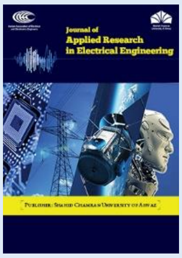
Shahid Chamran University of Ahvaz

Iranian Association of Electrical and Electronics Engineers

Journal of Applied Research in Electrical Engineering

E-ISSN: 2783-2864
P-ISSN: 2717-414X
Homepage: https://jaree.scu.ac.ir/



Research Article

Broken Conductor Fault Location in Power Transmission Lines Using GMDH Function and Single-Terminal Data Independent of Line Parameters

Mahyar Abasi [1,*], Nima Heydarzadeh [2], and Arash Rohani [3]

[1] *Department of Electrical Engineering, Faculty of Engineering, Shahid Chamran University of Ahvaz, Ahvaz 61357-85311, Iran*

[2] *Department of Electrical Engineering, Central Tehran Branch, Islamic Azad University, Tehran 13117-773591, Iran*

[3] *Khuzestan Regional Electric Company (KZREC), Ahvaz 61365-1373, Iran*

* *Corresponding Author: mahyarabasi1368@yahoo.com*

Abstract: The phenomenon of broken conductor faults (BCFs) in power transmission lines and, consequently, the suspension of the hot-line with no connection to ground, tower, or other conductive/non-conductive bodies is amongst special faults in terms of fault detection and location in the protection industry. Once such a failure occurs, the current of the faulty phase does not increase, which leads to the inability of standard fault detection functions in detecting the event. On the other hand, the variable nature of transmission line parameters due to weather conditions leads to misoperation and malfunction of fault detection and protection schemes of industrial relays in some cases. This paper, for the first time, presents a BCF location scheme without requiring line parameters data and only using magnitudes of current and voltage phasors of a single terminal based on Group Method of Data Handling (GMDH). In this method, a function is interpolated, the inputs of which are the current and voltage of the faulty phase, and its output are the accurate location of the fault. The function can be developed for all topologies of transmission lines. The proposed method is implemented in the MATLAB software and the obtained results verify the solidity and perfect performance of the method for different fault conditions.

Keywords: Broken conductor fault location, series conductor, GMDH, current and voltage phasors, single-terminal method, transmission line parameters.

Article history
Received 18 October 2020; Revised 19 February 2021; Accepted 16 March 2021; Published online 31 March 2021.

How to cite this article
M. Abasi, N. Heydarzadeh, and A. Rohani, "Broken conductor fault location in power transmission lines using GMDH function and single-terminal data independent of line parameters," *J. Appl. Res. Electr. Eng*., vol. 1, no. 1, pp. 22-32, 2022.
DOI: 10.22055/jaree.2021.35473.1012

1. Introduction

1.1. Motivation

In general, normal shunt and series faults always threaten the power system. Normal shunt faults include phase-to-ground and phase-to-phase faults which occur due to factors such as lightning, flashes or arcs, bird collision, the connection of a conductive object between phases, or between a phase and the tower, to name but a few [1]. Series faults include the interruption of one or more phases in which the phase or phases have no connection to ground or other conducting objects. Such faults typically happen due to broken conductors, misoperation of single-phase switchgear, or single-phase fuses [2]. In electrical transmission lines, the phase current is not increased when the phenomenon of broken phase occurs between the conductors connected to the towers, which results in the misoperation of standard protection algorithms embedded in the relays. Thus, manufacturers of protection relays attempt to find suitable protection functions and algorithms to detect, classify, and locate BCFs in transmission lines.

Another issue that always causes errors in protection algorithms is the implementation of line parameters in algorithms. Because electrical transmission lines are always exposed to changing weather conditions, their parameters change over a long time when compared to the initial values provided in their catalogs, hence leading to malfunctions [3]. Therefore, designing a protection algorithm requiring none of the transmission line parameters is a very useful advantage for protection schemes. According to the issues raised above, this study aims to design an algorithm for BCF location in transmission lines using current and voltage values of a single terminal without requiring line parameters.

1.2. Literature Review

In general, series fault location methods in transmission lines are divided into four basic categories including the impedance or phasor theory-based methods, the traveling waves-based methods, the digital signals analysis and processing-based methods, the methods based on teaching and learning, and those which focus on pattern designs such as artificial neural networks (ANNs), fuzzy logic (FL), and optimization [4].

Ref. [5] presents three methods for locating BCFs. These three methods include fault location based on capacitive charging current ratio, according to the line hyperbolic equation analysis, in which the third method is based on the analysis of positive-sequence components of the faulty network. Capacitive charging current ratio is the simplest approach to calculate the distance between the relay terminal and the broken conductor. The first method can be employed only for lines with significant capacitive charging current; otherwise, the relay cannot locate the fault. In the distance calculation method using full line equations, it is assumed that the lines are completely transposed and zero-sequence parameters are employed, which may not be accurate due to changes in weather conditions and the return paths of zero-sequence to ground. This method is computationally inefficient and the calculation of distance is erroneous due to the non-transposable nature of the lines and its dependence on zero-sequence parameters. Calculating the fault location using positive-sequence components utilizes only positive-sequence parameters, which are probably more accurate than zero-sequence parameters. This method is more computationally efficient as it does not use iterative methods to solve the equations. However, this method assumes that transmission lines are completely transposed and can therefore have computational errors due to the nature of the non-transposed lines.

In [6], BCF detection and location are presented using communication-based techniques. The authors in this paper have used an open conductor detection (OCD) system, where BCF sensors are used in towers and inter-conductor bases. OCD sends this data to the control center through some communication devices using GSM technology. The main purpose of this system is to transmit and interpret the abnormal conditions of the network concerning BCF conditions, and transfer the information of this power outage to the control center. The network operator searches for the last active OCD and the first inactive OCD, locates the fault, and then takes actions to prevent accidents and minimize the failure.

Two different methods based on other communication-based techniques, namely the F-PLCCG and the Hybrid AD Method, are also presented in [7]. The F-PLCCG method is designed to detect broken conductors between two substations, which requires very expensive hardware and highly advanced communication systems that are not cost-effective. Nonetheless, the Hybrid AD method is less expensive and provides the exact location. In this method, the power line guardian (PLG) plays a key role and can locate the BCF that does not touch the ground using the second-harmonic traveling waves. PLG uses a current transformer and measures the high-frequency range (traveling wave frequency). However, it should be noted that the implementation of communication-based techniques leads to additional hardware and software complexity and is not economical.

The two main BCF detection and location methods based on digital signal processing and analysis (harmonic components) are described in [8-11]. In the first method, the status of the BCF is provided based on monitoring harmonic components 1, 3, 5, and other harmonics in the neutral current of the transformer and using dominant component changes. Nevertheless, the technical justification behind this approach is not available. Determining the threshold value in this method is difficult because the measured harmonics can be affected by other factors such as resonance. As a result, applying this approach to different cases can be challenging [8-9]. The second method utilizes a voltage source in the neutral of the transformer and measures its corresponding excitation current. If the current is low, the BCF condition is detected [10].

The BCF detection scheme based on the third harmonic is described in [11]. This design is used for lines connected to a no-load transformer with a grounded star, and its principles are based on reducing (near zero) zero-sequence voltage and current on the primary side of the ground transformer. To detect BCFs in this method, it is necessary to determine the threshold values and measure the zero-sequence impedance of the transformer’s downstream network. To obtain threshold values in this paper, day-ahead measurements of zero-sequence current and voltage values were used. This method may also be affected by noise and abnormal harmonics (inter-harmonics) and may fail to correctly detect the BCF event.

