Chapter 1

INTRODUCTION

1.1 GENERAL

Distribution networks are prone to high power loss due to its larger R/X ratio compared to transmission networks. As most of the distribution networks are radial in nature, maintenance of good voltage profile is another challenge as voltage at remote end buses may become too low due to voltage drop in different sections of feeder. An unacceptable decrease of voltage magnitude at remote end buses may lead further to voltage instability in part or whole of the network. Therefore, proper control measures are required to reduce power loss in the network and improve voltage profile as well as voltage stability margin. Placement of distributed generations seems to be an effective solution to tackle these issues through real power injection and reactive power injection/ absorption. Such issues may also be controlled through opening/ closing of tie-line/ sectionalizer switches.

1.1.1 Distributed Generator (DG) – An overview

The concept of DG is as old as electricity itself. Thomas Edison comes with the first coal-based generation plant in Manhattan's Pearl Street station in 1882. The basic DC distribution system was capable of supplying 4,400 bulbs in 193 households and continued to supply for almost 8 years, until the first AC system was launched by Nicola Tesla. Since AC current is "transformable," it may be easily and efficiently transferred to remote areas through transmission lines with little power loss [1]. However as increased loads have congested the transmission lines, it was the need of time to increase the efficiency of power system. Distributed Generators play a crucial role to release the stress on power system lines by supplying the power to increased load demand, locally [2].

The prime objective of the Distributed Generation is to inject real power into the system. Hence for a DG; it is not required to have reactive power, though they could be supported with it. Several definitions of DG could be provided based on different issues associated with it, such as purpose; its location, rating, technology, mode of operation and others [3]. For the same, in literature, various definitions have been suggested for Distributed Generation with their application, based on voltage level (kV), capacity of DG (MW), technology – i.e. renewable, co-generation, dispatchable, non-dispatchable and others [3]. According to CIGRE DG is neither centrally planned nor dispatched, and should be smaller than 50-100 MW. DG should be connected to the distribution system [4]. Table 1.1 suggest some DG definitions based on their category and power ratings, as they could be defined as generating unit ranging from a few kW to few MW [3]. Figure 1.1 shows the outline of the power system in case of DG presence. Conventional combustion generators (such as diesel generators and natural gas turbines) and non-traditional generators such as bio-mass, storage devices, fuel cells, and wind and solar based energy producers can be used as DG sources [5]. The terminology of DG is subject to the regulations of respective regions or countries. For example, Anglo-Americans use ‘dispersed generation’ while North American uses the word ‘embedded generation’ to address the DG. Several Europeans and Asian countries call it ‘decentralized generation’ [3].

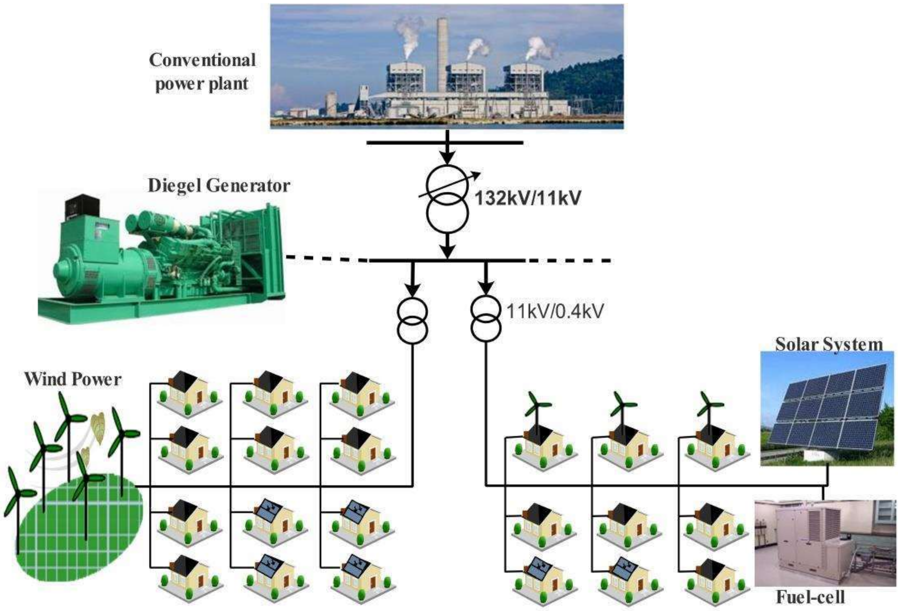

Figure 1.1: A typical power system with several DG sources

Table 1.1: DG ratings and corresponding category [3]

DG Ratings	Category
~ 1 W < 5 kW	Micro – distributed generation
5 kW < 5 MW	Small distributed generation
5 MW < 50 MW	Medium distributed generation
50 MW <~ 300 MW	Large distributed generation

Different possible benefits of DG technologies over traditional centralized generation [6]–[9] can be summarized as:

- Enhanced system voltage
- Reduced power losses
- Improved system stability
- Reduced pollutant emission
- Relieved congestion of power system and many more.

Based on different type of power injection characteristic, DG units are classified into four groups [10].

❖ Type-1: DG capable of delivering real power (P) only.

Photovoltaic, micro turbines, fuel cells are some example which falls in this category.

- Type-2: DG capable of delivering reactive power (Q) only.

  Pure reactive sources such as shunt capacitor, synchronous compensators fall under this category.

- Type-3: DG capable of delivering both real and reactive power.

  Example: Synchronous generator, gas-turbine and cogeneration etc.

- Type-4: DG capable of delivering real power but consumes reactive power.

  Example: Induction generators used in wind farms.

However, there are a number of issues concerning DG placement and integration with existing power system networks. With the incorporation of DG, power system no more remains passive rather it becomes active, and creates several technical and economic issues of protection, operation, reliability and cost [11]. Hence, the proper algorithm and technological advancement must be incorporated to deal with the issues of poor voltage, stressed lines and increased losses due to improper DG integration [12]. Since utilities are concerned with technical and economic benefits governed by DG integration, it must be operated in a sophisticated and planned manner. Optimal planning for the placement of DG units is the way to improve the system reliability and other technical aspects such as loss reduction [13]. As a result, optimal DG placement and sizing are required to better the voltage profile and consequent reduction in system losses.

As discussed earlier DG is considered as source of real power, it may or may not require injecting reactive power in the system. However, it is reported that DG with both the real and reactive power is quite effective in improving system's technical performances in terms of better voltage and power losses. DG integration follows a parabolic pattern (U-trajectory) between DG injection and power losses [4]. Beyond an optimal size DG leads to higher system losses [14]. Authors have also reported that DG could also have a positive impact on voltage stability margin of distribution system [15], [16]. The optimum placement of DG is necessary to achieve the maximum benefits with less investment cost [17], [18].

