ABSTRACT AND INTRODUCTION

The solution to the load flow problem constitutes an important aspect of the power system planning and operation. Traditionally, the electric power systems are assumed to be balanced and are represented by the single-line diagram[1,2,5]. The load flow and symmetrical fault studies are carried out on the basis of one phase. The voltages and currents for the remaining two phases are obtained on the basis of balanced system concept. The unbalancing caused to a balanced system due to asymmetrical short circuits, is analysed using the symmetrical component method[10]. These methods are, however, incapable of providing accurate results, if the system is basically unbalanced. The unbalancing can be due to untransposed transmission lines, single-pole switching, single-phase loading, conductors opening etc. Also the analysis of an unbalanced power system following a simultaneous fault using the symmetrical component technique is cumbersome and not practicable for real size power systems.

The analysis of an unbalanced power system is of paramount importance to power engineers and planners. This is due to several reasons. Unbalanced currents can cause serious operational problems. Negative sequence currents may cause overheating of the machinery[55-57]. Zero sequence currents can cause improper operation of protective relays and can greatly increase the effect of inductive coupling between parallel transmission lines.

Under unbalanced conditions, a power system cannot be represented by the single-line diagram. Consequently, all the available mathematical models(11-39) of the load flow problem are incapable of providing the solution.

By representing polyphase network conditions in terms of their phase co-ordinates, viz. phase voltages, currents and admittances/impedances, thereby preserving the physical identity of the system, instead of transforming the phase co-ordinates to symmetrical component co-ordinates, special problems of unbalancing can be analysed easily. This approach is called the "phase co-ordinate method". The phase co-ordinate method has gained considerable importance in recent years. The theory of the phase co-ordinate method was developed by Laughton(40). His pioneering work led to the solution of multiple unbalanced faults(47-50), load flow(43-46) and stability(51) problems on unbalanced power systems. The potential of the phase-co-ordinate approach has not been, however, fully realised for wider practical applications. This is due to several reasons. The available phase co-ordinate models of power system components have many limitations(43,45), and are not general. Generator model is not versatile(43,45). No provision exists for simulating induction and synchronous motor loads. The transmission line model is inadequate to simulate single-pole switching, conductor opening, phase opening etc. The star-delta transformer model is sensitive to system configurations. Three-phase load flow characteristics of the popular load flow techniques have not been fully assessed under different kinds of unbalancings. Many multiple unbalanced faults on unbalanced systems have not been analysed.

The work presented in this thesis aims at removing the above limitations of the phase co-ordinate approach and to study cases not considered previously. The thesis identifies the limitations of the existing phase co-ordinate models, develops new phase co-ordinate models, develops new Gauss-Seidel and Newton-Raphson three-phase load flow algorithms, analyses imbalances due to phase and conductor openings, investigates simultaneous occurrence of the single-line-to ground and conductor opening faults and assesses the effects of untransposed lines on the fault level.

The development of the subject matter of investigation reported in the thesis is on the following lines:

Chapter I:

A new and general phase co-ordinate machine model capable of simulating internal as well as external imbalances is developed. The model is valid for generators, synchronous motors and induction motors. It makes simulation of unbalanced induction motor and synchronous motor loads possible. Transmission line model is enlarged to incorporate bundled conductors and ground wires. New phase co-ordinate models are developed to simulate single-pole switching, single or multi-conductor and phase openings.

A method for step by step formulation of the poly-phase nodal admittance matrix using submatrices of system elements is presented. In addition to the principles of formulation, the rules of construction of mathematical models to simulate phase and conductor openings are embodied with the poly-phase admittance matrix. The model contains many features not included elsewhere. The software is developed in the modular from which permits the deletion or addition of a system element without disturbing the existing structure of the programme.

Chapter II:

A method for solving the load flow problem of unbalanced power systems is developed and presented. The method integrates the machine, phase opening and conductor opening models of Chapter I with the Gauss-Seidel method. The effectiveness of the method and machine model are demonstrated on a number of actual power systems. The unbalancings due to load, single-pole switching, conductor(s) opening and phase(s) opening are considered. The possibility of transmitting the power through two healthy phases in case one phase is isolated, is examined.

