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ORIGINAL ARTICLE

Series capacitor-compensated double-circuit transmission line directional relay system using a fuzzy expert system with a Haar wavelet

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Abstract
There has been no perfect methodology for directional relaying in a series capacitor-compensated double-circuit transmission (SCCDCT) line until now. As it is crucial to protect the SCCDCT line from inevitable fault consequences, intelligent techniques must be employed for immediate fault directional relaying. In this work, a fuzzy expert system (FES) is developed for non-unit protection in the SCCDCT line, due to its capacity for efficient handling of linguistic data. The validity of the proposed methodology is tested by simulating a 400 kV existing Indian SCCDCT network in MATLAB software. The suitable fault zones/sections, phase, and location are identified using a phase angle component, zero sequence component, and Haar wavelet transform currents. The simulations indicate that the proposed methodology is able to correctly detect the faulty section. Also, it precisely estimates the fault distance and classification, as the maximum recorded error and accuracy for faults remain within $\pm 0.232\%$ and above 99.98%, respectively. Finally, a comparison of the proposed methodology with related protection methodologies clearly demonstrates its superiority. This routine protection methodology is sufficiently rapid, discriminative, enormously reliable, robust, and incredibly responsive for isolating the targeted fault.

Keywords Haar wavelets · Fuzzy · Line · Error · Protection

Abbreviations

SCCDCT	Series capacitor-compensated double-circuit transmission
SVM	Support vector machine
NN	Neural network
MRE	Maximum recorded error
MOV	Metal oxide varistor
MVA	Mega-volt ampere
R	Resistance
L	Location
% X	Degree of compensation
I	Inception angle

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1 Introduction

Over the last few decades, the need for electrical energy has grown substantially worldwide, and energy is delivered from power stations to load centers through transmission and distribution systems. Transmission systems are continuously exposed to various faults. Hence, when faults occur in a system, it is vital to accurately and quickly pinpoint and isolate the faulty zone so that the remaining system can continue operation. Various benefits are gained by utilizing fault location in power systems, including increased power availability, reduced maintenance times, prevention of future accidents, and improved power quality. Fault location estimation has garnered growing interest among protective elements in the last few years.

In power systems, increasing the capacity and reliability of transmission lines is of particular importance. Recently, energy companies have used a series capacitor-compensated double-circuit transmission (SCCDCT) line to handle their power transfer capacity [28]. In their work, Gajare and Pradhan [14] optimized the SCCDCT line configuration for the required tasks by estimating the parameter values. The majority of protection schemes in SCCDCT reported in the literature are based on unsynchronized measurements [15], phase voltage–current [3, 8, 19, 40], impedance [10, 24, 25, 27], and phasor measurement [35], and there have been few studies focusing only on the location of the SCCDCT line. Researchers have found that a lack of mature technology for directional relaying and classification is impeding progress regarding the SCCDCT line. Thus, the authors have undertaken an assessment of the non-unit protection in a SCCDCT line.

With the rapid development of computing methods, the application of neural networks (NN) has been concentrated on several operation modes, i.e., directional relaying [5, 23, 37], classification [11, 43], and location [16, 41]. Recently, support vector machines (SVM) have been developed, such as directional relaying [33, 39], classification [6, 30, 34, 36], and location [9, 42]. Directional-based relaying techniques have also been reported in the literature [1, 2, 17], and several studies [12, 13, 18] have suggested including directional relaying, phase classification, and location. Nevertheless, the above methods have several difficulties, mainly inaccuracies and complexity, which require a huge volume of training data and extra computing time. In this context, an optimized Haar wavelet and a fuzzy expert system (FES)-based protection methodology in SCCDCT is the focus of the present study, which involves directional relaying, phase classification, and location.

In Refs. [22, 38], different schemes for shunt faults were explored using a Haar wavelet. The FES methodology was proven successful in various tasks including pattern recognition, classification, control, robotics, and detection. Mishra and Yadav [26] assessed the FES method for shunt faults, demonstrated using the current and voltages at the single end of the SCCDCT. In Naresh Kumar et al. [21] and Kavaskar et al. [20], the authors suggested a way to determine the location of faults using FES, which was implemented to assess the directional relaying, phase classification, and location [4, 31]. The modeling of control systems operating in a fuzzy tool environment is not solved effectively in the literature with MATLAB [4, 20, 21, 26, 31]. Although it seems that the FES approach is trending and makes it easy to find optimal configurations, there are still challenges in the FES process. Authors have addressed the new notion of a fuzzy-based inference system in LabVIEW [7, 29, 32].