1.1.2 Recent Advancement in DG Configurations

Unlike DGs represented as PQ sources injecting real power, reactive power or MVA at certain power factor as mentioned in previous section, new type of DGs are going to be mostly inverter based current controlled sources. However, such type of DGs may also be modelled as PQ sources. Current output of these sources together with their output voltages may be regulated to inject desired amount of real and reactive power to the system. Some common control strategies used in inverter for this purpose are:

- Voltage control: The inverter's control system can regulate the output voltage magnitude and phase angle to maintain a stable voltage at the point of connection. This helps in supplying or absorbing reactive power as needed to support the grid.
- Frequency control: In case of grid-connected inverters, the control system should synchronize the inverter's output frequency with the grid frequency to ensure proper power injection and grid compatibility.

- Current control: The inverter should be capable of controlling the output current to supply or absorb active power according to the power system's demand.
- Power factor control: The inverter's control system can regulate the power factor by adjusting the reactive power output to maintain a desired power factor level (typically close to unity for grid-connected inverters).

By implementing these control strategies, an inverter can effectively behave like a PQ source, injecting or absorbing both active and reactive power as required by the power system to maintain stability, voltage regulation, and overall reliability. PQ-controlled inverters are commonly used in modern power systems to support grid operations, enhance grid integration of renewable energy sources, and provide ancillary services like reactive power support and voltage regulation.

1.1.3 Network Reconfiguration – An overview

One of the important tools in the planning and operation of a distribution system is network reconfiguration. Network reconfiguration is defined as altering the structural topology .of distribution system by opening and closing the different set of switches associated with tie-lines and sectionalizer; however, keeping the radiality of the system intact under normal operating conditions [19]–[22]. Network reconfiguration proves to be a viable solution for lowering distribution system losses and increasing system voltage stability margin as a consequence of improved system voltage profile. As an illustration in Figure 1.2, if the line 18 is out of service due to fault or maintenance purpose, the loads at buses 19 to 22 will be isolated from the feeder substation bus and no power will flow to these loads. To restore these loads for power supply either line 33 or 35 must be closed. During the process of reconfiguration additional care must be taken so that:

1. The radiality of the system remains intact.
2. All load buses must be connected to feeder substation bus.
3. The bus voltages and line current must operate within their permissible range.
4. The feeder substation or transformer must be able to sustain the additional load.

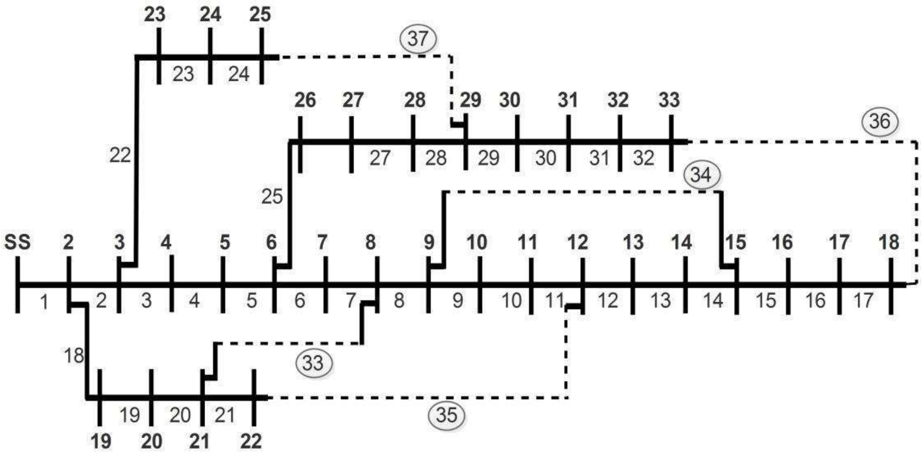

Figure 1.2: Reconfigurable distribution system

1.2 LITERATURE SURVEY

Due to increasing load demand and lack of infrastructural update efficiency and cost benefits of transmission and distribution system has also been compromised as most of the generated power couldn’t be available to the end customer due to higher power losses. In distribution system, more than 13% of generated power account for heating losses due to Joule effect [23]. The Joule effect refers to energy which is lost as heat in the conductors. Figure 1.3 presents the total transmission and distribution losses occurred (in per cent of total power generated) for some countries in the world [24]. According to World Bank reports, an average of around 8.25% of electrical power generated accounts for transmission and distribution losses annually for the whole world. Countries such as Iraq and Haiti experiences more than 50% of energy losses of their actual energy generated, Haiti being the most suffered by 60.11% energy loss. These losses are so huge that they not only create major technical issues by reducing the overall efficiency of the power grid but also severely impact the economy of these countries. Hence, this issue requires major focus of current research to utilize the existing infrastructure efficiently with better planning and using available technologies effectively.

