The Journal of CPRI,
Vol. 9, No. 1, March 2013 pp. 71–80

ANN Based Adaptive Relaying Scheme for Protection of Active Distribution Networks

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This paper presents a new adaptive relaying scheme for the protection of active distribution networks, i.e. protection of distribution networks connected with distributed generation/dispersed generation (DG). The traditionally radial distribution systems may no longer be radial in the presence of DGs, which can hinder the existing co-ordination between the protective relays. This paper addresses the relay co-ordination issues encountered due to the presence of DGs in the network and explores the application of Artificial Neural Networks (ANNs) as a solution for the protection of active distribution networks. The proposed method, based on ANN, shows that the issues regarding relay co-ordination can be overcome and only the faulted section can be isolated precisely.

Keywords: *Artificial neural networks, Distributed generation and Power system protection.*

1.0 INTRODUCTION

Large central generators feed electrical power to a high voltage interconnected transmission network. The transmission system is used to transport the power over long distances which is then extracted and distributed to the consumers through distribution transformers. Normally distribution networks are planned to operate passively in radial fashion, i.e. power flows in one direction, typically from the sub transmission/primary distribution network to the loads. Power is delivered to the consumers through distribution lines emanating from the distribution transformers. Normally at the consumer end there are no planned power generations to serve the loads locally. Lately, with the emergence of Distributed Generation (DG), these passive distribution networks have become active and they not only draw power from sources in the sub transmission/primary distribution systems but also supply power to the grid. The advent of DG technology has been a boon to the utility industry in a sense that the technical and commercial losses incurred in the passive distribution networks are reduced greatly. The voltage profile in distribution networks is also improved to a large extent [1].

However, the penetration of DGs in the network has introduced some noteworthy issues with respect to protection [1–4]. Some of the issues are:

1.1 Short Circuit Levels

The penetration of DGs in distribution networks results in an increase in the fault levels by some margin depending upon the strength of the DGs connected.

1.2 Current "seen" by Relays

During faults in a distribution system with DGs, the protective devices (relays, fuses etc.) may sense the fault contribution from DGs in reverse direction. The normal co-ordination of relays will

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not hold good in the presence of DGs and hence it is required to develop a relaying scheme which can adapt to the power system conditions online. Hence adaptive relaying is proposed for protection of such distribution systems which will also help in taking care of changes in practices followed by the utility on design and operational aspects.

Adaptive protection has been defined as "a protection philosophy which permits and seeks to make adjustments to various protection functions in order to make them more attuned to prevailing power system conditions" [5]. A. K. Jampala *et al.* [6] have presented the various computational issues involving adaptive relaying such as the topological problem, over current relay co-ordination etc. The feasibility and implementation of adaptive relaying for the protection of distribution systems has been explored in [7–9]. Adaptive relaying has also been proposed for protection of distribution networks with DGs in [10–11].

In this paper the drawbacks of conventional protection schemes applied to distribution systems with DGs are summarized and a new adaptive relaying scheme is proposed in order to overcome the protection issues. The proposed scheme employs Artificial Neural Networks (ANNs) as a solution for protecting distribution networks with DGs.

2.0 IMPACTS OF DG ON RELAYING

The impacts of DG on protection of a distribution feeder are studied with simulations using MiPower™ [18] and presented in this section.

A typical distribution system with a DG is shown in Figure 1. Faults were simulated at all buses with and without DG in the system. Studies revealed that there is an increase in the fault current when DG is connected in the system. For instance, the total fault current (I_f), for a fault at bus b4 is not only the current contributed by the network (I_{grid}) but also the current contributed by the DG (I_{dg}). Further, in order to analyze the impacts of DGs on protection of distribution networks in detail, the system shown in Figure 2 is considered. The test system considered has been presented in [2, 10], while additional breakers have been employed by the authors in this paper for the proposed adaptive relaying scheme. Breakers are placed to separate the line sections as shown in Figure 2.

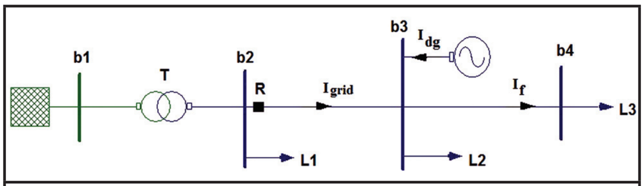

FIG. 1 TYPICAL DISTRIBUTION SYSTEM WITH DG.

