Chapter 1

Introduction

1.1 General

The current electric utilities include central power generation units connected to High Voltage (HV) lines. At the central generation units, electric power is generated and transferred to the distribution centers through HV lines. The transferred electric power is then distribution to the consumers through medium and low voltage lines. Generally, the distribution network is supplied power unidirectionally, as the structure of the distribution network is radial. Power conservation has been the major issue in the distribution networks. In the distribution system, minimization of power loss improves the efficiency and effectiveness of the power distribution. Generally, as compared to HV lines, distribution system power loss is higher because of the high r/x ratio in the distribution lines and due to low voltage operations of the systems.

The electric utility industry has been developing rapidly after creation of competitive market for power supply. In the current scenario, the most important concern of utilities is to address the increased demand for electricity without disturbing the existing networks. Besides, the profile of bus voltages needs to be maintained within a prescribed limit. Under the deregulated environment, the Optimal Power Flow (OPF) and Power Flow (PF) in general play an important role in power system planning and operation. PF analysis is essential before power system planning and operation can be taken up. The main objective of PF analysis is to minimize the power mismatches at all the system buses. The results from PF analysis provide solution for steady-state conditions. The major aim of OPF is minimizing the operating cost of the power utility while meeting the load demand by satisfying all the security constraints for the power networks. For the last two decades, research has been carried out to propose different kinds of numerical techniques to solve the PF and OPF problems of power networks. A detailed description of three-phase modeling of the network components for PF analysis have been provided in [3–7].

Several non-conventional and conventional techniques have been employed to solve these problems of PF because these problems are non-linear and/or non-convex. Due to the non-convexity of the PF and OPF problems, conventional optimization algorithms may be stuck on a local minimum. To address this issue, many population-based meta-heuristics have been utilized in the area of PF and OPF tool.

1.2 Existing Algorithms used in Power Flow Analysis

In [8], numerous challenges of modern power system analysis have been discussed. One of such challenges is that the current flow becomes bi-directional in many branches due to the inclusion of Distributed Generations (DGs) and sometimes applied PF techniques of distribution systems may diverge as a result of high penetrations of DGs. The new challenges have also evolved due to change in the system topology as a result of islanded Microgrids (MGs) and network reconfiguration [9]. Conventional PF techniques experience convergence issues when applied to a distribution system. The main reason behind this issue is the radial or weakly meshed structure of the distribution network with a high r/x ratio which leads to ill-conditioning of system of non-linear equations of PF problems [10, 11]. Consequently, algorithms such as Gauss-Seidel, Newton-Raphson (NR) or fixed-point-type algorithms have poor convergence. For such cases, a robust and efficient PF algorithms is required. Algorithms used to solve the PF problem of distribution systems can be categorized into three classes: Deterministic, Probabilistic, and Evolutionary power flow methods.

1.2.1 Deterministic Power Flow Methods

Backward/forward sweep methods

For distribution PF analysis, backward/forward sweep based algorithms are the most popular tool to obtain the steady-state solution of distribution networks. The first variant of this class of algorithm was introduced in [12], where only PQ nodes were considered in the radial structure of the network. Since this version, numerous improved versions have been proposed to solve weakly meshed distribution networks [13, 14], networks with DGs [15], three-phase distribution network [16, 17], and voltage-dependent loads [18]. A detailed review and comparison of this class of algorithms are presented in [19].

Newton-Raphson type methods

In [20], one of the first attempts to address the convergence issues of conventional NR for ill-conditioned test systems is proposed in an optimal sizing problem of capacitors. In [21], three algorithms based on work discussed in [20] were proposed to solve the PF problem of ill-conditioned systems. Based on the nodal current injection, a PF method, called the current injection method, is proposed for balanced and unbalanced distribution systems with voltage-dependent loads in [22–24], respectively. A detailed comparison between the backward/forward sweep algorithm and the current injection method is reported in [25].