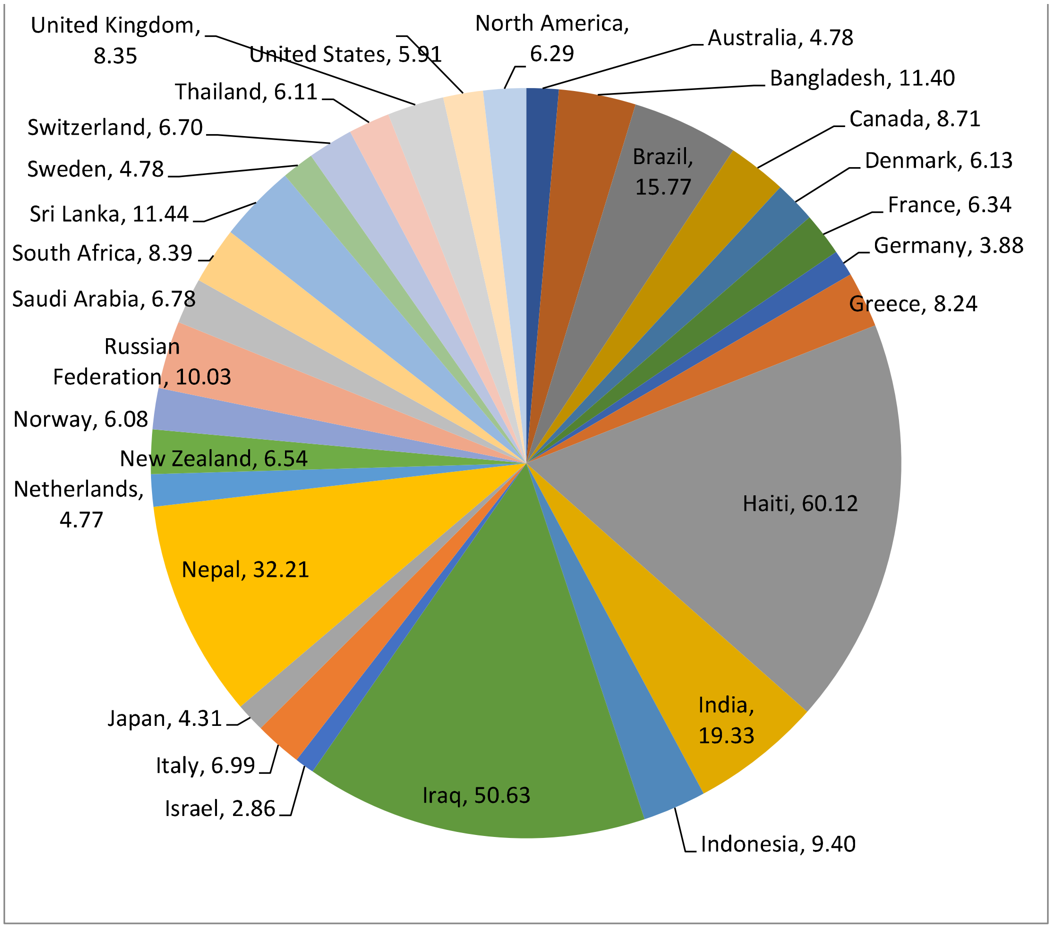

Figure 1.3: T&D losses as a percentage of power generated for year 2014 [24]

In the literature, researchers have focused on reducing real power losses to improve the efficiency of current system infrastructure [25]. Changing the distribution voltage level, using high-quality conductor material, replacing old conductors with larger diameters, reconfiguring the network, and placing a shunt capacitor bank and DGs have all been suggested by different authors as ways to reduce power losses. A brief literature survey on power loss reduction through DG placement and network reconfiguration have been presented in subsections 1.2.2, 1.2.3 and 1.2.5.

The phenomenon of voltage instability is not new to power system engineers and academics. The phenomenon is well-known and well-explained [26]–[28]. Despite this, the world has been plagued by blackouts caused by voltage instability. On distribution systems, voltage collapse and high or low voltages have occurred with much greater frequency and severity [29], [30].

Voltage collapse is a word that is frequently used to describe the severity of voltage instability issues. Voltage collapse occurs when a sequence of events preceding voltage instability results in a blackout or abnormally low voltages in a significant area of the power system [31]. Various blackout events have been observed in recent decades as a result of voltage instability problems, such as the North American blackout in August 2003 [26], the western North American power system blackout on 2 July 1996 [27], and the Belgium blackout during August 1981 [26], [32]. As happened in the S/SE Brazilian system in June 1997, voltage instability in a distribution network can migrate to the transmission network, resulting in a blackout [30]. As a result, during the planning and operating phases of distribution systems, voltage stability requirements must be considered.

1.2.1 Predicting voltage instability in distribution system

Using steady state analysis different indices of voltage stability have been proposed to predict voltage collapse in power system by several researchers. Jasmon and Lee in their work have proposed the network reduction techniques and developed a mathematical formulation to predict voltage collapse [33]. Mohagvemi *et al.* have developed and predicted voltage collapse by means of most critical line within the system [34]. Authors in [35] have reported different indices to predict voltage collapse point based on a power transfer in a single line.

Another group of researchers have studied singular-value and eigen-value analysis of Jacobian based voltage stability to predict the collapse point [36]–[38]. The idea behind the detection of voltage collapse point is to monitor the minimum singular-value or eigen-value of the system Jacobian, which turn out to be zero at the collapse point. The study of the system eigenvectors or singular vector helps in finding the most vulnerable buses and the most sensitive direction for change in power injection by right vector and left vector, respectively.

Voltage stability may be determined in terms of maximum loadability. Maximum loadability refers to the ability of power system network to serve the increased load demand until the point of voltage collapse also referred as the nose point. Numerous definitions and terms for loadability and maximum loadability of the system such as loading ability, load capability, loading margin, voltage stability limit and voltage stability margin have been revealed in [36], [39]–[54]. These definitions may vary with the constraints and stability of system considered and the representation of loading ability (either in percentage or pu of system kVA). In this thesis, voltage stability margin in terms of maximum system loadability has been considered.

Loading factor or loadability of the system may be defined as the increase in system load as a multiple of the base case load, without violating the physical and operating system constraints. The physical constraints are governed by current carrying capacity of line and operating constraint by voltage limit of the system buses. The loading of the system is increased gradually by multiplying the base case load till the load flow divergence observed. It is denoted by variable λ.

Maximum system loadability or **Voltage stability margin** is defined as distance between the initial operating point till the voltage stability limit that is the point of occurrence of voltage collapse where, load flow divergence is experienced. Maximum loadability of the system indicates the amount of load increment being served and system stressed before reaching the voltage instability or collapse. Thus, the maximum system loadability may be defined as the maximum increase in system load from the initial operating load till the load increment at which voltage collapse happens. The maximum system loadability of the system represents the load factor in multiple of initial operating load till the point of voltage collapse and denoted by the symbol λ_{max} The maximum system loadability of the system may also be termed as 'Voltage Stability Margin (VSM)'.

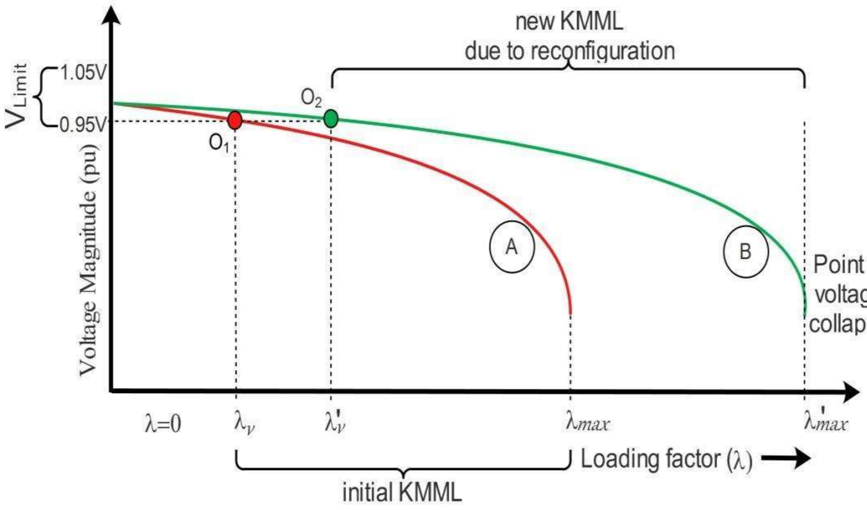

Figure 1.4: Effect of network reconfiguration on KMML [51]

Venkatesh et. al. have defined another terminology [51] for voltage stability margin as **kVA Margin to Maximum Loadability (KMML)**. It is defined as the distance (in kVA) from the system operating point at the allowed voltage limit 'O' to the point of voltage collapse. As an example, shown in Figure 1.4, reconfiguring the network by closing the different set of the switches leads to a different KMML value.

