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A Hybrid DWT-ANN Based Fault Location Algorithm for Parallel Transmission Lines

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Abstract— *In this paper, a new fault location method for inter-circuit faults as well as other shunt faults is proposed for sectional parallel transmission lines. A single artificial neural network (ANN) module for fault location estimation is designed which not only determines the fault location but also the faulty section and faulty phase. Discrete wavelet transforms (DWT) is used for pre-processing the phase current and voltage signals measured at one end of the double end fed parallel lines. Inputs given to the ANN module are standard deviation values of approximate DWT coefficients of three phase currents and voltages. Output of the proposed method will be total six representing three phases of two parallel lines; one for each phase representing the fault location. Performance of the proposed scheme is not affected by varying fault type, fault location, fault inception angle, fault resistance, earthed and un-earthed inter-circuit faults in all the three sections of transmission lines. Proposed method not only provides the primary protection but also the back-up protection to the adjacent forward as well as backward transmission line sections.*

Keywords— *Artificial neural network, Discrete Wavelet Transform, Fault location estimation, Inter-circuit faults, Back-up protection.*

1. INTRODUCTION

The transmission systems are widely inter-connected in order to maintain the reliability and availability of continuing power supply to distantly located consumers. Parallel transmission lines are used extensively because of their advantages over single-circuit lines. The transmission lines are exposed to vagaries of atmospheric condition thus most prone to fault. Power line faults must be located accurately to allow maintenance crews to arrive at the scene and repair the faulted section as soon as possible. Implemented distance relaying scheme has difficulties in protecting parallel transmission lines due to mutual couplings between two circuits and during inter-circuit faults. There have been several articles proposing fault location algorithms for transmission lines [1-18]. The fault location algorithms can be divided into two broad categories: one that utilizes single end information [1-6] and other that uses information from both the end of the line [7-10]. The majority of algorithms are based on impedance estimation [11-13] which uses the fundamental frequency voltages and currents, some uses travelling wave theory [5]. Various Soft Computing Techniques such as ANN [1], Fuzzy [14], SVM [15, 16], and combined wavelet-ANN-fuzzy [17, 18] has been applied for estimating the fault location in the transmission line. In [18] only single line to ground faults has been considered for fault location estimation and other types of fault are not considered. Author has also proposed modular ANN based algorithm (total four ANN modules) for fault location estimation but this scheme requires the fault type to be identified first before beginning of the algorithm [19].

Most of the above mentioned algorithms require the fault type to be known prior for estimating the fault location [12-19]. In order to overcome this pre-requisite of fault classification, a single artificial neural network based algorithm is proposed which accurately locate the faults phase wise using single terminal data without knowing the fault type. Additionally the algorithm also identifies the faulty section and the faulty phase(s). The proposed method for fault location is designed without knowing the fault type which is the advantage of the method. ANN is one of the best tools for fault location estimation which is used in this work with discrete wavelet transforms for signal processing. There are total six outputs (one each for three phases of circuit-1 and circuit-2 of double circuit line) which represent the location of fault in km from the relaying point. From these 6 outputs, the fault location is estimated and faulty section is identified along with faulty phase(s). The proposed scheme is accurate against variations in fault location, fault type (including normal shunt faults and inter-circuit faults), fault resistance and fault inception angle. Primary goal is to design a neural network based fault location module from which location of fault as well as faulty section and faulty phases can be identified. Advantage of designing such network is that from single ANN module many tasks can be performed simultaneously.

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2. FAULT LOCATION ESTIMATION IN PARALLEL TRANSMISSION LINE WITHOUT FAULT TYPE CLASSIFICATION: ANN SOLUTION

An innovative fault location algorithms based on wavelet and ANN is designed which take into account the distributed parameter line model with line shunt capacitances. The second contribution is that the proposed techniques also identifies the faulty section and faulty phase(s) in a three sectional double circuit transmission line in which zero sequence mutual coupling between two circuits has been considered. The complete steps involved in the designing of the proposed scheme is shown in the process flow diagram in Fig.1 where L represents location of fault and also discussed in detailed here under.

2.1 Power System Network Simulation

The single line diagram of the studied power system network is depicted in Fig. 2. The power system network consists of two 400kV Thevenin equivalent sources connected via a double circuit transmission line of 300 km length divided to three sections each of length 100km. The double circuit transmission line is modeled using the distributed parameter line model considering the line shunt capacitances and also the zero sequence mutual coupling between two circuits. The proposed ANN based relay is situated at middle section or section-2 which becomes the primary section to be protected and the section-1 is taken as reverse section and section-3 is taken as forward section. The three phase currents and voltages are obtained after simulating different fault cases. Different fault situations are simulated by varying different fault parameters such as fault type: LG, LL, LLG, LLL), fault locations: 5-95km in each section with a step of 5km, fault inception angles: 0°, 45°, 90°, 135° and 180°, fault resistances: 0, 10 and 100 Ω.

2.2 Signal Pre-Processing using Discrete Wavelet Transform

Signal pre-processing and feature extraction is done using discrete wavelet transform. Wavelet transform is used for signal processing due to its ability for extracting information from non-stationary and non-periodic signals. Daubechies wavelets are widely used for analyzing signals in power system [20, 21]. For short and fast transient disturbances DB-4 is chosen as better wavelet [22]. So DB-4 wavelet is selected as mother wavelet and used for signal processing. The three phase voltage and current signals obtained during different fault situations are pre-processed using DB-4 wavelet to extract the necessary and important feature which can utilized as input to ANN.