In [12], the ANN is employed as a BCF detector. The only problem with this design is its complexity in terms of hardware implementation. Moreover, only the BCF detection problem was taken into account with no idea on how to solve the BCF location problem.

Additionally, ABB-REL 521 and SIPROTEC 4 (7SA612) as industrial relays employ BCF detection methods based on the calculation of the asymmetry between phase currents. These methods are realized by measuring the ratio between maximum and minimum phase currents, i.e., they compare the minimum and maximum current values, and the relay issues a trip command if the minimum current is less than 80% of the maximum current for a certain time interval. After about five seconds, a "Broken Conductor" alarm or a three-phase interruption signal is issued by the relay [13-14]. Moreover, the BCF algorithm in the Areva MICOM P443 [15] relay is based on the negative-sequence phase current level or the ratio between negative- and positive-sequence currents. However, if the above-mentioned methods are used in a low-load line, the negative-sequence current caused by a series fault may be very close to or less than the full-load steady-state imbalance value which is caused by current transformer faults, load imbalance, etc. As a result, the negative-sequence module of the relay cannot work well in low-load conditions [16].

1.3. The Challenge

According to the literature review in the previous section, the BCF location problem without requiring the data of transmission line parameters has so far remained unsolved. The problems caused by this phenomenon threaten the stability of the power system because of the shortcomings of the proposed methods in this field. Many reports are submitted every year from the protection units of electrical energy companies complaining about the failures. On the other hand, a suspended line without connection to any point endangers lives due to direct contact of humans or their vehicles with the phases suspended in the air and creates irreparable damages. Therefore, designing a suitable fault location algorithm without the need for transmission line parameters in this field is necessary. The independent performance of such an algorithm is considered as a very desirable advantage for a BCF location scheme.

1.4. Contributions

The main contribution of this paper is proposing a BCF location algorithm in electric power transmission lines based on the GMDH function fitting method using current and voltage measurement data of a terminal requiring no information regarding transmission line parameters. The scheme hypothesis presented in this paper is that the interrupted phase is identified by a BCF detection algorithm. Then the current and voltage data of the interrupted phase, which were calculated during the conductor breakage period using the full-cycle Fourier algorithm with a sampling frequency of 2.4 kHz, are used as inputs for the BCF location function calculated by the GMDH function fitting method to estimate the fault location. The GMDH function fitting method is performed by teaching and learning the GMDH network, and finally, a function was extracted as the BCF location estimation function based on the current and voltage phasors of the interrupted phase. The successful output results of the algorithm test given in the simulation results section confirm the correct performance of the algorithm proposed in this paper.

1.5. Organization of the Study

The paper is organized into eight sections. Section 1 presents the introduction to the topic. In Section 2, the GMDH structure analysis theory is fully described. Section 3 explains the theory of the proposed method in detail. Section 4 provides test results of software simulation. In Section 5 of the paper, the types of sensitivity analyses affecting the algorithm results are given. In Section 6, the discussion and comparison between the results of the proposed algorithm and its counterparts are presented. Section 7 presents research suggestions for future work, and finally, in Section 8, the conclusion is presented.

2. STRUCTURE OF GMDH

The GMDH function fitting method was first introduced in 1968 by Ivakhnenko [17]. The bases of this structure are the repetition of a series of simple mathematical operations to find the relationship between inputs and outputs and the establishment of layers in which low-impact parameters are removed and more effective parameters are transferred to the next layers. In general, it can be said that the process of output estimation is such that by combining small and simple components, it will be able to describe and analyze large and complex systems. In the GMDH structure, an attempt is made to determine the relationship between correlated inputs x and outputs y. This relationship can be expressed clearly using (1) [18-19]:

$$Y(x_1,\ldots,x_n) = a_0 + \sum_{i=1}^{m} a_i f_i \quad (1)$$

where, a_0 is the bias coefficient, a_i is the i-th weighting coefficients, and f_i is the i-th base function. In (1), the function $\hat{f}$ is supposed to be a good approximation of f so that for the inputs $X = (x_1, x_2, x_3, \ldots, x_n)$ we will have the outputs $\hat{y}$, which is a good approximation of y. The value of $\hat{y}$ will an approximation of the value of y, and it can be replaced with an acceptable amount of error. A set of partial models are fitted by the least-squares method, and we will achieve the optimal model using the initial models based on the considered indices. By cascading the previous models and applying them to the next models, the final model will be created. This process will continue until we reach the final optimal model. The principle behind the technique is defined by expressing a few sentences of Volterra, known as Kolmogorov-Gabor [17]:

$$Y(x_1,\ldots,x_n) = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n}\sum_{j=i}^{n} a_{ij} x_i x_j + \sum_{i=1}^{n}\sum_{j=i}^{n}\sum_{k=j}^{n} a_{ijk} x_i x_j x_k + \ldots \quad (2)$$

As can be seen, (2) will increase exponentially as the number of inputs increases and the system practically begins to become too complex to solve this problem by dividing the model into smaller problems and solving them separately. According to Ivakhnenko's theory, a relation can be calculated for both inputs from *n* inputs. For *n* inputs, we have $\binom{n}{2} = \frac{n(n-1)}{2}$ primary nodes, each of which is calculated based on (3):

$$\hat{y}_l = G_l(x_i, x_j) = c_0 + c_1 x_i + c_2 x_j + c_3 x_i^2 + c_4 x_j^2 + c_5 x_i x_j \quad (3)$$

where, index *l* denotes the number of the layer that creates the nodes, and coefficients *c* are the weights that establish the relationship between the two inputs and outputs. These nodes are the primary nodes created by the GMDH equations. In the next step, and to minimize the error, the algorithm uses (4) to properly fit $\hat{y}_m$.

$$E = \frac{\sum_{i=1}^{M} (y_i - G_i)}{M} \rightarrow \min \quad (4)$$

Based on (4), which is considered as the fitting condition, it is possible to reach the final optimal model from the initial models. Using this method, a set of outputs are fitted in each step and sent to the next step and a set of them will be deleted. Then, in the next step, according to (3) by employing the input values from the previous step, the relationship between the winning inputs will be compiled in pairs and the fitting will be done. These steps continue until a certain level of error or

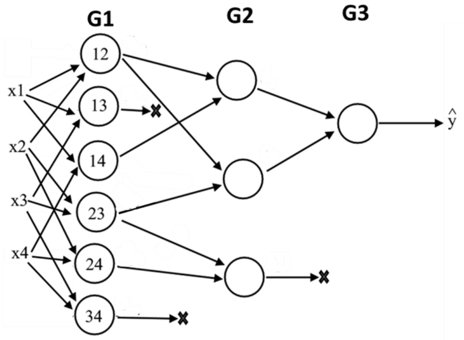


Fig. 1: Hypothetical structure of the considered GMDH network.

a certain number of layers is obtained. This problem can be represented graphically as in Fig. 1 [17-19].

