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A novel neural network and backtracking based protection coordination scheme for distribution system with distributed generation

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A B S T R A C T

With the increased installation of renewable energy based distributed generations (DGs) in distribution systems, it brings about a change in the fault current level of the system and causes many problems in the current protection system. Hence, effective protection schemes are required to ensure safe and selective protection relay coordination in the power distribution system with DG units. In this paper, a novel adaptive protection scheme is proposed by integrating fault location with protection relay coordination strategies. An automated fault location method is developed using a two stage radial basis function neural network (RBFNN) in which the first RBFNN determines the fault distance from each source while the second RBFNN identifies the exact faulty line. After identifying the exact faulty line, then protection relay coordination is implemented. A new protection coordination strategy using the backtracking algorithm is proposed in which it considers the main protection algorithm to coordinate the operating states of relays so as to isolate the faulty line. Then a backup protection algorithm is considered to complete the protection coordination scheme for isolating the malfunction relays of the main protection system. Several case studies have been used to validate the accuracy of the proposed adaptive protection schemes. The results illustrate that the adaptive protection scheme is able to accurately identify faulty line and coordinate the relays in a power distribution system with DG units. The developed adaptive protection scheme is useful for assisting power engineers in performing service restoration quickly so as to decrease the total down time during faults.

1. Introduction

Electric power systems that are growing in size and complexities are always exposed to the various types of component failures [1]. To decrease the failure time and minimize the damages, the faulty element or possibly faulty region should be detected and disconnected from the rest of the system as fast and accurate as possible [2]. In the deregulated power systems, competition is particularly fostered in the generation side thus allowing increased connection of generating sources to the utility network. These generating sources are called as distributed generation (DG) units and defined as plants, which are directly connected to a distribution network and are not centrally planned and dispatched. The rating of DG units can vary between few kW to as high as 100 MW. Various new types of DG units are such as micro-turbines and fuel cells in addition to the more traditional solar and wind power systems [3,4]. Due to the increased presence of DG units in the radial distribution system and their influences on the protection coordination, many conflictions with the current protection procedures may arise such as false tripping of protective devices, protection blinding, increase and decrease of short circuit levels, undesirable network islanding and out-of-synchronism reclosers [5–7]. To overcome the aforementioned issues and improve the protection scheme of a distribution system with DGs, several protection coordination methods have been introduced. The earliest method is based on checking the protection coordination after connecting each DG to the network [8]. However, this approach is only applicable at the time of low penetration of DGs into the system. To solve the fuse coordination problem, a recloser-fuse coordination scheme using microprocessor-based reclosers was proposed [9]. Here, all DG units located in the recloser downstream network must be disconnected first before recloser takes place to avoid asynchronous connection. This solution is not appropriate if DG units are widely installed in a distribution network.

An adaptive protection scheme for optimal coordination of the overcurrent relays was introduced to allow adaptation and track the changes in load, generation or system topology [10]. Here, the linear programming technique is applied to coordinate the overcurrent relays in power system without considering the DG units. However, the effect of changes in the network reconfiguration due to DG connection on the system protection coordination is questionable. An expert system was used for protective relay coordination in radial distribution network with small DG units

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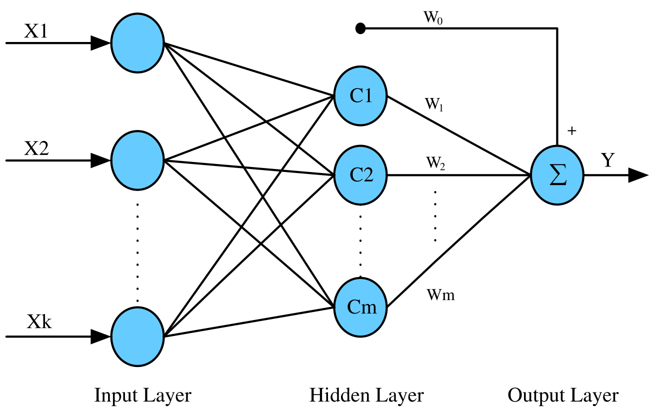

Fig. 1. A generic architecture of the RBFNN.

[11]. The method is useful for setting numerous protective relays in a distribution system. Nonetheless, this work has not properly considered the impacts of DG connections.

Another protection coordination strategy for DG embedded radial distribution networks was presented using microprocessor-based reclosers and feeder relays with directional elements so as to avoid using adaptive protective devices [12]. Since, increasing the number of installed DG units and the amount of injected energy by the DGs raise the ratio of DG penetration levels that can disturb coordination between the protection devices [13]. The drawback of the method in [12] is that it is not able to check the coordination between protective relays after connecting each DG in such distribution systems. A more recent protection scheme for a distribution network with DG units considers the application of multi-layer perceptron neural network (MLPNN) for fault location [14,15]. However, due to the structure and training algorithm of the MLPNN, the speed of this method is not suitable for fast and accurate protection.

To overcome the protection coordination problem in the presence of DG units, a more accurate and fast protection coordination strategy is required for coordinating the open/close states of the overcurrent relays so as to isolate the faulty line and protect the system. The first step in mitigating the impact of DG units in protection system is to quickly diagnose of the faults by identifying either the faulty bus or faulty line section. Without locating the

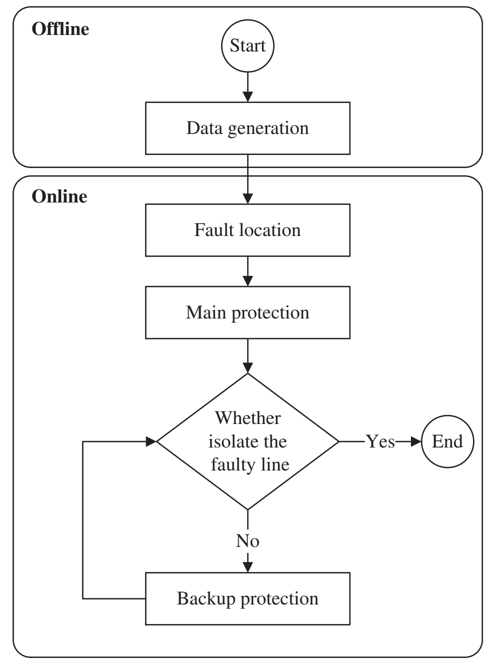

Fig. 3. Outline of the proposed adaptive protection scheme.

Table 1
Fault type classification data.