Though various feature extraction techniques have been used in the literature with regard to transmission line protection, no technique is able to sufficiently reduce location error and computational burden. Nevertheless, none of the studies have presented a solution to discriminate SCCDCT line faults without complex efforts considering Haar wavelet currents and FES methodology. Thus, a novel section identification methodology using FES is the focus of this study. The present work is also extended to monitor fault location and classification. The salient features of the current work can be summarized as follows:

(1) The purpose of this study is to enhance the reach setting and accuracy and minimize maximum recorded error (MRE).
(2) The methodology is not significantly affected by several fault sections, types, locations (L), fault resistance (R), level of compensation (% X), and incipient instance (I) changes.
(3) The methodology dissuades the awareness of multi-terminal data.
(4) The speed of this methodology is high.
(5) The methodology can be used to elucidate computationally complex problems.

The proposed paper is organized as follows. Section 2 outlines a SCCDCT line, the fault analysis, and input signal feature extraction. Section 3 contains the FES methodology of non-unit protection. Section 4 describes the test results, merits of the result, and comparisons. Finally, Sect. 5 concludes the study.

2 Power system under study

The single-line diagram for the SCCDCT line used to simulate numerous fault cases in this study is depicted in Fig. 1. It is a 200 km, 400 kV, and 50 Hz transmission line. This SCCDCT line is modeled and validated in MATLAB and LabVIEW, respectively. The level of series compensation (% X) selected is 55%. It consists of a doubly fed SCCDCT system in which source-1 is a generating plant consisting of a 250 MVA generator, and source-2 is the interconnected grid. The line between bus B1 and bus B2 is 100 km long, and the line between bus B2 and B3 is also 100 km long. All the optimization problems in this study are solved using MATLAB software. The fuzzy logic toolbox provided in LabVIEW is used to develop the fuzzy systems. A laptop with a high-speed processor was used to execute all the programs. Figure 2 represents the proposed study.

Four fixed series capacitor banks are located in circuit 1 and circuit 2 of the SCCDCT line. The series capacitor consists of a metal oxide varistor (MOV) for protection of the capacitor from over-voltages, and the MOV protection level needed to protect the capacitor is three times that of nominal capacitor voltages. The MOV consisting of zinc oxide discs are in parallel connection with the capacitor banks and provide nonlinear V–I characteristics. They are protected with a MOV as well as triggered forced spark gap. The MOV behavior during faults is nonlinear, depending on fault current value through the series capacitor. With the beginning of a fault, the nonlinear operation of the MOV in the SCCDCT