From Figure 1.4, it may be witnessed that for a certain configuration the curve A represents the loadability curve. In this scenario the distance between λ_v to λ_{max} i.e. $(\lambda_{max} - \lambda_v)$ is initial KMML. By closing a different set of switches a new curve B is drawn. Here the new KMML is evaluated using the new operating loading factor λ_v' and updated maximum loadability λ_{max}'. The updated switching configuration results in improved voltage profile across all the loading values. It is also worth noting that network reconfiguration results in an improved operating point from point O_1 to point O_2, at an increased loading factor λ_v'. Milano and Hedayati have proved that increase in system maximum loadability results in improved voltage profile of the system [49], [55] as shown in Figure 1.5.

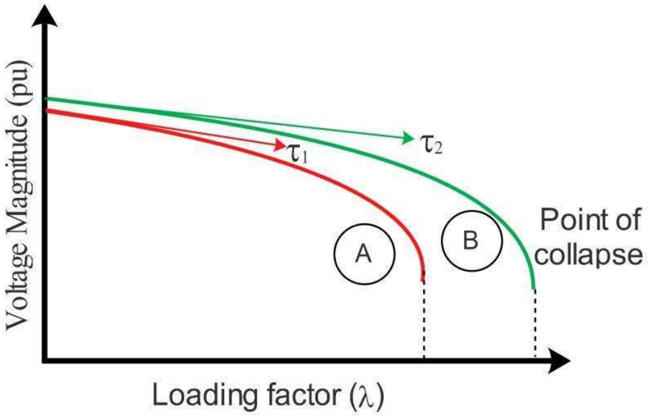

Figure 1.5: Effect of enhanced maximum system loadability on Voltage Profile[49], [55]

According to Figure 1.5, at each loading values curve B with improved maximum system loadability exhibits a better system voltage profile than curve A. In Figure 1.5, τ represents the predicted tangent vector at various loading values.

Several methods have been suggested in literature to determine maximum loadability of power networks [52], [56]–[58]. A novel fast voltage stability index has been formulated to determine the maximum loadability in a power system [41]. Remote end buses of radial distribution network may undergo very low voltages particularly under contingencies that may lead the system to limit resulting in voltage instability [47].

Maximum loadability (voltage stability margin) may be enhanced through optimal placement of distributed generations. Several techniques have been suggested in literature to enhance voltage stability margin in terms of maximum loadability through DG placement and network reconfiguration. A brief literature survey on maximum loadability enhancement through DG placement and network reconfiguration has been presented in subsections 1.2.4 and 1.2.6, respectively.

1.2.2 Analytical approaches to solve DG placement problem

The day by day increase in electrical power demand as load is increasing rapidly has rendered the existing central generation and transmission network unable to manage such a large burden. This increasing power demand has challenged the power engineer to maintain the power system reliably, securely as well as economically. Hence it is clear that either increasing the capacity of existing transmission network or production and supply in a small scale near the load centre can cope up with these issues. Power production of small generation units dispersed across the power grid or networks is defined as Distributed Generation (DG) [59]. These power producing technologies have led the multi-dimensional research opportunities in the field of Distribution system operation and planning [60]. Apart from traditional large-scale power generation utility, distributed generator installation near load centre requires very less capital, operation and maintenance costs. Renewable energy technology based distributed generators are environment friendly.

Placement of distributed generators changes the flow of power in the network and thus results in change in network losses. It has been shown that poor power factor, size and location of DG results in increased distribution losses compared to optimally placed DG [12], [61], [62]. Effective placement of DGs may lead to reduction in distribution network power loss, thus saves the revenue involved. Several works have addressed loss minimization using optimally placed distributed generators.

Various analytical approaches for determining optimal integration of DG by their location and size have been reported [63]–[65]. Proposed Capacitor placement method by Cook [66] was utilized to place DG by Willis using 2/3 thumb rule [67]. The 2/3 thumb rule of DG placement proposes an approximate location and size of DG that must be two-third of feeder length and load respectively. Based on the kind of load distribution in the system and DG penetration level authors have found different location for their installation [61]. Authors have proposed loss sensitivity expression to evaluate the best DG size using exact loss formulae at a particular location and utilizes this location to install DG into the distribution system [4]. Though in their work authors have computed sensitivity to only real power authors in [10] have modified the formulation to consider other types of DG that were capable of injecting not only real power but also injecting reactive power and their combinations. Using Branch-Current to Bus-Voltage (BCBV) and Bus-Injection to Branch-Current (BIBC) matrices loss sensitivity to current injection has been proposed to allocate DG [63]. Authors of [65] have further analysed the analytical method of exact loss formulae and improved it to consider the DG injection at optimal power factor for additional reduction in system losses. A novel analytical method was introduced by [68] to deal with the issues of convergence for the system with high R/X ratio. They developed a new factor which is able to calculate and find the best site for DG injection based on loss sensitivity to effective total load on receiving bus of equivalent two bus distribution network. In [64], a novel approach has been proposed that do not require calculation of Z-matrix required in [68] under the presence of novel remotely controlled buses. Another algebraic approach was proposed to improve the voltage profile by optimally allocating the DG location and size based on algebraic equations for uniformly distributed loads in the radial system [69].

1.2.3 Artificial intelligent methods to solve DG placement problem

Soft computing driven approaches have also been studied and reported for DG allocation considering single and multiple objectives into fitness function. Genetic Algorithm (GA) based optimization are proposed in [70]–[73] to optimally allocate the DG considering various objectives concerned. Hybrid GA-Fuzzy approach have been proposed to improve system loss voltage stability margin and profit of utility operating as DISCOs by optimal DG allocation [74]. A hybrid of GA and PSO was proposed to optimally locate the DG considering multiple objective of loss, voltage stability and voltage deviation into a single fitness function [75]. GA based approaches are useful in optimizing multi-objective functions with computationally slow in convergence [76].