To calculate coefficients C in (3), the problem can be analysed in matrix form. To this end, (3) can be rewritten as (5). Also, to simplify the calculations, (5) can be written in closed-form as given by (6):

$$\hat{y}_l = G_l = \begin{bmatrix} c_0 & c_1 & c_2 & c_3 & c_4 & c_5 \end{bmatrix} \begin{bmatrix} 1 \\ x_i \\ x_j \\ x_i^2 \\ x_j^2 \\ x_i x_j \end{bmatrix} \quad (5)$$

$$\hat{y}_l = G_l = C^T x \quad (6)$$

This equation should be rewritten for all inputs and outputs assuming the corresponding m:

$$Y_l = C^T X \quad (7)$$

In (7), Y as the outputs corresponding to X and C are the weighting coefficients of the function. To solve this equation, according to (8), both sides of the equation must first be multiplied by X^T and then by $(XX^T)^{-1}$.

$$YX^T = C^T XX^T \Rightarrow YX^T (XX^T)^{-1} = C^T XX^T (XX^T)^{-1} \quad (8)$$

In (8), as it is known, the right side of the equation, i.e., $XX^T(XX^T)^{-1}$, is equal to the unity matrix. Besides, if we show the final result of the matrix $X^T(XX^T)^{-1}$ as a matrix $X^\dagger$, then the constant coefficients of the final function can be calculated using (9):

$$YX^\dagger = C^T \quad (9)$$

Utilizing this solution, the values of the coefficients c_i in C^T are calculated and finally sent to (4) for fitting, and of the nodes in the next step will be formed step by step. The main point about the difference between GMDH and conventional neural networks concerns the topology form. Usually, in neural networks, the network topology is predetermined and the weights are calculated. However, in GMDH, as mentioned earlier, the network structure is organized by itself. Based on the fitting conditions, it will obtain the complexity required for describing the model. At the end of this section, as a complete summary of all the steps presented in this section, Fig. 2 illustrates the complete plan of the steps of the GMDH method. According to the proposed flowchart, the constant coefficients of (9) will eventually be calculated as the outputs of the GMDH algorithm.

3. Proposed Method

The main objective of this paper is to derive a function to determine the location of BCFs based on current and voltage phasors of the faulty phase. In general, protection of a transmission line consists of three basic stages. The fault detection stage is the phase of determining the faulty phase and the final stage is locating the fault point in the transmission line. In this paper, it is assumed that the time of fault incidence and the faulty phase are known and only the fault location problem is analyzed. Fig. 3 shows the electrical energy transmission line in the case of a broken conductor.

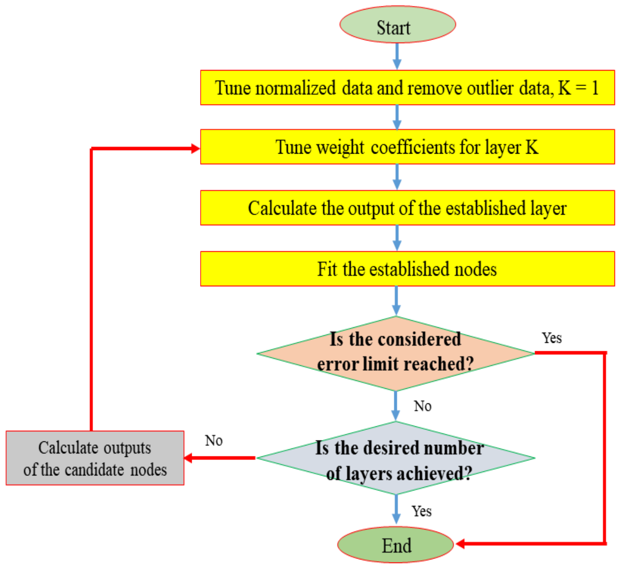


Fig. 2: Flowchart of GMDH network training and how constant coefficients of (3) are calculated.

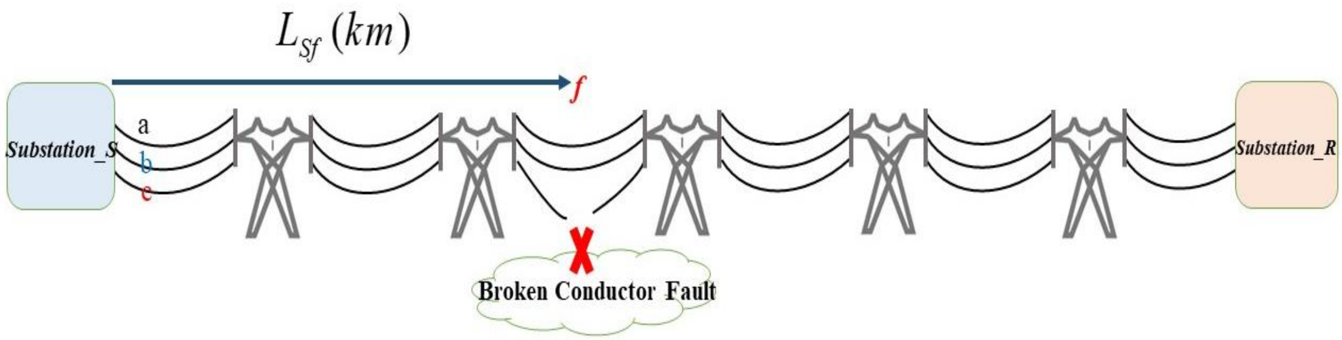


Fig. 3: Diagram of the electrical energy transmission line in case of a broken conductor.

According to Fig. 3, the ultimate goal in this scheme is to calculate L_{Sf} only by the current and voltage phasors of the local terminal S. The GMDH theory has been used to obtain the BCF location function. To achieve this, a sample transmission line has been used as a case study. The full data of the simulation system is given in the Appendix of the paper. To obtain the BCF location function in each phase based on the values of the current and voltage phasors of that phase, it is necessary to collect the current and voltage phasors of the faulty phase for specific spans of the transmission line. In this paper, it is assumed that the BCF phenomenon occurs for each phase with spans of 0.25 km, that the measurements of current and voltage phasors are the inputs to the problem, and that the fault location is used as the output for training the GMDH.

The magnitude of the current and voltage phasors considered in this paper have been calculated using the full-cycle Fourier algorithm with a sampling frequency of 2.4 kHz so that these 40 samples, in a complete cycle, are obtained after detecting the time of fault incidence from current and voltage waveforms. After storing the input and output data for each span of 0.25 km for each phase separately, BCF location can be used to train the GMDH network. Finally, the constant coefficients of the BCF location equation for each phase are extracted as follows:

$$L_{Sf\,(i=a,b,c)} = c_0 + c_1V_i + c_2I_i + c_3V_i^2 + c_4I_i^2 + c_5V_iI_i \qquad (10)$$

According to (2) and (5), a suitable approximation for calculating Y is provided in (10), where $L_{Sf\,(i=a,b,c)}$ is the length of the fault location in km, V_i denotes the voltage phasor magnitude of the faulty phase in volts, and I_i shows the current phasor magnitude of the faulty phase in amperes. In the end, according to the training and testing results of the GMDH network for the data collected for its training, constant coefficients of (10) are provided in the form of numbers in Table 1 for each phase when BCF occurs.

Fig. 4 shows the output diagram for the training data of the GMDH network for phase *a*. Fig. 4a illustrates the actual output value and the output value of the trained GMDH. As shown in this figure, the generated GMDHs perfectly follow the behaviour of the output data. Fig. 4b shows the difference between each sample and its true value as an error. Fig. 4c shows the histogram of the mean error and the standard deviation error of that data. Figs. 5 and 6 are the same as described in Fig. 4 but have been created and extracted for the data test and all the data. Also, the values of the regression coefficient for the training data, the test data, and all the data are calculated and displayed in Figs. 7a, 7b, and 7c, respectively.

