Open Access Journal

Journal of Power Technologies 99 (1) (2019) 49–57

journal homepage:papers.itc.pw.edu.pl

A Fuzzy Logic System to Detect and Classify Faults for Laboratory Prototype Model of TCSC Compensated Transmission Line

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Abstract

In this paper, an expert system-based fault detection and classification scheme is developed for a laboratory prototype model of TCSC compensated long transmission line (thyristor controlled series compensator). The equivalent model of laboratory prototype system is simulated in MATLAB Simulink. An expert system based on fuzzy logic is developed by using three-phase voltage and current signals from single end measurements. Obtained voltage and current signals are pre-processed with Discrete Fourier Transform (DFT) to obtain the fundamental component of these signals. Further zero sequence current and obtained fundamental voltage and current signals are used to develop a fuzzy inference system (FIS) for shunt fault detection and classification task. There are three different FISs developed for three individual phases of the transmission system and one FIS is developed for zero sequence current signal, which provides ground involvement information. The combined binary output of the developed four FISs provides fault classification. The performance of the developed FISs is rigorously tested with the variation of different fault parameters, and different location of the TCSC. The simulated results indicate that the proposed scheme performance is reliable in its zone of protection.

Keywords: FACTS; TCSC; Fuzzy Logic; DFT; Fault Detection; Fault classification; Power transmission,

1. Introduction

Flexible AC transmission system (FACTS) devices have been deployed increasingly in modern transmission line networks to enhance the performance of transmission networks. Series-compensated devices such as a fixed series capacitor (FSC) and thyristor controlled series compensator (TCSC) have been installed in order to increase transmittable power, to increase system stability, to increase voltage control and to minimize transmission losses [1]. Despite these advantages of series compensated transmission lines, conventional distance relays are prone to mal-operation in the presence of such devices. Conventional distance relaying experiences overreach in the case of FSC as well as TCSC. Moreover, dynamic control action of series flexible AC transmission system (FACTS) such as TCSC affects both steady-state and transient components of voltage and current signals at the relaying point. Therefore, it is a challenge to ensure reliable protection of series FACTS compensated transmission lines. Performance evaluation of distance relay in the presence of FACTS devices and some solutions have been discussed in [2–7]. In spite of conventional impedance based schemes, soft-computing based different algorithms have been proposed to protect FACTS compensated transmission lines in the last decade, which are suitable for non-linear and complex problems. A variety of machine learning and soft computing techniques have been utilized for fault analysis in TCSC compensated transmission lines. The artificial neural network (ANN) is considered one of the best AI methods and finds many applications in power systems fault studies such as fault classification, fault direction estimation, fault phase identification, fault section estimation and fault location, as presented in [8–11]. Neuro-fuzzy for fault classification and location in TCSC compensated transmission line is presented in [12]. Application of Discrete Wavelet Transform (DWT) and fuzzy logic (FL) for fault classification is discussed in [13]. Post-fault analysis such as fault section identification and fault classification utilizing support vector machine (SVM) is reported in [14–18]. S-transform and logistic model tree (LMT) for fault classification and section identification is dealt with in [18]. Fault location utilizing ANN and fuzzy logic for TCSC compensated transmission line is discussed in [19, 20]. Another technique based on Fisher Information is applied to power system fault detection in [21].

The methods based on training either ANN, SVM, DT, combined neuro-fuzzy and ANN-wavelet are time-

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consuming and increase the computational complexity. This paper presents an expert system approach to detecting and classifying all shunt faults for a laboratory model of a TCSC compensated transmission line. Fuzzy logic based relaying algorithms are developed by considering a wide variation in fault parameters such as fault type, fault location, and fault resistance. It is implemented by membership functions and fuzzy rules. Fuzzy membership functions can take different shapes depending on the designer's preference or experience. These classification techniques are comparatively simple, as they only require some linguistic rules. The fuzzy logic considers the three phases current and voltage signals for faulty phase detection and zero sequence current to determine ground associated fault. The proposed logic detects and classifies faults at a maximum delay of one cycle.

