ORIGINAL CONTRIBUTION

# Fuzzy-Wavelet Based Double Line Transmission System Protection Scheme in the Presence of SVC

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**Abstract** Increasing the power transfer capability and efficient utilization of available transmission lines, improving the power system controllability and stability, power oscillation damping and voltage compensation have made strides and created Flexible AC Transmission (FACTS) devices in recent decades. Shunt FACTS devices can have adverse effects on distance protection both in steady state and transient periods. Severe under reaching is the most important problem of relay which is caused by current injection at the point of connection to the system. Current absorption of compensator leads to overreach of relay. This work presents an efficient method based on wavelet transforms, fault detection, classification and location using Fuzzy logic technique which is almost independent of fault impedance, fault distance and fault inception angle. The proposed protection scheme is found to be fast, reliable and accurate for various types of faults on transmission lines with and without Static Var compensator at different locations and with various incidence angles.

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## Introduction

The performance of a power system is affected by faults on transmission lines, which result in the interruption of power flow. Quick detection of faults and accurate estimation of fault location, help in faster maintenance and restoration of supply resulting in improved economy and reliability of power supply. Flexible AC Transmission is a technology that provides the requisite corrections of transmission functionality in order to fully utilize existing transmission systems thus in turn minimizes the gap between the stability and thermal limits [1] and poses a challenge in conventional distance protection scheme. The conventional distance relay is likely to over reach or under reach depending upon the mode, type of FACTS devices incorporate in the transmission system [2]. Some research has been done on the performance of the distance relay for a transmission system with different FACTS devices. The impact of FACTS devices on digital multifunctional protective relays is discussed in [3]. The investigations of the existing transmission line distance protection scheme with the installation of shunt FACTS controllers [4] in the transmission line has been recently investigated and reported. The results of these investigations have shown that midpoint shunt FACTS compensation can affect the distance relays with regards to impedance measurement, phase selection and operating times. It has also been reported that there is an observation of the over-reaching and under- reaching phenomena in the presence of a midpoint SVC controllers.

Wavelet Transform (WT) is an effective tool in analyzing transient voltage and current signals associated with faults

both in frequency and time domain. Some researchers [5] have used wavelet transforms to detect the high impedance arcing faults. The investigators [6] have used Haar Wavelet to detect the faulty phases. Distance protection schemes using wavelet based phasor estimation are reported in the literature [7, 8]. Due to fast developing communication techniques, it is possible to develop communication-aided high-speed digital protection scheme, which suits the EHV transmission. Better performance can be achieved using two terminal synchronized sampling of signals.

Global Position System (GPS) based algorithms with better performance and accuracy have been proposed in the literature [9, 10]. The researchers [11] have introduced fuzzy based linguistic rules to classify the faults on transmission lines. Wavelet Multi Resolution Analysis is used for detection; classification and Fuzzy logic approach is used for the location of faults on transmission lines [12, 13].

The proposed protection scheme is an application of wavelet transforms for the detection, classification and location of faults on Transmission lines. A Global Positioning System (GPS) synchronizing clock is used to sample three phase current signals at both the ends of the transmission line over a moving window length of half cycle. The three phase current signals are analyzed with Bior1.5 wavelet to obtain detail coefficients of single decompositions. Fault indices are calculated based on the sum of local and remote terminal detail coefficients, and compared with threshold values to detect and classify the faults. The estimation of fault location Fuzzy inference systems is employed, that makes use of first level approximate decompositions of the currents of local end obtained with Bior1.5 wavelet. The proposed algorithm is tested successfully for different locations and types of faults as well as for various incidence angles and fault impedances.

## Wavelet Analysis

Wavelet transform has been introduced rather recently in mathematics, even though the primary ideas that lead to this development have been around for a longer period of time. It is a linear transformation much like the Fourier transforms, however with one important difference: it allows time localization of different frequency components of a given signal. In the case of the wavelet transform, the analyzing functions, which are called wavelets, will adjust their time-widths to their frequency in such a way that, higher frequency wavelets will be very narrow and lower frequency ones will be broader. This property of multi resolution is particularly useful for analyzing fault transients which contain localized high frequency components superimposed on power frequency signals. Thus, wavelet

transform is better suited for analysis of signals containing short lived high frequency disturbances superimposed on lower frequency continuous waveforms by virtue of this zoom-in capability.

Given a function f(t), its continuous wavelet transform (WT) be calculated as follows:

$$WT(a,b) = \frac{1}{\sqrt{a}} \int x(t) g\left(\frac{t-b}{a}\right) dt$$

where $a$ and $b$ are the scaling (dilation) and translation (time shift) constants respectively, and $\Psi$ is the wavelet function which may not be real as assumed in the above equation for simplicity.

Wavelet analysis which is a mathematical tool for Signal analysis is used to detect the type of fault occurring on the transmission line. The wavelet transform is introduced as a method for analyzing electromagnetic transients associated with power system faults and switching. This method, like the Fourier transform, provides information related to the frequency composition of a waveform, thus it is more appropriate than the familiar Fourier methods for the non-periodic, wide-band signals associated with electromagnetic transients.

Wavelet Transform provides a new tool for signal processing. In contrast to the traditional Fourier analysis that averages frequency features both in time and frequency. Wavelets allow the decomposition of a signal into different levels of resolution (frequency octaves). By this a much better signal characterization and a more reliable discrimination can be obtained. So it is an ideal technique for studying transient signals [14, 15]. The multi resolution Analysis of Wavelet can be utilized effectively in analyzing the power system transients [16]. The feature extraction property of Wavelets Transforms is exploited in the area of protection of transmission line to detect and classify the faults on various components.

## Proposed System to study

Figure 1 shows the single line diagram of the system considered along with the various blocks of the proposed scheme. Two 200-km parallel 500 kV transmission lines terminated in two 9,000-MVA short-circuit levels (SCLs) sources and the angle difference 20° with Static Var compensator is installed in the middle of the second transmission line. A 300-Mvar Static Var Compensator (SVC) regulates voltage on a 6,000-MVA 500-kV system. The SVC consists of a 500 kV/16-kV 333-MVA coupling transformer, one 109-Mvar Thyristor Controlled Reactor bank (TCR) and three 94-Mvar Thyristor Switched Capacitor banks (TSC1 TSC2 TSC3) connected on to the secondary side of the transformer.

