1. INTRODUCTION

1.1 INTRODUCTION

Load flow is the most extensively used analytical tool in any power industry. Starting from planning studies, power flow is required in economic analysis, operation and control studies and also in system security monitoring. Load flow, therefore, has rightly been termed as the workhorse of the power system. Extensive research has been reported on this topic during the last few decades and a large number of solution techniques have come out. Since power flow has wide range of applications, methods have been developed giving very high as well as low level of accuracies. In all cases, however, the equations that are solved are the nodal power equations represented in different forms and utilizing appropriate models of the system components. In some cases power equations are solved retaining their non linearity while in some other cases power equations have been linearized utilizing various levels of approximations. Load flow solution have been developed for balanced as well as unbalanced system representations. Solutions technique had also required to be developed for high voltage closely interconnected and low voltage radial systems.

Gauss – Seidel, Newton – Raphson [1] and fast decoupled power flows [7] are the generally referred load flow solution techniques. Besides these, DC load flow is also a widely used solution technique when approximate but fast solutions are needed. For improving the performance in different critical requirement a number of modifications of these basic methodologies have been suggested in literature.

General purpose load flow methods face difficulties in solving systems having high R/X ratios or when the system loading approach their loadability limits. Remedies for such cases, however, have been reported [6], [8], [14], [15]. Control variables like on-load tap changers, phase shifters etc. also create problem as these variables are discrete in nature. Normal load flow solutions are generally adjusted outside the iterative procedure in handling such variables [3], [4]. Sometimes the discrete variables are treated as continuous and rounded off after the solutions are obtained.

Load flow problem also have multiple solutions [16], [17], [55]. Of the total 2^N-1 possible solutions [17] of a N bus power system, only one is the operable solution and this solution is generally found by the iterative load flow methods. The reason behind obtaining this solution only from the iterative load flows is the starting values of the variables for any load flow method. Generally 1 p.u. votage magnitude and zero phase angle are taken as the starting values, as power systems generally are operated close to their declared voltage levels. Except the operable solution, all other solutions are generally low voltage solutions. These solutions, though carry very little physical significance are important because of the fact that they give useful information in respect of the voltage stability of the power system [55]. Particularly, the existence of a second load flow solution very close to the first one implies that the system is very near to its voltage collapse point [16]. Thus, determination of the solutions other than the normal one is also important. Conventional load flows fail to determine such solutions. Load flow problem has either been treated as an optimization problem- or solved using special search procedure to obtain such multiple solutions [16], [20], [21].

The development of Flexible AC Transmission devices such as UPFC, STATCOM, SVC etc. have open up new possibilities in the transmission and control of electrical power systems. Incorporation of such devices, however, at the same time has generated new challenges in respect of power flow solution. FACTS devices generally involve large number of variables and these variables can assume values in a specified range only. Incorporation of such variables, therefore, in the conventional formulation of power flow is rather inefficient [13]. On the other hand restructuring of power systems not only has expanded the physical dimension of power system; it has generated the necessity of greater control over the pattern of power flows. Determination of control settings for such constrained power flow requires power flow solution tool that can handle control variables in a better way than the conventional power flows can. Though such power flows can be taken care of through the general formulation of the so-called optimal power flow, a solution tool in the framework of the ordinary power flow perhaps is more desirable. To summarize, a general purpose framework of the power flow solution that is flexible enough to solve the power flow problem in varied operating conditions is perhaps the most desirable one.

The author's endeavour in the present thesis is to develop such general purpose power flows that are robust and versatile to be applicable for all possible analytical applications. It perhaps is not very difficult to guess that such power flows should not be based on the conventional approaches like solving the power flow equations or their linearized forms directly as the convergence of these approaches have been proved to be not very strong (most power flow algorithms either solve the power flow equations or their linearized form).

In recent years evolutionary/meta-heuristic computing techniques have emerged as very powerful general purpose solution tools. Basically these tools are search techniques capable of finding the optimum solution of a problem. The most remarkable feature of these tools is that they do not impose any restriction to the nature of the search space and type of the variables. Such tools are in wide use in solving many power system problems.

