NOVEL ALGORITHMS FOR MODERN POWER SYSTEMS

by

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"the end of wisdom is freedom;
the end of culture is perfection;
the end of knowledge is love; and
the end of education is character"
- Sri Sathya Sai Baba

Declaration

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Abstract

The restructuring of the electric power industry has brought about many interesting and new problems to be solved by researchers. Some of the problems have been considered and suitable intelligent techniques that have been developed are described in this thesis.

A new technique using wavelet transform and neural networks for fault location and protection of a practical tee-circuit has been developed. Fault simulation is carried out using EMTP software. The waveforms obtained from the simulation are then used in wavelet analysis to generate patterns for training and validation, which is carried out using Radial Basis Function network. Dynamic Protection Modelling (DPM) software developed by the University of Strathclyde, Centre for Electrical Power Engineering is used for the evaluation of relay settings.

A new approach is proposed to use object oriented techniques and improved genetic algorithms in developing software to estimate generator excitation control system parameters. Simulation studies are carried using data representing a generator, with its transformer connected to an infinite busbar.

Application of evolutionary programming to Optimal Power Flow is another technique that is proposed in this work. The objective is to minimize fuel cost keeping the system secure under both normal and contingent states. Studies are carried out using the IEEE - 30 bus test system.

A short-term load-forecasting model using Artificial Neural Networks and Genetic Algorithm has been developed and tested on data obtained from a power company. It is found that the time taken to obtain a satisfactory solution is long, as the problem is very complex. This points in the direction of evolutionary computing being integrated with parallel processing techniques to solve such practical problems.

A novel approach to the formulation and evaluation of transmission loss and line flow through a set of new loss coefficients and distribution factors respectively which are efficient, exact and robust and suitable for real time application is proposed. These loss coefficients and distribution factors are generated from the available load flow solution with trivial computational burden. Results on IEEE Test systems show that the coefficients need not be re-evaluated for wide changes in system operating conditions.

LIST OF PUBLICATIONS

Lecture Notes

1. L L Lai, H Subasinghe, N Rajkumar, E Vaseekar, B J Gwyn and V K Sood, 'Object-oriented genetic algorithm based artificial neural network for load forecasting', book chapter for Lecture Notes in Computer Science, LNCS, Springer-Verlag, Xin Yao et al. (Editors). May 1999

Referred Journal Paper

1. J Nanda, L L Lai, J T Ma, N Rajkumar, A Nanda and M Prasad, 'A Novel Approach to Computationally Efficient Algorithms for Transmission loss and Line Flow Formulations', International Journal of Electrical Power Systems Research, Elsevier Science Ltd, Nov 1999.

Referred Conference Papers

1. L L Lai, E Styvaktakis, A G Sichanie, N Rajkumar and R Yokoyama, 'Modelling, design and simulation of generator excitation systems with object-oriented techniques and improved genetic algorithms', Proceedings of the Fourth International Conference on Advances in Power System Control, Operation & Management (APSCOM – 97), IEE, Pub No 450, 332-337.

2. L L Lai, AG Sichanie, N Rajkumar, E Styvakis, M Sforna and M Caciotta, 'Practical application of object oriented techniques to designing neural networks for short-term electric load forecasting', Proceedings of the International Conference on Energy Management and Power Delivery (EMPD '98), IEEE, Singapore, March 1998, 559-563.

3. Q X Xang, Z Y Xu, L L Lai, Z H Zhang, N Rajkumar, 'Fault identification during power swings with symmetrical components', (EMPD '98), 108-112.

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5. L L Lai, E Vassekar, H Subasinghe, N Rajkumar, A Carter and B J Gwyn, 'Fault location of a teed-network with wavelet transform and neural networks', Loi Lei Lai (Editor), Proceedings of the International Conference on Power Utility Deregulation, Restructuring and Power Technologies 2000, CD-ROM version, IEEE catolog Number 00EX382, ISBN 0-7803-5902-X, April 2000, 505-509.

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Chapter I

INTRODUCTION

1.1 Need for Novel Techniques

As modern electrical power systems become more complex, operation of such systems using conventional methods and techniques may not be reliable, secure and effective. The conventional methods face difficulties such as slow response, problems related to maintenance, likely difficulties in upgrading for future expansion requirements and aging of the technology.

As such digital techniques have been used in implementing these functions. These techniques are advantageous in that they are fast in response, more reliable due to self-diagnostic capability, module can be easily upgraded and software controllable to adapt to future development and expansion needs.

To overcome the limitations of digital techniques, less rigorous techniques of artificial intelligence (AI) have been used. The main AI techniques applied to power systems are expert systems, fuzzy systems, artificial neural networks (ANN) and more recently evolutionary algorithms.

An expert system is a collection of programs or software that solve problems in much the same manner as human experts. It is called a system rather than just a program because it contains both problems solving component and a support component. It uses knowledge and reasoning procedures to solve problems that are normally handled by experts. The expert system consists of four major components: knowledge base, interference engine, working memory and user interface. The most useful feature of an expert system is the high level expertise it provides to aid in problem solving. This expertise can represent the best thinking of top experts in the field, leading to problem solutions that are imaginative, accurate and efficient. It is the high level expertise together with the skill at applying it that makes the system cost effective, able to earn its way in the commercial field. Another useful feature of an expert system is its predictive modelling power. The system can act as an information processing theory or model of a problem solving in the given domain, providing the desired answers for a given problem situation and showing how they would change for new situations. This lets the user evaluate the potential effects of new facts or data and understand their relationship to the solution. Similarly, the user can evaluate the effect of new strategies or procedures on the solution by adding new rules or modifying existing ones. Improved accuracy and speed, systematic consideration of all possible alternatives, performing routine tasks, easy availability of expertise and reproducibility and conservation of knowledge are some of the beneficial features of expert systems.

Application of expert systems to power system problems has been an area of strong research interest for a long time. A number of research findings have been published on the subject with emphasis on the application to power system planning, operation, monitoring and protection. An extensive bibliography [1], a review [2], and a survey [3] of the research activities have been provided. The main emphasis has been on energy management systems related applications such as system monitoring, operation and planning and protection [4-6]. An informative tutorial on expert systems and their applications to power systems has been published in three parts by K L Lo and I Nashid [7-9].

Fuzzy system is another AI technique that has received much attention in developing sophisticated control schemes for power systems [10-12]. Fuzzy logic is a method of representing human knowledge or experience as fuzzy rules. In a fuzzy system, the inputs are converted into their fuzzy representations by "fuzzifiers" and the fuzzified inputs execute all the rules in the knowledge base generating a new fuzzy set representing each solution variable. Defuzzification converts the fuzzy output into numerically precise solution variables. The difficulty of a fuzzy system is in the tuning and when applied to more complex systems it is very difficult to design the optimal fuzzy system in detail. In order to solve this problem, some self-tuning methods have been proposed such as fuzzy neural network using the back propagation algorithm for learning [13], fuzzy learning controller using radial basis function [14], use of genetic algorithm for choosing the shapes of membership functions and fuzzy rules [15,16].

Interest in artificial neural networks has grown rapidly over the past years. The improved understanding of the functioning of the neuron and the pattern of its interconnections has made it possible for researchers to produce mathematical models to conduct experiments on digital computers without involving human or animal subjects. These models showed that they were capable of performing useful functions in their own rights. These gave rise to neural networks that are computational system that perform brainlike functions.

Artificial neural networks have been applied in planning, operation and analysis of power systems. The following specific problems are most popular:

- Planning (long-term load forecasting, economic load dispatch, and unit commitment).

- Operation (optimal power flow, unit commitment, generator shedding, state estimation, static and dynamic security assessment, dynamic contingency analysis, fault location and protection, daily load forecasting, substation maintenance, voltage stability assessment).

- Analysis (dynamic stability assessment, generator voltage and speed control system design, harmonic analysis, bad data detection, monitoring and protection).

Evolutionary algorithms (EAs) are computer based problem solving systems which are computational models of evolutionary processes as key elements in their design and implementation. There are a variety of evolutionary algorithms and they all share a common conceptual base of simulating the evolution of individual structures via processes of selection, mutation and recombination. The processes depend on the perceived performance of the individual structure as defined by the environment. EAs maintain a population of structures that evolve according to rules of selection and genetic operators, such as recombination and mutation. These algorithms are sufficiently complex to provide robust and powerful adaptive search mechanisms. The most popular EA developed so far are Genetic Algorithms (GA), Evolution Strategies (ES), Evolutionary Programming (EP), Classifier Systems and Genetic Programming (GP). A detailed account of applications of evolutionary programming and neural network in power system engineering is presented in the book by L L Lai [17]

The restructuring of the electric power industry has produced many interesting and new problems for researchers to tackle. The separation of generation and transmission units has meant that operation and control of the high voltage grid system is independent of the generation pattern. Research is being done into ways of making the transmission grid more flexible and efficient and at the same time ensuring its high standard of security and reliability is maintained. Several new techniques have been proposed in this work to solve those problems encountered in the new restructured electric power industry.

Fault at any point in a power system produces large values of currents many times the normal capacity of the equipment, and the system should be immediately protected against such operation by switching off the faulty section. Hence fault location is important in order to clear faults from the system and restore supply as soon as possible with minimum interruption. Methods based on travelling wave theory, Fourier analysis and Wavelet analysis have been used for the estimation of fault location in power systems [18-20]. If the power system is more complicated, the above approach becomes more complex because of the power injection form the various paths of the system. The basic schemes of protection used for two-terminal lines cannot be applied to teed lines, as the problems involved are much more difficult. Such a complex problem can be solved by closely looking at the fault instant waveforms using an intelligent system.

Object-oriented programming (OOP) techniques are being used increasingly in the development of software for application areas in power systems. The structured programming techniques that have been used in the past suffer from the fundamental problem that information flow is one way. Because of insufficient feedback, the method leads to designs that cannot respond to changes in the software development. In OOP approach, each stage of the development is revisited throughout the process and the software is refined at each visit. Software to design and simulate an excitation control system for a large generator has been developed using OOP techniques and improved genetic algorithms.

Evolutionary algorithms are being used to solve wide variety of power system problems such as optimal reactive power generation, tap settings of under-load-tap change transformers, VAR source installations to minimize both the cost of energy loss in the network and the investment cost of VAR source installations and at the same time improve the voltage profile of the whole system [21-25]. Application of evolutionary programming for optimal power flow is one of the contributions described in this documentation. The objective is to minimize the fuel cost and keep as secure system in both normal and contingent states.

Accurate load forecasting is essential for the optimal planning and operation of large-scale power systems. Many techniques such as time series approach, regression approach, state-space models, pattern recognition and expert systems have been proposed and used for short-term load forecasting [26-30]. All the above approaches require lots of computational time due to the large number of complex equations involved in the methods. Artificial neural network techniques developed by several researchers have the limitation of poor convergence during training.

A new technique that uses object oriented programming to integrate ANN and GA to enhance the robustness of neural networks for load forecasting has been developed.

Transmission loss formulation using B coefficients is used by many power utilities for economic load dispatch (ELD). It is found that these B coefficients are not very accurate and hence cannot provide best economy in the cost of generation for ELD. As they are not robust, they need to be re-calculated for changes in the system operating conditions so as to achieve better economy in the system. A novel approach to powerful, effective and computationally efficient algorithms for evaluating transmission loss and line flow using a new set of loss coefficients and distribution factors has been developed. These coefficients are more exact and robust and can be efficiently realised with little computational burden.

1.2 Organization of the Thesis

Chapter 2 describes the origin of artificial neural networks, the different types of neural networks, their learning algorithms and lists the typical applications in power systems.

Chapter 3 is devoted to a brief description of the different types of evolutionary algorithms. A list of applications in power systems is also given.

Chapter 4 discusses the main issues and methods in the restructured electric power industry. Examples are used to illustrate the need for new technology on modern power systems.

Chapter 5 is devoted to fault location and protection of a teed-network using wavelet transform and neural networks. Types of teed-circuits, protection schemes used and their drawbacks are described. Major part of the work in which a practical tee-circuit is simulated using EMTP to obtain data for training and validation of a neural network that could be used for fault location and protection is illustrated. Results of Relay setting evaluation using Dynamic Protection Modelling software are analysed.

Chapter 6 describes a new approach in using object-oriented techniques and improved genetic algorithms to develop software for generator excitation control giving an example case.

In Chapter 7, application of evolutionary programming to optimal power flow in both normal and contingent states is presented. Two case studies using IEEE-30 bus system are described.

Chapter 8 deals with the use of an integrated computational intelligent technique using artificial neural network and genetic algorithm for power system load forecasting. Development of a short-term load-forecasting model and its validation are described.

Chapter 9 describes an algorithm for the evaluation of transmission loss and line flow using efficient loss coefficients and distribution factors respectively. Test results that reveal the suitability of the approach for practical applications are shown.

1.3 Original contributions

Some of the problems encountered due to the complexity of modern power systems and as a result of restructuring of the electric power industry have been considered and suitable intelligent techniques have been developed. A summary of the original contributions made in this research is given below:

1. Development of a new technique using wavelet transform and neural network for fault location in a teed-circuit. The impedance values obtained by this method tested by the Dynamic Protection Modelling (DPM) software

developed by the University of Strathclyde has shown that the values could be used as input to the distance relays for the protection of teed circuits.

2. Development of a software using object oriented programming techniques and genetic algorithms to select optimal parameter values of an excitation control system. This approach could be used for real time control of excitation systems.

3. Proposal of a solution using evolutionary programming to optimal power flow. Testing the proposed method has shown that it finds better results than the conventional methods.

4. Development of a short-term load forecasting model using artificial neural network and genetic algorithm. Accurate predictions are obtained when the model is tested with actual data provided by a power company.

5. Development of a computationally efficient method for evaluation of transmission loss and line flow through a set of A coefficients and a set of Distribution Factors respectively. Results of tests carried out on IEEE test system show that these A coefficients and Distribution factors are suitable for real time application, and that they need not be recalculated even for very wide changes in the system loading pattern.

Chapter II

NEURAL NETWORKS

2.1 Introduction

Interest in artificial neural networks has grown rapidly over the past few years. The improved understanding of the functioning of the neuron and the pattern of its interconnections has made it possible for researchers to produce mathematical models to their theories. Conducting experiments on digital computers without involving human or animal subjects can solve many practical problems. The models used for such experiments showed that they not only mimicked functions of the brain, but they were capable of performing useful functions in their own right. This gave rise to neural networks that are computational systems that perform brainlike functions.

A neural network is an interconnected network of simple processing elements. Communication between processing elements occurs along paths of variable connection strengths. By changing the values of these connection strengths the network can collectively produce complex overall behaviour. The first mathematical model of artificial networks was developed by McCulloch & Pitts in 1943 [31]. The starting point for artificial neural network (ANN) training algorithms was the learning rule that was proposed by D.O Hebb in 1949 [32]. The first simple but well-known ANN architecture to be described is called the perceptron developed by Rosenblatt [33]. Networks developed using perceptrons failed to solve some problems and this led to the development of rigorous theorems regarding network operation by Marvin Minsky. His research led to the publication of the book Perceptrons by Minsky and Papert in 1969 [34]. They proved that the single-layer networks then in use were theoretically incapable of solving many simple problems. During the 1970s and early 1980s researchers such as Carpenter and Grossberg [35,36] and Kohonen [37-39] continued to carry out research and came up with the more powerful multilayer networks which overcome the limitations presented by the single-layer networks.

2.2 Biological Neurons

Design of artificial neural network (ANNs) was inspired by biological research on the working of the human brain. The human nervous system is built of cells called neurons. The general structure of a pair of typical biological neurons is shown in figure 2.1. Each neuron shares many characteristics with other cells in the body, but has unique capabilities to receive, process and transmit electrochemical signals over the neural pathways that comprise the brain's communication system.

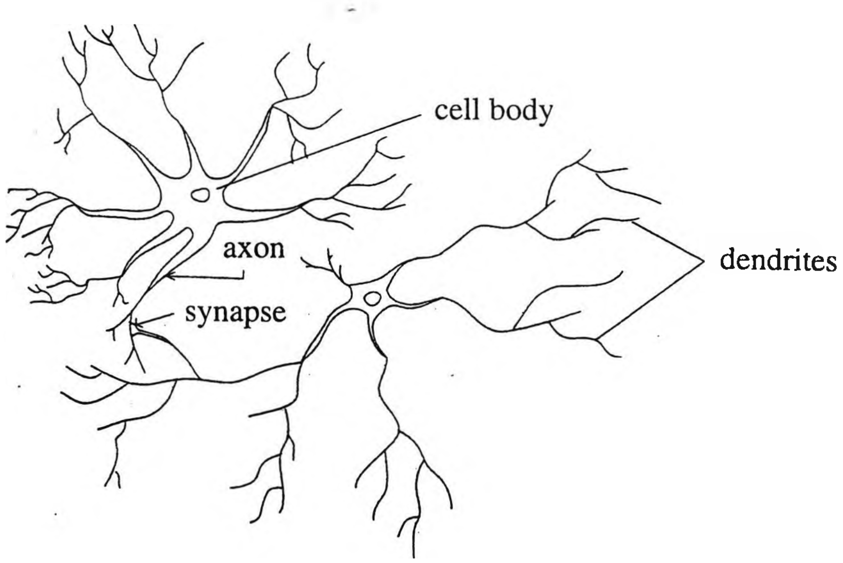

Figure 2.1 Biological neuron

The main component of a typical biological neuron is the **cell body**. **Dendrites** extend from the cell body to other neurons where they receive signals at a connection point called **synapse.** On the receiving side of the synapse, these inputs are conducted to the cell body, where they are summed. There are basically two types of synapses, one called excitatory and the other inhibitory. When the cumulative excitation in the cell body exceeds a threshold value, the cell fires, sending a signal along the axon to other neurons. The axon is connected via synapses to the dendrites of other neurons. Although the basic functional outline of the biological neuron has many complexities and exceptions, most artificial neural networks model only these simple characteristics.

2.3 The Artificial Neuron

The first artificial model of a biological neuron was established by McCulloch and Pitts [31]. In this model, a set of input x_p is applied, each representing the output of another neuron. Each input is multiplied by a corresponding weight w_{kp}, analogous to a synaptic strength. All weighted inputs are summed to produce u_k, given by the expression:

$$u_k = \sum_{p=1}^{n} w_{kp} x_p \qquad (2.1)$$

Where k refers to a particular neuron and n is the number of inputs to the particular neuron. If the combined input reaches a certain threshold level, a response is generated. This is then modulated by an activation function, which transforms u_k to give an output signal expressed by:

$$y_k = f(u_k - \theta_k) = f[\sum_{p=1}^{n} w_{kp} x_p - \theta_k] \qquad (2.2)$$

Figure 2.2 shows a model of an artificial neuron.

2.4 Activation functions

The activation function represents the amplification of the axon and determines the kind of information passed on from one neuron to another. This may be a simple linear function, a threshold function or a function that more accurately simulates the nonlinear characteristic of the biological neuron and permits more general network functions. The most commonly used activation functions are:

- Threshold
- Pure linear
- Linear saturated
- Log-sigmoid
- Tan-sigmoid
- Gaussian basis function

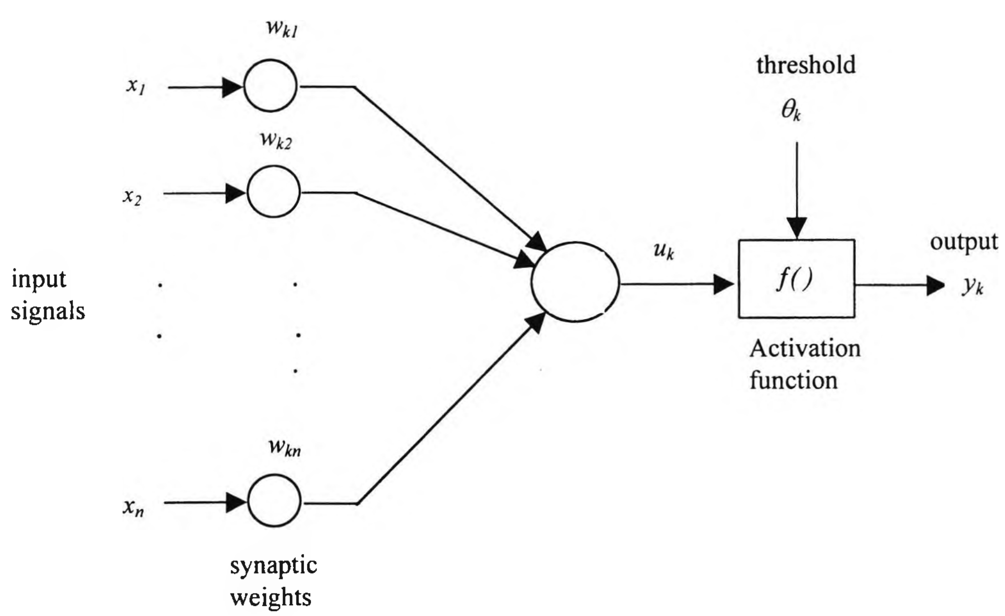

Figure 2.2 Model of an artificial neuron

2.5 Architecture of neural networks

Combining several neurons so that the output of one neuron serves as input to one or several other neurons leads to networks of artificial neurons. The architecture specifies the arrangement of neural connections as well as the type of units characterised by its activation function. There are four main types of ANN architecture in use:

- Single layer feed-forward networks
- Multilayer feedforward networks
- Recurrent networks
- Self-organising networks

2.5.1 Single-layer feedforward network

A layered network is a network of neurons organised in the form of layers. This has an input layer of source nodes and an output layer of neurons. The set of inputs x has each of its elements connected to each artificial neuron through a separate weight. Computation is performed only in the neurons. This network is illustrated in figure 2.3

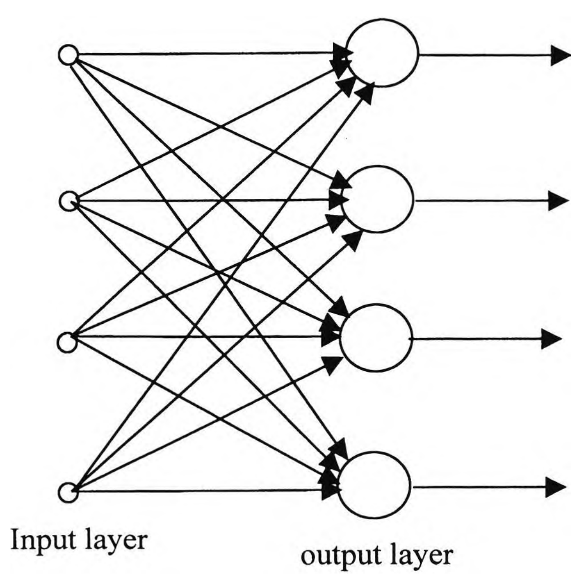

Figure 2.3 Single layer feedforward network

2.5.2 Multilayer feedforward network

A multilayer feedforward ANN is characterised by having one or more layers of neurons other than the input and output layers, known as hidden layers. It is also characterised by the one-directional flow of data between layers. The function of the hidden layer is to intervene between the external output and the network input. By adding one or more hidden layers, the network is enabled to extract higher order statistics, for the network acquires a global perspective despite its local connectivity by virtue of the extra set of synaptic connections and the extra dimension of neural interactions [36]. The ability of hidden neurons to extract higher order statistics is particularly valuable when the size of the input is large. The input layer of the network supplies the input signal to the neurons in the hidden layer. The output signals of the hidden layer are used as inputs to the third layer. This will go on for the rest of the network if there are more than one hidden layer. The set of output signals of the neurons in the output layer constitutes the overall response of the network to the input signal from the input layer. The structure of a multilayer feedforward neural network is shown in figure 2.4.

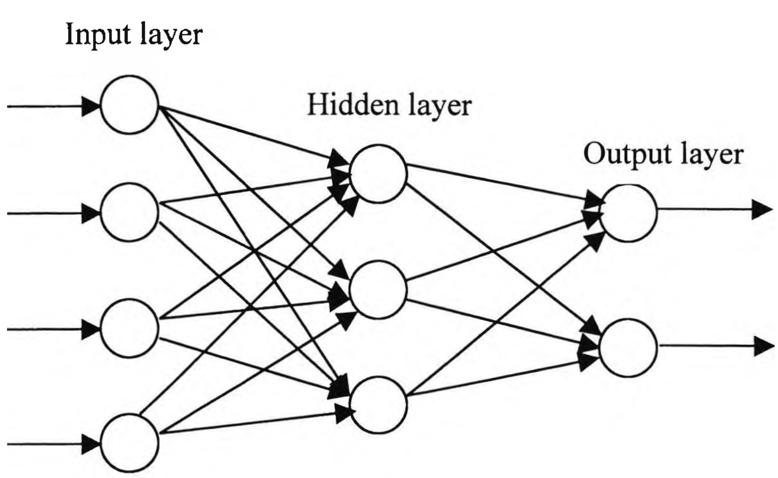

Figure 2.4 Structure of a multilayer feedforward network

This network is said to be fully connected as every node in each layer is connected to every node in the adjacent forward layer. If some of the synaptic connections are missing, then the network is said to be partially connected.

2.5.3. Recurrent neural networks

Networks that contain feedback connections are said to be recurrent. In this type of network, the inputs to a neuron are the net's previous outputs as well as inputs from external sources. For this reason, recurrent networks can exhibit properties very similar to short-term memory in humans in that the state of the network outputs depends in part upon their previous inputs. A recurrent network may consist of a single layer of neurons with each neuron feeding its output signal back to the inputs of all the other neurons. Recurrent networks may or may not have hidden neurons. Figure 2.5 illustrates a recurrent network with no hidden neurons. Another class of neural networks with hidden neurons is illustrated in figure 2.6.

The Hopfield network is a recurrent network that operates as a feedback system. The main limitation of Hopfield networks is the lack of hidden layers. Hidden neurons are known to learn internal representations of training patterns that enhance the performance of the ANN.

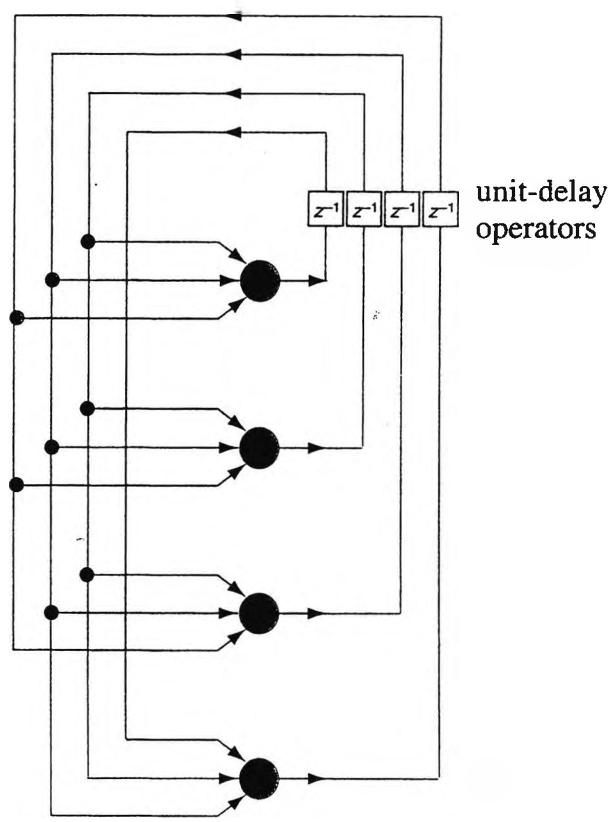

Figure 2.5 Recurrent network with no hidden layer

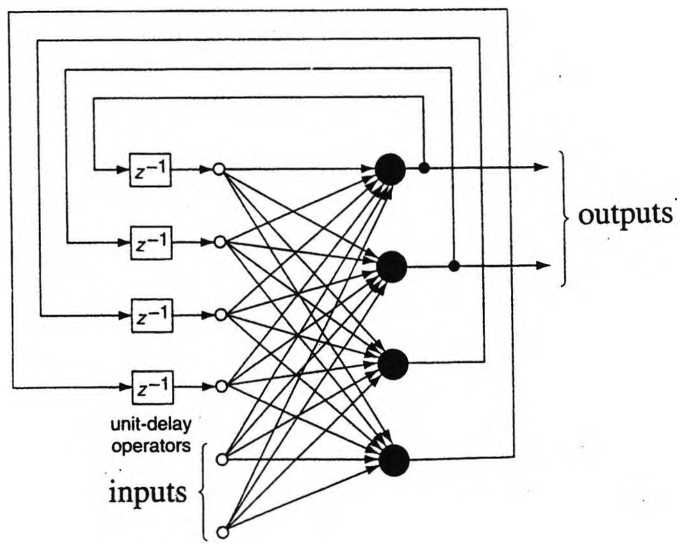

Figure 2.6 Recurrent network with hidden neurons

2.5.4 Self-organising networks

Developed by Kohonen in the early 1980s [37,38], the network mimics the brain's ability to organise itself in response to external stimuli. This algorithm is capable of learning without supervision. A Kohonen network typically consists of an input layer and a two dimensional Kohonen layer, which maps a distribution of m-dimensional vectors into two dimensional in a nonlinear way, preserving the ordering of the high dimension input data. The input data are fully connected to each Kohonen neuron and are presented sequentially in time without specifying the desired output [39].

2.6 The perceptron

The perceptron, shown in figure 2.7 is the simplest form of a neural network used for the classification of a special type of patterns. A single node computes a weighted sum of the input elements and the result is modified by a threshold function such that the output is either +1 or −1. The weights can be learnt by training based on 'error-correction learning'.

The disadvantage of this type of network is that it produces correct solutions only if the training patterns are linearly separable. If the relationship between inputs and outputs is non-linear, the network will have difficulty with training sets.

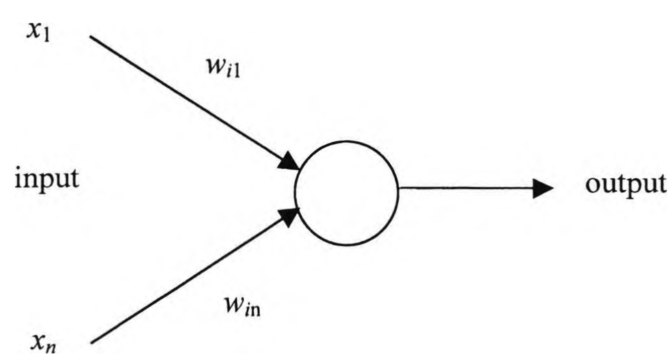

Figure 2.7 Single-layer perceptron

Despite the limitations of perceptron, they have been extensively studied. Their theory is the foundation for many other forms of artificial neural networks and they demonstrate important principles. For these reasons, they are a logical starting point for a study of artificial neural networks.

2.7 Training artificial neural networks

Artificial neural networks have the ability to learn. Their training shows so many parallels to the intellectual development of human beings. The network is trained so that application of a set of inputs produces the desired set of outputs. Each such input or output set is referred to as a vector. Training is done by sequentially applying input vectors, while adjusting network weights according to a predetermined procedure. The network weights gradually converge during training to values such that each input vector produces the desired output vector. Training algorithms are categorised as supervised and unsupervised. Supervised learning requires an external "teacher" that evaluates the behaviour of the system and directs the subsequent modifications. In unsupervised learning, the network organises itself to produce the desired changes.

2.8 Learning algorithms

A prescribed set of well-defined rules for the solution of learning problem is called a **learning algorithm.** There is no unique learning algorithm for the design of neural networks. There are a diverse variety of learning algorithms, each having its own advantages. Learning algorithms differ from each other in the way in which the adjustment to the synaptic weight is formulated and the manner in which a neural network relates to its environment. There are four basic learning algorithms: **error-correction learning, Hebbian learning, competitive learning and Boltzmann learning [40].**

2.8.1 Error-correction learning (The Delta rule)

Error-correction learning relies on the error signal to compute the correction applied to the synaptic weight of a neuron. The error signal of a neuron k is the difference between the desired response $d_k(n)$ and the actual response $y_k(n)$, as shown by

$$e_k(n) = d_k(n) - y_k(n) \qquad (2.3)$$

The ultimate purpose of the algorithm is to minimise a cost function based on the error signal $e_k(n)$, such that the actual response of each output neuron in the network approaches the target response for that neuron in some statistical sense. Once a cost function is selected, error correction learning is strictly an optimisation problem that may be solved by the usual methods.

A commonly used cost function is the mean square error, defined as the mean square value of the sum of squared errors, given by:

$$J = E[\frac{1}{2}\sum_k e_k^2(n)] \qquad (2.4)$$

where E is the statistical expectation operator, and the summation is over all the neurons in the output layer of the network. Minimisation of the cost function J with respect to the network parameters leads to the method of gradient descent.

The adjustment $\Delta w_{kj}(n)$ made to a synaptic weight w_{kj} is proportional to the product of the error signal $e_k(n)$ and the input signal $x_j(n)$ of that particular synapse.

$$\Delta w_{kj}(n) = \eta e_k(n)\, x_j(n) \qquad (2.5)$$

where η is a positive constant that determines the rate of learning. This learning rate parameter has to be chosen carefully so as to ensure stability of the error correction learning process as it behaves like a closed-loop system. If η is small, the learning process proceeds smoothly, but it may take a long time for the system to converge to a stable solution. If η is large, the rate of learning is accelerated, but the learning process may diverge and the system becomes unstable.

2.8.2 Hebbian learning

In 1949, the neuropsycologist Hebb [32] formulated the hypothesis that synapses change in efficacy according to the following principle:

1. If two neurons on either side of a synapse are activated simultaneously, then the strength of that synapse is selectively increased.
2. If two neurons on either side of a synapse are activated asynchronously, then that synapse is selectively weakened or eliminated.

Expressing the above in mathematical terms, the adjustment applied at time n to a synaptic weight w_{kj} with presynaptic and postsynaptic activities denoted by x_j and y_k, respectively, is expressed as:

$$\Delta w_{kj(n)} = F(y_k(n), x_j(n)) \qquad (2.6)$$

where F is a function of both postsynaptic and presynaptic activity. As a special case, synaptic learning can be expressed as a product of the incoming and outgoing signals.

$$\Delta w_{kj}(n) = \eta\, y_k(n)\, x_j(n) \qquad (2.7)$$

where η is a positive constant that determines the rate of learning. From this, it can be seen that the repeated application of the input signal x_j leads to an exponential growth that finally drives the synaptic weight w_{kj} into saturation. To avoid such saturation, a limit on the growth of the synaptic weights has to be imposed and introducing nonlinear forgetting factor into the formula for the synaptic adjustment does this. The formula can be rewritten as:

$$w_{kj}(n) = \eta\, y_k(n)\, x_j(n) - \alpha y_k(n)\, w_{kj}(n) \qquad (2.8)$$

2.8.3 Competitive learning

In competitive learning, the output neurons of a neural network compete among themselves for being the one to be active. The neuron that wins the competition is called a winner-takes-all neuron. This feature that a single output neuron is active at one time makes competitive learning highly suitable for discovering those salient features that may be used to classify a set of input patterns.