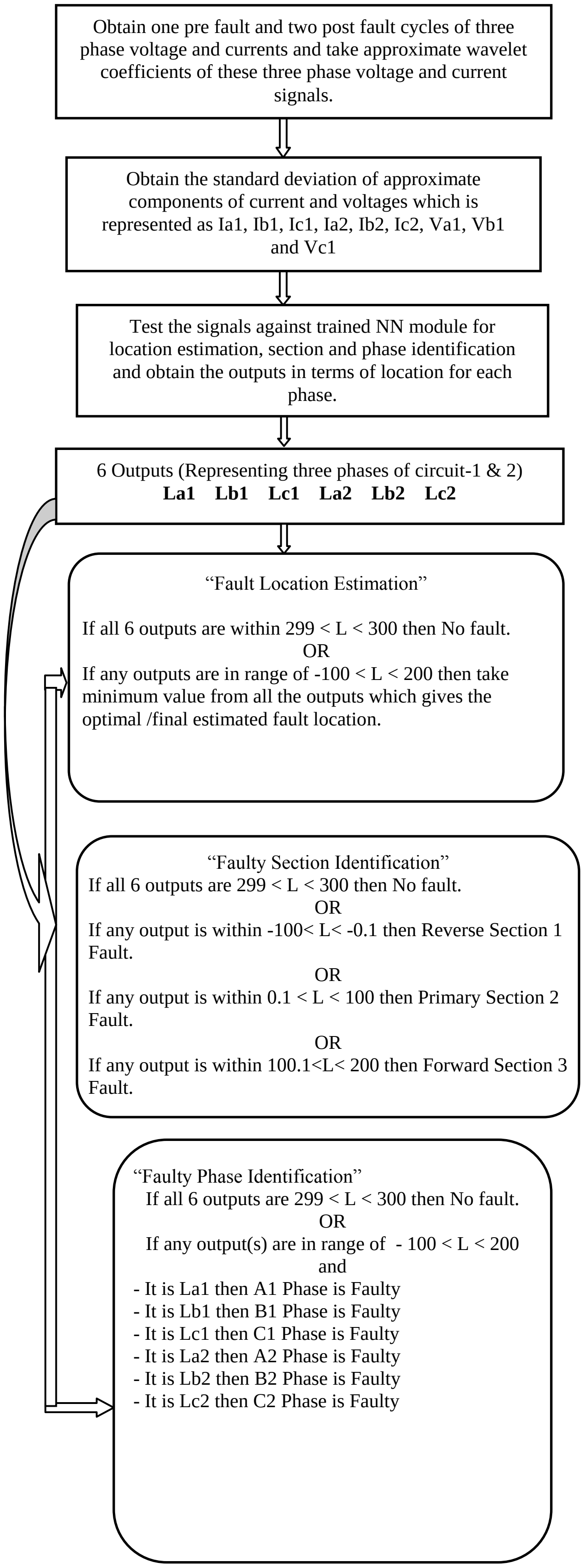


Fig. 1: Flow chart of the proposed wavelet and ANN based method.

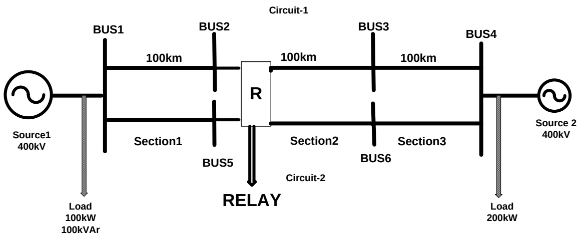


Fig. 2: Line diagram of the power system network.

The pre-processing process reduces the efforts required during training of ANN. One cycle of pre-fault and two cycles of post fault signals of three phase currents and voltages are taken and decomposed using DB-4 wavelet up to level 3. Standard deviations of the third level approximate coefficients of the three phase currents of circuit-1 and circuit-2 of double circuit line (Ia1, Ib1, Ic1, Ia2, Ib2, and Ic2) and voltage signals (Va, Vb, Vc) are calculated and used as inputs to artificial neural network.

Variation of standard deviations of the approximate coefficients of the three phase currents and voltage signals with different fault locations is depicted in Fig.3. Fig 3 (a) and (b) shows the variation of standard deviations of the approximate coefficients of current of the three phases of circuit-1& 2 and voltage signals respectively during B1C2G inter-circuit fault with R_f=0.001Ω, $Φ_i$=0^o in section-2 for different fault locations (5km to 95km). It can be seen from Fig.3 that there is distinct variation in standard deviation values for faults at different location in different sections. Thus these standard deviation values of current and voltage signals are used as input to proposed ANN based scheme.