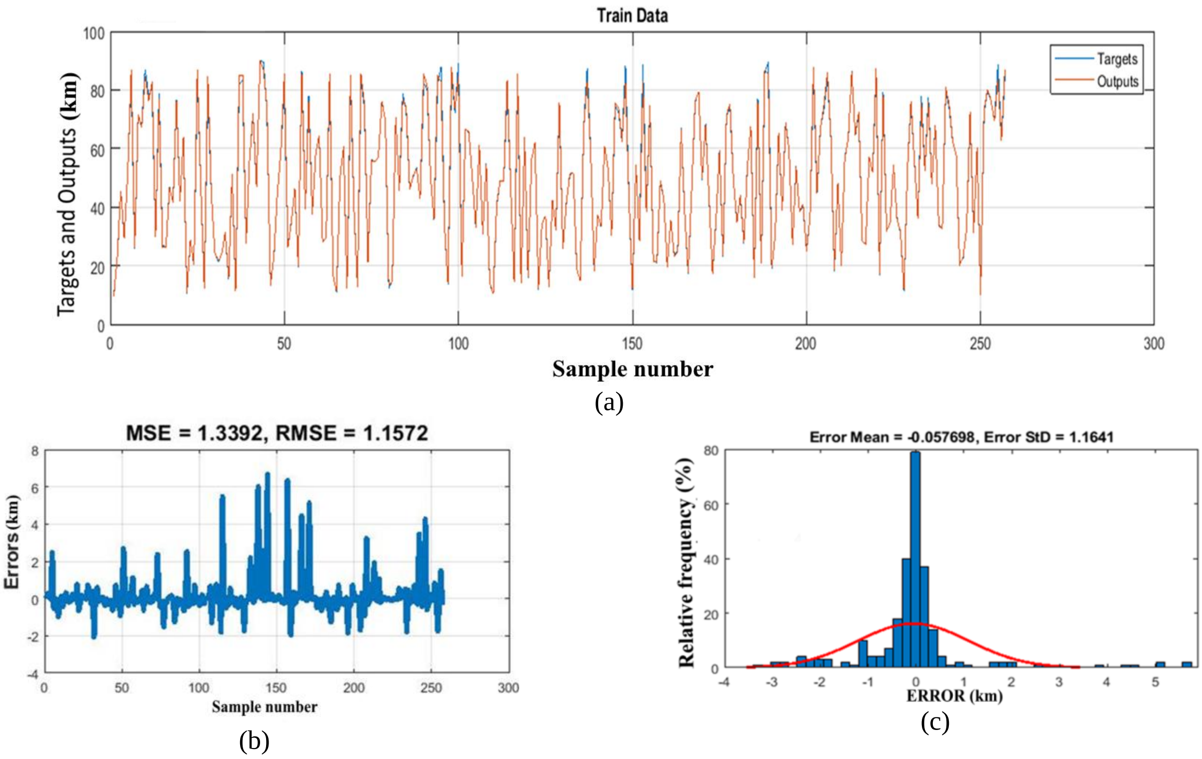


Fig. 4: (a) Random sample number training data and actual value, (b) error among output and actual value, and (c) the standard deviation error value histogram of phase *a*.

Table 1: Constant coefficients of the BCF location equation for each phase.

Coefficients	Faulty phase Phase a	Phase b	Phase c
c_0	-0.001807483476824	-0.000347153512442	0.000435823636190
c_1	0.001883852022470	-0.000729128826911	0.000060757724125
c_2	29.600376454232446	4.828049106209392	-5.292283067420200
c_3	-0.000000010043424	0.000000003885341	-0.000000000340196
c_4	0.000329108037455	0.000072001088415	-0.000849774628931
c_5	-0.000151549141822	-0.000019915640640	0.000034247064010

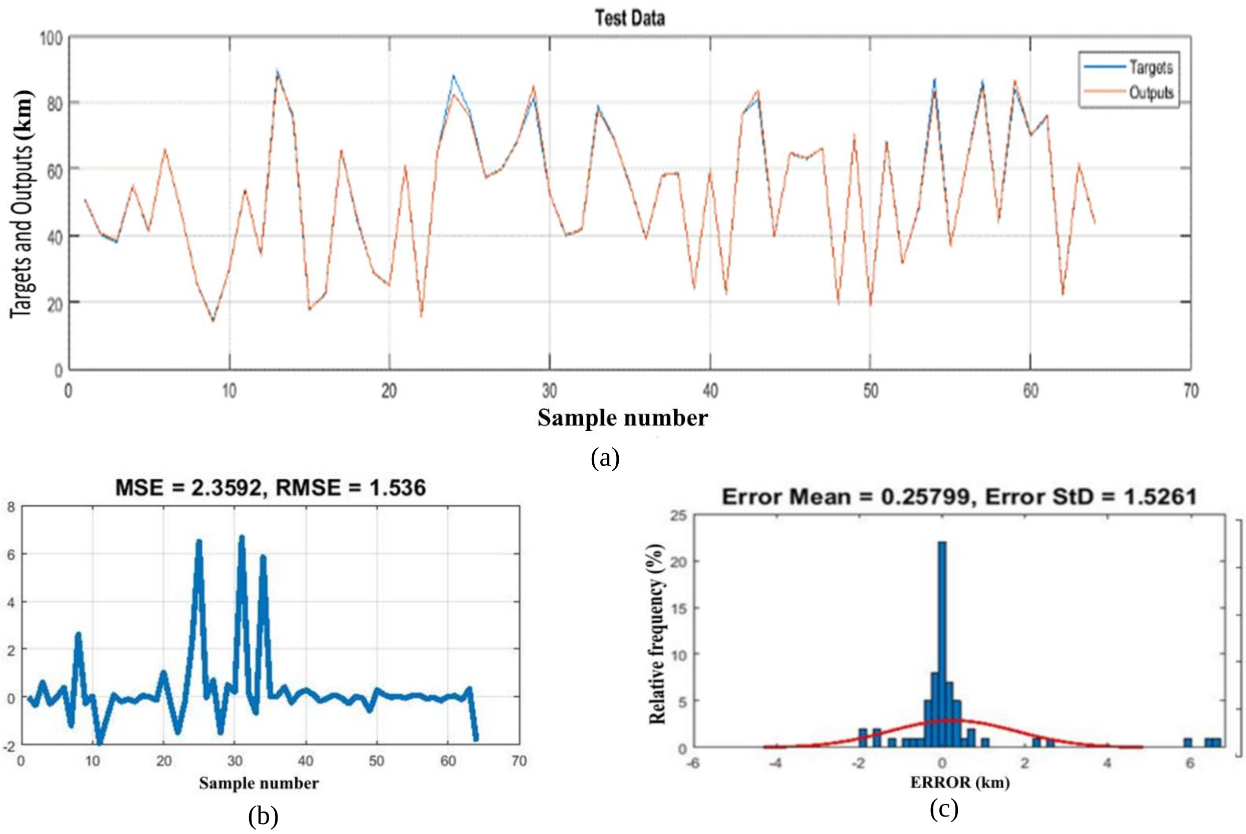


Fig. 5: Neuron analysis results of the test data of phase *a*. (a) Random sample number training data and actual value, (b) error among output and actual value, and (c) the standard deviation error value histogram