Fault type		I_a	I_b	I_c
1-Phase to ground	Ag	1	0	0
	Bg	0	1	0
	Cg	0	0	1
Phase to phase	AB	1	−1	0
	AC	1	0	−1
	BC	0	1	−1
2-Phase to ground	ABg	1	1	0
	ACg	1	0	1
	BCg	0	1	1
3-Phase	ABC	1	1	1

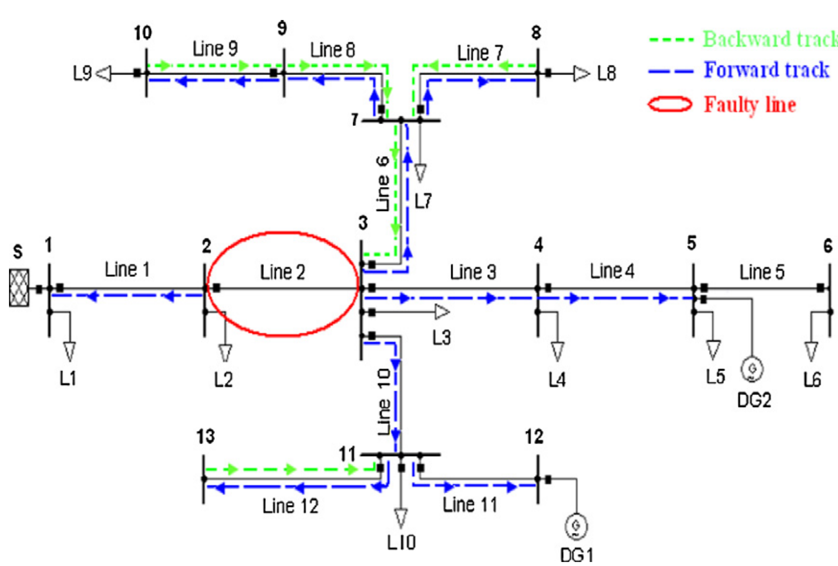

Fig. 2. The backtracking search in a distribution network with DG units.

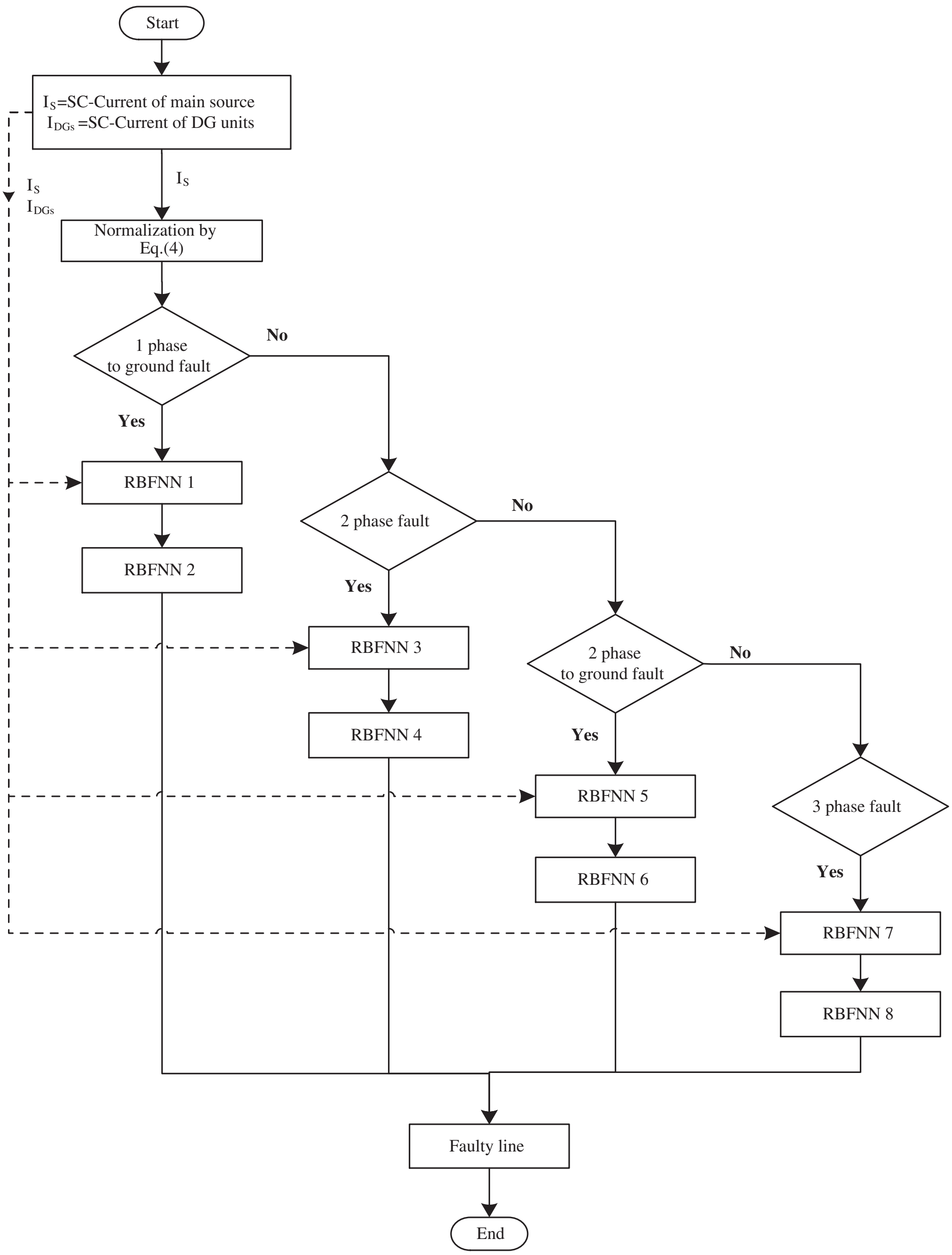

Fig. 4. RBFNN implementation for fault location.

faulty section, no attempt can be made to remove the faults and restore the power system. While, the second step is to coordinate the protection relays to isolate the faulty section in the minimum possible time and allow normal operation to the rest of the system. This paper presents a novel adaptive protection scheme for a distribution system equipped with DG. In the proposed protection scheme, fault location is integrated with protection relay coordination strategies. An automated fault location method has been developed using the two staged radial basis function neural network (RBFNN) in which the first RBFNN determines the fault distance from each source, while the second RBFNN identifies the exact faulty line. After identifying the exact faulty line, then protection relay coordination is implemented. A new protection coordination strategy using the backtracking algorithm is proposed in which it considers the main protection algorithm to coordinate the operating states of relays so as to isolate the faulty line. Finally, a backup protection coordination algorithm is introduced to complete the protection coordination scheme in case of failure in the primary protection scheme. The proposed method using the two staged RBFNN is better than the single staged neural network [12,13] because it is able to accurately determine the exact faulty line, which the previous neural network based methods cannot.

2. Theoretical background

This section presents the background theory of the radial basis function neural network and the backtracking algorithm, which are used in the proposed adaptive protection scheme for distribution network with DG units.

2.1. Radial basis function neural network

The RBFNN is a feed-forward neural network consisting of three layers, namely, an input layer which feeds the values to each of the neurons in the hidden layer, a hidden layer which consists of neurons with radial basis activation functions and an output layer which consists of neurons with linear activation function [16]. Different basis functions like spline, multi-quadratic, and Gaussian functions have been studied, but the most widely used one is the Gaussian function. The Gaussian RBFNN is found not only suitable in generalizing a global mapping but also in refining local features without altering the already learned mapping [17]. In comparison to the other types of neural network used for pattern classification like MLPNN, the RBFNN requires less computational time for learning and has a more compact topology. A generic architecture of RBFNN with k input and m hidden neurons is shown in Fig. 1.