1.2. TRADITIONAL LOAD FLOW METHODS

Though Gauss – Seidel load flow is the simplest as well as the oldest of the load flow methods, it is known to be very unreliable and hence is not generally used unless specially demanded by the situation. Transient stability study is one such example when Gauss – Seidel load flow using impedance representation of load is used.

Traditional power flow programs employ two classes of widely accepted solution algorithms: Newton methods and Fast Decoupled methods, both based on the linearization of the load flow equations using Taylor series expansion. Both polar [1] and rectangular[42] forms of the Newton method have been developed, but the polar form is more popular.

The polar form solves the equation

$$\begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{1.1}$$

Whereas the rectangular form solves an expanded set of equations as

$$\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \\ J_5 & J_6 \end{bmatrix} \begin{bmatrix} \Delta e \\ \Delta f \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta V^2 \end{bmatrix} \tag{1.2}$$

The Fast Decoupled load flow [7] is based on the decoupling property existing in a power system. A number of further simplifying assumptions by stott and Alsac has finally led to the set of equations

$$B'\Delta\delta = \frac{\Delta P}{V}$$

$$\text{and} \quad B''\frac{\Delta V}{V} = \frac{\Delta Q}{V} \tag{1.3}$$

While the Newton method have the attractive property of local quadratic convergence, they tend to take large amount of CPU time to find a local solution due to the expensive LU factorization of the power flow jacobian at each Newton iteration.

On the other hand, after a single, simple factorization, the Fast Decoupled methods have the desirable property of requiring only an inexpensive forward elimination and backward substitution on a smaller matrix at each Fast Decoupled half iteration. The disadvantage of using the Fast Decoupled approach is due to its weaker convergence properties.

The standard practice in the power industry is to use the fast decoupled load flow if there is no convergence problem and to use the Newton – Raphson load flow in case converge problem is encountered.

Several modifications of the Fast Decoupled methods, however, have been proposed [3]-[6], [8]. Conventional FDLF fail to converge in case of high R/X ratio lines in the system or during heavy loading conditions. In order to overcome the problem due to high line R/X ratios B′ and B″ matrices have been formulated in a slightly different way where resistance is ignored in B″ and considered in B′. This version of FDLF is called the BX version [8] whereas the conventional Stott – Alsac’s formulation is referred to as the XB version in this context. Hybrid Fast Decoupled load flow, super decoupled load flow [45] using multiple slack buses are some other variations of the decoupled load flow formulation.

1.2.1. SECOND ORDER METHODS

The traditional Newton formulation ignores all higher order terms of the Taylor series excepting the correction due to the first order term. The formulation therefore is approximate. Second order load flows [58]-[61] use the correction due to the second order terms as well. Though both polar and rectangular formulations have been proposed, rectangular one is more popular as in this case, the load flow equation reduces to

$$y(s) = y(x) + J(x)\Delta X + y(\Delta X) \tag{1.4}$$

and all higher order terms vanish.

The load flow equations take the form

$$\begin{bmatrix} \Delta f^{k+1} \\ \\ \Delta e^{k+1} \end{bmatrix} = J_o^{-1} \begin{bmatrix} P_s - P_o - P\left(\Delta e^k, \Delta f^k\right) \\ Q_s - Q_o - Q\left(\Delta e^k, \Delta f^k\right) \\ V_s^2 - V_o^2 - \left(\Delta V^k\right)^2 \end{bmatrix} \tag{1.5}$$

In the iteration process the values of Δe^{k+1}, Δf^{k+1} are substituted in the $P(\Delta e^k, \Delta f^k)$ and $Q(\Delta e^k, \Delta f^k)$ terms in the succeeding iteration, and convergence is achieved when the difference between succeeding voltage corrections become very small.