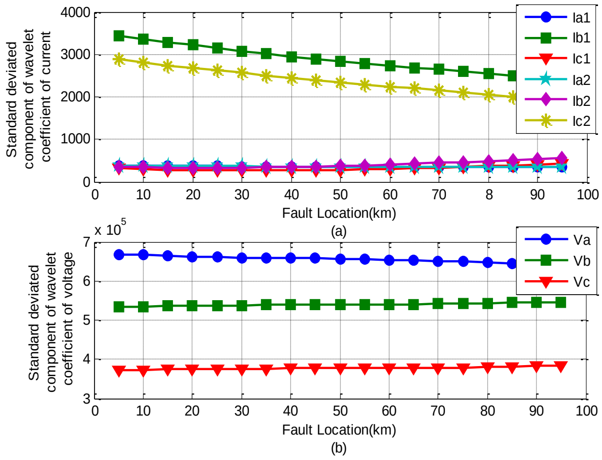


Fig. 3: B1C2G inter-circuit fault in section-2 at different locations (a) Standard deviation components of approximate coefficient of current signals and (b) Standard deviation components of approximate coefficient of voltage signals.

2.3 Design of Proposed Artificial Neural Network

The fault location method proposed in this paper is based on independent analysis of each line phase currents and voltages. The proposed ANN observes whether the analyzed phase(s) is/are faulty or not. As the proposed scheme is developed for each phase, it does not require the fault type to be known prior for beginning the fault location algorithm.

As discussed in the previous section, the standard deviated values of approximate coefficient of three phase currents and voltages are taken as input to ANN. Aiming to estimate the fault location, and keeping in view that the proposed scheme is developed for each phase, the output of ANN should point out location of fault in each phase. Thus three outputs representing the fault location in the three phases of circuit-1 and another three outputs for three phases of circuit-2 are provided by the proposed network i.e. total six outputs: La1, Lb1, Lc1, La2, Lb2 and Lc2. Once the input and output of ANN is decided, the next concern is to decide the number of hidden layer and number of neurons in the hidden layers. Method of determination of ANN structure is purely based on trial and error process. Different supervised network architectures were considered like Elman recurrent network, radial basis function neural network, and feed-forward back propagation network. Different parameters are required to design the ANN structure like number of hidden layers, number of neurons, transfer functions in order to obtain a better performance goal. During training the performance goal (mean squared error 'mse') reached to 10^{-6} in case of feed-forward back propagation network while the mse of other networks reached up to 10^{-4} only. As the main task of the proposed algorithm is to estimate the fault location with minimum error, thus the final neural network architecture chosen here is feed-forward back propagation network. The transfer function used is tan-sig in all layers after checking with different transfer functions like pure linear, log-sig, sat-lin, tan-sig etc. Further ANN consisting of three layers or four layers (including the input and output layer) which consist of one or two hidden layer respectively are commonly used for power system protection application. Network with two hidden layer generalizes well for unforeseen fault events at different location which has not been used during training. Also it is worthy to mention here that, the mse goal reached to 10^{-6} with two hidden layer and 10^{-4} in case of single hidden layer network. Finally the number of neurons in the two hidden layers is decided by adaptive process by adding/deleting the neurons as needed during training keeping a particular mse goal setting of 10^{-6}. Different ANN structures with two hidden layer each with 5 or 10 or 20 or 30 neurons have been studied and found that the two hidden layer each with 30 neurons is capable of minimizing the mse goal to 10^{-6}. Thus a single ANN structure consisting of four layered feed-forward back propagation network is designed using "Levenberg Marquardt" training algorithm [23] with 9 inputs, two hidden layers each with 30 neurons and 6 outputs neurons. The activation function used for all layers is tan-sigmoid and the mean square error goal set during training is 10^{-6} and the performance of the developed ANN is checked by presenting the network the test data set which consists of fault situation entirely different from that used in training data set. From the outputs of ANN not only the fault location is estimated but also the faulty section and faulty phase(s) can be identified as described below.

2.3.1 Fault Location Estimation

Outputs of the proposed ANN are total six fault location values corresponding to three phases of circuit-1: La1, Lb1, Lc1 and three phases of circuit-2: La2, Lb2 and Lc2 as shown in Fig. 1. During normal condition, all the six outputs are set to show 300km as fault distance which is much greater than the line section length to be protected (similar to the concept of distance protection scheme that impedance seen is much higher during no fault condition and it becomes lesser than the Zset value during fault condition). During fault condition, the location of faulty phase decreases to a value at which fault has occurred. For single line to ground fault (LG), the fault location value will be the obtained from the corresponding faulty phase location output. But for other types of fault say double line to ground (LLG), line to line fault (LL) and three phase fault (LLL), more than one phase are involved, thus here two phases in case of LL/LLG fault or three phases in case of LLL fault will show approximately same fault location value. Optimum final value of the fault location will be obtained from the faulty phase having minimum location value among all the faulty phases.

2.3.2 Faulty Section Identification

From the six outputs representing fault location in each phase of double circuit line, the faulty section can also be identified by checking the range of the each output as shown in Fig.3. When there is no fault all the six outputs values are approximately in the range (in kilometers) of $299 < L < 300$. When there is fault in any phase of the double circuit line, the corresponding faulty phase output location value lies between $-100 < L < 200$. If any of the six outputs is between the range $-100 < L < -0.1$ then fault is in the reverse section-1, or if $0.1 < L < 100$ then fault is in the primary section-2 or if $100.1 < L < 200$ then fault is in the forward section-3.

