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Design of Neural Networks for Fault Diagnosis of a Distribution System

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ABSTRACT

The application of a hierarchical distributed neural network to fault diagnosis of a distribution system is presented. The artificial neural network (ANN) design has been developed by considering the structure and functions of the distribution system. Three hierarchical distributed ANN modules are considered for the fault diagnosis of the distribution system. The proposed diagnosis system has been designed for a practical Tenaga Nasional Berhad (TNB) distribution system. In the ANN training process, the data sets are generated using the logic operation of relays and circuit breakers corresponding to the respective fault location for cases of single and multiple faults. The simulation results show that the proposed method using ANNs is encouraging and that the method can be in an on-line environment.

ABSTRAK

Penggunaan rangkaian neural teragih hierarki untuk diagnosis kerosakan bagi sistem agihan dicadangkan. Reka bentuk rangkaian neural telah dibangunkan dengan mengambilkira struktur dan fungsi sistem agihan. Tiga modul rangkaian neural teragih hierarki telah dibangunkan untuk diagnosis kerosakan bagi sistem agihan. Rangkaian neural telah direka bentuk secara hierarki sebab paras bawah rangkaian neural menjadi masukan kepada paras atas rangkaian neural. Sistem diagnosis kerosakan yang dicadangkan telah direka bentuk untuk sistem agihan Tenaga Nasional Berhad (TNB). Dalam proses melatih rangkaian neural, data set latihan dijana dengan menggunakan operasian logik bagi geganti dan pemutus litar sepadan dengan tempat berlaku kerosakan untuk kes kerosakan satu dan berbilang. Keputusan simulasi telah menunjukkan bahawa kaedah rangkaian neural yang dicadangkan adalah memberangsangkan.

INTRODUCTION

Fault diagnosis studies in power system has currently gained increasing attention and has become the subject of intensive research (Yasuji Sekine et al. 1992; Santiago Remauteria et al. 1995; Yurtsever & Brugger 1993). On-line fault diagnosis is needed for dynamic emergency control in the distribution automation system. In the process of emergency control, the fault situation should be first identified in order to take proper actions for system restoration as soon as possible. Distribution system fault diagnosis involves the identification of the location of system faults and, the detection of protection and switchgear maloperations. When a fault occurs, the alarm signals received in an automated substation would be the open/close status of the protective relays and breakers. From these binary symptom patterns, the operators are required to diagnose the fault.

The traditional fault diagnosis practices are largely manual and rely on the judgment of operator's experiences for diagnosis (Chang et al. 1993). As computers have become smaller and cheaper, the system operators have used computers for fault diagnosis of distribution systems. However, to handle the fault diagnosis facing an abnormal status, the experienced operators play a prominent role. Based on the alarm signals of the protective system, the operators of a substation are required to estimate the fault situation immediately after the occurrence of fault. To tell immediately the real situation and original cause of the fault is difficult for the operator, if not impossible (Hong–Tzer Yang et al. 1995).

Recent work has focused on knowledge-based systems as a method for processing complex combinations of decision conditions using the expert's knowledge. Rule-based expert system application for fault diagnosis have received much interest in recent years (Ypsilantis, Yee & Teo 1992; Eickhoff, Handschin & Hoffmann 1992; McDonald, Burt & Young 1992 and Minakawa, Kunugi & Shimada 1995). The fault diagnosis expert system uses heuristic rules based on the system operator's experiences. The expert system conducts reasoning and then produces the diagnosing outputs to help operators to make correct decisions. The rule-based approach offers powerful solution to fault diagnosis but it suffers from imperfections. Much amount of knowledge and a large number of rules are required to be collected and refined in building an expert system for fault diagnosis of power systems (Guo-Zhong Zhou 1993). This is a very difficult and lengthy process and therefore pose a major problem in expert system development. Furthermore, it is a burden to construct and manage an enormous knowledge base and also the knowledge base of a specific expert system for one power system must be changed when this expert system is transplanted to another power system. One potential solution to these problems is the use of artificial neural networks (ANNs). The application of ANNs to power system fault diagnosis have been presented by other workers (Swarup & Chandrasekharaiah 1991; Parten & Pap 1991; Kwang-Ho Kim & Jong-Keun Park 1993; Guo-Zhong Zhou 1993; da Silva, de Carvalho & Zaverucha 1994; Yang, Chang & Huang 1995; Chang et al. 1993). ANNs are useful in applications where the nature of the input-output functional relationship is neither well defined nor easily computable. ANN has the advantage of giving an answer quickly by using associations learned from previous experience or from practical experience. The neural network presents some attractive features such as, the ability to learn from examples and requires no expert's knowledge. Hence, a research project is conducted to develop a fault diagnosis system based on the ANN technology which includes the real-time features.