**Fig. 1** Power system physical model with SVC
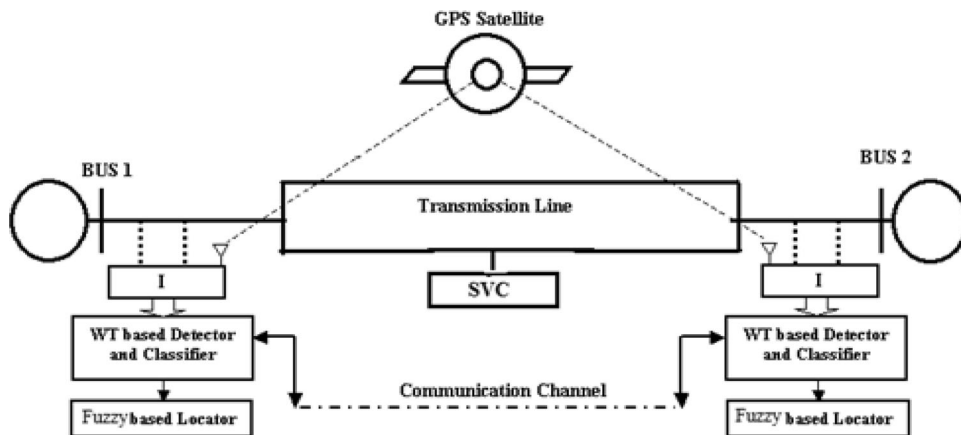


## Detection and Classification of FAULTS

Synchronized sampling of three phase currents at both the ends is carried out with the help of a GPS satellite. The detail D1 coefficients used for detection and classification of the type of fault are transmitted through the fiber-optic communication channel to the remote end. The three phase currents of the local terminal are analyzed with Bior1.5 mother wavelet to obtain the detailed coefficients ($D1_1$) at bus 1 over a moving window of half cycle length. These $D1_1$ coefficients are then transmitted to the remote end. The detailed coefficients received from the remote end at bus2 ($D1_2$) are subtracted from the local detail coefficients ($D1_1$) to obtain effective D1 coefficients ($D1_E$). The Fault Index ($I_{f1}$) of each phase is then calculated as $I_{f1} = \Sigma |D1_E|$.

Figures 2 and 3 shows the variation of three phase currents for AG fault at 40 % of the line at bus1 and bus2. Figure 4 illustrate the variation of Fault Index for phase-A for the same fault. The variation in effective D1 coefficients of three phase currents is shown in Fig. 5.

Figures 6 and 7 show the variation of three phase currents for AG fault at 40 % of the line with SVC at bus 1 and bus 2. Figure 8 illustrate the variation of Fault Index of three phase currents for phase-A for the same fault. The variation of effective D1 coefficients of three phase currents is shown in Fig. 9.

The types of faults considered in the analysis are L–G, L–L–G, L–L, L–L–L, faults. The simulations show that fault inception angle has a considerable effect on the phase current samples and therefore also on Wavelet transform output of post-fault signals. As the waves are periodic, it is sufficient to study the effect of inception angle in the range of 0°–180° in steps of 20°. The complete flow chart for the shunt fault classification is as shown in Fig. 10.

Figures 11, 12 and 13 illustrates the fault index of three phase currents for transmission line at varying distances of 20–200 km in steps of 20 km for LG, LLG and LLLG fault for incidence angle of 40° and 60°. Figures 14, 15 and 16
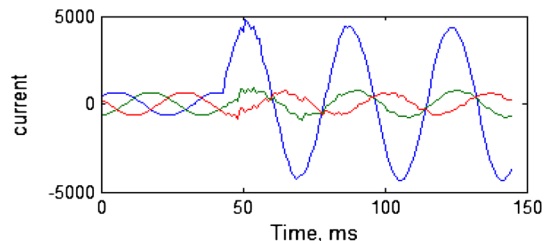


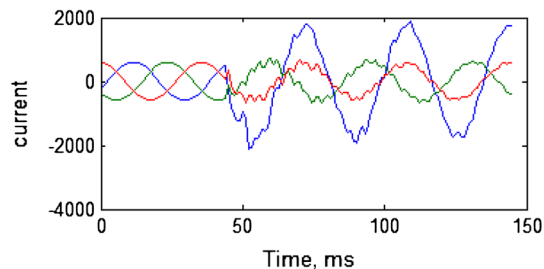**Fig. 2** Three phase currents at Terminal-1 of AG fault at 40 % of the line



