, level 1 detail D1 and level 2 detail D2) of phase A current are shown in Fig.4. In the same way, the waveforms of the three phase currents in case of 3LG fault after the SSSC and the wavelet coefficients of phase A current are shown in Fig.5 and Fig.6. Also, the three phase currents for an AG fault after the SSSC and the wavelet coefficients of phase A current are shown in Fig.7 and Fig.8, respectively, while the wavelet coefficients of phase A voltage are shown in Fig.9.

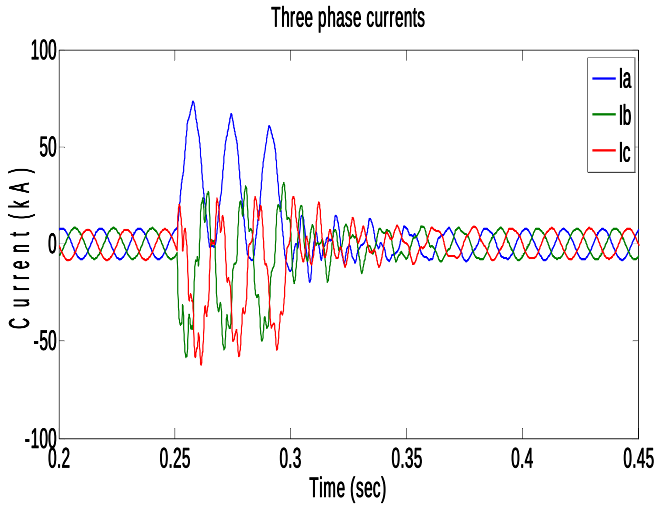


Fig.3 Three phase current waveforms during 3LG fault before the SSSC

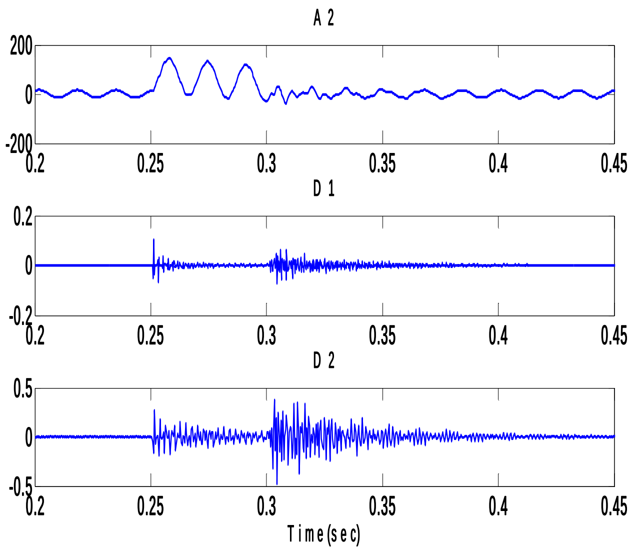


Fig.4 Approx. and details of phase A current during 3LG fault before SSSC

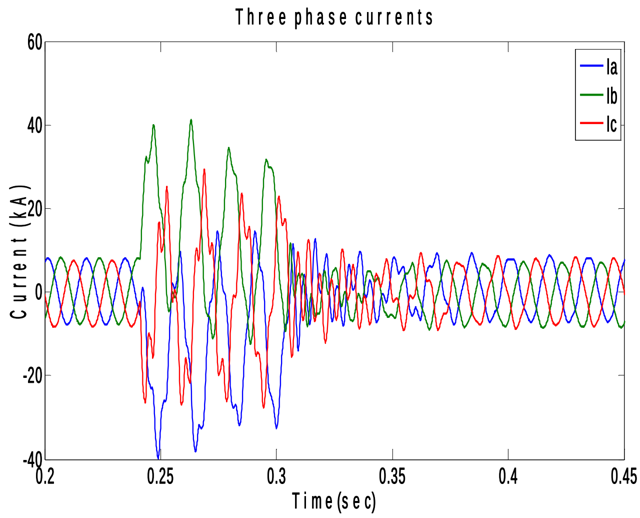


Fig.5 Three phase current waveforms during 3LG fault after the SSSC

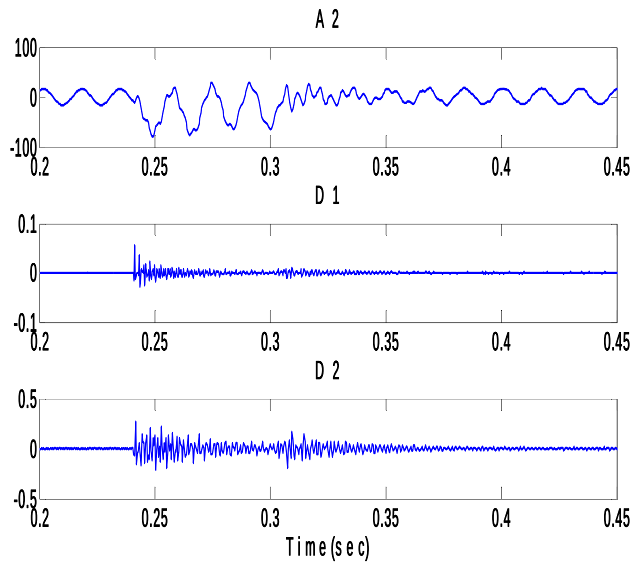


Fig.6 Approx. and details of phase A current during 3LG fault after SSSC