For the training of the RBFNN, the following computations are considered. When the network receives a k dimensional input vector, X, the network computes a scalar value using,

$$Y = f(X) = W_0 + \sum_{i=1}^{m} W_i \varphi(D_i) \tag{1}$$

where W_0 is the bias, W_i is the weight parameter, m is the number of neurons in the hidden layer and (D_i) is the RBF.

In this study, the Gaussian function is used as the RBF and it is given by

$$\phi(D_i) = \exp\left(\frac{-D_i^2}{\sigma^2}\right) \tag{2}$$

where σ is the radius of the cluster represented by the center node (Spread), D_i is the distance between the input vector X and all the data centers.

The Euclidean norm is normally used to calculate the distance, D_i which is given by

$$D_i = \sqrt{\sum_{j=1}^{k} \left(X_j - C_{ji}\right)^2} \tag{3}$$

where C is a cluster center for any of the given neurons in the hidden layer [18].

The implementation procedures in the training of the RBFNN are presented as follows:

Step 1: Obtain input data and target data from the simulation.
Step 2: Assemble and pre-process the training data for the RBFNN.
Step 3: Create the network object and train the RBFNN until the condition of network setting parameters are reached.
Step 4: Store the weights of the trained RBFNN.
Step 5: Test the trained RBFNN with the pre-processed testing data.

Steps 1 to 4 are usually performed offline while step 5 is an online process for testing with new input sets of data.

2.2. Backtracking algorithm

The backtracking algorithm which is based on heuristics is an optimal search method satisfied with certain constraint conditions [19]. It is a systematic search method of solution to the problem in which the searching method is realized by multi-stage confirmed step by step. At every stage, a branch is picked out from multi-selection branches. The algorithm must backtrack to the searched node and select other node once the finding solution is nonexistence. If all branches of this node are tried and there is no solution, then the procedure must backtrack to the quondam node which is named as the backtracking node satisfied with the backtracking

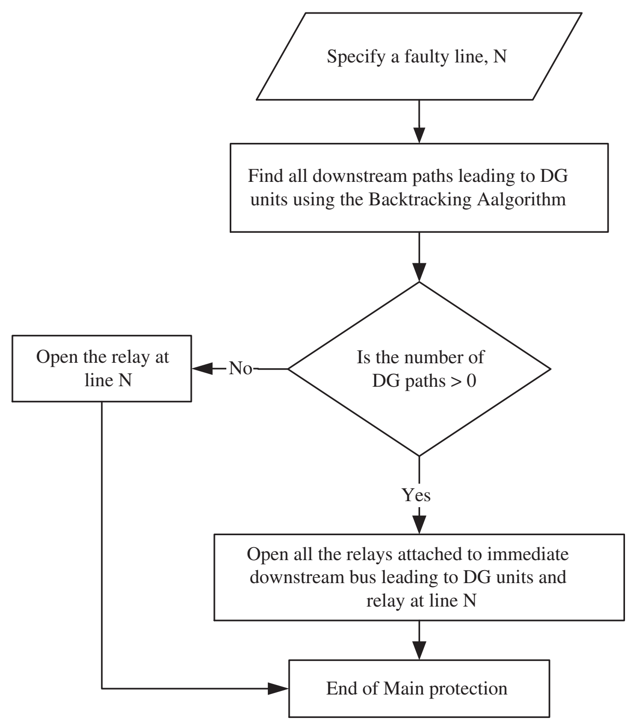

Fig. 5. Main protection algorithm for relay coordination.

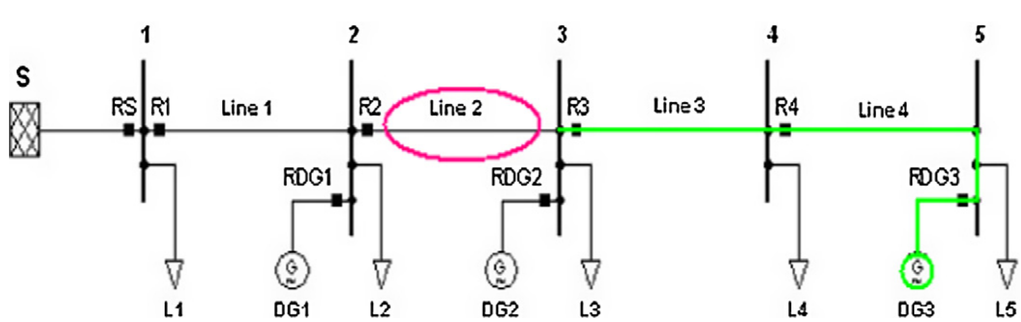

Fig. 6. Simple radial distribution network with a fault in line 2.

condition [19]. Therefore, the backtracking algorithm is able to search for a solution by moving forward, and if the algorithm cannot find a solution, another combination can be checked by backtracking to find the solution. Backtracking has been extensively studied and has long been used as a strategy for solving combinatorial problems [20,21]. The major advantage of the backtracking algorithm is that it is systematic and can guarantee to find a consistent solution given enough time [22].

In this study, the backtracking algorithm is applied for determining the location of DG units when a fault occurs in a distribution system with DG units. Finding the feasible solution for the problem can be formulated in terms of finding a solution path in