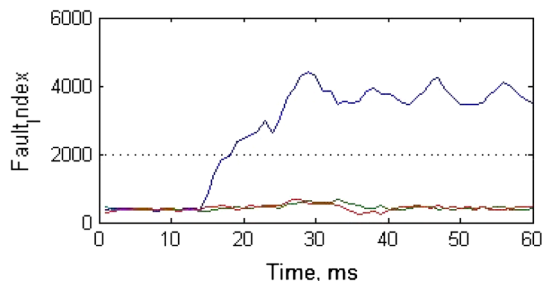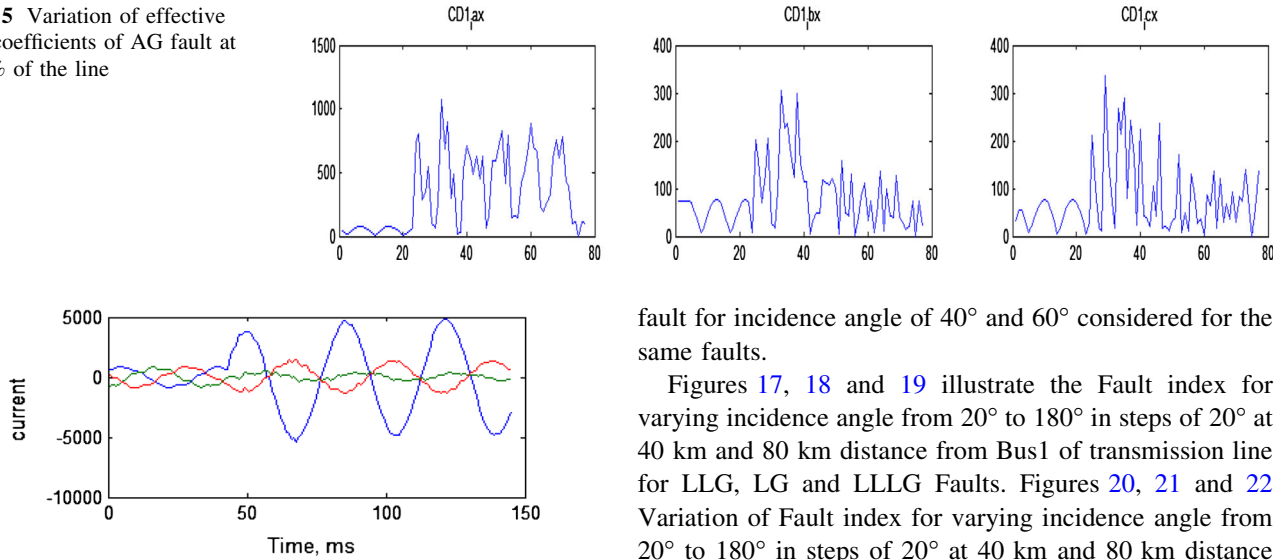**Fig. 3** Three phase currents at Terminal-2 of AG fault at 40 % of the line



**Fig. 4** Variation of fault indices of three phase currents for Phase-A fault at 40 % of the line

shows the fault index of three phase currents with SVC are placed at middle of the transmission line varying distances of 20–200 km in steps of 20 km for LG, LLG and LLLG

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**Fig. 5** Variation of effective D1 coefficients of AG fault at 40 % of the line





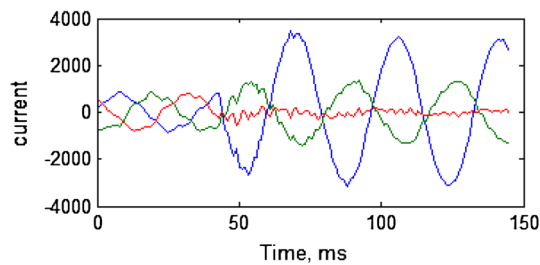**Fig. 6** Three phase currents at Terminal-1 of AG fault at 40 % of the line with SVC



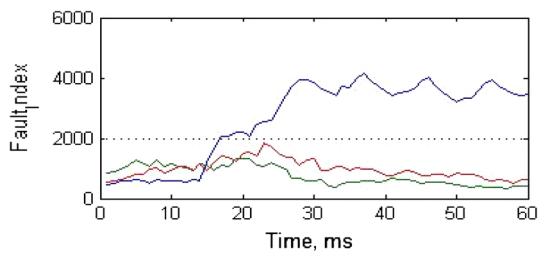**Fig. 7** Three phase currents at Terminal-2 of AG fault at 40 % of the line with SVC



**Fig. 8** Variation of fault Indices of three phase currents for Phase-A fault at 40 % of the line with SVC
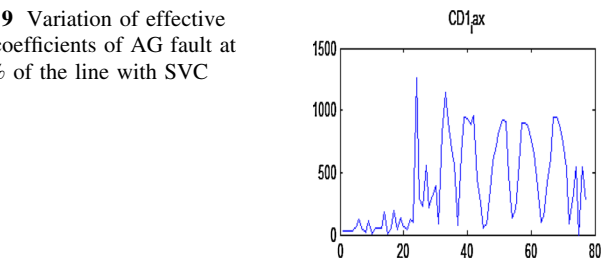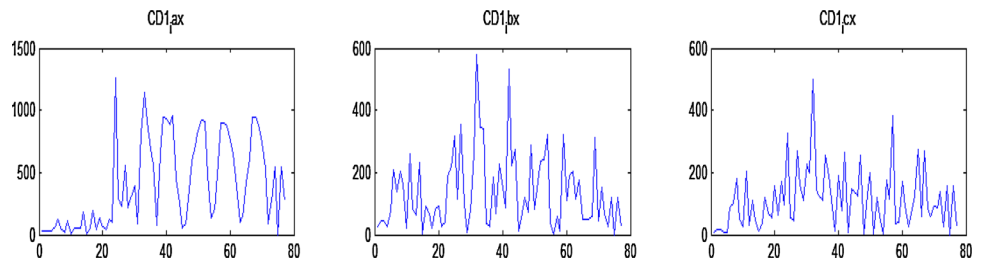
**Fig. 9** Variation of effective D1 coefficients of AG fault at 40 % of the line with SVC



fault for incidence angle of 40° and 60° considered for the same faults.

Figures 17, 18 and 19 illustrate the Fault index for varying incidence angle from 20° to 180° in steps of 20° at 40 km and 80 km distance from Bus1 of transmission line for LLG, LG and LLLG Faults. Figures 20, 21 and 22 Variation of Fault index for varying incidence angle from 20° to 180° in steps of 20° at 40 km and 80 km distance from Bus1 of transmission line with SVC for LG,LLG and LLLG Fault.

It is observed that the fault index of faulty phase is large compared to those of healthy phases. Thus the number of faulty phases is determined by comparing the Fault Index $(I_{f1})$ with a Fault Threshold $(I_{th})$.The proposed algorithm has been tested for all types of faults, considering variations in fault locations and fault incidence angles ($\theta$) in the range 0°–180°. This scheme is proved to be effective in detecting and classifying various types of faults.

## Estimation of Fault Location

Subsequent to detection and classification of fault, estimation of fault location is carried out using Fuzzy logic. For this purpose the sum of approximate coefficient obtained from multi-resolution analysis is summed up with Bior1.5 mother wavelet, and over a half cycle window is obtained. The wavelet MRA values, local and remote end corresponding to post-fault phase currents of both ends are the basis for fault location and therefore these values are used as inputs to the fuzzy inference system(FIS), as shown in Fig. 23.