Dynamic programming approach was proposed to get the maximum cost benefit in terms of loss and cost reduction by optimally allocated DG [77]. Modified PSO based wind DG allocation was carried out to improve the apparent power, voltage performance gas emission index [78].

Considering network loss and power quality improvement adaptive Ant Lion Optimizer was proposed under various scenario to allocate DG [79]. Authors have enhanced the reliability of the system using Ant Colony Search (ACS) Optimizer to locate the DG and recloser optimally [80]. An improved multi-objective Harmony Search (IMOHS) considering loss and voltage deviation was solved for optimal solution of DG [81]. A novel micro grid planning approach has been proposed considering different cost of DGs and profit to both the load and utility as optimization objective in a long term perspective to find the location, size and combinations of intermittent and dispatchable DG units using mix-integer programming (MIP) [82]. The placement of distributed generators (DGs) and shunt capacitors (SCs) are the most popular mechanisms to improve the distribution system performance. An enhanced version of GA by combining the virtues of GA and local search have been proposed to get the most suitable place and capacity of DGs and SCs simultaneously [83]. Improved Harris Hawks Optimization (IHHO) is developed and applied to find the optimal DG operation in distribution systems [84].

A utility and consumer benefitted Distributed Energy Resources (DER) allocation strategy based on nature inspired elephant herald optimization technique has been proposed [85]. N. Kanwar et. al. presented simultaneous placement of DERs and shunt capacitor using improved version of meta-heuristic particle swarm optimization to minimize power loss [86]. A two stage DG allocation with enhanced Taguchi Method (TM) has been proposed where DG location is decided using roulette wheel criterion and its size is optimized with improved TM [87]. A modified Cuckoo search algorithm based on Genetically Replaced Nests is applied for loss reduction and voltage profile improvement on benchmark networks considering different numbers of DGs placed in the system [88]. Optimal location and size of DGs with reconfiguration has been obtained for optimal performance of distribution network using non-dominated sorting Genetic Algorithm and Energy Not Supplied (ENS) to minimize power loss and associated cost [89]. The concept of network reconfiguration by opening and closing the tie switches and maintaining the radial nature of distribution network to minimize the losses and voltage deviation has been proposed [20], [90], [91]. Analytical expressions have been proposed for finding optimal size and location of DGs to minimize distribution loss and improve voltage profile of buses [4], [10], [92]. Placement of multiple DGs using Improved Analytical (IA) method has been proposed for loss minimization and voltage profile improvement [65]. A hybrid method for loss minimization using multiple DGs has been proposed [93]. A Grey wolf optimizer (GWO) based search algorithm have been studied in [94], [95] to optimally locate the multiple DGs of supplying real and reactive power and their combination to reduce the reactive power losses and voltage deviation. Energy Storage location and size based on GWO technique to reduce the annual cost has been studied incorporating Energy not supplied in [96]. Photovoltaic (PV) and Wind based renewable energy resource placement have been done in [97] to reduce the real power losses using GWO as optimization technique.

1.2.4 DG placement based on voltage stability approach

Researchers have also addressed the issue of voltage stability with the help of DG placement [39], [47]–[49], [98]. Authors have solved the optimal DG bus by GA considering voltage stability margin enhancement up to allowable voltage limit [39]. Distribution systems, in general are radial in nature and power flows from substation to downstream to the end node, and hence a significant amount of increasing voltage drop results in lower voltage level at the end node limiting the voltage stability and hence loadability of end buses as well as overall system [47]. Authors of [47] considered the weakest bus approach with the voltage stability margin to be maximum with optimal DG placement. Reference [49] also considered the weakest voltage bus as a possible bus for optimal DG placement to enhance voltage stability margin. The Continuation Power Flow (CPF) theorem is used to determine the weakest voltage bus [40], [56], [57], [99], [100]. Optimal placement of DGs based on Particle Swarm Optimization (PSO) has been considered for enhancement of maximum system loadability [48]. Reference [49] has also extended the work for multi DG unit placement after the first DG unit has been successfully placed.

Modal analysis based continuation power flow for optimal bus was used to analyses the impact of number of fixed DG penetration in a sequential manner to enhance voltage stability margin [15]. When more than one DG unit is placed, techniques based on sequential DG bus selection [15], [49] cannot achieve to the global maximum voltage stability limit. DGs were primarily regarded as a real power source [3], but with the increasing load and non-optimal DG penetration resulting in poor system voltages dictated reactive power compensation through DG integration to keep the voltages within permissible operating limit [101]–[107]. Non-optimal and non-dispatchable DG penetration may adversely impact the power management planning [104], [105]. For example due to a variety of load types and the intermittency of renewable based DGs, distribution systems become heavily and lightly loaded during different intervals of time, leading to disturbance in power quality as well as voltage deviation beyond the permissible limit. To mitigate voltage violations, reactive power compensator such as shunt capacitors and load tap changers are currently used. However, due to the penetration of DERs in distribution systems the response of these traditional devices is slower and not acceptable in fast voltage control. Fast-reacting, VoltVAr devices such as smart PV inverters [108] and Power electronics based soft-open-point [109], [110] and various other means [111] such as synchronous generator, shunt capacitor banks are helpful in reactive power compensation.

Fast Voltage Stability Index under varying load growth and penetration of wind and photo-voltaic have been reported for a practical Japanese distribution system to study its voltage stability enhancement [112]. An ε-constraints based teaching and learning algorithm has been proposed to maximize system loadability and minimize losses under reconfiguration and DGs placement [113]. A probabilistic nature of renewable DG and load modelling has been studied to decide the optimal location and size of DGs for voltage stability enhancement [114]. A new multi-objective index based optimization considering active and reactive power loss minimization in presence of DG unit has been proposed to enhance system loadability [16]. A voltage stability index driven optimal location of DG under increasing load has been reported for voltage stability improvement [18]. The hybrid differential evolutionary and particle swarm optimization approach has been reported to enhance the system loadability [115]. An analytical power stability index based DG placement algorithm has been proposed to realize the DG influence on loadability, network losses, and voltage magnitude [116]. An effective swarm-based optimization for DG placement has been reported to enhance voltage stability and reduce network losses [117], [118]. Placement of permanently connected capacitor wind-operated squirrel cage induction based dispersed generator has been performed to enhance voltage stability [119].

