DISSERTATION

Power System Planning with Multiple Distributed Generators

Submitted at the Faculty of Electrical Engineering and Information Technology, Technische Universität Wien in partial fulfillment of the requirements for the degree of Doktor der technischen Wissenschaften (equals Ph.D.)

under supervision of

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December, 2016.

Dedicated to

My Parents, Abdul Razzaq and Bibi Ruqayya; for their continuous support, encouragement, love and care which helped me to be the person I am today.

My wife, Sabeena Zaib Swati, and children Mano and Hani; Thank you for your support and love all along the way.

Abstract

Due to increasing energy demand, preferably from renewable resources, the conventional energy generation, transmission and distribution system is in transition phase. These days, energy generation is preferred near the load centers in order to reduce the burden of transmission lines and increasing environmentally friendly impacts of renewable based generation. Many policy and regulatory drivers have also contributed in motivating for increasing the share of Distributed Generation (DG). This has ignited a huge interest in DGs, resulting in the increased complexity in the operation, maintenance and control of distribution system. Under such scenario, modern power system is facing many challenges for all the stakeholders. It has been observed that the challenges in modern power system are increasing because of current "fit and forget" approach as a result of which the DGs are popping up like mushrooms. Subsequent to this, the operator of modern distribution system remains with very limited and costly options to keep the network operational in accordance with the regulatory bindings. The challenges for Distribution Network Operators (DNOs) may be reduced and advantages of DGs can be multiplied many folds by planning properly prior to their placement.

This work tries to propose a method of optimal DG placement with increased implement-ability in practical systems by addressing the hindrances in implementation of existing methods. The initial step is taken by splitting the problem of optimal DG placement into independent and logically separable parts; the location selection and the size calculation of DG(s). By suggesting this, it is aimed to make the method open for any modification and improvements. For example, the location selection can be made based on the completely opposing objectives of any of the stakeholders. Each stakeholder can formulate a factor in order to translate their objective(s) into respective variable such as "Load Concentration Factor (LCF)" proposed for minimizing the losses and "Geographical Factor" for identifying legally allowed locations. By mixing these factors, final locations are chosen for placement of DGs. If any other factors are required, these can be formulated and included. Consequently, the method becomes open for inclusion of as many objectives as needed. In the second part, where the optimal DG sizes are calculated, it is attempted to get the exact sizes of as many DGs as required for loss minimization using analytical method and *controlled* exhaustive method. If, due to any reasons, exact sizes are not feasible for implementation, nearest available sizes can be chosen at the cost of minor variation in the losses.

Next, the operational power factor is suggested for the DGs placed optimally in the network in order to improve the results further. However, unlike the previous methods, the operational power factor considers a range in which the power factor needs to be set. As a result, the power factor cannot be out of the acceptable range, as done in some of existing methods. To quantify the voltage improvement in the network, a novel "Voltage Quality Index (VQI)" is proposed with the ability to not only show the system's voltage status but also a clue about the exact voltage values at different nodes of the system. This unique index can be used to easily assess the voltage status of complex systems with high accuracy and efficiency. The validity and usefulness of all the proposed methods is compared with different methods *i.e.*, loss sensitivity factor method, improved analytical method and exhaustive method. From the presented results, not only a significant reduction in the active power losses is observed, but the voltage profile, voltage quality and line flows are also improved. Also, in case of varying loads, it has been observed that the voltage problems did not appear or appeared at worse system conditions (in comparison to other methods) which are mitigated comparatively easier with the used "Centralized Voltage Control Algorithm". It is hoped that the system will be flexible for expansion and working with any other parameters, constraints and/or objectives desired in future.

Acknowledgments

All praise be to ALLAH the most beneficent and merciful, Who helped me throughout the course of my life in reaching this milestone. After being thankful to ALLAH, I would like to pay my sincerest gratitude and thanks to Prof. Wolfgang Gawlik who provided an excellent guidance and supervision, yet patiently, for achieving the research goals and completing this PhD thesis successfully.

A very special thank to Austrian Institute of Technology for helping me in fulfilling the research targets by utilizing their broad infrastructure, research platform, and highly skillful and distinguished scientific community. A very special thanks and respect to Prof. Peter Palensky for his guidance and trust to work in the Complex Energy Systems research group. I am also grateful to the other team members, Dr. Wolfgang Hribernik, Dr. Edmund Widl, Dr. Hadrien Bosetti, Dr. Atiyah Elsheikh, Dr. Sohail Khan, Ishtiaq Ahmad, Aadil Latif, Ikramullah and Hamid Aghaie for their continuous support, help and useful stimulating discussions throughout. Especially, the refreshing time spent with Dr. Sohail Khan in Austrian alps is a memorable and remarkable contribution which kept me going.

I am also desperately missing my mother, who died while waiting for this special day of remarkable achievement in my life. Very special thanks to my grandparents, father and family members for their continuous support and prayers. My younger brothers, Mudassar Shahzad and Musadiq Hussain, and my sisters also deserve same appreciation and thanks for their best wishes, support and encouragement. I would like to pay my special love and thanks to my better half, Sabeena Zaib Swati, for her ongoing support and sacrifices, and the care she took for me, my kids and my home with utmost love, patience and courage. My love and promise of utmost care for my kids, Abdul Rehman and Haniah, who have missed many things over the course of my PhD work.