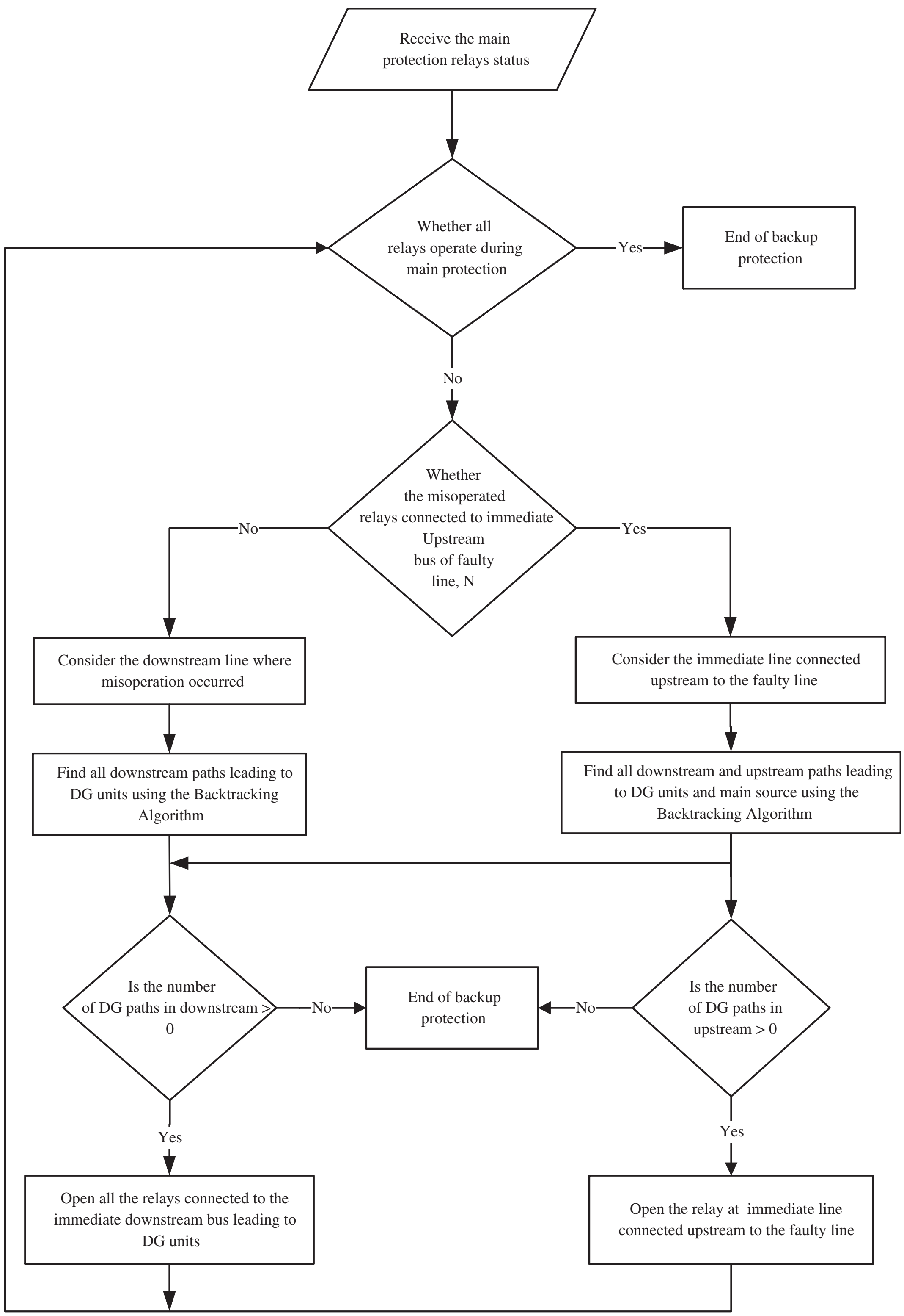

Fig. 7. Backup protection algorithm for relay coordination.

an implicit directed state-space tree from an initial bus to a goal bus. The search begins by expanding the initial bus and generating its successor. At each later step, one of the last generated buses is expanded. If the last generated bus does not have any successors or DG unit, then another path can be checked by backtracking and if the last generated bus has a DG unit, the searching algorithm should stop at that path. Fig. 2 illustrates the backtracking search algorithm in a sample distribution network with two DG units. From the figure, the backtracking algorithm begins at the faulty line which is line 2 and the search for DG units in the next buses are through lines 1, 3, 6 and 10 as four independent paths. If the detected bus at each path does not have any DG unit, the next bus in the path should be checked. In this example, this procedure continues until detecting the paths leading to the main source S, DG1 and DG2. It should be noted that the algorithm used backtracking at bus 8, 10, and 13 because these buses are the last bus in the path without DG unit.

3. Proposed adaptive protection scheme

Fig. 3 shows the outline of the proposed adaptive protection scheme for a distribution network with multiple DG units. An important consideration in protection of distribution networks is to first determine the type and location of faults occurring in its protection zone. Here, the protection scheme considers offline step for data generation and three online steps in which the first online step is to identify the fault type by using the normalized currents, and determine the exact fault location in terms of the faulty line number. The second step applies the main protection algorithm to isolate the faulty line and the final step applies the backup protection algorithm to complete the protection coordination scheme in case of failure in the main protection scheme.

3.1. Data generation for RBFNN

Before executing the protection procedure, it is necessary to perform power flow and short circuit analyses so as to generate training data for the RBFNNs. The DIgSILENT Power Factory 14.0.524 software was used for simulating various types of faults created at every 100 meter of each line. From the simulation outputs, the currents flowing through the main source and all DG units at the time of fault occurrence are selected as input variables for the RBFNN. The fault distance from each source and the faulty line number are regarded as outputs of the RBFNNs.

Note that in case of motor starting conditions, it is assumed that the relay settings have reasonable time delay so that the produced inrush current caused by motor starting can be identified from short circuit current.

3.2. Fault type classification

The first step in the fault location procedure is to identify the various types of faults using the normalized currents of the main source. At normal operating condition, the sum of current contribution from all sources is equal to the total load current. When a fault occurs at any point, fault current will be significantly larger than the total load current. Thus, a comparison between the total currents of generators and loads can be used for the detection of fault conditions. To identify the various fault types, the three phase currents of the main source from the feeding substation are used. The three phase output fault currents at the main source or the feeding substation are normalized using,

$$I_{normal} = \frac{I_f}{I_{\max}} \tag{4}$$

where I_f is the fault current and $I_{\max}$ is the maximum fault currents for each type of fault.

Based on the normalized three phase fault currents and rounding the obtained values to the nearest one, the types of faults can be classified as shown in Table 1 [23]. From the table, “1”, “−1” and “0”, indicate that a fault occurs in the phase, a fault occurs in the phase but the short circuit current is in the opposite direction and no fault, respectively. The symbols Ag, Bg and Cg indicate the single phase to ground faults for phase A, B and C, respectively while symbols AB, AC and BC indicate the phase to phase faults for the respective phases. Consequently, symbols ABg, ACg and BCg indicate 2 phase to ground faults for the respective phases.

3.3. Determination of faulty line

After identifying the fault type, the fault location has to be determined. In this study, an automated fault location scheme for a distribution network with DG units using the RBFNN) is presented. RBFNN is considered to be a better neural network model for solving engineering problems. Furthermore, to increase the selectivity of the proposed protection system, the two staged RBFNNs have been developed in which the first RBFNN is for determining fault distances from the main source and each DG units (RBFNN 1, 3, 5, 7) and the second RBFNN (RBFNN 2, 4, 6, 8) is for determining the faulty line for the respective fault types [24]. Fig. 4 shows the procedures in determining the fault location. From the figure, for each fault type, first the three phase currents of main source and all the DG units are used as inputs to the first RBFNN. The outputs of the first RBFNN, which are the distances of fault from the main source and the DG units, are then used as inputs to the second RBFNN. Hence, the output of the second RBFNN is the exact faulty line.

3.4. Main protection algorithm

After identifying the faulty line using the RBFNN method, the main protection algorithm starts by determining all the downstream paths leading to DG units using the backtracking algorithm. In the presence of any DG unit in the downstream path, a signal is sent to open relay at the faulty line, N as well as all the relays attached to the immediate downstream bus leading to the DG units.

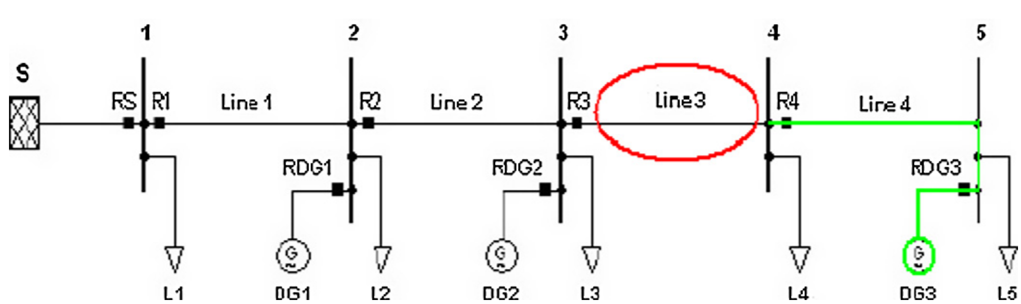

Fig. 8. A fault in line 2 and misoperated relay R3.