In competitive learning, the neural network has a single layer of output neurons, each of which is fully connected to the input nodes. According to the standard competitive rule, the change Δw_{ji} applied to a synaptic weight w_{ji} is defined by

$$\Delta w_{ji} = \begin{cases} \eta(x_i - w_{ji}) & \text{if neuron } j \text{ wins the competition} \\ 0 & \text{if neuron } j \text{ loses the competition} \end{cases} \qquad (2.9)$$

This rule has the overall effect of moving the synaptic weight vector of winning neuron toward the input pattern. Figure 2.8 shows the concept of a competitive single-layer neural network with three nodes and three inputs, where the first node is winning.

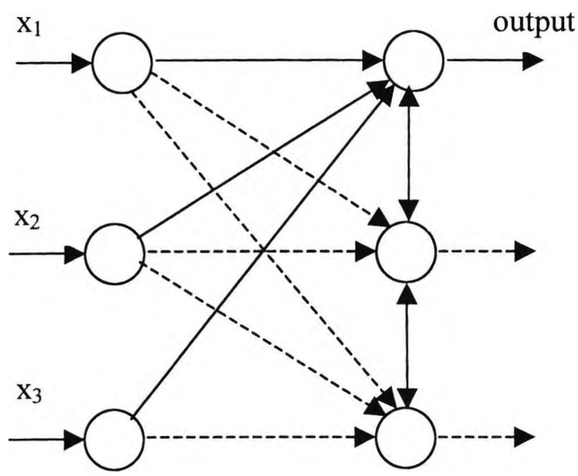

Figure 2.8 Competitive learning with node 1 winning

2.8.4 Boltzman learning

This is a stochastic learning algorithm derived from thermodynamic considerations. It is characterised by an energy function E, the value of which is determined by the particular states occupied by the individual neurons as given by

$$E = -\frac{1}{2}\sum_{i}\sum_{j} w_{ji} s_j s_i \qquad (2.10)$$

Where s_i is the state of neuron i, and w_{ji} is the synaptic weight connecting neuron i to neuron j.

2.8.5 Supervised learning

In supervised learning each input vector is paired with a target vector representing the desired output. The network is usually trained over a number of such training pairs. The output of the network is calculated for an input vector and compared with the corresponding target vector. The difference is fed back through the network and weights are changed according to an algorithm that tends to minimise the error. The vectors of the training set are applied sequentially, errors calculated and weights adjusted for each vector until the entire training set is at an acceptable level. Error correction learning, reinforcement learning and stochastic learning are all examples of supervised learning. There are two sub categories of supervised learning: structural learning and temporal learning. Examples of supervised learning algorithms include least mean square algorithm and back propagation algorithm. Figure 2.9 shows a block diagram representation of supervised learning.

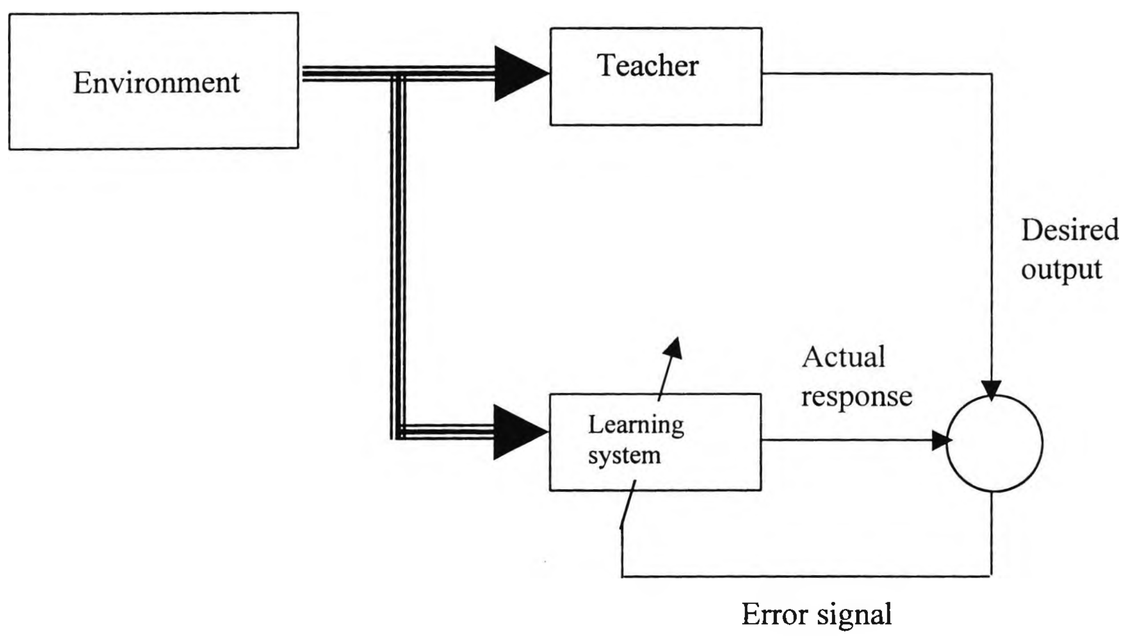

Figure 2.9 Block diagram of supervised learning

2.8.6 Unsupervised learning or Self-organised learning

Unsupervised learning is a far more plausible model of learning in the biological system. Developed by Kohonen [37] and many others, this training method does not require any target vector for outputs and hence no comparison to predetermined ideal responses. The training set consists of input vectors only. The training algorithm modifies network weights to produce output vectors in such a way that both application of one of the training vectors or application of a vector that is sufficiently similar to it will produce the same pattern of outputs. The training process extracts the statistical properties of the training set and groups similar vectors into classes. Although a vector from a given class applied to the input will produce a specific output, there is no way to determine prior to training which output pattern will be produced by a given input vector class. Therefore, the outputs of such networks have to be transformed into a comprehensive form after training.

2.8.7 Back-propagation learning algorithm

Back-propagation (BP) algorithm is a systematic method for training multilayer artificial neural networks. Based on this algorithm, the network learns a distributed associative map between the input and output layers. The process by which the weights are calculated during the learning phase of the network in BP differs from other algorithms. Difficulty with multilayer networks is calculating the weights of the hidden layers in such a way that the output error is least. The more hidden layers there are, the more difficult it becomes. The error at the output layer is easily measured, as this is the difference between the actual and desired outputs. As there is no direct observation of the error at the hidden layer, some other technique has to be used to calculate an error at the hidden layers that will minimise the output error.

There are two distinct phases to the operation of back-propagation learning, the forward phase and the backward phase. In the forward phase the input signals propagate through the network layer by layer, producing some response at the output of the network. The error signals generated by comparing the actual response with the desired response are then propagated in a backward direction through the network. The free parameters of the network are adjusted in this backward phase so as to minimise the sum of squared error. The algorithm has a slow training speed due to the extensive calculations involved.

2.9 Typical applications

Artificial neural networks have been applied in planning, operation and analysis of power systems. The following specific problems are most popular:

- Planning (long-term load forecasting, economic load dispatch, unit commitment)

- Operation (optimal power flow, unit commitment, generator shedding, state estimation, static and dynamic security assessment, dynamic contingency analysis, fault detection , fault location, daily load forecasting, substation maintenance, voltage stability assessment)

- Analysis (dynamic stability assessment, generator voltage and speed control system design, harmonic analysis, bad data detection, monitoring and protection.

2.10 Conclusion

A brief history of the development of artificial neural networks is presented here. The four main types of ANN architecture and their learning algorithms are described. Some of the applications in power systems have been highlighted. The use of ANN is demonstrated in chapters 5 and 7.

Chapter III

EVOLUTIONARY ALGORITHMS

3.1 Introduction

Evolutionary Algorithms (EA) are computer-based problem solving systems that use the principle of evolution theory. An evolutionary algorithm begins by selecting an initial set of contending solutions to a problem. The set may be chosen by generating solutions randomly or by the use of any available knowledge of the problem. These initial (parent) solutions then generate new solutions (offspring) by a preselected means of random variation. The resultant solutions are evaluated for their effectiveness (their "fitness"). Finally, a selection criteria is applied to remove those solutions that are the least fit. The process is repeated over successive generations until a specific criteria is met. Figure 3.1 shows the process.

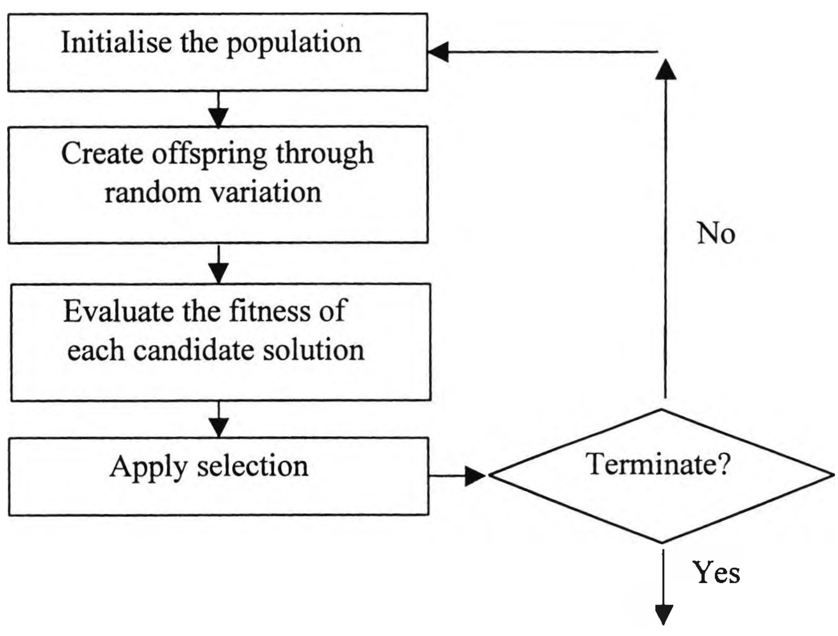

Figure 3.1. Flow chart showing an evolutionary algorithm

Traditional optimisation algorithms require many assumptions about the way in which to evaluate the fitness of a solution, whereas evolutionary algorithms do not require such assumptions. The performance index must determine that one solution is in some way better than another. Evolutionary approach for solving engineering problems has the advantage that it is adaptable to changing situations. In many traditional optimisation procedures, the process has to be restarted from the beginning if any variable in the problem changes. With EA, restarting from the beginning is not necessary as the current population serves as a reservoir of stored knowledge that can be applied to a dynamic problem. EA is also able to generate useful results very much faster than traditional approaches.

There are a variety of evolutionary algorithms and the major ones are Genetic Algorithms, Evolution Strategies, Evolutionary Programming, Classifier Systems, and Genetic Programming. They all share a common conceptual base of simulating the evolution of individual structures via processes of Selection, Mutation and Reproduction. The processes depend on the perceived performance of the individual structures as defined by the environment.

3.2 Genetic Algorithms

Genetic Algorithms (GA) are the most popular and widely used of all evolutionary algorithms. A genetic algorithm is a computational technique that transforms a set (population) of individual mathematical objects (usually fixed length character or binary strings), each with an associated fixed value, into a new population (next generation) using operations similar to the process of evolution in nature [41]. GAs perform a global search on the solution space of a given problem domain [42].

3.2.1 General structure of GA

The simplest from of genetic algorithm involves three types of operators: Selection, Crossover and Mutation.

Selection: This operator selects chromosomes in the population for reproduction. The fitter the chromosome, the more number of times it is likely to be selected to reproduce.

Crossover: It is the main genetic operator. This operator randomly chooses a locus and exchanges the sequences before and after that locus between two chromosomes to create two offspring. The crossover operator roughly mimics biological recombination between two single-chromosome organisms. Crossover is not performed on every pair of individuals, its frequency being controlled by crossover probability. This probability should have a large value (e.g., 0.8.)

Mutation: This operator randomly flips some of the bits in a chromosome. Mutation can occur at each bit position in a string with some probability, usually very small (e.g., 0.001). Some bit values (genes) may be lost during selection and mutation can bring them back, if necessary.

A GA is a very simple process where a random initial population is first generated, this is then evaluated and new populations are created by applying genetic operators. Given a clearly defined problem to be solved, a suitable representation for possible solutions to the problem in the form of a string of figures must be defined. The string is often encoded in binary. Execution of GA begins with a randomly generated population of n l-bit chromosomes , which are the candidate solutions to the problem. The fitness $f(x)$ of each chromosome x is then calculated. A pair of parent chromosomes is selected from the current population, using a biased random selection process in that candidates with a better function of fitness are more likely to be chosen.

The crossover operator then simulates the mating of the pair with the crossover probability at a randomly chosen point (chosen with uniform probability). If no crossover takes place, two offspring that are exact copies of their respective parents are formed. The crossover rate is defined to be the probability that two parents will crossover in a single point. There are also "multi-point crossover" versions of the GA in which the crossover rate for a pair of parents is the number of points at which a crossover takes place.

The two offspring are mutated at each locus with the mutation probability and the resulting chromosomes are placed in the new population. The process is repeated until *n* offspring have been created. If n is odd, one new population member can be discarded at random. The current population is replaced with the new population.

Each iteration of this process is called a **Generation**. A GA is typically iterated for anywhere from 50 to 500 or more generations. The entire set of generations is called a **Run**. At the end of a run there are one or more highly fit chromosomes in the population. Randomness plays a large role in each run. Two runs with different random-number seeds will generally produce different detailed behaviours. The success of the algorithm depends greatly on the details such as the size of the population and the probabilities of crossover and mutation. There are more complicated versions of GAs e.g., GAs that work on representations other than strings or GAs that have different types of crossover and mutation operators.

3.2.1.1 A detailed example

String length (l)	= 8
Fitness $f(x)$	= number of ones in bit string x (simple fitness function)
Population size (n)	= 4
Crossover probability (p_c)	= 0.7
Mutation probability (p_m)	= 0.001

The initial (randomly generated) population is as follows:

Chromosomes	**Chromosome string**	**Fitness**
A	00000110	2
B	11101110	6
C	00100000	1
D	00110100	3

A common selection method in GAs is the **fitness-proportionate selection**, in which the number of times an individual is expected to reproduce is equal to its fitness divided by the average fitnesses in the population. A simple method of implementing fitness-proportionate selection is "roulette-wheel sampling" [41]. This is equivalent to giving each individual a slice of a circular roulette wheel equal in area to the fitness of the individual. When the roulette wheel is spun, the ball comes to rest on one wedge-shaped slice, and the corresponding individual is selected. In the above example where $n = 4$, the roulette wheel is spun four times. If the roulette wheel were spun many times, the average result would be closer to the expected values.

Once a pair of parents is selected, they cross over to form two offspring. If they do not cross over, then the offspring are exact copies of each parent. In the above example, let us assume that parents B and D cross over after the first bit position to form offspring E = 10110100 and F =01101110 respectively, and parents A and C do not cross over, thus forming offspring that are exact copies of A and C. Each offspring is then subject to mutation at each locus with probability p_m. Suppose offspring E be mutated at the sixth locus to form E' = 10110000, offspring F and C are not mutated at all, and offspring B is mutated at the first locus to form B' = 01101110, then the new population will be the following:

Chromosomes	Chromosome string	Fitness
E'	10110000	3
F	01101110	5
C	00100000	1
B'	01101110	5

In the new population the average fitness has risen from 12/4 to 14/4, although the best string with fitness 6 was lost. Continuing the iteration will result in a string with all ones.

3.2.2 Advantages of GA

There are three major advantages of GAs to optimisation problems.

(1) GAs do not have much mathematical requirements about the optimisation problems. Due to their evolutionary nature, genetic algorithms will search for solutions without regard to specific inner workings of the problem. GAs can handle any kind of objective functions and any kind of constraints, linear or non-linear, defined on discrete, continuous, or mixed search spaces.

(2) The ergodicity of evolution operators makes GAs very effective at performing global search. The traditional approaches perform local search by a convergent stepwise procedure, which compares the values of nearby points and moves to the relative optimal points. Global optima can be found only if the problem possesses a certain convexity properties that essentially guarantee that any local optima is a global optima.

(3) GAs provide a great flexibility to hybridise with domain-dependent heuristics to make an efficient implementation for a specific problem.

3.3 Evolutionary Strategies

Evolutionary Strategies (ES) were conceived by I. Rechenberg in 1960, to solve technical optimization problems. ES employ real-coded variables and in its original form relied on mutation as the search operator, and a population size of one. It is similar to GA in that they both maintain populations of potential solutions and use a selection mechanisms for choosing the best individuals from the population. The main differences are at three levels:

- Different representation methods: ES operate directly on floating point vectors while classical GAs operate on binary strings.

- Different operators: GAs rely mainly on recombination to explore the search space, while ES uses mutation as the dominant operator. However, some variants of ES also use recombination as a search operator.

- ES are an abstraction of evolution at individual behaviour level, stressing the behavioural link between an individual and its offspring, while GAs maintain the Genetic Link.

An additional feature of ES is the self-adaptation of mutation variances by incorporating these parameters in the solution itself. ES are also capable of solving high dimensional, multimodal, non-linear problems subject to linear or non-linear constraints. The objective function can also, for example, be the result of a simulation, it does not have to be given in a closed form.

3.4 Evolutionary Programming

Evolutionary Programming (EP) was originally conceived by Lawrence J. Fogel in 1960 [43,44]. It is a stochastic optimisation process similar to GAs, which places emphasis on the behaviourial linkage between parents and their offspring, rather than seeking to emulate specific Genetic Operators as observed in nature. EP is similar to Evolution Strategies(ES), although the two approaches developed independently.

Like both ES and GA, EP is a useful method of optimisation when other techniques such as gradient descent or direct analytical discovery are not possible. Evolutionary programming is well suited for combinatorial and real valued function optimization in which optimization surface or Fitness landscape is "rugged" possessing many local optimal solutions.

Like GA, EP assumes that a Fitness landscape can be characterized in terms of variables, and that there is an optimum solution (or multiple such optima) in terms of those variables. The basic EP method involves three steps and the steps are repeated until a threshold for iteration is exceeded or an adequate solution is obtained. The steps are:

(1) Choose an initial POPULATION of trial solutions at random. The number of solutions in a population is highly relevant to the speed of optimization, but no definite answers are available as to how many solutions are appropriate and how many solutions are just wasteful.

(2) Each solution is replicated into a new population. Each of these offspring solutions are mutated according to a distribution of mutation types, ranging from minor to extreme. The severity of mutation is judged on the basis of the functional change imposed on the parents.

(3) Each offspring solution is assessed by computing its fitness. The number of solutions to be retained for the population of solutions is determined by a stochastic tournament or performed deterministically.

EP does not use any crossover as a genetic operator.

EP differs from GA in the following two ways:

(1) The typical GA approach involves encoding the problem solutions as a string of representative tokens, the Genome. In EP, the representation follows from the problem. A neural network can be represented in the same manner as it is implemented, for example, because the mutation operation does not demand a linear encoding.

(2) The mutation operation simply changes aspects of the solution according to a statistical distribution which weights minor variations in the behaviour of the offspring as highly probable and substantial variations as increasingly unlikely. The severity of mutations is often reduced as the global optimum is approached.

3.5 Classifier Systems

Classifier systems are rule-based machine learning systems that are capable of learning by examples [45]. Classifier system is a cognitive system capable of classifying the goings on in its environment and then reacting to them accordingly.

3.6 Genetic Programming

Genetic Programming (GP) is the extension of the genetic model of learning into the space of programs. In GP, the objects that constitute the population are fixed length character strings as in GA. They are programs that when executed, are the candidate solutions to the problem. These programs are expressed as parse trees, rather than as lines of code. The main operation in GP is recombination, similar to GA, but the mutation operator is not adopted in GP. The selection is based on the fitness of each individual. The crossover operation is implemented by taking randomly selected sub-trees in the individuals and exchanging them.

3.7 Typical Applications in Power Systems

Evolutionary algorithms have been applied to several power system problems [17,46,47]. Some of them are listed below:

(1) Reactive power planning
(2) Optimal reactive power dispatch
(3) Transmission network planning
(4) Generator parameter estimation
(5) Economic dispatch
(6) Optimal power flow
(7) Fault section estimation

3.8 Conclusion

The different types of evolutionary algorithms, their advantages and disadvatages are described in this chapter. As Genetic Algorithms are the most popular and widely used of all evolutionary algorithms, its structure is illustrated with an example. The use of Genetic Algorithm is shown in chapters 6, 7 and 8.

Chapter IV

TECHNIQUES FOR THE RESTRUCTURED ELECTRIC POWER INDUSTRY

4.1 Introduction

Restructuring and privatization of the electric power industry is underway worldwide [48-53]. In some countries, the electric industry is a government department, in some others it is a government-owned statutory body and in others it is a privately owned industry. Restructuring is about separating the highly regulated and vertically integrated industry into regional, competitive and functionally separate entities. The main reason for change is that under the regulated structure, the interconnected generation, transmission and distribution systems operate inefficiently. The change therefore, is expected to increase efficiency through better management and better use of existing equipment and in turn lower the price of electricity to all types of consumers and maintain a reliable system.

The aim of deregulation is to enable competition based on regional efficiencies and to disable the monopoly control and market imperfections that exist under the present vertically integrated utility structure, namely, generation, transmission, distribution and load.

4.2 Privatized structure

There are several ways in which the industry can be restructured depending on the degree of competition to be introduced. In under developed countries where the power system is so small, competition may be limited to generation only. Whereas, in developed countries with large sophisticated systems, retail competition may be introduced so that all customers are able to choose their supplier. There is open access to transmission and distribution network. However, to maintain efficient and integrated operation, the industry should be held together commercially by appropriate contracts. Deregulation focus changes from obligation of supply and cost minimization to competition and maximization of profit.

In most countries where the electric power sector is government-owned or government-controlled, the vertically integrated industry is being separated into Generation, Transmission and Distribution units. The concept of competition has been introduced in the area of generation by splitting the power producing entity into small units and also by letting other generation companies and Independent Power Producers (IPPs) to enter the field so that no single unit has market power. This will enable customers to have a choice of their supplier of power. In highly regulated power utilities, the price of electricity is based on the cost of production, where as in the new competitive system, prices will be dictated by the market. In order to be competitive, it will be necessary for the power producing sectors to better understand the cost involvement. Generators can supply energy and ancillary services.

Whatever the level of restructuring, system operation and power exchange functions have to be fully independent and must offer indiscriminatory services to all concerned. Transmission and distribution are natural monopolies and have to be shared by all.

4.3 Impact of Restructuring and Deregulation

Deregulation means that customers can choose who supplies their electricity. And providing great service at an affordable cost is critical if you want to be the provider of choice. It has never been more important to keep customers happy. When competition reaches all sectors, it will be possible for all industrial consumers to contract with the supplier of their choice and negotiate better deals. Removal of the bureaucratic management system and reduction in staff strength is expected to increase efficiency which will lower tariffs and improve customer service.

The electricity sectors which are being separated to encourage competition will remain physically interconnected and will be held together commercially by the contracts signed between the generation, transmission and distribution companies. Electricity does not flow in a direct path from generator to consumer. Generating companies supply electricity into the transmission network and the buyers take it from the network. Since any buyer could take electricity from the network as and when required, it becomes necessary for contracts to be drawn up between sellers and buyers. The main benefits of contracts are savings in transaction costs, sharing and spreading risks in unpredictable future and improving incentives.

In the competitive structure of the electricity industry of the future, the main issue will be to balance supply and demand instantaneously so as to maintain the voltage, frequency and stability of the network. This could be achieved by some form of bilateral spot trading between sellers and buyers. When such spot trading is not fast enough to maintain equilibrium, it becomes necessary for someone to be responsible for the maintenance or restoration of equilibrium and the cost involved has to be borne by someone.

Funds accumulated by the former nationalized utilities as a result of many years of operating surpluses is not available to privatized sectors. As a result, working capital and capital for any new projects is only available at market rates. It is therefore, necessary to have more elaborate systems for planning, control and monitoring of the activities.

Privatization is expected to enhance economic activity in power plant construction. There will be considerable interest in building new plants to enhance competitiveness. Competitiveness is based on their ability to make economic investments over long term and their efficient usage. In doing so, plant and fuel mix will have to be fully analyzed before making any decision so that dependence on costly and difficult to obtain fuel is reduced. Market oriented approach to the construction of new power plants will benefit customers as well as producers.

Electricity generators will face intensified international competition. Harmonization of environmental requirements will be needed to ensure neutral competitive conditions. International competition requires proper security in energy supply. Instead of individual companies being responsible for ensuring supply security, an alternative system must be considered.

Market-oriented policies of the restructured industry have a better chance of delivering secure, diverse and sustainable forms of energy with much greater efficiency than the old nationalized industry ever would. Promotion of competition and choice of customers will eventually give rise to a flexible and adaptable industry that will provide the customer with what he or she wants, rather than what the utility is prepared to offer.

4.4 The Issues and Methods

It will not be possible to go through all the issues and methods in the restructuring of the electric power industry. Only some are reported below:

4.4.1 Reactive Power

Acceptable voltage limits are defined in the planning and operating standards, and sufficient reactive power has to be provided in order that these standards are met. Reactive power cannot be easily transported like real power and the reactive requirement has to be provided locally. A number of companies have expressed interest in providing reactive power which will increase competition and downward pressure on price and help to avoid the monopoly power that may characterize some of the many reactive markets [54].

Any change in the system configuration or system demand may result in higher or lower voltage profiles. In order to maintain desired levels of voltage and reactive power flow under various operating conditions and system configurations, power system operators may utilize a number of control approaches such as switching VAR sources, changing generator voltages, and/or adjusting transformer tap settings. By an optimal adjustment of these controls, the redistribution of the reactive power would minimize transmission losses and improve the voltage profiles. However, reactive power planning (RPP) is one of the most complex problems of power systems as it requires the simultaneous minimization of two objective functions. The first objective deals with the minimization of real power in reducing the operation cost and improving the voltage profile. The second objective minimizes the allocation cost of additional reactive power sources. RPP is a non-linear, non-continuous and non-differentiable optimization problem for a large scale system with a lot of uncertainties. During the last decade there have been a lot of optimization methods used in RPP problems [55].

Optimization techniques based on mathematical programming methods have been developed and some of these methods have been employed in practice. Owing to the complexities of power systems and the non-linearities of the characteristics of the equipment in them, established methods often fail both to solve the problems efficiently and provide global optimum solutions to the problems. The conventional calculus-based optimization methods, which are based on successive linearizations and use the first and second differentiation of objective function and its constraint equations as the search directions are not suitable to deal with RPP problems in the real-life systems. The devising, testing and refining of new techniques for finding optimum solutions are important areas of current research.

In the last few years, evolutionary algorithms (EAs), which include genetic algorithms (GAs) and evolutionary programming (EP) have been used to find out the optimal reactive power generations, tap settings of under-load-tap-change transformers and VAR source installations to minimize both the cost of energy loss in the network and the investment cost of VAR source installations, and at the same time, improve the voltage profile of the whole system [17,21-25].

4.4.2 Optimal Power Flow

As the power industry moves into a more competitive environment, use of OPF will become increasingly more important in maximizing the capability of the existing transmission system asset [56-59].

The increasing need for OPF to solve problems of today's deregulated industry and the unsolved problems in the vertically integrated industry has caused the deregulated electricity market to seek answers from OPF to address a variety of different types of market participants, data model requirements and real time processing and selection of appropriate costing for each unbundled service evaluation. It requires that all lines and voltages be within limits while minimizing investment (including losses during normal operating conditions) in a particular area or zone of interest. During contingencies, line loading and voltages have to be within limits while minimizing investments. Losses are generally unimportant during outages. It is important to obtain feasible solutions with minimal amount of engineering time. OPF programs will have the potential to save a utility substantial capital investment and considerable engineering time. A utility having such a OPF will be more competitive in a rapidly changing deregulated power industry.

The key elements in a robust electricity market are enforcing transmission security, allocating transmission capacity and pricing transmission services. OPF incorporates capabilities of the power flow, for explicit representation of the transmission network, within the formulation of a constrained optimization problem, to address open access issues.

In a traditional power company that provides bundled generation and transmission services, the cost of reactive power support has been treated at planning stage as a capital expenditure issue. With the present "open" access transmission network, VArs delivered by power producers of the system need to be paid directly. It is therefore, necessary to minimize the net VAr cost. This is considered as a form of economic reactive power dispatch [25]. To fully account for transmission network restrictions, this needs to be a security constrained optimal power flow calculation. For conventional OPF, constraints must be carefully reviewed and objective function costs must be "tuned". Other problems are due to discrete problems and local minima.

Due to the complexity of modern power systems and the constraints that have to be met, use of genetic algorithm and evolutionary programming is envisaged an appropriate approach. This is illustrated in chapter 7.

4.4.3 Cogeneration

Combined heat and power generation use a third less fuel to generate the same amount of energy as separate heat and electricity generating units. The efficiency of co-generation plants can be higher than 90% compared to around 40% for plants generating only electricity. The fuel saving also serves to reduce the environmental impact of energy generation. Emission levels of carbon dioxide, sulphur dioxide and nitrogen oxide released by the use of fossil fuel are reduced considerably by the use of pollution control equipment.

If small-scale combined heat and power (co-generation) or gas-fired fuel cell become the available technology, there will be a very different power sector from the one today. The efficiency of cogeneration systems depends on the production of heat and electricity. The use of a Genetic Algorithm (GA) or Evolutionary Programming (EP) to solve the optimization problem of the cogeneration system has been proposed in [60]. GAs are more flexible and robust than the conventional optimization methods, therefore GAs are suitable to the optimization problem for the cogeneration systems, which have non-linear characteristics.

The operation scheduling problem concerns about an industrial cogeneration system operated in the bottoming cycle, which produces mainly the thermal energy to supply the thermal load demand, while the electric energy production depends on the production of thermal energy. It is one of the two types of cogeneration systems. The other is the topping cycle which generates mainly the electricity but uses the remaining heat and auxiliary boiler to supply some thermal load demand. Cogeneration system can be operated by connecting with several auxiliary devices. Therefore reference [60] proposes an operation scheduling method for a cogeneration system which has four kinds of auxiliary devices such as the auxiliary boiler, heat storage tank, electricity charger and independent generator. The objective of scheduling is to minimize the total operation cost, while satisfying system constraints. A daily operation scheduling is established based on the load level and characteristics of the cogeneration system and auxiliary devices. Different prices for buying and selling the electricity between the cogeneration system and electric utility have been considered. The GA/EP approach could achieve a better operation for the cogeneration system to minimize the total operation cost. The results show a high potential in using GA/EP for the optimal scheduling of practical industrial cogeneration systems. All continuous and discrete variables and functions are easily considered by the GA/EP, while with the conventional optimization methods, such discrete variables would not be so easy to deal with.

4.4.4 Substation monitoring

To reduce controllers' costs and improve efficiency, it has been planned to develop substation automation [61], which enable system operation without the requirement of permanent staffing at substations. Substation automation, being software based, can provide considerable self-checking and diagnostic output. Potential problems can be diagnosed quickly and reported to either the local or the remote operator.

The increasing complexity of large electric power systems has resulted in a greater need for maintenance in order to maintain a reliable supply of power. Remote vision is included so that user is able to see the scenes of different important locations within the sub-stations on a real-time manner. The employment of Internet technology allows simultaneous multiple access for all parties concerned. This feature is particularly helpful under emergency conditions.

Modern metering technology will provide benefits in terms of improved service and enhanced choice for the customer. Additional benefits will be achieved for the supplier together with better information for system control purposes. Any communication system must provide a complete open access by any party, such as the suppliers and customers.

4.4.5. FACTS

Transmission companies are required to maintain a stable and secure transmission system. In a system where there is complete privatization, a generating company should be able to sell electricity over the transmission network to a customer at any point. Transmission companies may also be expected to accommodate demands for transmission from independent power producers. In order to provide transmission services, the transmission companies will have to maintain transmission equipment such as towers, overhead lines, underground cables and other related hardware in addition to a number of ancillary services such as frequency control. It is not possible to charge for the use of reserve energy or reactive power supplied or consumed by a customer, as they are not normally metered. It is also known that most reactive power is consumed within the transmission network and does not flow through any consumer's meter.

Flexible AC Transmission System is a means of line compensation using power electronic devices to improve the performance and flexibility of the system. Transmission system limitations are caused by steady state and transient stability limits. Voltage limits, thermal limits, loop flows, short-circuit levels, subsynchronous resonance, transient stability, voltage control and voltage stability are some of the issues that can be solved by FACTS, complementing the conventional solutions. Careful planning and coordination is required during the different stages of the project for studies involving the application of FACTS. These studies must be able to solve all technical problems as well as have proper coordination between all companies and regulatory bodies involved in the project.

Flexible AC Transmission System devices are used to increase power system transmission capacity, to improve first swing margin, to actively damp oscillations and to help weakly coupled systems in the event of critical faults. In large interconnected systems, low frequency oscillations arise due to the dynamics of inter-area power transfer and when the aggregate power transfer is high relative to the strength of transmission, the oscillations exhibit poor damping. With restructuring, there is increase exchange of power over a fixed transmission network and there is a direct need for new equipment to damp these oscillations. The controllers must be able to operate satisfactorily during many modes of power swings and during a wide range of operation. Generator excitation control using Power System Stabilizers are traditionally used to aid power swing damping. This scheme cannot be used in FACTS controllers as speed deviations of the machines are not available at the controller location. Also, if the necessity is to damp complex swings which involve large number of machines, speed signals are not the best choice. It will be necessary to obtain useful input signals from the controller location.

Unified Power Flow Controller (UPFC) is one of the Flexible Alternating Current Transmission Systems (FACTS) devices. The UPFC consists of two solid-state voltage source inverters which are connected through a common dc link capacitor. Each inverter is coupled with a transformer at its output. The first voltage source inverter, known as STATic Synchronous Compensator (STATCOM), injects an almost sinusoidal current, of variable magnitude, at the point of connection. The second voltage source inverter, known as Static Synchronous series Compensator (SSSC) injects an almost sinusoidal voltage, of variable magnitude, in series with the transmission line. This injected voltage can be at any angle with respect to the line current. The exchanged real power at the terminals of one inverter with the line flows to the terminals of the other inverter through the common dc link capacitor. In addition, each inverter can exchange reactive power at its terminals independently.

Unwanted loop power flow and parallel power flow between utilities which are serious problems in heavily interconnected power systems can be easily regulated by the use of phase shifter and or other control facilities based on fast acting power electronic components. It is possible to use circuit reactance and voltage angles as power flow controllers because the unified power flow controller (UPFC) with voltage source converters can be operated as shunt compensator, series compensator, tap-changer and phase-shifter. As good coordination is required for the control facilities to work without interfering with each other, tools such as optimal power flow used in power system analysis have to be extended to represent FACTS control. Optimal power flow problem with series compensation may lead to a solution that is stuck in local minima. An algorithm capable of adaptively searching for the global optimal point has to be developed [62,63]. Genetic algorithm is one such tool that is based on mechanics of natural selection and natural genetics which is robust and adaptively searches the global optimal point.