2.3.3 Faulty Phase Identification

As the proposed ANN scheme is based on independent analysis of each phase currents and voltages and the proposed scheme is developed for each phase; hence the faulty phases can be identified from the six fault location outputs (in km) as depicted in Fig. 3. When there is no fault in the system all the six outputs will be in the range $299 < L < 300$. When fault occurs in any phase of the double circuit line, then respective faulty phase output value will change and lie between -0.1 to 200 km. If any of the six output(s) is/are in range of $-100 < L < 200$ and it is La1 then A1 phase is faulty and/or it is Lb1 then B1 phase is faulty and/or it is Lc1 then C1 phase is faulty and/or it is La2 then A2 phase is faulty and/or it is Lb2 then B2 phase is faulty and/or it is Lc2 then C2 phase is faulty. Proposed fault location estimation module is tested for different fault cases with varying fault parameters and results obtained are discussed in the next section.

3. RESULTS AND DISCUSSIONS

In order to check the performance of the proposed scheme under different fault situation, all types of shunt faults including inter-circuit faults have been investigated with varying fault inception angle, fault resistance and fault locations. Extensive fault simulation studies has been carried out using Matlab software by varying the above parameters which results in around 10,000 fault case studies. The proposed method determines the fault location without knowing the type of fault which is the advantage of the proposed method over other methods which requires know the fault type to begin the fault location algorithm. The performance of the Proposed ANN based fault location method is also checked in terms of accuracy and percentage error in fault location estimation for different mean squared error performance goal set during designing/training of the neural network. Obtained results indicate that the proposed scheme is suitable for both forward and reverse short circuit faults including the Inter-circuit faults. The results shows that the proposed scheme is not affected by variation in fault inception angle, fault type, fault location, fault resistance. Moreover it is also suitable for high impedance fault also and the average error in fault location estimation did not exceed 2%.

3.1 Performance During Inter-Circuit Faults

The conductor geometry of the double circuit lines makes it prone to occurrence of inter-circuit faults also. Inter-circuit faults are those faults which involve phases of both the circuits like A1 & B2, A1 & C2 etc. Proposed ANN based method is also tested for inter-circuit faults at different locations which will be discussed below.

3.1.1 Inter-Circuit Faults During Varying Fault Inception Angle

Owing to the un-predictable nature of occurrence of fault at any time, the proposed method is tested with fault occurring at different fault inception angle. Some of the test results for different fault inception angle e.g. $\phi=0°$, 45°, 90°, 135° & 180° are shown in Table 1. The six outputs of ANN: La1, Lb1, Lc1, La2, Lb2 and Lc2 indicate the estimated location of fault in each phase of the double circuit lines. The output location of the phase(s) which is not involved in the fault loop shows 300km while others show a particular value of estimated fault location in each case. The output which shows negative value between -0.1 to -100km indicates fault has occurred in the reverse section or section-1. When the output(s) is positive and lie between 0.1 to 100km, it indicates that the fault has occurred in primary section or section 2 and if the output(s) lie between 100.1 to 200km; it indicates that the fault has occurred in the adjacent forward section or section 3. The output phase(s) showing value between -100 to 200km in any of the six phase(s) are the faulty phases. So the fault location, fault section identification and the faulty phase are identified by the proposed scheme simultaneously. Percentage error in estimated fault location is calculated using (1) to evaluate the performance of the proposed relay

$$\%\ \text{Error} = \left[\frac{\text{Actual Location} - \text{Estimated Location}}{\text{Line length}}\right] * 100 \qquad (1)$$

Table 1 depicts the six outputs of the proposed ANN based fault location, section identification and faulty phase identification method for faults with different fault inception angles. It can be seen that that the error in estimation of fault location is within 2% in all the cases and from the location estimation outputs, the faulty section as well as the faulty phase(s) can also be identified. Fig.4 shows the fault location for different fault inception angles 0°, 45°, 90°, 135° & 180°. It can be observed from Fig. 4 that the error in locations is between 0-2km for different fault inception angles.

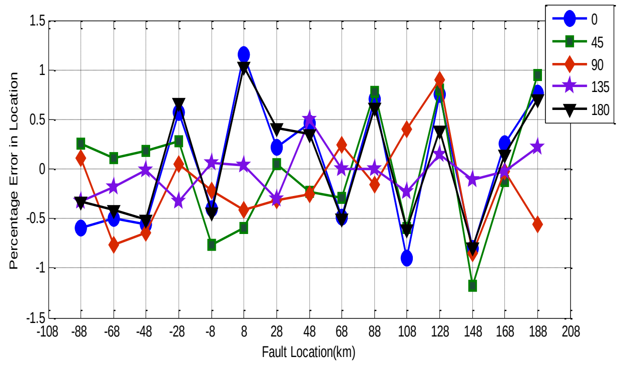


Fig. 4: Fault location error for A1B2G fault with different fault inception angles 0°, 45°, 90°, 135° & 180°.

3.1.2 Inter-Circuit Fault with High Fault Resistance

The estimation of location of faults when the line conductor gets short circuited with the ground or surface having very low resistance is not very difficult. Such faults which occur without any fault/ground resistance are called as bolted faults. On the other hand high impedance fault (HIFs) results when a conductor makes unwanted contact with a high impedance substance. The amount of fault current in this case is usually less. Fault resistance may vary for different fault locations and fault type. Thus in this section the proposed method is tested for faults with different fault resistances including high resistance and some of the test results of high fault cases are shown in Table 2.