The proposed ANN-based system for fault diagnosis is designed for solving the fault location problem in a practical distribution system. The design of ANNs is based on the structure of the distribution system as well as the function of the protection system. Several independent ANNs in the same low voltage level are designed for several loops of the distribution network to diagnose the line and bus faults within the loops. Therefore, each loop which consists of several line sections and buses has one representative ANN. The lower level ANNs are later combined together at a higher level in which the higher level ANN makes use some of the outputs from the lower level ANNs as its inputs. The higher level ANN is used to diagnose the faults in the main feeders and the substation buses of the distribution system. Consequently, the neural network design for fault diagnosis is based on the hierarchical distributed neural networks. The proposed diagnosis system has considerable advantages in terms of adding sample data into its training sets and changes of the distribution system configurations.

NEURAL NETWORK APPROACH TO FAULT DIAGNOSIS

In an automated distribution system, a fault situation would result in a particular binary symptom pattern of the open/close states of relays and breakers expressed as binary values of '1' or '0', with '1' standing for 'open or operate' and '0' for 'close or not operate'. By correctly recognizing the symptom pattern, the fault location can be identified. However, for patterns with failure operation of relay or breaker, the problem would be complicated. A fault situation may bring about several possible symptom patterns, and a symptom pattern confronted by the operators may be caused by a number of possible fault situations such as single or multiple faults. In the cases of failure operation of protective devices or multiple faults, there will be a large number of alarm signals which will pose a difficulty for the operators to on-line identify the fault situation. In such a situation, it is important to quickly diagnose the faults so that system restoration can be done as soon as possible. To achieve a fast on-line fault diagnosis it is necessary to develop support or automatic systems for fault diagnosis and restoration so as to help the operators in decision making process. In this paper, the use of ANNs as support systems for fault diagnosis is proposed. The ANN approach designs the fault diagnosis problem by firstly forming a set of training patterns, where the inputs are the open/close states of the relays and circuit breakers and the outputs are the corresponding fault locations which are the lines or bus faults. Secondly, the ANN is trained by using the training patterns. The trained ANN is then used to diagnose the faults by inputting the information of the operating relays and circuit breakers to the ANN. The proposed neural network design is based on hierarchical distributed neural networks which consider both the structure and the functions of the protective devices of the distribution system. In the following section, the composition of the distributed neural networks is described.

COMPOSITION OF HIERARCHICAL DISTRIBUTED NEURAL NETWORKS

In a large distribution system, there are usually several primary feeders, a substation and a distribution network which consist of several lines and bus sections. There are also a great number of protective relays and circuit breakers for the distribution protection system. If a single ANN is used to diagnose the faults for the entire distribution system, this ANN will have too many nodes and connections and hence become very large in scale. A large scale ANN has some disadvantages such as too long training time and inflexible structure. When there are changes in the distribution system configuration, the entire ANN has to be retrained. Therefore, an approach to fault diagnosis for a large distribution system is proposed based on hierarchical distributed neural networks (HDNN).

The structure of the ANN coincides with the components and functions of the distribution system. Several independent ANNs are used to diagnose the faults in the lines and buses within the distribution network and these ANNs are called first level ANNs. The second level ANN makes use of outputs from the first level ANN as its inputs so as to determine the operating conditions of the substation relays and circuit breakers. In this case, it is assumed that any faults occurring in the lines or buses of the distribution network will cause the substation relays and circuit breakers to operate. Another higher level ANN is designed which makes use of outputs from the independent second level ANNs so as to diagnose the faults in the primary feeders and the substation buses. This higher level ANN is called as the third level ANN.