4.4.6 Power Quality

It is a fact that it may not be always possible for the transmission companies to generate enough income required for system reinforcement to ensure good quality supply to consumers and alternative methods may be necessary without upgrading existing equipment or installing new ones. Recent techniques such as remote switching, automation, Flexible AC Transmission System (FACTS) and reliable reactive power planning have enabled the use of the existing equipment to be used more effectively.

With increasing harmonic pollution in the power system, real-time monitoring and analysis of harmonic variations have become important. Because of limitations associated with conventional algorithms, particularly under supply-frequency drift and transient situations, the use of neural networks for real-time harmonic evaluation is much more appropriate [64]. A set of data taken on site was used as a real application of the approach.

4.4.7 Congestion Management

Congestion management is one of the operational applications in the power exchange environment. Congestion management identifies those transactions that have the greatest sensitivity with respect to power flow in transmission facilities and sends requests to suspend transactions accordingly. From a power exchange client's perspective, this application should also provide alternative transactions that do not cause overloads and provide equivalent trading opportunities.

The approach is based on the use of optimization methodologies. Optimization approaches for transmission system congestion management are loosely related to the optimum power flow (OPF) techniques commonly used in power system analysis. However, traditional OPF does not fit well within the requirements and data constraints found at either power exchanges [65].

Congestion management is most commonly used in an on-line mode to relieve observed overloads. It can also be used in a study mode to design strategies to reduce the likelihood of causing the overloads in the first place.

4.4.8 Energy Trading System

The energy trading system must have low client cost and ease of customer addition. Internet based systems are preferable.

A trading system is used by individual traders as they buy and sell energy, use analytical tools or view historical and current market data. It must also provide software and analytical components for centralized operation and maintenance, such as trading control and load forecasting [65].

In a deregulated environment, a generating company has in principle no other objective than to produce electricity and sell with maximum profit. So the problem formulation is by giving a forecast of future market price, establish a generation scheduling that maximizes expected profit over the planning period with all relevant constraints taken into account. The spot market price is a very important factor however, it is varying and uncertain. Therefore to integrate it into the new arrangement for system operation will be a major concern.

Intelligent agents have been applied to identification of alarms and network management in telecommunication systems [66]. Agents are software components developed out of research in artificial intelligence. It could be foreseen that this technique could be used in energy trading systems.

4.4.9 Intelligent Protection and Control

High-speed communications under current development will allow multiple Intelligent Electronic Devices from different vendors to exchange data, status and control information in real time, thus eliminating the need for complex and extensive wiring. This will result in reduced cost and improved efficiency. The number of such systems will increase and allow the overall performance of the protection and control system during disturbances to be continuously improved [67].

Digital relays and controllers are building blocks of the power system protection and control system with distributed intelligence. A hierarchical structure is considered with intelligent Electronic Devices being the lower level, substation integration systems providing the next level and Wide Area Network based systems providing the system level [67]. Each level executes protection and control functions based on locally measured or monitoring parameters. It also interfaces with the upper or lower levels of the system to exchange status or metering data. This allows the design of very sophisticated special protection and control systems with minimal increase in the cost of the system.

Remote switching of circuits following a fault can restore supply to the affected consumers within a short time and the nature and location of the fault could be identified through the use of computational intelligence, which enable fast repair of the affected section.

Adaptive relays adapt to the changes in power system conditions, thus ensuring optimal performance [68]. This is very important to prevent the development of a disturbance in the system into a blackout with severe economical consequences.

Neural networks, fuzzy logic and expert systems are just a few of the methods that can be used in an artificial intelligence based system [69]. They can be extremely valuable in the detection of abnormal system conditions and fine tuning of the protection and control system performance during a power system disturbance.

4.4.10 Transmission System Planning

Transmission system planning is another area that will be of interest to transmission companies to cater for the increasing demand from generation companies and consumers. Non-convex problem observed in network expansion planning cannot be solved effectively by the conventional linear or non-linear programming. New techniques have been developed to overcome this problem. Application of evolutionary programming is one such technique that can be used to solve transmission system planning. Evolutionary programming is an optimization algorithm using artificial intelligence method based on the mechanics of natural selections - mutation, competition and evolution. EP is a suitable technique for solving transmission system planning [70].

4.4.11 HVDC

HVDC transmission for long distance transmission and interconnections is becoming popular due to the development of new devices in power electronics. Meeting additional power requirements by adding HVDC infeed will not increase fault current levels since no fault current contribution can come through the HVDC link, whereas additional AC infeeds bring with them a need for increased short circuit capacity for the receiving system. An HVDC link can easily be developed in stages. Fault diagnosis in HVDC systems with intelligence techniques has been a popular research area in recent years [71-73].

4.4.12 Saving Energy & the Environment

Efforts must be made to protect earth's environment. Measures have to be taken to reduce air pollution by introducing clean fuels and advanced control equipment. SO_2 emission can be minimized by the use of low sulphur oil. Advanced electronic precipitators and flue-gas desulfurization devices reduce the emission of carbon monoxide and sulphur dioxide. Nitrogen dioxide emissions can be reduced by using improved boiler burning methods, low nitrogen dioxide burners, low nitrogen fuels and by installing flue-gas denitrification devices.

In view of the need for environmental protection and efficient use of energy, alternative energy sources have to be introduced. New sources of energy that can be considered are fuel cell power generation, photovoltaic power generation and wind power generation.

Energy storage by peak sharing and valley filling decrease investment and operating costs. Super-conduction with high current density has an improved efficiency of about 95%, compared to other storage technologies that have efficiency in the region of 80%.

4.4.13 System Operation and Power Exchange Functions

System operation and power exchange functions have to be fully independent. Maintaining system security is a major concern of system operators. Operation of the transmission company has to be properly coordinated among the various generators, control areas, pools and regions. This will include coordination of equipment outages, voltage levels, monitoring of MW and MVAR flows and switching that affects more than one system. System operator should be authorized to use corrective action such as load reductions to prevent voltage collapse when reactive resources are insufficient. Any corrective action taken should not impose unacceptable voltage stress on generation or transmission equipment or reduce system reliability.

Since the transmission system will be used by many generation companies, it becomes necessary to make sure that the transmission system can safely withstand all the required transactions at any given time. This can be solved by at least one of the following two methods.

Generating companies send bid prices to a pool operator who also receives buy orders and prices from large industrial loads and distribution companies. The pool operator will then match the buy and sell orders and provide an adequate schedule for the operation of the generators.

In the other approach, the generation companies make direct arrangements with buyers or through brokers and then obtain permission from the transmission company for the transaction. Transmission companies have to make sure that the required power can in fact be transferred from a seller to a customer while keeping the transmission system within its operating limits.

In both approaches, there are several computational problems. The first approach requires algorithms for unit commitment that incorporates the limitations of transmission. Very fast security analysis and optimal power flow algorithms must be developed to give a realistic model of the transmission system's ability to be operated as desired by the unit commitment schedule. In the second approach, it becomes necessary to know whether the security analysis and OPF algorithms make the necessary calculation fast enough for the operators to make decisions regarding granting access to each and every transaction. It is also important that accurate information on available transmission capacity is made known fast enough to the generators and customers.

4.5 Conclusions

Restructuring of the electric power industry and its impact are described. There are several issues that go with it. Some of the problems encountered as a result of restructuring has been described and methods of solution have been proposed. Intelligent techniques that have been developed to solve some of the problems are demonstrated in the chapters that follow.

Chapter V

FAULT LOCATION AND PROTECTION OF A TEED-NETWORK USING WAVELET TRANSFORM AND NEURAL NETWORKS

5.1 Introduction

Locating faults in the fastest possible time is important in a power system in order to clear the faults from transmission lines and to restore supply as soon as possible with minimum interruption. Several methods have been used in the past with different techniques based on travelling wave theory [18,19], Fourier analysis and Wavelets analysis [20]. In travelling wave method for fault detection a discriminant is defined based on the transient voltage and current waveforms in order to detect a transmission line fault. A correlation based technique where the cross correlation between stored sections of the forward and backward travelling waves were used to estimate the travel times has also been used [20]. Travelling wave methods require high sampling rate and have problems in distinguishing between waves reflected from the fault and from the remote end of the line. In Fourier and Wavelets analysis methods the fundamental frequency component of the signal, which is noise free is abstracted and the location of the fault is then estimated by calculating the impedance of the transmission line from the observation point using the knowledge of the transmission line parameters.

If the transmission line is more complicated, then the above approach becomes complex because of the power injection from the various paths of the system. It is found that such complex problems can be solved by closely looking at the fault instant waveforms using an intelligent system. It is possible by analysing the waveform on the time scale rather than on the frequency scale. Two cycle waveforms of each pre-fault and post-fault instant are abstracted for further analysis. These signals are then used in discrete wavelet transform (DWT) to generate a training set using statistical information about the signal. The wavelet analysis is a very good approach in signal processing because of its ability to perform local analysis in time and frequency. It also has the advantage over Fourier analysis in revealing breakdown points, discontinuities in higher resolution and self-similarity. A comparative study of Fourier transforms, short time Fourier transform and Wavelet transforms and the application of wavelet transform for the analysis of power system transients is given in [74].

5.2 Teed or Tapped lines

Teed or Tapped line is defined as one having three or more terminals, one or more of which are connected to loads with negligible or no backfeed. Teed circuits provide an easy connection to a third point from an existing point-to-point interconnection without breaking it and without necessarily unbalancing the transfer impedances. Teed feeders are economically and environmentally beneficial alternatives to two-terminal lines for transmission of power at EHV levels.

5.3 Types of teed circuit

There are three different types of teed connections most commonly used in practice. They are:

1. Single-circuit Tee (figure 5.1)
2. Double-circuit Tee (figure 5.2)
3. Tee and Mesh (figure 5.3)

Because single-circuit tee connection has only one circuit termination at each of the three points, the interconnection would be lost for a permanent fault. The additional circuits and the associated circuit breakers in the Tee and Mesh circuit will improve the security of supply. The double-circuit tee gives two-circuit termination at each end.

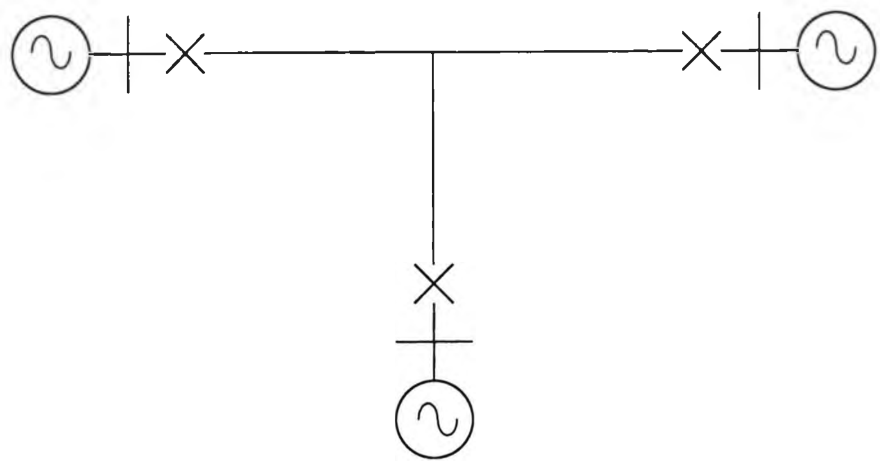

Figure 5.1 Single-circuit Tee

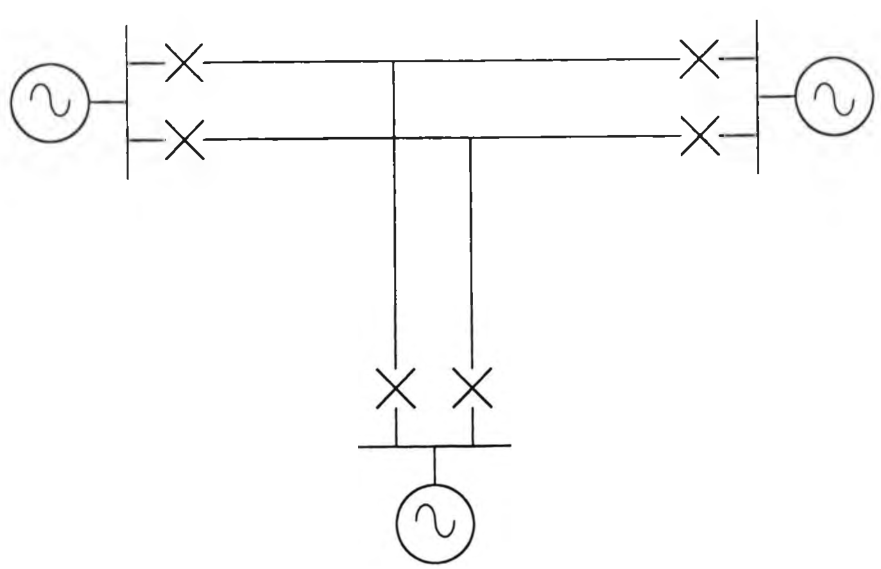

Figure 5.2 Double-circuit Tee

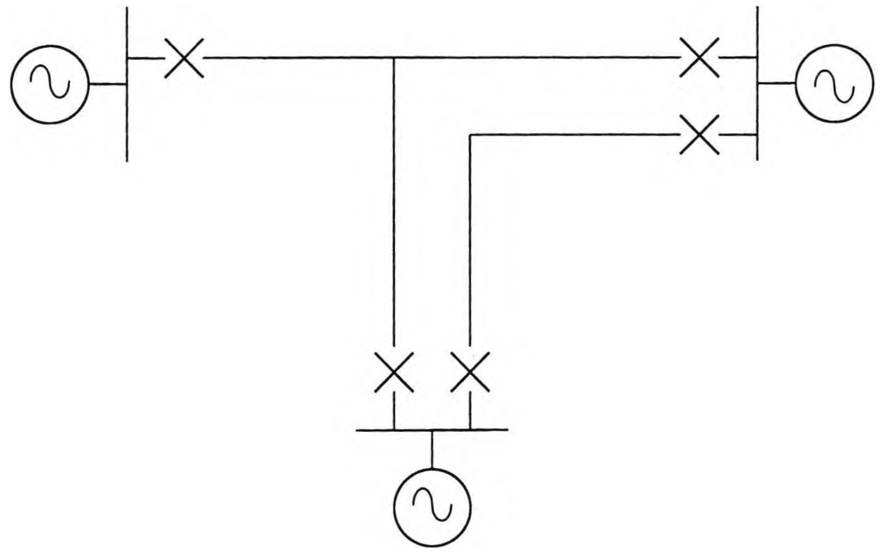

Figure 5.3 Tee and mesh

5.4 Protection of teed circuits

Protection schemes used in two-terminal lines can also be used for teed lines; but the problems involved in applying the schemes to multi-terminal lines are much more difficult.

Overcurrent relays have the following disadvantages when used for phase protection of lines.

1. discrimination between load and fault current.
2. distinguish between near and far end faults by time delay only.
3. maloperation due to transient power swings.
4. nonselective operation or inoperation due to changing system generating conditions.

Distance relays overcome the above problems encountered by overcurrent relays. For a teed line, protection with distance relays becomes more complex and under certain conditions, may not afford the desired degree of protection or may not be applicable at all.

Errors are introduced in impedance measurement due to the following reasons:

1. fault resistance
2. nontransposition of conductors
3. variation in earth resistivity for a given compensation setting
4. initial power loading
5. intercircuit mutual coupling in double circuit lines
6. fault infeeds other than that behind the measuring relays.

5.4.1 Factors that affect the suitability of distance relays

5.4.1.1 Unequal impedances to remote terminals

Figure 5.4 shows a typical three-terminal line with the setting of zone 1 at terminal A. Let the length of the line A-B be such that the first-zone setting of the line is close to the minimum possible setting of the relay at A. If the impedance of section A-C is less than that of section T-S, the zone 1 setting of the relay at A will reach beyond C, which is not acceptable. The relay at A has to be one with a smaller minimum ohm rating or the CT ratio has to be increased if relay at A must not see a fault beyond C with breaker at B open. Increasing the CT ratio may not provide enough current for reliable operation of the relay at A. To prevent overreach under all operating conditions, the zone 1 setting must be 80% to 90% of the least actual impedance to the nearest remote station.

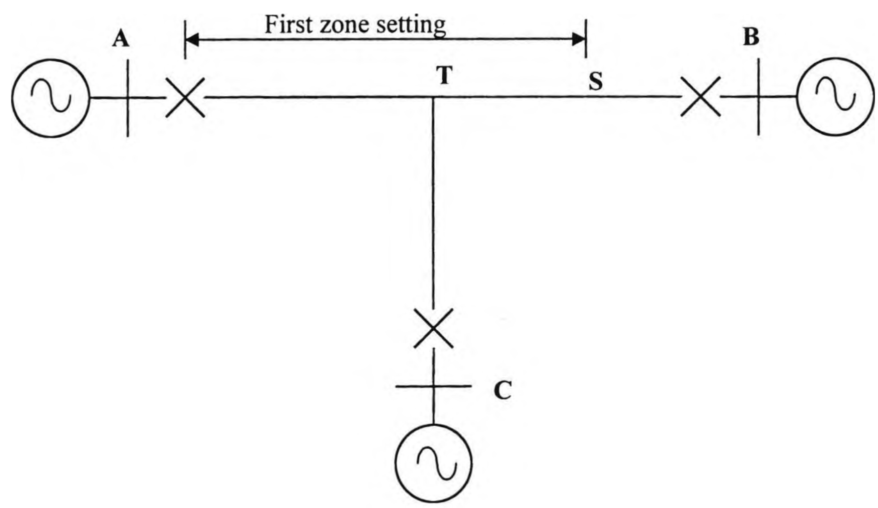

Figure 5.4 Three-terminal line with zone 1 setting

If section T-C is much longer than T-B, first zone setting of the relay at A will protect only a small portion of section T-C. This means that zone 2 setting has to be extended to cover section T-C, which in turn will reach well beyond terminal B. This may be avoided by reducing the coverage of zone 2 setting to be within terminal C and using zone 3 protection to protect the remainder of line section T-C. This will lead to faults near terminal C taking longer clearing time.

5.4.1.2 Effects of infeed

Effects of infeed from another source can be seen from figure 5.5.

For a fault at F, there is a contribution to the fault current from each of the three terminals.

Measurement of impedance in distance protection is made from relaying signals derived from primary voltage and current at the relay location. Consider the relay R_1 at A.

The voltage at bus A is given by

$$E_1 = Z_1 \times I_1 + Z_f (I_1 + I_3) \quad (5.1)$$

and the apparent impedance seen by relay R_1 is

$$Z_{app} = \frac{E_1}{I_1} \quad = \quad Z_1 + Z_f (1 + \frac{I_3}{I_1}) \quad (5.2)$$

The current I_3 which is the contribution to the fault from the tap is known as the infeed current when it is approximately in phase with I_1, and is known as the outfeed when its phase is opposite to that of I_1. In most cases, the phase relationship is such, that the current I_3 is an infeed.

From the equation for Z_{app}, it is clear that the apparent impedance seen by the Relay R_1 is different from the true impedance to the fault, i.e. (Z_1 + Z_f). When the tap current is an infeed, the apparent impedance is greater than the correct value. Thus, if the zone 1 setting of the relay is about 80% of the line length A - C, most of the faults inside the zone of protection will appear to be outside the zone and the relay will not operate.

This is acceptable, since when the tap is out of service, the relay will operate correctly. It would be insecure to set zone 1 of the relay to a high value in order that the apparent impedance for all faults inside the 80% point fall within the zone setting. For such a setting, if the tap source is out of service for some reason, faults beyond the 80 % point will cause zone 1 operation.

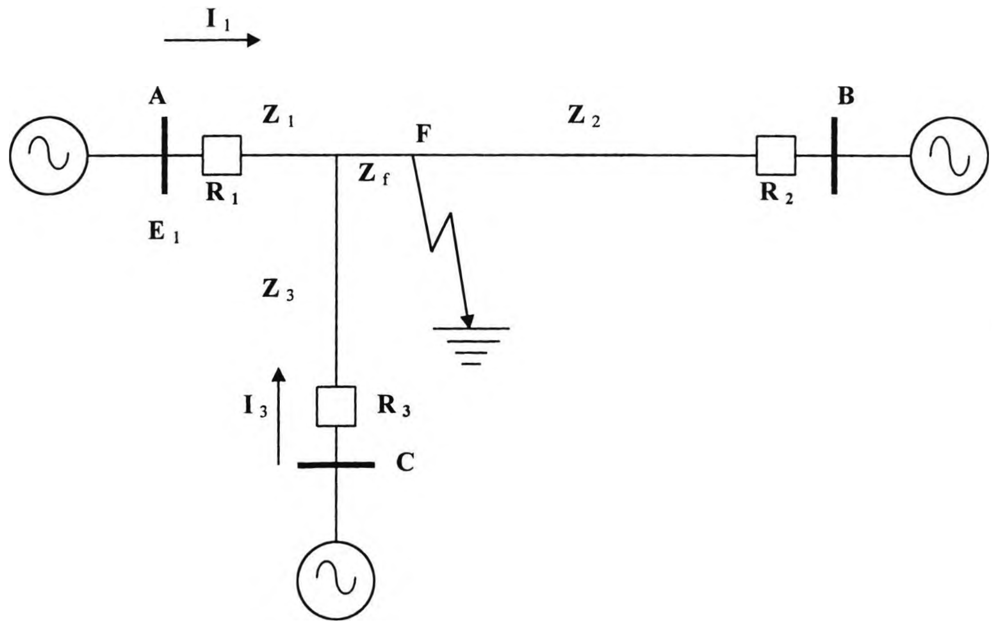

Figure 5.5 Three-terminal line showing current contributions for a fault at F

Zones 2 and 3 of relay R_1 must reach beyond buses B and C respectively under all possible configurations of the tap. For these zone settings, zones must be set with all infeeds in service. If some of the infeeds have been made out of service, the impedance seen by the relay will be smaller and will be definitely inside the corresponding zones.

Under-reaching zones are set with infeeds removed and over-reaching zones are set with the infeeds restored.

5.4.1.3 Changes in system generating conditions

The fault current can vary appreciably due to changes in system conditions at terminals A and C. If the generation at the terminals is reduced due for some reason or other, the current during these periods will be reduced from that of the heavy-load period when all units are in service. These changes can cause the impedance seen by the relays to vary drastically.

5.4.1.4 Load current effect

Load currents are normally considered not to have any undue effect on the impedance seen by the distance relays. However, there are situations where load current effect has to be considered in setting the relays.

If one considers a load connected to terminal C instead of the generator, the apparent impedance at terminal A is, as before in equation 5.2.

The current from terminal C is now in the opposite direction and therefore the apparent impedance seen by relay at A is reduced. This will result in overreach of the relay at A.

5.4.1.5 Effect of voltage magnitude and phase displacement between the terminals

The variation of apparent impedance at terminal A when the voltage magnitudes are maintained constant and the phase displacement of one end is varied with respect to the other ends can be plotted on an impedance diagram (R-X plane). Similar plots can be obtained when the voltage magnitude and phase of one terminal is varied with respect to the other end. The variation of apparent impedance is defined by a pattern of interconnected curvilinear quadrilaterals. Knowledge of the extremes of impedance is required for the purpose of setting the protective relays.

5.4.1.6 Effect of fault resistance

Earth fault resistance gives rise to a voltage component in the earth-fault loop because of the product of fault resistance and remote fault infeed current. This voltage component can cause errors in impedance measurement. Fault resistance compared with those with solid faults for the same fault location increases the fault areas in the impedance plane.

W D Humpage and D W Lewis [75] have derived a complex factor K_f that provides a means of assessing the error in impedance measurement due to fault resistance. K_f varies with the tee position for faults at the tee point and for a particular combination of faults.

They also derived a multiplying factor in deriving an expression for apparent impedance taking account of remote infeeds. For a solid fault at distance x from the tee point the impedance seen by relay at A, neglecting the effects of interphase and intercircuit mutual coupling is given as

$$Z_{app} = (n_1 + x)Z + k_i xZ \tag{5.3}$$

where n_1 is the distance of the tee point from end A, Z is the impedance per unit length of the protected line and K_i is a factor accounting for remote fault infeeds. K_i is shown to be equal to $\frac{Z_{sA} + n_2 Z}{Z_{sB} + n_2 Z}$ in terms of source and line impedances. Z_{sA} and Z_{sB} are the impedances of sources A and B respectively and n_2 is the distance of tee from end B.

For a single-phase-to-earth fault through resistance R_f, distance x from the tee point, the apparent impedance at end A is given by

$$Z_{app} = (n_1 + x)Z + k_i xZ + k_f R_f \tag{5.4}$$

5.4.1.7 Double-circuit lines

In three-terminal lines which involve paralleling ties as shown in figure 5.6, it is possible for fault power to flow out of one terminal for a fault on the line near another terminal. It is necessary to discriminate against impedances presented to relays on one circuit when the fault is in the other. The impedance loci presented to the relays in the healthy lines for faults on adjacent lines provide a basis for the choice of relay characteristic in order to avoid encroachment. Figure 5.6 shows a three-terminal line with parallel ties.

Co-ordination of distance relays is difficult in three-terminal lines because of the following problems:

1. Unequal impedances to remote terminals.

2. Mutual impedance effects from fault and load currents entering or leaving at the tap.

The forward reach relays must be set on the basis of anticipated infeeding conditions, and the characteristics of the relays shaped to avoid encroachments that may otherwise result in the tripping of the healthy circuit in double circuit line constructions when the other circuit is faulted or which may render the protection unduly sensitive to heavy power transfers, voltage transients and to system swinging conditions.

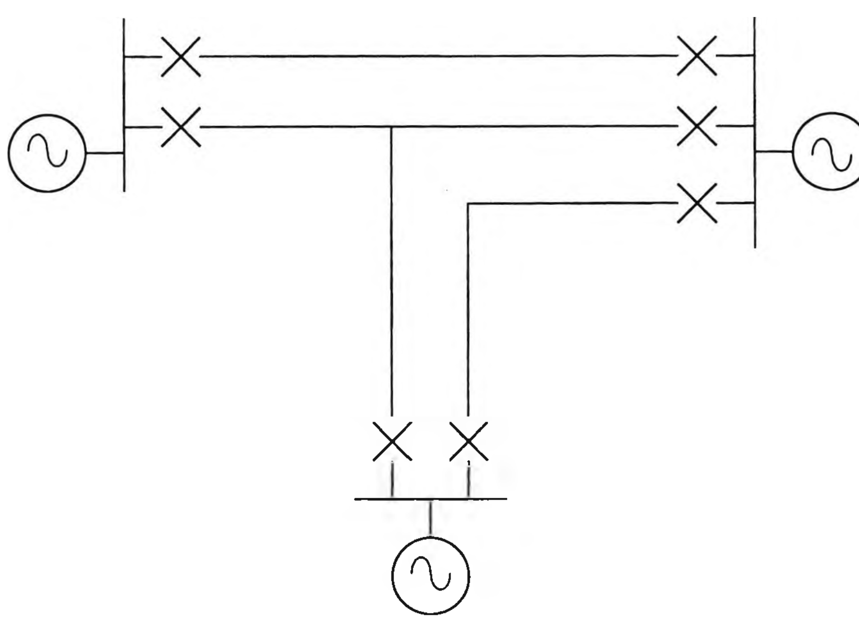

Figure 5.6. System showing three-terminal line with parallel ties

5.4.2 Other relaying systems

5.4.2.1 Direct intertripping from local ends

In this scheme, the protection at one or more ends signals to the other ends, either to intertrip the circuit breakers or to increase the settings to enable tripping. For this scheme to function properly, protection at least at one end should operate properly for faults at any location within the teed interconnection. This scheme provides high-speed tripping of all faults within the protected circuit as long as this is achieved without overreaching beyond the circuit ends.

The following three different applications have to be considered in determining the relay settings at each end.

1. The teed circuit is such that all three reach points overlap about the tee point.
2. All three reaches overlap, but the corresponding zone of simultaneous tripping does not enclose the tee point.
3. The reaches overlap in pairs on two or more sections of the interconnection.

The forward-reach settings in the first case are based on covering the circuit interconnection between each relay location and the tee point, taking into consideration all the errors involved in the measurement of impedance. Settings are calculated taking into consideration the worst conditions of underreaching without causing overreaching under the extreme conditions that are most likely to give rise to it and a margin is allowed.

W D Humpage et al [75] have developed a computer program to calculate and check the settings of the protection at each end in the above three categories of applications.

5.4.2.2 Limitations of direct intertripping schemes

Both the overreach and underreach requirements cannot be satisfied when two of the sections from the termination to the tee point are much shorter than the third and the fault currents at the ends are wide ranging. In the case of parallel ties, difficulties arise when the impedance of the ties are low compared with the teed lines, because of the flow of fault current out of the teed lines for an internal fault. This causes an increase in the apparent impedance seen by the relays making it difficult to provide the necessary margins for an intertripping scheme to be applied. If one of the circuits in a double-circuit line is isolated and earthed, the mutual impedances in the zero sequence circuit changes affecting the compensation allowed for inter-phase mutual coupling. This can lead to an overreach error.

5.4.2.3 Blocking schemes

Blocking schemes in distance protection uses signaling between the three terminals of the teed lines. The distance relays at each terminal are arranged to reach beyond both remote circuit ends for all conditions of fault. Reverse set relays which see the external faults which fall within the setting of the overreaching relays send signal to the other two terminals to block tripping of the circuit breakers there. Consideration has to be given to the faults at the remote end and the conditions that cause the greatest underreaching in determining the forward settings. The reverse set relays should cover beyond the reach of the forward-looking remote relays.

This scheme may not function properly for a Tee and Mesh circuit shown in figure 5.3. A fault close to busbar B is fed from all three terminals. The fault current component from C flows through the parallel tie and that from A flows through the teed circuit as well as through the tie. At busbar C, fault current flows out of the teed circuit causing the reverse set relays to block tripping at all three terminals. This unnecessary blocking can be overcome by using a short-reach forward-set relay at B to trip for faults from B to the tee point. It is also possible to use the protection in the tie to provide blocking instead of the reverse set relays.

In all blocking schemes, the tripping units at any terminal should operate for all internal faults under all system conditions. If it is not possible to set the relays, special solutions such as sequential tripping, out-of-step blocking, the use of separate relays for carrier and time-zone tripping and remote tripping have to be used.

The blocking signal may be sent over the transmission circuit, microwave, or higher frequency or d.c signal over pilot wires. Blocking type relays may be either directional comparison or phase comparison. In directional comparison type relays, the location of the fault is determined by the directional relays and the relative phase position of the currents entering and leaving the line is used in phase comparison relays.

5.4.2.4 Sequential tripping

The most common problem encountered in teed lines is the increased apparent impedance caused by the infeed from the third terminal. If the terminal B is strong compared to terminal A, the relays at A have to be very sensitive to detect a fault near C. This means even a very small swing between terminals A and B will cause tripping of terminal A. Figure 5.7 shows the characteristic of the relay at A to include the apparent impedance up to C'.

Sequential tripping is a possible scheme that can be used to avoid tripping of terminal A for small swings between A and B. The relay characteristic at A has to be made smaller to allow good load carrying ability. The relay at A can see the fault at C and trip the circuit breaker only after the circuit breaker B has opened. This is called **sequential tripping**. Sequential tripping, although tolerable, can cause difficulty in high-speed reclosing of the line.

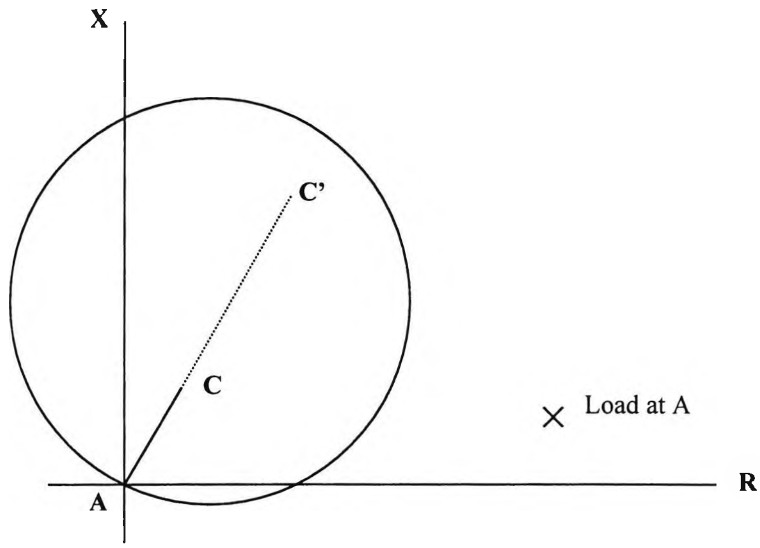

Figure 5.7 Relay characteristic showing apparent impedance

Reducing the tripping area is a possible method of obtaining high speed tripping for all line faults and still avoid tripping during a swing unless there is an actual out-of-step condition. One such method of reducing tripping area is by the use of two circles as shown in figure 5.8.

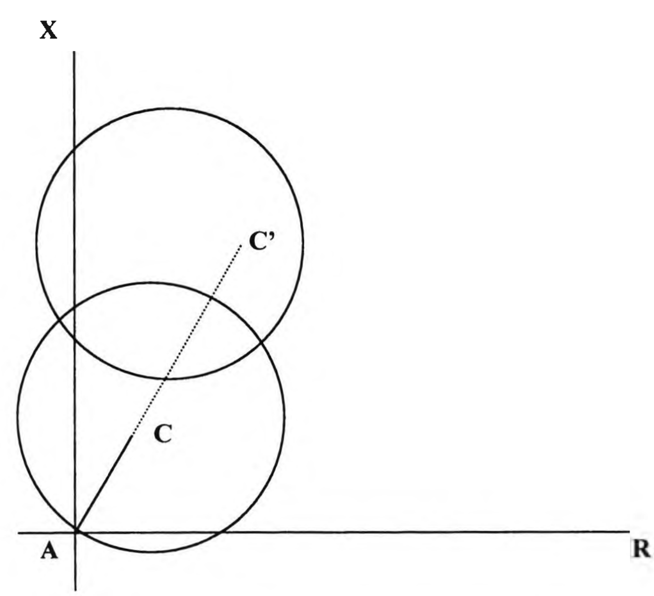

Figure 5.8 Two circles to reduce tripping area

5.4.3 Teed transformer feeders

When a transformer is in one of the lines with no circuit breaker on the line side, the transformer has to be treated as part of the line with respect to phase faults and the use of low-voltage side potential causes the line to appear to be much longer than it actually is.