1.2.1.1. ILL CONDITIONING OF THE LOAD FLOW PROBLEM

Newton based load flows face convergence difficulties. The non-convergence of power flow is due to failure of a power flow method or due to infeasible operating point. Conventional power flow methods are known to have difficulties in solving cases for ill conditioned system. A matrix is considered to be ill conditioned if it has a sufficiently large condition number. For power system analysis, the matrix of concern is the power flow jacobian. The condition number of J is defined as

$$\text{Cond}(J) = \| J \| \bullet \| J^{-1} \| \tag{1.6}$$

Where ||*|| represents matrix norm. Large condition number leads to round off error accumulation during the course of iterative solution and may give rise to oscillations or divergence of power flow solution. The ill conditioning can be due to special features of the network such as high r/x ratios of lines, connections of very low and very high impedance lines at a bus.

1.2.2. OPTIMAL MULTIPLIER METHOD

For solving ill conditioned system an optimum multiplier technique has been proposed by Iwamoto and Tamura in 1981 [15]. The non linear power flow equation in rectangular coordinates may be written an $y_s = y(x)$. The Taylor series expansion of the equation is

$$Y_s = y\,(x_e) + J\Delta x + y(\Delta x) \quad (1.7)$$

Where x_e = Estimate of x, J the jacobian and Δx the error. Introducing an optimal multiplier μ, above equation is rewritten as, $y_s - y\,(x_e) - \mu J\,\Delta x - \mu^2 y\,(\Delta x) = 0$. The value of μ is obtained by minimizing an objective function $F = ½\,(a + \mu + c)^T\,(a + \mu b + c)$

Where

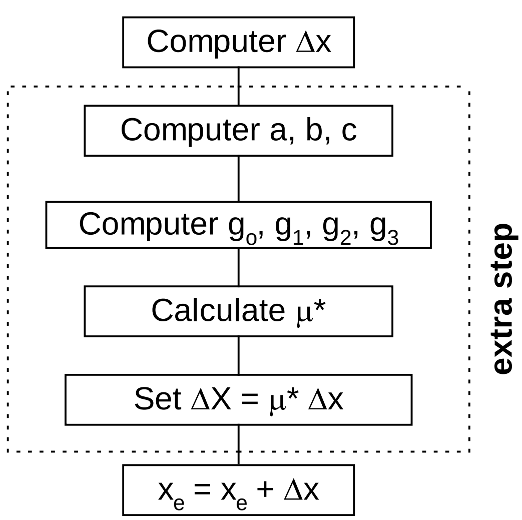
$$a = y_s - y\,(x_e),\;\; b = -J\Delta x,\; c = -\;Y(\Delta x) \quad (1.8)$$

The optimality condition results in the cubic equation

$$g_o + g_1\mu + g_2\mu^2 + g_3\mu^3 = 0 \quad (1.9)$$

$$\text{where } g_o = a^T b,\;\; g_1 = b^T b + a^T C,\;\; g_2 = 3b^T c,\;\; g_3 = 2c^T c. \quad (1.10)$$

If there is more than one real solution for μ, the lowest solution is used. The optimal multiplier load flow requires minor modification in the rectangular Newton load flow.



For oscillatory solution it is observed that if:

$\mu^* \rightarrow 0$ = solution does not exist

$\mu^* \rightarrow 1$ = solution exists but does not converge due to precision deficiency of the computer.

1.2.3. THE CONTINUATION POWER FLOW

The load flow problem becomes unsolvable at the maximum loading condition as the jacobian of the Newton power flow becomes singular. Continuation power flow [14] has been developed to overcome this problem. Continuation power flow is based on locally parameterized continuation technique.

Continuation power flows are very useful in voltage stability analysis problem which occurs due to system loading approaching the critical point. Popular method of analyzing the problem is to draw the system PV curve.

In general, in the conventional power flow, the load increase is expressed in terms of a parameter λ, the loading factor. The load flow equations can be written as

$$G(V, \theta, \lambda) = 0 \tag{1.11}$$

Above equation can be rewritten as

$$\lambda P^{sp} - P(\theta, V) = 0, \lambda Q^{sp} - Q(\theta, V) = 0. \tag{1.12}$$

and can be solved by conventional PF method. However varying λ presents numerical difficulties near and at maximum loading point.