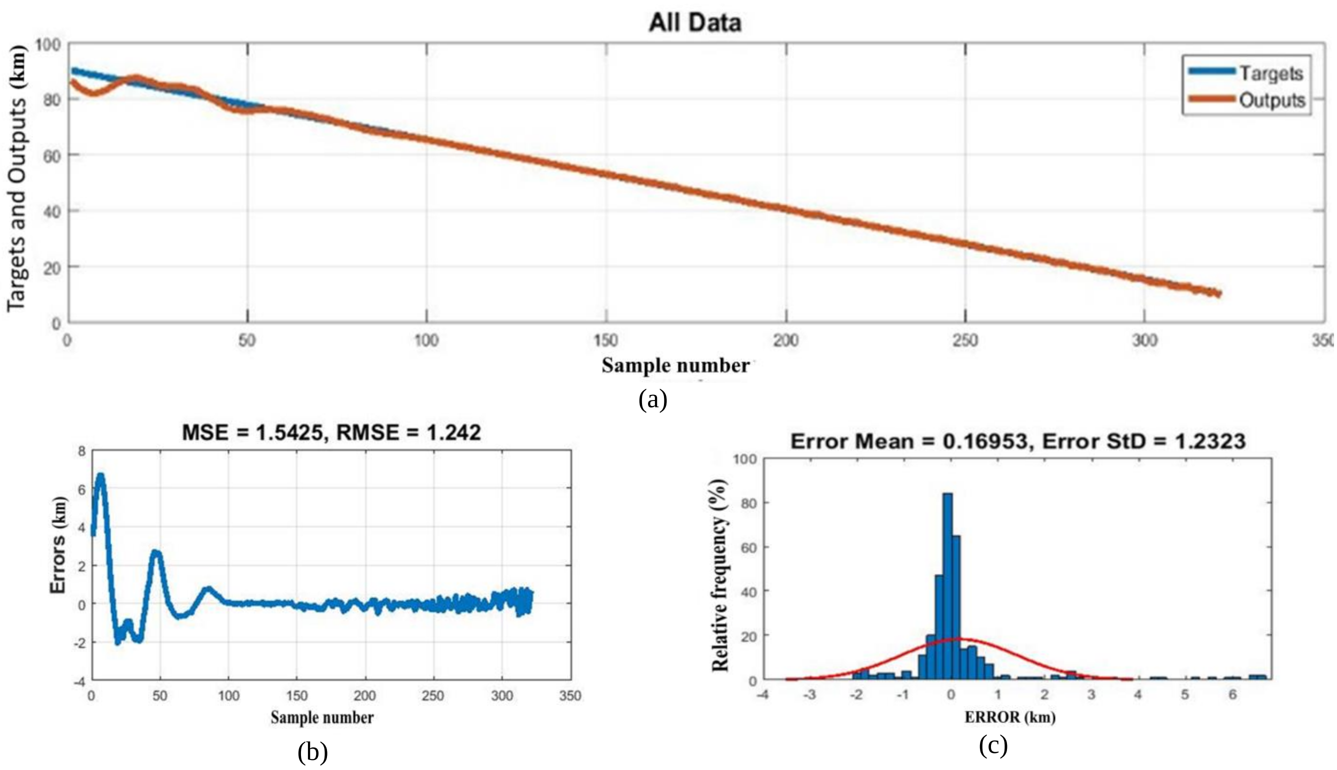


Fig. 6: Neuron analysis results of all the data of phase *a*, (a) Training data, actual value, (b) error among output and actual value, and (c) the standard deviation error value histogram.

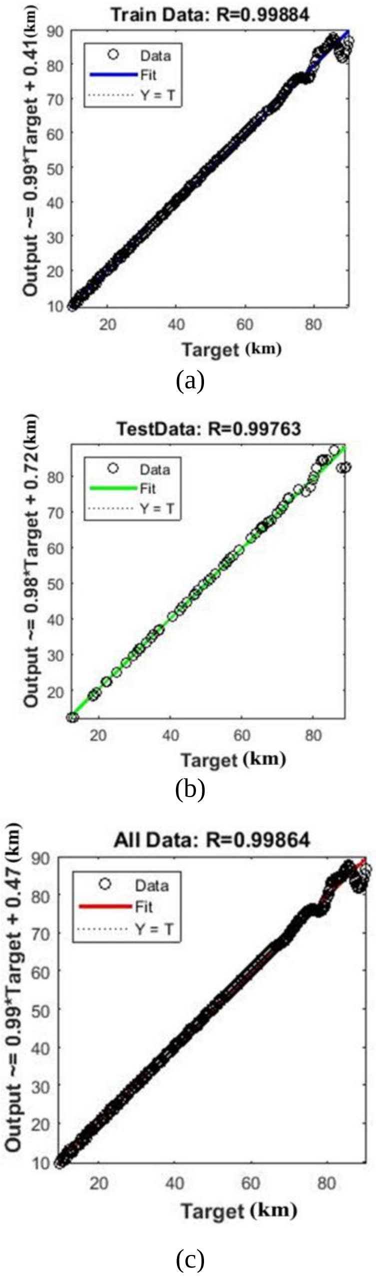


Fig. 7: Regression coefficient governing the (a) training data, (b) the test data, and (c) all the data of phase *a*.

The results presented in Figs. 4-7 correspond to the analysis of a BCF for phase *a*. The output results can be displayed in the same way for the other two phases, which are neglected due to similarity. Finally, using the BCF location function for each phase, the fault location can be calculated in proportion to the magnitudes of current and voltage phasors of the faulty phase. As it turns out, the presented function is completely independent of line parameters, and this is an advantage for the proposed scheme in this paper. Fig. 8 shows the final flowchart of the proposed BCF location scheme.

4. Simulation Results

This section presents the test results of the designed algorithm in MATLAB/Simulink environment. To test the algorithm, a bidirectionally-fed transmission line (see Fig. 9) has been used. The purpose is to implement several faults in different phases for different locations and to calculate the magnitudes of current and voltage phasors of the faulty phase in terminal S. These values can be used as input values for the function given in (10) to calculate the BCF location. According to the results tabulated in Table 2, the maximum fault location estimation error according to the proposed algorithm is +0.814%. The BCF location estimation error given in Table 2 is calculated using the equations given in [20-21]. the tolerance level of the system to the error can be considered by the calculated standard deviation value. To put it simply, if the input value differs from the specified value by the actual value, the generated GMDH structure will delete it and display the actual output value.

5. Sensitivity Analysis

This section investigates the sensitivity of the algorithm to some critical conditions in the power system. The selected scenarios are the most probable conditions that can have negative and destructive effects on fault location algorithms. This section also examines five critical scenarios to evaluate the robustness of the suggested algorithm.