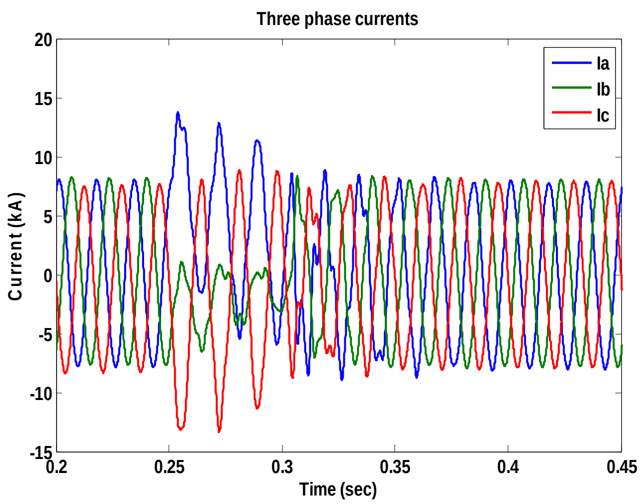


Fig.7 Three phase current waveforms during AG fault after the SSSC

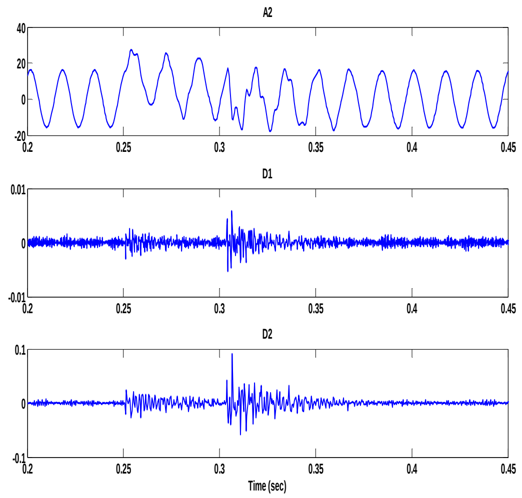


Fig.8 Approx. and details of phase A current during AG fault after SSSC

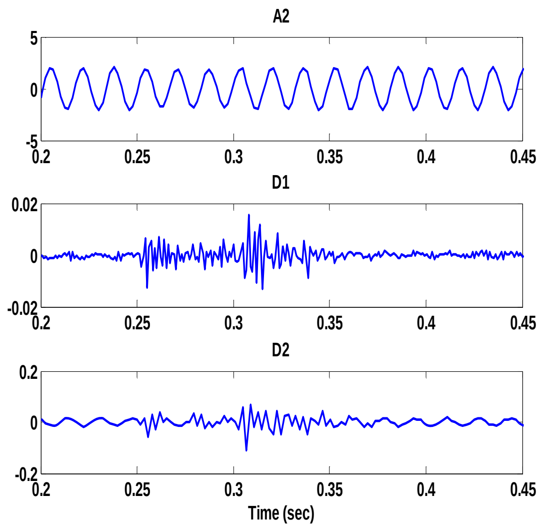


Fig.9 Approx. and details of phase A voltage during AG fault after SSSC

## 5.2 System Compensated with UPFC

For different fault types before and after the UPFC the sum of absolute entropies of the coefficients of each current is given in Table 3.

In the same way, as in case of SSSC compensation, the phases included in a SLG fault after the UPFC were determined using the voltage entropies. The sum of entropies of the coefficients of each of the phase voltages were calculated and the phase with the minimum sum was considered as the faulted phase. The sum of entropies of the coefficients of the phase voltages in case of a SLG fault after UPFC are given in Table 4.