Each input variable is quantized for location of fault from bus-1 and bus-2 into five linguistic variables namely
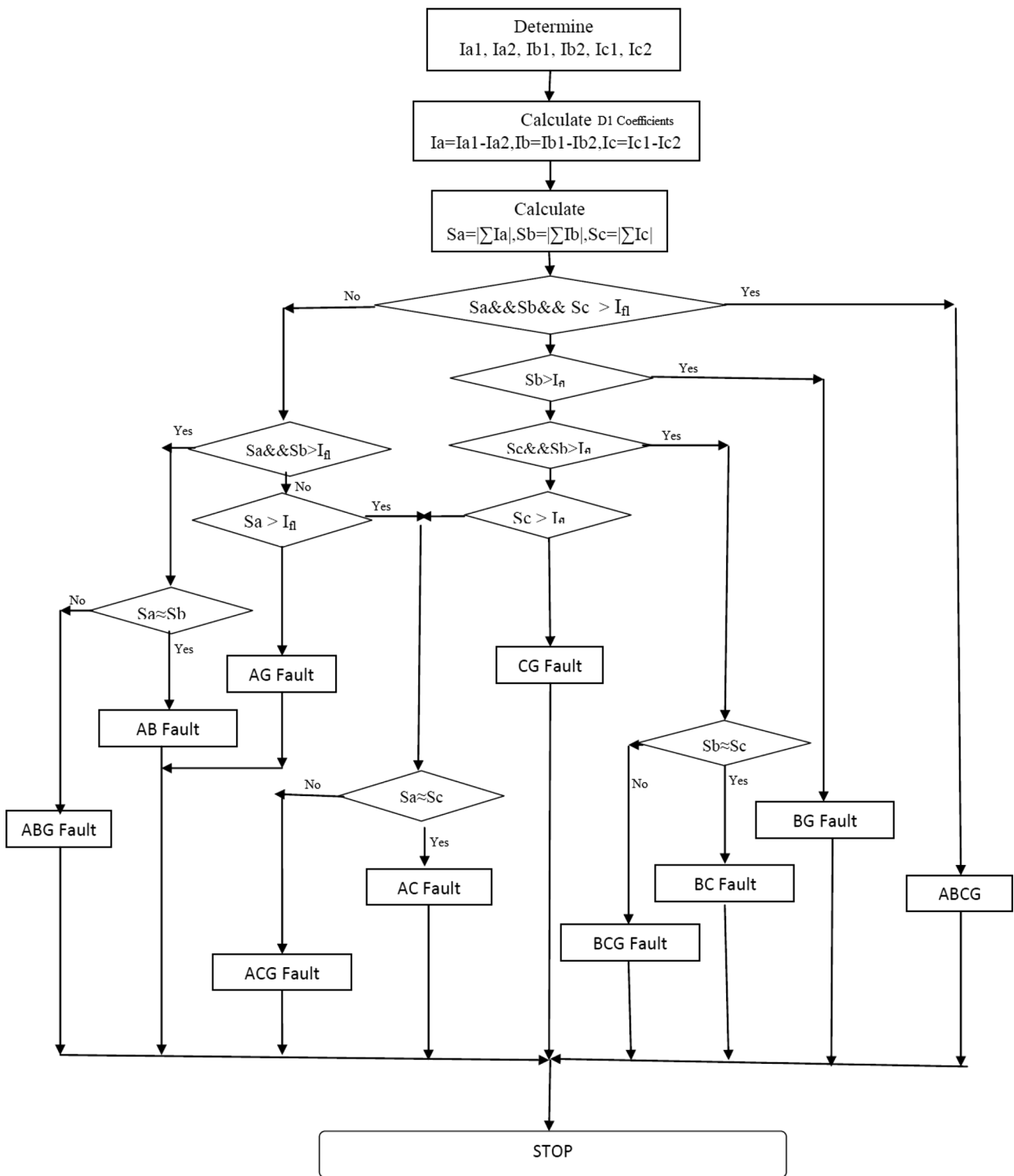
**Fig. 10** Flow chart for the fault classification

VS, VL, L, H, VH and VHH for the above mentioned universe of discourse spanning over 0–1 as shown in Figs. 24 and 25. The output variable is the length of the transmission line. This universe of discourse is divided into

linguistic variables according to different fault zones. For the case study, universe of discourse is quantized into 11 linguistic variables, namely Z1–Z10 corresponding to ten fault zones, as shown in Fig. 26.

**Fig. 11** Variations in fault indices of three phase currents for AG fault for incidence angle of 40° and 60°
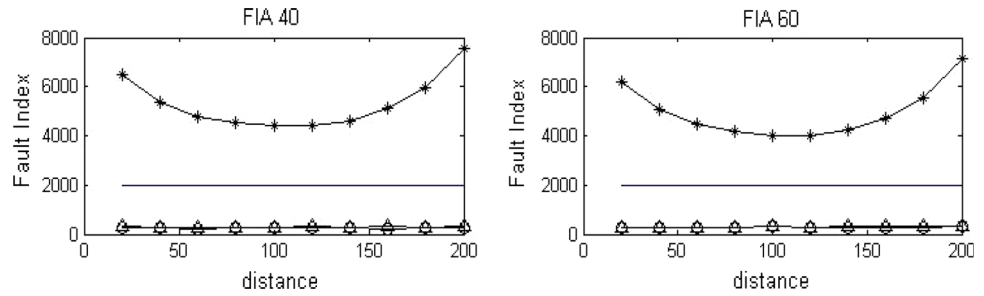