Fixed-Point type methods (or Gauss-Seidel)

Some algorithms based on Gauss-Seidel technique are proposed to solve three-phase distribution systems in [26–28]. Some other algorithms based on the above-mentioned Gauss-like approach are proposed in [29] in which loop frame of reference and Grid Lab-D are utilized.

1.2.2 Probabilistic Power Flow Methods

Deterministic models cannot consider uncertainties of the different aspects of power systems. Therefore, different numerical approaches are need in existing systems for considering uncertainties. The first algorithm of this class, probabilistic PF, was proposed in 1974 and thereafter many improved algorithms have been proposed and utilized in the steady-state analysis of power system [30–35]. In [35, 36], an extensive review on probabilistic PF is presented. The probabilistic PF algorithms are usually classified into analytical approaches and numerical approaches. In numerical solution approaches, probabilistic PF uses deterministic PF to solve nonlinear equations for numerous times with different combinations of inputs [34]. The different combination of inputs are generated as per the requirement of probabilistic parameter considered. Results obtained from probabilistic PF are considered as a reference solution to investigate the accuracy of the other probabilistic PF solutions [37]. The primary purpose of the analytical technique is to determine the density functions of the random variables applying the density functions of random inputs and by dealing with arithmetic computations. Two difficulties usually occur in dealing with probabilistic PF equations. The first one is the high non-linearity of equations and the second one is that of correlation between output and input power variables. To address these difficulties, some simplifications have been suggested to determine probabilistic PF by an analytical technique. The simplest approach is to implement probabilistic PF by linearizing the PF equations employing first-order Taylor series expansion around the predicted mean of the PF variables [30]. Besides this technique, the density function of load and generation can be assumed as a normal distribution for simplicity. Different approaches have been established to deal with the linearization error introduced in PF equations by utilizing quadratic probabilistic PF in [31, 32]. The utilization of point estimation method in probabilistic PF was initiated in [34]. Thereafter, several works based on the point estimation method to overcome the issues of probabilistic PF have been suggested in [38, 39].

In [33], a merger of Gram-Charlier and cumulants expansion theory is introduced to increase the capability of a probabilistic PF method. Similarly, in [40], the Cornish-Fisher expansion is recommended as a substitute for different distribution than the normal distribution to reduce convergence issues.

1.2.3 Power Flow Methods based on Slack Bus

Several algorithms have been proposed to solve non-linear simultaneous equations which are based on numerical computation. PF problem is also a type of non-linear simultaneous equation. Therefore, several numerical techniques have utilized to solve the PF problem. In this thesis, those algorithms which uses the conventional numerical computation approach to solve PF is referred as numerical PF methods. A numerical technique is introduced to determine the PF solution in [41]. Another numerical technique based approach to deal with the PF problems is suggested in [42]. Some of these approaches are based on the NR approach to solve non-linear simultaneous equations [23, 43], while other alternatives are based on the Gauss-Seidel approach [26, 28]. To enhance the convergence aspects of the Gauss-Siedel method for ill-conditions and large systems, some techniques based on iterative design have been established [44, 45]. Several decoupled versions of NR have also been introduced to improve the computing time and speed of convergence [46–48]. Among all the proposed numerical techniques, NR based techniques have became the de facto industry models due to its simplicity and higher speed of convergence.

PF algorithms based on NR and its decoupled versions fail to provide solutions for the PF problems of Distribution Systems and microgrids due to the presence of high value of r/x in lines [49, 50].

In [51], an iterative method based on primitive electric circuit rules is presented for solving the PF problems in radial distribution systems. Using the NR-based technique, an optimal multiplier based technique for solving for PF problem is designed in [52]. A revised algorithm, named backward/forward sweep algorithm, is proposed in [52]. An implicit Z-Bus algorithm is designed in [27] to deal with the PF equations by using a superposition rule where only one source is considered at a time.