Chapter III:

Inherent drawbacks of the conventional Gauss-Seidel single-phase load flow algorithm are found to be present in the three-phase Gauss-Seidel load flow algorithm of Chapter II. To minimize the computational requirements and improve reliability of convergence, a three-phase load flow algorithm is developed. In this algorithm the P,Q type nodes are analysed using the Newton-Raphson technique and machine internal nodes are analysed using the Gauss-Seidel technique. The characteristics of this "composite algorithm" are assessed for balanced as well as unbalanced cases. All the imbalances mentioned in Chapter II are analysed using the composite algorithm.

Chapter IV:

The single-phase Newton-Raphson (N-R) load flow[15-26] algorithm is versatile and reliable. The N-R technique has been extended to the three-phase load flow study[43-45]. The full potential of the N-R technique has not been, however, utilised for wider practical applications. This is due to the limitations on the phase co-ordinate models of machine, transformer and transmission line. Consequently, Chpater IV of the thesis deals with the development and assessment of a versatile three-phase N-R algorithm. The machine and transmission line models of Chapter I are incorporated in the N-R algorithm. The work reported here supplements and extends the work already done(43,45). All the unbalancings mentioned in Chpater II are analysed using this new algorithm.

Chapter V:

Analysis of the simultaneous occurrence of a single-line-to-ground and a conductor opening faults is of paramount interest to protection engineers. Analysis of this simultaneous fault has been attempted in the past using the symmetrical component method but with limited success. The principal limitations of the existing methods(52-54) are:

(a) that they assume that the power system is balanced prior to the occurrence of the simultaneous fault

(b) that the two faults are on the opposite sides of the star-delta transformer

(c) that the rules of assembling the sequence networks at the point of fault are known.

The modern power systems may not be balanced due to a variety of reasons, such as the presence of large single-phase loads, untransposed and bundled conductor lines, converters etc. The evaluation of the effect of these imbalances in conjunction with those contributed by simultaneous faults becomes an imperative need, as the design and protection of turbine generators are strongly influenced by their requirements for negative sequence duty[55-57]. Also, the coordination of zero sequence relays is dependent upon the zero sequence currents.

The application of symmetrical components to the analysis of simultaneous faults on inherently unbalanced power systems tends to be unwieldy and cumbersome. Also the determination of the sequence constraint equations and assembly of sequence networks for different types of simultaneous faults is not always easy. In addition to these difficulties, separate computer soft ware is required to analyse different combinations of series and shunt faults, and the phase shift due to star-delta transformers is not taken into account in the computation. To overcome these problems, Laughton[40,41] used phase co-ordinate technique to analyse different types of shunt faults. Out of the two solution techniques available in the literature[41] he demonstrated the applicability of the source transformation method, but not of the distributed source method, although later method possesses several inherent promising features, such as the use of the Y matrix which is very sparse. Accordingly its modification following changes in the system configuration is easily accomplished. In addition, sparsity and optimal ordering techniques can be used with advantage. On the other hand, the main difficulty associated with the source transformation method is that it involves inversion of Y matrix to get Z matrix.

This tends to be impracticable for large size power systems. The second limitation is that separate computer soft ware is needed to analyse different types of faults. In addition to these limitations of the source distributed method, the phase co-ordinate technique was not applied for the analysis of simultaneous faults involving series and shunt short circuits.

Thus the primary objective of this chapter is to examine the application of the distributed source method for the analysis of simultaneous faults with different combinations of series and shunt unbalances on structurally unbalanced power systems in the frame work of extended/ enlarged version of the phase co-ordinate approach.

The chapter also includes an assessment of the effects of untransposed lines on the fault levels.

Chapter VI:

On the basis of an extensive numerical experimentation, it has been established that the phase co-ordinate model of the star-delta transformer[40] is not valid for all kinds of system configurations. The limitations of this model are identified for load flow and short circuit problems.