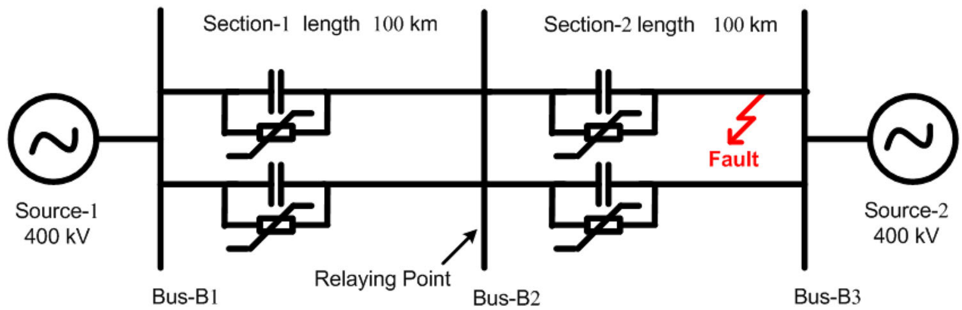

Fig. 1 The fault simulation on the SCCDCT line

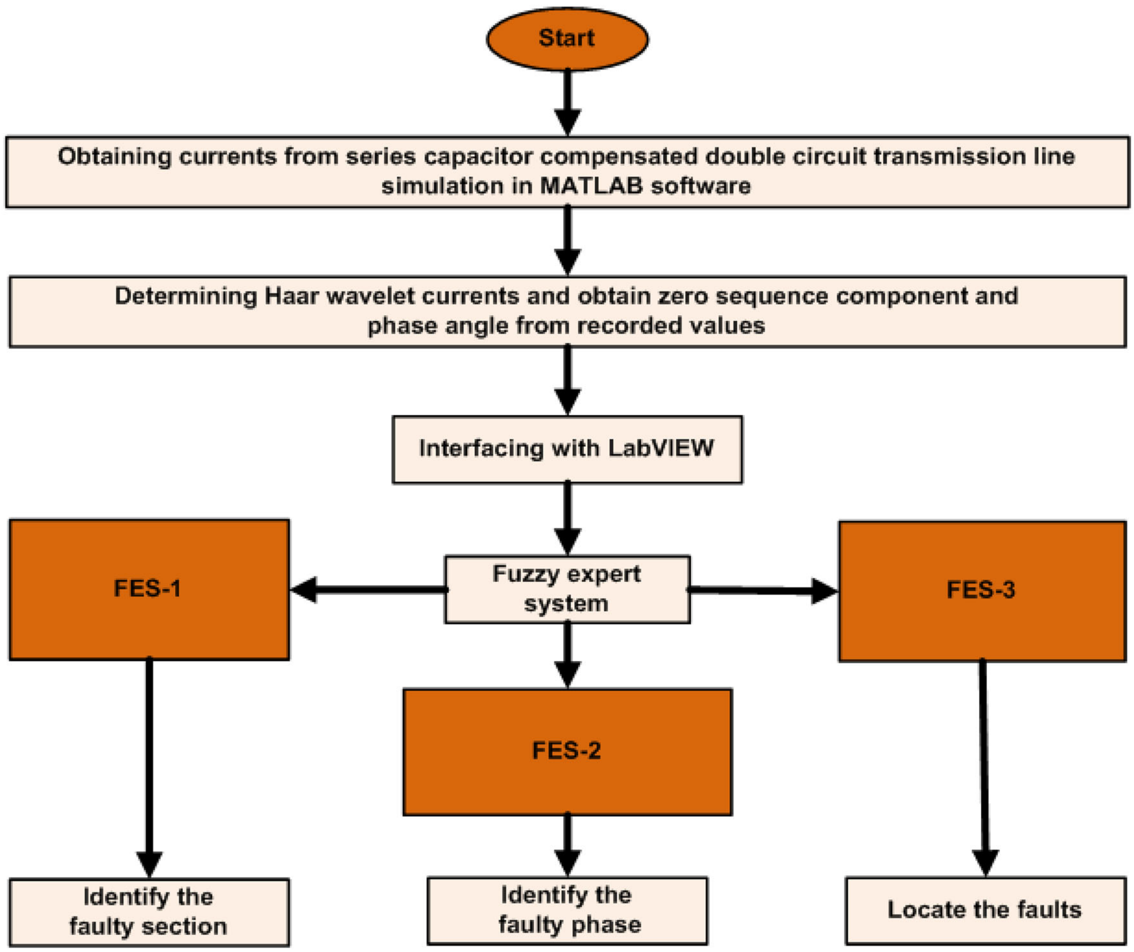

Fig. 2 Flow chart of the proposed methodology

causes malfunction of the technique. The insertion of a series capacitor in the SCCDCT line with an over-voltage protective MOV makes the protection arrangement more difficult. It may lead to inadvertent function of the technique for a fault outside the working zones. Thus, the effect of the MOV in the simulation was considered. In case of a faulty condition, current in capacitor bank is high; thereby the capacitor voltage increases. As long as the capacitor voltage is less than the threshold value, the MOV provides excessive resistance; alternatively, when the capacitor voltage becomes more than the threshold value, the MOV resistance value becomes too small. The SCCDCT parameters are given in Table 1.

Haar wavelets are the simplest possible wavelets. These are the sequence of rescaled square-type functions in mathematics which are combined to form the wavelet family. This analysis allows an output function over a period to be indicated in the form of an orthonormal family. These are now recognized as the first wavelet family and are widely used in many applications. They require additions only and are not for multiplications. In the Haar matrix, most of the elements are zeros. Input and output lengths are the same,

Table 1 System parameters

SCCDCT line parameter	
Section-1 and section-2	200 km
Impedance of positive sequence	$0.03292 + j0.3183$ Ω/km
Capacitance of positive sequence capacitance	0.011365 µF/km
Impedance of zero sequence	$0.2586 + j1.1741$ Ω/km
Capacitance of zero sequence capacitance	0.007689 µF/km
MOV element rating	
Rated voltage	200 kV
Current level	2 kA
Source parameter	
Impedance of positive sequence	$0.06978 + j1.99879$ Ω/km
Impedance of zero sequence	$0.2095 + j5.9962$ Ω/km

and thus the computational time is much shorter than that of other wavelets. They can analyze the frequency component of input signals and the localized feature of signals owing to the orthogonal property. The main feature of this wavelet is the analysis of signal with sudden transitions, viz. monitoring of tool failures in machines and fast computation. Thus, the proposed work is focused on Haar wavelets. Here, the third level of Haar wavelets is used for feature extraction (i.e., detailed coefficients and approximated coefficients) from the currents obtained from the SCCDCT line simulation. To predict the directional relaying, input–output variables are simulated according to the fault cases. Standard Haar wavelets can be expressed as

$$\psi(t = \begin{cases} 1, & 0 \le t \le 1/2 \\ -1, & -\frac{1}{2} \le t \le 1 \\ 0 & \text{otherwise} \\ & - \end{cases} \quad (1)$$