5.4.4 Pilot-wire and Carrier Pilot Protection

M A Bostwick and E L Harder [76] have shown that Pilot-Wire and Carrier Pilot Protection are effective solutions to the problems of relaying three-terminal lines. They have considered two types of pilot protection, the directional comparison or blocking type used with d.c pilot-wire or carrier-current channels and the two-wire a.c pilot-wire type.

In the directional comparison scheme, directional fault-detectors at each end are set to trip for any faults in the forward direction unless blocked by a signal received from the far end. This blocking signal is started by a directional element when fault power flow is out of the line at that terminal. Step-type directional impedance relay may be used as the fault-detecting element and as the directional element for initiating the blocking signal. In paralleling ties where fault power may flow out of one terminal for a fault on the protected line near another terminal, this scheme is useful in that the first zone element trips the terminal nearest the fault preventing further flow of fault power and enabling the carrier or pilot controlled relays to trip the other two terminals. First zone element tripping the terminal nearest the fault also removes the mutual impedance effect.

A single-element a.c pilot wire scheme which is used in short three-terminal lines has been studied by M A Bostwick and E L Harder [76].

R K Aggarwal and A T Johns [77] have proposed a new high speed current differential protection scheme which utilises a wide-band fibre optic link. The special filtering and signal processing techniques developed provides maximum relay stability for through faults.

5.4.5 Superimposed component impedance relay

J S Daniel, R K Aggarwal and A T Johns [78] have proposed a new impedance relaying principle by using prefault and superimposed components of relaying voltages and currents. The total quantities in the network are considered as the sum of steady state and superimposed quantities. The design is suitable for Teed feeder application, applied in conjunction with a directional protection scheme.

The design has good fault coverage, the reach characteristic is insensitive to fault point on wave and prefault conditions. The disadvantages are that it requires triggering by a directional relay, operating time is not fast and the design is more complex than a conventional relay.

5.5 Artificial Neural Networks for Distance Protection

Artificial neural networks use a large number of simple parallel processors to recognise preprogrammed or "learned" patterns. This approach can be adapted to recognise learned patterns of behaviour in electric power systems where exact functional relationships are neither well defined nor easily computable, and is able to compute the answer quickly by using associations learned from previous experience. A number of approaches in distance protection using ANNs have been adopted.

Inaccuracy due to the mutual coupling of parallel lines has been reduced in a method where ANN is used to estimate the actual power system condition and calculate the appropriate tripping impedance [79]. Adaptive approach is used to integrate the scheme. A technique using ANN that calculates the voltage across non-linear capacitor installation using local voltage and current measurements has been found to be suitable for implementation in a digital relay to improve its performance [80]. The actual problem is to make the relay intelligent enough to understand the outage of a series capacitor and not to trip. An ANN based fault direction discriminator for protecting transmission lines has shown very good performance in terms of time [80]. The type of fault, phases involved, power flow conditions, fault location, variation in source impedance and the presence of fault resistance do not affect the determination of direction. Multilayer perceptron has been used to detect high impedance arcing faults [81]. The detector is able to identify fault conditions distorted by arcing noise and fault-like load conditions. A high speed digital relaying algorithm has been developed using ANN [82]. The proposed ANN models are trained with the input patterns of distorted voltage and current signals passed through a low-pass filter and with the target patterns of real and imaginary components of a dc offset real current and voltage signals conditioned by dc offset removing algorithm. The ANN plays the roles of a dc offset removing filter and a Fourier filter.

Artificial neural networks have also been used for fault area estimation and fault classification [82-86]. Their basic difference is in the variable that each of them uses as input.

5.6 Wavelets

Wavelets are mathematical functions that decompose data into different frequency components and study each component with a resolution matched to its scale. Wavelets are functions that satisfy certain mathematical requirements and are used in representing data or other functions. Wavelets are well suited for approximating data with sharp discontinuities. The primary applications of wavelets has been in signal processing, image compression, sub-band coding, medical imaging, data compression, seismic studies, computer vision, sound synthesis, and pure mathematics applications such as solving partial differential equations.

Unlike Fourier analysis, which relies on a single basis function, wavelet analysis uses basis functions of a rather wide functional form. The basic concept in wavelet analysis is to select an appropriate wavelet function called analysing wavelet or "mother" wavelet and then perform an analysis using shifted and dilated versions of this wavelet. Wavelets can be chosen with very desirable frequency and time characteristics as compared to Fourier techniques.

The basic difference is that in contrast to the short time Fourier transforms which uses a single analysis window, the wavelet transform uses short windows at high frequencies and long windows at low frequencies. Thus windowing of wavelet transforms is adjusted automatically for low or high frequencies (i.e. every window, whether for high frequency or for low frequency has the same number of cycles) and each frequency component gets treated in the same manner without any reinterpretation of the results. The basic functions in wavelet transforms employ time compression or dilation rather than a variation in time frequency of the modulated signal. The few simple conditions imposed on wavelets allow freedom in the choice of the mother wavelet. Therefore, for some applications, the mother wavelet can be made to fit and model a specific application or phenomenon [87].

Wavelet techniques applied to power engineering fall into two broad overlapping areas: identification and analysis. The identification phase relates to the categorisation of signals, their decomposition into fundamental components, and their representation as a sum of basis functions. The decomposition forms a pattern that models the identity of the transient. By comparison of this pattern with a library of previously identified signals, it is possible to classify a given transient. This application may be used to identify such signals as lighting surges, transformer inrush current and other commonly encountered signals.

5.7 Study of a practical Teed-circuit

The teed-circuit used for this study is a part of the 400 kV transmission system in England and Wales. Figure 5.9 shows the single-line representation of the Teed-circuit with the parameters used in the simulation study. The purpose of this study is to generate sets of data of voltages and currents for faults along the transmission line from the Tee-junction to source C. This data is then used for training and validation of a neural network that could be used for fault location and protection.

The geometric configuration of the transmission line between source C and Tee-point is given in Appendix A. The transmission lines are supported by lattice steel towers shown in Appendix B (figures B1, B2 and B3). Legend for transmission line configuration data is given in Appendix D.

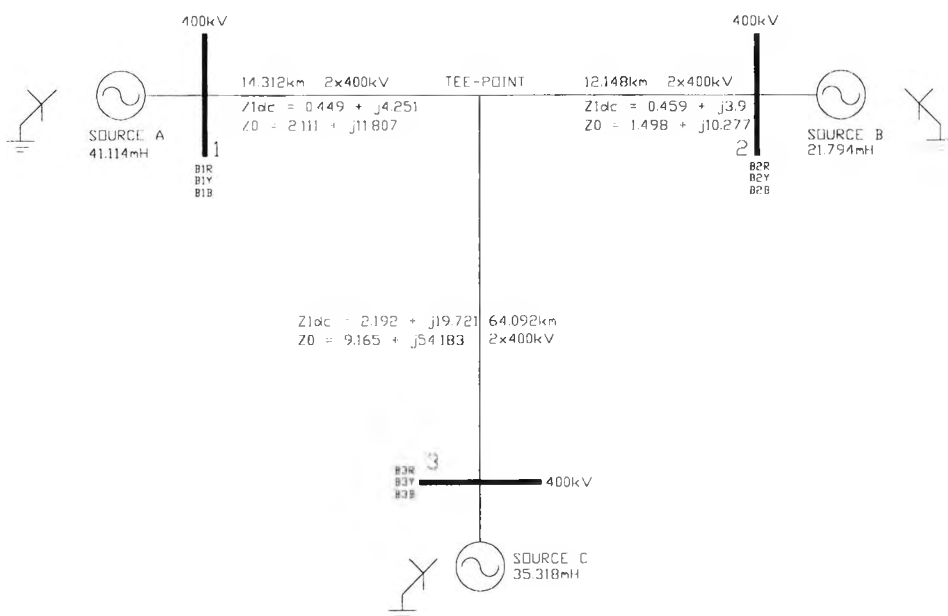

Figure 5.9 Single-line representation of the Teed-circuit

5.8 Simulation of Teed-circuit

Simulation for the 400 kV double-circuit tee-network mentioned above is carried out using EMTP. Circuit parameters of the network shown in figure 5.9 are used for the simulation. The length of each branch of the network is given in Table 5.1. Several simulation runs are carried out for a single phase (phase-A) to ground fault at point F which is moved from the Tee-junction towards source C in steps of 500 metres. The voltage and current signals at the relay location at substation B are recorded. Simulation is carried out for 0.06 seconds covering three cycles of the signals. A step size Δt of 2.5 μs is used in order to capture the high frequency component of the signals. Every 100 calculated points are generated as output for further investigation. The sampling frequency is 4kHz. The waveforms obtained by the simulation are transferred to Matlab files by selecting the ICAT option in the EMTP miscellaneous data card as 3.

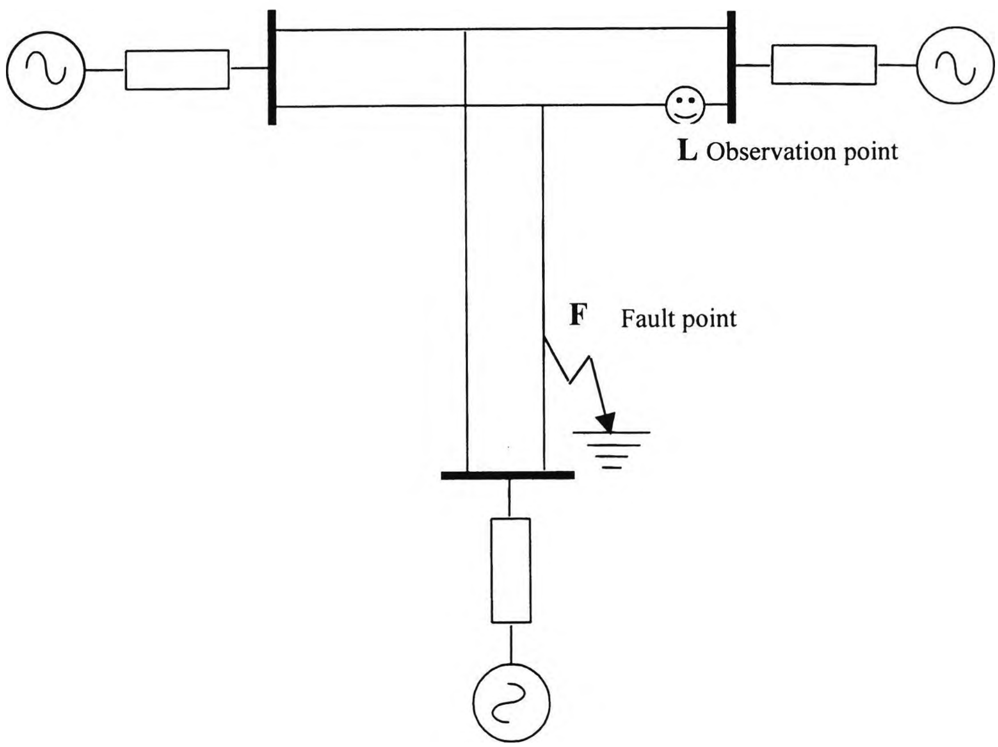

Figure 5.10 Circuit diagram used in EMTP simulation

Table 5.1 Lengths of each branch of the Teed-circuit

Leg	A	B	C
Length (km)	14.312	12.148	64.092

5.9 EMTP Simulation

Simulation of faults on the tee branch of the network is carried out using EMTP. The teed circuit is modelled using Alternative Transient Programme (ATP) which has a graphical pre-processor, ATP Draw. In ATP Draw, the circuit is modelled using graphical representations of components selected from menus. The network drawn using ATP Draw is shown in Appendix E. The processor then gives names to unspecified nodes automatically and creates the ATP file in correct format. Parameters of the components are entered in a pop up window by clicking the appropriate components. The ATP line/cable constants support programme (ATP_LCC) prepares the data case for EMTP. A typical data case prepared for a fault at 3 km from tee junction is given in appendix F. The transmission lines are modelled using frequency dependent parameters [88]. The traditional frequency dependent model is based on phase-domain modelling using Wedepohl/Hedman's model decomposition theory. Figure 5.11 shows the block diagram representation of the fault simulation programme.

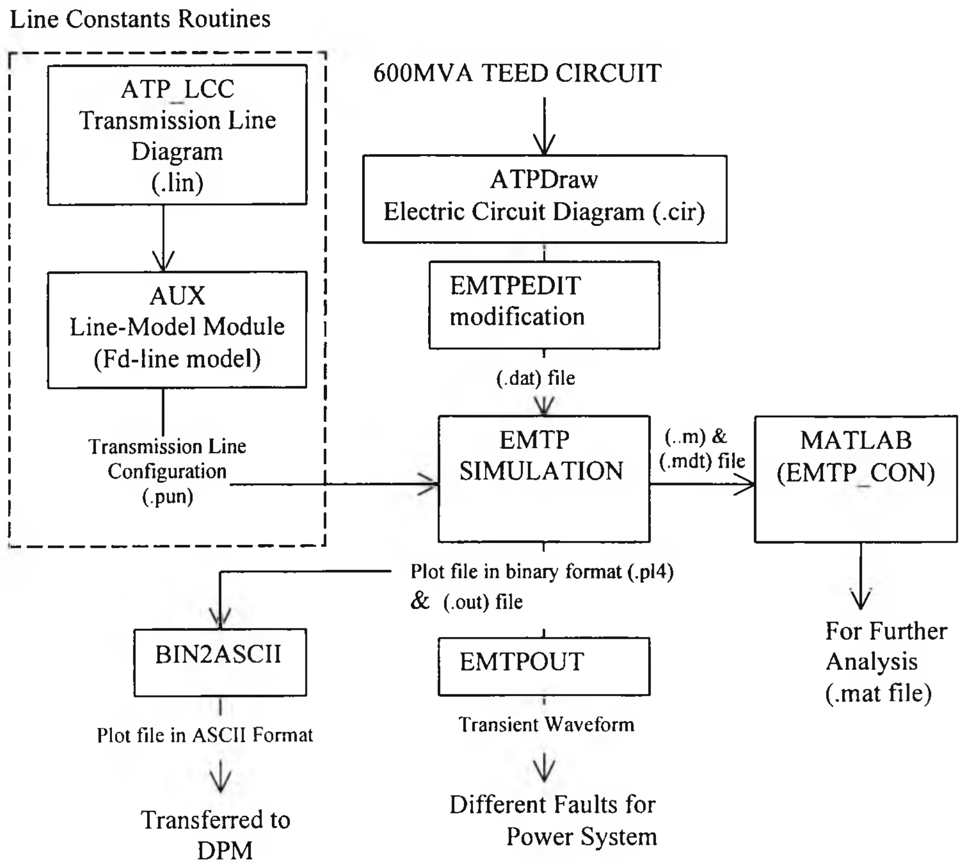

Figure 5.11 Block diagram representation of fault simulation in EMTP

5.10 Multiresolution Analysis and Wavelet Analysis

Wavelets are mathematical functions, used for signal analysis, that split the data into different frequency components and study each component with a resolution matched to its scale. This function is then dilated and translated to form a family of analysing functions [89]. These are normalised as,

$$h_{a,b}(x) = a^{-1/2} h\left(\frac{x-b}{a}\right), \quad a,b \in \mathrm{R} \tag{5.5}$$

Then any function f can be analysed as a two variable function given by:

$$WT(f) = \langle f, h_{a,b} \rangle = \int a^{-1/2} f(x) h\left(\frac{x-b}{a}\right) d \tag{5.6}$$

This time scale representation of f is called wavelet transform.

If the wavelet h satisfies the admissibility condition,

$$C_h = 2\pi \int \frac{|\hat{h}(\omega)|^2}{|\omega|} d\omega < +\infty, \tag{5.7}$$

Then the transform can be inverted as,

$$f(x) = \frac{1}{C_h} \int \int WT(f) h_{a,b}(x) \frac{da db}{a^2}, \tag{5.8}$$

This formula converges in many-function-space, where as Fourier transform fails to do so.

If we choose

$$a = 2^{-j} \text{ and } b = 2^{-j} k \ (j, k \in Z) \tag{5.9}$$

as the discrete values for a and b, then the wavelet function can be written as,

$$h_{j,k}(x) = 2^{j/2} h(2^j x - k), \quad j, k \in Z \tag{5.10}$$

And the function f can be decomposed as,

$$f = \sum_{j,k \in Z} \langle f, h_{j,k} \rangle h_{j,k}, \tag{5.11}$$

The coefficients $h_{j,k}$, are found by using the pyramidal scheme algorithm that decomposes the signals into sub-bands. This concept is known as multiresolution analysis.

The multiresolution analysis is an improved concept of closed, nested subspace $\{V_j\}_{j\in Z}$ that is obtained from V_{j+1} by a dilation factor of 2. It follows that the function f satisfies the relation of the form

$$\varphi(x) = 2\sum h_n \varphi(2x - n) \quad (5.12)$$

The function φ known as 'Mother wavelet', plays an essential role in the theory of wavelet function.

Now by defining,

$$\Psi(x) = 2\sum (-1)^n \bar{h}_{1-n} \varphi(2x - n), \quad (5.13)$$

it is possible to generate the function whose translates form an ortho-normal basis for the orthogonal complement. This follows the complete families of wavelets that are currently in use. The linear combination of φ's translates provide the approximation for the function f, while the translates of Ψ carries the details that allows the approximation to refine on the next step (level). Since the algorithm is discrete, the sampled data are analysed as approximation coefficients. These coefficients are identified with impulse response of a Conjugate Quadrature Filter (CQF) that satisfies the following relation

$$|m_0(\omega)|^2 + |m_0(\omega+\pi)|^2 = 1. \quad (5.14)$$

This fundamental technique is best described for three levels of decomposition shown in figure 5.12. These filtering properties allow the transform to construct different levels of decomposition [18,90]. The decomposition process can be iterated, with successive approximations by breaking down the signal into many lower-resolution components.

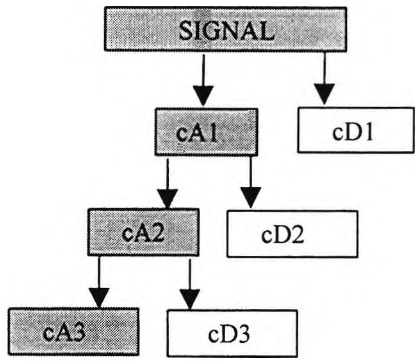

Figure 5.12 Multi-level decomposition diagram

One major advantage of wavelet analysis in signal processing, is its time localisation. Unlike Fourier Transform, where the signal is converted as the summation of sine and cosine waveforms, wavelet transform converts them into a summation of dilated and shifted versions of a fundamental waveform.

As shown in figure 5.12, the shaded boxes are the levels of decomposition and the others are the final decomposed signals available for analysis. Every time the signal is filtered with lowpass and highpass filters, it is divided into two signals known as high frequency component (details) and low frequency component (approximation) and its frequency drops by half. So the final approximation can be considered as the fundamental frequency. The high frequency component, known as details will contain the noise part of the signal. This property in wavelet transform gives the ability to abstract any abnormality in the signal.

Since the fault is simulated at every 500metres from the tee-junction, 130 sets of voltage and current waveforms are obtained from the simulation. In this simulation, two types of mother wavelets, Biorthogonal (bior4.4) and Coiflets (coif4) have been considered for analysis. Coiflets are orthogonal and compactly supported wavelets, their main difficulty being poor regularity. Biorthogonal wavelets are also compactly supported, the main difficulty being loss of orthogonality. A 6-level decomposition is selected to make the low frequency (62.5Hz) component almost equal to the nominal frequency (50Hz) of the signal. It is also possible to abstract more details about the high frequency component present in the signal due to the fault. As shown in figure 5.12, for a 6-level decomposition there will be seven signals available, out of which six are details and one is an approximation. In this case, only the 6 details are taken for further analysis. The Training pattern is generated using three types of statistical information for all 6 details and for all 6 waveforms of voltage and current. The training data therefore, consists of 108 inputs and 130 patterns for each wavelet type.

5.11 Radial Basis Function Network

A network structure that employs local receptive field to perform function mapping is known as Radial Basis Function Network (RBFN) [87].

The activation level of the *i*-th hidden unit is given in equation 5.15.

$$w_i = R_i(\vec{x}) = R_i\left(\|\vec{x} - \vec{c}_i\| / \sigma_i\right), \quad i = 1,2,\ldots..n \tag{5.15}$$

where $\vec{x}$ is a multi-dimensional input vector,
$\vec{c}_i$ is a vector with the same dimension as $\vec{x}$,
n is the number of radial basis function and
$R_i(\cdot)$ is the i – th radial basis function.

The output of a radial basis function can be obtained by equation 5.16.

$$f(\vec{x}) = \sum_{i=1}^{n} f_i w_i = \sum_{i=1}^{n} f_i R_i(\vec{x}), \tag{5.16}$$

where f_i is the output value associated with *i*-th layer. A more complicated method is to calculate weighted average as,

$$f(\vec{x}) = \frac{\sum_{i=1}^{n} f_i w_i}{\sum_{i=1}^{n} w_i} = \frac{\sum_{i=1}^{n} f_i R_i(\vec{x})}{\sum_{i=1}^{n} R_i(\vec{x})}. \tag{5.17}$$

Several algorithms have been proposed to identify the parameters. In this fault estimation process the least squares algorithm is used to find those parameters.

Four different RBF networks are developed for each type of mother wavelets. All the networks are designed during the training as it iteratively creates the RBF network, one neuron at a time. Following parameters are used during the training of each RBF network.

- Sum square error goal - 0.0001
- Maximum RBF neurons in the hidden layer
- RBF spread constant - 0.01

Networks are trained in a P-166 machine with 64M of memory until the sum square error is 0.0001 and the training time for each network is found to be less than 4 minutes.

Figure 5.13 shows bior 4.4 RBF network response for the training data used. Each network is cross-validated with unseen data and the results are shown in Figure 5.14. The networks are also tested with randomly generated fault locations for a given fault type. A comparison of the actual location of the fault and the location estimated by the four different types of RBF networks is shown in table 5.2. Cross-validation shows significant variations between the expected results and those obtained by using either bior4.4 or sym4. The results obtained with Coif4 and db4 networks are very close to the expected results.

Table 5.2. Comparison of the estimated fault location using four types of RBF networks

Actual Location	bior4.4	coif4	db4	sym4
0.7	5.8333	0.8352	0.6894	2.0568
2.7	8.4031	2.3355	2.5682	1.5156
5.7	11.3403	6.6658	5.7232	2.1405
15.8	14.2287	15.9536	16.0027	4.7349
24.6	26.4253	24.8114	24.8622	12.9314
33.9	36.8914	33.9052	33.793	18.2254
39.9	43.8311	39.7246	40.2537	27.4687
44.1	48.4098	44.2176	44.5514	32.6919
54.2	59.5067	54.9426	54.8608	44.3345
62.2	58.4745	59.1235	61.9442	49.1153

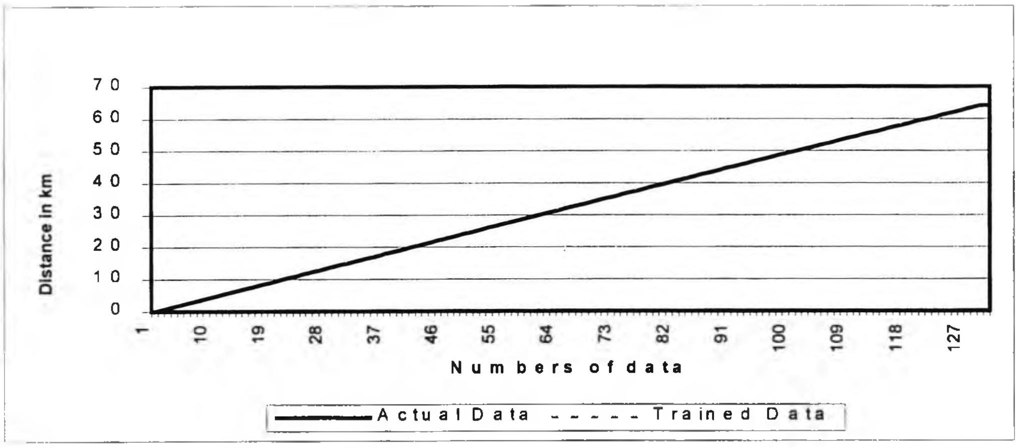

Figure 5.13 Bior4.4 RBF network response for training data

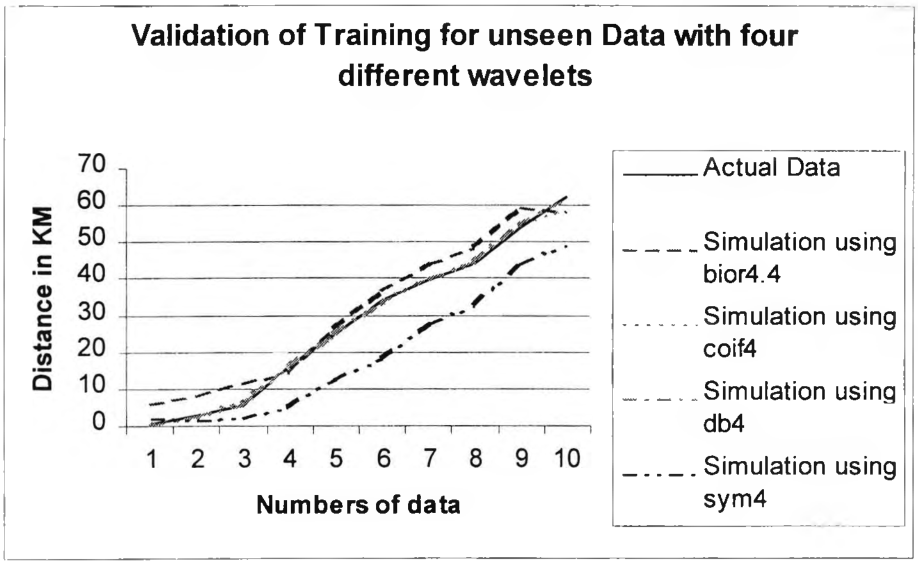

Figure 5.14 Validation with unseen data

5.12 Relay setting evaluation

Dynamic Protection Modelling (DPM) software developed by the University of Strathclyde, Centre for Electrical Power Engineering, is used to evaluate the settings of the distance relay at substation B. It is assumed that the network is protected by a normal three-stage distance scheme applied at each end of the feeder. In this case, the zone overlap of the first stage providing instantaneous tripping is usually much smaller than in the case of the two-terminal line. Because of this, the use of carrier link becomes more important.

The relay model used for testing shows the relay characteristics for zone 1, zone 2, zone 3 and reverse reach zone on an R-X diagram. The locus of the impedance presented to the relay by the faulted line can be superimposed on the same R-X diagram and a trip or no-trip decision taken depending on the position of the impedance relative to the relay characteristic. Three sample cases of testing are shown in figures 5.15 to 5.21. Zone 1 setting of the relay at substation B is expected to reach about 11 km from the tee-junction. Figures 5.15, 5.16 and 5.17 show the impedance trajectory for a fault at 3 km from the tee-junction. In figure 5.15, the fault is seen by zone 3 at 0.1181s, and in figure 5.16 the fault is seen by zone 2 in 0.1183 s.

Figure 5.17 shows the following:

- Zone 2 at 0.1183 s.
- Zone 1 at 0.1192 s.
- Trip at 0.12 s

Figures 5.18 to 5.19 are the test case for a fault at 10 km, where the relay trips again at 0.12 s.

Figures 5.20 and 5.21 show the response for a fault at 20 km and the relay does not trip as expected. This fault will be seen by the relay at substation C that would trip its circuit breaker. The inter-tripping scheme would trip the other two circuit breakers at substations A and B. This shows that the impedance values of the faulted line obtained by the proposed technique could be used as input to the distance relays for the protection of teed circuits.

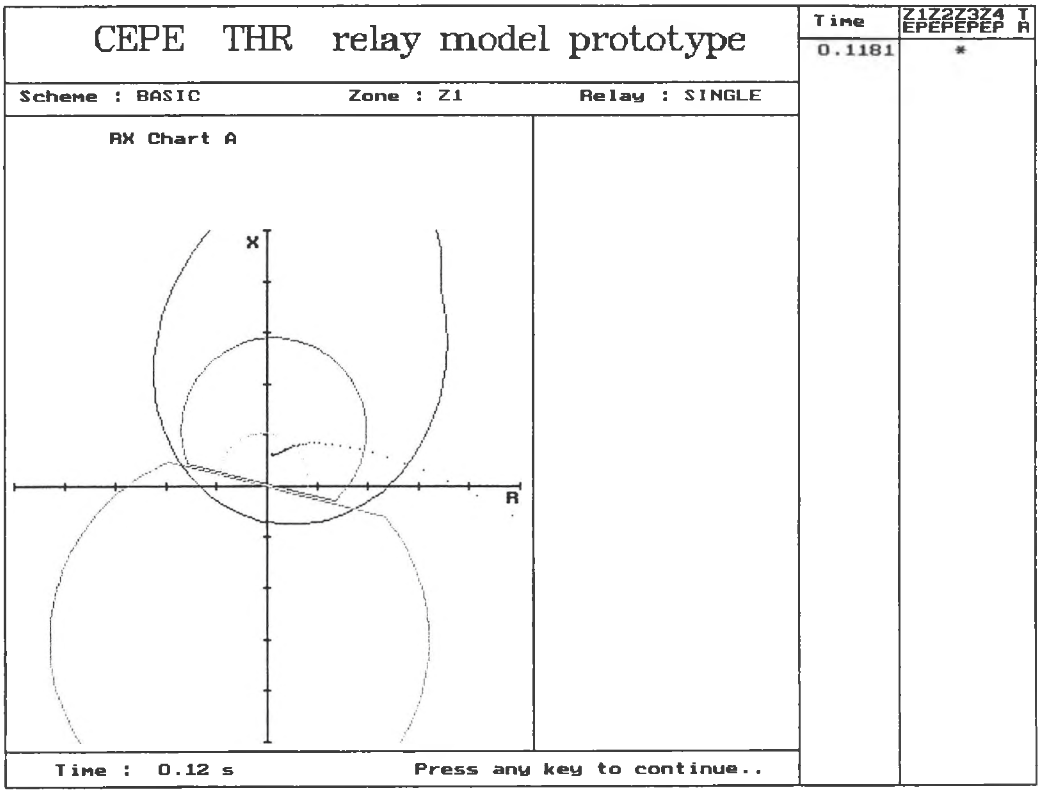

Figure 5.15 Impedance trajectory for fault at 3 km from tee-junction

In the last column of the figures, Z1, Z2 and Z3 and Z4 stand for zone1, zone 2, zone 3 and zone 4 (reverse reach zone) respectively.

E stands for earth fault, P for phase fault and TR for trip.

An asterisk mark shows up below the zone number when the impedance trajectory moves into that zone in the relay characteristic.