Continuation methods are useful tools to generate solution curves for general non linear algebraic equations with a varying parameter. In continuation method λ is considered as a dependent variable and then changed automatically. Since normal load flow has $2n_{pq} + n_{pv}$ number of equations an additional equation is needed because of the inclusion of the new variable. The difference among the continuation methods is in the way this new variable is handled and how the jacobian signularity is avoided. These methods have four basic elements : a predictor, a corrector, a step size control and a parameterization. The parameterization step is necessary to avoid the singularity. Different types of continuation methods have been proposed in literature. For example, tangent predictor and a perpendicular inter section corrector.

Any one of the n+1 unknown can be defined as a parameter by specifying a value for it. A proper choice of the continuation parameter depends on the variable that has the greatest rate of change near a given solution.

Among the several different predictors found in literature, the tangent and the secant methods are most popular. In tangent method, the estimate of the next solution is found by taking an appropriately sized step in the direction of the tangent to the current solution.

The first task in the predictor process is to calculate the tangent vector from

$$dF = 0 = \frac{\partial F}{\partial \delta} d\delta + \frac{\partial F}{\partial V} \Delta V + \frac{\partial F}{\partial \chi} d\lambda$$

as (1.13)

$$[F_\delta, P_V, F_\lambda] \begin{bmatrix} d\delta \\ dV \\ d\lambda \end{bmatrix} = 0$$

(1.14)

The tangent vector sought is t = $[d\delta \ \ dV \ \ d\lambda]^T$ and F_δ, F_V actually are the elements of the jacobian matrix. Once the tangent vector is formed the predicted solution is calculated as

$$\begin{bmatrix} \delta * \\ V * \\ \lambda * \end{bmatrix} = \begin{bmatrix} \delta \\ V \\ \lambda \end{bmatrix} + \sigma \begin{bmatrix} d\delta \\ dV \\ d\lambda \end{bmatrix}$$

(1.15)

When σ is a scalar that designates the step size.

The estimated solution obtained by a good predictor is very close to the correct solution. A few Newton iterations are generally employed to obtain the corrected solution.

1.2.4. MULTIPLE LOAD FLOW

Load flow problem may have many solutions, only one of which is feasible. Standard load flow methods determines this feasible solution only. Though all other solutions of the load flow equations do not carry much significance, the existence of a low voltage solution near the normal one is an indicator of the proximity of the system to the voltage collapse point. Determination of this second solution is therefore very important for voltage stability analysis of power system. the optimal multiplier method has been extended for obtaining such solution using only minor adjustments [16]. The solution algorithm works as follows:

1. Start load flow calculation by conventional N – R method in rectangular coordinates from an initial condition.
2. Calculate optimal multipliers in every iterative process. If three real roots ($\mu_1 < \mu_2 < \mu_3$) are obtained estimate the 2nd solution as $x_o = x_e + \mu_3\, \Delta x$.
3. Continue iteration and obtain the first solution.
4. Check if x_o satisfies the converge criterion, if not proceed to the next step.
5. Start the second load flow calculation taking x_o as the initial condition and obtain the second solution.

Though optimal multipliers are calculated at each step, they are not utilized for accelerating the solution as the multiplier μ_1 modifies straight convergence loci. For obtaining the accurate solution the tolerance for the second solution has to be kept very low (as 10^{-8} *p.u.*).

If no real roots can be found during the first load flow solution, it indicates that there is no solution close to the first one.

1.2.5. SERIES LOAD FLOW

Series load flow [11] solves the load flow equation in a reverse way. A Taylor series expansion of the load flow equation Y = f(X) forms the basis for the well known Newton – Raphson load flow. For series load flow Taylor series expansion is performed on the inverse load flow function X = g(Y) and ΔX is calculated as

$$\Delta X = \frac{\partial X}{\partial Y}\Delta Y + \frac{1}{21}\Delta Y^t \frac{\partial^2 X}{\partial Y^2}\Delta Y + \text{..........}$$

where, (1.16)

$Y_o = f(X_o)$: the known solution point.