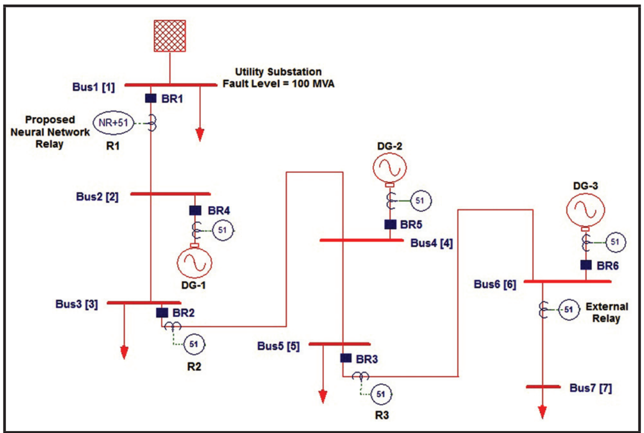

FIG. 2 SYSTEM CONSIDERED FOR ANALYSIS.

Relay co-ordination simulations were carried out in MiPower™ to co-ordinate relays R1, R2 and R3 assuming that the DGs are not present in the network. Figure 3 shows the relay co-ordination curves for R1, R2 and R3 without DGs.

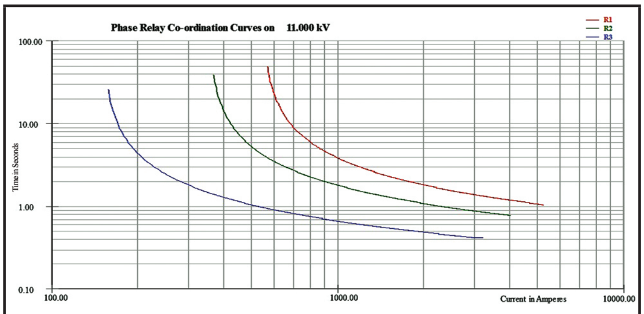

FIG. 3 COORDINATION OF R1, R2 AND R3 WITHOUT DGs.

Further, relay co-ordination was performed with DGs 1 and 2 connected and the co-ordination curves are shown in Figure 4. From Figures 3 and 4 it can be seen that there is an increase in the fault currents seen by the relays with the introduction of DGs. The maximum fault current sensed by relay R3 when DGs are not connected in the system is around 3200 A. With the penetration of DGs, the maximum fault current sensed by relay R3 is increased to 4000 A.

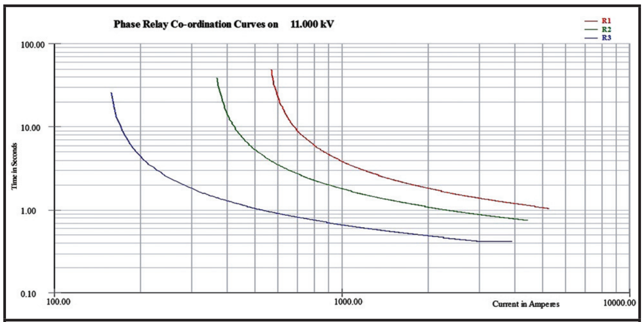

FIG. 4 COORDINATION OF R1, R2 AND R3 WITH DGs 1 AND 2.

When all the DGs are operating, for any fault upstream of section 2, say at bus 2, the relay R1 will sense a current in the forward direction and R2 and R3 will sense a back flow of current. Relay R1 isolates the fault contribution from the utility substation according to its characteristics. The back flow of current sensed by R3 may cause R3 to operate if the current seen by it is greater than its pickup. For any fault at bus 2 it is desirable that relay R2 isolates the contribution from the DGs in order to satisfy the selectivity aspect of protection design. However, it is possible that R3 operates before R2 which can cause even the healthy part of the network to get isolated. Table 1 illustrates the operation of the relays for fault at bus 2 and the possible loss of coordination between R2 and R3. The coordination has been done assuming the normal inverse characteristics (as per IEC standards). It is not possible to coordinate R2 and R3 for this back flow of current and hence the selectivity aspect of protection design will be affected.