In [28], an implicit Z-Bus method integrated with the Gauss-Siedel approach is introduced to cut down the computational burden of the PF study. A three-phase PF algorithm based on the backward/forward method is proposed in [53] that is suitable only for a system with one power source. Consequently, this method does not provide solutions for the PF problem of distribution systems with DGs or droop control based islanded microgrids.

The quadratic equations of the PF equations are used to solve for the voltage magnitude in [54, 55]. However, the voltage angle is ignored in the calculation process of the PF solution to reduce computational time. In [56], a three-phase PF analysis is proposed addressing characteristics of islanded microgrids with decentralized droop controlled distributed generations.

In [57], a second-order PF algorithm has been presented using current injection equations represented in rectangular form instead of classical polar form.In [58], an iterative procedure is proposed to solve the PF problem that improves the computation complexity (number of iterations and CPU time). In this approach, or impedance matrix is utilized in place of the admittance matrix.

To solve the PF problem, high-order NR algorithms have been proposed in [59]. The foremost advantages of these algorithms as compared to NR are their simple structures, faster and significant reduction of CPU time.

Iwamoto *et al.* proposed a NR-based algorithm for ill-conditioned PF solution [60]. In this approach, an optimal multiplier is calculated at each iteration to minimize the power mismatches ($\triangle P$ and $\triangle Q$). In literature, several algorithms have been proposed to address the PF problem of ill-conditioned power systems [10,61–66]. In [67], concavity theory is utilized to calculate an optimal multiplier at each iteration and polar coordinates are used instead of rectangular coordinates. In [68], the quadratic discriminant index is employed to improve the performance of optimal multiplier based PF techniques for evaluating solutions at the maximum loading conditions.

In [69], the Levenberg-Marquardt (LM) algorithm is proposed to solve the PF problem in ill-conditioned systems. In such cases, this approach is a reliable and efficient technique. In [70], a Continuous variant of Newton-Raphson (CN) method is developed to solve the PF problem in ill-conditioned systems. Additionally, several algorithms based on LM and CN have been proposed in [71, 72]. In large-scale test systems, algorithms based on CN provide fast convergence and are more robust than other numerical techniques.

Authors of [73] have presented a variant of LM to solve the PF problem in case of ill-conditioned as well as well-conditioned power systems. However, LM-based algorithms have several issues such as dependence of convergence rate on λ, and inaccuracy in final solution. To address this issue, the authors of [74] have proposed High-Order Levenberg-Marquardt (HOLM). In this approach, good performance is obtained in the case of ill-conditioned test systems.

Authors of [70] have proposed a Fourth-order Runge-Kutte (RK4) algorithm to solve the PF problem. However, RK4 requires four matrix inversions of the Jacobian matrix at each iteration. Moreover, the number of required iterations to solve the problem is also higher than NR-based algorithms. Nevertheless, the performance of RK4 is better than NR-based algorithms in case of ill-conditioned power systems [70].

1.2.4 Power Flow Methods for Droop Controlled Islanded Microgrids

In [2, 75–82], few PF tools have been introduced to deal with the PF problem of an islanded microgrids with decentralized droop controlled DGs and the shortcomings of the traditional PF tools have also been discussed. The concept of droop controlled DGs has been applied to control the power distribution among the DGs without employing the inter-communication among them. The decentralized droop control approach gives way to centrally controlled microgrids having low costs, low complexity, expandability, and enhanced reliability. Thus, such an arrangement can waive the need of inter-communication networks and cut down the investment costs [83–93].

To determine the PF solution for DCIMG, new algorithms have been introduced. These techniques have considered linear equations of the droop characteristics of DGs. In [94], a new PF method that employs particle swarm optimizer is introduced to solve the PF problem of Droop Controlled Islanded Microgrids (DCIMGs).

A revised technique based on the traditional NR approach is presented in [2] for PF evaluation in the presence of decentralized droop controlled DGs. However, this method does not consider unbalanced systems. The power-sharing among the DGs has been examined in [78] but, the voltage angles are not evaluated in this approach. Also the approach, does not consider the PV and PQ models of DGs in their study.