2. Sample System

The laboratory prototype model of the TCSC compensated line is shown in Fig. 1. Three phase input supply is provided through either 415 V, 15 A, 5 kVA three-phase auto-transformers or a three-phase DC motor driven 415 V, 500 VA alternator. The transmission line is the pi equivalent model of a 180 km line equally divided into 18 sections of 10 km each. Each section is a pi model with a series combination of resistance and inductance and equally divided shunt capacitance. Corresponding values of transmission line parameter are given in Appendix A. A series capacitor is connected with the thyristor controlled reactor (TCR) in parallel, a combination of these devices termed TCSC. The control action of TCSC is provided with the DSP controller (TMS320F2812). A bypass switch is provided in the laboratory model to bypass the TCSC model from the network so that it works as an uncompensated transmission line. The controller provides three operating regions for the TCSC operation i.e. capacitive region, resonance region, and inductive region. All three operating regions can be obtained in either open loop control or closed loop control by changing the firing angle α of the thyristor valve. Operation of TCSC in the resonance region is avoided; that said, the capacitive region is the operating region used most. The main purpose of the laboratory prototype model is to analyze the voltage and current signals and their behavior during different fault conditions in conditions of either a TCSC compensated transmission line or an uncompensated transmission line. To create a fault in a transmission line, two fault creator switches are used: one is for all line to ground associated fault, the other is for line to line faults. Two multifunction meters are used to measure the values of voltage, current, active power, reactive power and power factor of the source bus and load bus. An over-current relay is used on the source side to protect the sensitive thyristor valve and other controller devices. An equivalent model of 180 km, 50 Hz transmission line compensated with TCSC was simulated in MATLAB software [22]. Fig. 2 shows the single line diagram of the transmission line compensated with source end (BUS-1) TCSC. Thevenin equivalent voltage sources and source impedances are denoted with S1 and Z1 at BUS-1 and load is connected at BUS-2 respectively. The detailed parameters of the transmission line and TCSC are given in Appendix A. It is possible to increase the transfer capability of existing power transmission systems at a lower investment cost and with a shorter installation time compared to building new, additional lines using series compensation. TCSC provides powerful means of controlling and increasing power transfer level of the system by varying the apparent impedance of a specific transmission line. Change of impedance of TCSC is achieved by changing the thyristor controlled inductive reactance of inductors connected in parallel to the capacitor. TCSC can operate in a capacitive or inductive mode, although the latter is rarely used in practice. As the impedance of the controlled reactor, $X_L(\alpha)$, is varied from its maximum (infinity) toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, $X_{TCSmin}= X_C = 1/\omega C$, (and thereby the degree of series capacitive compensation) until parallel resonance at $X_C = X_L(\alpha)$ is established and X_{TCSmax}theoretically becomes infinite. Decreasing $X_L(\alpha)$ further, the impedance of the TCSC, $X_{TCSC}(\alpha)$ becomes inductive, reaching its minimum value of $X_L X_C/(X_L- X_C)$ at $\alpha = 0$, where the capacitor is in effect bypassed by the TCR. Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor, X_L, is smaller than that of the capacitor, X_C, the TCSC has two operating ranges around its internal circuit resonance one is capacitive and other is inductive

3. Proposed Fuzzy Based Fault Detection and Classification

Fuzzy logic is a logical system, which is an extension of multi-valued logic. However, in a wider sense, fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with un-sharp boundaries in which membership is a matter of degree. Even in its narrower definition, fuzzy logic differs both in concept and substance from traditional multi-valued logical systems. In this paper, the fuzzy logic based expert system is developed for detection and classification of all shunt faults in a laboratory prototype model of a TCSC compensated long transmission line. A power transmission system with a line length of 180 km is initially considered as uncompensated and, further, TCSC is considered in a different location of the transmission line. Different shunt faults with varying fault parameters are then introduced at different locations. In each, simulated and recorded voltage and current signals are analyzed for the maximum and minimum range of magnitude. Based on the different ranges of the voltage and current magnitude values or variation in both voltage and current signal, a two input variable is decided. To map these input variables with the output space in FIS, Mamdani type with triangular membership function is used. A different rule base is designed to map input space to output space. After obtaining the input variables, a fuzzy logic expert system is applied to detect and classify the fault type as shown in