3 Fuzzy expert system methodology

The FES has pervaded a myriad of fields including management, business, engineering, and science and technology. The fuzzy approach is the most frequently employed technique. FES is conceptually simple. It consists of an input unit, processing unit, and output unit. The input unit maps the input variable to the suitable subset and truth value. Then, the processing unit invokes each if–then rule and gives corresponding results. After that, the results are combined. Lastly, the output unit transforms the combined results back into a precise output value. The core steps in the process, reasoning, and the fuzzy rules are shown in Fig. 3. Development of the proposed study is done on a computer system having specifications of 4 GB of RAM and an Intel Core i5-4005 CPU @1.70 GHZ. This computation runs on LabVIEW software in a fuzzy environment.

The working models of the FES are presented according to the directional relaying (FES-1), classification (FES-2), and location (FES-3). Three FES models are considered. In the first FES model (FES-1), the phase angle is established as the input, whereas the fault in section is implemented as the output. In the second model (FES-2), seven Haar wavelet currents and a zero sequence component information are established as the inputs, whereas the faulted phases in two circuits and ground is implemented as the outputs. In the third model (FES-3), six Haar wavelet currents are established as the inputs, and the faulted location is implemented as the output.

3.1 Fuzzification

Several types of subsets, such as triangular function, Gaussian function, and trapezoidal function, can be used while developing a FES. In this work, a trapezoidal subset and triangular subset are chosen owing to the concise notation and smoothness. The range and subset of the FES models are defined as per the measurement of data attained. For the FES-1, there is input having three subsets. For the FES-2, there are

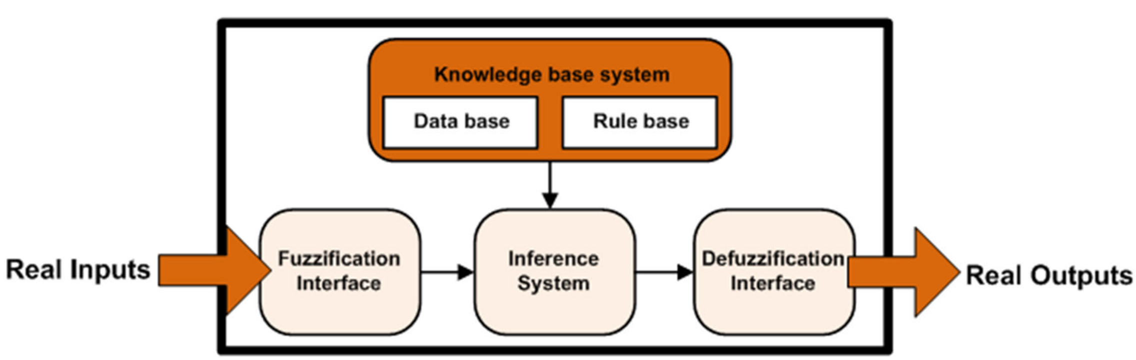

Fig. 3 The core steps in the FES process

Table 2 Design parameters of fuzzy models

Model	FES-1		FES-2		FES-3	
System variable	Inputs (1)	Outputs (1)	Inputs (7)	Outputs (7)	Inputs (6)	Outputs (1)
Linguistic variable	Phase angle	Section	HI1A, HI1B, IH1C, IH2A, IH2B, IH2C, and IZ	1-A, 1-B, 1-C, 2-A, 2-B, 2-C, and G	HI1A, HI1B, IH1C, IH2A, IH2B, and IH2C	L
Subset names	L, M, and H	SC-1, SC-0, and SC-2	L and H	Faulty and healthy	R1, R2, R3, R4, and R5	G1, G2, G3, G4, and G5
Subset type	Triangular subset	Triangular subset	Trapezoidal subset	Triangular subset	Triangular subset	Triangular subset
Type of model	Mamdani		Mamdani		Mamdani	
Number of rules	3		22		5	