The time column indicates the time of at which the trajectory reaches the zone

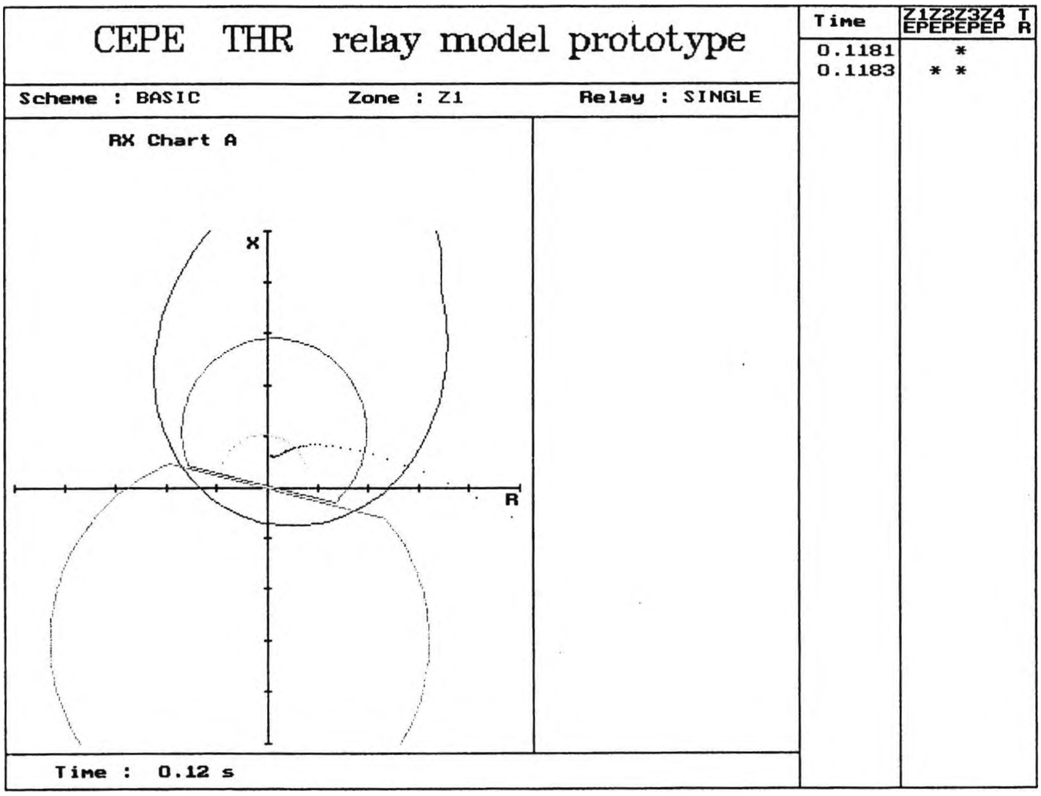

Figure 5.16 Impedance trajectory for fault at 3 km from tee-junction

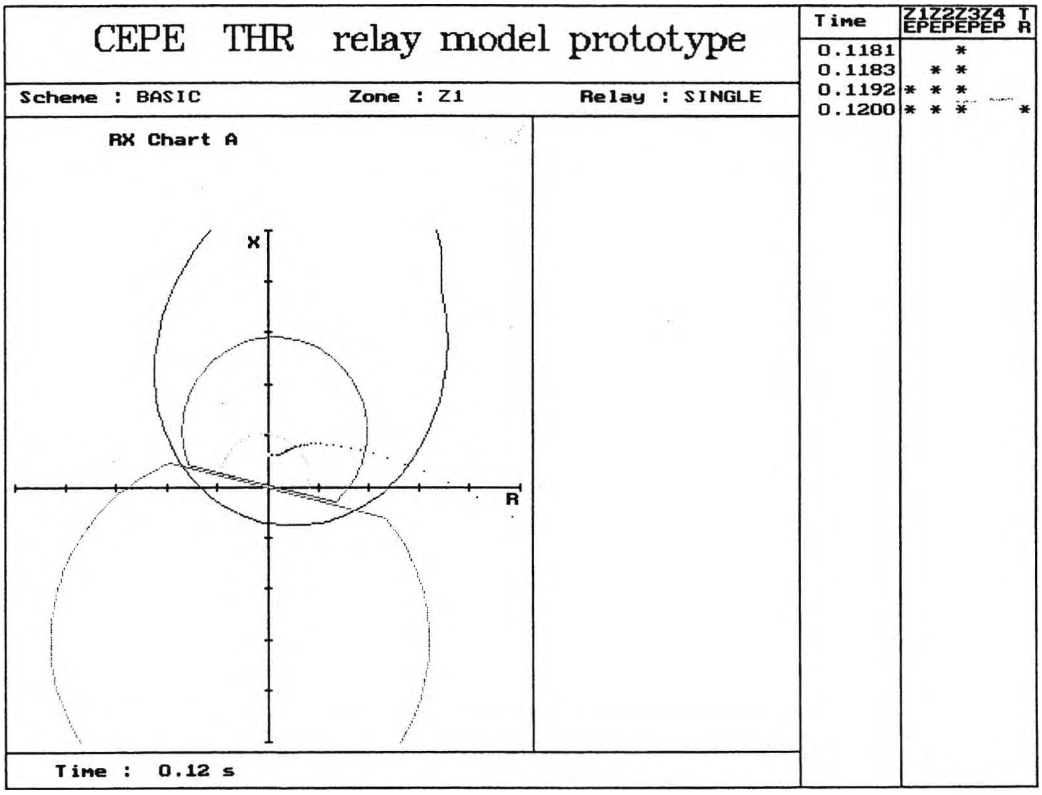

Figure 5.17 Impedance trajectory for fault at 3 km from tee-junction

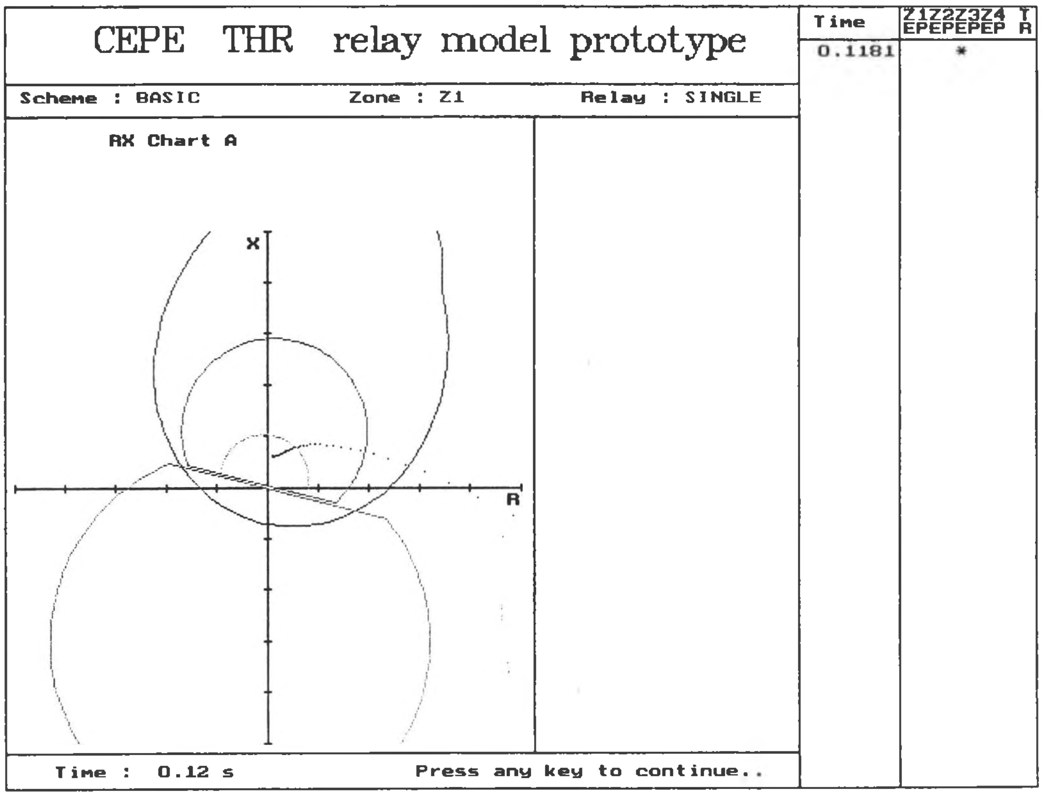

Figure 5.18 Impedance trajectory for fault at 10 km from tee-junction

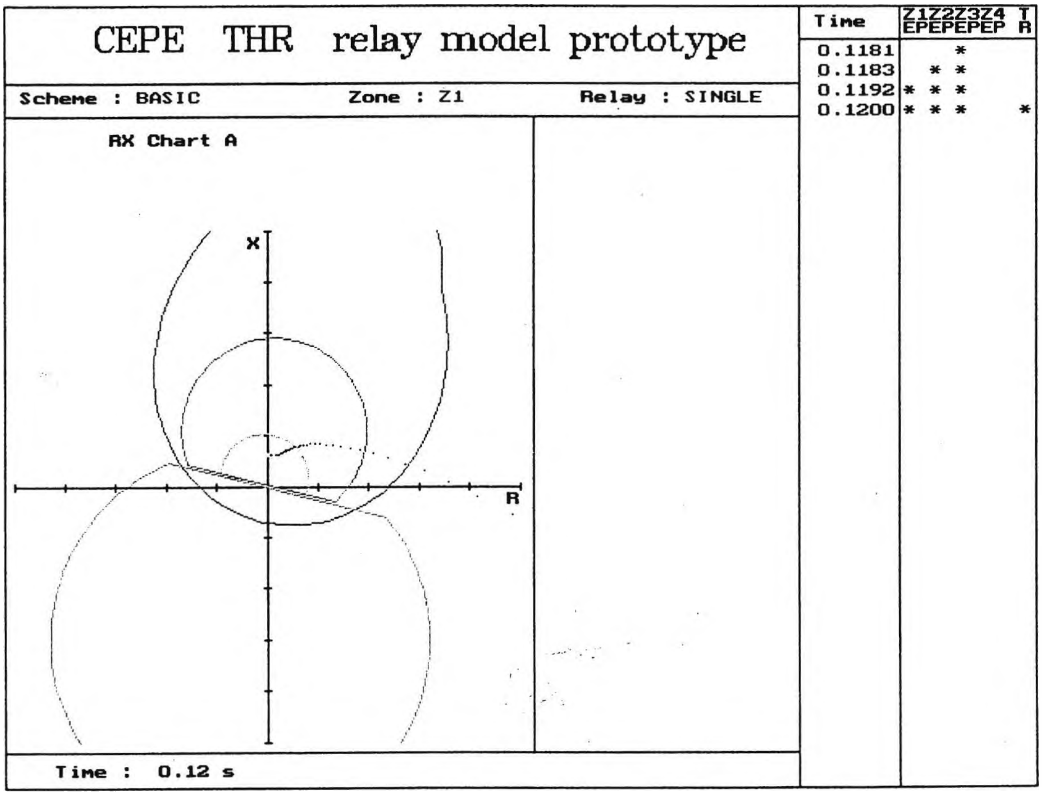

Figure 5.19 Impedance trajectory for fault at 10 km from tee-junction

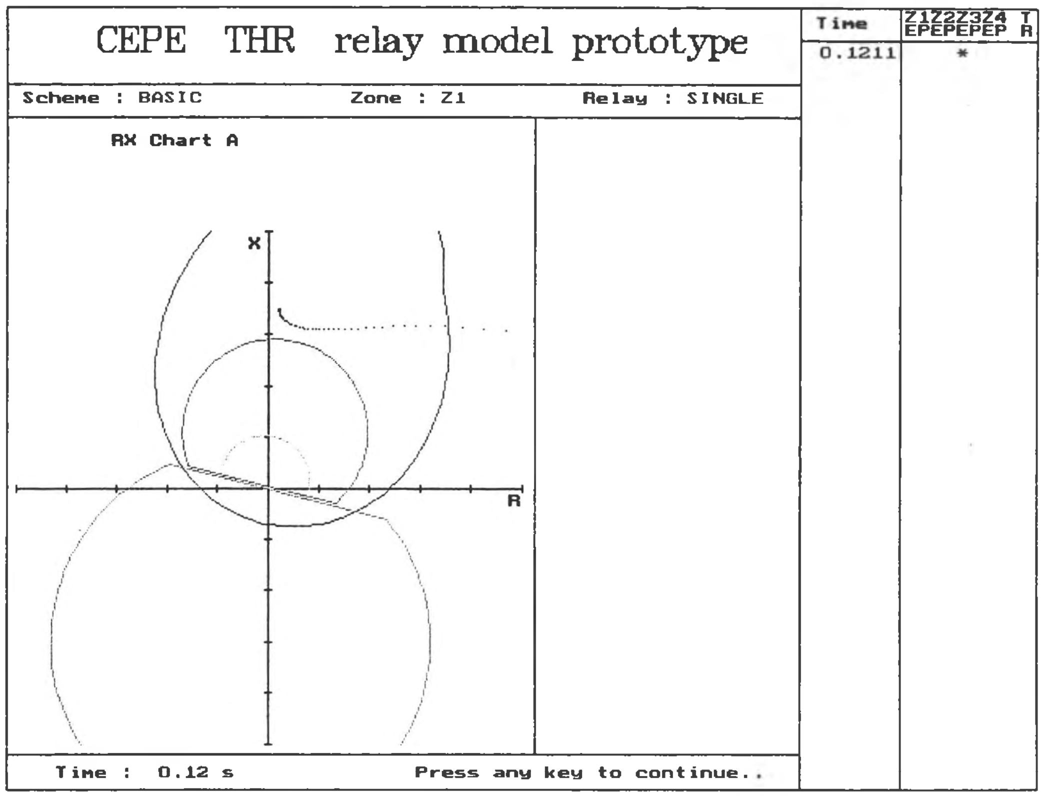

Figure 5.20 Impedance trajectory for fault at 20 km from tee-junction

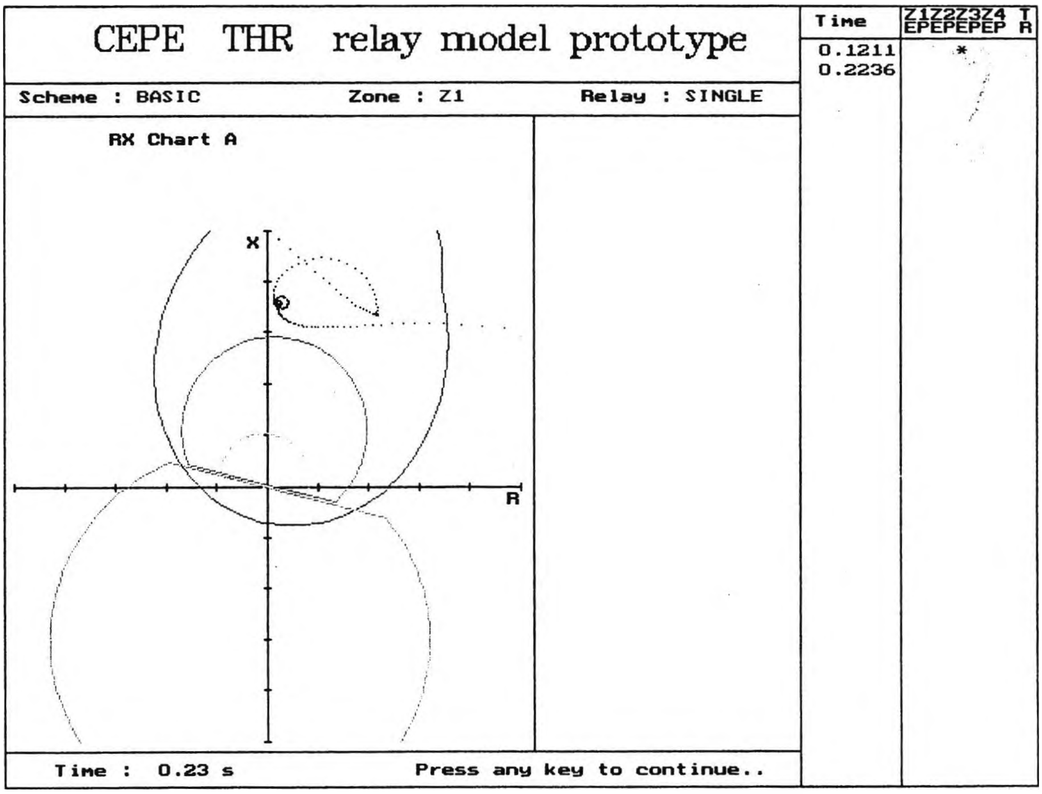

Figure 5.21 Impedance trajectory for fault at 20 km from tee-junction

5.12 Conclusion

A suitable technique using wavelet transform and radial basis function network has been developed for the location of faults in teed networks. The relay model of the Dynamic Protection Modelling software developed by the University of Strathclyde is used to evaluate the accuracy of this fault location technique. The results show that the impedance values of the faulted line obtained by the proposed technique could be used as input

Chapter VI

ESTIMATION OF GENERATOR EXCITATION SYSTEM PARAMETERS USING OBJECT ORIENTED TECHNIQUES AND IMPROVED GENETIC ALGORITHMS

6.1 Introduction

Turbine generator excitation system practice began to undergo a widespread and radical change in the early 1960s [91] as the availability of high-power semiconductor devices promised significant improvements in both performance and reliability. Since then semiconductor technology has progressed steadily and its exploitation has largely been responsible for excitation system development being able to keep pace with that of the generators themselves. High-current thyristors that became readily available about forty years ago proved to be an almost ideal power control element for use in automatic voltage regulators (AVRs). They are completely static, very fast in response, small in size for a given output and relatively cheap. Thyristor excitation systems require minimum operating maintenance and convert ac power to dc power at high efficiency throughout the life of the power station to yield low operating costs and high return on investment. A review of the development, construction, testing and operation of excitation rectifier schemes associated with large generators is given in reference [92]. Since of late, excitation sources for large turbine generators of 1200 MW capacity are also being constructed [93,94].

The range of operation of all turbine generators synchronised to electric power systems is constrained by stability limits. Generators in modern power systems are often required to operate with reduced stability margins in the under-excited region. In most networks, the machines are run well away from steady-state stability limits due to the possibility of a fault such as a short circuit occurring. If, however, a fault occurs and is not cleared fast enough or there is insufficient margin of safety between the steady-state operating point and the stability limit, the machine loses synchronism and pole slips. Any oscillations that develop have to be damped out and steady-state operation restored as quickly as possible in order to avoid disturbances propagating to other machines in the system.

It is also necessary for the AVR and exciter to operate under varying conditions such as no-load with generator circuit breaker open, load shedding, full load and circuit switching etc. The setting for these conditions may well be conflicting so that compromises have to be made to give a good response for voltage and reactive power control. Heuristics or trial and error methods have been used in previous work in the field [95,96] to determine the settings for 'optimal' performance of the excitation control system (ECS). The problem formulation was over-simplified with certain assumptions that lacked generality.

In the past, structured programming techniques that follow a linear model approach have been used for the development of software for design and simulation of power electronic systems. The model thus developed suffers from the fundamental problem that information tends to flow one way. This lead not only to a deficient design, but also to lack of response to changes in the software requirements because of the insufficient feedback.

Object oriented Programming (OOP) techniques offer a radically different approach to software design [97,98]. When OOP approach is used, software developments become an incremental process. Each stage of the development is revisited repeatedly throughout the development process and each visit refines the software at that stage. Extensibility and portability of programs can be done by identifying key concepts and assigning each concept to a class. The relationships between the classes can be represented as inheritance. This can be done repeatedly at different levels of abstraction. OOP facilitates the production of programs with a 'clear' internal structure.

The development of a software using OOP techniques to integrate improved genetic algorithms (IGAs) in selecting parameter values of an excitation control system (ECS) is described in this chapter. Vector and matrix classes act as case classes for chromosome strings and population respectively. The population size is kept between 100 and 200, as small population size does not offer enough variation to obtain stable populations. Bit string mutation is used to present premature convergence and loss of genetic information.

Settling time and overshoot for different operating conditions are set as the decision variables (fitness). The range and precision of each parameter is carefully controlled by mapping the decoded integer linearly within an upper and lower bound and then scaling them accordingly.

6.2 Modern Excitation System

Figure 6.1 shows the components of a practical ECS used to increase the system reliability. The rotating field ac exciter supplies a static diode bridge rectifier, the output of which is the main generator field supply. The field supply for the exciter is from a substantially constant voltage pilot exciter via the output stage of an AVR.

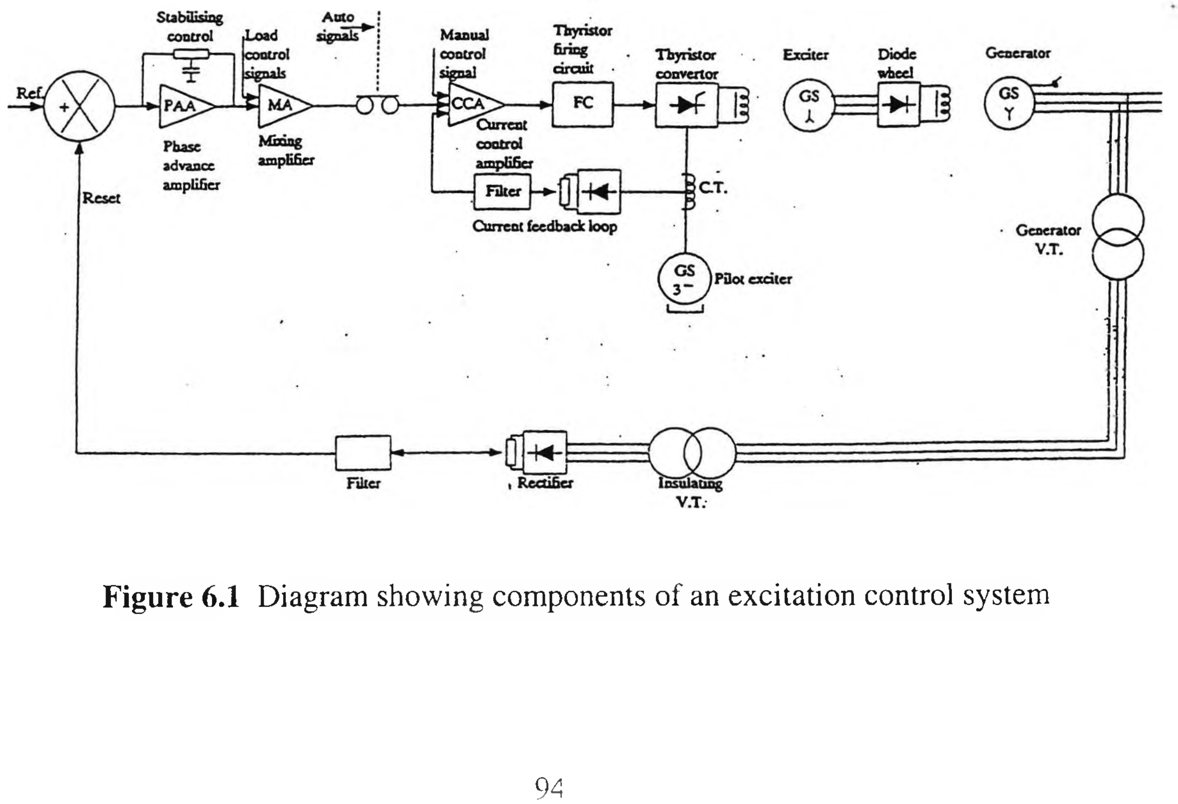

Figure 6.1 Diagram showing components of an excitation control system

The power rectifier bridges operate as phase-controlled variable dc voltage source to control the generator field voltage. By using thyristors in place of conventional diode rectifiers, the dc output voltage (generator field voltage) can be controlled by delaying the point of conduction on the supply voltage cycle.

The generator is a 776 MVA, 23.5 kV machine. The automatic voltage regulator is a solid state electronic device with two automatic channels and a manual control. Each of the twin automatic channels contributes 50% of the required output to allow full utilisation of large generator capability. It is also a standard practice to provide 20% reserve capacity in the rectifier by having extra paths in the bridge arms so that in the unlikely event of a failure, replacement could be carried out when a convenient time for the shut down of the plant occurs.

The firing circuit provides firing pulses to the thyristors in the three-phase bridge arrangement. The position of the pulses and hence the dc output of the power bridge is controlled by a low-level input signal normally in the range 0-10V. The output pulses are applied to the thyristors via pulse transformers for isolation purposes. The thyristor converter is a fully controlled, full wave, three phase bridge unit capable of supplying the normal output current required plus a margin for quick response when conditions so demand. Using a fully controlled bridge enables a rapid and effective reduction in output current by operating the thyristors in the inversion region, thereby allowing the current in the inductive exciter field winding to regenerate back into the supply. For full commutation, each thyrisor is fired by two pulses, the second lagging the first by 60°. The second pulse is necessary when the excitation is low and the thyristors are working in the non-continuos current region. The pulses are advanced by 30° on the three-phase bridge supply and delayed by an angle dependent on the demand for excitation. For maximum output, firing takes place at or just after the crossover point of the rectified waveform. Inversion takes place at delays greater than 90°. The delay angle is limited in the firing circuits to about 150°.

A current transformer in the thyristor converter power supply produces a three-phase signal, which is rectified and smoothed to give a dc signal proportional to the exciter current. This is the current feedback signal and it is also taken to the control amplifier where it is summed to the manual control signal. The resultant is fed to the thyristor converter as the control signal for the firing circuits. Thus the excitation level is set by the position of the manual control potentiometer, the current feedback signal holding this level constant against fluctuations in pilot exciter output.
The power rectifiers are sized to co-ordinate with the overall excitation system and generator performance requirements. Because of the high induced voltages and currents in a generator field circuit under fault conditions it is necessary to take great care in rating the thyristor converter. The voltage of the bridge must be adequate to withstand the combined effects of the supply voltage and any voltage induced in the field under pole-slipping conditions. As well as being capable of handling full-forcing excitation current for several seconds, the bridge must be capable of coping with the much higher short-duration surge currents which occur under certain types of fault conditions. Rectifier peak forward and reverse voltage blocking capability is at least 2.75 times the normal operating peak inverse voltage. Highly reliable, current limiting fuses are connected in series with each thyristor to open the circuit automatically in the event of a failure of the thyristor to block reverse voltage.

Three-phase bridge connection is used for the excitation system. The main advantages here are low voltage stresses on the semiconductors and maximum utilisation of the installed transformer capacity. With this circuit and the high peak reverse voltage capacitors of modern thyristors, usually two thyristors per branch connected in series are adequate for any given installation.

The major factors that determine the number of thyristors to be connected in parallel are the short-time overloads. Induced currents during system short circuits, faulty synchronisation, asynchronous running or maloperation of the automatic voltage regulator can cause these overloads. The number of thyristors to be connected in series depends on the magnitude of the no-load dc voltage. This is obtained by adding the ceiling voltage to the sum of all the voltage drops (for example, resistive voltage drop) and the required factor of safety.

The main exciter is an a.c. rotating armature exciter. The armature consists of laminations of low loss electrical sheet steel shrunk onto the shaft. The armature winding is a three phase two layer winding consisting of diamond shaped coils wound in open slots. The output from the three phase rotating armature is fed along the exciter shaft to the three phase diode bridge, where it is rectified to produce the main generator d.c. excitation. The diode wheel has been simplified considerably by the use of high peak inverse voltage diodes, so eliminating voltage surge capacitors. In order to reduce the possibility of a short circuit across the a.c. side of the bridge due to diode failure, two diodes in series on each side of the bridge are used.

6.3 Improved Genetic Algorithms

Genetic algorithms (GAs) invented by Holland in the early 1970s [99] were put into practical applications in the late 1980s [100]. GAs are search algorithms based on the mechanics of natural selection and natural genetics. GAs are different from other optimization methods in the following features:

- GAs search from a population of points, not single point. The population can move over hills and across valleys. GAs can therefore discover a globally optimal point. Because the computation for each individual in the population is independent of others, GAs have inherent parallel computation ability.

- GAs use payoff (fitness or objective functions) information directly for the search direction, not derivatives or other auxiliary knowledge. GAs therefore can deal with non-smooth, non-continuous and non-differentiable functions that are the real-life optimization problems.

- GAs use probabilistic transition rules to select generations, not deterministic rules, so they can search a complicated and uncertain area to find the global optimum. GAs are more flexible and robust than the conventional methods.

These features make GAs robust and parallel algorithms to adaptively search for the global optimal point. However, to make GAs practicable, the problems of memory and computing time arising from the coding of large number of variables in real life systems need to be solved. The mutation and crossover needs further studies. The work described in this chapter deals with these problems and improves GAs ability in dealing with practical large-scale systems.

The procedure of the improved GA (IGA) is as follows:

Initialization

The initial population of strings, s_i, $i=1, 2, \ldots m$, where m is the population size, is randomly selected in the binary-coded domain of control variables. Each s_i will be decoded back to the control variables to compute its fitness score f_i.

Statistics

The maximum fitness (f_{max}), minimum fitness (f_{min}), sum of fitnesses (f_Σ) and average fitness (f_{avg}) of this generation are calculated as follows:

$$
\begin{aligned}
f_{max} &= \{f_i \mid f_i \geq f_j \;\; \forall f_j,\, j = 1, \ldots, m\} \\
f_{min} &= \{f_i \mid f_i \leq f_j \;\; \forall f_j,\, j = 1, \ldots, m\} \\
f_\Sigma &= \sum_{i=1}^{m} f_i \\
f_{avg} &= \frac{f_\Sigma}{m}
\end{aligned}
\tag{6.1}
$$

Reproduction

The strings of the same number as the population size will be copied into a "mating pool" according to their fitness values. The higher the fitness value, the more the number of copies the string would probably have in the "mating pool". A simulated weighted roulette wheel is used to select mates. Each string in the current population has its sector slot in the wheel. The ratio of slot area of s_i to the whole wheel area is the ratio of f_i / f_Σ.

Mutation

Every string in the "mating pool" may be mutated with the given mutation probability. For the string that is undergoing the mutation, a number will be randomly selected from a uniformly distributed (0,1) domain. If this number is less than the mutation probability, the bits in a string will be changed from 1 to 0, or vice versa. The mutation operator produces a new string.

In general GAs, mutation probability is fixed throughout the whole search processing. However, in practical applications, a small fixed mutation probability can only result in premature solution, and the search with a large fixed mutation probability will not converge. An adaptive mutation probability is given to solve the problem as follows:

$$p_m(k+1) = \begin{cases} p_m(k) - p_{mstep}, & \text{if } f_{max}(k) \text{ unchanged} \\ p_m(k), & \text{if } f_{max}(k) \text{ increased} \\ p_{mfinal}, & \text{if } p_m(k) - p_{step} < p_{mfinal} \end{cases} \qquad (6.2)$$

$$p_m(0) = p_{minit}$$

where k is the generation number, p_{minit}, p_{mfinal} and p_{mstep} are fixed numbers. P_{minit} would be around 1 and p_{mfinal} would be 0.005. p_{mstep} depends on the maximum generation number.

The selected individuals are then modified through the application of genetic operators, in order to obtain the next generation. Genetic operators manipulate the characters (genes) that constitute the chromosomes directly. Genetic operators can be divided into two main categories, namely, crossover which causes pairs of individuals to exchange genetic information with one another; and mutation which causes individual genetic representations to be changed according to some probabilistic rules.

After crossover and mutation, individual chromosomes are decoded, evaluated, and selected according to their fitness, and the process continues.

6.4 Object Oriented Programming

Structured programming techniques follow a linear model of development or 'waterfall model' in which development progresses linearly from analysis to testing. OOP technique involves designing software around objects. The objects are instances of abstract data types or classes. An abstract data type is a type that contains both data and methods or operations that operate on the data. OOP emphasises re-use of component software, which is advantageous when new or similar programs are developed while the basic concepts have not been changed. OOP allows previously defined classes to be extended using inheritance and new classes defined where necessary. This reduces code duplication and time spent in rewriting similar code for different problems and thus increases efficiency. Some basic classes that have been defined to capture the features of a GA include the following:

- Class chromosome which contains strings defining the chromosome.
- Class parameter which contains information of the decoded parameters of the problem.
- Class population which contains the population of chromosome.

6.5 Methodology

For calculations of initial response, the speed can be assumed to be constant and a solution could be obtained by the Laplace transform method. The only method available for calculations over long periods is a numerical step-by-step computation. The models used depend upon the particular method of simulation. Large scale digital computer studies performed in the time domain involve the repetitive calculations. The models in such studies involve differential equations, which are converted into difference equations with small discrete time steps for the ECS. The fourth-order Runge-Kutta method is used for the power system simulation.

The effects of the ECS can be included in the model by adding a block, E = f(I), to the feedback branch of the block diagram of figure 6.2, between the model output representing voltage regulator sensing, and the model input, representing generator field voltage or excitation system output voltage. The behaviour of the power system is specified by a set of three-phase variables arranged into first order differential equations which can be solved by numerical analysis using a digital computer.

The generator is represented as a lumped parameter system. There is one rotor damper winding along the direct axis and one along the quadrature axis. In addition to the field circuit on the direct axis, one fictitious field winding is added in the quadrature axis to simulate the system more accurately especially at leading power factor operations. The transformer and the transmission line are represented by a reactance and resistance in each phase [95]. The phase co-ordinate equations have the greatest generality and allow all varieties of transients to be investigated. Consequently, it can be used to investigate features due to nonideal generator parameters which can be included only with difficulty by other models [101]. The system design work is made more straightforward and practical by avoiding the use of complex mathematical operation.

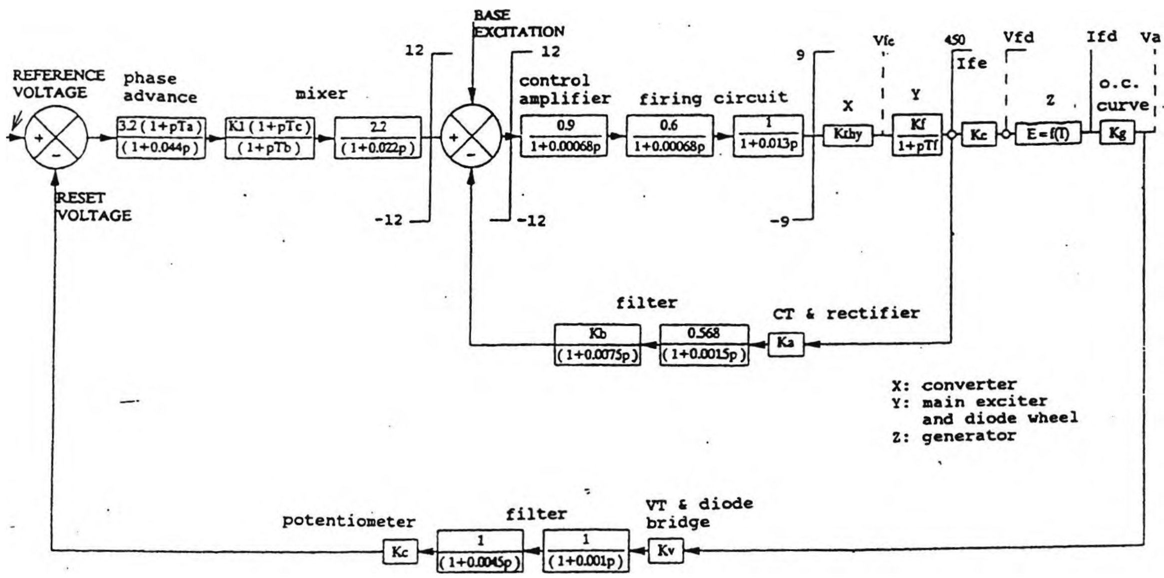

Figure 6.2 Block diagram of an excitation control system

Excitation system models that are suitable for large, severe disturbance as well as for small perturbation have been developed [102]. The complexity of the modelling should depend upon the particular application and the assessment of whether or not the increased complexity will have any significant impact on the results.

It is known that engineers usually perform parameter tuning without exact theoretical knowledge. They have their own performance criteria for a transient response. The time domain features may include settling time and overshoot. The use of GA is to find the values for the parameters with respect to the criteria preferred by engineers. The problems include the finding of parameter values to produce the minimum settling time, minimum overshoot and certain combinations of the two criteria such as minimum settling time but having a maximum allowable overshoot.

A quality measure for a transient response is produced by the fitness function. The evaluation is performed with the software as reported in reference [95]. Only successful cases will produce parameter values and fitness.

The stability is not sensitive to the AVR settings if the system connections of a generator are strong. A strong connection is when the fault infeed from high-voltage busbar is at least six times the generator MVA rating. For weaker system connections it is necessary to set the open-circuit response for longer settling times (up to 5 seconds).

This involves some sacrifice of no-load response, since this is largely determined by the strength of the system connections.

The fitness function is obtained by assuming that the optimisation task is to find the parameter values that minimise the settling time, given maximum allowable overshoot (maxo).

The fitness is defined by equation 6.3 with the assumption of the following set of parameters:

- settling time (tsetk)
- overshoot of the step response (ok)
- maximum simulation time (tobsk)

$$f(k) = \begin{cases} f_0 & \text{no good} \\ f_0 + (f_1 - f_0)\,(maxo/ok) & ok \geq maxo \\ f_1 + (f_2 - f_1)\,(tobsk - tsetk)/tobs & ok < maxo \end{cases} \qquad (6.3)$$

where f_0 and f_2 are the upper and lower bounds of the fitness function used to normalise the fitness values, and f_1 is a threshold fitness value discriminating parameter setting satisfying the maximum overshoot constraints from the ones violating this requirement. The function defined above ranks candidate solutions with respect to the degree of satisfying the optimality criterion, thus producing the simulated evolution.

For the ECS, only the coefficients of the transfer functions need to be encoded in the bit strings. If four bytes are used to represent each parameter, 20 bytes will be required for each bit string in the population for the five parameters. The resulting strings are then concatenated to form an individual in the population. An initial population of 100 or more randomly generated individual is highly desirable. This provides a good spread of genetic information in the initial population and an adequate sampling space for the selection mechanism to operate reliably. The parameters decoded are subjected to constraint requirements that must be met if the system is to be stable. The solution strings that do not meet the requirements for stability are killed off by assigning an arbitrarily low fitness value. The parameter values have been scaled so that they fall within an initial specified range. If for example, *Ta* is encoded in a string length of 10, the decoded value is given by:

$$Ta = \frac{(decoded\ string\ value)}{2^{10} - 1} * range \qquad (6.4)$$

6.6 Analysis of Results

Studies were made with data representing a 776MVA generator, with its transformer connected to an infinite busbar. As stability was expected to be worse at leading power factor conditions, a high leading power factor loading was chosen to study the effect of AVR settings. Conditions such as the open-circuit, under-excited operating region (generator load 660MW/-250MVAr) have been considered.

It has been shown that an acceptable solution for a step change from 90% to 100% of nominal generator voltage, the settling time of the response has to be from 3 to 6 seconds [95].