To illustrate the conceptual design of the HDNN for fault diagnosis of a distribution system, a simple model of a distribution system is considered. Figure 1 shows a one-line diagram of a model distribution system with 3 primary feeders, 2 substation buses, 9 line sections and 9 buses in the distribution network. Figure 2 shows the HDNN for this distribution system, where faults at buses B3, B4, B5 and lines L1, L2, L3 are diagnosed by NN1, faults at buses B6, B7, B8 and lines L4, L5, L6 are diagnosed by NN2 and faults at buses B9, B10, B11 and lines L7, L8, L9 are diagnosed by NN3. Neural networks NN1, NN2 and NN3 serve as the first level ANNs and they are designed to diagnose faults at the lines and bus sections of the distribution network. The second level ANNs are the NN4, NN5 and NN6 and they are designed to determine the operating states of the substation relays and buses. The operating states of the relays and circuit breakers are determined such that relays R1, R2 and circuit breaker CB1 are determined by NN4, relays R3, R4 and circuit breaker CB2 are determined by NN5 and relays R5, R6 and circuit breaker CB3 are determined by NN6. The third level ANN which is NN7, diagnose the faults of the primary feeders P1, P2, P3 and the substation buses B1, B2. All the outputs of the second level ANNs, which are NN4, NN5 and NN6, are used as inputs of the NN7. The proposed structure of HDNN has considerable advantages over one single ANN in terms of the changes in the system configuration and addition of training knowledge.

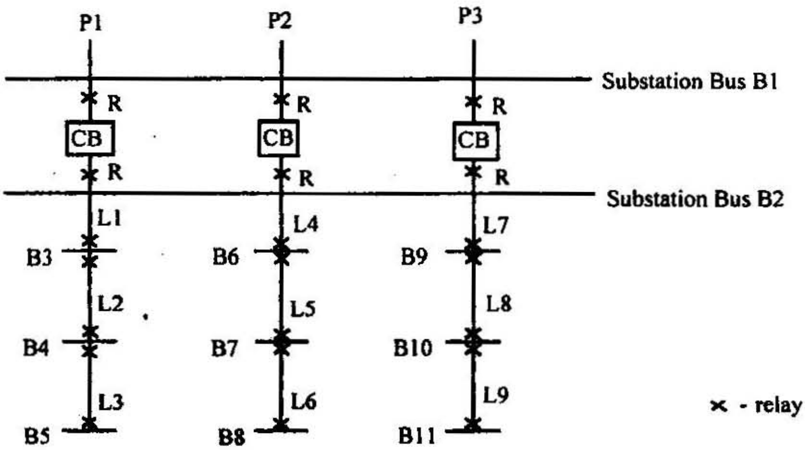

FIGURE 1. One-line diagram of a model distribution system

The ANN model used is the back-propagation model (Neural Ware Inc. 1991) which is the most widely used ANN models in practice. This model is a multilayer feed forward neural network which consists of three layers (the input layer, the hidden layer and the output layer), and all the nodes of the three layers are fully connected. Every ANN is trained with binary patterns and the activation values of the units take on any real value between 0 and 1 which is based on the sigmoid activation function. The learning algorithm for the ANN model is called the error back-propagation algorithm.

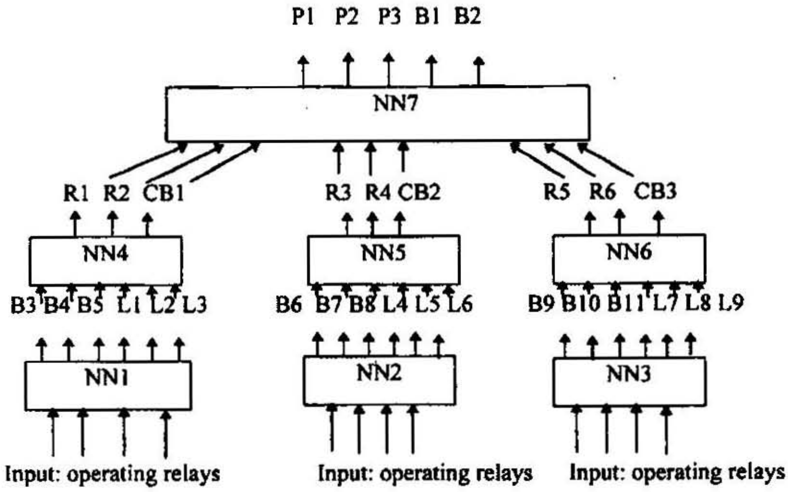

FIGURE 2. The HDNN for the model distribution system

PRACTICAL SYSTEM TEST CASE

A practical implementation of the neural network based fault diagnosis is considered. The test system description, the ANN design for the system and the training sets generation are described in the following section.

