ABSTRACT AND INTRODUCTION

Load flow calculations provide voltages, power flows and power losses for a specified power system subject to the regulating capability of generators, condensers, and tap-changing-under-load transformers as well as specified net power interchange between individual operating systems. This information is essential for the continuous evaluation of the operating performance of a power system and for analysing the effectiveness of alternative plans for system expansion to meet the increasing load demand. Load flow studies are also necessary for power system state estimation, contingency evaluation and economic operation. The significance of these studies has become more relevant in the modern time due to control and operation of interconnected large-size power systems in the real-time environment.

The start towards the digital solution of load flow problem dates back to the early 1950's in terms of the work by Ward and Hale[1], Clair and Stagg[2], Henderson[3] and Jordan[4], Hale and Goodrich[5], Glimn and Stagg[6], Brown and Tinney[7] besides many others. Over the last 25 years,an enormous amount of effort has been expended in research and development on the numerical calculation process and several hundreds technical papers had been written.

The first really practical automatic digital solution approach was based on the admittance (Y) matrix formulation of the network. Y-matrix iterative methods were well suited to the first generation computers and small systems. Although, these algorithms perform satisfactorily on small systems, they tend to create convergence problems on large systems. The incentive to overcome this deficiency led to the development of Z-matrix methods[8-12], which converge more reliably. However, the difficulty associated with these methods is that they sacrifice some of the advantages of Y-matrix methods, notably storage and speed when applied to large networks. Around the same time, the Newton-Raphson (NR) method was shown to have very powerful convergence properties[13-14], but was computationally incompetitive. Major breakthroughs in power system load flow computation came in mid-1960's, with the development by Tinney et. al. of a very efficient sparsity programmed ordered elimination technique[15,16]. One of its earliest success was in dramatically improving the computing speed and storage requirements of the NR method, which has now to be widely regarded as the standard general-purpose load flow approach[16], and has been adopted by most of the power industry. However, the practical difficulties associated with this method are that for large size networks, the storage and computing time tend to be prohibitive. This is more so in the real-time environment where a number of computations are carried out simultaneously. In addition, recent investigations have revealed that the NR method does not perform well on ill-conditioned networks[26].

In early 1970's, attention was paid to the exploitation of the loose physical interaction between MW and MVAR flows in power systems. This led to the emergence of a decoupled method[18]. The algorithm is simple, faster and has lower core requirements compared to the NR method. A further approximation and simplification of the decoupled method resulted in an algorithm, named fast decoupled (FD) method[21], which is considered as 'the state of the art method'. The computational requirements (storage and time) of this technique are the minimal among the known load flow algorithms, and hence seems to enjoy wide acceptance.

The FD method works quite well on majority of networks. However, recent investigations have revealed a number of limitations of this method whenever the decoupling and other assumptions are not complied with.

In summary, these limitations are[23-30] :

(i) Slow or oscillatory convergence is encountered at buses connected to branches with R/X ratios of unity or higher[23,24].

(ii) Convergence rates of $P\theta$ and QV decoupled algorithms are determined by how well B' and B'' matrices[21] approximate to the slopes of functions $\Delta P/V$ and $\Delta Q/V$, respectively. These approximations are excellent around the $\theta = 0$, $V = 1$ p.u. point. At high system active or reactive power loadings (large θ_{ik}'s and poor V's)the approximations deteriorate[24].

(iii) The rates of convergence are strongly influenced by the coupling between $P\theta$ and QV mathematical models. This coupling increases with system loading levels and branch R/X ratios,and consequently convergence rates decrease[23,24].

(iv) On ill-conditioned power systems, the method either fails to provide a solution or results in oscillatory convergence[25,26].

(v) The method also fails with most of the load flow equivalancing techniques due to the emergence of a large value of shunt and series admittances, contributed by an equivalent of the external (unobservable) parts of an interconnected power system[29,30].