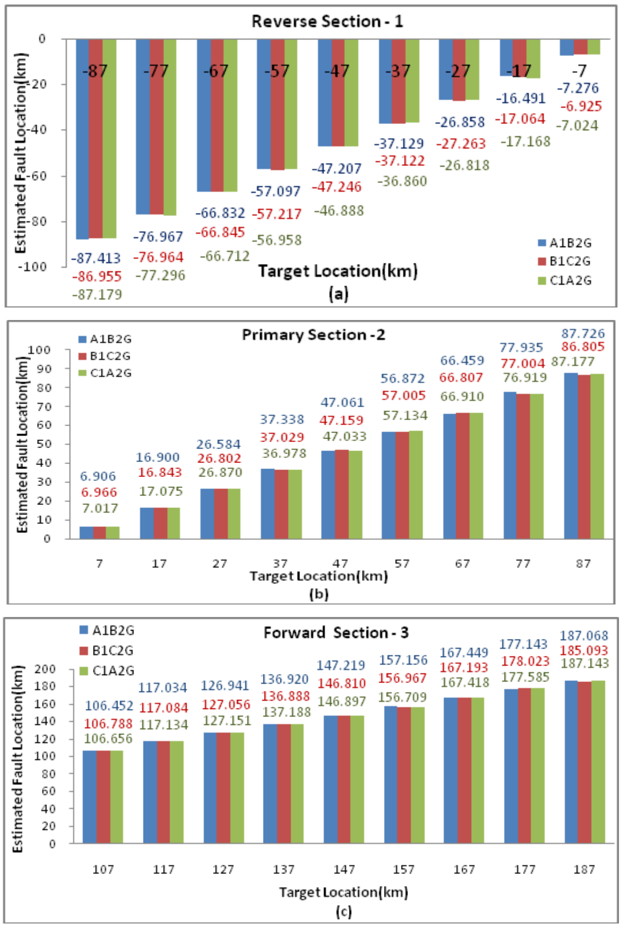


Fig. 5: Fault Location estimation and %errors during inter-circuit faults at different locations with 100Ω high fault resistance (a) Section –1 (b) Section – 2 and (c) Section - 3.

From table 2 it can be observed that %errors are within 1%. Performance of the fault location algorithm is not affected by variation of fault resistance. Fig.5 shows the actual fault location and estimated fault location at different fault locations with high fault resistance of 100Ω in all the three sections of the line. It indicates that the scheme proposed in this paper can correctly locate the inter-circuit faults with high fault resistance also with reasonable accuracy.

3.2 Performance in Case of Normal Shunt Faults

Here the performance of the proposed method is evaluated for all ten types of shunt fault (LG, LL, LLG, LLL) with varying fault parameters and discussed here under.

3.2.1 Varying Fault Inception Angle

Proposed method is tested for different types of shunt fault with varying inception angle and the results are given in Table 3. From Table 3 it can be observed that fault location error is within 2% for all the faults. Faulty

Table 1: Fault location estimation and %error for different fault inception angle for earthed and un-earthed inter-circuit faults.

Fault type	*Fault Inception Angle (°)*	*Actual Fault Location (km)*	*Estimated Fault Location (km)*						*Fault Location*		*FSI*	*FPI*
			La1 (km)	*Lb1 (km)*	*Lc1 (km)*	*La2 (km)*	*Lb2 (km)*	*Lc2 (km)*	*OEL (km)*	*% Error*		
Earthed Inter-circuit Faults	0	-12	-13.075	300	300	300	-13.039	300	-13.039	1.039	1	A1, B2
		12	11.793	300	299.99	300	11.855	300	11.793	0.207	2	A1, B2
		112	110.607	300.00	299.99	300	110.719	300	110.607	1.393	3	A1, B2
	45	-42	300	-41.779	300	300	300	-41.712	-41.712	-0.288	1	B1, C2
		42	300	42.218	300	300	300	42.247	42.218	-0.218	2	B1, C2
		142	300	142.462	300	300	300	142.439	142.439	-0.439	3	B1, C2
	90	-62	300	300	-61.729	-61.705	300	300	-61.705	-0.295	1	C1, A2
		62	300	300	62.217	62.189	300	300	62.189	-0.189	2	C1, A2
		162	300	300	161.944	161.962	300	300	161.944	0.056	3	C1, A2
	135	-72	300	-71.913	300	-71.962	300	300	-71.913	-0.087	1	B1, A2
		72	300	72.165	300	72.101	300	300	72.101	-0.101	2	B1, A2
		172	300	173.482	300	173.400	300	300	173.400	-1.4	3	B1, A2
	180	-82	-81.789	300	300	300	300	-81.790	-81.789	-0.211	1	A1, C2
		82	82.183	300	300	300	300	82.094	82.094	-0.094	2	A1, C2
		182	181.735	300	300	300	300	181.770	181.735	0.265	3	A1, C2
Un-earthed Inter-circuit Faults	0	-19	-19.146	300	300	300	-19.116	300	-19.116	0.116	1	A1, B2
		19	20.010	300	300	300	20.136	300	20.010	-1.01	2	A1, B2
		119	119.044	300	300	300	119.080	300	119.044	-0.044	3	A1, B2
	45	-29	-28.948	300	300	300	300	-28.957	-28.948	-0.052	1	A1, C2
		29	28.990	300	300	300	300	28.967	28.967	0.033	2	A1, C2
		129	128.670	300	300	300	300	128.675	128.670	0.33	3	A1, C2
	90	-39	300	300	-39.159	-39.148	300	300	-39.148	0.148	1	C1, A2
		39	300	300	39.239	39.280	300	300	39.239	-0.239	2	C1, A2
		139	300	300	139.317	139.338	300	300	139.317	-0.317	3	C1, A2
	135	-49	300	-48.947	300	-48.939	300	300	-48.939	-0.061	1	B1, A2
		49	300	48.948	300	48.823	300	300	48.823	0.177	2	B1, A2
		149	300	149.193	300	149.238	300	300	149.193	-0.193	3	B1, A2
	180	-59	-58.643	300	300	300	300	-58.611	-58.611	-0.389	1	A1, C2
		59	58.992	300	300	300	300	58.981	58.981	0.019	2	A1, C2
		159	158.964	300	300	300	300	158.964	158.964	0.036	3	A1, C2