In [95,96], NR based PF study has been introduced that employs virtual impedance in the model of droop controlled DGs. Limited case studies have been conducted in this work where voltage-dependent and frequency-dependent loads are not modeled. Consequently, dependance of the bus admittance matrix on the frequency is ignored in the computation process. A PF analysis of balanced islanded microgrids is performed in [97] by employing power injection equations in polar form. Nevertheless, droop equations and islanded operations for DGs units have not been studied.

References [98], [99] and [100] address the PF problem of a DCIMG. However, these PF techniques cannot be applied to the PF problem of DCIMG because a DG unit is considered as a slack bus. These algorithms assume this DG unit as an infinite bus, but this assumption cannot work for the DCIMG system. In [98], a direct backward-forward sweep technique is proposed to solve the PF problem of DCIMGs. In [101], a new methodology based on Nested-iterative NR is proposed for DCIMGs. However, this approach does not provide convergence for a system having high r/x ratio and thus is not applicable for distribution systems having high r/x ratio.

In [100], to solve the three-phase PF problem, a model based on sequence components is introduced for voltage source inverter and synchronous generators. This model is improved in [102] by considering constraint of DGs and operational limits. However, the model discussed in [102] does not consider the behavior of DCIMGs.

The Newton-Trust Region (NTR) method has been proposed [56] to solve equations obtained after consolidating (i) linear droop bus equations, and (ii) power-flow equation. To solve this optimization problem using NTR algorithm, gradient and Hessian of the objective function are required in the optimization procedure. Therefore, as concluded in [103], the solution of such a transformed problem is not acceptable as the solution is non-trivial.

In NR-based PF algorithm, there is requirement of calculation of the Jacobian matrix at each iteration. System frequency has been considered as a PF variable in Modified Newton-Raphson (MNR) and NTR. Therefore, elements of Jacobian matrix contain derivatives of bus admittance matrix with respect to system frequency. To calculate the gradient of the admittance matrix, the coupling of line parameters have not been considered [2]. Therefore, the gradient of the admittance matrix cannot be accurate in the case of coupling of lines. In the case of coupling of lines, the gradient of the bus admittance matrix cannot be calculated directly. Therefore, a finite difference approximation of the gradient of the bus admittance matrix has been done in [56]. Use of finite difference approximate Jacobian matrix in place of analytic Jacobian matrix affects the convergence property of NR-based algorithms [100]. In addition, finite difference approximation of gradient of the bus admittance matrix increases the time and space complexity of the algorithm. In present thesis, this issue of MNR and NTR has been fixed in the algorithm proposed in this thesis where the gradient of the bus admittance matrix is not required in the PF process.

In [104, 105], three types of droop characteristic are reported on the basis of output impedance of the DG. The NTR algorithm can accommodate only inductive droop characteristics. On the other hand, MNR can perform PF incorporating any particular droop characteristics out of three options but is not able to perform PF for a system having a mix of droop characteristics. This issue is also addressed in present thesis and the algorithm proposed in this thesis is able to perform PF for a system having a mix of droop characteristics.

1.2.5 Power Flow Methods based on Evolutionary Algorithm

During the last three decades, comprehensive research works have been published and a substantial number of numerical techniques have been developed. Since PF analysis has been used in range of applications, several types of approaches have been proposed. In few situations, PF equations must be solved with their non-linearity. Similarly, in other situations, PF equations may be solved by using their linearized models with different levels of approximations. PF solutions have been established for unbalanced as well as balanced power systems. PF algorithms have also been proposed for low voltage radial systems.