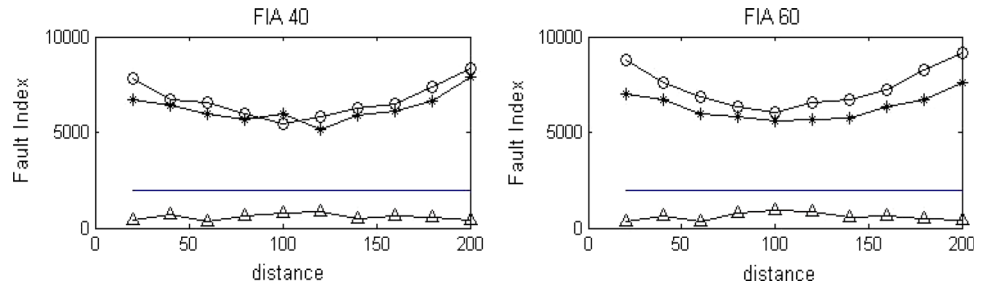**Fig. 12** Variations in fault indices of three phase currents for ABG fault for incidence angle of 40° and 60°



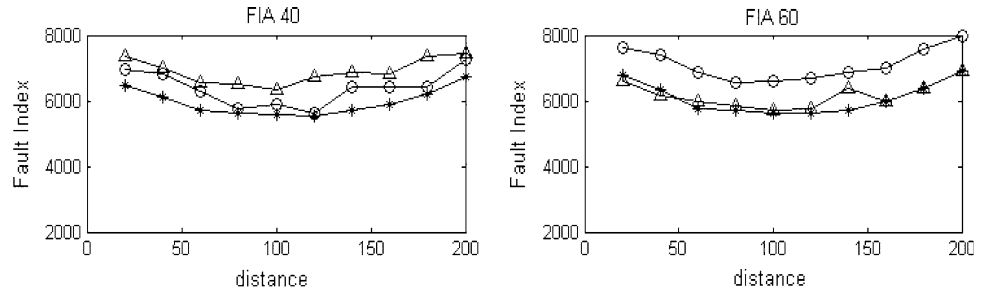**Fig. 13** Variations in fault indices of three phase currents for ABCG fault for incidence angle of 40° and 60°



**Fig. 14** Variations in fault indices of three phase currents for AG fault at incidence angle of 40° and 60° of transmission line with SVC
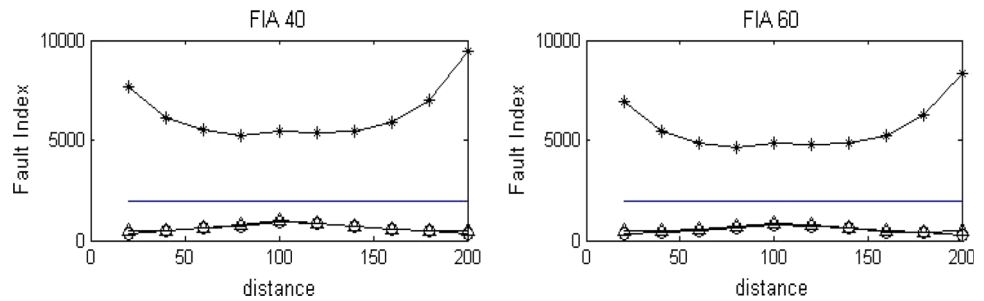


**Fig. 15** Variations in fault indices of three phase currents for ABG fault for incidence angle of 40° and 60° of transmission line with SVC
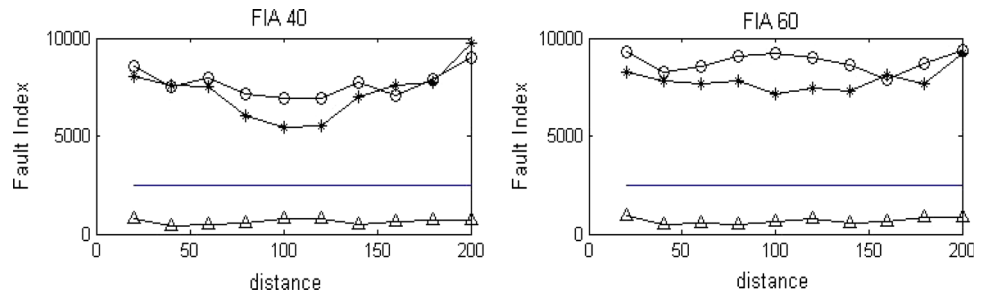
**Fig. 16** Variations in fault indices of three phase currents for ABCG fault for incidence angle of 40° and 60° of transmission line with SVC
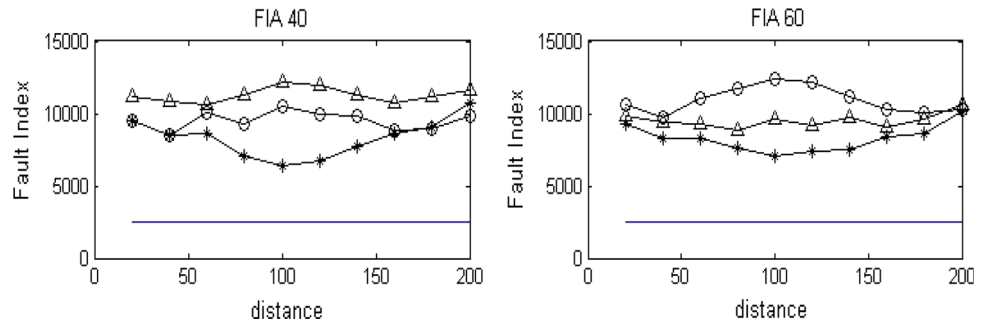


**Fig. 17** Variation of fault Indices for varying incidence angle at AG Fault distance 40 km and 80 km from Terminal-1
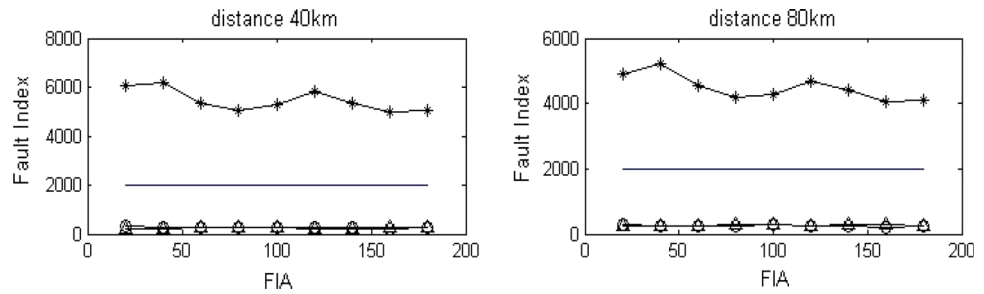