Voltage stability is a critical factor, that analyse the security level of a system [56]. The increasing load growth in distribution network may lead to growing voltage instability and creates hindrance to load served by distribution utilities. Voltage instability in distribution systems could lead to voltage collapse and thus power blackouts in a certain or whole part of power system. One prime cause of this problem is the inability of the system to supply the reactive power demand. Additional power injection through integrated reactive power source and/ or renewable distributed generation (DG) in a small scale located near the load centres seems to be remedies to these challenges [112]. At the maximum load level, buses would experience a drastic voltage drop to sustain the system security in terms of voltage stability. Presence of Renewable energy sources has a great mitigation effect on these challenges. These renewable energy sources not only improve system performances but also prove to be the key solution for such kinds of voltage insecurity if planned properly. The location and size of these resources for planning and execution of the power network are very important in terms of active and reactive power losses, voltage profile enhancement, network securities and other key features. Furthermore, the proper penetration of renewable leads to economic and environment friendly concerns over the traditional centralized generation [1]. These renewable energy sources are located at the customer or load end in the distribution network and comes with a viable solution with increased load demand and other challenges to deal with.

Voltage stability has been improved by identifying the weakest bus prone to voltage collapse and allocating reactive power compensation at this bus with novel reactive loss index and fuzzy logic approach [120]. Static VAR Compensator placement has been done by calculating sensitivity of load factor with respect to reactive power to improve the system voltage stability [121]. A sensitivity based Allocation of different types of DG based on PSO techniques have been investigated for enhancement of System Loadability [48]. Maximum loadability in terms of voltage stability limit has been enhanced through renewable DG by allocating optimally within the distribution system [122]. In another work, on a practical Japanese test system, penetration of solar and wind renewable energy sources improves the overall performance of the system in terms of voltage stability and maximum loadability [112]. The hybrid of particle swarm optimization and differential evolutionary algorithm has been presented to enhance the system losses as well as maximum loadability [123]. An analytical approach for DG placement based on stability index for line flow has been proposed to realize the DG impact on loadability, voltage stability, system losses, and voltage profile [9-11]. Wind-based induction generator (SCIG) with a permanently connected capacitor is installed to enhance the voltage collapse index, voltage profile [119].

1.2.5 Classical approaches of network reconfiguration

Network reconfiguration is another important strategy that is being utilized for performance enhancement of distribution networks through closing and opening the sectionalizers and/or tie lines. Altering the network topology by opening and closing the switches and transferring the load to other feeder path is termed as reconfiguration [124]. Merlin and Back were the pioneer in introducing the concept of network reconfiguration. They suggested and proved it as viable tool to maximum reduction in the power losses [90] first of all in 1975. They closed all the tie-lines in the system initially that resulted in a weakly meshed network. Following the opening of one switch at once successively based on minimum power loss they arrived at a radial network with different topology than earlier. Further, Shirmohammadi and Hong upgraded the Merlin approach by escaping the approximation considered by them [90]. Shirmohammadi also started with closing all the tie-switches initially assuming each branch switch as a fictitious current source and running optimal power flow considering one switch at a time to open in a loop based on minimum resistive line loss. Consequently, they considered reconfiguring the network maintaining its with radial topology and minimum system losses [125]. The method proposed has considered the line ampacity constraints and proved to be more efficient in terms of computational burden compared to Merlin approach.

In 1988, Civanlar and their other associates have proposed an effective “feeder exchange approach” to change the topology of the network by altering the switches and considering the load transfer among different feeders to reduce the network losses [19]. Later on in 1989, Baran and Wu enhanced the branch exchange method [19] by approximating the power flow equations and programming the reconfiguration as an integer problem to achieve the maximum reduction in network losses [126]. In the same year, Lin and Chin have solved the reconfiguration problem with the objective of service restoration, along with maximizing the loss reduction [127]. Zhu et al. performed the network reconfiguration based on modified heuristic solution and experience system operation rules [128]. Zin and their other associates [21] have analysed the heuristic approach for network reconfiguration considering maximum reduction in losses proposed by Baran and all [126]. The heuristic approach utilizes the minimum current carrying branch found to obtain the final solution.

Since most of the approaches reported above select one branch at a time to arrive at a decision and hence results in a computationally exhaustive mechanism, these approaches proved to be inefficient in terms of time consumed and memory used as the network becomes larger and complex. Different nature inspired swarm based intelligent and greedy heuristic optimization approaches have been suggested in literature to overcome these challenges. These are referred as Artificial Intelligent (AI) approaches. Artificial intelligent based approaches are a distinction of heuristic approaches [129]. Intelligent based optimization methods have also been utilized in finding optimal set of switches for network reconfiguration. Authors used Genetic Algorithms (GA), fuzzy [130], neural networks [131], [132] Fuzzy- GA [133], Matroid Theory [134], Bacterial Foraging Algorithm [135], and Discrete Artificial Bee Colony (DABC) [136] etc.

1.2.6 Network reconfiguration based on voltage stability approach

In general, distribution system constitutes a mix of residential, commercial and industrial types of loads. The feeder of these systems may experience variable load patterns at different time frames with changing days and seasons. At some point of time, the system is loaded heavily while at another time it is lightly loaded. In such a scenario, load scheduling by reconfiguration may lead to optimal performances with regard to system losses and voltage stability. Reconfiguration of radial network smoothens peak demands that improve the voltage profile, and maximum loadability thus making the network quite reliable [46]. Optimal reconfiguration with different optimization techniques have been reported to enhance the system loadability [51], [137]–[140]. A fuzzy genetic rule-based optimization for reconfiguration is studied to enhance voltage stability [141]. A discrete artificial bee colony approach is adopted based on Continuation Power Flow algorithm to enhance maximum loadability of system [136], [142]. A two-stage algorithm for reactive power loss minimization to enhance voltage stability, and loadability enhancement through network reconfiguration has been proposed [143]. A two-stage hierarchical optimization approach has been presented to tradeoff between enhanced maximum loadability and reduced network losses under reconfigurable [134] and integrable DG environment [144], [145]. The matroid theory based reconfiguration was carried out with the help of graph theory [146].

Das and Savier [147], [148] have proposed a novel fuzzy based approach to reduce network losses considering novel voltage stability index. Su et al. have considered loss minimization and the operating constraints assigning penalty to the latter and combined them to form a single fitness function [149]. The fitness function was optimized using ACS algorithm. Simultaneous cost minimization and reliability enhancement were proposed by [150] to determine optimal values of feeder routes and network switches in two different steps. Reconfiguration of radial network smoothens peak demands that improves the voltage profile and maximum loadability thus making the network quite reliable [46]. Optimal reconfiguration with different optimization techniques have been reported to enhance the voltage stability margin [137], [139], [140]. A fuzzy genetic rule-based optimization for reconfiguration is studied to enhance voltage stability [151]. A discrete artificial bee colony approach is adopted based on Continuation Power Flow algorithm to enhance maximum system loadability [152]. A two-stage algorithm for reactive power loss minimization to enhance voltage stability and loadability enhancement through network reconfiguration has been proposed [143]. A two stage hierarchical optimization approach has been presented to trade-off between enhanced maximum loadability and reduced network losses under reconfigurable [153] and integrable DG environment [145], [154].