Table 3
The sum of absolute entropies of the coefficients of each current before and after UPFC

| Fault Type | Before x $10^5$ | | | | After x $10^5$ | | | |
|---|---|---|---|---|---|---|---|---|
| | suma | sumb | sumc | sumg | suma | sumb | sumc | sumg x$10^{-5}$ |
| AG | 2.82 | 1.94 | 1.92 | 1.52 | 1.83 | 2.09 | 3.59 | 5.06 |
| BG | 1.59 | 1.79 | 2.52 | 1.79 | 2.23 | 1.76 | 2.84 | 4.05 |
| CG | 1.98 | 1.51 | 1.58 | 1.81 | 2.93 | 2.11 | 3.13 | 4.59 |
| AB | 9.98 | 8.57 | 1.82 | 0.07 x$10^{-5}$ | 4.29 | 3.58 | 1.75 | 0.002 |
| BC | 1.56 | 6.66 | 3.39 | 0.03 x$10^{-5}$ | 1.51 | 3.49 | 3.04 | 0.0001 |
| CA | 9.83 | 1.56 | 1.14 | 0.08 x$10^{-5}$ | 3.98 | 1.48 | 4.92 | 0.07 |
| ABG | 1.08 | 4.31 | 8.16 | 3.49 | 1.87 | 1.78 | 0.92 | 3.55 |
| BCG | 1.61 | 1.56 | 6.98 | 3.42 | 5.52 | 3.05 | 1.19 | 4.91 |
| CAG | 10.1 | 4.02 | 1.62 | 1.52 | 11.5 | 4.79 | 0.96 | 3.76 |
| 3LG | 15.1 | 5.53 | 8.7 | 3.75 | 10.4 | 4.5 | 0.29 | 2.29 |
| Load-ing | 1.69 | 1.69 | 1.95 | 0 | 1.69 | 1.69 | 1.95 | 0 |
| No Fault | 1.66 | 1.67 | 1.92 | 0 | 1.67 | 1.67 | 1.92 | 0 |

Table 4
The sum of entropies of the coefficients of the phase voltages in case of a SLG fault after UPFC

| Fault Type | sum a | sum b | sum c |
|---|---|---|---|
| AG | 652.423 | 673.6073 | 673.517 |
| BG | 662.1051 | 666.0345 | 674.0677 |
| CG | 661.2325 | 674.5866 | 663.4631 |

As a sample, the waveforms of the three phase currents in case of 3LG fault before the UPFC are shown in Fig.10. The wavelet coefficients (approximate A2, level 1 detail D1 and level 2 detail D2) of phase A current are shown in Fig.11. In the same way, the waveforms of the three phase currents in case of 3LG fault after the UPFC and the wavelet coefficients of phase A current are shown in Fig.12

and Fig.13. Also, the three phase currents for an AG fault after the SSSC and the wavelet coefficients of phase A current are shown in Fig.14 and Fig.15, respectively, while the wavelet coefficients of phase A voltage are shown in Fig.16.