**Fig. 18** Variation of fault Indices for varying incidence angle at ABG fault distance 40 km and 80 km from Terminal-1
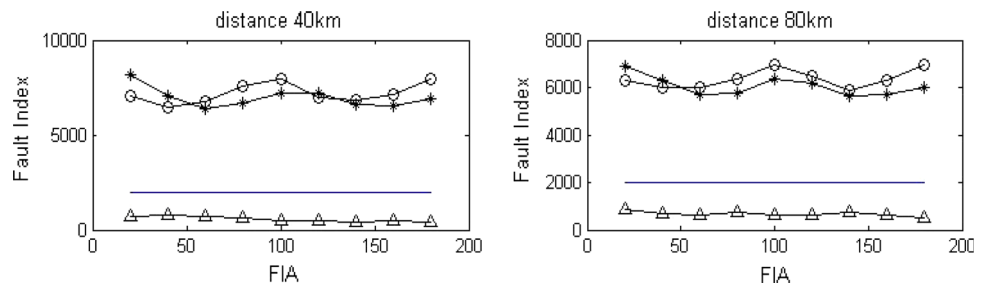


**Fig. 19** Variation of fault Indices for varying incidence angle at ABCG fault distance 40 km and 80 km from Terminal-1
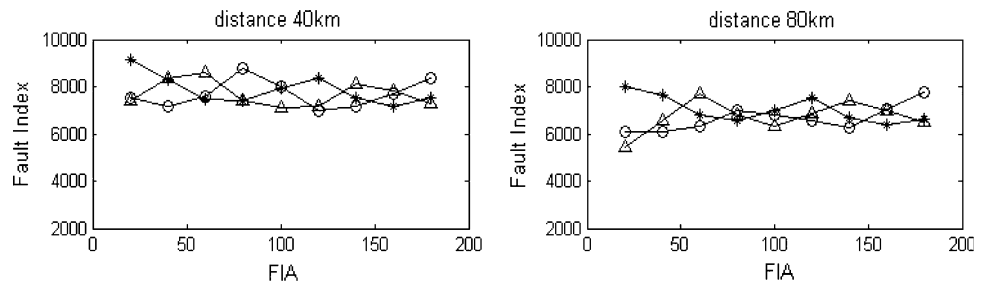


**Fig. 20** Variation of fault indices for varying incidence angle at AG fault distance 40 km and 80 km from Terminal-1 of transmission line with SVC

**Fig. 21** Variation of fault Indices for varying incidence angle at ABG fault distance 40 km and 80 km from Terminal-1 of transmission line with SVC
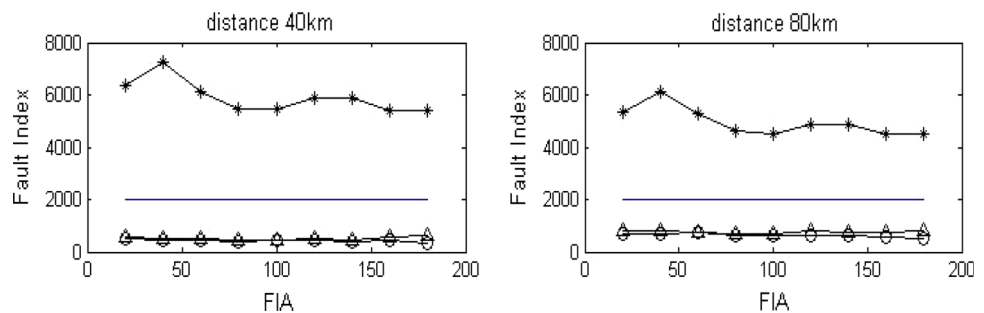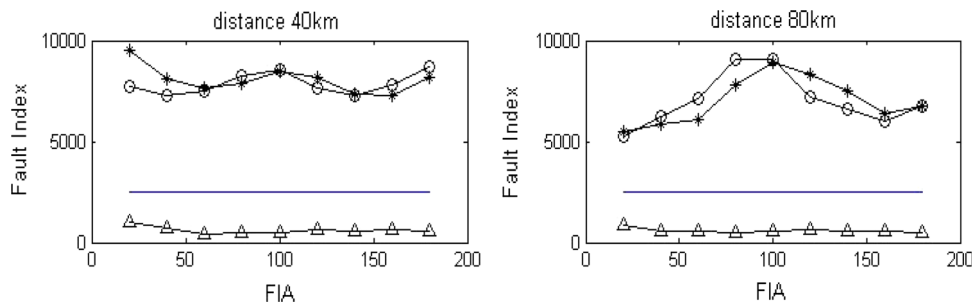


**Fig. 22** Variation of fault Indices for varying incidence angle at ABCG fault distance 40 km and 80 km from Terminal-1 of transmission line with SVC
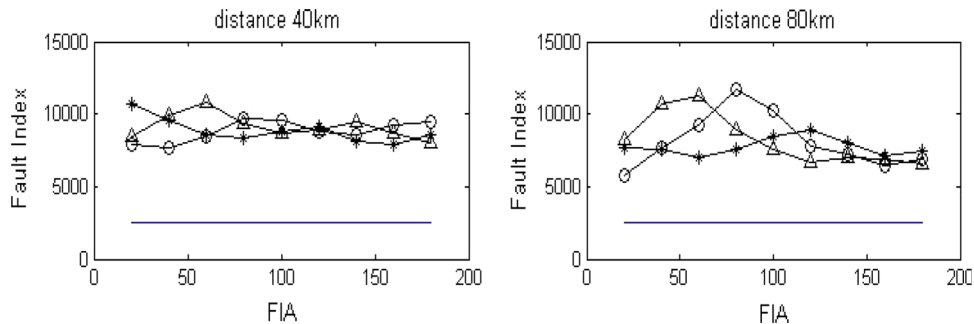