*OEL-Optimal estimated location, FSI-Faulty section identification, FPI- Faulty phase identification.

phases and faulty sections are also correctly identified from the output location. Fig.6 shows the estimated fault location values for different fault inception angles 0°, 90° & 180°.

3.2.2 Varying Fault Resistance

Proposed method is tested for faults with different fault resistances including high resistance and some of the test results are shown in Table 4. From table 4 it can be observed that %errors are within 1%. Fig.7 shows the actual fault location and estimated fault location with high fault resistance of 100Ω in all the three sections of the line. It indicates that the scheme proposed in this paper can correctly locate the different types of faults with high fault resistance also with reasonable accuracy.

3.3 Performance During Back-Up Protection to Reverse and Forward Section

The transmission line considered here is three section double circuit lines, thus it is imperative to check the performance of the proposed scheme for fault in adjacent forward and reverse sections. Test results for faults in reverse section-1 and forward section -3 are shown in Tables 1, 2 and 4. It can be seen that the proposed method locates the faults in forward and reverse sections with error less than 2%, which is an additional advantage of the proposed method.

Table 2: Fault location estimation and %error for high fault resistance of 100Ω.

Fault Type	*Actual Fault Location (km)*	*Estimated Fault Location (km)*						*Fault Location*		*FSI*	*FPI*
		La1	*Lb1*	*Lc1*	*La2*	*Lb2*	*Lc2*	*OEL (km)*	*%Error*		
A1B2G	-6	-6.580	300	300	300	-6.647	300	-6.580	0.58	1	A1, B2
B1C2G	-26	300	-26.051	300	300	300	-26.187	-26.051	0.051	1	B1, C2
C1A2G	-46	300	300	-45.812	-46.208	300	300	-46.208	0.208	1	C1, A2
A1C2G	-66	-66.163	300	300	300	300	-66.198	-66.163	0.163	1	A1, C2
B1A2G	-86	300	-85.971	300	-85.574	300	300	-85.574	-0.426	1	B1, A2
C1B2G	-96	300	300	-94.781	300	-94.041	300	-94.781	-1.219	1	C1, B2
A1B2G	6	5.816	300	300	300	5.793	300	5.793	0.207	2	A1, B2
B1C2G	26	300	25.777	300	300	300	25.828	25.777	0.223	2	B1, C2
C1A2G	46	300	300	46.072	46.067	300	300	46.067	-0.067	2	C1, A2
A1C2G	66	66.223	300	300	300	300	66.266	66.223	-0.223	2	A1, C2
B1A2G	86	300	86.078	300	86.117	300	300	86.078	-0.078	2	B1, A2
C1B2G	96	300	300	96.339	300	96.294	300	96.294	-0.294	2	C1, B2
A1B2G	106	105.693	300	300	300	105.663	300	105.663	0.337	3	A1, B2
B1C2G	126	300	126.134	300	300	300	126.130	126.130	-0.13	3	B1, C2
C1A2G	146	300	300	145.901	145.802	300	300	145.802	0.198	3	C1, A2
A1C2G	166	166.348	300	300	300	300	166.351	166.348	-0.348	3	A1, C2
B1A2G	186	300	186.532	300	186.397	300	300	186.397	-0.397	3	B1, A2
C1B2G	196	300	300	197.360	300	194.614	300	194.614	1.386	3	C1, B2

Table 3: Fault location estimation and %error for different fault inception angle in normal shunt faults

Fault Inception Angle (°)	*Actual Fault Location (km)*	*Estimated Fault Location (km)*						*Fault Location*		*FSI*	*FPI*
		La1 (km)	*Lb1 (km)*	*Lc1 (km)*	*La2 (km)*	*Lb2 (km)*	*Lc2 (km)*	*OEL (km)*	*%Error*		
0	12	11.980	300	299.99	300	300	300	11.980	0.020	2	A1
	42	42.035	300	299.99	300	300	300	42.035	-0.035	2	A1
	82	81.968	300.00	299.99	300	300	300	81.968	0.032	2	A1
45	12	300	12.061	300	300	300	300	12.061	-0.061	2	B1
	42	300	42.705	300	300	300	300	42.705	-0.705	2	B1
	82	300	82.260	300	300	300	300	82.260	-0.260	2	B1
90	12	12.056	12.049	299.99	300	300	300	12.049	-0.049	2	A1, B1
	42	41.807	41.804	299.99	300	300	300	41.804	0.196	2	A1, B1
	82	81.895	81.893	299.99	300	300	300	81.893	0.107	2	A1, B1
180	12	11.969	11.969	11.968	300	300	300	11.969	0.031	2	A1, B1, C1
	42	42.027	42.024	42.022	300	300	300	42.022	-0.022	2	A1, B1, C1
	82	81.923	81.932	81.928	300	300	300	81.923	0.077	2	A1, B1, C1

Table 4: Fault location estimation and %error in case of different forward and reverse faults with different fault resistance.