5.1. Sensitivity Analysis with Respect to the Noise

The presence of noise in the power system and the measuring devices is undeniable. To investigate the effect of

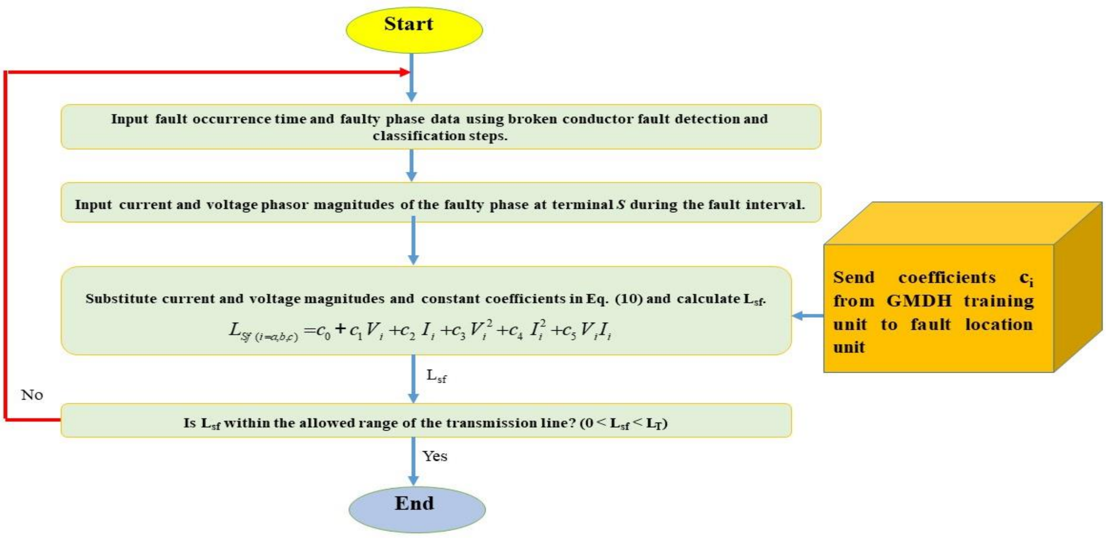


Fig. 8: Flowchart of a complete layout of BCF location in electrical power transmission lines.

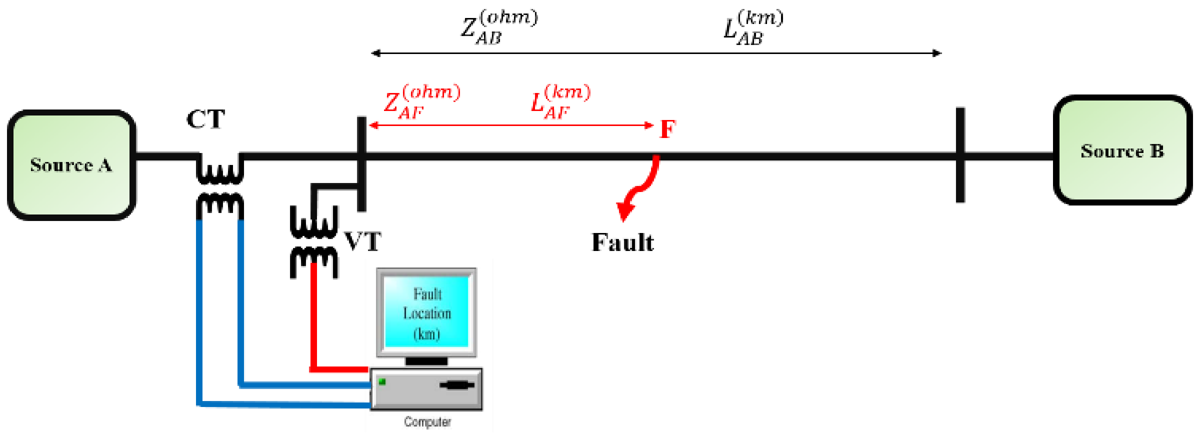


Fig. 9. Single-line diagram of the network under study.

Table 2: Test results of the proposed algorithm.

Faulty phase	V (V)	I (A)	Real value (km)	Algorithm test results (km)	Error (%)
a	187846.3	8.67981	10	9.3323	+0.667
	187937.4	23.3095	25.5	25.559	-0.059
	187996.5	31.7863	34.75	34.798	-0.048
	188111.3	54.9415	60	59.981	+0.018
	188249.6	80.1913	85	86.061	-1.061
b	187897.1	13.4925	15	14.837	+0.162
	187926.4	21.9055	24.25	24.003	+0.246
	188048.9	45.7785	50	50.008	-0.008
	188143.8	57.6458	62.75	62.909	-0.159
	188683.5	82.5139	95	94.005	+0.995
c	187862.2	9.52651	4	5.2051	-1.205
	187930.5	19.8844	21.75	21.811	-0.061
	188004.1	43.0578	47	47.180	-0.180
	188162.1	59.4319	64.75	64.835	-0.085
	188193.7	77.7361	83.5	83.864	-0.364

noise, the efficiency of the proposed method has been investigated for different signal-to-noise (SNR) ratios. This quantity represents the ratio of signal power to noise power that contaminates the signal in dB. White noise is used here to simulate the noise effects. To investigate this scenario, white Gaussian noise with different SNR ratios was added to the received current and voltage samples. The intended noise level is 30 dB. On the other hand, as can be seen in Fig. 6.c, In this case, it is assumed that a BCF occurs at a distance of 10 km from terminal S at t = 0.5 s in phase *c*. In this case, the calculated distance of fault from terminal S by the proposed algorithm is 9.09 km, where the estimation error is 0.91%.

5.2. Sensitivity Analysis with Respect to the Transformer Saturation

In this section, the sensitivity of the algorithm to the CT saturation installed in terminal S is investigated. The damping constant of the DC component for this CT is set 50 ms. This value is considered as the maximum critical value for this algorithm. The algorithm performs well for damping constants lower than 50 ms but it fails and shows poor performance for values higher than 50 ms. The detailed data of the CT can be found in [4]. In this case, it is assumed that a BCF occurs at a distance of 50 km from terminal S at t = 1.5 s in phase *a*. The damping constant of the DC component is assumed to be 48 ms. The calculated value for the fault distance from terminal S by the proposed algorithm is 49.17 km, where the estimation error is 0.83%.

5.3. Sensitivity Analysis with Respect to the Power Swing

Power swing is one of the most controversial issues in the protection of power systems due to the occurrence of some dynamic disturbances such as abrupt changes in electrical loads, irregular operation of reclosers, uncontrolled switching operations, phase-to-phase and phase-to-ground short circuits, etc. The occurrence of this phenomenon may lead to malfunctioning of distance relays and improper interruption of transmission lines, which endangers the stability of the power system. As a result, the malfunction of the remote relay should be prevented during power swing. To simulate the effect of power swing on the performance of the proposed method, we assume that the voltage phase angle starts fluctuating by 40° with 1° steps and with a frequency of 1 Hz in the generator located in terminal S. In this case, it is assumed that a BCF occurs at a distance of 70 km from terminal S at t = 2.8 s in phase *b*. The calculated value of the fault distance from terminal S using the proposed algorithm is 69.55 km, where the estimation error is 0.45%. In this case, it is assumed that a BCF occurs at a distance of 40 km from terminal S at = 3 s in phase *a*. The calculated value of the fault distance from terminal S in this case is 41.39 km, where the estimation error is 1.39%.

5.4. Sensitivity Analysis with Respect to a Harmonic-Polluted Voltage Source

The presence of harmonic power sources is one of the main challenges that affect all parts of the power system. The proposed scheme in this paper employs current and voltage phasors with the fundamental frequency of the system, i.e., 60 Hz, to solve the problem. These quantities are calculated by the phase measurement units (PMUs), installed at the measurement points, which are then given to the algorithm. Algorithms designed in PMUs use the discrete full-cycle Fourier theory along with the DC offset removal algorithm or a frequency filtering to calculate the fundamental frequency phasor. This section presents a scenario for analyzing the sensitivity of the algorithm to harmonic pollution. To investigate the effect of the harmonic current and voltage of terminal S, a harmonic voltage source with harmonic orders of 3, 5, 7, 9, 11, and 13 are connected to terminal S. In this case, it is assumed that a BFC occurs at a distance of 80 km from point S in phase *c*. The calculated value of the fault distance from terminal S by the proposed algorithm is 79.50 km, where the estimation error is 0.5%.