**Fig. 23** Fuzzy inference system editor for location fault on transmission line with SVC
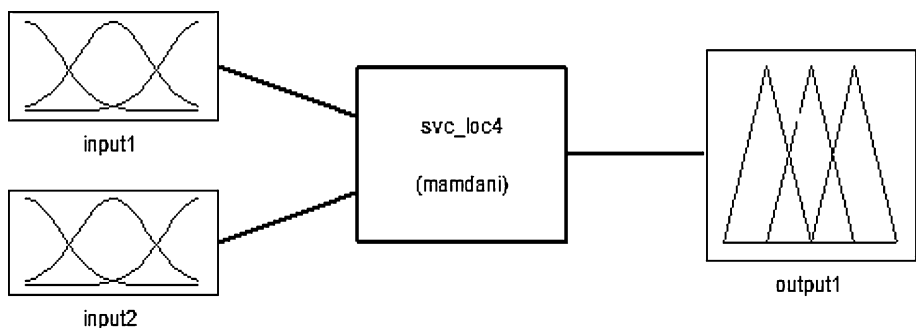


**Fig. 24** Input variable for location of fault on transmission line with SVC from Bus1
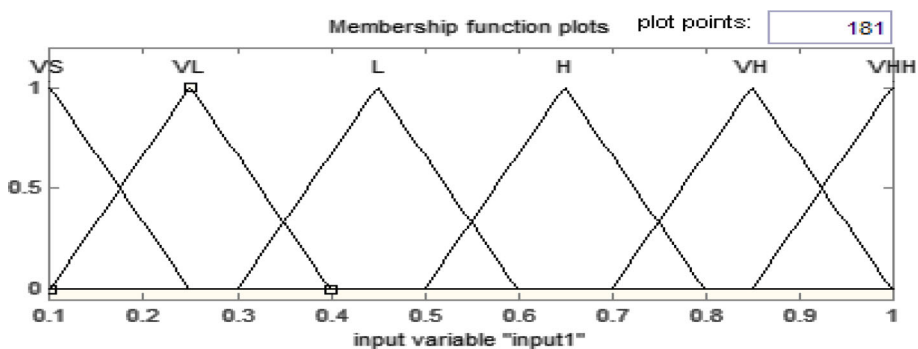


The analyses of fault distance estimation using Fuzzy Interfacing System of transmission line with and without UPFC are depicted in Table 1.

The inputs are combined together based on the expert opinion, all through possible rules are framed and then the output is defuzzified using bisector rule to get the crisp value of Distance. Simulation studies were carried out considering wide variations in fault location; fault inception angle, fault resistance and load angle for different types of fault have proved the validity of the proposed approach.

**Fig. 25** Input variable for location of fault on transmission line with SVC from Bus2
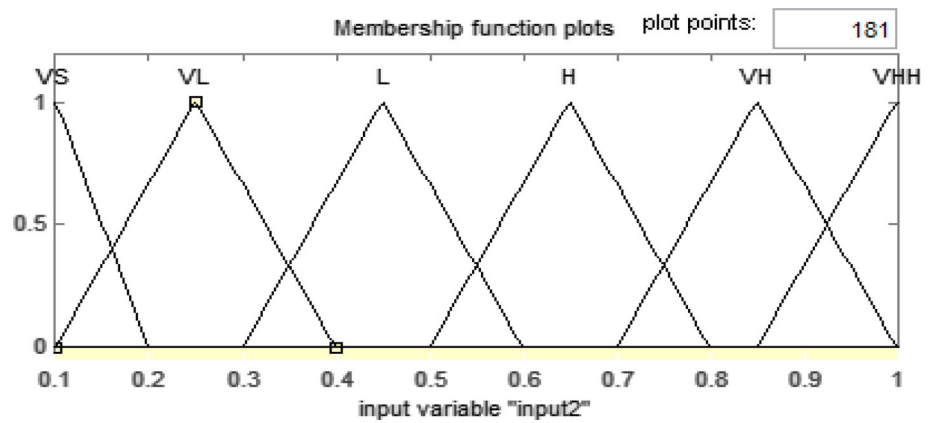


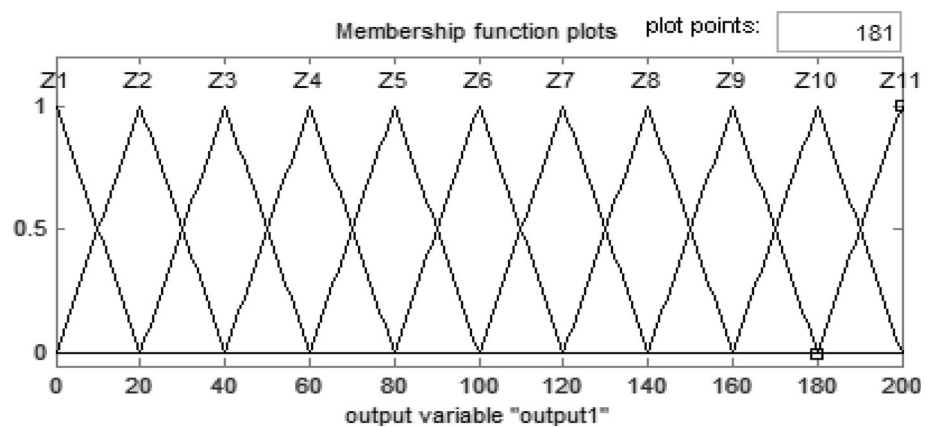**Fig. 26** Output variable for location of fault distance on transmission line with SVC from Bus1