FES-1 system IF–THEN rules (3): (1) IF the phase angle is L, THEN the section is SC-2. (2) IF the phase angle is M, THEN the section is SC-0. (3) IF the phase angle is H, THEN the section is SC-1. FES-2 system IF–THEN rules (22): (1) IF the phase current is L, THEN the phase is HEALTHY (11 rules). (2) IF the phase current is H, THEN the phase is FAULTY (11 rules). FES-3 system IF–THEN rules (5): (1) IF (HI1A is R1) or (HI1B is R1) or (HI1C is R1) or (HI2A is R1) or (HI2B is R1) or (HI2C is R1), THEN (L is G5). (2) IF (HI1A is R2) or (HI1B is R2) or (HI1C is R2) or (HI2A is R2) or (HI2B is R2) or (HI2C is R2), THEN (L is G4). (3) IF (HI1A is R3) or (HI1B is R3) or (HI1C is R3) or (HI2A is R3) or (HI2B is R3) or (HI2C is R3), THEN (L is G3). (4) IF (HI1A is R4) or (HI1B is R4) or (HI1C is R4) or (HI2A is R4) or (HI2B is R4) or (HI2C is R4), THEN (L is G2). (5) IF (HI1A is R5) or (HI1B is R5) or (HI1C is R5) or (HI2A is R5) or (HI2B is R5) or (HI2C is R5), THEN (L is G1)

seven inputs each having two subsets. For the FES-3, there are six inputs each having five subsets. The type of model, the number of if–then rules, the number of inputs–outputs, and the subsets are given in Table 2.

3.2 Inference mechanism

The rules can easily be developed according to existence of real data or expert knowledge. The FES model's linguistic rule base is constructed by considering each combination of inputs–outputs. Therefore, the first FES model (FES-1) has three rules, the second FES model (FES-2) has 22 rules, and the third FES model (FES-3) has five rules. The "and" conjunction is employed in FES-1 and FES-2 model, and the "or" conjunction is employed in FES-3. The rules of FES models are explained below.

3.3 Defuzzification

Lastly is the defuzzification, which is employed when it is functional to change the output fuzzy set to a numerical value. Two most common techniques are the maximum and centroid. In the max technique, one of the variables at which the fuzzy subset has its maximum value is selected as the numerical value of outputs. In the centroid technique, which has been employed in this study, the numerical output value is calculated by determining the variable center of gravity value of the subset for a fuzzy value. It enhances the defuzzification efficiency owing to the normal method which determines the two-dimensional function centroid.

4 Experimental results

In this section, performance of this methodology is evaluated using the SCCDCT system. To evaluate the performance of the FES-based methodology, firstly, simulation analysis was conducted. The various indicators for methodology validation were reach setting, accuracy, and MRE as discussed in Tables 3 and 4 and Figs. 4, 5, 6, 7, 8, and 9. In testing the systems, more than 50,000 several case studies were chosen. These studies have been obtained by taking different faulty conditions, as follows:

(1) Various sections such as section-1 and section-2
(2) Various fault types including all faults
(3) Various fault locations such as 1–99 km
(4) Various fault resistances such as 1–90 Ω
(5) Various %*X* such as 5, 15, 25, 35, 45, and 55
(6) Various fault incipient instants such as 0°–360°

$$\text{MRE }(\%) = \frac{|\text{Computed fault location } - \text{Real fault location}|}{\text{Line Length}} \times 100 \quad (2)$$

4.1 Performance evaluation of FES-1

Prior to fault classification and location, directional relaying evaluations were done in this subsection. When the system is normal, the output of FES-1 will be zero. If the system is faulty, the output adjusts either 1 or −1 depending on the

Table 3 Performance evaluation of FES-1

Parameter Varied	Section	Type	*L* (km)	*R* (Ω)	(%*X*)	*I* (°)	FES-1
Section is changing	1	1B-G	54	15	5	60	– 1
	2	1B-G	54	15	5	60	1
	1	1B-G	54	15	5	60	– 1
	2	1B-G	54	15	5	60	1
	1	1B-G	54	15	5	60	– 1
	2	1B-G	54	15	5	60	1
Fault type is changing	1	1A-G	21	30	15	120	– 1
	1	1AB	21	30	15	120	– 1
	1	2C-G	21	30	15	120	– 1
	1	2ABC	21	30	15	120	– 1
	1	2BC	21	30	15	120	– 1
	1	1ABC	21	30	15	120	– 1
L is changing	2	2AC	12	45	25	180	1
	2	2AC	26	45	25	180	1
	2	2AC	34	45	25	180	1
	2	2AC	56	45	25	180	1
	2	2AC	61	45	25	180	1
	2	2AC	85	45	25	180	1
R is changing	1	1ABC-G	74	15	35	240	– 1
	1	1ABC-G	74	30	35	240	– 1
	1	1ABC-G	74	45	35	240	– 1
	1	1ABC-G	74	60	35	240	– 1
	1	1ABC-G	74	75	35	240	– 1
	1	1ABC-G	74	90	35	240	– 1
%*X* is changing	2	2AB	92	60	5	300	1
	2	2AB	92	60	15	300	1
	2	2AB	92	60	25	300	1
	2	2AB	92	60	35	300	1
	2	2AB	92	60	45	300	1
	2	2AB	92	60	55	300	1
I is changing	1	2C-G	81	75	55	60	– 1
	1	2C-G	81	75	55	120	– 1
	1	2C-G	81	75	55	180	– 1
	1	2C-G	81	75	55	240	– 1
	1	2C-G	81	75	55	300	– 1
	1	2C-G	81	75	55	360	– 1