The NR and decoupled algorithms are based on 1st order derivaties of polar version power flow equations in Taylor series, the second and other higher order derivatives have been neglected for mathematical conveniences and efficient numerical computations. Inclusion of 2nd order derivatives of Polar version power flow equations in Taylor series does not hold much promise due to the presence of Sine and Cosine terms, which are to be computed in each iteration[31].

Recently, a method based on full Taylor series expansion of load flow equations in Cartesian Coordinates has been proposed by Roy[32,34], Iwamoto and Tamura[33]. The fact that the rectangular coordinate version of power flow equations in Taylor series contains terms upto 2nd order derivatives only (the other higher order terms being zero), led to the development of an exact solution model, named exact second order (ESO) method in which the Jacobian matrix is constant and is required to be computed and factorized once only in the iterative process. This leads to considerable saving in solution time.

More recently, the effect of second order derivatives on the performance characteristics of the ESO method has been thoroughly examined by El-Hawary and his associates[42].

Initially, it appeared that the ESO method is several to more than ten times faster than the NR method and has the same memory requirement. However, on closer examination, it was recognised that the ESO method is only 2.5 to 3 times faster and requires about one-third more computer storage[34-36]. Further, it was identified that the inclusion of control adjustments on generator and transformer alters the constant character of the Jacobian matrix[37-41]. When a Q-limit is exceeded, the corresponding voltage controlled bus has to be converted to a load bus. This changeover necessitates modification and refactorization of the Jacobian matrix, and the essential feature of the ESO method, namely its improved computational efficiency is lost. Also, the change of a tap on a tap-changing transformer alters the nodal admittance matrix. This modifies the Jacobian matrix and the effects are the same as in the case of Q-limits on generators as mentioned above. In addition, the ESO method, inspite of being exact and faster than the NR method, does not stack-up well against the most popular FD method in terms of computational efficiency. In fact, Stott et. al.[35,36] have estimated the time and storage requirements of the ESO method to be about twice of those of FD method.

For the past several years, the FD method has been acknowledged in the power industry to be superior to other load flow methods as far as computational speed and storage requirements are concerned. Hence, any new load flow method must eventually demonstrate significant advantages over the FD method in order to find extensive practical use. Probably, due to its inability to compete effectively with the FD method as a viable practical alternative, the ESO method was not adopted by the power industry.

Since the FD method does not appear to be suitable for all power systems under all operating conditions, and the computational requirements of the ESO method are large, there appears to be a need for developing a new method which is devoid of such limitations of the FD and ESO methods. Such a method is developed and experimented in this thesis. The new method is based on a complete Taylor series expansion of nodal performance equations in Cartesian coordinates and reorganization of ESO solution models. The mathematical model of the proposed method, named, fast exact second order (FESO) is of the same size as that of the FD algorithm, and so both the methods require comparable storage. As the coefficient matrices are constant, and the solution model is of the same size, computation time requirement by both the methods in each load flow iteration is almost the same. Also, the coefficient matrices are constant, and hence need to be computed and factorised once only in the iterative process.

The following outstanding features characterizing the proposed method have been identified on the basis of digital simulation studies conducted on several sample power systems. They are summarised below in comparison with the performance of the FD method.

(i) Under normal operating conditions, with no system ill-conditioning, the performance of the FESO and FD methods are comparable in all respects, viz., accuracy, computational time, storage and convergence rate.

(ii) For ill-conditioned networks, FESO method performs as efficiently and reliably as it does for well-behaved power systems under all loading conditions, unlike the FD method which generally diverges. In addition, its computational requirements are significantly less due to better convergence characteristics which could be attributed to the exact (without approximation) formulation of the method.

(iii) On well-behaved networks, under unusual operating modes (which could conceivably occur due to loss of large generation or loads, or transmission line outages), the FESO method still retains its quadratic type convergence and provides a reliable solution, whereas the FD method not only suffers a significant deterioration in convergence rate but also gives at best an erroneous solution.