Fault Resistance (Ω)	*Actual Fault Location (km)*	*Estimated Fault Location (km)*						*Fault Location*		*FSI*	*FPI*
		La1	*Lb1*	*Lc1*	*La2*	*Lb2*	*Lc2*	*OEL (km)*	*%Error*		
0	-92	-92.797	299.99	299.999	300	300	300	-92.797	0.797	1	A1
	92	91.965	91.971	299.999	300	300	300	91.965	0.035	2	A1, B1
	192	190.756	190.74	190.738	300	300	300	190.745	0.127	3	A1, B1, C1
10	-92	299.999	-94.66	299.999	300	300	300	-94.668	0.668	1	B1
	92	299.999	92.040	92.036	300	300	300	92.036	-0.036	2	B1, C1
	192	193.165	193.17	193.169	300	300	300	193.165	0.417	3	A1, B1, C1
100	-92	299.999	299.99	-92.554	300	300	300	-92.554	0.554	1	C1
	92	91.956	91.971	299.999	300	300	300	91.956	0.044	2	A1, B1
	192	192.350	192.41	299.999	300	300	300	192.350	-0.175	3	B1, C1

Table 5: Fault location estimation and %error for IEEE 9-bus test system.

Fault Type	*Actual Fault Location (km)*	*Estimated Fault Location (km)*			*Fault Location*		*FSI*	*FPI*
		La	*Lb*	*Lc*	*OEL(km)*	*%Error*		
AG	-94	-94.589	299.999	299.999	-94.589	0.589	1	A
BG	-84	299.997	-83.997	299.995	-83.997	-0.003	1	B
CG	-74	299.999	299.998	-73.822	-73.822	-0.178	1	C
ABG	-64	-64.119	-64.122	299.999	-64.119	0.119	1	A, B
BCG	-54	299.999	-53.989	-53.981	-53.981	-0.019	1	B, C
CAG	-44	-43.963	299.999	-43.968	-43.963	-0.037	1	C, A
AB	-34	-34.002	-34.000	299.999	-34.000	0.000	1	A, B
BC	-24	299.999	-24.000	-23.995	-23.995	-0.005	1	B, C
CA	-14	-14.013	299.999	-14.019	-14.013	0.013	1	C, A
ABC	-4	-4.008	-4.061	-4.0471	-4.008	0.008	1	A, B, C
AG	4	4.276	299.998	299.999	4.276	-0.276	2	A
BG	14	299.994	14.008	299.999	14.008	-0.008	2	B
CG	24	299.999	299.999	23.997	23.997	0.003	2	C
ABG	34	34.051	34.045	299.999	34.045	-0.045	2	A, B
BCG	44	299.999	44.011	44.004	44.004	-0.004	2	B, C
CAG	54	54.018	299.999	54.011	54.011	-0.011	2	C, A
AB	64	64.046	64.042	299.999	64.042	-0.042	2	A, B
BC	74	299.999	73.888	73.890	73.888	0.112	2	B, C
CA	84	83.976	299.999	83.970	83.970	0.030	2	C, A
ABC	94	94.002	94.005	94.003	94.002	-0.002	2	A, B, C

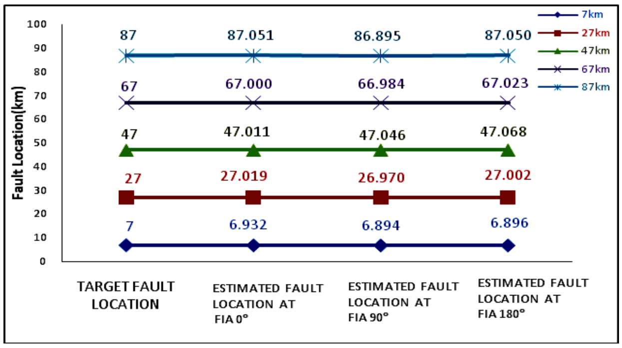
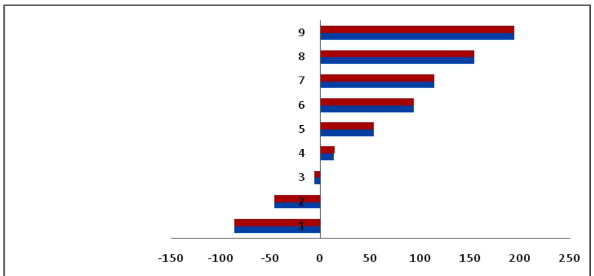
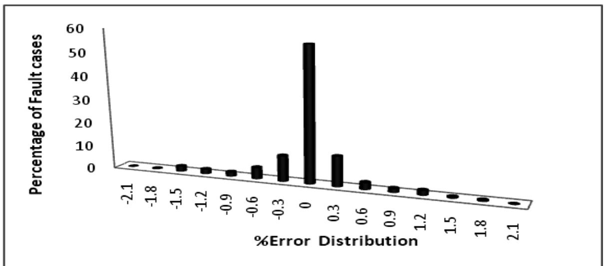


Fig. 6: Fault location estimation for different fault inception angles 0°, 90° & 180°.