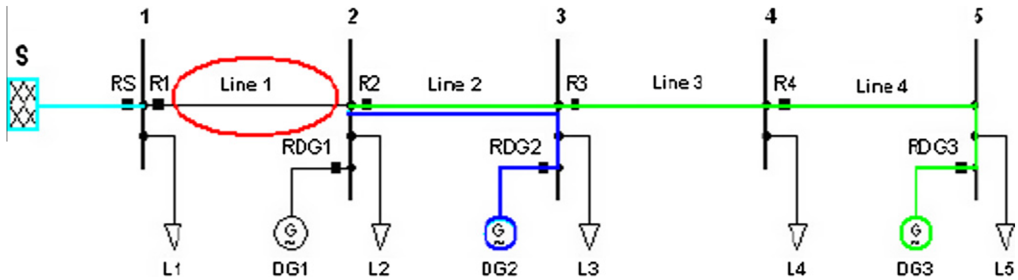

Fig. 9. A fault in line 2 and misoperated relay R2.

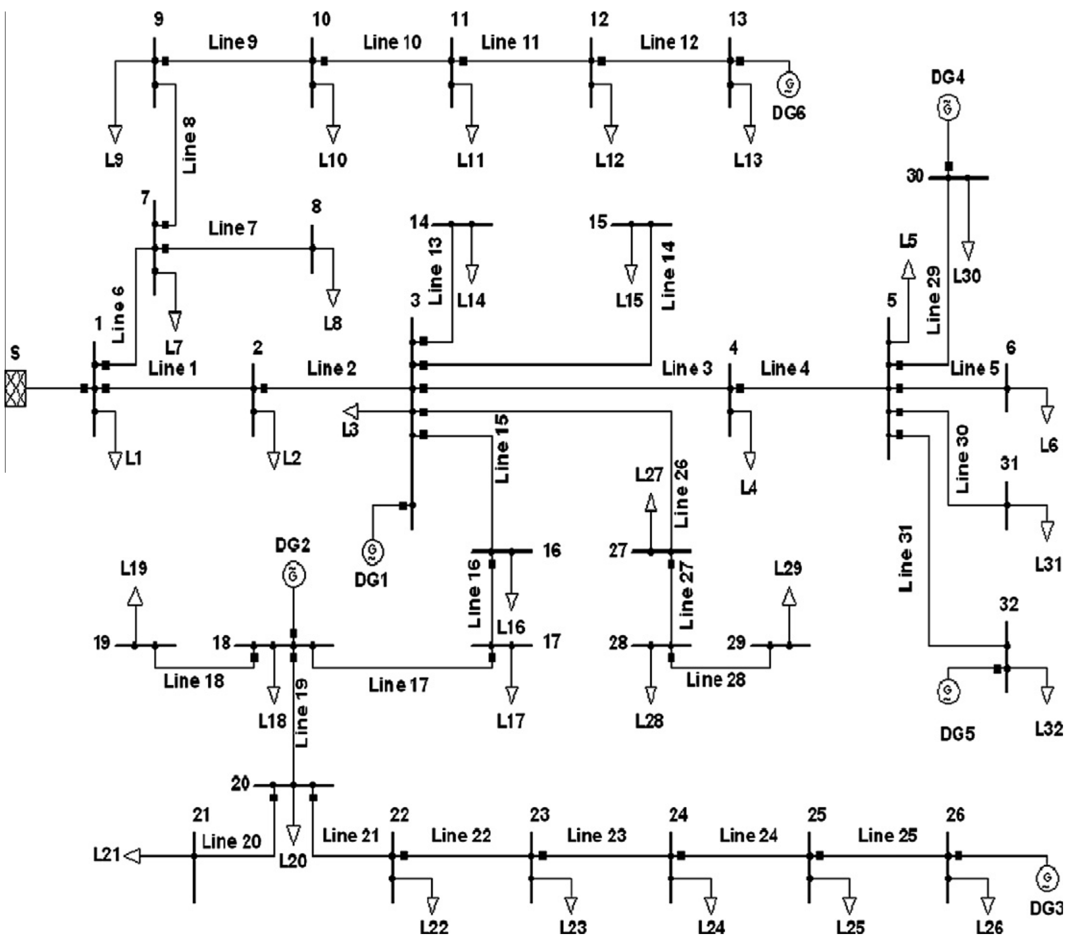

Fig. 10. Single line diagram of the 32 bus test system.

Table 2
Description of inputs and outputs of the RBFNN for the 32-bus test system.

RBFNN no.	Number of input neurons	Input variables	Number of output neurons	Output variables
1, 3, 5, 7	21	3 Phase short circuit current of main source and 6 DG units	7	Fault distances from the main source and 6 DG units
2, 4, 6, 8	7	Fault distances from main source and 6 DG units	1	Faulty line

Table 3
Training performances of the RBFNNs for the 32 bus test system.

Fault type	RBFNN	Goal	MSE
1-Phase to ground	RBFNN 1	0.0001	5.68e−005
	RBFNN 2	0.0001	2.25e−005
Phase to phase	RBFNN 3	0.0001	6.53e−005
	RBFNN 4	0.0001	4.94e−005
2 Phase to ground	RBFNN 5	0.0001	8.47e−005
	RBFNN 6	0.0001	7.56e−005
3 Phase	RBFNN 7	0.0001	8.45e−005
	RBFNN 8	0.0001	6.75e−005

Table 4
Fault location results using RBFNN.