(iv) Even more importantly, the FESO method assures convergence to the right solution even when an unmonitered part of the system is replaced by a load flow equivalent, unlike the FD method, which either fails or encounters convergence problems.

Thus, because of its ability to perform accurately, efficiently and reliably on well - as well as ill-conditioned power systems under all operating modes, the proposed method is seen to be a practically viable and preferred alternative analytical tool for load flow solution of power systems.

The thesis develops an approximate mathematical model which is faster and more economical than the FESO method. The resulting algorithm is obtained by neglecting the block diagonals of the constant coefficient matrix of the FESO approach. The approximation reduces the computational requirements considerably without sacrificing the accuracy significantly. Although, the proposed method is approximate, it provides a solution that could be acceptable for power system planning and operation. The new algorithm is quite suitable for the contingency evaluation of power systems, where a number of repeat load flows are required and where the accuracy requirement is moderate. It could also be well suited for repeat computations in the real-time environment. Numerical investigations indicate that the proposed method works quite well not only on well-behaved systems but even on ill-conditioned networks where the FD method encounters convergence problems. The success of the new algorithm could be attributed to the fact that it is derived from a complete Taylor's series expansion of power flow equations and the nature of approximations made is different from that in the FD method.

One of the problems encountered in Power System is the generation of unbalanced voltages and currents in the presence of long transmission lines with few or no transpositions, including possible unbalances arising in source and load conditions, or indeed in any items of plant such as shunt and series reactors. To analyse the effects of these unbalances in any detail, a 3-phase load flow solution that allows representation of all possible unbalances as they exist in power systems without making any assumptions, is essential. The development of accurate models of power system components using phase-coordinate parameters made it possible to integrate such models with the NR and FD techniques for application to 3-phase load flows[43-48]. While these methods do provide solution to the load flow problem of unbalanced power systems, their computational requirements tend to be enormous as compared to their single-phase counterpart, thereby rendering them impractical for large-size networks. This is primarily due to the number of non-zero elements in 3-phase admittance and Jacobian matrices being nearly nine times as many as in the single-phase case.

The success and adoptability of a digital method depend upon its speed and core requirements. Consequently, application of the phase coordinate technique to analyse unbalanced load flows is restricted due to large storage and long computation time requirements by the available algorithms. To overcome these limitations, a method is suggested in this thesis. The proposed method involves full Taylor series expansion of 3-phase load flow equations in cartesian coordinates, and is referred to as the exact 3-phase method since no approximation is involved in the formulation of solution model. Previously reported methods have used only first order derivatives in the polar form, and are referred to as first order 3-phase methods.

On the basis of a digital investigation on a number of power systems, the exact 3-phase method is found to possess the following characteristics :

(i) It provides the same solution as is obtained by first order 3-phase load flow methods, but is three to five times faster. Also, the storage requirement is comparable with those of the first order methods.

(ii) Convergence characteristics are nearly independent of the size and configuration of the system.

(iii) The method is suitable for on-line computer control of power systems, where a number of tasks is performed simultaneously.

(iv) The larger the system is,the more advantageous the proposed method becomes.

(v) Programming is easier because the Jacobian matrix and table of factors can be computed off-line and are constant.

(vi) The proposed algorithm makes possible the solution of large networks on relatively small computers.

The development of the subject matter of investigation reported in the thesis has already been described above. However, the organisation of the thesis is briefly as follows :

Chapter 1 :

A fast version of the exact second order load flow method, without involving any approximation or assumption is developed. The proposed method is demonstrated to have the following characteristics (in addition to those outlined earlier) :

(1) The saving in solution time increases with the system size, and finally levels off at 50 per cent, making the new version twice as fast as the initial one. In addition, its computational efficiency is comparable to that of the FD method.

(2) The coefficient matrix storage requirement of the new method is nearly one-half of that of the ESO method. However, as the nodal admittance matrix is of the same size in both the cases, the overall saving in core storage is of the order of 35-40 per cent.