forward (section-2) and backward (section-1) faults of line, respectively. In Table 3, the test results for some backward and forward faults occurring at several fault sections, types, L, R, $\%X$, and I are tabulated. The protective methodology is able to operate all faults, and it remains stable during normal load condition and fault condition. The results indicate that the proposed methodology has desirable performance in several fault parameters.

4.2 Performance evaluation of FES-2

In this work, correctly and incorrectly classified faults are indicated as 1 and 0, respectively. The performance of this methodology is evaluated for several types of faults with varying test parameters over 20,000 cases, and the results are listed in Table 4. It can be seen that the proposed methodology is able to discriminate between fault condition and normal condition, showing average accuracy of 99.98%. The test results confirm that the application of the proposed methodology for transmission protection is useful for ensuring relay stability in all fault cases with various fault parameters.

4.3 Performance evaluation of FES-3

To completely protect the SCCDCT line, after directional relaying and fault classification determination, it is necessary to find the faulty location. In each parameter, 20,000 case studies including several fault quantity sets have been

Table 4 Performance evaluation of FES-2

Parameter Varied	Section	Type	L (km)	R (Ω)	(%X)	I (°)	FES-2						
							1-A	1-B	1-C	2-A	2-B	2-C	G
Section is changing	1	1B-G	54	15	5	60	0	1	0	0	0	0	1
	2	1B-G	54	15	5	60	0	1	0	0	0	0	1
	1	1B-G	54	15	5	60	0	1	0	0	0	0	1
	2	1B-G	54	15	5	60	0	1	0	0	0	0	1
	1	1B-G	54	15	5	60	0	1	0	0	0	0	1
	2	1B-G	54	15	5	60	0	1	0	0	0	0	1
Fault type is changing	1	1A-G	21	30	15	120	1	0	0	0	0	0	1
	1	1AB	21	30	15	120	1	1	0	0	0	0	0
	1	2C-G	21	30	15	120	0	0	0	0	0	1	1
	1	2ABC	21	30	15	120	0	0	0	1	1	1	0
	1	2BC	21	30	15	120	0	0	0	0	1	1	0
	1	1ABC-G	21	30	15	120	1	1	1	0	0	0	1
L is changing	2	2AC	12	45	25	180	0	0	0	1	0	1	0
	2	2AC	26	45	25	180	0	0	0	1	0	1	0
	2	2AC	34	45	25	180	0	0	0	1	0	1	0
	2	2AC	56	45	25	180	0	0	0	1	0	1	0
	2	2AC	61	45	25	180	0	0	0	1	0	1	0
	2	2AC	85	45	25	180	0	0	0	1	0	1	0
R is changing	1	1ABC-G	74	15	35	240	1	1	1	0	0	0	1
	1	1ABC-G	74	30	35	240	1	1	1	0	0	0	1
	1	1ABC-G	74	45	35	240	1	1	1	0	0	0	1
	1	1ABC-G	74	60	35	240	1	1	1	0	0	0	1
	1	1ABC-G	74	75	35	240	1	1	1	0	0	0	1
	1	1ABC-G	74	90	35	240	1	1	1	0	0	0	1
% X is changing	2	2AB	92	60	5	300	0	0	0	1	0	1	0
	2	2AB	92	60	15	300	0	0	0	1	0	1	0
	2	2AB	92	60	25	300	0	0	0	1	0	1	0
	2	2AB	92	60	35	300	0	0	0	1	0	1	0
	2	2AB	92	60	45	300	0	0	0	1	0	1	0
	2	2AB	92	60	55	300	0	0	0	1	0	1	0
I is changing	1	2C-G	81	75	55	60	0	0	0	0	0	1	1
	1	2C-G	81	75	55	120	0	0	0	0	0	1	1
	1	2C-G	81	75	55	180	0	0	0	0	0	1	1
	1	2C-G	81	75	55	240	0	0	0	0	0	1	1
	1	2C-G	81	75	55	300	0	0	0	0	0	1	1
	1	2C-G	81	75	55	360	0	0	0	0	0	1	1