TEST SYSTEM DESCRIPTION

The practical Tenaga Nasional Berhad (TNB) distribution system utilised to test the effectiveness of the proposed ANN fault diagnosis is shown in Figure 3. The system consists of 9 main feeders, 2 buses in the substation and several line and bus sections in the radial distribution network. The distribution system is divided into three loops for ease in planning the distribution network for fault diagnosis as well as for fault restoration control strategies. The main feeders are grouped into three loops such that feeders L1, L2 and L3 are grouped in the first loop, feeders L4, L5 and L6 in the second loop and feeders L7, L8 and L9 in the third loop. Feeders L1, L4 and L7 are used as standby or back-up feeders and are only used during fault restoration.

In the first loop, there are 10 line sections and 10 buses, in the second loop 10 line sections and 10 buses and in the third loop 12 line sections and 12 buses. The line and bus sections are protected by alarm relays, isolator switches and circuit breakers. There are 18, 20 and 24 alarm relays in the first, second and third loops, respectively. The substation buses and the main feeders are protected by relays and circuit breakers in the substation.

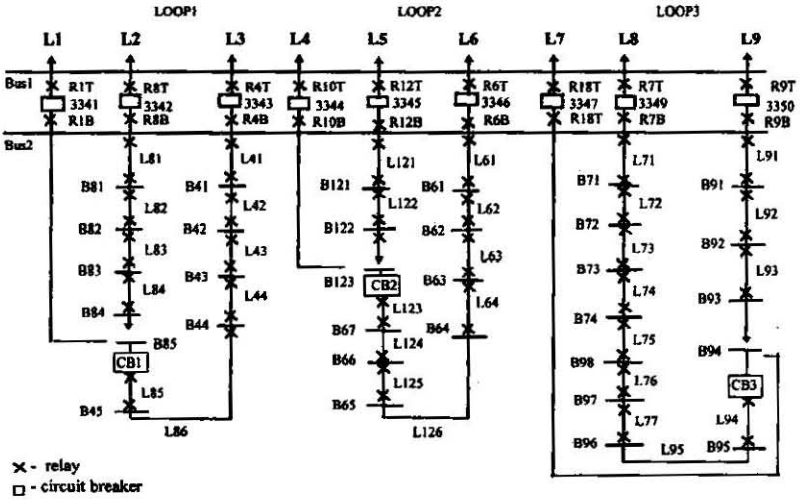

FIGURE 3. Practical TNB distribution system

NEURAL NETWORK DESIGN FOR THE TEST SYSTEM

The ANN design for the test system is based on the concept of hierarchical distributed neural networks as shown in Figure 4. There are three hierarchical modules: ANN1, ANN2 and ANN3. The module ANN1 is considered as the first level ANN which is further divided into three sub-modules, ANN11, ANN12 and ANN13. These submodules are used to diagnose faults in the lines and bus sections of loop1, loop2 and loop3 respectively. The module ANN2 is the second level ANN, which is also consisted of three submodules, ANN21, ANN22 and ANN23. These are used for determining the operating states of relays and circuit breakers in the substation corresponding to loop1, loop2 and loop3 respectively. The module ANN3 is the third level ANN which is used for diagnosing faults in the primary feeders and the substation buses. The corresponding inputs and outputs of the ANN submodules are tabulated as shown in Table 1.

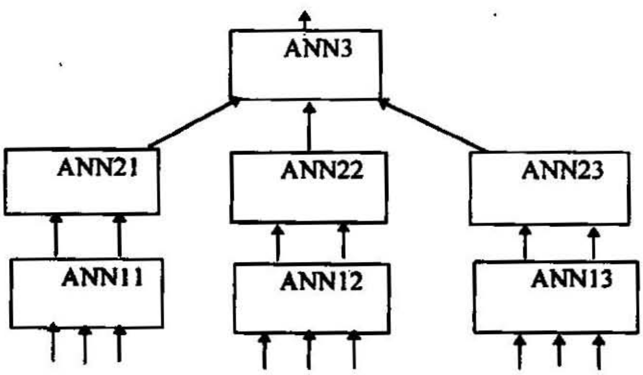

FIGURE 4. ANN design for the practical test system

TABLE 1. Inputs/outputs of the ANN submodules

ANN models	Inputs	Outputs
ANN11	Alarm relays of loop1	Fault states of line sections L81-L86, L41-L44 and bus sections B81-B85, B41-B45
ANN12	Alarm relays of loop2	Faults states of line sections L61-L64, L121-L126 and bus sections B61-B67, B121-B123
ANN13	Alarm relays of loop3	Fault states of line sections L71-77, L91-L95 and bus sections B71-B74, B91-B98
ANN21	Output of ANN11	Operating states of R8T, CB3342, R8B, R4T, CB3343 and R4B
ANN22	Output ANN12	Operating states of R12T, CB3345, R12B, R6T, CB3346 and R6B
ANN23	Output of ANN13	Operating states of R7T, CB3349, R7B, R9T, CB3350 and R9B
ANN3	Outputs of ANN21, ANN22 and ANN23	Fault states of primary feeders L1-L9 and substation buses B1 and B2