(3) The coefficient matrix remains constant even after inclusion of the control adjustments on generators and transformers. This eliminates modification and refactorization of the coefficient matrix, and results in significant computational efficiency enhancement.

(4) The effects of control adjustments on the convergence behaviour of the proposed method are similar to those of other popular (NR, FD, ESO) methods.

(5) The new method possesses all the attractive features of the FD method, while remaining exact. In addition, unlike the

FD method, it is found to provide a solution even in ill-conditioned cases because of the exact nature of the method.

(6) In situations where a fast, reliable and efficient a.c. load flow is required, as in real-time monitoring, contingency studies, etc. the proposed method would seem to have considerable potential.

Inherent drawbacks of the existing methods to provide a solution to the power flow problem of ill-conditioned net-works are identified. It is found that most of the algorithms encounter convergence difficulties. Even those methods which do converge require considerable computation time and storage, and hence tend to be impractical, especially on large power systems. On the other hand, the FESO algorithm developed in this Chapter is found to be effective for the solution of ill-conditioned networks. The suitability of the method is examined on a number of known ill-conditioned power systems. The ill-conditioning is due to :

(a) position of reference-slack bus
(b) existence of negative line reactance
(c) certain types of radial systems
(d) large ratio of long-to-short line reactance
(e) lines with R/X ratio of unity and more than unity.

On the basis of digital simulation studies, it is found that the FESO method is not only effective on ill-behaved networks, but even its computational requirements are comparable to those of the best known FD method, which fails on such networks[25,26]. In essence then, this chapter endeavours to demonstrate the practical viability of the FESO technique as preferred analytical tool for ill-conditioned power systems also.

In conclusion, this chapter develops a new load flow method and establishes its computational superiority over known popular methods.

Chapter 2

A method is suggested in this chapter for contingency testing. The proposed method is developed from the FESO algorithm by neglecting its block diagonals. The mathematical model is of the same size as that of the FD method. The suitability of the new method has been examined on well - as well as ill-behaved networks. On the basis of elaborate numerical investigation, it is found that the new algorithm performed quite well on all kinds of systems studied, unlike the FD method which encounters convergence problems on ill-conditioned networks. Further, the computation efficiency of the proposed algorithm is higher than that of the FD method, thereby making the new algorithm computationally more attractive and general.

Essentially, then, the objective of this chapter is to put forward a new method for repeat load flows and contingency evaluation which, while retaining all the desirable features of the FD algorithm, is free from its limitations (failure to converge on ill-conditioned systems).

Chapter 3

The load-flow solution of unbalanced polyphase power systems is obtained using the phase-coordinate technique in which only the 1st-order derivatives of load flow equations in polar form are used.

However, the use of these previously developed methods is considerably limited because of the long solution time and large core-storage requirements.

This chapter develops and presents an exact method for solving the load flow problem of unbalanced electrical networks in which full Taylor series expansion of load flow equations is used. The load flow equations are expressed in cartesian co-ordinates. The new algorithm is exact as, unlike previous methods, no approximation is involved in its formulation.

The applicability of the new method is demonstrated through digital simulations on a number of sample networks, for load as well as structural unbalances. Finally, these results are compared with those of currently available three-phase load flow algorithms. These investigations reveal that the proposed algorithm is three to five times faster than the 1st-order 3-phase method but requires comparable storage. Owing to the high computational efficiency, the new method could be more suitable for real-time studies, especially on large systems. A detailed characteristics of the proposed algorithm is described earlier in the synopsis.

A part of the work reported in the thesis has appeared in the following papers :

(i) ''Second-order, 3-phase load flow'', International Journal of Electrical Power and Energy Systems, Vol. 3, No. 1, Jan. 1981, U. K., pp. 50-56.

(ii) ''A Fast Exact second order Load Flow method for large power systems'' Proc. Large Engineering Systems 4, pp. 35-41, June 1982, Canada.