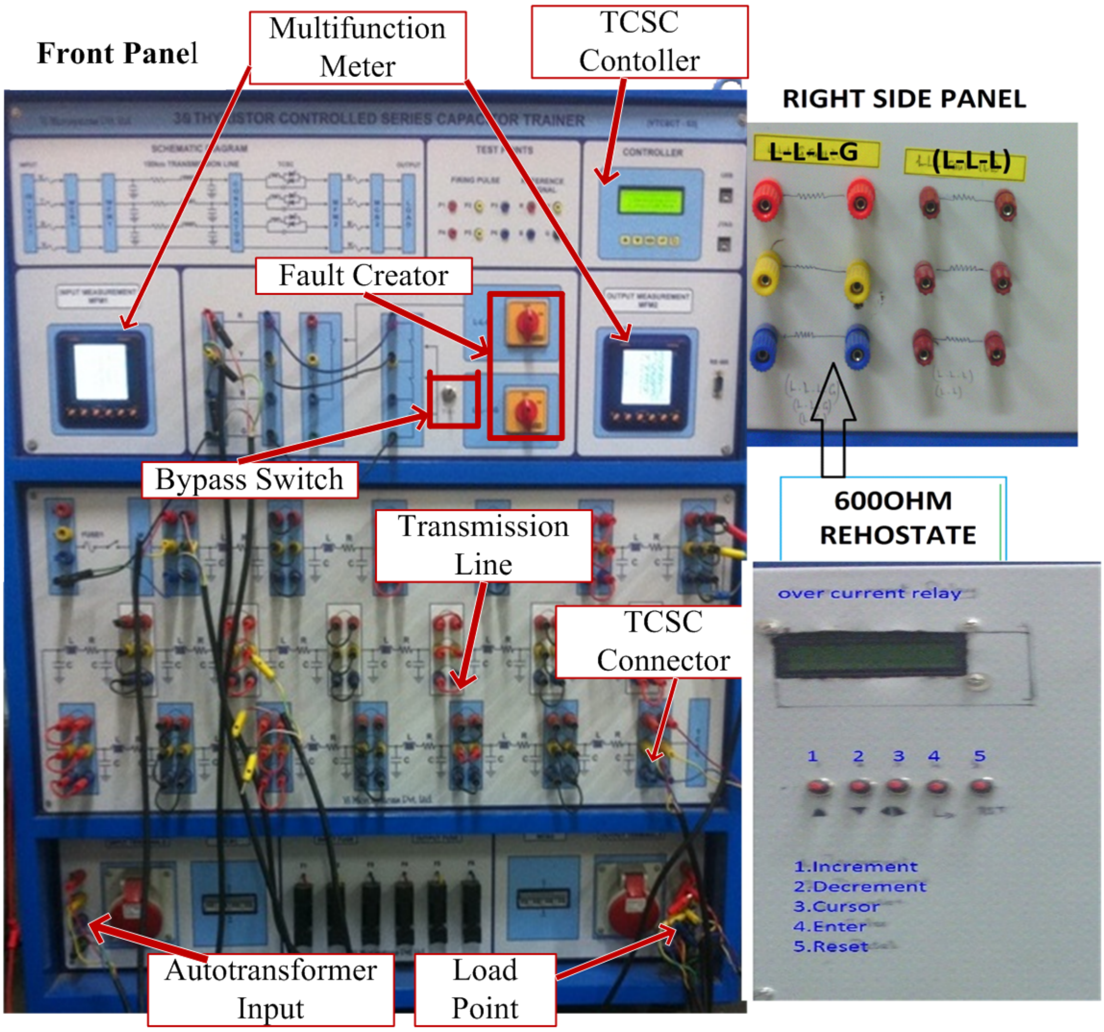

Figure 1: Prototype Model of TCSC Connected 180km long Transmission Line

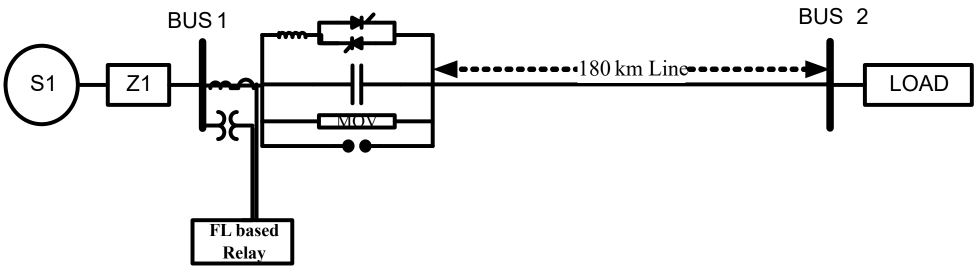

Figure 2: Single line diagram of TCSC compensated transmission network

Table 1: Ranges of the membership function

Input Variables	Membership Function	Ranges of Fundamental signal Magnitude
Voltage	MF1 (Low)	[0, 100, 170]
	MF2 (Med)	[150, 180, 200]
	MF3 (High)	[200,300,400]
Current	MF1 (Low)	[0, 1, 2.1]
	MF2 (Med)	[2.1, 2.7, 4.1]
	MF3 (High)	[3, 6, 10]
Zero Se-quence Current	MF1 (Low)	[0, 0.2, 0.23]
	MF3 (High)	[0.2, 2.5, 5]

Figure 3: Block diagram of the proposed algorithm

Table 2: Rule base of FIS

Parameter	V_{LOW}	V_{MID}	V_{HIGH}
I_{LOW}	Low	Low	Low
I_{MID}	High	High	High
I_{HIGH}	High	High	High

Fig. 3. The fuzzy block first detects whether or not there is any fault in the respective phase. Thereafter it combines the results of all three phase and zero sequence elements to classify the fault type. The basic general layout of a fuzzy system involves fuzzification, fuzzy inference system, fuzzy rule base and defuzzification. In the fuzzification stage, crisp members are mapped into the fuzzy set. After fuzzification, the fuzzy inputs are given to the FIS, which follows the developed rule base. Finally, in the defuzzification stage, fuzzy outputs are mapped into the crisp fault type. The degree of membership function for input variable is shown in Fig. 4. There are three triangular membership functions chosen for voltage and current signal: 'Low', 'Med' and 'High'. There are two triangular membership functions for zero sequence current signal: 'Low' and 'High'. The different ranges of the membership function for the simulated system are shown in Table 1. Here, four separate FISs have been developed for fault identification and a combined output of these FISs provides the fault type classification. The input to the FIS is the fundamental component of three-phase voltage and current signals for faulty phase selection and zero sequence current signal for ground identification. Morever, the output variable is fuzzified using two triangular membership functions. The output of FIS is high (1) in case of faulty condition, otherwise low (0). Total Four outputs of FISs denote the three phases of the TCSC compensated transmission system, viz. A, B and C and G for ground. Two ranges of triangular membership function have been developed as low (0) and high (1) for the output trip logic. The rule bases used in different FISs for fault detection and classification are tabulated in Table 2.