5.5. Sensitivity Analysis with Respect to the Changes in Transmission Line Parameters

The algorithm proposed in this paper is completely independent of the system parameters and the transmission line parameters. Referring to (10), the only inputs to the fault location function are the magnitudes of current and voltage phasors at terminal S during the BCF period. Therefore, changes in system parameters for any reason in any situation will not affect the performance of the proposed algorithm. In this scenario, it is assumed that after calculating the coefficients of the BCF location function by GMDH, positive- and zero-sequence parameters of the line are increased by 20%. To investigate the sensitivity of the algorithm to line impedance changes, it is assumed that a BCF occurs in phase *b* at 50 km from terminal S in t = 2 s. The calculated value of the fault distance from terminal S by the proposed algorithm is 49.63 km, where the estimation error is 0.47%.

5.6. Sensitivity Analysis of the Algorithm Performance in Low-Load Mode

In this section, the purpose is to investigate the performance of the algorithm in low -load mode. According to the network topology designed in this paper, both sides of the protected transmission line are modelled as Thevenin-equivalent circuits. To create low -load conditions in this topology, the magnitude and angle of the source voltages on both sides of the line must be controlled. Thereby, the active and reactive power flow will be controlled and thus the electric current flowing in the transmission line can be controlled. To implement this mode, the voltage magnitude and angle of the sources on both sides must be equalized. According to the information provided in the appendix of the paper, the voltage of the two sources is equal and it is only necessary to make the angle of the two sources equal, so the angle is set 9.2°. In this case, the amplitude of transmission line current is reduced from 2000 A (in the initial state of the simulation) to 100 A (in the case of low -loaded conditions).

To examine the results of the algorithm, in this case, three scenarios are considered, which are presented below.

Scenario 1. In this scenario, a phase interruption fault occurs in phase *a* at a distance of 50 km from station S. The values of faulty voltage and current phasors during the fault are 188061.853V and 45.227 A, respectively. According to (10) and constant coefficients presented in the first column of Table 1, the estimated distance for the fault location is 49.49 km from station S. The fault location estimation error in this case is 0.52%.

Scenario 2. In this scenario, a phase interruption fault occurs in phase *b* at a distance of 75 km from station S. The values of faulty voltage and current phasors during the fault are 188076.181V and 68.027 A, respectively. According to (10) and constant coefficients presented in the second column of Table 1, the estimated distance for the fault location is 74.25 km from station S. The fault location estimation error in this case is 0.75%.

Scenario 3. In this scenario, a phase interruption fault occurs in phase *c* at a distance of 90 km from station S. The values of faulty voltage and current phasors during the fault are 188103.753V and 81.775A, respectively. According to (10) and constant coefficients presented in the third column of Table 1, the estimated distance for the fault location is 88.72 km from station S. The fault location estimation error in this case is 1.28%.

Regarding the performed sensitivity analysis, one can observe that the proposed algorithm in this paper is robust against critical conditions and shows good performance.

6. Discussion and Comparison

This section aims to analyse and compare different BCF location algorithms in electrical power transmission lines with the results presented in the literature. Six basic indices are used to make this comparison, as introduced below.

Index 1: This index specifies the scope of problem analysis. As explained in the Introduction section, there are generally five areas of analysis to solve fault location problems, including phasor analysis (Ph), equation analysis in the time domain (TW), signal processing (SP) analysis, Teaching-Learning (TL) and Pattern extraction analysis, and communication-based (CM) analysis.

Index 2: This index determines the number of terminals from which current and voltage data is received. If the number of terminals is more than one, the number is determined using this index whether the data is synchronized or not.

Index 3: This index determines the sampling frequency rate in kHz.

Index 4: This index determines the dependence of the algorithm on system parameters.

Index 5: This index determines the coverage of the algorithm for all the three stages of line protection. In other words, the designed algorithm covers several stages of protection. The first stage is related to fault detection (FD), the second stage concerns fault classification (FC), and the third stage is fault location (FL).

Index 6: This index determines the average error value of the algorithm for all simulation output results.

Index 7: This index determines the level of implementation of the algorithm in terms of hardware.

Table 3: The analysis results of the proposed method and different literature.

Ref.	Index1	Index2	Index3	Index4	Index5	Index6	Index7
[5]	Ph	1	1000	✓	FD&FL	3.3	-
[6]	CM	many	NA	-	FD&FL	NA	✓
[7]	CM	many	NA	-	FD&FL	NA	✓
[8]	SP	1	NA	-	FD	NA	-
[9]	SP	1	NA	-	FD	NA	-
[10]	SP	1	256	✓	FD	NA	✓
[11]	SP	1	256	✓	FD	NA	✓
[12]	TL	1	1000	✓	FD&FC	NA	-
Proposed method	TL	1	2.4	-	FL	0.8	✓

According to the results listed in Table 3, the scheme presented in this paper can completely analyze the BCF location problem without requiring the transmission line parameters. It can also be implemented in industrial relays in terms of sampling frequency. Furthermore, the average error presented in this method is significantly low and appropriate as compared to the other methods.

7. FUTURE WORKS

As stated in this paper, the problem of protecting transmission lines against the broken conductor phenomenon is one of the major challenges in protection systems. Due to the special conditions of this type of fault, the design of the relay function to protect the line against this type of fault is different from normal shunt faults. According to the literature review conducted in the Introduction section, detecting these types of faults and discriminating them from low-load conditions constitute a major problem. On the other hand, locating these types of faults along the transmission line with specific topologies is a vital issue in the protection industry. The following are the suggestions of the authors for future research in this field:

A) Designing and presenting normal and series shunt fault detection algorithms relative to each other in transmission lines.

B) Designing a faulty phase detection algorithm when BCF occurs.

C) Designing detection, classification, and location algorithms for BCFs in transmission lines compensated with FACTS devices, series capacitor compensators, and single- or dual-terminal data.

8. CONCLUSION

This paper presents a complete scheme for broken conductor fault location in electric power transmission lines based on the GMDH function fitting method using single-terminal data without the need for transmission line parameter data. The scheme presented in this paper utilizes currents and voltage phasors of the faulty phase during the fault as the input to the fault location function. The collected data from each of the 0.25 km spans of the transmission line for each phase, once the fault occurred, is used to train the GMDH network. Eventually, a model is suggested for estimating the fault location based on the magnitudes of current and voltage phasors of one terminal during the fault without the need for transmission line parameters. BCF location equations for each phase are tested and analyzed for important factors under different scenarios in normal and fault conditions as well as critical conditions. The results in the Simulation and Sensitivity Analysis sections confirm the suitable performance of the proposed scheme. Additionally, based on the simulation results, the average error of location estimation is −1.205% and in the Sensitivity Analysis section, its value is 1.39%.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Mahyar Abasi: Conceptualization, Data curation, Formal analysis, Methodology, Software, Supervision, Validation, Roles/Writing - original draft, Writing - review & editing. **Nima Heydarzadeh:** Data curation, Investigation, Software, Visualization. **Arash Rohani:** Investigation, Project administration, Visualization.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

APPENDIX

Table 4 provides Simulink system data. The system under test is implemented in MATLAB ver.2018, and the line protection program is coded in an m file.