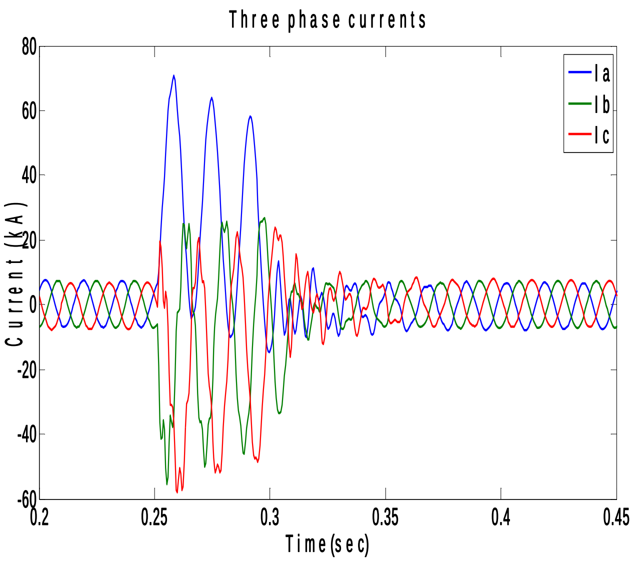


Fig.10 Three phase current waveforms during 3LG fault before the UPFC

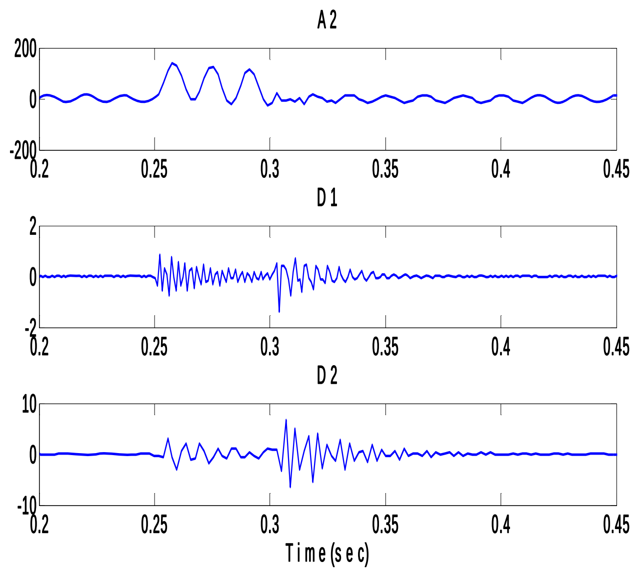


Fig.11 Approx. and details of phase A current during 3LG fault before UPFC

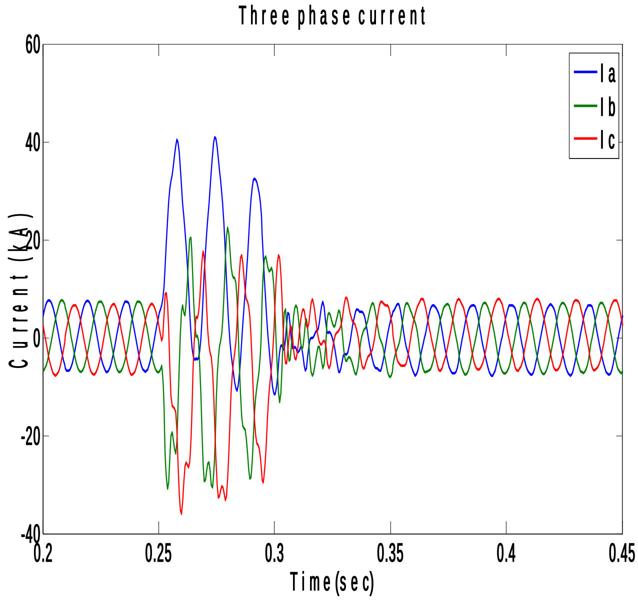


Fig.12 Three phase current waveforms during 3LG fault after the UPFC

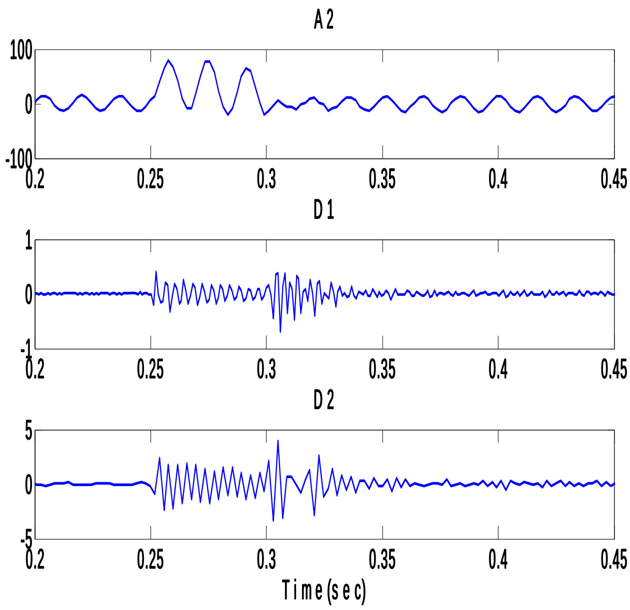


Fig.13 Approx. and details of phase A current during 3LG fault after UPFC

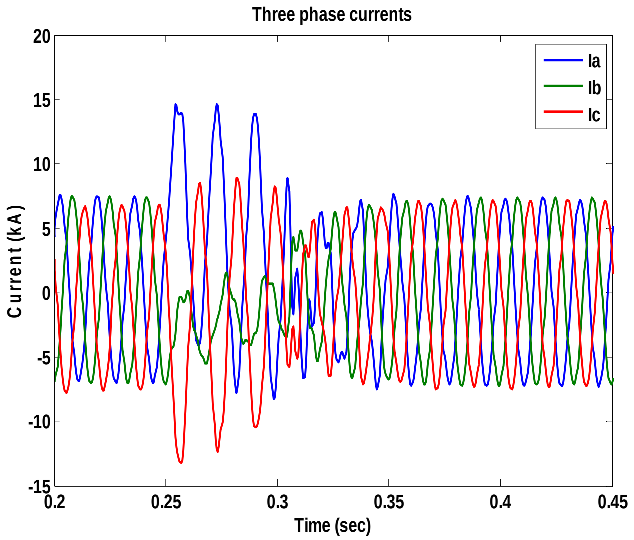


Fig.14 Three phase current waveforms during AG fault after the UPFC

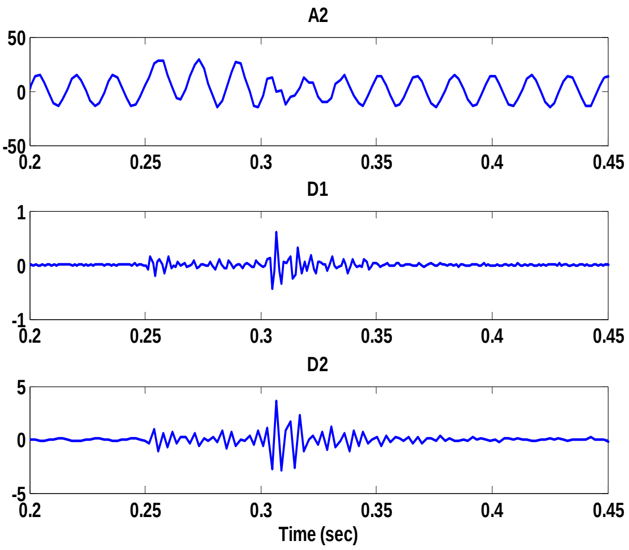


Fig.15 Approx. and details of phase A current during AG fault after UPFC

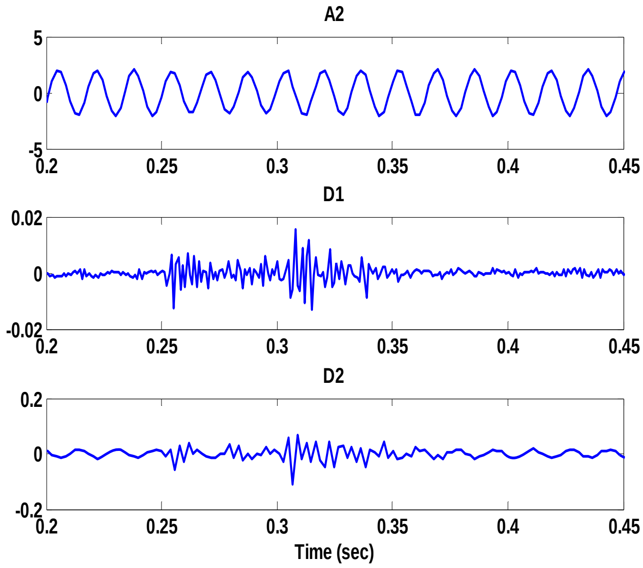


Fig.16 Approx. and details of phase A voltage during AG fault after UPFC

## 6 Conclusion

As shown in the paper, the proposed algorithm was very accurate and simple in the same time. The algorithm succeeded in detecting the fault, determining its type and position with respect to compensating device and identifying the phases included in fault. Test results showed the effectiveness of the proposed algorithm under any type and position of fault.

## Appendix

### System Parameters of Fig.2 (Base MVA = 100)

Area 1: Rated Voltage: 13.8 kV
Short Circuit Capacity: 21000 MVA

Area 2: Rated Voltage: 735 kV
Short Circuit Capacity: 30000 MVA

Transformer 1 (Δ/Y): Rated Voltage: 13.8/735 kV
Rated Power: 2100 MVA
Leakage Impedance: 0.002+j 0.08 pu

Transformer 2 (Y/Y): Rated Voltage: 735/230 kV
Rated Power: 300 MVA
Leakage Impedance: 0.002+j 0.15 pu

Transmission Lines:
Resistance: 0.001 pu
Reactance: 0.0195pu

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 Impedance: 0.002+j 0.05 pu

Shunt Coupling Transformer(Y/Y):
Rated Voltage: 138/735 kV
Rated Power: 100 MVA
Leakage Impedancde: 0.002+j 0.15 pu

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