Table 3: Rules for faulty phase identification

Sl. No.	Rules
Rule 1	If (voltage is low) and (current is low)then (trip is low)
Rule 2	If (voltage is low) and (current is high) then (trip is high)
Rule 3	If (voltage is low) and (current is med) then (trip is high)
Rule 4	If (voltage is high) and (current is low) then (trip is low)
Rule 5	If (voltage is high) and (current is high) then (trip is high)
Rule 6	If (voltage is high) and (current is med) then (trip is high)
Rule 7	If (voltage is med) and (current is low) then (trip is low)
Rule 8	If (voltage is med) and (current is high) then (trip is high)
Rule 9	If (voltage is med) and (current is med) then (trip is high)

There are 9 different rules created, based on the if-then rules for faulty phase identification, as depicted in Table 3. These rules are sufficient to discriminate between in zone and out of the zone shunt fault. All the rules are developed by considering 98% of total transmission line length in the presence of TCSC in a different location of the line section. The range of different membership function is set by analyzing the fundamental component of voltage and current signal. Approximately all possible fault type and fault parameters are varied to decide the different ranges of membership functions.

4. Results and Discussion

In this study, initially, FIS was designed in reference to a two bus system as shown in Fig. 2. Here four FISs, for fault detection and fault classification were simultaneously tested to evaluate their accuracy and reliability. Initially, the TCSC was considered in a local bus, further test results regarding the midsection of the line length and remote end were examined to test robustness and reliability of the proposed fuzzy-based scheme. In the proceeding sections, the overall performance of the proposed fuzzy-based scheme was evaluated with the obtained time domain voltage and current signals at bus 1.

4.1. Performance during line to ground fault

When an unsymmetrical fault occurs, faulty phases experience under-voltage as compared to healthy phases. The FACTS device would provide equal compensation for all three phases. Moreover, overcompensation of the healthy phase can result in an increased reactive current in healthy phases. This increased current may give rise to the possibility of incorrect phase selection in the conventional distance and current based relaying scheme. For example, TCSC operation in capacitive mode was initiated at 0.2 s and at time $t = 0.5$ s, and fault resistance of 0 Ω, a BG line to a ground fault was simulated at 5 km from bus 1. The test result of the proposed scheme for a BG internal fault is depicted in Fig. 5. Fig. 5(a) and Fig. 5(b) show the current and voltage signals during BG fault condition. It can be clearly seen from Fig. 5(a) and Fig. 5(b) that at 0.2 s when the TCSC is inserted in the system, current signals increase in all the three phases whereas voltage signals decrease respectively, because TCSC cancels some part of line reactance thereby reducing the effective line impedance. Furthermore, at 0.5s, the current signal in phase B is increased drastically and, simultaneously, the voltage signal in phase B decreases because a fault occurs. It can be seen that FIS for fault detection detects the fault within 8 ms for the fault associated near the relaying bus, as shown in Fig. 5(c), simultaneously the fault type is accurately classified, as depicted in Fig. 5(d). In the case of fault near to remote terminal (bus 2) with high resistance (100 Ω), the performance of the proposed scheme is exemplified in Fig. 6. From Fig. 6(a) and Fig. 6(b), it is clearly depicted that current and voltage signals are not significantly altered compared to the pre-fault situation and different in nature from Fig. 5(a) and Fig. 5(b) because of high resistance fault. In this situation, current and voltage signals do not vary drastically compared to low resistance fault. These cause the conventional distance relay to maloperate In the meantime, from Fig. 6(c) and Fig. 6(d) it can be clearly observed that the proposed scheme is able to detect the high resistance fault reliably in 20 ms and classify it correctly. The proposed scheme is validated for different

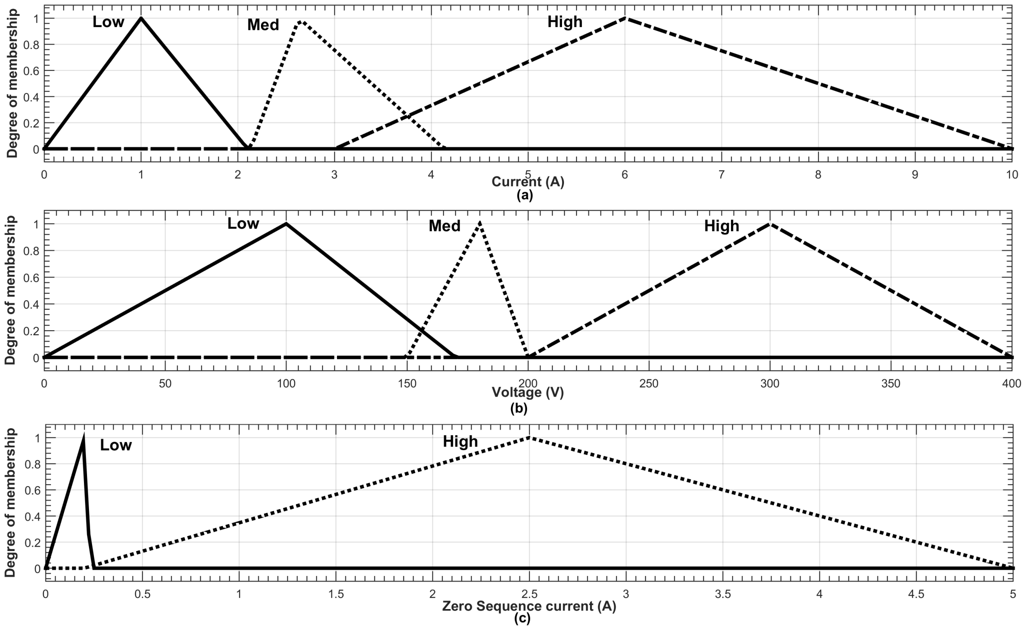

Figure 4: Degree of fuzzy membership function for input variable (a) current for phase fault detection (b) voltage for phase fault detection (c) zero sequence current for ground fault detection