The authors of [46], used the voltage stability index proposed in [62] to find the best switches using heuristic approach. Voltage profile and maximum loadability margin based multi-objective fuzzy model have been considered to optimize the reconfiguration switches using evolutionary algorithm. [155] has proposed a heuristic based voltage stability maximization algorithm by evaluating the voltage stability index (VSI) reported in [156]. Such approaches improve the voltage stability margin of the system, but they do not achieve the best solution.

1.2.7 Simultaneous solution of network reconfiguration and DG placement problems

Optimal DG and switch allocation are treated as two different issues. Though, Researchers have integrated these issues and solved the issue of optimal system performances. For example, the DG allocation has been carried out with the optimal allocation of switches and reclosers. [157]–[163]. Tie-switches and reclosers are the elements capable of operating faulted system by isolating the faulty area and restoring or rebalancing the system in a combined manner. Recloser as circuit breaker works on principal of arc-quenching while by turning itself on and off at short-circuit and normal current values. However, the motive of sectionalizer or tie-switch is to isolate different areas of system, during de-energized situation. Hence it is imperative to operate recloser first in order to safely operate the sectionalizer switches. Combination of DG with recloser and switches allow the operator to isolate the faulty section and continue to supply the system with DG sources in case of upstream fault, as shown in Figure 1.6 [158]. Operation of DG in association with switches and reclosers increases the overall performance of distribution.

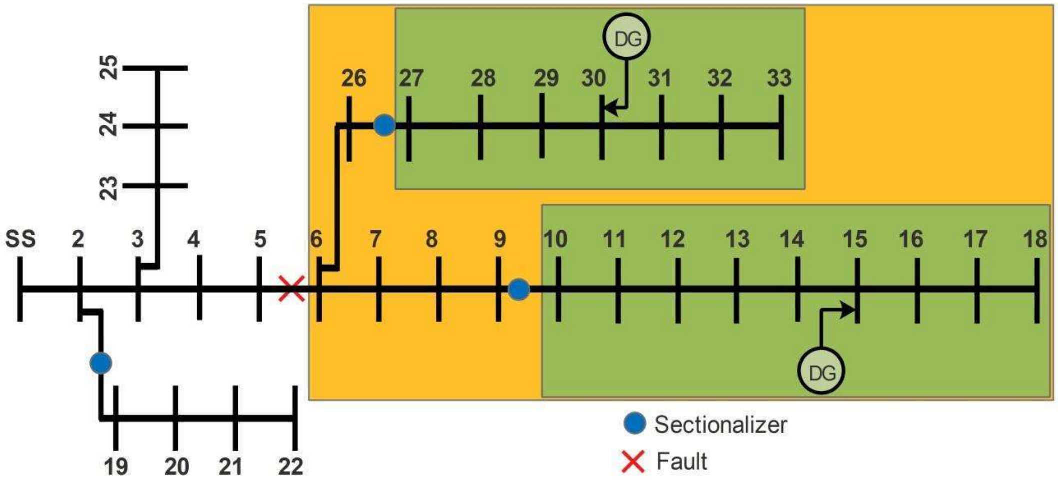

Figure 1.6: Improved system reliability by switch allocation in presence of DG

In literature researchers have carried out the analysis of DG allocation and network reconfiguration individually or by using both of them one followed by other and simultaneously [20]. These applications may be categorized as given below:

Scenario 1: This scenario considers only network reconfiguration.

Scenario 2: This scenario considers only DG placement problem.

Scenario 3: This scenario considers DG placement followed by network reconfiguration.

Scenario 4: This scenario considers network reconfiguration followed by DG allocation.

Scenario 5: This scenario considers simultaneous DG allocation and network reconfiguration.

It has been observed that either DG placement or network reconfiguration alone reduces the distribution losses to a great extent and enhances the system performance. However, if these tools are exercised simultaneously, they results in a higher loss reduction compared to individual application of these or their sequential application [20].

1.2.8 DG placement and reconfiguration under P, Q and PQV buses

In traditional transmission and distribution systems, the presence of PV and PQ buses is very common. Static voltage stability analysis has been carried out by introducing a novel bus type referred to as bus AQ with known reactive power demand and bus voltage angle [164]. Thus, voltage magnitude and real power at the AQ bus remain unknown. In recent publications, the concept of voltage control at PQV buses by remotely located P buses has been introduced. The dedicated P bus having pre-defined real power injection has variable reactive power source that controls the voltage of PQV bus [165]–[167]. A PQV bus is defined as the bus with pre-specified quantities of active power, reactive power and voltage magnitude. Only the voltage angle of this bus is unknown. A P bus is defined as a reactive power generator bus which is maintaining the voltage magnitude at PQV bus constant at the required value [165]. For a P bus, the quantity of active power is pre-specified. The quantities reactive power, voltage magnitude and voltage angle at this bus remain unknown and hence need to be calculated. Injection of regulated reactive power at generator bus P results in maintaining the desired value of the voltage magnitude of PQV bus located remotely [166]. The PQV bus thus has pre-defined voltage magnitude in addition to predefined real and reactive power injections. Loss minimization under reconfigurable and optimally integrated DG environment has been performed in a system employed with remotely located PQV bus with its voltage magnitude being maintained by variation of reactive power injection at the selected P bus [64], [168]. The bus with minimum voltage magnitudehas been chosen as PQV bus while P bus in the system is chosen with the reactive power injection. A Q bus is defined as a bus that has pre-defined reactive power injection with active power, voltage magnitude and angle as unknowns. No attempt seems to be made in loss minimization and loadability enhancement through use of Q and PQV bus consideration.

1.2.9 DG placement and reconfiguration under voltage dependent time-varying loads

In classical static analysis of power system, loads at system buses are considered as constant real and reactive powers and are independent of frequency and voltage. However, it is not true for practical loads. Voltage dependent loads may be classified in three categories as constant current, constant impedance, constant power loads, or any combination of these three types of loads [169]. The residential, commercial and Industrial loads are functions of system voltage, in general [170]. Common static load models for active and reactive power are expressed in a polynomial or an exponential form. Moreover, load characteristics have significant effects on load flow solutions and convergence ability [171]. This voltage dependency, if modelled properly, results in quite different power flow solutions.