The parameters of the ECS are encoded into bit strings to form the decision variables. For this study, only the time constants of the phase amplifier Ta, mixing amplifier Tb and Tc, and converter Tf have been considered. Mapping the decoded integers linearly within upper and lower limits and then scaling them accordingly can carefully control the range and precision of each decision variable. These are then concatenated to give a coding that represents the strings (chromosomes) in the population. Single point crossover is used, coupled with bit string mutation. Crossover probability, f_0, f_1 and f_2 are 0.7, 0.01, 0.5 and 1 respectively. The population size is 100.

With adaptive mutation probability, the software developed using OOP technique integrating improved genetic algorithm produces a better solution than the one obtained using normal GA. The maximum simulation time is 30 seconds.

Figure 6.3 shows the relationship between settling time and the number of generations. It can be seen that with a population size of 100, about 30 generations are enough for the ECS to produce an acceptable performance. Studies also show that the parameters selected by this method improve power system stability [103]. Figure 6.4 shows a comparison of the generator terminal voltage profile with ECS parameters selected by the genetic algorithm approach and conventional approach.

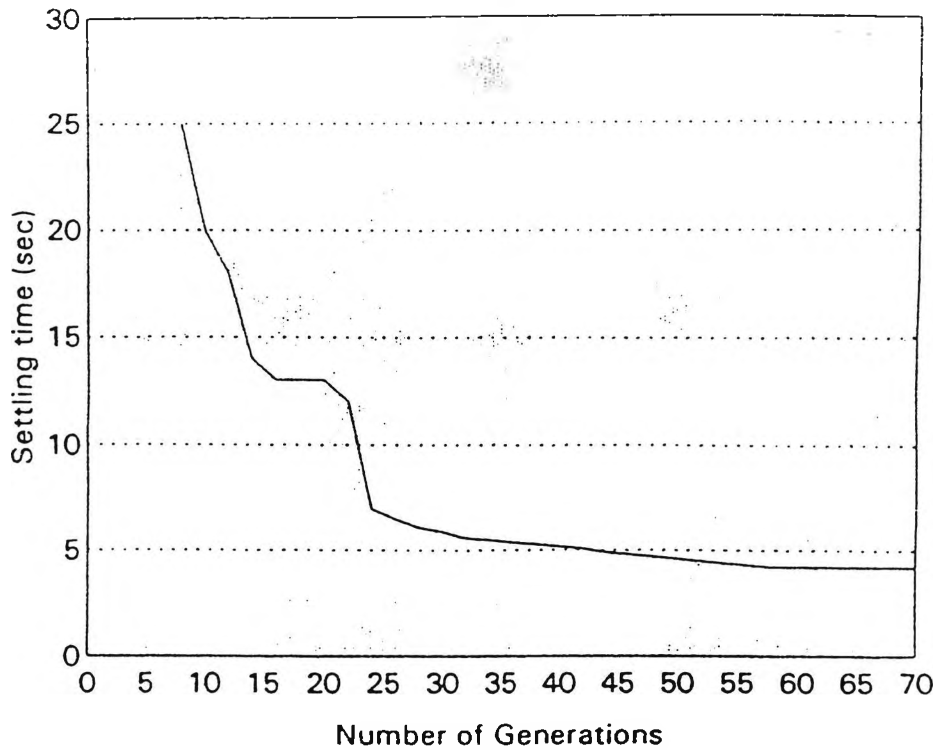

Figure 6.3 Settling time against number of generations

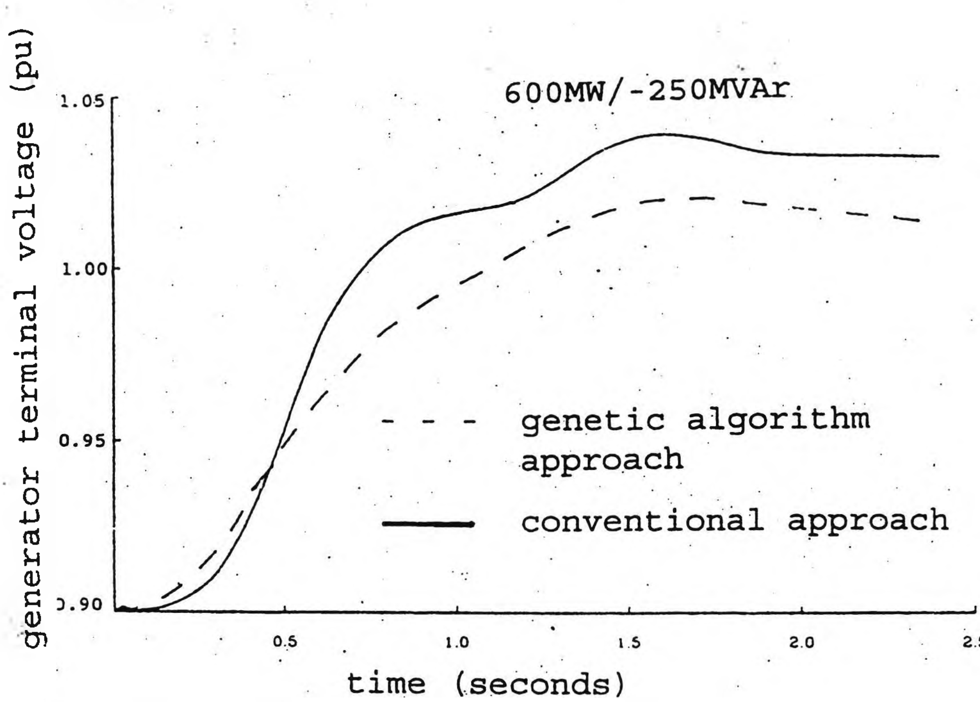

Figure 6.4 Generator terminal voltage variations

6.7 Conclusion

Object oriented techniques and genetic algorithms have been integrated to develop software for the design and simulation of power electronic systems. The application of this software for selecting optimal parameters for generator excitation control is illustrated. Tests carried out show that the method produces better solution than that obtained by using normal genetic algorithm.

Chapter VII

EVOLUTIONARY PROGRAMMING FOR OPTIMAL POWER FLOW

7.1 Introduction

Optimal power flow (OPF) programs have been widely used by electric power industry as a useful tool for power system analysis and operation. Application of evolutionary programming to OPF is illustrated in this chapter. The objective is to minimize the fuel cost and keep a secure system in both the normal and contingent states. Studies are carried out on IEEE 30-bus system for both normal and contingent operation states. Contingent state is simulated by introducing circuit outage in one branch that causes power flow violation in the other branch. In addition to obtaining better results, this method also eliminates operational and insecure violations.

The formulation of the OPF was introduced [103,104,105] more than thirty years ago. OPF has been used to regulate the generator active power outputs and voltages, shunt capacitors/reactors, transformer tap-settings and other controllable variables to minimize the fuel cost, the pollution of the environment and the network active power loss, while keeping the load bus voltages, generator reactive power outputs, network power flows and all other state variables in the power system in their operational and secure limits.

The optimal power flow procedure consists of methods of determining the optimal steady state operation of an electrical power generation-transmission system, which simultaneously minimises the value of a chosen objective function and satisfies certain physical operating constraints. It is a non-linear programming (NLP) problem.

The Optimal Power Flow constraints are the MW generation limits, transformer tap limits, MVA limits on lines and transformers, and bus voltage limits. To control voltage and MVAr, some of the methods, such as, LTC transformer taps, switched capacitors, SVC control setting, load shedding and line switching may be used.

OPF is used to study for problems that require iterative use of conventional power flows. An example of OPF applications could be for Flexible AC Transmission Systems (FACTS) dispatching to overcome voltage violation. The key elements in a robust electricity market are enforcing transmission security, allocating transmission capacity and pricing transmission services. OPF incorporates capabilities of the power flow, for explicit representation of the transmission network, within the formulation of a constrained optimisation problem, to address open access issues.

Conventional calculus-based optimization algorithms have been used in OPF for many years. The conventional optimization methods are based on real and reactive power coupling [106], successive sparse and nonsparse quadratic programming [107], Newton's method [108], interior point method [109,110], constraint method and goal programming [56]. They use successive linearizations and use the first and second derivatives of objective function and its constraint equations as the search directions. The conventional optimization methods usually go to a local minimum. The constraint method has the drawback of requiring the specification of the tolerance parameters associated with the 'soft constraints' that represent the secondary objectives. These parameters are not easy to specify for OPF problems. Goal programming requires the system operator to specify goals for each objectives. The method then tries to obtain an acceptable solution that minimizes the deviation from these goals. However, this approach does not provide the degree of satisfaction for any deviations from the specified goal [56]. Newton's Method is fast on some problems, however, it is poor at handling inequality constraints and has a poor overall reliability. Interior Point method has an excellent convergence reliability, but it is slow for convergence and has difficulties in formulating some constraints.

In most existing OPF algorithms discrete controls are treated as continuous variables until they are approximately optimized. Then they are rounded off to their nearest discrete steps. Linear programming based OPF algorithms [57], in general, permit substantial recognition of control discreteness by setting the cost curve segment break points at discrete control steps. However, most methods that solve for a non-separable objective function by non-linear programming methods do not presently model discrete controls properly. Simply rounding off discrete controls which have large step sizes can cause unnecessary increase in the objective function and/or violations of inequality constraints. This deficiency, which reduce the scope and practical value of OPF, has been recognized, but fully developed and well tested methods for overcoming it have not yet been offered.

The OPF solution is sensitive to the initial starting point for the following reasons:

(a) there are several local minima in the solution region and which one is reached in the solution depends on the initial starting point.

(b) the solution method is unable to reach a true optimal solution. The solution method is unable to reach a true local or global minimum may be due the OPF program used or may be due to an inherent limitation of the chosen solution method.

Recently the use of genetic algorithms to optimal power flow and load flow problems has been reported in [21,111]. This approach has a good chance to search for a global optimal solution. Another similar approach, namely, Evolutionary Programming, has not been explored and it is the purpose of the chapter to report the findings of the work done.

Application of evolutionary programming to Optimal Power Flow (OPF) is presented here. The objective is to minimize the fuel cost and keep a secure system in both the normal and contingent states. Two cases in the IEEE 30-bus system for both normal and contingent operation states have been studied. In contingent state, the circuit outage is simulated in one branch which causes the power flow violation in the other branch. EP always finds better results and eliminates operational and insecure violations.

7.2 Problem formulation

List of Symbols

N_i = set of numbers of buses adjacent to bus i, including bus i
N_{PQ} = set of PQ - bus numbers
N_g = set of generator bus numbers
N_E = set of numbers of total branches
N_T = set of numbers of tap - setting transformer branches
N_B = set of numbers of total buses
N_{B-1} = set of numbers of total buses, excluding slack bus
V_i = voltage magnitude at bus i (pu)
θ_{ij} = voltage angle difference between bus i and bus j (rad)
P_i, Q_i = active and reactive powers injected into network at bus i (pu)
G_{ij}, B_{ij} = mutual conductance and susceptance between bus i and bus j (pu)
G_{ii}, B_{ii} = self conductance and susceptance of bus i (pu)
P_{gi}, Q_{gi} = active and reactive power generations at bus i (pu)
Q_{ci} = reactive power of shunt capacitor / reactor at bus i (pu)
S_k = apparent power flow in branch k (pu)
T_k = tap - setting of transformer branch k (pu)
$N_{VPQ\,lim}$ = set of numbers of PQ - buses at which voltages violate the limits
$N_{Qg\,lim}$ = set of numbers of buses at which reactive power generations violate the limits
$N_{Sk\,lim}$ = set of numbers of branches in which apprent power flows violate the limits

The objective function of OPF is expressed as follows:

$$
\begin{aligned}
& min\, f_p = \sum_{i \in N_g} (a_i + b_i P_{gi} + c_i P_{gi}^2) \\
& s.t.\ 0 = P_i - V_i \sum_{j \in N_i} V_j (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) \quad i \in N_{B-1} \\
& 0 = Q_i - V_i \sum_{j \in N_i} V_j (G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}) \quad i \in N_{PQ} \\
& P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad i \in N_g \\
& Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \quad i \in N_g \\
& Q_{ci}^{min} \le Q_{ci} \le Q_{ci}^{max} \quad i \in N_c \\
& |S_k| \le S_k^{max} \quad k \in N_E \\
& T_k^{min} \le T_k \le T_k^{max} \quad k \in N_T \\
& V_i^{min} \le V_i \le V_i^{max} \quad i \in N_B
\end{aligned}
\tag{7.1}
$$

where power flow equations are used as equality constraints; active and reactive power generation restrictions, shunt capacitor/reactor reactive power restrictions, apparent power flow restrictions in branches, transformer tap-setting restrictions and bus voltage restrictions are used as inequality constraints. The active power generation at the slack bus P_{gs}, load bus voltages V_{load}, reactive power generations Q_g and branch apparent power flows are state variables, which are restricted by adding them as the quadratic penalty terms to the objective function to form a penalty function. Equation (7.1) is therefore changed to the following generalized objective function:

$$
\begin{aligned}
\min f = & \sum_{i \in N_g} (a_i + b_i P_{gi} + c_i P_{gi}^2) \\
& + \lambda_{Pgs}(P_{gs} - P_{gs}^{lim})^2 + \sum_{i \in N_{VPQ\,lim}} \lambda_{Vi}(V_i - V_i^{lim})^2 + \sum_{i \in N_{Qg\,lim}} \lambda_{Qgi}(Q_{gi} - Q_{gi}^{lim})^2 + \sum_{i \in N_{Sk\,lim}} \lambda_{Sk}(|S_k| - S_k^{max})^2 \\
s.t.\ & 0 = P_i - V_i \sum_{j \in N_i} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \quad i \in N_{B-1} \\
& 0 = Q_i - V_i \sum_{j \in N_i} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \quad i \in N_{PQ} \\
& P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \qquad i \in N_g,\ i \ne s \\
& Q_{ci}^{min} \le Q_{ci} \le Q_{ci}^{max} \qquad i \in N_c \\
& T_k^{min} \le T_k \le T_k^{max} \qquad k \in N_T \\
& V_i^{min} \le V_i \le V_i^{max} \qquad i \in N_g
\end{aligned}
\tag{7.2}
$$

where s is the number of slack bus; λ_{Pgs}, λ_{Vi}, λ_{Qgi} and λ_{Sk} are the penalty factors which can be increased heuristically in the optimization procedure; the inequities are only control variable constraints so they are self-restricted; $P_{gs}{}^{lim}$, $V_i{}^{lim}$ and $Q_{gi}{}^{lim}$ are defined in the following equations:

$$
\begin{aligned}
P_{gs}^{lim} &= \begin{cases} P_{gs}^{min} & \text{if } P_{gs} < P_{gs}^{min} \\ P_{gs}^{max} & \text{if } P_{gs} > P_{gs}^{max} \end{cases} \\
V_i^{lim} &= \begin{cases} V_i^{min} & \text{if } V_i < V_i^{min} \\ V_i^{max} & \text{if } V_i > V_i^{max} \end{cases} \\
Q_{gi}^{lim} &= \begin{cases} Q_{gi}^{min} & \text{if } Q_{gi} < Q_{gi}^{min} \\ Q_{gi}^{max} & \text{if } Q_{gi} > Q_{gi}^{max} \end{cases}
\end{aligned}
\tag{7.3}
$$

It can be seen that the generalized objective function f is a non-linear and non-continuous function. Gradient-based conventional methods are not good enough to solve this problem.

7.3 Evolutionary Programming

Evolutionary Programming (EP) is different from conventional optimisation methods. It does not need to differentiate cost function and constraints. It uses probability transition rules to select generations. Each individual competes with some other individuals in a combined population of the old generation and the mutated old generation. The competition results are valued using a probabilistic rule. The winners of the same number as the individuals in the old generation constitute the next generation.

The procedure of EP for OPF is described as follows:

Initialization: The initial control variable population is selected by randomly selecting $p_i = [V_g^i, P_g^i, T^i]$, $i = 1, 2, \ldots, m$, where m is the population size, from the sets of uniform distribution ranging over $[V^{min}, V^{max}]$, $[P^{min}, P^{max}]$, and $[T^{min}, T^{max}]$. The fitness score f_i of each p_i is obtained by running P-Q decoupled power flow.

Statistics: The maximum fitness, minimum fitness, sum of fitnesses and average fitness of this generation are calculated as follows:

$$
\begin{aligned}
f_{max} &= \{ f_i \mid f_i \geq f_j \ \ \forall f_j, j = 1, \ldots, m \} \\
f_{min} &= \{ f_i \mid f_i \leq f_j \ \ \forall f_j, j = 1, \ldots, m \} \\
f_{\Sigma} &= \sum_{i=1}^{m} f_i \\
f_{avg} &= \frac{f_{\Sigma}}{m}
\end{aligned}
\tag{7.4}
$$

Mutation: Each p_i is mutated and assigned to p_{i+m} in accordance with the following equation:

$$p_{i+m,j} = p_{i,j} + N(0, \beta(x_{jmax} - x_{jmin})\frac{f_i}{f_{max}}), \quad j = 1,2,\dots,n \tag{7.5}$$

where, $p_{i,j}$ denotes the *j*th element of the *i*th individual; $N(\mu, \sigma^2)$ represents a Gaussian random variable with mean μ and variance σ^2; f_{max} is the maximum fitness of the old generation which is obtained in **Statistics**; x_{jmax} and x_{jmin} are the maxmum and minimum limits of the *j*th element of the individual; β is the mutation scale which is given as $0 < \beta \leq 1$. If any $p_{i+m,j}$, $j=1, 2, \dots, n$, where n is the number of control variables, exceeds its limit, $p_{i+m,j}$ will be given the limit value. The corresponding fitness f_{i+m} is obtained by running power flow with p_{i+m}. A combined population is formed with the old generation and the mutated old generation.

Competition: Each individual p_i in the combined population has to compete with some other individuals to get its chance to be transcribed to the next generation. A weight value w_i is assigned to the individual according to the competition as follows:

$$w_i = \sum_{t=1}^{q} w_t \tag{7.6}$$

where q is the competition number; w_t is a number of $\{0, 1\}$, which represents win, 1, or loss, 0, as p_i competes with a randomly selected individual p_r in the combined population. w_t is given in the following equation:

$$w_t = \begin{cases} 1 & \text{if } u_1 < \dfrac{f_r}{f_r + f_i} \\ 0 & \text{otherwise} \end{cases} \tag{7.7}$$

where f_r is the fitness of randomly selected individual p_r and f_i is the fitness of p_i; u_1 is randomly selected from a uniform distribution set, $U(0,1)$. When all individuals p_i, $i=1, 2, ..., 2m$, get their competition weights, they will be ranked in descending order of their corresponding value w_i. The first m individuals are transcribed along with their corresponding fitnesses f_i to be the basis of the next generation. The maximum, minimum and average fitness and sum of fitnesses of this generation are then calculated in the **Statistics** process.

Determination: The convergence of maximum fitness to minimum fitness is checked. If the convergence condition is not met, the **Mutation** and **Competition** processes will run again. If it converges, the program will check overlimits of state variables. If there is no overlimit, the program stops. If one or more state variables exceed their limits, the penalty factors of these variables will be increased, and then another loop of the process will start.

To make EP practicable, the following two techniques have been developed [113]:

1. **Adaptive mutation scale:**

   In general, EP mutation probability is fixed throughout the whole search processing. However, in practical applications, a small fixed mutation probability can only result in a premature convergence, while the search with a large fixed mutation probability will not converge. An adaptive mutation scale is given to change the mutation probability to solve the problem as follows:

$$\beta(kk+1) = \begin{cases} \beta(kk) - \beta_{step}, & \text{if } f_{min}(kk) \text{ unchanged} \\ \beta(kk), & \text{if } f_{min}(kk) \text{ decreased} \\ \beta_{final}, & \text{if } \beta(kk) - \beta_{step} < \beta_{final} \end{cases} \tag{7.8}$$

$$\beta(0) = \beta_{init}$$

where k is the generation number; β_{init}, β_{final} and β_{step} are fixed numbers. β_{init} would be around *1* and β_{final} would be *0.005*. β_{step} would be *0.001* to *0.01*, depending on the maximum generation number. The mutation scale will decrease as the process goes on. The decreasing speed of the mutation scale depends on the fitness value, that is, the lower the fitness value is, the faster the mutation scale decreases. Such an adaptive mutation scale not only prevents the premature convergence but also produces a smooth convergence.

2. Relative fitness values:

In practical problems, the fitness value of one individual does not have a significant difference from the others, the difference between the minimum point and the original operating point is small. In deterministic transition rules, there may be no problem arising from this situation. However, in probabilistic transition rules, such small difference will sink into oblivion because of added uncertainties, e.g. u_1 in EP. To deal with the problem, the program trims the fitness value and the maximum fitness value that are used in the mutation and competition procedure. The method is illustrated in equation 7.9.

$$\begin{aligned} f_{proci} &= f_i - \varepsilon f_{min} \qquad i = 1, 2, \ldots, m \\ f_{proc\,max} &= f_{max} - \varepsilon f_{min} \end{aligned} \tag{7.9}$$

where $0.95 \leq \varepsilon < 1$, so f_{proci} and $f_{procmax}$ will be always larger than 0. Only the relative fitness values are used in the process of mutation and competition. The relative values are quite distinct among the fitness values so the better individuals become more competitive. It is the only way for EP to be practicable in real-life systems.

7.4 Numerical results

In this section, IEEE 30-bus system has been used to show the effectiveness of the algorithm. The system is shown in Fig7.1 and the network parameters of the system are given by [114]. The network consists of 6 generator-buses, 21 load-buses and 41 branches, of which 4 branches, *(6,9)*, *(6,10)*, *(4,12)* and *(28,27)*, are under-load-tap-setting transformer branches. Buses *10, 12, 15, 17, 20, 21, 23, 24* and *29* have been selected in [114] as shunt capacitor/reactor compensation buses.

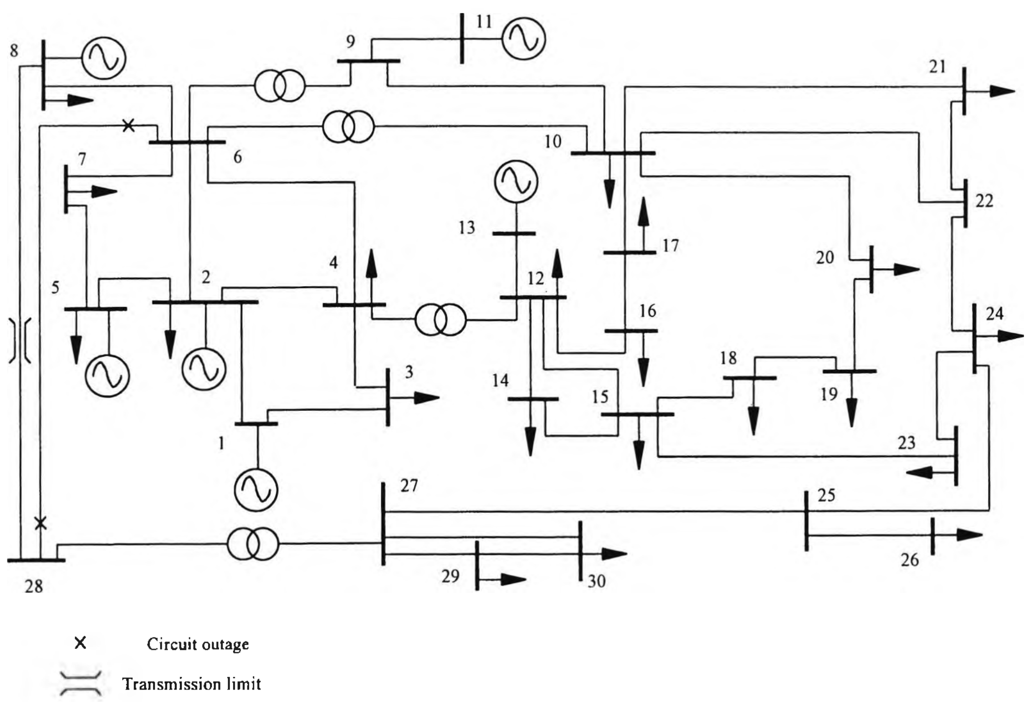

Figure 7.1 IEEE 30-bus system

Two cases are studied. One is the normal operation case and the other is the contingent case, in which a circuit outage is simulated in Branch *(6,28)* and thus causing the power flow violation in Branch *(8,28)*. The variable limits and generator cost parameters are listed in Table 7.1. The initial active power generations, voltages and transformer taps are given in Table 7.2.

The initial fuel costs and the state variable violations are given in Table 7.3. The optimal results are given in Tables 7.4. All power and voltage quantities are in per-unit values. The base power is *100 MVA*.

Table 7.1 Variable limits and generator cost parameters

Power Generation Limits and Fuel Cost Parameters (S_B=100 MVA)						
Bus	*1*	*2*	*5*	*8*	*11*	*13*
P_g^{max}	2	0.8	0.5	0.35	0.3	0.4
P_g^{min}	0.5	0.2	0.15	0.1	0.1	0.12
Q_g^{max}	2	1	0.8	0.6	0.5	0.6
Q_g^{min}	-0.2	-0.2	-0.15	-0.15	-0.1	-0.15
a	0	0	0	0	0	0
b	200	175	100	325	300	300
c	37.5	175	625	83.4	250	250

Bus Voltage Limits				*Branch Apparent Power Limit S_k^{max}*
V_g^{max}	V_g^{min}	V_{load}^{max}	V_{load}^{min}	*Branch (8,28)*
1.1	0.95	1.05	0.95	0.12

Transformer Tap Setting Limits				
Branch	*(6,9)*	*(6,10)*	*(4,12)*	*(28,27)*
T_k^{max}	1.1	1.1	1.1	1.1
T_k^{min}	0.9	0.9	0.9	0.9

Capacitor / Reactor Installation Limits									
Bus	*10*	*12*	*15*	*17*	*20*	*21*	*23*	*24*	*29*
Q_c^{max}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Q_c^{min}	0	0	0	0	0	0	0	0	0

Table 7.2 Initial active power generations, fuel costs, generator voltages and transformer taps

	Active Power Generations						*Fuel Cost ($/hr)*
Bus	*1*	*2*	*5*	*8*	*11*	*13*	
Case 1	*0.99655*	*0.8*	*0.5*	*0.2*	*0.2*	*0.2*	*903.137*
Case 2	*0.99948*	*0.8*	*0.5*	*0.2*	*0.2*	*0.2*	*903.942*
	Generator Bus Voltages						
Bus	*1*	*2*	*5*	*8*	*11*	*13*	
Case 1	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	
Case 2	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	
	Transformer Tap Settings						
Branch	*(6,9)*	*(6,10)*	*(4,12)*	*(28,27)*			
Case 1	*1.0*	*1.0*	*1.0*	*1.0*			
Case 2	*1.0*	*1.0*	*1.0*	*1.0*			

Table 7.3 The state variable violations

	Load Bus Voltage Violations													
Bus	*15*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*29*	*30*
Case 1	*0.949*	*0.947*	*0.937*	*0.933*	*0.937*	*0.938*	*0.939*	*0.935*	*0.926*	*0.933*	*0.914*	*0.948*	*0.926*	*0.914*
Case 2	*0.949*	*0.947*	*0.937*	*0.933*	*0.937*	*0.938*	*0.938*	*0.934*	*0.923*	*0.926*	*0.906*	*0.937*	*0.915*	*0.902*

Reactive Power Generator Violation	*Bus*	*8*	*Branch Apparent Power Flow Violation*	*Branch*	*(8,28)*
	Case 1	*0.734*		Case 1	
	Case 2	*0.764*		Case 2	*0.179*

Table 7.4 Optimal active power generations, fuel costs, generator voltages, transformer taps and shunt capacitor/reactor compensations

Active Power Generations and Fuel Costs							*Fuel Cost ($/hr)*
Bus	*1*	*2*	*5*	*8*	*11*	*13*	
Case 1	*1.77644*	*0.49108*	*0.21090*	*0.20325*	*0.12327*	*0.12000*	*800.540*
Case 2	*1.75509*	*0.48499*	*0.20634*	*0.10052*	*0.16821*	*0.21593*	*807.296*

Generator Bus Voltages						
Bus	*1*	*2*	*5*	*8*	*11*	*13*
Case 1	*1.086*	*1.068*	*1.034*	*1.041*	*1.10*	*1.068*
Case 2	*1.085*	*1.066*	*1.036*	*1.052*	*1.084*	*1.034*

Transformer Tap Settings				
Branch	*(6,9)*	*(6,10)*	*(4,12)*	*(28,27)*
Case 1	*1.0*	*0.975*	*0.95*	*1.0*
Case 2	*0.975*	*1.1*	*1.05*	*0.925*

Shunt Capacitor/Reactor Compensations									
Bus	*10*	*12*	*15*	*17*	*20*	*21*	*23*	*24*	*29*
Case 1	*0.002*	*0.008*	*0.024*	*0.016*	*0.008*	*0.017*	*0.049*	*0.05*	*0.026*
Case 2	*0.043*	*0.017*	*0.048*	*0.023*	*0.048*	*0.044*	*0.045*	*0.040*	*0.024*

The fuel cost savings are given as follows:

Case 1: $Saving\% = \frac{903.137 - 800.54}{903.137} \times 100 = 11.36\%$

Case 2: $Saving\% = \frac{903.942 - 807.296}{903.942} \times 100 = 10.70\%$

The savings are quite attractive. All violations are eliminated. In Case 2, the apparent power flow in Branch *(8,28)* is regulated back to *0.11927 pu*. If the power flow limit is released, the optimal fuel cost will be *800.854 ($/hr)* in Case 2 and the apparent power flow of Branch *(8,28)* will be *0.1690 pu.*

7.5 Conclusion

Application of evolutionary programming to Optimal Power Flow is presented in this chapter. It has been shown that the method using EP is superior to the steepest descent method when the generator cost characteristics are highly non-linear.

Chapter VIII

OBJECT-ORIENTED ARTIFICIAL NEURAL NETWORKS AND GENETIC ALGORITHM FOR ELECTRIC LOAD FORECASTING

8.1 Introduction

This chapter illustrates the use of an integrated Computational Intelligence (CI) technique using Artificial Neural Networks (ANN) and Genetic Algorithm (GA) for Electric Load Forecasting. A load forecasting model has been developed using ANN and GA. The model produces a short-term forecast of the load in the 24 hours of the forecast day concerned. The Genetic Algorithm finds best learning rate and the best momentum for training the weights and the threshold of ANN. The learning rate and the momentum so found are used to modify the weights. The technique has been tested on data provided by an Italian power company and the promising results obtained through the application of integrated computational intelligence approach show that the approach is very effective in that it gives accurate predictions. However, because the problem is very complex, it takes a much longer time to obtain a comparable solution. This points in the direction of evolutionary computing being integrated with parallel processing techniques to solve practical problems

An accurate and stable load forecast is essential for many operating decisions taken by utilities. In fact, it is well known that a cheap and reliable power system operation is definitely the result of good short-term load forecasting. The short-term load forecast provides the information to be adopted in the on-line scheduling and security functions of the energy management system, such as unit commitment, economic dispatch and load management. Hence, accurate load forecasting is essential for the optimal planning and operation of large-scale power systems.

Many techniques have been proposed and used for short-term load forecasting. Time-series models based on extrapolation are used for the representation of load behaviour by trend curves. The time series approach, regression approach, state-space models, pattern recognition and expert systems are also some of the other techniques used [26-29]. The time series approach assumes that the load of a time depends mainly on previous load patterns, such as the auto-regressive moving average models and the spectral expansion technique [27]. The regression method utilises the tendency that the load pattern has a strong correlation to the weather pattern. The weather-sensitive portion of the load is arbitrarily extracted and modelled by a pre-determined functional relationship with weather variables.

All the above approaches use a large number of complex equations that involve much computational time. More recently, several researchers have used artificial neural network (ANN) techniques [115-122]. These techniques have poor convergence during training. Therefore, a new technique using integrated Computer Intelligence (CI) has been implemented to enhance the robustness of neural networks for forecasting in a distributed environment. Object Oriented programming (OOP) technique is used to integrate ANN and Genetic Algorithm (GA). GA is used for obtaining the best learning rate and the best momentum for training the weights and the threshold of ANN and for finding the optimum number of hidden layers. If many Neural Networks (NNs) are required, then the inheritance properties could be used to reduce the time to redesign new NNs [121]. A Neural Network can be specified at the highest level in terms of architectures, motivation function, learning and update rules. It is also seen from current literature [122], that EP-ANN has some advantages over the ANN with a (Back propagation (BP) learning approach. E H T Hung et al [123] have proposed an Artificial neural network model trained by a genetic algorithm for short-term load forecasting. They have used the software Genehunter from Ward Systems Group to develop three-layered backpropagation ANN network to forecast one-day ahead hourly loads for weekdays and weekends. They have implemented the model on real load and temperature data and found that the model can forecast with greater accuracy than the traditional statistical model. They have concluded that the results could be improved with more data such as humidity, rain factor, special events, etc, and that the model could be improved by fuzzifying the load inputs. The disadvantage of the model is that it will not be able to detect sudden changes of load due to special events. The Mean Average Percentage Error (MAPE) seems to vary between 1.31 and 2.57.

8.2 Load forecasting with ANNs

Power load demand is sensitive to weather variations, such as temperature, wind speed, relative humidity and cloud cover (sky cover/light intensity). Although the daily load profile depends on such weather variables, only temperature is considered here. There are 58 inputs to the developed model. The features that are taken into account as input factors in the load forecast system are as follows: two 24-hour load records of day i-1 and i-2 (the forecast day is day i). Six more inputs are the maximum and minimum temperatures of day i, i-1 and i-2. Three inputs as a binary code to show seven days of the week. One binary code is dedicated to the holidays or any yearly special occasions that may affect the forecast. The designed NN is of the multilayered preceptron type and is used to learn the relationship between the 58 inputs and 24 outputs.

The inputs are:

Hourly loads for two days prior to the forecast day	24
Hourly loads for the day prior to the forecast day	24
Max. and Min. temps for two days prior to the forecast day	4
Max. and Min. temps for the forecast day	2
Day of the week	3 bits
Holiday	1 bit

The outputs are:

Load forecast for all 24 hours of the day	24

The network architecture is shown in Figure 8.1. The above values are normalised as indicated by Equation 8.1.

$$\text{Normalised} = \frac{\text{Actual Value - Min.}}{\text{Max. - Min.}} \qquad (8.1)$$

where Max. and Min. are the maximum and minimum of the attribute, respectively.