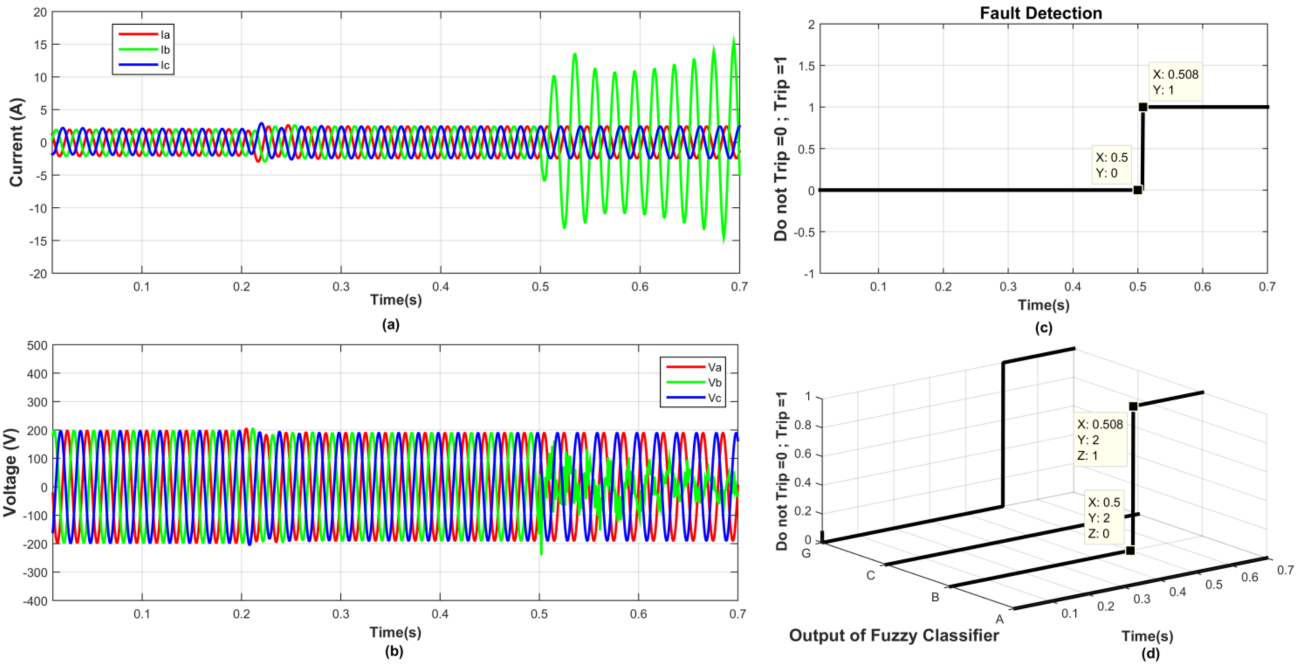

Figure 5: Performance during BG internal fault at near end (a) Current Signals (b) Voltage Signals (c) Fault detection (d) Fault classification

fault cases with the variation of fault location from bus 1 to bus 2, with varying fault resistance (0 Ω - 100 Ω). Test results illustrating the operating time with the variation of fault location and fault resistance for a single line to ground (AG) fault when TCSC is considered at local terminal are tabulated in Table 4. Fault detection time is calculated by taking the difference between the time instant when the fault is incepted and the relay initialized trip decision. All the simulation studies were performed in LENOVO idea-center desktop PC with 8-GB RAM and 3.4-GHz, Intel Core i7 processor. From Table 4, it is observed that fault detection time is within one cycle for most of the test cases, which demonstrates the ability of the proposed scheme to detect internal fault, including high resistance fault.