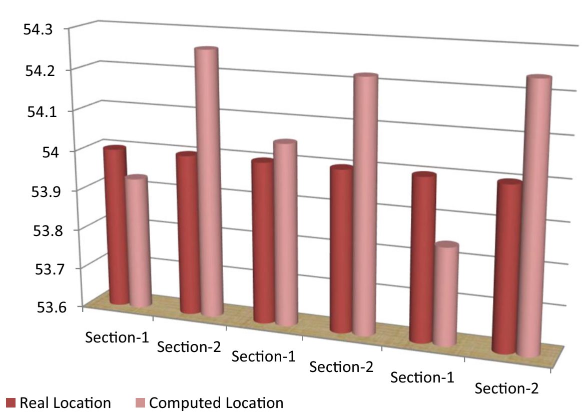

Fig. 4 Various sections with (1B-G type, $L = 54$ km, $R = 15\Omega$, $\%X = 5$, and $I = 60°$)

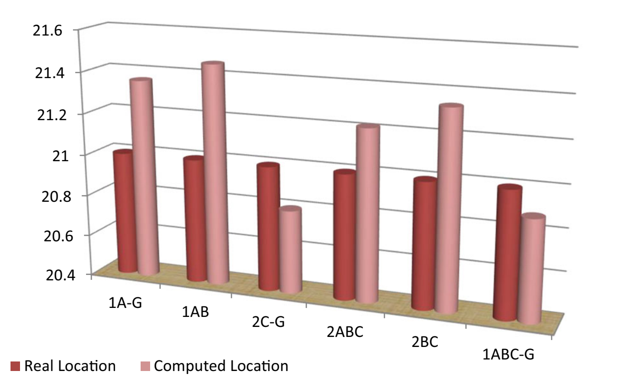

Fig. 5 Various fault types with (Section-1, $L = 21$ km, $R = 30\Omega$, $\%X = 15$, and $I = 120°$)

chosen. In Figs. 4, 5, 6, 7, 8, and 9, some of the test results for several fault sections, types, L, R, $\%X$, and I are tabulated. Figure 4 presents real location and computed location for the remaining parameter constants of various sections (types, L, R, $\%X$, and I). Figure 5 presents real location and computed location for various types of remaining parameter

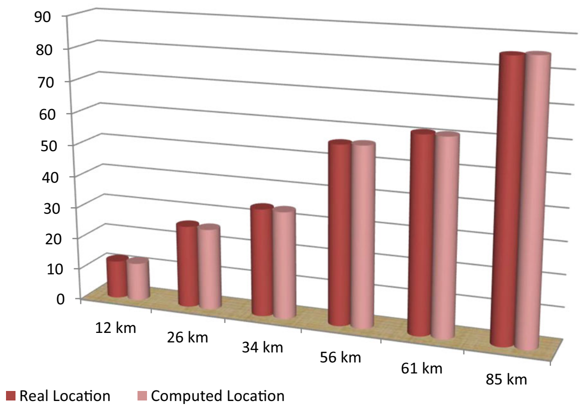

Fig. 6 Various fault locations with (Section-2, 2AC type, $R = 45\Omega$, $\%X = 25$, and $I = 180°$)

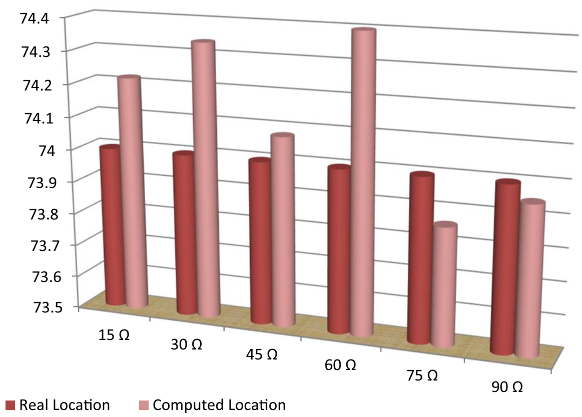

Fig. 7 Various fault resistance values with (Section-1, 1ABC-G type, $L = 74$ km, $\%X = 35$, and $I = 240°$)

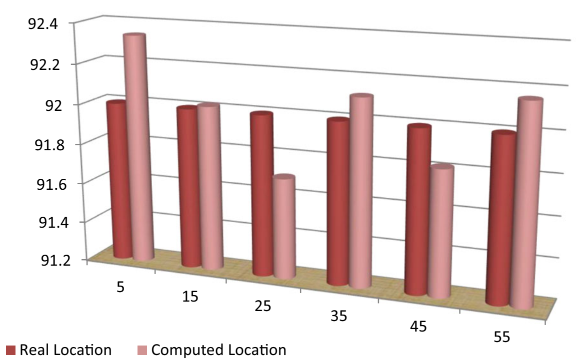

Fig. 8 Various $\%X$ with (Section-2, 2AB type, $L = 92$ km, $R = 60\Omega$, and $I = 360°$)

constants (sections, L, R, $\%X$, and I). Figure 6 represents the real location and computed location for various L remaining parameter constants (sections, types, R, $\%X$, and I). Figure 7 presents real location and computed location for various R remaining parameter constants (sections, types, L, $\%X$, and I). Figure 8 presents real location and computed location for various $\%X$ remaining parameter constants (sections, types,