**Table 1** Fuzzy based fault location analysis of transmission line

| Fault type | Actual distance | Transmission line | | | Transmission line with SVC | | |
|---|---|---|---|---|---|---|---|
| | | Fuzzy distance | Error distance | %Error | Fuzzy distance | Error distance | %Error |
| ag | 20 | 26 | 6 | 3 | 26 | 6 | 2 |
| | 40 | 40 | 0 | 0 | 40 | 0 | 0 |
| | 80 | 80 | 0 | 0 | 80 | 0 | 0 |
| | 100 | 110 | 5 | 2.5 | 104 | 4 | 2 |
| | 130 | 132 | 2 | 1 | 130 | 0 | 0 |
| | 160 | 160 | 0 | 0 | 158 | −2 | −1.0 |
| bg | 20 | 24 | 4 | 2 | 24 | 4 | 2 |
| | 40 | 40 | 0 | 0 | 44 | 4 | 2 |
| | 80 | 82 | 2 | 1 | 80 | 0 | 0 |
| | 100 | 110 | 10 | 5 | 106 | 6 | 3 |
| | 130 | 134 | 4 | 2 | 130 | 0 | 0 |
| | 160 | 160 | 0 | 0 | 164 | 4 | 2 |
| bc | 20 | 26 | 6 | 3 | 26 | 6 | 3 |
| | 40 | 40 | 0 | 0 | 38 | −2 | −1 |
| | 80 | 80 | 0 | 0 | 80 | 0 | 0 |
| | 100 | 110 | 10 | 5 | 100 | 0 | 0 |
| | 130 | 130 | 0 | 0 | 130 | 0 | 0 |
| | 160 | 160 | 0 | 0 | 156 | −4 | −2 |
| abcg | 20 | 28 | 8 | 4 | 22 | 2 | 1 |
| | 40 | 38 | −2 | −1 | 40 | 0 | 0 |
| | 80 | 80 | 0 | 0 | 80 | 0 | 0 |
| | 100 | 106 | 6 | 3 | 102 | 2 | 1 |
| | 130 | 130 | 0 | 0 | 130 | 0 | 0 |
| | 160 | 160 | 0 | 0 | 156 | 4 | 2 |

## Conclusions

The conventional distance relay is likely to over reach or under reach depending upon the mode, type of FACTS devices incorporate in the transmission system can be rectified by wavelet based multi-resolution analysis approach that is applied for effective detection, classification and location of faults in transmission lines. Fault location can be estimated with a fair degree of accuracy from the approximate decomposition of phase currents of local end buses using Fuzzy Inference system. This scheme is proved to be unaffected by the presence of SVC by testing the protection scheme on same transmission system without SVC. The proposed protection scheme is found to be fast, reliable and accurate for various types of faults on transmission lines with and without flexible AC transmission control device such as SVC at different locations and with various incidence angles.

## References

1. L. Gyugyi, in *Unified Power Flow Control Concept for Flexible AC Transmission Systems*. IEEE Proceedings of the 5th International Conference on AC and DC Power Transmission Conference, London, UK, issue 345, pp. 19–26, 1991
2. X. Zhou, H. Wang, R.K. Aggarwal, Performance evaluation of a distance relay as applied to a transmission system with UPFC. IEEE Trans. Power Deliv. **21**(3), 1137–1147 (2006)
3. M. Khederzadeh, in *The Impact of FACTS Devices on Digital Multifunctional Protective Relalys*. IEEE PES Transmission Distribution Conference Exhibition, vol. 3, pp. 204–2048, 2002
4. T.S. Sidhu, R.K. Verma, P.K. Gangadharan, F.A. Albasri, G.R. Ortiz, Performance of distance relays on shunt-FACTS compensated transmission lines. IEEE Trans. Power Deliv. **20**(3), 1837–1845 (2005)
5. C.-H. Kim, H. Kim, Y.-H. Ko, S.-H. Byun, R.K. Aggarwal, A.T. Johns, A novel fault-detection technique of high-impedance arcing faults in transmission lines using the wavelet transform. IEEE Trans. Power Deliv. **17**(4), 921–929 (2002)
6. J.-A. Jiang, P.-L. Fan, C.-S. Chen, C.-S. Yu, J.-Y. Sheu, in *A fault detection and faulted phase selection approach for transmission lines with haar wavelet transform*. IEEE PES Transmission and Distribution Conference and Exposition 2003, 7–12 September, vol. 1, pp. 285–289, 2003
7. F. Liang, B. Jeyasura, Transmission line distance protection using wavelet transform algorithm. IEEE Trans. Power Deliv. **19**(2), 545–553 (2004)
8. A.H. Osman, O.P. Malik, Transmission line distance protection based on wavelet transform. IEEE Trans. Power Deliv. **19**(2), 515–523 (2004)
9. D. Chanda, N.K. Kishore, A.K. Sinha, A wavelet multiresolution analysis for location of faults on transmission lines. Electr. Power Syst. Res. **25**, 59–69 (2003)
10. H.Y. Li, S. Potts, A new type of differential feeder protection relay using the global positioning system for data synchronization. IEEE Trans. Power Deliv. **12**(3), 090–1099 (1997)
11. A. Ferrero, S. Sangiovanni, E. Zapitelli, A fuzzy set approach to fault type identification in digital relaying. IEEE Trans. Power Deliv. **10**(1), 169–175 (1995)
12. B. Das, J.V. Reddy, Fuzzy-logic-based fault classification scheme for digital distance protection. IEEE Trans. Power Deliv. **20**(2), 609–616 (2005)
13. O.A.S. Youssef, Combined fuzzy-logic wavelet-based fault classification technique for powersystem relaying. IEEE Trans. Power Deliv. **19**(2), 582–590 (2004)
14. R.M. Rao, A.S. Bopardikar, *Wavelet Transforms, Introduction to Theory and Applications* (Addison Wesley, 1998)
15. S. Mallat, A theory for multiresolution signal decomposition: the wavelet presentation. IEEE Trans. Pattern Anal. Mach. Intell. **11**(7), 674–693 (1989)
16. J. Liang, S. Elangovan, J.B.X. Devotta, A wavelet multiresolution analysis approach to fault detection and classification in transmission lines. EPSR **30**(5), 327–332 (1998)