TRAINING SETS GENERATION

The training sets for the developed ANN models are generated as follows:

1. Prepare the one-line diagram of the distribution system. List the possible faults that would occur in the system by considering single and multiple faults.
2. Consider the protective relaying scheme. The status of the relays and circuit breakers is represented by binary signals in which '0' characterises a closed circuit breaker or non-operated relay, while '1' characterises an open or tripped circuit breaker or an operated relay. In the system, the relays are classified as alarm relays and protective relays. The alarm relay protects a ground fault from occuring in the line and bus sections of the distribution network and it is also called as the earth-fault relays. The alarm relay operates such that it will indicate '1' when there is a fault and '0' when there is no fault and it determines the fault location of either the lines or bus sections based on the last operated alarm relay. The protective relays and circuit breakers in the substation are used to locate faults in the main feeders and substation buses as well as protecting the equipment in the substation. For any faults occuring in the bus and line sections of the distribution network will cause the associated relays and circuit breakers connected to these bus and line sections to operate.
3. Associate the faults with the relay and breaker open/close states based on the logic of the protective system.

TABLE 2. Training sets of ANN11 for loop1 (for single fault)

INPUT Alarm Relays	OUTPUT (Fault Location)																	
	L81	B81	L82	B82	L83	B83	L84	B84	L41	B41	L42	B43	L44	B44	L86	B45	L85	B85
100000000 0 0 0 0 0 0 0 0 0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
010000000 0 0 0 0 0 0 0 0 0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
001000000 0 0 0 0 0 0 0 0 0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
000100000 0 0 0 0 0 0 0 0 0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
000010000 0 0 0 0 0 0 0 0 0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
000001000 0 0 0 0 0 0 0 0 0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
000000100 0 0 0 0 0 0 0 0 0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
000000010 0 0 0 0 0 0 0 0 0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
000000001 0 0 0 0 0 0 0 0 0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
000000000 1 0 0 0 0 0 0 0 0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
000000000 0 1 0 0 0 0 0 0 0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
000000000 0 0 1 0 0 0 0 0 0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
000000000 0 0 0 1 0 0 0 0 0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
000000000 0 0 0 0 1 0 0 0 0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
000000000 0 0 0 0 0 1 0 0 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
000000000 0 0 0 0 0 0 1 0 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
000000000 0 0 0 0 0 0 0 1 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
000000000 0 0 0 0 0 0 0 0 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1

1 operating or open or tripped relay
0 non operating or closed relay

L = line section
B = bus

1 - fault
0 - no fault

TABLE 3. Training sets of ANN21 for loop 1 (for single faults)

INPUT (Fault States)																		OUTPUT					
L81	B81	L82	B82	L83	B83	L84	B84	L41	B41	L42	B43	L44	B44	L86	B45	L85	B85	R 8B	CB 3342	R 8T	R 4B	CB 3343	R 4T
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1

L = line section
B = bus

1- fault occurred
0 - no fault occurred

R = relay, T = top, B = bottom
CB = circuit breaker
1 - tripped CB & R
0 - non tripped CB & R

TABLE 4. Training sets of ANN3

Input																								Output									
R 1B	CB 3341	R 1T	R 8B	CB 3342	R 8T	R 4B	CB 3343	R 4T	R 10B	CB 3344	R 10T	R 12B	CB 3345	R 12T	R 6B	CB 3346	R 6T	R 7B	CB 3349	R 7T	R 9B	CB 3350	R 9T	L1	L2	L3	L4	L5	L6	L8	L9	B1	B2
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
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1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	1	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	i	1	1	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	0	0	1	1	1	1	0	1	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	1	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	1	1	1	1	1	0	1	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	1	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0

CB = circuit breaker B = bottom T = top R = relay
1 - tripped or open circuit breaker & relay
0 - closed CB &R

L = main feeder
B1, B2 = substation bus
1 - faulty or non operating
0 - operating feeder

The training sets are generated based on the logic operation of relays and circuit breakers corresponding to the respective fault situation. Single and multiple faults have been considered in the generation of the training sets so that the system can diagnose faults due to either single or multiple faults. Some of the sampled training sets generated are shown in Tables 2, 3 and 4 for ANN11, ANN21 and ANN3, respectively.