Table 4: Data of substations and transmission lines implemented in MATLAB software.

Substation Information					
Substation	V (kV)	F (Hz)	S (MVA)	X/R	Config.
S	230	60	9000	10	Yg
R	230	60	9000	10	Yg
Line Information					
$[R_1 , R_0]$ (Ohm/km)	[0.01273*2 , 0.3864]				
$[L_1 , L_0]$ (H/km)	[0.9337e-3 , 4.126e-3]				
$[C_1 , C_0]$ (F/km)	[12.74e-9 , 7.75e-9]				
Length (km)	100				
Frequency (Hz)	60				

REFERENCES

[1] A. Ghaderi, H. L. Ginn, and H. A. Mohammad pour, “High impedance fault detection: A review.” *Electric Power Systems Research*, vol. 143, pp. 376-388, 2017.

[2] B. Patel, and P. Bera, "Fast fault detection during power swing on a hybrid transmission line using WPT", *IET Generation, Transmission & Distribution*, vol. 13, no. 10, pp. 1811-1820, 2019.

[3] M. Abasi, S. G. Seifossadat, M. Razaz, and S. S. Moosapour, “Presenting a new Formulation to analyze and determine unbalance voltage produced at the place of load resulting from network and loads unbalance and asymmetry of transmission”, *Majlesi Journal of Energy Management*, vol. 4, no. 3, pp.1-7, 2015.

[4] A. Saffarian, and M. Abasi, “Fault location in series capacitor compensated three-terminal transmission lines based on the analysis of voltage and current phasor equations and asynchronous data transfer”, *Electric Power Systems Research*, vol. 187, 106457, 2020.

[5] K. Dase, S. Harmukh, and A. Chatterjee, "Detecting and locating broken conductor faults on high-voltage lines to prevent autoreclosing onto permanent faults", in *46th Annual Western Protective Relay Conference Spokane*, Washington 2019.

[6] S. H. Al-Ghannam, Y. Khan, U. Ahmad, N. H. Malik, A. A. Al-Arainy, and B. S. Al-Shahrani, "Development of open (broken) conductor detection system for high resistivity areas", in *2017 Saudi Arabia Smart Grid*, Jeddah, Saudi Arabia, IEEE, pp. 1-8, 2017.

[7] B. Nuthalapati, and U.K. Sinha, "Fault Detection and Location of Broken Power Line Not Touching the Ground", *International Journal of Emerging Electric Power Systems*, vol. 20, no. 3, pp.1-10, 2019.

[8] W. Johnson, "Nuclear maintenance application center: Development and analysis of an open-phase detection scheme for various configurations of auxiliary transformers," *EPRI, Palo Alto, CA, USA*, Rep. 3002000764, 2013.

[9] W. Johnson, "Interim report: EPRI open-phase detection method," *EPRI, Palo Alto, CA, USA*, Rep. 3002004432, 2014.

[10] X. Wang, T. Ding, and W. Xu, "An Open Conductor Condition Monitoring Scheme Using Natural Voltage and Current Disturbances", *IEEE Transactions on Power Delivery*, vol. 34, no. 3, pp. 1193-1202, 2019.

[11] X. Wang, and W. Xu, "A 3rd harmonic power based open conductor detection scheme", *IEEE Transactions on Power Delivery*, vol. 36, no. 2, pp. 1041-1050, 2021.

[12] A. M. Abdel-Aziz, B. M. Hasaneen, and A. A. Dawood. "Detection and classification of one conductor open faults in parallel transmission line using artificial neural network", *International Journal of Scientific Research & Engineering Trends*, vol. 2, no. 6, pp. 139-146, 2016.

[13] ABB, REL 521 Line distance protection terminal, ABB Technical brochure, 2003. [Online]. Available: https://library.e.abb.com/public/433f46304583cd01c12578570041e44b/1MRK506069-UEN_en_Technical_reference_manual_REL_521_2.3.pdf (accessed March 24, 2021).

[14] SIEMENS, AG. "SIPROTEC 4–Distance Protection 7SA6-Catalog", 2003. [Online]. Available: https://www.downloads.siemens.com/download-center/Download.aspx?pos=download&fct=getasset&mandator=ic_sg&id1=DLA06_4794 (accessed March 24, 2021).

[15] AREVA, "MiCOM P443 fast multifunction distance protection." [Online]. Available: https://download.schneider-electric.com/files?p_enDocType=User+guide&p_File_Name=P44y_EN_M_Kc3__K1__M.pdf&p_Doc_Ref=P44y_EN_M_Kc3_K1_M (accessed March 24, 2021).

[16] X. Song, F. Gao, Z. Chen, and W. Liu. "A negative selection algorithm-based identification framework for distribution network faults with high resistance", *IEEE Access*, vol. 7, pp. 109363-109374, 2019.

[17] A. G. Ivakhnenko, "Polynomial theory of complex systems." *IEEE Transactions on Systems, Man, and Cybernetics*, vol: SMC-1, no. 4, pp. 364-378, 1971.

[18] S.J. Farlow, *Self-organizing methods in modeling: GMDH type algorithms*. 1st ed., CRC Press, 1984.

[19] N. Narimanzadeh, A. Darvizeh, M. Darvizeh, and H. Gharababaei, "Modeling of explosive cutting process of plates using GMDH-type neural network and singular value decomposition", *Journal of Materials Processing Technology*, vol. 128, no. 1-3, pp. 80-87, 2002.

[20] A. Rohani, M. Joorabian, M. Abasi, and M. Zand, "Three-phase amplitude adaptive notch filter control design of DSTATCOM under unbalanced/distorted utility voltage conditions", *Journal of Intelligent & Fuzzy Systems*, vol. 37, no. 1, pp. 847-865, 2019.

[21] M. Abasi, A. Saffarian, M. Joorabian, and S. G. Seifossadat, "Fault location in double-circuit transmission lines compensated by generalized unified power flow controller (GUPFC) based on synchronous current and voltage phasors", *IEEE Systems Journal*, 2020 , to be published.

BIOGRAPHY

Mahyar Abasi was born in 1989 in Iran. He received the Ph.D. degree in Electrical Power Engineering in 2021 from the Shahid Chamran University of Ahvaz, Ahvaz, Iran. He is currently a research assistant in scientific and industrial research in the field of power electrical engineering at Shahid Chamran University of Ahvaz. His research interests are fault location, power system protection, FACTS devices, and power quality assessment.

Nima Heydarzadeh was born in 1990 in Iran. He received his B.Sc. degree in electronics engineering at Islamic Azad University of Arak Branch, Arak, Iran in 2012 and his M.Sc. degree in electronics engineering majoring in digital at Islamic Azad University of Central Tehran Branch, Tehran, Iran in 2020. He is currently working as a design engineer in the field of intelligent systems, automation, and instrumentation in engineering companies in Tehran, Iran. His scientific and professional interests are in the fields of artificial neural networks, deep learning, optimization algorithms, reverse engineering, and Industrial Motion Controller.

Arash Rohani received the B.Sc. and M.Sc. degrees in electrical engineering from the Shahid Chamran University of Ahvaz, Iran, in 2009 and 2013, respectively. Currently, he works for the Khuzestan Regional Electric Company. His research interests are Power Electronics, Power System Protection, and AC/DC microgrid.