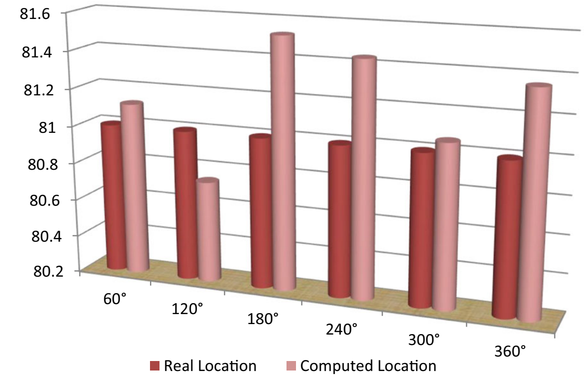

Fig. 9 Various incipient instants with (Section-1, 2C-G type, $L = 81$ km, $R = 75\Omega$, and $\%X = 55$)

L, R and I). Figure 9 presents real location and computed location for various I remaining parameter constants (sections, types, L, R, and $\%X$). In the following figures, the MRE of computed fault location is measured as Eq. 2. The MRE in forward faults is within 0.232%; on the other hand, the MRE lies between 0.114 and 0.232% in the case of backward faults. Also, the proposed methodology shows satisfactory performance against fault parameters. It is clearly evident that the proposed methodology can preserve its MRE in practice.

4.4 Comparison

In this section, the reach setting, accuracy, and MRE performance of the FES-based methodology are compared with related works. Quantitative comparison of the suggested methodology with some other intelligent schemes [3, 8, 10, 26–28, 40] is illustrated in Table 5. It can be seen that in reported approaches, the reach setting is normally 95–99%, except in [26], in which it is 99.81%. The accuracy is generally 99–99.96% in all reported studies, but it is 99.98% in this work. The MRE of the fault locators presented in [3, 10, 27, 40] is more than 0.5%, while our proposed FES is estimating the faulty location with an MRE of 0.232%. It can be inferred that a NN is complex, which also indicates that it is complex in train models. The experimental results show that the recommended methodology outperforms all other recent methods, with 99.81%, 99.98%, and 0.232% for reach setting, accuracy, and MRE, respectively. The comparison results clearly indicate that the suggested approach produces better results in terms of reach setting, accuracy, and MRE. Hence, a fast, efficient, accurate, stable, and reliable methodology has been presented in this study.

Table 5 FES with comparison with related works

Ref No.	Monalisa et al. [28]	Swetapadma and Yadav [40]	Aleena et al. [3]	Coteli et al. [8]	Monalisa [27]	Dina Mourad and Shehab [10]	Mishra and Yadav [26]	Proposed methodology
Protection function	Direction relaying	Location	Classification and location	Direction relaying and classification	Location	Direction relaying and location	Direction relaying	Direction relaying, classification, and location
Method used	Voting technique	NN	NN	SVM	Adaptive algorithm	Imaginative Cos-Sin concept	FES	FES
System studied	SCCDCT	SCCDCT	SCCDCT	SCCDCT	SCCDCT	SCCDCT	SCCDCT	SCCDCT
Reach setting (%)	99	–	–	98.967	–	98	99.72	99.81
Accuracy (%)	–	–	99	98.754	–	–	–	99.98
MRE (%)		1	1	–	2.465	0.5	–	0.232

5 Concluding remarks

Conventional directional relaying methodology malfunctions during fault conditions in a SCCDCT lines. To solve this problem, a FES with a Haar wavelet transform-based methodology has been proposed in this study. The proposed methodology consists of three units: determining the fault section, determining the faulty classification, and determining the fault location. The proposed methodology overcomes problems such as the need for line information, synchronizing received data from the two sides of the transmission line, and knowing the fault type that is being presented in the SCCDCT line protection. Simulation results emphasize the efficient performance of this methodology for different fault quantity sets. In addition, the proposed methodology is valid for forward and backward faults. Moreover, the MRE is less than 0.232% for all fault cases. The simulations point out that this methodology is a fast, efficient, accurate, stable, and reliable methodology to determine the three functions.

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