$\Delta X = X_s - X_o$: vector of bus voltage corrections

$\frac{\partial^k X}{\partial Y^k}$: k th order derivative or sensitivity matrix of X with respect to Y.

$\Delta Y = Y_s - Y_o$: vector of bus power injection mismatches.

Series load flow needs inversion of jacobain matrix. It is faster than N – R method. There is no convergence problem, no question of jacobian singularity at extreme loading conditions. But the only limitation of the method is that handling of PV buses is difficult.

1.2.6. SOLUTION OF LARGE SYSTEMS: QUASI NEWTON LOAD FLOW

During a Newton power flow not all equations converge together. So there is no need for updating the whole jacobian at every step. For example, at a certain step in the iteration process it is commonly found that (a) some residuals have already converged ; (b) most residuals are decaying fast enough to converge with a constant jacobian within a few iterations; and (c) a few residuals will converge fast only if the corresponding part (row) of the jacobian is updated.

The Quasi – Newton Power Flow (QNPF) [57] exploits the combination of: (a) Newton steps where the whole jacobian is computed and consequently refactorized; (b) Simple steps where the most recent Jacobian is reused with forward and backward substitutions; (c) Partial Jacobian updates where only a small portion of the jacobian matrix is updated. Partial Jacobian updates are introduced in Power flow program in two ways; (i) Partial LU refactorization of the Jacobian; and (ii) Using Matrix Modification Lema (MML).

It can be observed that major changes in jacobian matrix occur in the initial iterations. During later iteration changes are very small (less than 10^{-3}). Therefore, reusing the jacobian for one or more steps seems to be reasonable.

For large power systems, savings in the order of 50% compared to Newton's method has been obtained. For systems smaller than 1000 buses with no special loading conditions, the classical Newton's method is recommended.

For large systems and high accuracy requirements, or for large and small systems with laggard residuals the Quasi Newton method performed better than the Newton's method. (Laggard residual – most slowly converging residuals).

1.2.6.1. USING PRECONDITIONS

A major disadvantage of the NPF, when using traditional LU solvers, is that the jacobian matrix needs to be refactorized at every step. As the size of the system increases, the number of floating point operations (flops) of LU factorizations becomes prohibitively large, even for the solution of sparse systems. Very efficient iterative solvers have been developed for solving large sparse systems of linear equations [56]. Such solvers for symmetrical systems are conjugate gradient (CG), minimal residual (MINRES), and Chebyshev iteration. For non-symmetrical systems the generalized minimal residual (GMRES), bi-conjugate gradient (BiCG), bi-conjugate gradient stabilized (BiCGSTAB), conjugate gradient squared (CGS), and quasi-minimal residual (QMR) methods are at the forefront.

A Newton formulation of load flow results in a variable non-symmetric positive definite matrix. While the fast de-coupled formulation results in a constant positive definite matrix (that could be made symmetric). In both formulations the condition number of the matrices involved is large (10^3 to 10^5 or higher) and increase with the size of the system.

for AX = b A is positive definite if $X^T A X > 0$

System	**Condition number**
14	1.13 E2
24	1.83 E2
39	1.59 E3
118	2.99 E3
354	5.18 E3
1062	1.60 E4
3186	5.60 E4

All iterative solvers work very nicely for a system with a small condition number ($<10^3$). Therefore, for the solution of the power flow equations a pre-conditioner is often necessary.

A good pre-conditioner does not only guarantee convergence, but the overall efficiency of the solver is also very much dependent on the characteristics of the pre-conditioner.

The idea of a pre-conditioner is to premultiply the system of equations by a good approximation of the matrix inverse. Thus the preconditioned matrix is as close as possible to the unity matrix.

A commonly used preconditioner in power system is the incomplete LU (ILU) factorization of the matrix. A family of preconditioners uses the topology of the matrix to drop elements to form the incomplete factors. Typically, the ILU (0) is used, which consists of the LU factorization of the matrix, but dropping all the fills. The ILU (1) includes the first order fills only, and so on. Thus, some relatively important entries may be dropped while keeping some smaller element. The ILU (0) has been found to be inadequate for the application of iterative solvers to load flow problem.