Conventional PF algorithms encounter bottlenecks in dealing with systems having lines with high r/x ratios or when the loading condition approach maximum loadability limit of the system. PF problems have multiple solutions i.e. total $2^N - 1$ for a N-bus test system. However, among all possible solutions, only one is the operating point solution which is generally calculated by iterative numerical techniques. The main reason behind the use of iterative numerical techniques is the local search capability around the starting point solution of system. In general, 1 p.u. is considered as the initial seed for bus voltages because the power system is operated close to predefined rated voltage levels. Solutions other than operating point solution are low voltage solutions which have little physical significance in many applications. However, they may provide information related to the voltage stability study of the system. Hence, the determination of such solutions are also required in the power system analysis. To address this issue, the PF problem has been formulated as an optimization problem and solved by using special search procedures to find multiple solutions.

In such circumstances, PF analysis can also be expressed as an optimization problem in which active and reactive power mismatches and voltage mismatches at buses are to be minimized. Several conventional optimization algorithms have been utilized to solve the PF problem and the maximum loadability problem in the literature. However, most of the non-linear programming techniques may converge to local optimum solutions. The optimization algorithm (especially search based) inherently have high chance of convergence due to their formulations and techniques. The above advantages though were obvious at all times, however their practical implementation were subject to contemporary computational advancements. In the present times the computational resources have improved quite significantly (or exponentially increased). This has lead to several successful implementations of computationally demanding algorithms as apparent from literature. Thus it is imperative to revisit and explore the performance of algorithms vis-a-vis contemporary computational resource scenario.

Nature-Inspired algorithms are prevalent for solving non-smooth/non-convex optimization problems from different engineering fields. The algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Differential Evolution (DE) have been introduced as a PF solver for balanced power systems and for computing maximum loadability limit for a system.

DE is a simple yet powerful technique for the global optimization problem. It provides better convergence property and it requires only a few parameters to be tuned. Similar to other evolutionary algorithms, it involves three basic operators, i.e., mutation, crossover, and selection.

GA was first proposed in [106]. It is a population-based search algorithm based on the Darwinian theory of evolution which contains three basic operators such as mutation, recombination, and selection. The initial population of solutions is initialized randomly throughout the search-space. These solutions are called chromosomes which are updated iteratively by using the above-mentioned operators. The fitness of the individuals is evaluated on the basis of their objective function value. The fittest chromosomes are selected as parents to generate offsprings for the next generation. Generations of offspring comprises of recombination and mutation operations. The maximum number of function evaluations is considered as a termination criterion for the optimization process.

Besides the above-mentioned numerical models, numerous studies that analyze PF analysis based on nature-inspired optimization algorithms have been approached in the literature. The best feature of these algorithms is that they are independent of the initial seed of the decision variables. Elrayyah et al., [94] introduced a method based on PSO algorithm to solve the PF problem of DCIMGs. In this method, PSO is employed to calculate the optimum droop parameters for sharing the reactive power. However, this method did not consider the sharing of active power among the DGs. An algorithm based on PSO solves the PF problem for DCIMGs in [107]. In this method, PSO is utilized to find the droop parameters to optimize the reactive power sharing among the DGs. However, this algorithm does not achieve optimized active power sharing among DGs. GA has also been used as an optimization tool to minimize the voltage and power mismatches at the buses [108, 109].

A GA based PF technique is proposed in [108]. This method includes a voltage differential technique and a gradient technique. In [109], a hybrid of PSO and GA based algorithm is proposed to solve the PF problem of islanded microgrids. In this algorithm, two different steps of GA and PSO are employed to find unknown parameters. To solve the optimal PF problem, an algorithm based on DE is proposed in [110]. However, the main drawback of this method is that solution quality is dependent on initial population.

1.3 Objectives of the Thesis

PF evaluation of distribution systems is a prerequisite for any kind of investigation and analysis of the system. However under certain circumstances PF of a distribution system may not be possible due to following reasons.

1. Due to high r/x ratio and unbalanced loading in distribution system, the ill-conditioning of PF equations may appears. Conventional algorithms either cannot provide solution or poorly converge in such situations. In order to resolve this issue, topology based algorithms have been proposed, but these algorithms perform poorly in case of multi-source distribution systems. Thus, it is required to introduce new robust algorithms which perform effectively in case of ill-conditioned distribution systems.