TABLE 1

OPERATION OF RELAYS FOR FAULT AT BUS 2

Description	**R1**	**R2**	**R3**
Current (A)	5531	979	482
Operating time (s)	1.07	1.95	1.065

The analysis also revealed that, with the increase in penetration of DG, the magnitude of fault current seen by some of the relays may reduce. To understand the phenomenon, a short circuit study result is presented in Table 2. It can be seen from Table II that the fault current seen by relay R1 for a fault at bus 7, reduces to 2706 A when all three DGs are connected as compared to 2956 A when all DGs are OFF. This suggests that with the penetration of DGs, relay R1 gets desensitized.

TABLE 2

CURRENT SENSED BY R1 FOR FAULT AT BUS 7

Description	**Without DGs**	**With all DGs**
R1 current (A)	2956	2706

However, the phase plug setting of R1 will generally be set at around 100–125% (of CT rating) in practice, as per the current carrying capacity of the feeder. The earth plug setting maybe set to about 20–30% depending upon the magnitude of unbalance that is expected in the feeder. Therefore, the pickup of relay R1 is sensitive enough to detect faults even with penetration of DGs.

The following section provides a brief description about artificial neural networks (ANNs) and its applications to power system protection.

3.0 APPLICATION OF ANN IN RELAYING

Generally speaking, Artificial Neural Network (ANN) or simply Neural Network (NN) is a mathematical model or a computational model that is inspired by the structure and/or functional aspects of biological neural networks. It is a type of Artificial Intelligence that attempts to imitate the way a human brain performs a particular task. Neural networks are usually implemented by using electronic components or simulated in software on a digital computer. The definition of a neural network viewed as an adaptive machine can be as follows:

- A neural network is a massively parallel distributed processor made up of simple processing units which has a natural propensity for storing experiential knowledge and making it available for use. It resembles the brain in two respects:
  a) The knowledge is acquired by the network from its environment through a learning process.
  b) Inter-neuron connection strengths, known as synaptic weights, are used to store the acquired knowledge [12].

The strength of a neural network lies in its ability to learn from the input-output relations presented to it during training. Many algorithms for learning process of a neural network have been presented in [12–13]. However, the back propagation being the most popular amongst the learning algorithms and the log sigmoid activation function have been used in the proposed scheme.

Previously, several researchers have investigated the application of ANNs to power system protection such as fault classification [14], adaptive transmission line relaying [15], adaptive protection of double circuit lines [16] etc. The robustness of ANNs has been very well established in the references mentioned and hence needless to explain the benefits of ANNs. Therefore, it was intended to exploit the strengths of ANN for the protection of active distribution networks as well.

4.0 PROPOSED SCHEME

All protection schemes need to satisfy the basic criteria of protection design i.e. Selectivity, Reliability, Sensitivity and Speed of operation. Therefore, keeping in mind all the important aspects of protection design, an adaptive relaying scheme is proposed in this paper for the protection of an active distribution network. The inputs required for the proposed scheme are the RMS current magnitudes measured by the Intelligent Electronic Devices (IEDs - numerical relays/ Phasor Measurement Units) in each section up to the downstream DG, the connection statuses of the DGs, pickup status of the relay (external relay) below the downstream DG and direction of current from the main substation breaker.

With modern day communication infrastructure (optic-fiber communication links) the currents seen by the IEDs and the pickup status of the external relay can be easily transmitted to the proposed relay [11, 17]. The proposed scheme is explained in this section with respect to the test system shown in Figure 2.

In order to realize the proposed method, various off-line analyses were carried out which are explained in section 4.1 and the operation of the proposed relay is explained in section 4.2.

4.1 Off-line Analysis

The distribution system shown in Figure 2 was modelled in MiPower^{TM}, power system analysis software. Short circuit analysis was carried out at all the buses for various types of faults, i.e. LLL, LG, LLG and LL. The phase current measured at each IED location, for all types of faults, was recorded. The analysis was repeated for various operating conditions of the system by considering the status signals from the DGs in the feeder. A complete database was prepared for training the proposed relay. Here training of the neural network is required for faults between the location of upstream and downstream DG only. Therefore, training the ANN should not be very time consuming. With the data available the proposed relay was trained and the weights generated by the training program were stored as the Group I settings of the relay. Also, an over-current relay co-ordination was carried out, without considering DGs in the network, and the settings obtained were stored as Group II settings of the relay. Group II settings basically comprise the plug setting and time multiplier setting of a typical overcurrent relay.