Sample	Fault type	Identified fault location							
		RBFNN 1, 4, 7, 10							RBFNN 2, 5, 8, 11
		Distance from main source (km)	Distance from DG1 (km)	Distance from DG2 (km)	Distance from DG3 (km)	Distance from DG4 (km)	Distance from DG5 (km)	Distance from DG6 (km)	Faulty line no.
250 m of line 2	1 Ph-G	1.245	0.745	3.753	9.748	3.744	3.746	7.251	2.08
	2 Ph	1.254	0.749	3.751	9.751	3.749	3.748	7.251	2.03
	2 Ph-G	1.253	0.751	3.750	9.754	3.750	3.751	7.255	1.99
	3 Ph	1.248	0.759	3.752	9.750	3.752	3.755	7.250	2.02
	Actual	1.250	0.750	3.750	9.750	3.750	3.750	7.250	2
550 m of line 4	1 Ph-G	3.545	1.551	4.553	10.545	1.454	1.451	9.553	4.02
	2 Ph	3.546	1.550	4.552	10.551	1.451	1.454	9.560	3.99
	2 Ph-G	3.551	1.548	4.551	10.552	1.453	1.452	9.559	4.00
	3 Ph	3.553	1.546	4.548	10.555	1.455	1.457	9.558	4.01
	Actual	3.550	1.550	4.550	10.550	1.450	1.450	9.550	4
480 m of line 8	1 Ph-G	1.483	3.486	6.489	12.478	6.476	6.481	4.517	8.03
	2 Ph	1.484	3.485	6.487	12.476	6.479	6.486	4.510	8.05
	2 Ph-G	1.486	3.488	6.486	12.481	6.481	6.483	4.519	8.00
	3 Ph	1.481	3.480	6.488	12.479	6.487	6.488	4.521	8.01
	Actual	1.480	3.480	6.480	12.480	6.480	6.480	4.520	8
870 m of line 12	1 Ph-G	5.867	7.872	10.878	16.867	10.878	10.879	0.128	11.98
	2 Ph	5.861	7.871	10.871	16.861	10.874	10.871	0.129	11.96
	2 Ph-G	5.878	7.876	10.874	16.865	10.870	10.873	0.131	12.01
	3 Ph	5.871	7.879	10.871	16.871	10.879	10.865	0.132	12.08
	Actual	5.870	7.870	10.870	16.870	10.870	10.870	0.130	12
350 m of line 15	1 Ph-G	2.351	0.345	2.657	8.651	3.351	3.352	8.351	15.05
	2 Ph	2.354	0.353	2.651	8.655	3.357	3.354	8.354	15.01
	2 Ph-G	2.352	0.352	2.659	8.657	3.353	3.356	8.358	15.02
	3 Ph	2.349	0.356	2.652	8.645	3.358	3.357	8.359	15.09
	Actual	2.350	0.350	2.650	8.650	3.350	3.350	8.350	15
790 m of line 21	1 Ph-G	6.789	4.796	1.795	4.211	7.798	7.791	12.783	20.91
	2 Ph	6.788	4.797	1.793	4.209	7.794	7.793	12.788	21.01
	2 Ph-G	6.787	4.790	1.793	4.210	7.796	7.794	12.799	21.10
	3 Ph	6.799	4.793	1.791	4.220	7.791	7.795	12.791	21.03
	Actual	6.790	4.790	1.790	4.210	7.790	7.790	12.790	21
690 m of line 28	1 Ph-G	4.684	2.691	5.691	11.698	5.694	5.693	10.699	28.04
	2 Ph	4.692	2.693	5.693	11.694	5.687	5.686	10.685	28.01
	2 Ph-G	4.698	2.699	5.692	11.692	5.691	5.699	10.697	28.07
	3 Ph	4.690	2.692	5.699	11.695	5.690	5.692	10.692	28.05
	Actual	4.690	2.690	5.690	11.690	5.690	5.690	10.690	28

Otherwise, the control signal is only sent to the relay at the faulty line. Fig. 5 illustrates the implementation procedure of the proposed main protection algorithm for relay coordination in terms of a flowchart.

To illustrate the implementation of the main protection algorithm, a simple test system is considered as shown in Fig. 6. From the figure, if a single line fault occurs in line 2, after identifying the faulty line using the RBFNN method, the main protection algorithm then determines the downstream path leading to DG units using the backtracking algorithm as shown by the path in green color. A signal is then sent to trip the relay at the faulty line, R2 as well as all the relays, R3 and RDG2, which are attached to the immediate downstream bus leading to the DG unit. By tripping all these relays, the faulted line 2 will be isolated by using the main protection algorithm.

3.5. Backup protection algorithm

In case of misoperation of the main protection relay, the backup protection relay is activated from its standby mode to protect the network. For this purpose, the location of the misoperated relay should be determined, which is either at the immediate upstream or downstream bus of the faulty line, N. If the relay is located at the immediate upstream bus of the faulty line, all downstream and upstream paths leading to the DG units and the main source related to upstream line of this bus are determined by using the backtracking algorithm. In the presence of any DG or source in the downstream and upstream path, a signal is sent to open the related relays attached to the immediate buses of that line leading to the DG unit or the main source. While, if a misoperated relay is located at the immediate downstream bus of the faulty line, all the downstream paths leading to the DG units of this line are determined by using the backtracking algorithm. However, in the presence of any DG in the downstream path, a signal is sent to trip all the relays connected to the immediate downstream bus leading to the DG units. Otherwise, the backup protection is considered terminated. The above-mentioned process is continued until achieving absolute isolation of a fault. Fig. 7 shows the flowchart of the proposed backup protection algorithm for relay coordination.

To illustrate the implementation of the backup protection algorithm, consider the simple test system as shown in Fig. 8. Firstly, determine the location of the misoperated relay, which is placed at either immediate upstream or downstream bus of the faulty line, line 2. For example, if R3 does not trip in the main protection algorithm, the backup protection will consider line 3, which is the immediate line downstream to the faulty line. Using the backtracking algorithm, a downstream path leading to the DG unit, DG3 is determined as indicated by the green[1] colour in Fig. 8. Then, a signal is sent to trip the relay, R4 which is connected to the imme-

[1] For interpretation of color in Figs. 1, 2, 6, 8, 9, 11, the reader is referred to the web version of this article.