2. Presence of PV buses in a distribution system can be considered as a problem of modern system due to adoption of renewable generations at distribution level. The renewable generations are power converter based interconnection to distribution systems which have a capability to provide voltage control at the interconnection behaving as PV buses. Thus, it is required to revisit the PF algorithms which were developed with PQ buses only so that modifications and improvements can be incorporated in the PF algorithms.

3. Nowadays, MGs have come up as a reality which may be operated either in an autonomous mode or in a grid connected mode. Further, the autonomous MGs can also get into arrangements of power sharing among them. In MGs, unlike transmission system or distribution system, there is no concept of swing bus or root node, respectively.

4. Also, in autonomously operated MGs, the excursion in frequency can be tolerated which may lead to wide variations in frequency dependent loads and line impedance apart from voltage dependency of loads. Thus, the above scenario of MGs requires a fresh approach and perceptive in relation to PF solutions of MG systems.

The problem statement of this thesis is as follows. Development and formulation of new algorithms to solve PF and optimal PF problems efficiently, accurately and in robust manner for distribution system having ill-conditioned equations, large number of PV buses and autonomous/islanded and grid connected microgrid mode of operations.

The main objectives of the thesis are as follows.

1. To develop new robust and efficient algorithms to solve the PF problem for grid-connected and islanded microgrids.

2. To investigate the performance of evolutionary algorithms in solving the above-mentioned PF problems.

3. To determine the maximum loadability limit of power system using evolutionary algorithm.

4. To formulate an optimization problem to solve the optimal PF problem of grid-connected and islanded microgrids.

1.4 Outline of the Thesis

- **Chapter 1:** This chapter describes the background and motivation for the thesis and provides an overview of the research work and objectives of the thesis.

- **Chapter 2:** This chapter presents robust and efficient PF algorithms to obtain fast and accurate PF solution for ill-conditioned unbalanced distribution systems or grid-connected microgrids.

- **Chapter 3:** This chapter discusses evolutionary algorithm based approaches to find out the maximum loadability limit of unbalanced distribution systems or grid-connected microgrids.

- **Chapter 4:** This chapter describes and proposes new robust and efficient numerical algorithms to solve the PF problem for decentralized droop controlled islanded microgrids.

- **Chapter 5:** This chapter presents an evolutionary algorithm based approach to solve the PF problem for decentralized droop controlled islanded microgrids.

- **Chapter 6:** This chapter describes application of different PF tools to find the optimum value of power system variables for operating robustly with minimum cost.

- **Chapter 7:** This chapter proposes an approach to minimize the system losses by calculating optimal setting of droop using evolutionary computation.

- **Chapter 8:** This chapter concludes the works done in this thesis and also proposes future scope of work.

Chapter 2

Power Flow Algorithms for Ill-conditioned Unbalanced Distribution Systems

2.1 Introduction

Most of the power systems are well-conditioned and their PF problem can be easily evaluated using NR-based algorithms. Nevertheless, in certain circumstances, the conditions of the system may become ill-conditioned. Consequently, the aforementioned algorithms can diverge or have poor convergence characteristics. This chapter addresses the issue of solving PF for ill-conditioned distribution system and proposes some numerical techniques to solve these kind of problems.

For the steady-state analysis, solving the PF problem has been one of the major area of investigation in the power systems since mid 1950s [111]. Different methods have been proposed to solve the PF problem in the literature. Different metrics are utilized to compare these algorithms on the basis of basic requirements of PF calculations. These metrics are as follows: (i) The memory requirements and CPU time (computing efficiency). (ii) The reliability and flexibility of algorithms. (iii) The convergence characteristics of algorithms.

In a power system, determining the voltage magnitude and phase of each bus, as well as the flow of active and reactive power through each bus, are the main objectives of the PF problem. In some circumstances, the Jacobian matrix may get near singular or may