4.2 Relay Operation

The proposed scheme is illustrated in Figure 5. The DG status, measured IED currents (one sample of

RMS value per cycle upon fault detection) and external relay status are read by the proposed relay. If fault is detected in forward direction and the external relay has not picked, then the proposed relay switches to Group I settings, otherwise it operates with Group II settings.

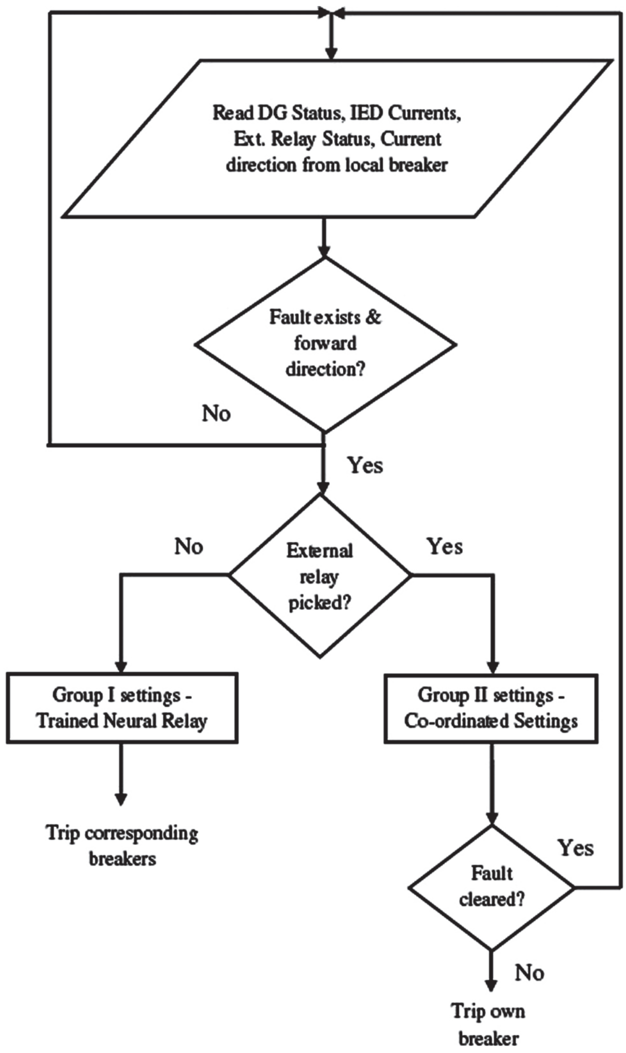

FIG. 5 FLOWCHART OF THE PROPOSED SCHEME.

The proposed relay, referred to as the Neural Network (NN) relay, is placed at the sending end of the main feeder to which DGs are connected (refer Figure 2). The zone between the location of the NN relay and the last downstream DG on the feeder is referred to as internal zone and the zone beyond the last DG is referred to as external zone. With the help of aforesaid inputs it is possible to design a relay which can precisely identify the faulted section of the feeder and trip the corresponding breaker. The proposed scheme has two groups of settings: Group I – invoked during internal faults; Group II – invoked during external faults (grid side faults or faults on same feeder in the external zone). At any given time only one of the setting groups is active and the other is blocked. The pickup status of the external relay is used to discriminate between internal fault and external fault on the same feeder. In case the external relay picks up, it indicates that the fault is external to the zone and hence the normal co-ordinated settings (group II settings) will be selected. The current direction signal from the local breaker is required for distinguishing between faults on the same feeder and faults on grid side or any of the parallel feeders. If a fault occurs on the grid side or any of the parallel feeders the DGs will contribute to the fault, which implies that the current direction at the location of the neural network relay is reversed. Group II settings will be selected in this case as well. Instead, if the fault is internal to the zone, the proposed relay determines the faulted section of the feeder based on the measured fault currents and its prior knowledge about the possible network faults through training.

Once the fault has been located the relay sends a trip command to the corresponding breaker, i.e. the breaker which isolates the healthy part of the network from the faulted section. Nowadays almost all breakers will be facilitated with remote communication; hence the output of the NN relay can be communicated to the appropriate breaker.

It is to be noted that the system presented in Figure 2 is protected by over-current relays only. In practice, distribution systems are protected by not only relays, but also with the help of fuses, reclosers and sectionalizers. The lateral feeders in the system are to be protected by communicable relays which act as external relays for the proposed scheme. Apart from relays, the laterals are also protected by fuses, reclosers etc. Since the lateral feeders lie outside the zone of protection, they are simply represented as loads in the system.