1.2.7. THREE-PHASE LOAD FLOW

There is a growing concern about asymmetrical three phase load flow study [52]-[54] with the introduction of untransposed transmission lines and asymmetrical loads. the asymmetry in transmission lines and loads produce a certain degree of unbalance in real power systems. Under these conditions low quantities of negative and zero sequence voltages can be observed in power networks. These magnitudes are considered to be a disturbance whose level must be controlled by power quality standards. As with the conventional load flow study, three phase load flow also specifies three types of buses. For slack bus, the magnitude and phase angle of the positive sequence component of voltage are specified. For PV buses total three phase active power injections and the magnitudes of the positive sequence components of their voltages are specified. For PQ buses active and reactive loads in different phases as in single phase load flow, are specified.

Defining PQ loads on a per phase basis is equivalent to an unbalanced and grounded load. In practice, however, many large unbalanced loads in transmission systems, such as high speed trains and arc furnaces are ungrounded. Representing the components at branch level overcome this limitation but results in a very large Jacobian matrix.

Most of the mathematical models employed in 3-phase load flows are established in a-b-c phase reference frame. It is because the mutual inductances between different phases of the asymmetrical lines are not equal to each other. As a result, untransposed line model established in positive – negative – zero sequence reference frame cannot be broken into independent positive, negative and zero sequence models. But once the a-b-c phase reference frame is used the decoupling feature of other symmetrical element models, such as those of generators, transformers and symmetrical lines, in positive – negative – zero sequence reference frame can not be used further. This is the most important disadvantage of using the a-b-c phase reference frame.

This difficulty has been avoided by using a decoupling – compensation method where three sequence decoupled models of the untransposed lines have been proposed by injecting sequence compensation currents at the two end nodes of the asymmetrical line. The asymmetrical three-phase network thus can be decoupled. A mixed combination of sequence and phase component mismatch is used in another method. At PQ bus bars, power mismatches are in phase components, while at generator bus bars, all mismatches are in sequence components. As most bus bars are PQ, the overall solution is for the phase component system nodal voltages.

The current injection method [52] is another variation. An interesting property of the formulation is that the structure of the jacobian matrix is the same as the bus admittance matrix and thus retains its sparsity properties. Moreover the number of elements that has to be recalculated during the iteration process is very small.

Newton Raphson method conventionally uses real arithmetic. Newton Raphson load has also been formulated in complex form leading to complex jacobian matrix. The complex form has been reported to have a better convergence characteristic particularly in solving unbalanced operating conditions and voltage quality analysis.

The multiple load flow solution is typically associated with the voltage instability problem. A different type of multiple solutions associated with the degree of supply and load unbalances have been identified in a recent publication [51]. It has been found that if the degree of unbalance is reduced, the two solutions merge into one solution. Careful analysis of the results obtained revealed that the difference between the solution sets is concentrated at the neutral voltages of a few star-connected components.

1.2.8. LOAD FLOW FOR DISTRIBUTION SYSTEMS [10], [46], [47]

Low voltage distribution system are characterized by radial configuration and high r/x ratio lines. Load flows developed for interconnected high voltage systems thus either fail to converge or become very inefficient in solving the distribution system problems. This necessitated the development of special load flow techniques that employ the structural speciality of the network in order to have high efficiency. Most of the solution techniques developed for distribution system utilizes branch-oriented techniques. The iterative solution technique consists of two steps: the forward sweep and the backward sweep. In the backward sweep step branch currents are calculated using the most recent node voltages. The calculation starts at the furthest terminals of the network and moves in the backward direction until the source node is reached. Using these branch currents, the forward sweep step calculates the node voltages starting at the node closest to the source node and moving in the forward direction upto the terminal nodes of the network.