To illustrate the training set generation in Table 2, for example, in case of a fault in line section L81 as denoted by '1' in the output, the associated alarm relay also indicates a value '1' to show that the alarm is operated. The values '0' represent relays those are not operated.

SIMULATION TEST RESULTS

The developed ANNs are implemented using the Neural Works Professional II/PLUS and Neural Works Explorer software (Neural Ware Inc. 1991). The training and testing results of the developed ANNs are presented in the following sections.

TRAINING OF THE ANNS

The composition of the training and testing data sets of the developed ANN models are summarised in Table 5. The number of input and output nodes of the respective ANNs are also shown. The generated data sets are divided into two groups in which the first group consists of data sets used for training and the second group consists of data sets used for testing the ANNs. The idea is to test the ANN's ability to classify data which it had not seen before. The selection of the data sets for training and testing are made arbitrarily among the total generated data sets.

In the ANN training process, the design parameters such as the number of hidden neurons, learning rate and momentum are varied so as to determine their optimum values. These values are determined based on the most accurate results of the ANN outputs. Table 6 shows the optimum values of hidden nodes, learning rate and momentum for the various ANNs. The number of the hidden neurons needed for an ANN is problem dependent and therefore a trial and error method is used to determine the optimum number. The ANNs are trained using the back propagation algorithm until the root mean square (RMS) error in the outputs between successive iterations is less than or equal to 0.1.

The effect of reducing the RMS errors with increased number of iteration during training for the developed ANNs is shown in Figures 5 to 11. ANN11, ANN12 and ANN13 are trained for 25000, 15000 and 25000 iterations, respectively, and their corresponding RMS errors are 0.0001, 0.001 and 0.001. On the other hand, ANN21, ANN22 and ANN23 are trained for 15000 iterations and their RMS errors are found to be 0.001, 0.0001 and 0.0002, respectively. ANN3 is trained for 20000 iterations and the error is 0.0002. In fact, the RMS errors for all the trained ANNs are less than 0.1%.

TESTING OF THE ANNS

The performance of the ANN models have been tested with the testing data sets which are created outside the training sets. Some of the sampled testing

TABLE 5. Composition of training and testing data sets

ANN models	Total no. of generated data sets	Training data sets	Testing data sets	No. of ANN inputs	No. of ANN outputs
ANN11	152	121	31	18	18
ANN12	156	116	40	20	20
ANN13	195	162	33	24	24
ANN21	135	104	31	18	6
ANN22	156	129	27	20	6
ANN23	195	168	27	24	6
ANN3	52	34	18	18	10

TABLE 6. Optimum values of hidden nodes, learning rate and momentum

ANN models	Hidden nodes	Learning rate	Momentum
ANN11	28	0.9	0.7
ANN12	30	0.9	0.7
ANN13	34	0.9	0.7
ANN21	24	0.9	0.7
ANN22	28	0.9	0.7
ANN23	30	0.7	0.7
ANN3	30	0.7	0.7

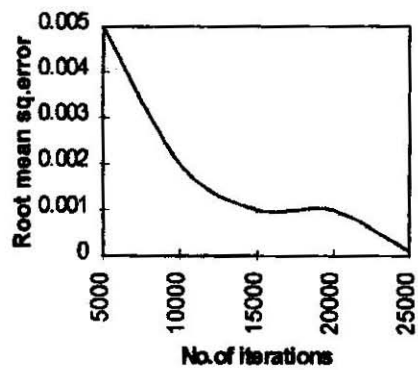

FIGURE 5. Training of ANN11

data sets used in evaluating the performance of the trained ANNs are shown in Tables 7, 8, and 9. Table 10 shows the accuracy of the developed ANNs based on the minimum and the maximum absolute errors.