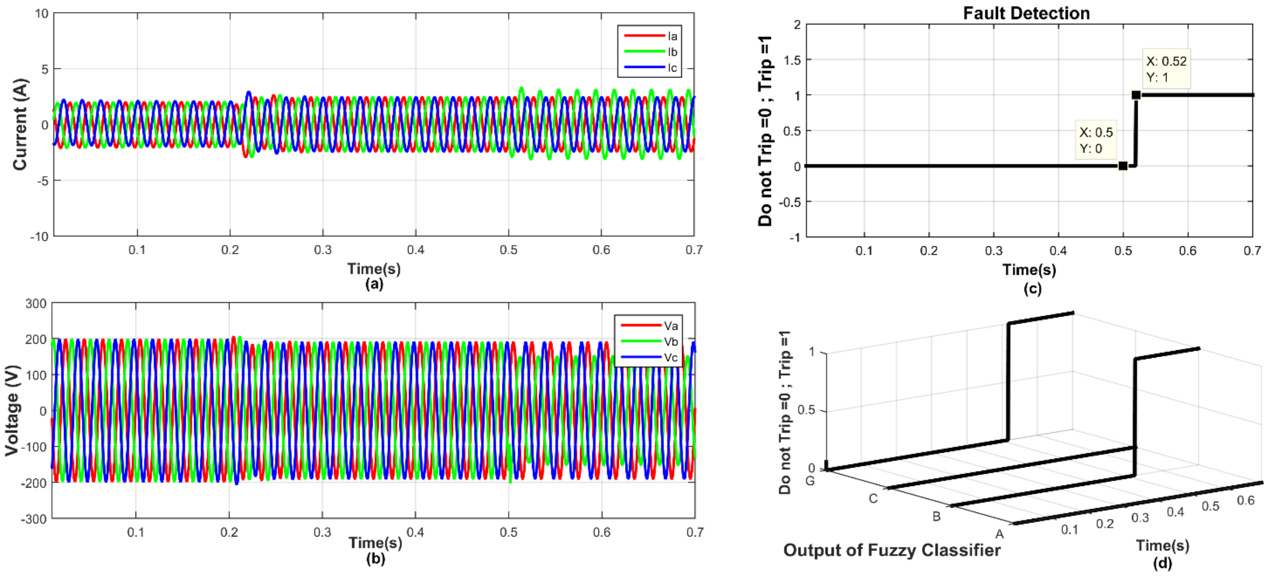

Figure 6: Performance during BG internal fault at remote end (a) Current Signals (b) Voltage Signals (c) Fault detection (d) Fault classification

Table 4: Fault detection time in case of AG fault (TCSC at Local Terminal)

Fault Location/ Fault Resistance	Fault detection time (in ms)										
	0 Ω	10 Ω	20 Ω	30 Ω	40 Ω	50 Ω	60 Ω	70 Ω	80 Ω	90 Ω	100 Ω
5 km	10	11	11	12	13	13	18	18	19	19	20
10 km	10	11	11	11	12	13	18	18	19	19	20
20 km	10	11	11	12	12	13	18	19	19	19	20
30 km	10	11	11	12	12	13	18	19	19	19	20
40 km	11	11	11	12	13	13	18	19	19	20	20
50 km	11	11	12	13	13	14	18	19	19	20	20
60 km	11	11	12	12	13	14	18	19	19	19	20
70 km	11	11	12	12	13	14	19	19	20	20	20
80 km	11	12	12	13	13	15	19	19	20	20	21
90 km	11	12	12	13	14	18	19	20	20	20	21
100 km	11	12	12	13	14	18	19	20	20	21	21
110 km	11	12	13	13	14	18	19	20	20	21	21
120 km	12	12	13	13	15	19	20	20	21	21	21
130 km	12	12	13	14	15	19	20	20	21	21	22
140 km	12	12	13	13	16	19	20	21	21	22	22
150 km	12	13	13	14	18	20	20	20	21	22	22
160 km	12	13	14	15	19	20	21	21	22	22	22
170 km	12	13	14	15	20	20	21	21	22	22	23
175 km	12	13	14	15	20	20	21	22	22	22	23

4.2. Performance during double line to ground (LLG) and double line fault (LL)

To evaluate the performance of the proposed scheme for discrimination between LLG and LL fault, an AB (double line) and ABG (double line to ground) fault have been simulated at 120 km from bus 1 when TCSC is considered in the midsection with fault resistance and FIA of 10 Ω and 0° respectively. The test result is graphically exemplified in Fig. 7 and Fig. 8. From Fig. 7 it can be clearly observed that LL fault has been detected, meanwhile, LL fault has been classified successfully, as depicted in Fig. 7(d). Test results demonstrating ABG internal fault are depicted in Fig. 8. From Fig. 7 and Fig. 8 it can be observed that the proposed fuzzy-based scheme can differentiate between LL and LLG fault. Moreover, the proposed scheme is validated for different locations of TCSC, by varying fault location and fault resistance; test results illustrating the fault detection time for BG fault when TCSC is considered at midsection and CG fault when TCSC is considered at remote terminal are tabulated in Table 5 and Table 6 respectively The reach setting of the fuzzy-based relay is 97% of the total line length when TCSC is considered at the local terminal (source end) and midsection of the transmission line length as shown in Table 4 and Table 5. It is also apparent from the test results shown in Table 4 and Table 5 that the reach of the relay is not overly affected by high resistance fault up to 100 Ω. However, from Table 6, it can be observed that when TCSC is considered at a remote terminal (load end), the reach coverage of the fuzzy-based relay is 61.6% of total line length for faults with 100 Ω of fault resistance. The reach of the fuzzy-based relay is 97% of the total line length for fault resistance up to 30 Ω. A comparison of the proposed scheme with the recently published article is tabulated in Table 7. The advantage of the fuzzy logic-based system over the compared technique is that it did not require