Distribution networks sometimes, may have a few meshes. Such weakly meshed systems are solved by converting the meshed network into a radial one by breaking the meshes at suitable ‘break points’. The converted radial network is then solved using radial network solution techniques and the results obtained are used to generate some ‘compensation currents’ at the break points which are calculated so as to maintain a common voltage at the meshed nodes.

Some of the solution techniques have been developed utilizing loop based approach where during each iteration loads are converted into impedances at the most updated node voltages. Though this approach guarantees the convergence always for both radial and weakly meshed system the solution speed is slower compared to those of the forward – backward sweep based approaches.

A reduced – variable Newton – Raphson technique applied on the branch power flow equations has also been developed. This technique, where the active and reactive powers are used as variables rather than the voltages and the phase angles have found application in reactive power / loss minimization problems.

1.3. NON-CONVENTIONAL APPROACHES FOR LOAD FLOW SOLUTION

The most common load flow approach, by far, is the deterministic load flow (DLF) where the system condition represents a snapshot in time or, more typically, set of deterministic (crisp) values chosen by the analyst for input variable. This approach provides the solution for only one particular case. Often, these specified values are found by making several assumptions about the system under study, for example, future load growth.

Since uncertainty is always present under such assumptions and one never knows the precise real conditions in the system, there is a need for numerous cases to be studied. In practice, analysis is repeated for varying system conditions. The advent of deregulation and competitive power markets has increased such uncertainty even more. In this new environment, the well-known generation pattern cease to exist, the injection of power into system nodes become more unpredictable, and the paths of supply are more diverse.

The need for a different approach to the load flow problem, which would incorporate uncertainty into the solution process, has been recognized. The results from such approach are expected to give solutions over the range of the uncertainties included i.e., solutions that are sets of values instead of single points. Two families of such load flow algorithms have evolved.

The first one is the so-called probabilistic load flow [12]. It considers load and generation as random variables with appropriate probability distributions. The results of the load flow i.e, voltage and power flows are also random variables with the resultant probability. Because of the complexity introduced by using random variables, PLF solutions are obtained using a linearized model and the results are rough approximation.

The second family of load flow algorithms incorporating uncertainty has been developed more recently and it utilizes fuzzy sets for its modeling [18]. This is qualitatively different way of expressing uncertainty. It represents imprecise, or vague, knowledge rather than uncertainty related to a frequency of occurrence. One inherent advantage of this approach in the ability to easily incorporate expert knowledge about the systems under study. With this approach, input variables are represented as fuzzy numbers, which are special types of fuzzy sets. Although the calculations in fuzzy analysis are somewhat simpler than that in a probabilistic case, it is still far too complex to be applied directly to the full system model. Therefore, again a linearized model of the system is used. Fuzzy interval arithmetic has been employed in handling uncertainties associated with the load, generation or system parameters [48]-[50]

With the increase in the complexity of power system particularly due to the increased use of the non-linear loads gradient-based load flows are facing more problems in arriving at a solution. On the other hand evolutionary computing techniques are getting increased acceptance in solving power system optimization problems [26]- [28], [31] as these techniques are not derivative based and most of the real life power system problems involves discrete variable and thus discontinuous objective functions. Attempts, therefore, have also been made to formulate the load flow as optimization problem and solve through the evolutionary computing techniques [39], [40]. There have been successful implementations of the genetic algorithms and evolutionary programming techniques in load flow problem [19]-[21].

The advantages of using these techniques in solving the load flow problem are the avoidance of singularity problem of the load flow jacobian. Moreover since these search techniques are population based, they can successfully determine multiple solutions as well. The objective function for the load flow problem is designed as

$$H = \sum_{i \in N_{pq} + N_{pv}} \left| P_i^{\delta p} - p_i \right|^2 + \sum_{i \in N_{pq}} \left| Q_i^{\delta p} - Q_i \right|^2 + \sum_{i \in N_{pv}} \left| V_i^{\delta p} - V_i \right|^2 \quad (1.17)$$

Where N_{pq} + N_{pu} are the total number of PQ and PV nodes respectively.