The absolute errors shown are the difference between the target or desired values based from the model and the ANN outputs.The results indicate that the maximum and minimum absolute errors are 0.365 and 0.000, respectively. The testing results can be considered satisfactory based on the fact that an output of less than " 0.5 " is considered "0", and an output

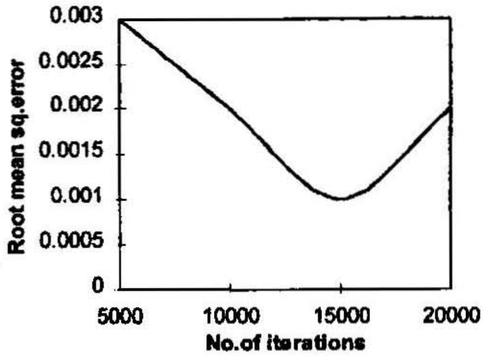

FIGURE 6. Training of ANN12

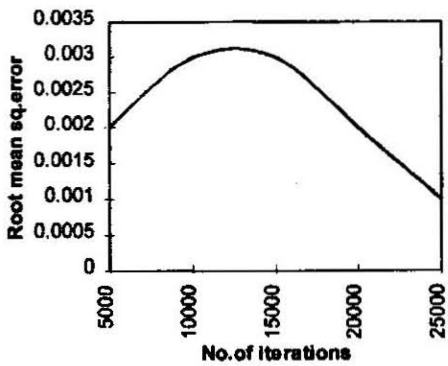

FIGURE 7. Training of ANN13

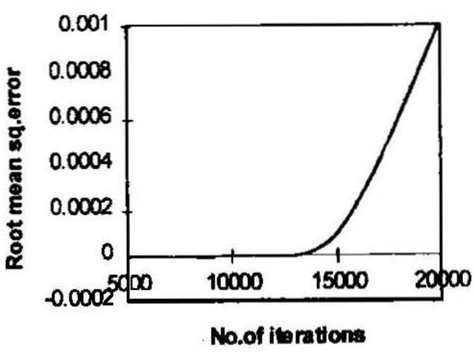

FIGURE 8. Training of ANN21

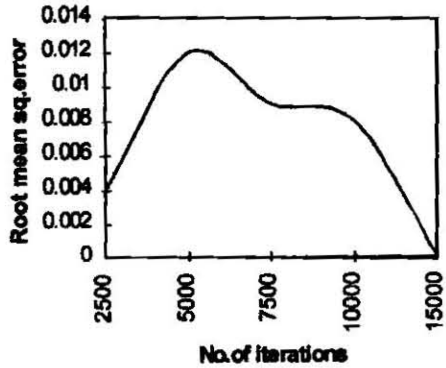

FIGURE 9. Training of ANN22

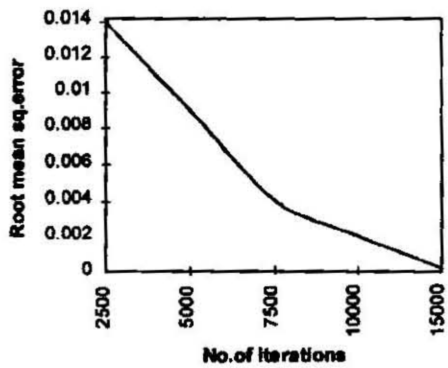

FIGURE 10. Training of ANN23

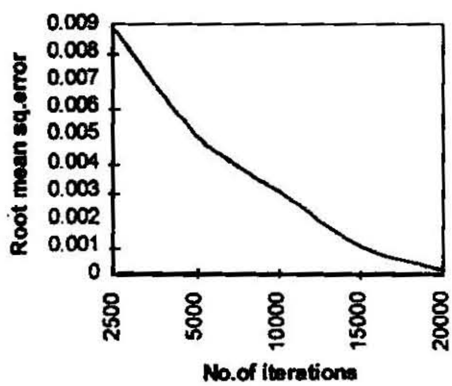

FIGURE 11. Training of ANN3

TABLE 7. Sampled testing data sets of ANN11 for loop 1

INPUT	OUTPUT																	
Alarm Relays	L81	B81	L82	B82	L83	B83	L84	B84	L41	B41	L42	B43	L44	B44	L86	B45	L85	B85
00 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
10 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
10 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
10 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
11 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
11 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
11 0 0 0 0 0 1 0 0 0 0 0 0 0 1 0 0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
11 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
11 1 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
11 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
11 1 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0	1	1	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0
11 1 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0	1	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
11 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
11 1 1 1 0 0 0 0 0 1 0 0 0 0 0 0 0	1	1	1	1	1	0	0	0	0	0	1	0	0	0	1	0	0	0
11 1 1 1 0 0 0 0 0 0 0 0 0 0 0 1 0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0
11 1 1 1 1 0 0 0 0 0 0 1 0 0 0 0 0	1	1	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0
11 1 1 1 1 1 0 0 1 0 0 0 0 0 0 0 0	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	0
00 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
00 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
10 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
11 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
11 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
11 1 1 1 0 0 0 0 0 0 0 1 0 0 0 0 0	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
11 1 1 1 1 0 0 0 0 0 0 0 1 0 0 0 0	1	1	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0
11 1 1 1 1 1 1 1 0 0 0 0 0 0 0 1 0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	0
00 0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
00 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
10 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
11 0 0 1 0 0 0 0 0 0 0 0 0 1 1 0 0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0
11 1 0 1 1 1 0 0 0 0 0 0 0 1 1 0 0	1	1	1	0	1	1	1	0	0	0	0	0	0	0	1	1	0	0