The mean square error (MSE) is used to measure the accuracy of the model. The sigmoid activation function given in Equation 8.2 is adopted.

$$F(x) = \frac{1}{1+\exp(-x)} \qquad (8.2)$$

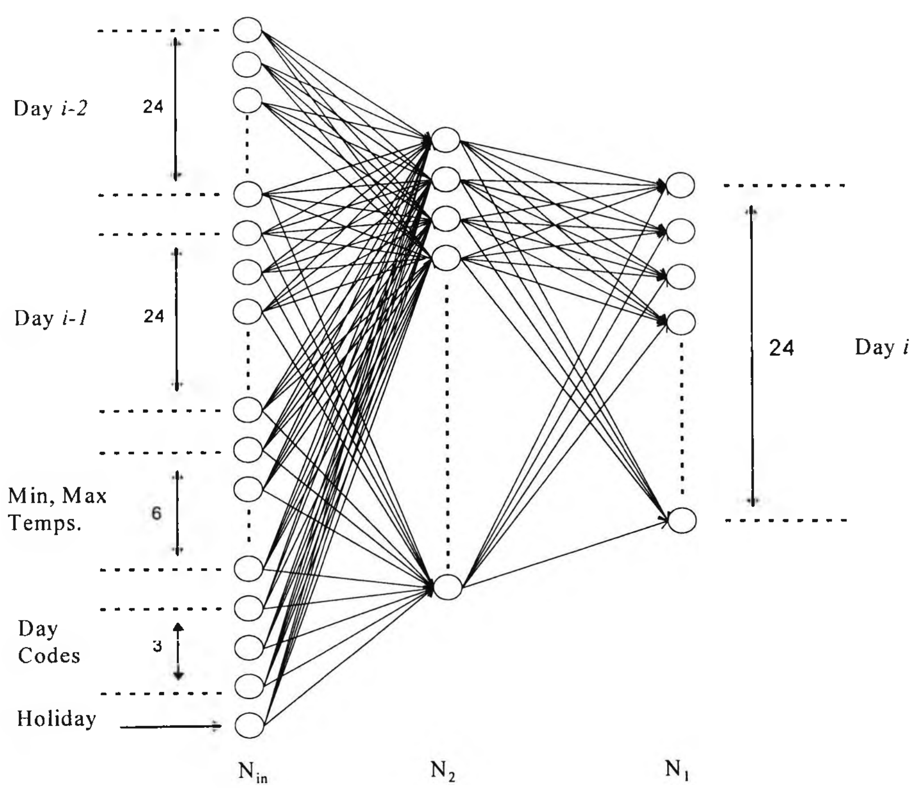

Figure 8.1 Network architecture

The number of neurons in the hidden layer is determined by trial-and-error method using the validation set. This guarantees the proper selection of the number of neurons in the hidden layer. Various neurons have been tested and the MSE error on training, validation and testing has been measured. Lowest error on the validation set is produced with 15 neurons in the hidden layer.

8.3 Data preparation

An Italian Power Company provided the raw data of the load profile for three months. Three sets of data for training, validation and testing were selected using cross-validation technique. Ninety patterns were chosen from the data available by randomly selecting the days. Each pattern represents the load profile for a single day. Random selection of days gives a better pattern for training than sequential selection. Out of these 90 patterns, 83 were used for training and validation and the remaining seven patterns were used to test the neural network. The training set is unseen to the system.

8.4 GA and ANN Hybridisation

There are three levels at which GA search procedures can be introduced to ANNs.

- Connection weights and Biases
- Architectures
- Training algorithms

In this work GA is used to optimise the connection weights and biases of the neural network.

8.4.1 Optimising ANN weights using GA

Supervised training has mostly been formulated as a weight training process, in which effort is made to find an optimal (near optimal) set of connection weights for a network according to some optimality criteria. One of the most popular training algorithms for feed-forward ANNs, back-propagation (BP), is a gradient descent search algorithm, which tries to minimise the total Mean Square Error (MSE) between actual output and target output of an ANN. This error is used to guide BP's search in the weight space. There have been some successful applications of BP algorithms in various areas. However, drawbacks with the BP algorithm do exist due to its gradient descent nature. It often gets trapped in a local minimum of the error function and is very inefficient in searching for a global minimum of a function which is vast, multimodal, and non-differentiable. One way to overcome the short comings of BP and other gradient descent search-based training algorithms' shortcomings, is to consider the training process as the evolution of connection weights towards an optimal (near optimal) set defined by a fitness function and the training task as the environment in which the evolution occurs. From such a point of view, global search procedures like EP or GAs can be used effectively to train an ANN. The fitness of a GA_ANN procedure can be defined by the aforementioned total MSE. The selective pressure in such evolution is against those GAs which are less fit i.e., having large errors.

The GAs' training approach is divided into two major steps:

- the first one is to decide the representation scheme of connection weights, e.g., binary strings.
- the second one is the evolution itself driven by GA.

Different representation schemes and GAs can lead to quite different training performance in terms of training time and accuracy. A typical cycle of the evolution of connection weights with GA is shown in figure 8.2.

The training method adopts the batch training mode. In batch training, node weights are changed only after all training patterns have been presented to the GA_ANN. This is different from most sequential training algorithms, like sequential BP, where weights are updated after each training pattern is presented to the network. The batch training mode is particularly suitable for performing the training in parallel.

When using GA, the most convenient representation is binary, since GA uses binary representation (chromosomes) of the problem parameters and binary operators for combination. The range of each free parameter depends on the problem complexity and the required resolution of the system parameters.

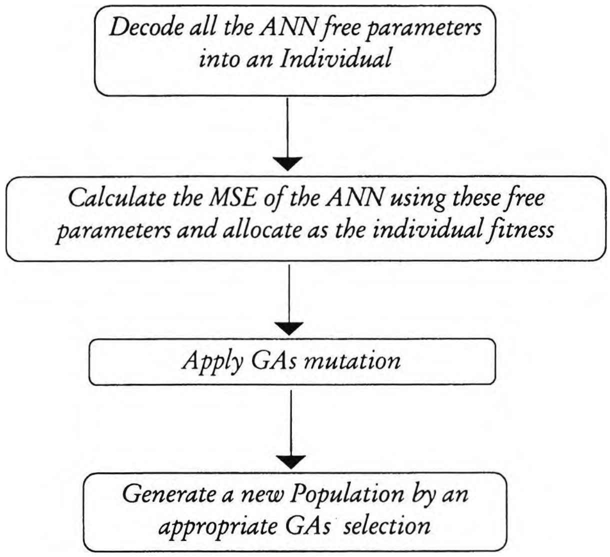

Figure 8.2 A typical cycle of the evolution of connection weights

A key issue here is to decide how much information about an architecture should be encoded into a representation. This includes the number of layers and the number of neurons in each layer. The computational cost increases as more architecture parameters are decoded in GA individuals. There is a trade off between these two factors as the combination differs for different classes of problems.

8.5 Object Oriented GA-ANN

Object Oriented Technique gives us the ability to combine the existing developed objects and create new components. In order to perform this task, a thorough analysis on both objects should be taken including understanding the principles of the hybrid systems, identifying objects which will remain important in the life of the hybrid system and finally identifying the relationships between the different objects and the ways in which the objects interact.

The new hybrid system is obtained by combining the previously designed and developed GA and ANN objects. New membership functions are created in the existing GA and ANN classes to integrate these two objects. Object oriented development paradigm is employed to construct the complete GA-ANN system. The System Dynamic Model is shown in figure 8.3.

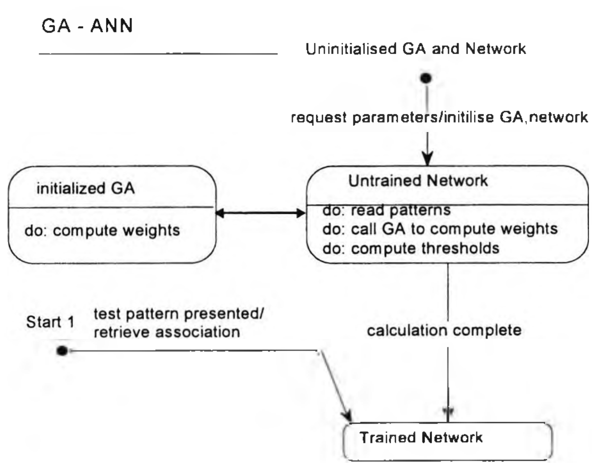

Figure 8.3 The System Dynamic Model

Adaptation of classes in the new environment is performed after analysing the system which includes identifying the object interactions. This task also includes composing the free parameters of ANN including weights and biases, and decoding them into chromosomes. The number of free parameters of ANN is calculated using equations 8.3 and 8.4 to form the chromosomes.

$$n_{free} = \left[(n_{in} \times n_{hid}) + (n_{hid} \times n_{out}) + n_{hid} + n_{out} \right] \tag{8.3}$$

$$S_{free} = n_{free} \times n_{byte} \tag{8.4}$$

n_{in} = *Number of Nodes in Input Layer*

n_{hid} = *Number of Nodes in Hidden Layer*

n_{out} = *Number of Nodes in Output Layer*

n_{byte} = *Number of Bytes each Parameter*

n_{free} = *Number of Free Parameters*

s_{free} = *Size of Free Parameters in Bytes*

Figure 8.4 shows the coding/decoding configuration of ANN parameters into chromosomes.

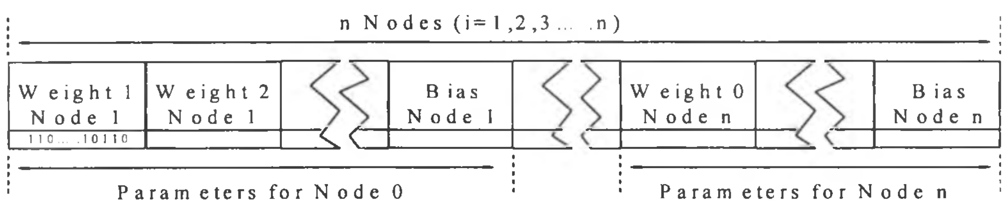

Figure 8.4 The coding/decoding configuration of ANN parameters

Other parameters such as architecture and training algorithms can be added to the chromosomes as an extension. The interaction between ANN and GA objects is performed by message passing. Both ANN and GA instances are created at the beginning of the optimization procedure and last until the end. The GA object makes calls to ANN object and passes messages to fitness function. The optimisation is processed to find the near optimum global solution for each applied problem. Since GA_ANNs are highly application dependent, the system is tested on two power systems applications as explained in the following sections.

8.6 Simulation results

Following system parameters were used after a number of tests on the system and are proven to be the best.

- Population Size = **150**
- ANN Free Parameters = **1269**
- Bits each Parameter = **15 (2 Bytes)**
- Size of Each Chromosome = **1538 Bytes**
- Mutation = **0.1**
- Crossover = **0.80**

The fast Back-propagation method was also used to train another ANN which is then used as a reference to make a comparison between the two algorithms. The training Mean Square Error (MSE) of the training processes of both BP and GA-ANN for the first 100 generations is shown in figure in figure 8.5.

From figure 8.5 it can be seen that BP converges much faster than GA, meaning that an optimum ANN is found in less generations (or iterations for BP). However, the optimised ANN using BP, under test, is not as good as the optimised ANN using GA/BP. In general, the GA-ANN system has more computational time for each iteration than BP, but for this specific application, the computational time was higher than BP because of the size of the ANN. The GA-ANN system shows improvement over the BP and presents the best solution to this problem. Figure 8.6 shows the GA_ANN forecast results and the actual data. The data pattern used here is about 20% smaller than the one used in [121] in order to test the GA/ANN capability.

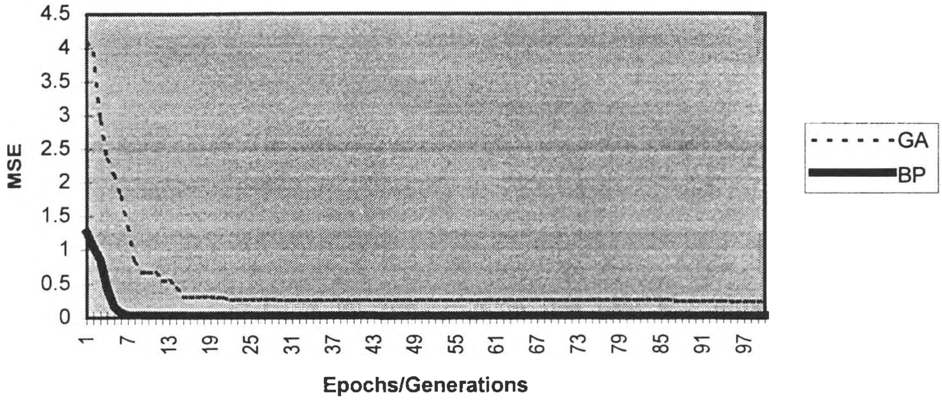

Figure 8.5 Comparison between GA_ANN and ANN (BP) for load forecasting problem

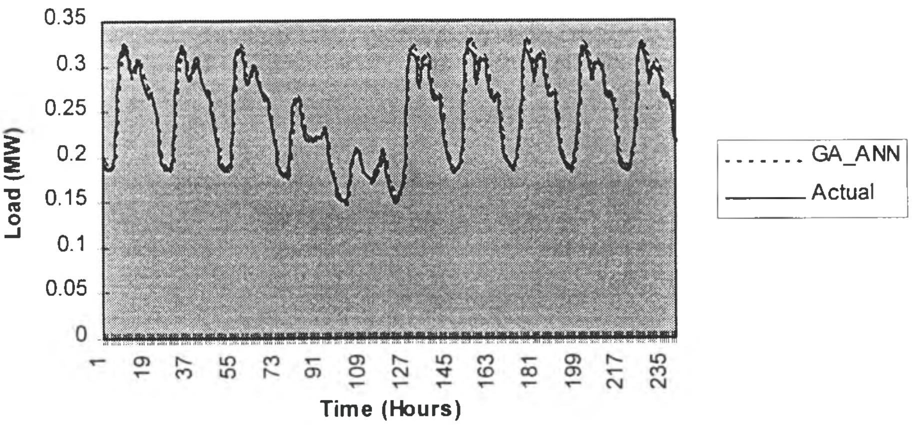

Figure 8.6 GA_ANN forecast results

8.7 Comparison between ANN and GA-ANN

The main question is whether GA_ANN is more efficient than conjugate gradient (e.g. BP) methods. It is found that GA_ANN gives better solutions for problems with a small number of parameters; but for systems with large number of problem parameters, it becomes impractical as it increases the computational time and hence higher computational cost. Initial ANN parameters for the load forecasting problem were obtained from GA and finally the GA_ANN results (weights and biases) were fine tuned using BP because of the longer computational time and the inadequate computer hardware to complete the training using GA_ANN. If powerful computer facilities are available the EANN are generally the preferred methods for creating ANNs by means of optimising ANN weights, biases, architecture and training method. Parallel GA_ANN is one way to reduce training time. If adequate hardware is not available, combination of GA_ANN and BP can be used to obtain an optimum solution where initial training is done using GA and then fine tuning the results by BP. This approach moves the final results towards a global solution.

The OO methodology was a very useful framework in the development of GA_ANN as it reduced the development time. The developed OO models of all algorithms gave this flexibility to upgrade and maintain the software constantly and form different configurations.

8.8 Conclusion

A short-term load forecasting model that is capable of accurately forecasting the load profile for a 24-hour period has been developed using Artificial Neural Network and Genetic Algorithm. The Genetic Algorithm is used to find the best learning rate and the best momentum for training the weights and the neural network's threshold. As the problem is very complex, the time taken for a reasonable solution is longer.

Chapter IX

TRANSMISSION LOSS AND LINE FLOW FORMULATIONS

9.1 Introduction

Transmission loss (P_L) formulation in a power system through B coefficients or through generalised loss formulation is well known. Such formulations, however, are based on several assumptions, are quite involved and time consuming and hence are unsuitable for real time application. The use of B coefficients appears to be still popular with many utilities for economic load dispatch (ELD). It is well known that such B coefficients are inexact and hence cannot provide best economy in the cost of generation for ELD. Further, these coefficients are far from robust and need to be re-evaluated for changes in the system operating conditions so as to achieve better economy in the system

In the past [124] A coefficients have been used to formulate P_L which are evaluated from a load flow solution but the algorithm involved a matrix inversion the size of which increases with the increase in the number of plants in the system. Moreover, the effectiveness and robustness of such A coefficients for loss evaluation and ELD solution have not been totally explored or reported in any journal.

Generalised generation distribution factors (GGDF) as developed by W.Y. Ng [125] can be used to formulate line flows as functions of power generations to check line flow limits in ELD solution, but such distribution factors are based on several unrealistic assumptions as critically discussed by Nanda et al [124]. Nanda et al [126] have used a set of distribution factors [DFs] which are devoid of such assumptions as these are evaluated from a load flow solution. They have absorbed that such distribution factors are quite effective but are not robust and hence need to be re-evaluated with changes in the system operating conditions. However, the evaluation of such DFs again involved the inversion of a matrix whose size increases with the increase in the number of generating plants.

The main thrust in this method is to explore the feasibility of computationally more efficient algorithms for formulating P_L and line flows through a set of loss coefficients and distribution factors which are quite exact and can be very efficiently realised with trivial computational burden so as to be uniquely suitable for real time applications for optimisation studies, like ELD and optimal power flow etc.

9.2 Transmission loss formulation

The transmission loss P_L is expressed as a quadratic function of plant generations through a set of A coefficients as

$$P_L = \left[\sum_{i=1}^{n} A_i P_i \right]^2 \tag{9.1}$$

where n = total number of generating plants in the system P_i = generation at plant i.

With B coefficient P_L is expressed as:

$$P_L = \sum_m \sum_n P_m B_{mn} P_n \tag{9.2}$$

where m = n = number of generating plants.

Comparing Equations 9.1 and 9.2 it can be seen that the two formulations have close similarity. The self coefficients in B (like B_{11}, B_{22} etc) reflect the square of the self coefficients in A (like A_1^2, A_2^2 etc) and the mutual coefficients in B (like B_{12}, B_{23} etc) reflect the products of the self coefficients in A (like A_1A_2, A_2A_3 etc). It may be seen that when P_L is expressed through A coefficients as in Equation (9.1) only n numbers of A coefficients need to be evaluated unlike n(n+1)/2 number of B coefficients when P_L is expressed by Equation 9.2. This n number of A coefficients can be evaluated in an innovative manner with trivial computational burden from the hidden treasures of an available load flow solution in the computer memory by taking advantage of the sensitivity matrix and using a prudent perturbation technique. No inversion of any matrix is encountered at any stage for evaluating the A coefficients.

This is explained briefly below:

Let n be the total number of buses in the system and bus 1 is the swing or slack bus. From the based load flow (BLF) solution the transmission loss $P_L^{(0)}$ and $P_i^{(0)}$ (for i = 1, 2,..., n) are all known. Thus from Equation 9.1 we can write:

$$\sqrt{P_L^{(0)}} = A_1 P_1^{(0)} + A_2 P_2^{(0)} + \ldots + A_r P_r^{(0)} + \ldots + A_n P_n^{(0)} \qquad (9.3)$$

Superscript (o) refers to the base load flow conditions. To evaluate all the 'n' number of A_i (for i = 1,..., n) loss coefficients we need another (n-1) number of equations similar to Equation 9.2. These additional equations are obtained through a perturbation technique from available BLF information as follows:

For a known small perturbation $\Delta P^{(r)}$ at the rth plant bus (perturbation considered one at a time for r = 2,..., n) and keeping P, Q, and P, |V| conditions fixed at all other buses except the slack bus 1, let the change in system loss be $\Delta P_L^{(r)}$ change in slack bus active and reactive power be $\Delta P_1^{(r)}$ and $\Delta Q_1^{(r)}$ and change in voltage vector profile $[\Delta V^{(r)}]$. Superscript (r) refers to perturbation at the rth plant bus. Thus we have

$$\Delta P_L^{(r)} = \Delta P_1^{(r)} + \Delta P^{(r)} \text{ and } P_L^{(r)} = P_L^{(0)} + \Delta P_L^{(r)}$$

$$\sqrt{\Delta P_L^{(r)}} = A_1 (P_1^{(0)} + \Delta P_1^{(r)}) + A_2 P_2^{(0)} + \ldots + A_r (P_r^{(0)} + \Delta P^{(r)}) + \ldots + A_n P_n^{(0)} \qquad (9.4)$$

$r = 2, \ldots, n$

It can be seen that the n number of A coefficients in A_1 to A_n can be solved from the n number of equations given by equations 9.3 and 9.4, if only $\Delta P_1^{(r)}$ can be evaluated for r = 2, 3, .., n. Once $\Delta P_1^{(r)}$ is known, the As are evaluated by inverting an (nxn) matrix of the form

$$
\begin{bmatrix}
P_1^{(0)} & P_2^{(0)} & P_3^{(0)} & \cdots & P_r^{(0)} & \cdots & P_n^{(0)} \\
(P_1^{(0)} + \Delta P_1^{(2)}) & (P_2^{(0)} + \Delta P^{(2)}) & P_3^{(0)} & \cdots & P_r^{(0)} & \cdots & P_n^{(0)} \\
\vdots & \vdots & \vdots & & \vdots & & \vdots \\
\left(P_1^{(0)} + \Delta P_1^{(r)}\right) & P_2^{(0)} & P_3^{(0)} & \cdots & \left(P_r^{(0)} + \Delta P^{(r)}\right) & \cdots & P_n^{(0)} \\
\vdots & & & & & & \\
\left(P_1^{(0)} + \Delta P_1^{(r)}\right) & P_2^{(0)} & P_3^{(0)} & \cdots & P_r^{(0)} & & \left(P_n^{(0)} + \Delta P^{(n)}\right)
\end{bmatrix}
$$

(A)

Such a matrix inversion has been adopted by Nanda et. al. in [124]. However, this matrix inversion can be avoided for computing the A coefficients by the following procedure. Subtracting Equation (9.3) from (9.4) we get

$$
\sqrt{P_L^{(0)} + \Delta P_1^{(r)} + \Delta P^{(r)}} - \sqrt{P_L^{(0)}} = A_1 \, \Delta P_1^{(r)} + A_r \Delta P^{(r)} \quad \text{for r } = 2, \ldots, \text{n} \tag{9.5}
$$

Examining Equation (9.5) it is seen that since ΔP (r) (for r=2, .., n) is a known small perturbation, A_r (for r=2,.., n) can all be expressed in terms of A_1 if only the change in the slack bus power $\Delta P_1^{(r)}$ (for r=2,..,n) can be determined for corresponding perturbations at the plant buses (r=2, ..,n) considered one at a time. Once all A_r (for r=2,...,n) are expressed in terms of A_1, these are substituted in Equation (9.3) to evaluate A_1 and hence all A_r are evaluated. It shall be demonstrated that the evaluation of change in slack bus power $\Delta P_1^{(r)}$ due to perturbation at the rth plant bus requires trivial computational burden and hence the generation of A_r coefficients is extremely fast. A brief explanation for the evaluation of $\Delta P_1^{(r)}$ is provided below.

In the last iteration of BLF solution using Newton-Raphson technique in rectangular coordinates, when the two column vectors have approached zero, for a small known perturbation $\Delta P^{(r)}$ at rth plant bus and keeping P, Q and P, $|V|$ conditions same at all buses except at slack we can write:

$$\left[\Delta P_1^{(r)} \ldots \Delta P^{(r)} \ldots \Delta Q_1^{(r)} \ldots 0\right]^T_{(2N\times1)} =$$

$$[J^*]_{(2N\times2N)}\left[\Delta e_1^{(r)} \Delta e_2^{(r)} \ldots \Delta e_r^{(r)} \ldots. \Delta e_N^{(r)}\ \Delta f_2^{(r)} \ldots. \Delta f_r^{(r)} \ldots \Delta f_N^{(r)}\right]^T_{(2N\times1)} \tag{9.6}$$

where [J*] of (2Nx2N) dimension is completely known from BLF. Δe^s and Δf^s are the changes in the real and imaginary parts of the voltages. Since bus 1 is slack, Equation (9.6) can be written as:

$$\left[0 \ldots \Delta P^{(r)} \ldots 0\right]^T_{(2N-2)x1} = [J]\left[\Delta e_2^{(r)} \ldots. \Delta e_r^{(r)} \ldots \Delta e_N^{(r)} \ldots \Delta f_2^{(r)} \ldots. \Delta f_N^{(r)}\right]^T_{(2N-2)x1} \tag{9.7}$$

for r = 2, ..., N

[J] of (2N-2 x 2N-2) is the usual Jacobian encountered in Newton-Raphson load flow solution method. Equation (9.4) can be expressed in the compact form as:

$$\left[\Delta V^{(r)}\right] = [J]^{-1}[\Delta s] \tag{9.8}$$

where $\left[\Delta V^{(r)}\right] = \left[\Delta e_2^{(r)} \ldots\ \Delta e_N^{(r)}\ \Delta f_2^{(r)}\ \Delta f_N^{(r)}\right]$ is the change in the voltage profile due to a change of $\Delta P^{(r)}$ at the rth bus as:

$$[\Delta s] = \left[0 \ldots\ \Delta P^{(r)} \ldots 0\right]$$

Computation of $\left[\Delta V^{(r)}\right]$ from Equation (9.8) is trivial, as $[J]^{-1}$ is already available from BLF solution and there is only one non-zero element in $[\Delta s]$ which is the known perturbation $\Delta P^{(r)}$ at the rth plant bus and hence only elements of the corresponding column of $[J]^{-1}$ need to be multiplied by $\Delta P^{(r)}$ to obtain the elements of $\left[\Delta V^{(r)}\right]$. Knowing $\left[\Delta V^{(r)}\right]$ the change in slack bus power at bus 1 can be easily computed as:

$$\Delta P_1^{(r)} = \frac{\partial P_1}{\partial e_2} \Delta e_2^{(r)} + \ldots + \frac{\partial P_1}{\partial e_N} \Delta e_N^{(r)} + \frac{\partial P_1}{\partial f_2} \Delta f_2^{(r)} + \ldots + \frac{\partial P_1}{\partial f_N} \Delta f_N^{(r)} \tag{9.9}$$

(r = 2, .., n)

Note that the derivatives of the $\frac{\partial P_1}{\partial e}$ and $\frac{\partial P_1}{\partial f}$ in Equation (9.9) are all known from the elements of J* of the available BLF solution. No matrix inversion at any stage is encountered in evaluating the A coefficients.

9.3 Line flow formulation through distribution factors

The line flows can be expressed [126] through distribution factors (DF) in the form

$$I_i = \sum_{j=1}^{n} (DF_{ij} P_j) \quad i = 1, 2, .., NL \tag{9.10}$$

where n = total number of generating plants

P_j = generation of the jth plant

NL = Total number of lines

I_i = Current in the ith line

For each line there will be n number of DFs and hence total number of DFs for the system is (NLxn).

The line flows can be expressed in terms of the voltages and line admittance as

$$I_i = (V_j < \delta_j - V_k < \delta_k) Y_{ser} \quad i = 1, 2, \ldots, NL. \tag{9.11}$$

where Y_{ser} is the series admittance of the ith line connected between buses j and k.

Consider buses 1 to n have plants and bus 1 as the slack. From the base load flow (BLF) solution we know I_i^b, $P_1^{(0)}$, $P_2^{(0)}$, ..., $P_n^{(0)}$. Thus, we can write

$$I_i^{(0)} = DF_{i1} P_1^{(0)} + DF_{i2} P_2^{(0)} + \ldots + DF_{ir} P_r^{(0)} + \ldots + DF_{in} P_n^{(0)} \quad i = 1, 2, .., NL \tag{9.12}$$

The n number of Distribution Factor (DFs) for each line and hence n x NL number of total distribution factors for the system can be found out most elegantly with trivial

computational time while concurrently evaluating the A coefficients. No inversion of any matrix at any stage is encountered while evaluating the DFs.
This is clearly explained below.

In order to evaluate the n number of DFs for the ith line in Equation (9.12) we need another (n-1) number of similar equations which can be duly obtained by perturbing the active power generation at each plant bus one at a time by n small amount and keeping the P,Q and P,|V| conditions same at all other buses except at the slack. These (n-1) equations can be written in the form:

$$I_i^{(r)} = \mathrm{DF}_{i1}\left(P_1^{(0)} + \Delta P_1^{(r)}\right) + DF_{i2}\, P_2^{(0)} + \ldots + \mathrm{DF}_{ir}\left(P_r^{(0)} + \Delta P^{(r)}\right) + \ldots + \mathrm{DF}_{in}\, P_n^{(0)} \qquad i = 2, 3, .., n \tag{9.13}$$

where 1 is the slack bus and $\Delta\ P_1^{(r)}$ is the change in the slack bus power due to small known perturbation $\Delta P^{(r)}$ at the rth plant bus. For each small perturbation (r=2, 3, .., n) considered one at a time, the change in the voltage profile $\Delta V^{(r)}$ and hence $\Delta P_1^{(r)}$ have already been evaluated with trivial computational burden from Equations 9.8 and 9.9 while evaluating the A coefficients. Since $\Delta V^{(r)}$ is known, the new voltage profile $V^{(r)}$ is computed and hence the new line currents $I_i^{(r)}$ (i = 1, 2, .., NL) for perturbations at the buses (r = 2, 3, .., n) are all computed from Equation 9.11 with trivial computational time. Subtracting Equation 9.12 from Equation 9.13 we get

$$\left(I_i^{(r)} - \mathrm{I}_i^{(0)}\right) = \mathrm{DF}_{i1} \cdot \Delta P_1^{(r)} + \mathrm{DF}_{ir}\, \Delta P^{(r)} \tag{9.14}$$

for r = 2, 3, ..., m & i = 1, 2, .., NL.

Thus DF_{ir} (r = 2, 3,..,n) can all be expressed in terms of DF_{i1} since all other quantities in Equation 9.12 are known in Equation 9.14. These are substituted in Equation 9.12 and hence DF_{i1} is evaluated. Once DF_{i1} is known, all other DF_{ir} are computed from Equation 9.14.

It is of interest to observe that both A coefficients and the DFs can be concurrently evaluated since most of the major computations like $\Delta V^{(r)}$ and $\Delta P_1^{(r)}$ (r = 2, 3, ...n) are common for both. It is therefore quite obvious that the evaluation of distribution factors also takes trivial computational time.

It may be mentioned here that Nanda et. al [126] have used such DFs but their algorithm involved the inversion of a matrix of the form given in (A) whose size increases with the increase in the number of generating plants in the system. Their studies reveal that line flows evaluated by such DFs are quite effective for ELD but these DFs are not robust and need to be re-evaluated for changes in the operating conditions. The main intention of providing a computationally more efficient algorithm for line flows evaluation has been fulfilled in the present work.

9.4 Economic Load Dispatch

In this section ELD algorithm is briefly discussed using classical co-ordination equations

The objective is to minimize the total cost of generation $F = \sum_{i=1}^{n} F_i$ subject to

$$\left(\sum_{i=1}^{n} PG_i\right) - P_L - P_D = 0 \text{ and}$$

$$PG_i^{min} \leq PG_i \leq PG_i^{max} \text{ and } I_i \leq I_i^{max} \quad (i = 1, ..., NL)$$

corresponding to line flow constraints where n = total number of plants, P_L is the total system loss, P_D is the total system load demand and NL is the total number of lines. Using the method of Lagrangian multiplier, the new objective function ψ can be obtained as:

$$\psi = F - \lambda\left[\left(\sum_{i=1}^{n} PG_i\right) - P_L \ P_D\right] \tag{9.15}$$

λ is the Lagrangian multiplier. For minimum F, the co-ordination equations are given as

$$\frac{dF_i}{dPG_i} + \lambda \frac{\partial PL}{\partial PG_i} = \lambda, \qquad i = 1, 2, ..., n \qquad (9.16)$$

The solution of equation 9.10 gives optimum active power generations (PGs) and is dependent on the prudent selection of λ while satisfying the system constrains

Gauss-Seidel technique is used for solving Equation 9.16 which after substituting $P_L = (\Sigma A_i P_i)^2$ in Equation 9.10 reduces to the form

$$PG_i^{K+1} = \frac{\lambda - b_i 2\lambda A_i \sum_{\substack{j=1 \\ j\neq i}}^{NG} (A_j PG_j^K)}{(a_i + 2\lambda A_i^2)}, \qquad i = 1, ..., NG \qquad (9.17)$$

where K = number of iterations, a_i and b_i are fuel cost coefficients for the i[th] generating plant and As are loss coefficients. Equation 9.17 is solved by Gauss-Seidel technique and the inequality constraints in generations and line flows are handled very effectively as discussed in [126]. The results are ELD using loss formulation through A coefficients and line flows through distribution factors are subsequently compared with those obtained by more rigorous techniques in order to establish the effectiveness of such A coefficients and distribution factors.

9.5 System studies

System Studies are carried out on IEEE 14 and 30 bus test systems [127], on IEEE 57 bus system [128] and on IEEE 118 bus system. The 14 and 30 bus systems have real power generations at 3 buses. The 57 and 118 bus system have four and nineteen plants respectively. Convergence criteria of 0.0001 pu on power mismatch in the load flow solution and 0.001 pu on power balance residual $|P_{eq}| = \left[\sum_{i=1}^{m} (PG_i - P_L - P_D)\right]$ and on power generations PGs in Gauss-Seidel technique for solving ELD problem by classical coordination equations are considered in the program. n represents the total number of buses having real power generation and P_D the total system load demand.

The loss coefficients (the A coefficients) are evaluated by a perturbation technique as discussed in the model. Table 9.1 provides three of the A coefficients for two systems at base load (or nominal load) conditions. These A coefficients are used to represent the system loss P_L and hence the incremental transmission loss in the classical coordination equations for ELD and the minimum cost of generations obtained for the systems [Table 9.2] are compared with those obtained by more rigorous techniques like LP [129] and QP [130] techniques. Results of Table 9.2 clearly reveal the effectiveness and efficiency of the A coefficients for ELD.

Table 9.1 Loss coefficients for IEEE 14 bus and 30 bus systems at base load (nominal load) condition.

Test System	A_1	A_2	A_3	P_L in MW
14 bus	0.14362	0.07737	0.04083	11.676
30 bus	0.14787	0.08205	0.01655	15.119

Table 9.2 Comparison of costs of generation ($/hour) for ELD by different models

	Cost by		
Test System	QP Model	LP Model	Classical model using A coefficient
14 bus	1134.27	1134.07	1135.14
30 bus	1244.42	1245.28	1245.71

In computer controlled power systems, when the system loading changes, there is always a corresponding load flow solution and hence as explained earlier in the model, the corresponding A coefficients can be evaluated in real time with trivial computational burden from the information of this available load flow solution.

Table 9.3 provides three of the A coefficients for different operating conditions and power factors for 14 and 30 bus systems.