Evolutionary techniques, however, requires a fitness function to be maximized. The fitness function is therefore proposed to be

$$F = \frac{M}{10^{-5} + H}, \quad (1.18)$$

Where M is a constant for amplifying the fitness value.

Special measures are needed for satisfying the power balance at the PQ nodes and power balance and Q limit satisfaction at the PV nodes.

Though evolutionary based load flows have been reported to be robust, special techniques adopted for constraint enforcement and solution acceleration have made the evolutionary based load flows computation intensive.

ANNs have been proved to be capable of learning from raw data. For energy management load flow and optimal power – flow problems have been solved by ANNs [22], [23]. Power flow applications involve complex numbers. Although conventional ANNs are able to deal with complex numbers by treating real and imaginary parts independently, their performance is not satisfactory. Therefore, complex ANN has been used for load flow solution.

When both real and complex ANN are applied to load flow problem of the 6 bus test system with 14 training set it has been observed that after 500 iteration real ANN attained a steady state error around 0.032. The complex ANN could catch up with real ANN after 4300 iterations. After 23000 iterations the error become 0.019. It seems that the real ANN can easily get itself into a local minima after a small number of iterations, whereas the complex ANN can continuously improve itself during learning process.

1.4. CONCLUSION

In the present thesis an endeavour has been made to explore the solution of the load flow problem using non-conventional approaches. Of the various non-conventional approaches used to solve the load flow problem the author has selected the heuristic and evolutionary approaches. Since the general load flow problem has already very efficient solvers, evolutionary and heuristic approaches to solve the problem cannot actually compete with existing ones as the evolutionary and the heuristic approaches are inherently slow. The author, therefore, feel that these approaches may prove to be useful where the conventional load flows fail specially in handling the ill conditioned systems, finding the critical loading condition, solving the load flow problem in constrained situations such as with the line flow or voltage constraints, finding multiple power flow solutions and in voltage stability assessment.

Besides exploring the applicability of the evolutionary and heuristic approaches in solving the power flow problem during such special situations, applicability of these approaches in solving the normal power flow problem has also been studied.

Today power systems need efficient control of node voltages and line power flows to meet the challenges of the changed operating conditions. Flexibility AC transmission devices are increasingly being used to meet the above mentioned requirements. FACTS devices involve additional problem variables and power flow and voltage constraints. Incorporation of these constraints and variables make the conventional power flow methods less efficient. Handling of FACTS devices has, therefore, been considered by the author in the developed evolutionary power flows. A number of methods have been developed in this endeavour which are reported in the following sequence.

Chapter two reports the application of heuristic technique in solving the load flow problem. The developed heuristics are based on local or network-wise perturbation mechanism. These methods have been found to succeed when the conventional load flows fail.

Chapter three and four are devoted to the discussions on the application of the PSO technique to the power flow problem. Chapter three reports the development of a power flow technique useful in finding the normal power flow solutions. The developed method may be of great use in solving the constrained power flow problem.

PSO is applied to find the multiple power flow solutions in chapter four. This method does not make any assumption in report of the decoupling between the power system quantities. Newton-Raphson power flow performs very efficiently if the starting values are chosen properly. Rectangular version of the Newton-Raphson power flows are used to find the low voltage solution close to the normal one using the optimal multipliers method. In chapter four evolutionary techniques are used to generate good starting values only for the rectangular power flow methods in order to find the two multiple low voltage solutions. It has been shown that the optimal multiplier based rectangular Newton-Raphson load flow can be applied to find a pair of low voltage solutions as well. Evolutionary algorithm are used to find the starting values of N-R iteration. The proposed method thus is hybrid of the evolutionary and the optimal multiplier based N-R method.

Chapter five discusses the application of the Genetic Algorithm on the load flow problems. A two-stage GA based power flow method has been developed. Attempts have been made to retain the simplicity of the evolutionary methods in developing the GA based load flow.

Voltage collapsed buses and FACTS devices in the developed power flows are discussed in chapter six. Moreover a performance comparison of the PSO and GA based power flows are also presented in this chapter. This chapter finally draws a conclusion on the presented research work based on the results obtained.