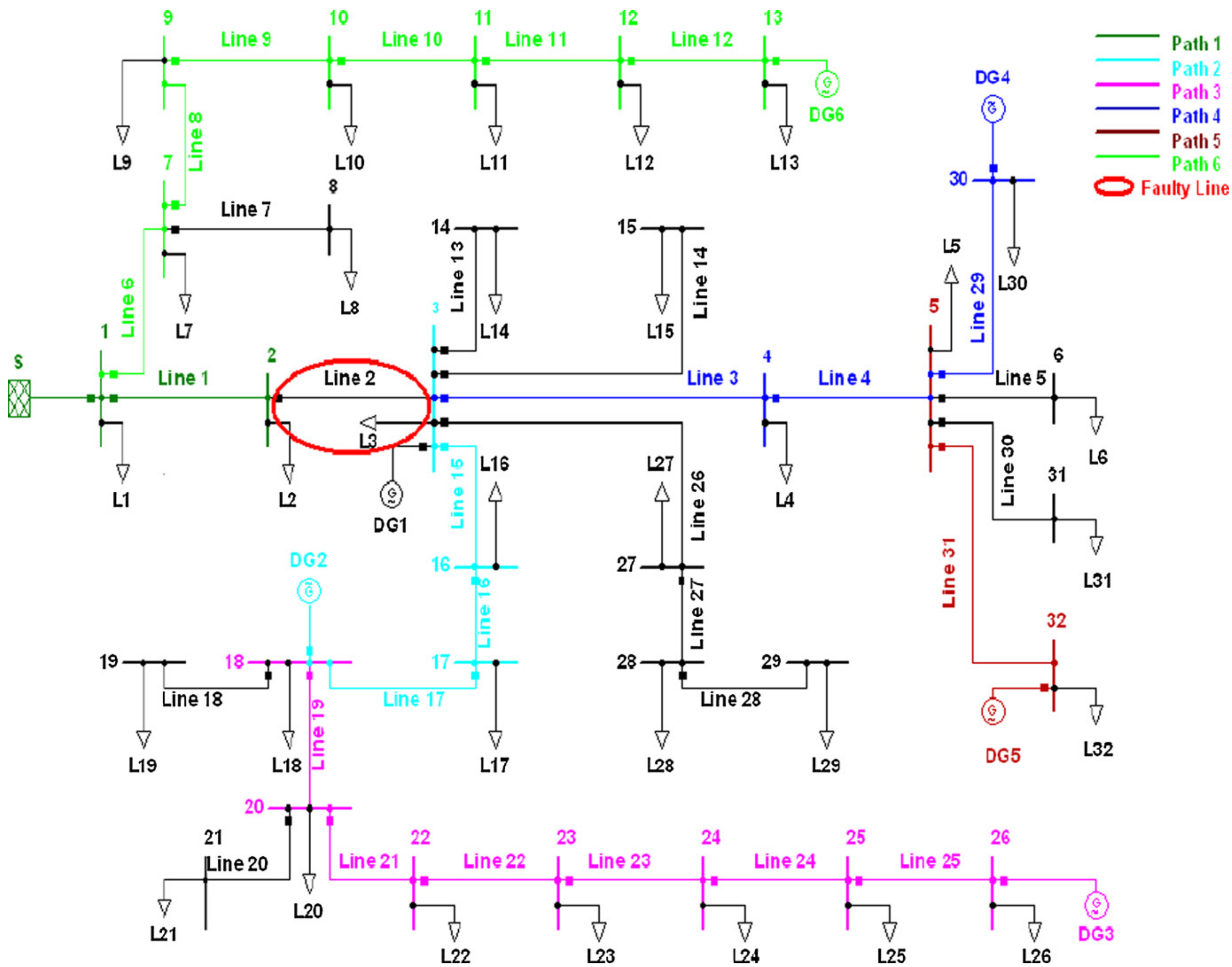

Fig. 11. The 32 bus test system with 2 upstream and 4 downstream paths for a fault in line.

diate downstream bus leading to the DG unit, DG3.

If the misoperated relay, R2 is located at the immediate upstream bus of the faulty line, line 2, the backup protection will consider line 1, which is the immediate line upstream to the faulty line as shown in Fig. 9. Using the backtracking algorithm, two downstream paths leading to the DG units and one upstream path leading to the main source are determined as shown in Fig. 9. Then, a signal is sent to trip relay, R1, as well as relay, RDG1 that is connected to the immediate downstream bus leading to the DG unit. The above-mentioned process continues until achieving absolute isolation of a fault.

In practice, the proposed method can be implemented quite easily in a microprocessor-based embedded systems as the main control unit in supplying substation (sub-transmission substation) [25], which has a direct communication with all distributed protection relays through wireless communication network technologies or fiber optic networks [26].

4. Results and discussion

To verify the performance and accuracy of the proposed adaptive protection scheme, a 32-bus test system, 20 kV distribution network with 6 DG units is used as shown in Fig. 10. The system data are given in Appendix A. The calculated penetration factor of the DG units is 0.52, hence this test system can be considered as a distribution network with high penetration of DG units [27].

In this study, the DIgSILENT Power Factory 14.0.524 software is used to simulate the above mentioned test system and various types of faults are created in each line. Then the two-staged RBFNN method is applied and implemented in MATLAB software to estimate the fault distance from each source and faulty line number, respectively. To complete the protection scheme, the proposed main and backup protection algorithms described in Figs. 5 and 7 are written in MATLAB codes to determine the operation sequence of the main and backup relays. However, the training data for the RBFNNs have been generated by simulating various types of faults, including single phase to ground fault (1 Ph-G), phase to phase fault (2 Ph), two phases to ground fault (2 Ph-G) and three phase fault (3 Ph) created at each 100 meter of every line. The target (output) vector of the RBFNNs is obtained from the simulations. Table 2 summarizes the description of the inputs and outputs of the training data for the developed RBFNNs for the 32 bus test system.

About 8091 training and testing data sets for each fault type have been generated, from which 80% of the data sets are used for training the RBFNNs, and 20% are used for testing to evaluate the performance of the RBFNNs. Table 3 shows the accuracy of

Table 5
The number of paths created for various faulty lines of the test system.

Faulty line	Determined paths			Start bus	End bus	Lending to
	Path no.		Status			
Line 2	6 Paths	Path 1	Upstream	2	1	S
		Path 2	Downstream	3	18	DG2
		Path 3	Downstream	3	26	DG3
		Path 4	Downstream	3	30	DG4
		Path 5	Downstream	3	32	DG5
		Path 6	Upstream	2	13	DG6
Line 4	7 Paths	Path 1	Upstream	4	1	S
		Path 2	Upstream	4	3	DG1
		Path 3	Upstream	4	18	DG2
		Path 4	Upstream	4	26	DG3
		Path 5	Downstream	5	30	DG4
		Path 6	Downstream	5	32	DG5
		Path 7	Upstream	4	13	DG6
Line 8	7 Paths	Path 1	Upstream	7	1	S
		Path 2	Upstream	7	3	DG1
		Path 3	Upstream	7	18	DG2
		Path 4	Upstream	7	26	DG3
		Path 5	Upstream	7	30	DG4
		Path 6	Upstream	7	32	DG5
		Path 7	Upstream	7	13	DG6
Line 12	6 Paths	Path 1	Upstream	12	1	S
		Path 2	Upstream	12	3	DG1
		Path 3	Upstream	12	18	DG2
		Path 4	Upstream	12	26	DG3
		Path 5	Upstream	12	30	DG4
		Path 6	Upstream	12	32	DG5
Line 15	6 Paths	Path 1	Upstream	3	1	S
		Path 2	Downstream	16	18	DG2
		Path 3	Downstream	16	26	DG3
		Path 4	Upstream	3	30	DG4
		Path 5	Upstream	3	32	DG5
		Path 6	Upstream	3	13	DG6
Line 16	7 Paths	Path 1	Upstream	16	1	S
		Path 2	Downstream	17	3	DG1
		Path 3	Downstream	17	18	DG2
		Path 4	Upstream	16	26	DG3
		Path 5	Upstream	16	30	DG4
		Path 6	Upstream	16	32	DG5
		Path 7	Upstream	16	13	DG6
Line 21	7 Paths	Path 1	Upstream	20	1	S
		Path 2	Upstream	20	3	DG1
		Path 3	Upstream	20	18	DG2
		Path 4	Downstream	22	26	DG3
		Path 5	Upstream	20	30	DG4
		Path 6	Upstream	20	32	DG5
		Path 7	Upstream	20	13	DG6
Line 28	7 Paths	Path 1	Upstream	28	1	S
		Path 2	Upstream	28	3	DG1
		Path 3	Upstream	28	18	DG2
		Path 4	Upstream	28	26	DG3
		Path 5	Upstream	28	30	DG4
		Path 6	Upstream	28	32	DG5
		Path 7	Upstream	28	13	DG6

Table 6
The actual relays that must be operated to isolate faults in various lines of test system.

Faulty line	Main protection	First backup		Second backup		Third backup	
		Downstream	Upstream	Downstream	Upstream	Downstream	Upstream
Line 2	R2–R3–R15–RDG1	R4–R16	R1	R17–R29–R31	RS–R6	R19–RDG2–RDG4–RDG5	R8
Line 4	R4–R29–R31	RDG4–RDG5	R3	–	R2–R15–RDG1	–	R1
Line 8	R8–R9	R10	R6	R11	R1–RS	R12	R2
Line 12	R12, RDG6	–	R11	–	R10	–	R9
Line 15	R15, R16	R17	R2, R3, RDG1	R19, RDG2	R1, R4	R21	RS, R6 R29, R31
Line 21	R21–R22	R23	R19	R24	RDG2–R17	R25	R16
Line 28	R28	–	R27	–	R26	–	R2, R3, R15, RDG1

the trained RBFNNs in which the MSE is less than 8.47e−005 while the goal is set to 0.0001.