Table 9.3 Loss coefficients for 14 bus and 30 bus systems for different operating conditions and power factor

Test System	Loading	A_1	A_2	A_3
	Nominal P + jQ	0.14362	0.07737	0.04083
	1.5 (P + jQ)	0.14360	0.07839	0.04046
	1.25 (P + jQ)	0.14360	0.07771	0.04049
14 bus	0.75 (P + jQ)	0.14390	0.07812	0.04250
	0.5 (P + jQ)	0.14600	0.08343	0.04994
	1.25 P + jQ	0.14338	0.07735	0.04043
	0.75 P + jQ	0.14416	0.07853	0.04241
	Nominal P + jQ	0.14787	0.08205	0.01655
	1.5 (P + jQ)	0.14796	0.08398	0.01667
	1.25 (P + jQ)	0.14790	0.08284	0.01627
30 bus	0.75 (P + jQ)	0.14808	0.08227	0.01890
	0.5 (P + jQ)	0.15008	0.08692	0.02909
	1.25 P + jQ	0.14742	0.08207	0.01533
	0.75 P + jQ	0.14876	0.08332	0.02028

In the present work the nominal load conditions on a system wide basis is represented by P+jQ, so that we can represent other operating conditions of the system in terms of P+jQ. For example, a loading of 1.25 (P+jQ) on a system wide basis shall denote that the loading at each bus of the system is 1.25 times its nominal value and 1.25 P+jQ shall mean that the P parts of the loads at all buses are increased by 1.25 times their base values with Q values unchanged, thus also simultaneously improving the power factors of all the loads. Results of Table 9.3 reveal that the A coefficients evaluated for different operating conditions are close to the values obtained at the nominal load condition. The set of A coefficients evaluated at the nominal loading condition shall be henceforth called nominal A coefficients.

Table 9.4 provides transmission loss P_L for different loading conditions evaluated from AC load flow solution (this P_L is also the same when computed using the corresponding A coefficients at different loading conditions) and compared to P_L computed from nominal A coefficients and the generations corresponding to the load flow solutions for different loading conditions. Comparison clearly reveals that the losses evaluated by the set of nominal A coefficients are pretty close to the actual losses evaluated from the AC load flows for a very wide change in the system loading and power factor conditions. It should, therefore, be inferred that the nominal A coefficients are quite robust in representing the system losses and thus need not be unnecessarily re-evaluated for different operating conditions.

However, for light load and poor power factor conditions, the nominal A coefficients lose their robustness and under such conditions it is recommended to compute the corresponding A coefficients which incidentally need trivial computational burden as clearly explained in the model.

Table 9.5 gives the comparison of the costs of generation for ELD through classical technique for several operating conditions using nominal A coefficients and the corresponding A coefficients. The cost figures are found to be practically the same. These results again speak volume about the robustness of the nominal A coefficients for ELD even for wide changes in the system operating conditions and power factors.

Table 9.4 P_L for different loading conditions and power factors computed from AC load flow and nominal A coefficients.

		P_L in MW from		
Test System	Loading	AC load flow solution	Nominal A coefficients	% error
↑	Nominal P+jQ	11.676	11.676	0.00
	1.5 (P+jQ)	27.860	27.814	0.17
	1.25 (P+jQ)	18.760	18.757	0.02
14 bus	0.75 (P+jQ)	6.444	6.398	0.71
	0.5 (P+jQ)	2.932	2.778	5.25
	1.25 P+jQ	18.683	18.747	-0.34
	0.75 P+jQ	6.472	6.400	1.11
	0.25 (P+jQ)	0.7425	0.6773	8.79
↓	0.25 P+jQ	0.883	0.680	22.91
↑	Nominal P+jQ	15.119	15.119	0.00
	1.5 (P+jQ)	36.654	36.470	0.50
	1.25 (P+jQ)	24.474	24.431	0.18
30 bus	0.75 (P+jQ)	8.288	8.243	0.54
	0.5 (P+jQ)	3.746	3.564	4.86
	1.25 P+jQ	24.231	24.396	-0.68
	0.75 P+jQ	8.397	8.253	1.71
	0.25 (P+jQ)	1.1475	0.868	24.33
↓	0.25 P+jQ	1.413	0.875	38.00

		P_L in MW from		
Test System	Loading	AC load flow solution	Nominal A coefficients	% Error
	P+jQ	27.826	27.826	0
	1.5 (P + jQ)	67.656	65.838	2.69
	1.25 (P+JQ)	44.707	44.508	0.45
57 bus	0.75 (P+jQ)	15.128	15.304	-1.17
	0.5 (P+jQ)	6.604	6.660	0.84
	1.25 P+JQ	43.3999	44.372	-2.24
	0.75 P+JQ	16.253	15.373	5.42
	0.25 (P+jQ)	1.965	1.639	16.57
	0.25 P+jQ	3.654	1.673	54.21
118 bus	Nominal P+jQ	133.14	133.14	0
	1.02 (P+jQ)	147.14	145.84	0.88
	0.98 (P+jQ)	122.94	121.53	1.15

Table 9.5 Comparison of the costs of generation for ELD through classical technique for several loading conditions and power factors using nominal A coefficients and corresponding A coefficients.

		Cost of generation in $/hr for ELD using	
Test System	Loading	Nominal A coefficients	A coefficients from corresponding loading conditions
	Nominal P+jQ	1135.14	1135.14
	1.5 (P+jQ)	1745.64	1745.68
	1.25 (P+jQ)	1427.82	1427.82
14 bus	0.75 (P+jQ)	854.29	854.29
	0.5 (P+jQ)	596.68	596.69
	1.25 P+jQ	1427.55	1427.54
	0.75 P+jQ	854.39	854.39
	Nominal P+jQ	1245.71	1245.71
	1.5 (P+jQ)	1929.64	1929.70
	1.25 (P+jQ)	1572.41	1572.43
30 bus	0.75 (P+jQ)	931.27	931.28
	0.5 (P+jQ)	644.97	644.98
	1.25 P+jQ	1571.48	1571.47
	0.75 P+jQ	931.68	931.68

9.6 Conclusion

A computationally efficient method of evaluating transmission loss and line flow has been demonstrated in this chapter. The set of A coefficients and Distribution Factors used for this purpose are obtained with trivial computational burden from load flow solution. It has also been shown that the coefficients need not be re-evaluated even for very wide changes in the loading pattern of the system.

Chapter X

CONCLUSION

This thesis has demonstrated the implementation of some useful novel and intelligent techniques for modern power systems. As power systems become more complex, new techniques have to be developed to solve the many new problems that are encountered.

The old system prior to privatization was very fixed in installation, operation and development. The new system has introduced a new culture for all parties participating, together with the introduction of new advanced technology. Modern metering and communication technology can also contribute to competitive electricity market. They can enable customers to have choice between suppliers; enable suppliers to offer a greater variety of contracts and tariffs; enable suppliers to read meters remotely and exactly without visits or estimated bill; provide better information to customers to understand their use of electricity; and ensure that new generation and transmission lines are only built when and where required.

Application of object oriented techniques and artificial intelligence to the solution of some of the problems have been described.

Fault location and protection of a Teed-network is a complex problem that has been solved by using wavelet transform and neural networks. An attempt has been made to identify a suitable wavelet family that is more appropriate for use in transmission line fault location. Four different types of wavelets have been analysed to identify fault location using radial basis function network. It is found that the wavelet types ‘db4’ and ‘coif4’ produce better results than ‘bior4.4’ and ‘sym4’.

The difficult part in this exercise is abstracting voltage and current waveform data from EMTP simulation. This is because of the EMTP waveform conversion into MATLAB by using the platform known as 'EMTPCAT' provided with EMTP96. This allows the user to abstract the waveform on the plot window by selecting the waveform one by one for each data file punched through EMTP simulation. This is time consuming and is prone to human error during the transfer of bulk data. These conversion files have been modified to convert any number of data and to save it with appropriate name for further analysis. The data is used to evaluate the distance relay using the Dynamic Protection Modelling software developed by the University of Strathclyde. The result show that the impedance values for the faulted line obtained by the proposed technique could be used as input to the distance relays for the protection of teed-circuits.

The software development industry is making increasing use of object-oriented technology, which is consequently being applied, to an increasing number of applications areas. As a result of this, object-oriented design methodologies and associated software development tools have matured rapidly in the last few years. Object oriented techniques and improved genetic algorithms have been integrated to develop to design and simulate a practical generator excitation control system.

Due to the limitations of conventional optimal power flow (OPF) programs, a new method using evolutionary programming (EP) for OPF has been demonstrated. Under different operation conditions, EP always finds a better solution. It has been shown that EP is better in searching a global or near global optimal point than the conventional method. Due to increased power transactions between various power systems and continuing postponement of transmission reinforcements, power systems are being operated closer to the secure limits. Better utilization of system resources will result in substantial annual savings due to reduced operating costs.

Artificial Neural Network and Genetic Algorithm have been used to design a suitable neural network for short-term load forecasting. The forecasting model has been used to produce a simultaneous forecast of the load in the 24 hours of the forecast day concerned, using data provided by an Italian power company. The results obtained are very promising. In this particular case, the comparison between the results from the GA-ANN and NN shows that the GA-ANN does not provide a faster solution than the NN. This is owing to the fact that the initial randomly selected starting solution is a poor one. The size of the problem is very large and as such the amount of memory and computation time is also large. This points in the direction of parallel processing techniques being integrated with evolutionary computing to solve complex practical problems.

It has been shown that as long as the system structure remains constant a set of A coefficients equal to the number of generating plants to evaluate transmission loss and a set of Distribution Factors equal to the number of generating plants to evaluate line flows can be generated extremely elegantly and efficiently from the hidden treasures of an available load flow solution with trivial computational burden. These A coefficients and Distribution Factors faithfully represent the system transmission loss and line flow and are uniquely suitable for real time application. Investigation further reveals that a set of A coefficients evaluated at the nominal operating condition is extremely robust and need not be re-evaluated even for very wide changes in the loading pattern of the system from the consideration of evaluation of system transmission loss or cost of generation from ELD solution.

It is strongly believed that these powerful A coefficients and Distribution Factors shall greatly appeal to the utilities for their rich potential for practical application. It is recommended that utilities using inexact and inefficient B coefficients can very conveniently switch over to such A coefficients and Distribution Factors for real time ELD in order to derive better efficiency and economy in their system.

Advanced technology will be a driver for shaping the future energy systems. New technologies are now being overlaid on the traditional ones. In particular, the new communications capabilities, information technology and power electronics are transforming this business. The power electronics revolution will impact the power delivery system at every level. It will improve the transmission grid, differentiate the products' quality, and improve the customers' processes. The monitoring, communications and control needs of electric power system continue to grow and become increasingly interdependent. The power electronics based UPFC will provide unprecedented high speed control of the transmission grid. The business implications are significant. Integration of multiple FACTS devices provides an excellent example of how communications, computers, power electronics and fundamental power systems engineering can shape the future.

Technology is an important key to success in these difficult, changing and exciting times. Combined with Internet, this provides the basis for the new energy information services business. The ability to analyze power quality problems is important. It is essential to maintain quality of service, improve system availability, keep power lost through faults on the system low and maintain the stability of frequency and voltage, while coping with the highest number of connections. The electricity market is now facing deregulation and open competition. This results in low electricity prices.

Fuel, equipment and new technology will all have impact on energy products. Looking to the future, there are a variety of technologies that will be key to the new power delivery business in terms of asset utilization, safety and cost reduction. Besides challenges from technical, environmental, and economic requirements, the measures implemented or initiated in many countries with a view to the liberalization of the existing electricity laws will also have a decision influence on the future development of interconnected operation.

Future Work

The electricity supply industry is currently undergoing a dramatic change in both technology and industry structure. Liberalisation of the electricity supply industry is an ongoing process. It is expected that many countries will introduce competition in generation and distribution of electricity and open their retail market by unbundling the existing vertically integrated industry allowing fair access to the network. There are a number of issues that will affect the future of the industry and there will be no single solution to all of them. The solutions have to be adaptive to the different environments.

The transmission grid in the restructured industry will become a vast interconnected system for the transport of electric energy from any generator of electricity to a customer at any point. The monitoring, metering and control technologies of such large systems have to be improved.

There will be a need for developing new or improved techniques to cater for a unified system of power pools and system operators. They have to work together with suppliers and consumers to maintain system security, reliability and operation. To improve reliability of the transmission systems, neural networks aided tools could be developed to predict and minimise major outages.

In a deregulated electricity industry, customers will be able to choose their supplier of electricity. It is therefore, conceivable that the industry will adopt Internet based electronic reservations and trading systems that provide open access to all transmission services information for all market participants. Intelligent software agents technology has to be developed to perform such complex tasks efficiently. Artificial intelligence techniques, auction theory and negotiation through augmentation techniques need to be incorporated into agents technology.

Some of the areas in which application of intelligent techniques need improvement are distributed generation, energy storage, demand side management technology, load dispatch control, power quality management and energy saving technology.

In the operation of modern power systems there are problems related to economics, accounting and environmental aspects. In order to cope with such diverse problems, engineers, accountants, lawyers and politicians need to work together to develop new and improved methodologies.

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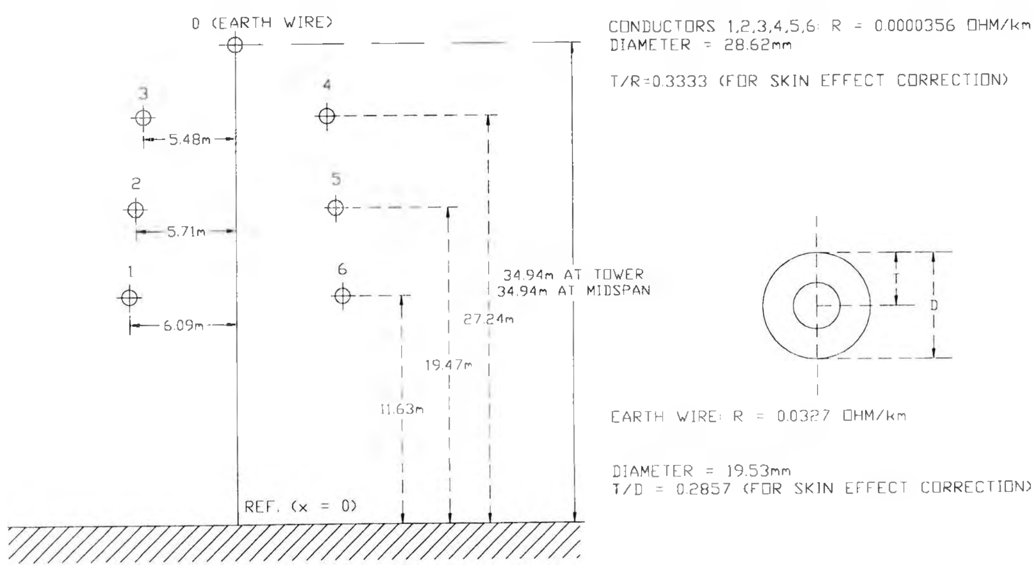
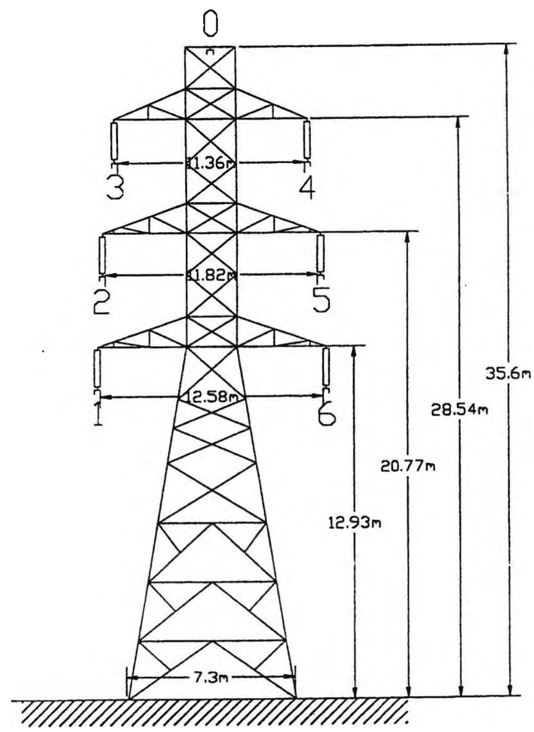
Appendix A

Geometrical configuration of the line from Tee-point to C

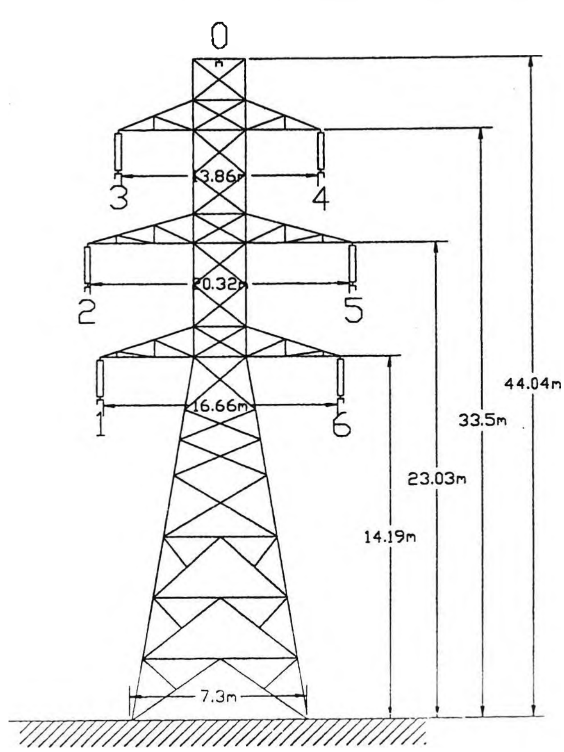


Appendix B

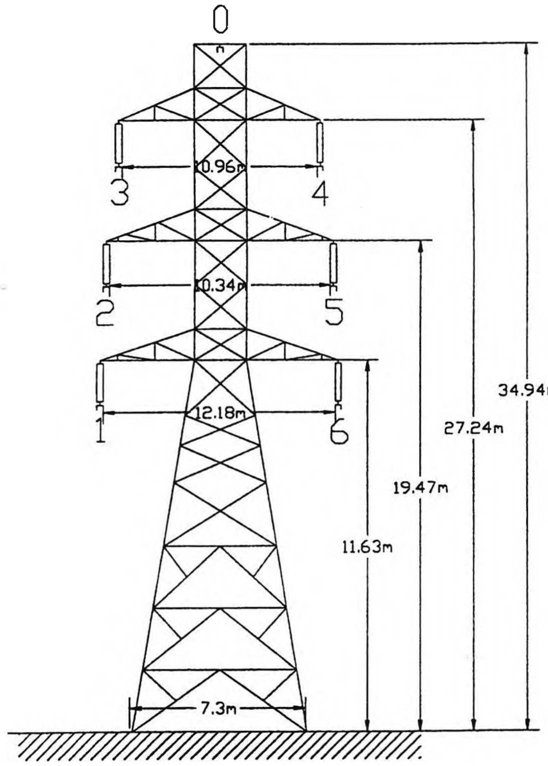
B1. Double circuit overhead line tower for source A to Tee junction



B2. Double circuit overhead line tower for source B to Tee junction

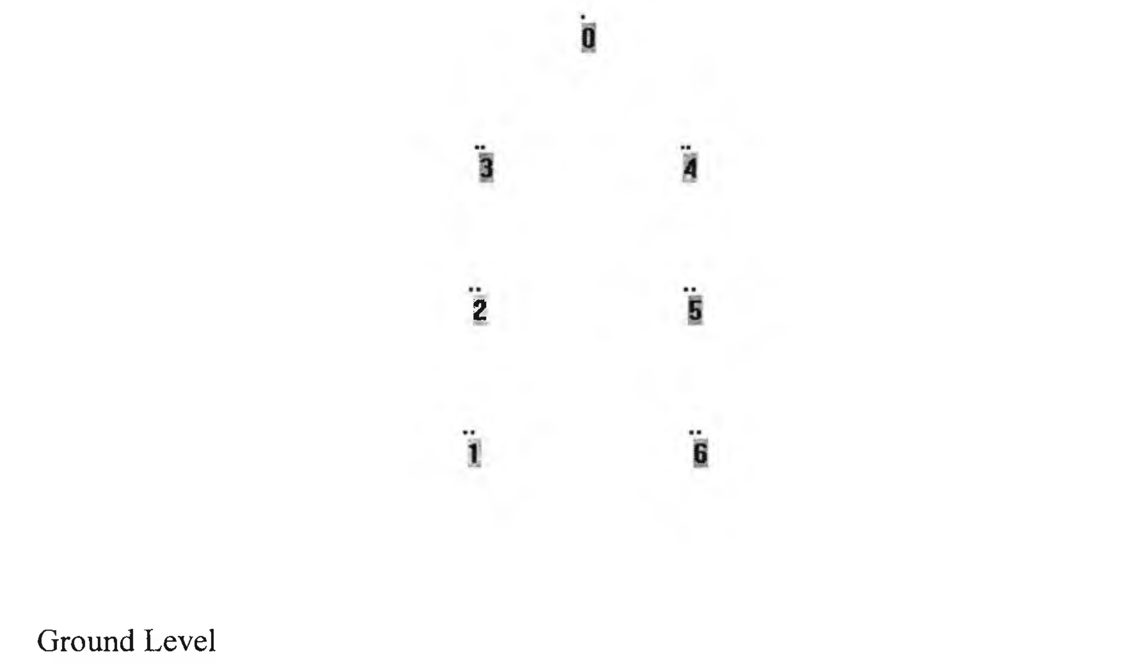


B3. Double circuit overhead line tower for source C to Tee junction



Appendix C

C1. Transmission Line Configuration from Source A to Tee junction

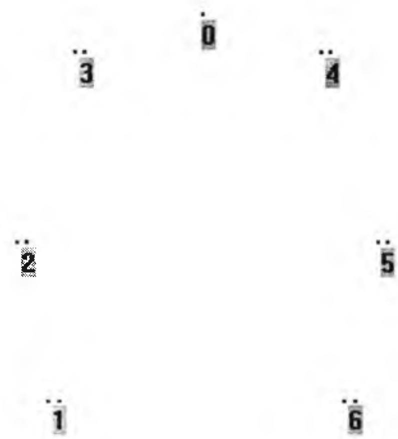


Data

	Ph. No	Skin	Resis.	IX	React	Diam	Horiz	Vtower	Vmid	Seper	Alpha	NB
#			[Ω/km]			[mm]	[m]	[m]	[m]	[mm]	Deg.	2
1	1	0.5	6.24E-5	4	1.0	31.5	-6.29	12.93	12.93	400	180	2
2	2	0.5	6.24E-5	4	1.0	31.5	-5.91	20.77	20.77	400	180	2
3	3	0.5	6.24E-5	4	1.0	31.5	-5.68	28.54	28.54	400	180	2
4	4	0.5	6.24E-5	4	1.0	31.5	5.68	28.54	28.54	400	180	2
5	5	0.5	6.24E-5	4	1.0	31.5	5.51	20.77	20.77	400	180	2
6	6	0.5	6.24E-5	4	1.0	31.5	6.29	12.93	12.93	400	180	2
7	0	0.2857	1.95E-4	4	1.0	19.53	0.0	35.6	35.6	0.0	0.0	0.0

Appendix C

C2 Transmission Line Configuration from source B to Tee junction



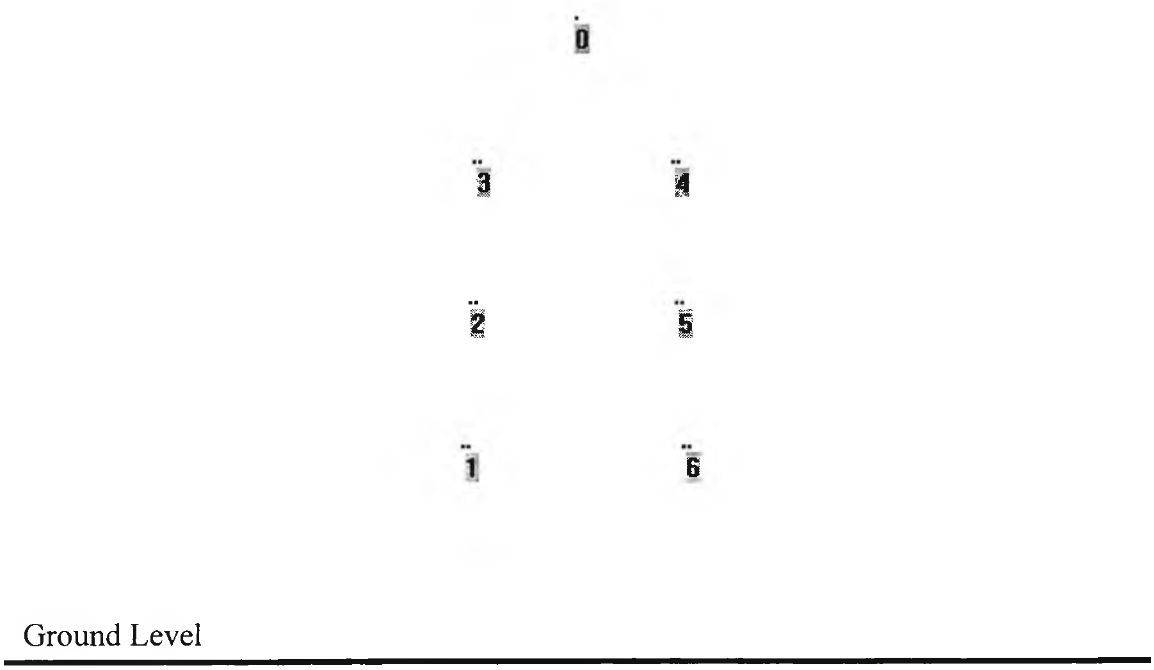
Ground Level

<u>Data</u>

	Ph. No	Skin	Resis.	IX	React	Diam	Horiz.	Vtower	Vmid	Seper	Alpha	
#			[Ω/km]			[mm]	[m]	[m]	[m]	[mm]	Deg.	2
1	1	0.5	2.36E-5	4	1.0	41.04	-8.33	14.19	14.19	583	0.0	2
2	2	0.5	2.36E-5	4	1.0	41.04	-10.16	23.03	23.03	583	0.0	2
3	3	0.5	2.36E-5	4	1.0	41.04	-6.93	33.5	33.5	583	0.0	2
4	4	0.5	2.36E-5	4	1.0	41.04	6.93	33.5	33.5	583	0.0	2
5	5	0.5	2.36E-5	4	1.0	41.04	10.16	23.03	23.03	583	0.0	2
6	6	0.5	2.36E-5	4	1.0	41.04	8.33	14.19	14.19	583	0.0	2
7	0	0.2857	1.04E-4	4	1.0	19.53	0.0	44.04	44.04	0.0	0.0	0

Appendix C

C3. Transmission Line Configuration form Source C to Tee junction



Data

	Ph. No	Skin	Resis.	IX	React	Diam	Horiz	Vtower	Vmid	Seper	Alpha	NB
#			[Ω/km]			[mm]	[m]	[m]	[m]	[mm]	Deg.	2
1	1	0.3333	3.56E-5	4	1.0	28.62	-6.09	11.63	11.63	300	180	2
2	2	0.3333	3.56E-5	4	1.0	28.62	-5.71	19.4	19.4	300	180	2
3	3	0.3333	3.56E-5	4	1.0	28.62	-5.48	27.24	27.24	300	180	2
4	4	0.3333	3.56E-5	4	1.0	28.62	5.48	27.24	27.24	300	180	2
5	5	0.3333	3.56E-5	4	1.0	28.62	5.71	19.47	19.47	300	180	2
6	6	0.3333	3.56E-5	4	1.0	28.62	6.09	11.63	11.63	300	180	2
7	0	0.2857	0.0327	4	1.0	19.53	0.0	39.94	39.94	0.0	0.0	0.0

Appendix D

Legend for Transmission line configuration data

IP : phase number, 0=ground wire (eliminated)

SKIN : = 0 : no skin effect (RESIS = AC resistance)
= T/D: Skin effect (RESIS = DC resistance)
(tubular thickness/conductor diameter.
Solid conductor: 0.5)

RESIS : Resistance ohm/km or ohm/mil. See SKIN.

IX : = 0 : REACT = reactance for one unit spacing (m or foot) at Freq.
= 1 : REACT = reactance for one unit spacing (m or foot) at 60 Hz
= 2 : REACT = Geometric mean radius (cm or inch)
= 3 : REACT = GMR/R (Solid conductor: 0.7788)
= 4 : REACT = Blank. Correction for skin effect.

REACT : Self-inductance parameter.

DIAM : outside diameter of one conductor.

HORIZ : Horizontal distance from the centre of bundle to a user selectable reference line.

Vtower : vertical bundle height at tower (m or foot).

VMid : vertical bundle height at mid-span (m or foot).

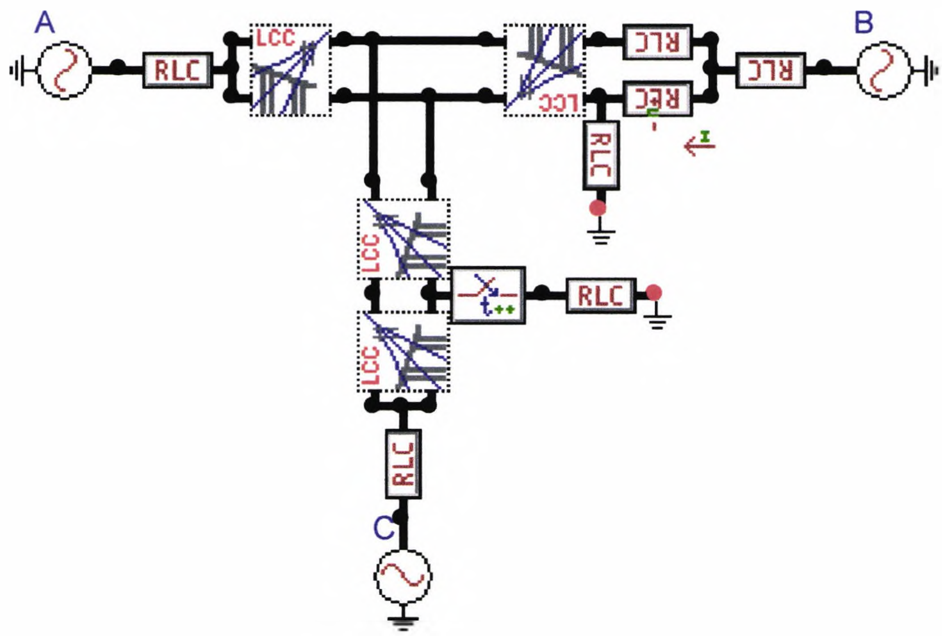
SEPAR : Distance between conductors in a bundle (cm or inch)

ALPHA : Angular position of one of the conductors in a bundle measured counter-clockwise from the horizontal line.

NB : Number of conductors in a bundle.

Appendix E

Teed network drawn by ATP Draw



Data:

- Fault level is 600MVA.
- The line-to-neutral voltage is 230kV, and the line-to-line voltage is 400kV.
- Source impedance are: L_1=41.114mH, L_2=21.794mH and L_3=35.318mH.
- Length of each leg are: d_1=14.312km, d_2=12.148km and d_3=64.092km.
- Fault is single-phase-to-ground (phase-a) at d km from Tee-point towards source C.
- Voltage measurement resistance (voltage) is: R_V=1GΩ.
- Current measurement resistance on phase 1 and phase 2 are: R_{C1}=1nΩ and R_{C2}=1nΩ.
- Fault resistance is: R_F=1nΩ.
- S_1 is a non-symmetric three-phase time controlled switch.

Appendix F

SAMPLE DATA CASE

EMTP Program for fault simulation at 3 km from tee junction

```
BEGIN NEW DATA CASE
C -----------------------------------------------
C Trawsfynydd - Deeside - Legacy Teed Circuit
C -----------------------------------------------
C LNF_000E
$WIDTH. 80
C Miscellaneous Data Card ....
C DELTAT| TMAX | XOPT | COPT | EPSILN| TOLMAT| TSTART|
 2.5E-6  0.24          1.E-15
C Second miscellaneous data card
C  IOUT | IPLOT | IDOUBL| KSSOUT| MAXOUT| IPUN | MEMSAV| ICAT | NERERG| IPRSUP|
   100    100     1     1     1     1     0     2
C Card for varying the printout frequency for the option IPUN=-1
C  KCHG | MULT  | KCHG  | MULT  | KCHG  | MULT  |
C    100    200    200    400
C Source impedance data card
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C < n 1>< n 2>          < R  >< L  >< C  >
C Trawsfynydd
 T1A  T2A            35.318
 T1B  T2B            35.318
 T1C  T2C            35.318
C Legacy
 L1A  L2A            21.794
 L1B  L2B            21.794
 L1C  L2C            21.794
C Deeside
 D1A  D2A            41.114
 D1B  D2B            41.114
 D1C  D2C            41.114
C
C Current  measurement by inserting a very very small resistance
C
 L2A  L4A          1.E-9                              1
 L2B  L4B  L2A  L4A                                   1
 L2C  L4C  L2A  L4A                                   1
 L2A  L3A          1.E-9
 L2B  L3B  L2A  L3A
 L2C  L3C  L2A  L3A
C
C Voltage measurement by connecting a very large resistance to bus
C
 L4A             1.0E9                             2
 L4B       L4A                                     2
 L4C       L4A                                     2
$INCLUDE. D:\Line_pun\TWD_DEED.PUN
$INCLUDE. D:\Line_pun\LEG_DEED.PUN
$INCLUDE, D:\Line_pun\LEGD.PUN
```

```
$INCLUDE, D:\Line_pun\DEED.PUN
$INCLUDE, D:\Line_pun\TWD_F030.PUN
$INCLUDE, D:\Line_pun\F_TEE030.PUN
C $VINTAGE, 1



C Fault resistance data card
  F-A              1.E-9
  F-B              1.E-9
  F-C              1.E-9
C $VINTAGE, 0
BLANK CARD ENDING ALL NETWORK CARDS
C Switch card to connect the fault resistance
C | BUS1| BUS2| T close |  T open |
 0TFA  F-A   0.100     0.20
C 0TFB  F-B   0.025     0.0350
C 0TFC  F-C   0.025     0.0350
BLANK CARD ENDING ALL SWITCH CARDS
C Voltage Source card generated by load flow
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><  A1   ><   T1   >< TSTART >< TSTOP >
14T1A     326599.  50.0       -90.              -1.0
14T1B     326599.  50.0       150.              -1.0
14T1C     326599.  50.0        30.              -1.0
14D1A     326599.  50.0       -90.              -1.0
14D1B     326599.  50.0       150.              -1.0
14D1C     326599.  50.0        30.              -1.0
14L1A     326599.  50.0       -90.              -1.0
14L1B     326599.  50.0       150.              -1.0
14L1C     326599.  50.0        30.              -1.0
BLANK CARD ENDING ALL SOURCE CARDS
BLANK
BLANK CARD ENDING ALL PLOT CARDS
BEGIN NEW DATA CASE
BLANK
```