5.0 SIMULATIONS AND TRAINING

Short circuit analysis was carried out at all buses on the system modeled. Results of short circuit analysis are used for training the proposed neural network relay. The proposed relay has to be trained to identify the faulted section between the locations of the upstream and downstream DGs only and hence various cases such as change in grid fault level, location of fault and fault resistance (upto 20 Ω) were considered for training.

Sample training input-output patterns for single line to ground fault at bus 4 are shown in Tables 3–4 for various operating conditions of the DGs. Tables 5–6 show the input-output patterns for 3-phase to ground fault at bus 3 for various operating conditions of the DGs.

TABLE 3
INPUT TO THE RELAY FOR SLG FAULT AT BUS 4

Status			**Current seen in A**		
DG1	**DG2**	**DG3**	**R1**	**R2**	**R3**
0	0	0	2657	2657	0
0	0	1	2704	2704	488
0	1	0	2715	2715	0
0	1	1	2747	2747	489
1	0	0	2553	2887	0
1	0	1	2598	2936	488
1	1	0	2609	2947	0
1	1	1	2640	2980	489

TABLE 4
DESIRED OUTPUT OF THE RELAY FOR SLG FAULT AT BUS 4

Trip Status					
BR1	BR2	**BR3**	**BR4**	**BR5**	**BR6**
0	1	0	0	0	0
0	1	1	0	0	0
0	1	0	0	1	0
0	1	1	0	1	0
0	1	0	0	0	0
0	1	1	0	0	0
0	1	0	0	1	0
0	1	1	0	1	0

Tables 3 and 5 show the inputs given to the NN relay corresponding to the three DG status signals (0 indicating OFF condition and 1 indicating ON condition) and the currents measured by IEDs in the three sections of the feeder (only one of the phase currents is shown for simplicity). Tables 4 and 6 show the desired outputs of the NN relay. The relay output corresponds to 1 or 0 for all the breakers considered where trip status 1 indicates "trip" and 0 indicates "no trip".

TABLE 5
INPUT TO THE RELAY FOR THREE PHASE TO GROUND FAULT AT BUS 3

Status			**Current seen in A**		
DG1	DG2	DG3	**R1**	**R2**	**R3**
0	0	0	4027	0	0
0	0	1	4027	503	503
0	1	0	4027	517	0
0	1	1	4027	1006	496
1	0	0	3975	0	0
1	0	1	3975	503	503
1	1	0	3975	517	0
1	1	1	3975	1006	496

TABLE 6
DESIRED OUTPUT OF THE RELAY FOR THREE PHASE TO GROUND FAULT AT BUS 3

Trip Status					
BR1	**BR2**	**BR3**	**BR4**	**BR5**	**BR6**
1	0	0	0	0	0
1	1	0	0	0	0
1	1	0	0	0	0
1	1	0	0	0	0
1	0	0	1	0	0
1	1	0	1	0	0
1	1	0	1	0	0
1	1	0	1	0	0

The neural network architecture used for the proposed relay is a simple feed forward multi-layer perceptron model. After much training it was found that a neural network with 12 neurons in the input layer, 9 neurons in the hidden layer and 6 neurons in the output layer can be used in the relay. Note that the number of input neurons depends upon the number of DGs and line sections in the network and the number of output neurons depends upon the number of breakers lying in the internal zone of protection.

6.0 RESULTS

In order to validate the operation of the proposed relay, faults were simulated at various locations of the network shown in Figure 2 with the grid fault level of 125 MVA. Tables 7–8 present the relay input and output respectively for 3-phase to ground fault at the boundary of line section I i.e. bus 3. Similarly, Tables 9–10 present the relay input output respectively for double line to ground fault at bus 4 and Tables 11–12 present the input output respectively for single line to ground fault at the boundary of line section II i.e. bus 5. For in-zone faults the relay operation is nothing but the output of the neural network which sends trip command to the appropriate breaker. Table 13 shows the input to the relay for fault at bus 7. However, since the external relay picks up for a fault at bus 7, the proposed relay switched to group II settings as per the co-ordination and acts as a backup relay. Table 14 shows the output of the relay for 3-phase to ground fault at bus 7. In order to test the performance of the proposed relay during resistive faults, a single line to ground fault was simulated with 10 Ω fault resistance.