To verify the accuracy and effectiveness of the proposed protection scheme at the time of fault occurrence, the following scenarios are considered:

I. Four types of faults at 250 m of length of the line 2.
II. Four types of faults at 550 m of length of the line 4.
III. Four types of faults at 480 m of length of the line 8.
IV. Four types of faults at 870 m of length of the line 12.
V. Four types of faults at 350 m of length of the line 15.
VI. Four types of faults at 790 m of length of the line 21.
VII. Four types of faults at 690 m of length of the line 28.

The protection results for the 32 bus test system are shown in Table 4. Column 2 of the table shows the results of the identified fault type. After recognizing the fault type, the trained RBFNN 1, 3, 5 and 7 were then tested to evaluate its performance in locating various fault types. Table 4 shows some samples of the RBFNN testing results in which RBFNN 1, 3, 5 and 7 predicts fault locations in terms of distances from the main power source and the six DG units while RBFNN 2, 4, 6 and 8 predicts the faulty line.

From Table 4, it can be seen that the RBFNNs give accurate results in which the maximum error for RBFNN 1, 3, 5 and 7 is about 0.01 km. Considering that each distribution line section is 1 km in length in the studied network, a difference of 0.01 km is considered as acceptable. The RBFNN 2, 4, 6 and 8 also give accurate results because the faulty lines identified by the RBFNN are similar to the actual faulty lines.

As mentioned previously, after occurrence of a fault in the network, the location of the faulty line is identified using the RBFNN method and then the main protection algorithm starts to determine all downstream paths leading to DG units using backtracking algorithm. For instance, when a fault occurs in the line 2 of the test system, the main protection determined 6 paths. Each path started from the immediate upstream or downstream bus of faulty line, while the end of each path is the DG unit or the main source. As shown in Fig. 11, paths 1 and 6 are situated upstream of the faulty line, while the location of paths 2, 3, 4 and 5 are downstream of the faulty line. Furthermore, Table 5 shows the results of downstream and upstream paths created by the backtracking algorithm after occurrence of faults in various lines of the 32-bus test system. After determining all the paths leading to the DG units, the actual main and backup protective relays which should be operated to isolate the faulty lines are determined as shown in Table 6.

The main protection algorithm is then implemented to identify the main relays that must operate to isolate the faulty lines. Table 7 shows the results of the relays identified by the main and backup protection algorithm for faults occurring at various lines in the test system.

Comparing the main and backup relay results of Table 7 with the actual main and backup relays shown in Table 6, it is observed that similar relays have been identified by the main protection algorithm to that of the actual relays. Thus, the main protection algorithm can accurately determine the main relays that should operate to isolate the faulty line. Furthermore, it is proven that the proposed protection coordination algorithm can accurately identify backup relays for isolating faults in case the main relays do not operate. Table 8 shows the advantages of the proposed protection coordination scheme in comparison with the conventional ANN based schemes. The calculated implementation time of the proposed protection coordination method is less than 0.236 s for various fault types, which is quite fast and meets the IEEE Std. 242-2001 requirements [28].

Table 7
Results of the relays identified by the main and backup protection algorithms.

Faulty line	Protection steps			
	Main protection	First backup	Second backup	Third backup
Line 2	R2	R1	RS	–
			R6	R8
	R3	R4	R29	RDG4
			R31	RDG5
	R15	R16	R17	R19
				RDG2
	RDG1	–	–	–
Line 4	R4	R3	R2	R1
			R15	R16
			RDG1	–
	R29	RDG4	–	–
	R31	RDG5	–	–
Line 8	R8	R6	RS	–
			R1	R2
	R9	R10	R11	R12
Line 12	R12	R11	R10	R9
	RDG6	–	–	–
Line 15	R15	R2	R1	RS
				R6
		R3	R4	R29
				R31
		RDG1	–	–
	R16	R17	R19	R21
			RDG2	–
Line 21	R21	R19	RDG2	–
			R17	R16
	R22	R23	R24	R25
Line 28	R28	R27	R26	R2
				R3
				R15
				RDG1

Table 8
Comparison between proposed and conventional ANN based methods.

Functions	Proposed method	Method in [14]	Method in [15]
Maximum selectivity	√	×	×
Backup protection scheme	√	√	√
More reliable protection system	√	×	×
Fast ANN training time	√	×	×
Maximum speed of protection scheme	√	×	×
Minimum cost of protection scheme	√	×	×
Network restoration	√	√	√

5. Conclusion

In this paper, a new adaptive protection scheme has been developed for distribution systems with high penetration of DG units by integrating fault location with protective relay coordination strategies. The proposed protection coordination algorithm was tested on the 32-bus test system with 6 DG units. The fault location results showed that the first group of RBFNN gives accurate results because the maximum error between the actual and estimated distances of fault from the main source and all DG units is less than 0.01 km. Since, each distribution line section is 1 km in length in the studied networks, a deviation of 0.01 km is considered acceptable. The second group of RBFNN outputs after rounding to the nearest ones shows the exact number of faulty line. In addition, the protection coordination results showed that the proposed backtracking algorithm is reliable since there is no any miscoordination in the studied cases. The developed adaptive protection schemes would be useful for assisting power engineers in performing

Table 9
Technical data of distribution lines.

Conductor name	Type	A
HYENA	ACSR	126 mm^2
Technical data	R (Ω)	0.303
	X (Ω)	0.3383
	R_0 (Ω)	0.4509
	X_0 (Ω)	1.5866
	I_n (A)	250

Table 10
Technical data of DGs.

Machine type	IEC 909		Salient pole series 1
Voltage (kV)	20	X′d (pu)	0.256
Pn (MW)	2.5, 3, 3.5, 4.5, 5	X″d (pu)	0.168
PFn	0.8	X0 (pu)	0.1
Connection	YN	X2 (pu)	0.2
Xd (pu)	1.5	R0 = R2 (pu)	0
Xq (pu)	0.75	Rstr (pu)	0.504

service restoration quickly so as to decrease the total down time of the power distribution systems with DG units.

Appendix A

The distribution feeder is 20 kV with 32 bus feeders and 6 DG units. All the distribution conductors are of HYENA type with 1 km length and the technical information of the conductors is given in Table 9.

The peak load for all loads is 0.75 MW and the power factor for all of them at each time is assumed 0.9 lagging. The system consists of a 3.5 MVA diesel generator as DG1 connected to bus 3, a 4.5 MVA diesel generator as DG2 connected to bus 18, a 3 MVA diesel generator as DG3 connected to bus 26, a 2.5 MVA diesel generator as DG4 connected to bus 30, a 2.5 MVA diesel generator as DG5 connected to bus 32 and a 5 MVA diesel generator as DG6 connected to bus 13. The technical data of all the DGs is presented in Table 10.

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