L = line section
B = bus

TABLE 8. Sampled testing data sets of ANN21 for loop1

INPUT (Fault States)																		OUTPUT					
L81	B81	L82	B82	L83	B83	L84	B84	L41	B41	L42	B43	L44	B44	L86	B45	L85	B85	R8T	CB3342	R8B	R4B	CB3343	R4T
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1
1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1
1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1	1	1	1	1
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	1	1
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	1	1
1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1
1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1
1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
1	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1
1	1	1	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1
1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0
1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	1
1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0	1	0	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1

L = line section
B = bus

1 - fault occured
0 - no fault occured

R - relay, T - top, B - bottom
CB - circuit breaker
1 - tripped CB & R
0 - non tripped CB & R

TABLE 9. Sampled testing data sets of ANN3

INPUT																		OUTPUT							
R 8B	CB 3342	R 8T	R 4B	CB 3343	R 4T	R 12B	CB 3345	R 12T	R 6B	CB 3346	R 6T	R 7B	CB 3349	R 7T	R 9B	CB 3350	R 9T	L2	L3	L5	L6	L8	L9	B1	B2
0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
1	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
0	0	0	1	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0
0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	0	0
1	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
0	0	0	1	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0
1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0
0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
0	0	0	1	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0
0	0	0	1	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	0	1	0	0	0
1	1	1	0	0	0	1	1	1	0	0	0	0	0	0	1	1	1	1	0	1	0	1	0	0	0
0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	0	1	0	1	0	1	0	0
1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	0	1	0	0	0
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	0	0
1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	1	1	1	1	1	1	1	0	1	0	0

B = bottom
T = top
1 = tripped or open circuit breaker & relay
0 = closed CB & R

L = main feeder
B1, B2 = substation bus
1 = faulty or non operating
0 = operating feeder

TABLE 10. Results of testing the ANN models

ANN models	Testing data sets	Min. Absolute error	Max. Absolute error
ANN 11	31	0.000	0.365
ANN 12	40	0.0006	0.175
ANN 13	33	0.0007	0.131
ANN 21	31	0.000	0.222
ANN 22	27	0.000	0.317
ANN 23	27	0.000	0.310
ANN 3	18	0.001	0.222

equal to or greater than " 0.5 " is considered "1" (Neural Ware, Inc. 1991). Hence, satisfactory fault diagnosis has been achieved by the developed ANN models. The proposed diagnosis system can make correct identifications for single and multiple faults when there are correct operations of relays and circuit breakers. However, to improve the accuracy of the developed ANNs, further work is to be carried out by considering proper selection and organisation of the training patterns.

FUTURE WORK

Future work is to design ANNs for fault restoration and faulty components identification. In fault restoration, the proposed work is to provide the recovering actions to system operations so as to speed up the fault restoration process. On the other hand, the proposed ANN design for faulty components identification is to identify the circuit breakers and relays which are faulty during a fault. An on-line test of the proposed diagnosis system is also to be considered in the future.

CONCLUSION

The application of a hierarchical distributed neural network (HDNN) to fault diagnosis of a practical TNB distribution system has been presented. The design of the ANNs is based on the structure and the function of the protection system and the generation of the training sets is based on logic of the protection system. The proposed HDNN design is also modular in structure so as to provide flexibility to configuration changes and also to reduce the computational burden in training the ANN, compared with the conventional method which use one neural network for the whole power system. The developed ANN models have been trained and tested to a practical distribution system to locate the line and bus faults of several loops in the system and to locate faults in the main feeders and substation buses of the distribution system. Based on the testing results so as to determine the accuracy of the developed ANNs, satisfactory fault diagnosis can be achieved considering both single and multiple faults. However, to achieve better performance, proper selection and organisation of the training patterns need to be considered.

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