TABLE 7

INPUT TO THE RELAY FOR THREE PHASE TO GROUND FAULT AT BUS 3

Status			Current seen in A		
DG1	**DG2**	**DG3**	**R1**	**R2**	**R3**
0	1	1	4743	1006	496
0	1	0	4743	517	0

TABLE 8

OUTPUT OF THE RELAY FOR THREE PHASE TO GROUND FAULT AT BUS 3

Trip Status					
BR1	**BR2**	**BR3**	**BR4**	**BR5**	**BR6**
1	1	0	0	0	0
1	1	0	0	0	0

TABLE 9

INPUT TO THE RELAY FOR DOUBLE LINE TO GROUND FAULT AT BUS 4

Status			Current seen in A		
DG1	**DG2**	**DG3**	**R1**	**R2**	**R3**
1	0	1	3154	3521	502
1	1	0	3154	3521	0

TABLE 10

OUTPUT OF THE RELAY FOR DOUBLE LINE TO GROUND FAULT AT BUS 4

Trip Status					
BR1	**BR2**	**BR3**	**BR4**	**BR5**	**BR6**
0	1	1	0	0	0
0	1	0	0	1	0

TABLE 11

INPUT TO THE RELAY FOR SLG FAULT AT BUS 5

Status			Current seen in A		
DG1	**DG2**	**DG3**	**R1**	**R2**	**R3**
1	0	1	2367	2629	0
1	1	0	2445	2713	505

TABLE 12

OUTPUT OF THE RELAY FOR SLG FAULT AT BUS 5

Trip Status					
BR1	**BR2**	**BR3**	**BR4**	**BR5**	**BR6**
0	1	0	0	0	0
0	1	1	0	0	0

TABLE 13

INPUT TO THE RELAY FOR THREE PHASE TO GROUND FAULT AT BUS 7

Status			Current seen in A		
DG1	**DG2**	**DG3**	**R1**	**R2**	**R3**
1	1	0	2742	3001	3346
1	1	1	2706	2962	3303

TABLE 14					
OUTPUT OF THE RELAY FOR THREE PHASE TO GROUND FAULT AT BUS 7					
Trip Status					
BR1	**BR2**	**BR3**	**BR4**	**BR5**	**BR6**
0	0	0	0	0	0
0	0	0	0	0	0

Tables 15–16 show the input and output of the scheme respectively. The performance of the proposed relay has been satisfactory for both internal as well as external faults as it ensures isolation of the faulted section of the network and retains the healthy part. Proper selectivity has been achieved by appropriate training of the proposed relay and problems associated with conventional protection schemes are overcome.

TABLE 15					
INPUT TO THE RELAY FOR SLG FAULT AT BUS 3 (R_F = 10 Ω)					
Status			**Current seen in A**		
DG1	**DG2**	**DG3**	**R1**	**R2**	**R3**
1	0	0	538	598	0
1	0	1	476	528	80

TABLE 16					
OUTPUT OF THE RELAY FOR SLG FAULT AT BUS 3 (R_F = 10 Ω)					
Trip Status					
BR1	**BR2**	**BR3**	**BR4**	**BR5**	**BR6**
0	1	0	0	0	0
0	1	1	0	0	0

7.0 CONCLUSIONS

In this paper, results of various studies conducted to analyze the existing protection schemes for the protection of distribution networks are presented. The studies revealed that any change in the distribution system configuration due to DGs connected may lead to mal-operation of the existing protection systems. Therefore it is important to design a protection scheme which can adapt to the changing system configurations. Adaptive relaying can be implemented in order to overcome the impact of DGs on the protection system of the network. With the proposed method it can be seen that the relay at the sending end of the feeder can be trained to identify the faulted section and trip the corresponding breakers. Normally, the relays in the distribution network will be coordinated in time and hence even for in-zone faults the time taken for the fault to be cleared is very high. With the proposed scheme, the in-zone faults will be cleared as desired.

The architecture of the neural network relay ultimately depends upon the amount of DG penetration in a particular feeder. As the penetration of DG increases the size of the neural network increases and so does the communication complexity. However, it should be mentioned that in case of any failure of communication, group II settings could be enforced. The proposed scheme can be implemented in active distribution networks in order to enhance the system reliability.

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