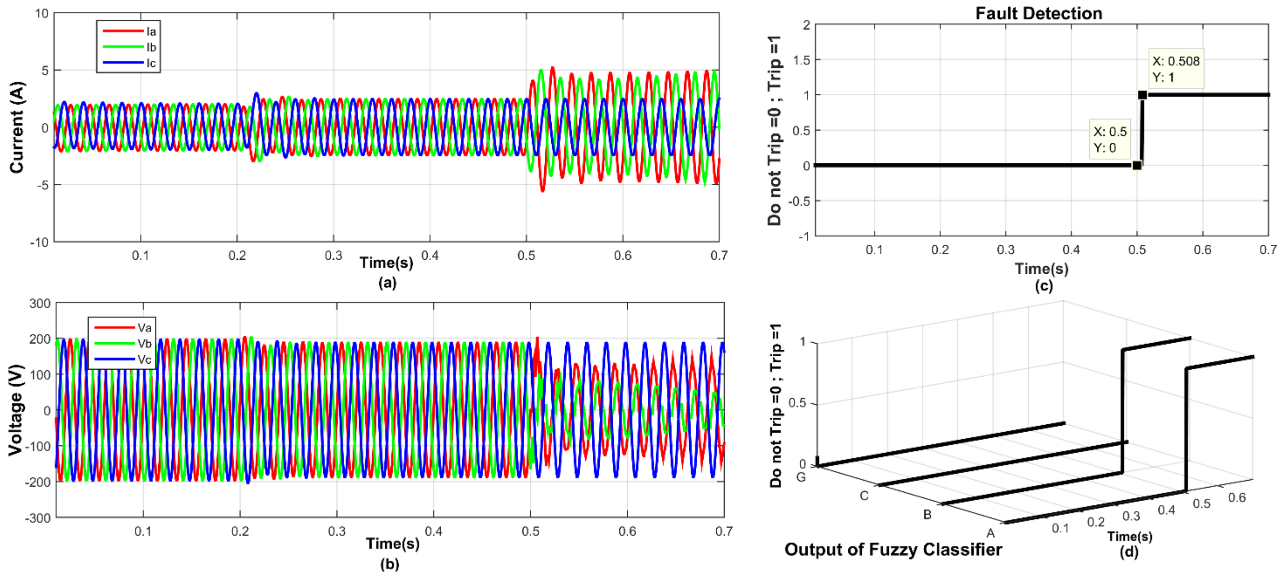

Figure 7: Performance during LL fault (a) Current (b) Voltage (c) Fault detection (d) Fault classification

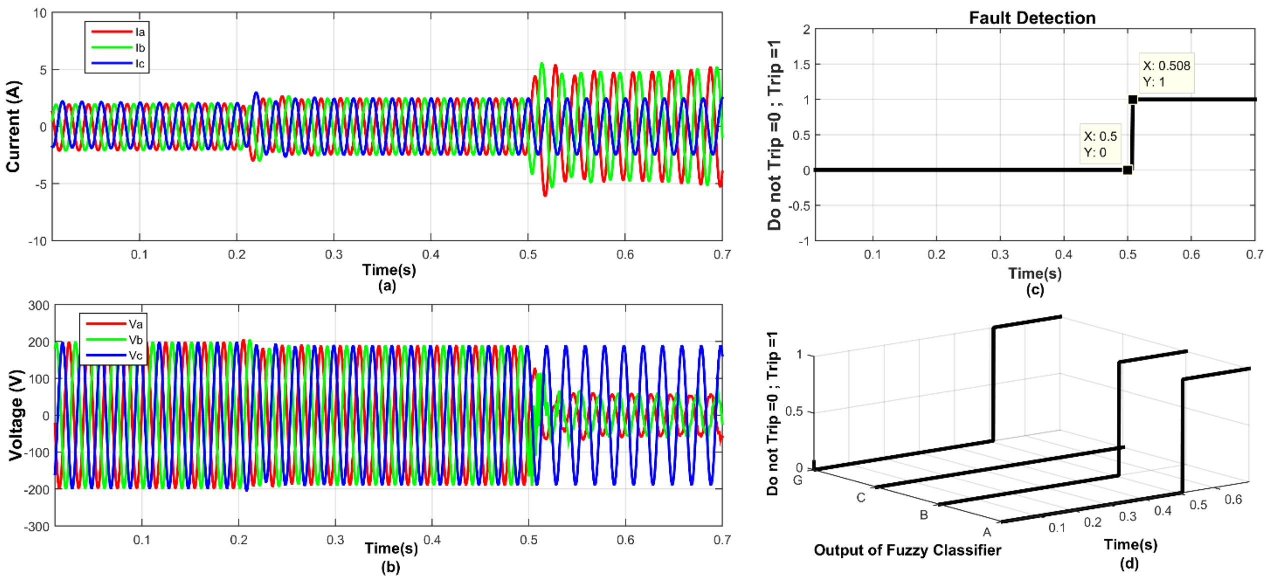

Figure 8: Performance during LLG fault (a) Current (b) Voltage (c) Fault detection (d) Fault classification

a long time to train the system data. It only required keen observation of system behavior under various fault conditions. Based on observation an expert system can be constructed. Compared to [4], the proposed fuzzy logic system increased the reach setting of 97% of the protected line length. However, compared with [14] and [15] the proposed scheme increased the reach setting without considerably compromising the classification accuracy. Moreover, the performance of the proposed fault detection and classification is unaltered by the change in TCSC posistion.