	1	2	3	4	5	6	7	8	9
Estimated Fault Location	-86.033	-46.162	-6.073	14.026	53.98	93.957	113.909	153.937	194.167
Target Location	-86	-46	-6	14	54	94	114	154	194

Fig. 7: Fault Location estimation and %errors during A1B1G fault at different locations with 100Ω high fault resistance.



	-2.1	-1.8	-1.5	-1.2	-0.9	-0.6	-0.3	0	0.3	0.6	0.9	1.2	1.5	1.8	2.1
% of Fault cases	0	0.2	2.3	2	1.9	4.9	11	57	12.	3	1.7	2.1	0.6	0.5	0

Fig. 8: Overall % error range of total fault cases tested.

3.4 Performance of Proposed Method for Standard IEEE 9-BUS System

Proposed fault location method is tested with standard IEEE 9-bus system. The line diagram of IEEE 9-bus system is shown in Fig.9. Relay is placed near to bus -8, so the line section of 100km length between bus-8 to bus-9 is considered as primary section and line section (100km) between bus-7 and bus-8 is considered as reverse section. Signal processing process is same as described in section 2.2 above, except that in standard IEEE 9-bus system the transmission line section is single circuit line. Different fault situations both forward and reverse faults are simulated by varying different fault parameters such as fault type: LG, LL, LLG, LLL), fault locations: 5-95km in each section with a step of 5km, fault inception angles: 0°, 45°, 90°, 135° and 180°, fault resistances: 0, 10 and 100 Ω. Inputs to the proposed ANN are three phase currents and voltages i.e. 6 inputs. Output of the network is in terms of fault location La, Lb and Lc. The ANN module is designed using Levenberg Marquardt algorithm with 6 inputs, two hidden layers each with 20 neurons and 3 outputs neurons. The activation function used for all layers is tan-sigmoid and the mean square error goal set during training is 10^{-6}. After training the ANN module; different test fault cases are generated and tested against the trained network to check the performance of the network. Some of the test result of the proposed scheme is shown in Table 5. From table 5 it can be observed that the proposed method can correctly estimate the faulty section, faulty phase and fault location in standard IEEE 9-bus system.

4. OVERALL FAULT LOCATION ERROR ANALYSIS

The proposed scheme is tested for various fault cases and % error in fault location estimation is calculated using (1). Up to 10,000/- cases of forward and reverse faults are tested at 25 different locations in the three sections with varying fault type (LG, LL, LLG, LLL and Inter-circuit faults), fault inception angle and fault resistances. The percentage error in fault location estimation is within 2% for all the fault cases. Moreover in order to know the distribution of locating errors for total fault cases tested, Fig.8 shows the % error distribution range for all fault cases tested. One can observe that the proposed scheme for fault location estimation yield ±0.01% error for 57% of total fault cases tested while the % error lies within error range ±0.3% for 23.8% cases. Further 7.9% of cases are located with ±0.6% error, 3.6% of cases are located with ±0.9% error, 4.1% of cases are located with ±1.2% error, 2.9% of cases are located with ±1.5% error, and the highest error in location estimation is up to 1.8% which consists of 0.7% of total fault cases.

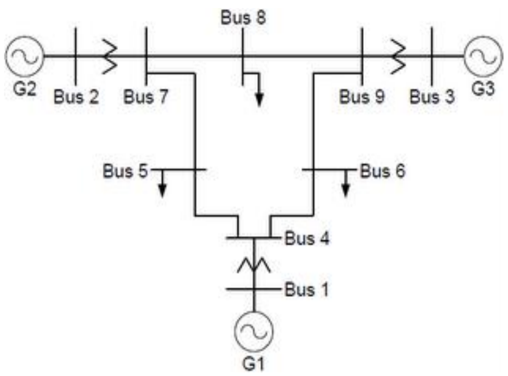


Fig. 9: Line diagram of IEEE 9-bus system.

5. CONCLUSION

This paper shows how artificial neural network can be used to estimate fault location in three sectional double circuit lines without fault classification including inter-circuit faults. A single artificial neural network (ANN) module for fault location estimation in each phase(s) is designed which not only determines the fault location but also the faulty section and faulty phase. The proposed method determines the fault location without knowing the type of fault using single terminal data. One cycle pre-fault samples and two cycles post fault samples of three phase current and voltage signals are used to calculate the approximate coefficients using DB-4 wavelet. Standard deviation of approximate coefficients is then given as input to the neural network which finds the location of fault in each phase separately in double circuit line. Extensive simulation studies have been carried out to demonstrate that the distances to faults are accurately calculated and the percentage error in fault location is within 2% under variety of fault situations. Further the proposed scheme is adaptive to variations in different fault parameters like fault location, fault type including inter-circuit faults, fault resistance, fault inception angle. Additional advantage of the proposed method is that from a single ANN module many tasks can be performed simultaneously such as fault location estimation, faulty section identification and faulty phase identification.

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