PSO based multi-objective optimization approach was carried out for placement of multiple DG units in a radial distribution network considering load power demand as function of bus voltage [172]. The multi-objective index included intake from the feeder substation, short circuit level, line loading, real power loss and reactive power loss, and voltage regulation. For placement of photovoltaic unit placement, an analytical expression based multi-objective approach was established to reduce the real and reactive power loss and voltage deviation considering different types of time-varying voltage-dependent load models [173]. In purview of maximum utilization of DG power injection, an extensive analysis was performed under the aegis of multiple DG units of different types considering pre-defined voltage dependent yearly load pattern [174]. A quantum inspired evolutionary optimization was proposed to establish the effect of different voltage dependent load models on location and sizing of DG units on system loss and voltage profile [175]. A pareto front based optimization was proposed to minimize loss and voltage deviation to consider the technical and economic benefits by optimal DG placement considering different types of voltage dependent yearly load [176]. Photovoltaic and wind based DG placement was considered under the aegis of reduction of real power loss, reactive power loss, voltage deviation and line volt-ampere with the time-varying voltage-dependent load models [177].

Reconfiguration was proposed to minimize the network loss by estimating the daily and seasonal voltage dependent load variation [178]. Automatic and manual switching operations were considered for reconfiguration. Singh et. al. have presented a brief overview of system minimum loss vs. system minimum intake considering the different load model and reconfiguration in their studies [179]. Based on their analysis they have concluded that system reconfiguration draws higher amount of power from substation and hence results in high power loss if proper load model is not considered. Network

Reconfiguration was performed with voltage dependent load by accumulating the actual network voltages to reduce system loss [180]. A genetic algorithm based reconfiguration was proposed to minimize the loss and voltage deviation in presence of multiple PV generators considering different types of time varying voltage dependent load aggregated at different feeder sections [181]. Artificial intelligence method was used to reconfigure the distribution network to reduce power loss based on ANN technique considering time varying combinations of different types of static load models [182]. In an another attempt under the influence of time varying voltage dependent loads DG placement and network reconfiguration was performed to reduce the network loss and voltage profile improvement [183].

1.3 MOTIVATIONS

From the limited literature survey carried out in this thesis, it seems that many researchers have considered loss minimization and voltage profile improvement through optimal placement of distributed generations. Meta-heuristic approaches seem to be simple and effective approaches in obtaining optimal location and size of DGs. Work may be carried out in finding a still better meta-heuristic approach in terms of its effectiveness and convergence rate as far as DG placement is considered. Optimal DG placement and network reconfiguration may be effectively utilized in loss reduction and voltage stability enhancement of distribution networks. Limited work has been reported regarding simultaneous reconfiguration and DG placement for loss minimization and no work seems to be made in voltage stability enhancement through simultaneous reconfiguration and DG placement. Very limited work seems to be made in loss minimization under presence of P, Q and PQV buses. No effort seems to be made in loss minimization and voltage stability enhancement through simultaneous DG placement and reconfiguration under presence of P, Q and PQV buses. Very few attempt seems to be made in loss minimization and voltage profile enhancement under time varying voltage dependent loads. Therefore, motivations behind work carried out in this thesis are:

- To propose a meta-heuristic approach that gives accurate estimation of power loss and voltage profile in distribution network with fast convergence rate.
- To suggest an approach for simultaneous DG placement and network reconfiguration that is very effective in loss minimization and voltage stability enhancement of distribution network.
- To see the impact of P, Q and PQV buses in loss reduction and voltage stability margin enhancement.
- To investigate power loss and voltage profile of distribution network under time varying voltage dependent loads, and to see impact of DG placement and reconfiguration in loss reduction and voltage profile improvement under presence of such loads.

1.4 OBJECTIVES

The main objective of this research is to minimize the network losses and/or maximize the voltage stability margin in terms of maximum loadability of the distribution system following the system and operation constraints. To enhance the system performance in terms of above objectives novel set of P/Q and PQV buses are modelled in distribution network. Firstly, a P/Q bus is identified and corresponding power injection has been calculated to enhance the system performances. Further, simultaneous optimal tie-switches as well as DG location with their optimum size have been evaluated to additionally enhance the system objectives. These approaches will help in the effective utilization of the existing distribution network, and additional load demand can be served without violating the maximum and minimum bus voltage limits and line capacity limits. The thesis also intends to examine the impact of DG and reconfiguration in distribution network performance under time varying voltage dependent loads. In order to achieve these, the following objectives have been defined:

1. To propose a modified Gray Wolf Optimization algorithm to solve power system optimization problem.
2. To solve DG allocation and network reconfiguration problem simultaneously without or with remotely controllable PQV bus by P/Q bus, considering multi-objective fitness function based on voltage stability margin enhancement and loss reduction.
3. To propose a new multi-objective fitness function formulation based on real power loss reduction and maximization of quality load index and solve DG allocation and network reconfiguration problem simultaneously under remotely controllable PQV bus by P/Q bus.
4. To propose a methodology to minimize network loss and improve voltage profile for time varying voltage dependent load model considering DG and reconfiguration sequentially.

1.5 THESIS ORGANIZATION

This thesis has been organized in following six chapters:

Chapter 1 presents a brief introduction of distributed generations and network reconfiguration and their impact in improving distribution system performance, presents a limited literature survey carried out on loss reduction, voltage stability and profile improvement through optimal DG placement and reconfiguration of distribution network, sets the motivation behind the work carried out in this thesis and outlines main research objectives of the thesis.

In **Chapter 2**, a modified grey wolf optimization (GWO) technique has been suggested for optimal placement of different types of multiple DGs to minimize network loss and improve voltage profile.

In C**hapter 3,** voltage stability enhancement and loss minimization under simultaneous DG placement and network reconfiguration have been presented. A multi-objective function has been proposed that minimizes weighted sum of power loss and negated voltage stability index (in order to consider maximization of voltage stability margin). Optimization has been performed using modified GWO algorithm.

In **Chapter 4**, a new multi-objective function has been proposed based on loss reduction and voltage stability enhancement using quality load index. The quality load index considers voltage level and loading at different buses. Impact of P, Q and PQV buses have been studied in voltage stability enhancement and loss reduction. Optimization has been performed using modified GWO algorithm.

In **Chapter 5**, determination of candidate buses for DG placement has been done using sensitivity based approach while DG size have been obtained using modified GWO algorithm. Thereafter, network reconfiguration has been performed. Impact of DG placement and network reconfiguration has been studied under time varying voltage dependent loads. Two types of time varying voltage dependent loads have been considered (i) Residential Summer night loads and (ii) Electric Vehicle loads.

Chapter 6 summarizes main findings of thesis and sets further research directions.