5. Conclusion

A fuzzy logic based fault detection and classification scheme for a laboratory prototype TCSC compensated transmission line model is presented in this paper. From various simulation studies, it is found that the proposed scheme is very efficient and effective under various fault conditions. The reach setting of the fuzzy-based relay is 97% of the total line length and it has high fault resistance coverage up to 100 Ω. In various fault conditions, the operating time of the proposed scheme is under one cycle of the system power frequency. Moreover, the accuracy of the proposed scheme is not greatly affected by the variation of fault parameters such as fault location and fault resistance

Table 5: Fault detection time in case of BG fault (TCSC at Mid Terminal)

Fault Location/ Fault Resistance	Fault detection time (in ms)										
	0 Ω	10 Ω	20 Ω	30 Ω	40 Ω	50 Ω	60 Ω	70 Ω	80 Ω	90 Ω	100 Ω
5 km	8	8	8	9	9	9	10	10	11	12	12
10 km	8	8	9	9	9	10	10	10	11	11	12
20 km	8	8	9	9	9	10	10	11	11	12	13
30 km	8	8	9	9	9	10	10	11	11	12	16
40 km	8	9	9	9	10	10	10	11	11	12	16
50 km	8	9	9	9	10	10	11	11	12	13	17
60 km	9	9	9	10	10	10	11	11	12	13	18
70 km	9	9	9	10	10	11	11	12	12	17	18
80 km	9	9	9	10	10	11	11	12	13	18	19
100 km	9	9	10	11	12	16	16	17	17	18	18
110 km	9	9	10	11	14	16	17	17	18	18	18
120 km	9	10	10	11	15	16	17	17	18	18	19
130 km	9	10	10	11	16	17	17	18	18	18	19
140 km	9	10	11	12	16	17	17	18	18	19	19
150 km	9	10	11	12	16	17	18	18	18	19	19
160 km	10	10	11	13	17	17	18	18	19	19	20
170 km	10	10	11	14	17	18	18	19	19	19	20
175 km	10	10	11	16	17	18	18	19	19	20	20

Table 6: Fault detection time in case of CG fault (TCSC at Remote Terminal)

Fault Location/ Fault Resistance	Fault detection time (in ms)										
	0 Ω	10 Ω	20 Ω	30 Ω	40 Ω	50 Ω	60 Ω	70 Ω	80 Ω	90 Ω	100 Ω
5 km	12	13	14	14	14	15	15	15	16	16	16
10 km	12	13	14	14	14	15	15	15	16	16	16
20 km	12	13	14	14	14	15	15	15	16	16	16
30 km	13	13	14	14	15	15	15	16	16	16	17
40 km	13	14	14	14	15	15	16	16	16	17	17
50 km	13	14	14	15	15	15	16	16	16	17	17
60 km	13	14	15	15	15	16	16	16	17	17	18
70 km	13	14	15	15	16	16	16	17	17	17	18
80 km	14	15	15	15	16	16	17	17	18	18	19
90 km	14	15	15	16	16	17	17	17	18	18	19
100 km	15	15	16	16	17	17	17	18	18	19	20
110 km	16	16	16	17	17	17	18	18	19	20	29
120 km	16	16	17	17	18	18	19	20	20	-	-
130 km	16	17	17	18	18	19	20	20	-	-	-
140 km	17	17	18	18	19	19	20	-	-	-	-
150 km	17	18	18	19	19	20	-	-	-	-	-
160 km	18	18	19	20	21	-	-	-	-	-	-
170 km	19	19	19	21	-	-	-	-	-	-	-
175 km	19	19	20	21	-	-	-	-	-	-	-

Table 7: Comparative Assessment

Reference	[4]	[13]	[14]	[15]	[Proposed Scheme]
Techniques used	Adaptive reach boundary from single end measurement using ANN	Wavelet Fuzzy combined approach for fault classification	Support Vector Machine based fault classification	Support Vector Machine based fault classification	Fuzzy logic based fault detection and classification
Required Signals	Three-phase voltage and current signals from single end	Three phase current signals from single end	Three phase current signals from single end	Three phase current signals from single end	Three-phase voltage and current signals from single end
Sampling Frequency	-	10 kHz	1 kHz	4 kHz	1 kHz
Compensating Device	TCSC, TCPST, UPFC	Fixed Series Compensator	TCSC	Fixed Series Compensator	TCSC
Operating Time	-	-	-	-	0.4– 1.05 cycle
High Resistant Fault	0 Ω - 200 Ω	0 Ω - 50 Ω	0 Ω - 200 Ω	0 Ω - 50 Ω	0 Ω - 100 Ω
Different location of TCSC	Local end Midsection	Midsection	Midsection	Midsection	Local end Midsection Remote end
Classification Accuracy	-	-	97.8%	98.18%	95%
Reach of the Relay	95%	90%	85%	80%	97%

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Appendix A

Source: Three-Phase Auto-transformer (415V, 15A, 5KVA).
Transmission Line – 180 km with 18 PI sections of 10 km each.
Transmission line parameters: R = 0.01273?/km, L = 0.9337mH/km, C = 12.47nF/km.
Load: Three-Phase Lamp Load (300 W), Three phase Induction motor load (1HP), 600 Ω Rheostat per phase.
TCSC Parameters: TCR inductance – 3 mH, TCSC capacitance - 109μF, 440V.