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1 Introduction

1.1 Motivation

1.1.1 Conventional Power System

Traditionally, the power system has a vertical structure with clear distinctive roles of its subparts namely the generation, transmission and distributions systems. The generation system, mostly comprised of bulk generation plants whether the fossil fuels based, nuclear based or huge hydro dams, are responsible for the producing the total energy required. Due to this feature, they are mostly called as centralized generation plants. In case of fossil fuel based generations, which are a most common source of producing electrical energy, emission of huge amount of greenhouse gases lead to the environmental pollution and global warming issues. Similarly, the disposal of nuclear wastes as well as the safety and security of the workers at nuclear power plants is a big question [1]. To build hydro dams for bulk generation, large pieces of land are required for making reservoirs, leading to the displacement of large number of people as well as creating troubles for wild life and ecosystem [2]. The bulk energy is then transmitted over large distances at high, ultra high or extra high voltage levels over the transmission networks. Transmission system also tends to connect geographically separated power plants from different grids. The generation systems/plants are to produce huge amount of power usually at 11 kV to 25 kV levels, while distribution system is for distributing power to the consumers, either industrial, commercial or domestic. It is worth mentioning that the distribution voltage level may vary for different consumers, *e.g.*, the industrial or commercial consumers may require high power which is supplied at higher voltage level by sub-transmission level. Figure 1.1 shows different levels of power system along with the symbolic voltage levels and consumptions. Subsequently, at the receiving end, it is step-down to the medium and low voltage levels for being used by the consumers over the distribution network.

In this vertically integrated structure of the system [3], there has been a clear dominance and control over all the functions by single utility, which is either government owned or government granted. This results in a kind of monopoly franchise [4]. In conventional power system, generation systems are planned separately from those of transmission and distribution systems [5]. It is worth mentioning that this conventional structure of the power system has an advantage of being dispatchable and firm output power. This has made the system more stable and secure. Yet the disadvantages such as incapability of modular installation, higher system losses due to bulk transmission over long distances and limited capability to recover in case of cascaded failure are among the other important factors along with the environmental and geographical impacts.

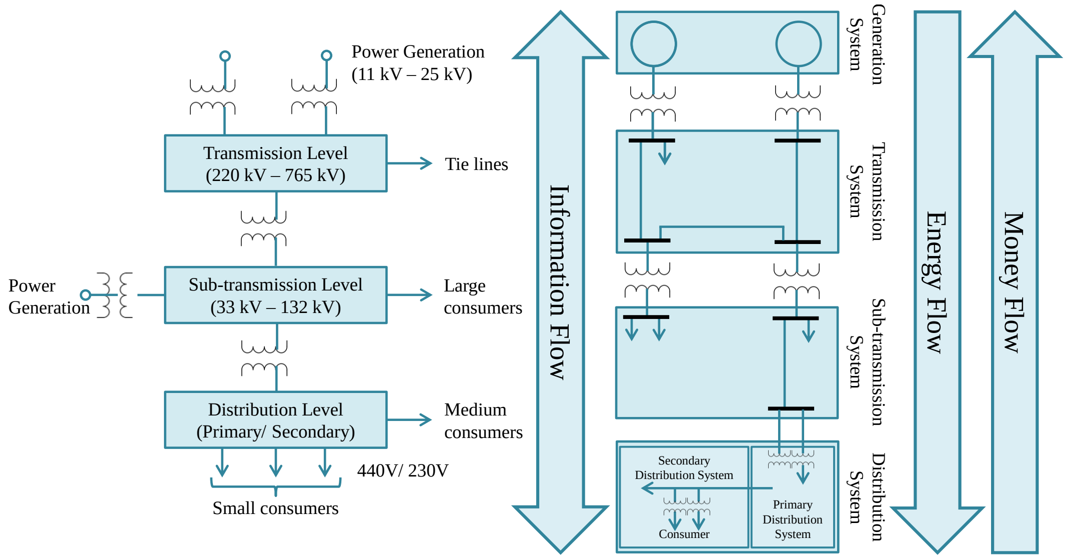


Figure 1.1: Hierarchy in conventional power system structure; Voltage levels at difference network stages; Unidirectional flow of energy and money, and bidirectional flow of information

1.1.2 Transition in Power System

Over the period of about last two decades, there has been an increasing focus to reduce the factors affecting the environment. As well as, the day by day increasing demand of (electric) energy is forcing for producing more and more. Such factors have lead the conventional power system to evolve radically. As a consequence of all these important factors, the conventional power system has now become a horizontally integrated utility with deregulated environment. Interest in small scale generation, which has to be preferably renewable based and are connected to the medium or even the low voltage levels, has increased. The resulting structure of power system has now bidirectional power flow. As mentioned in [6], the important developments in Distributed Generation (DG) technologies has ignited this shift of a paradigm from vertically integrated to horizontally integrated structure of the power system. Several advantages of DGs also contributed as the main factors along with their technical developments [7]. Few of them are as follows [8, 9]:

- These can be installed as small modular units.
- Generation of (electrical) energy with reduced or no emission.
- Reduction in dependence on fossil fuels.
- Possibility of generation from variety of sources.
- Technical improvements in the electrical system such as reduced power loss, improved voltage profiles, enhanced system reliability, improved power quality etc.

The primary energy for the DGs can be acquired from number of sources, such as solar, wind, fuel cells, run of river, biogas, Combined Heat and Power (CHP) and many others. Based on the source of primary energy, the DGs can be categorised as:

- Dispatchable and non dispatchable [10], if they can provide certain amount of power consistently such as CHP or biogas, or not.
- Renewable and non-renewable [11], if the source of primary energy is renewable such as solar, wind or run of river, or not.
- Intermittent and firm, if source of primary energy is intermittent such as solar and wind, or not.

Although the renewable based DGs have low operation and maintenance cost, and they produce emission free energy, their intermittent nature causes the uncertainty and reliability issues in output power of DGs [12]. This influences and affects the amount of power available and the electricity markets [13, 14]. Moreover, the transient and steady state stability of power system with high level of penetration of solar based generation is adversely affected because of their differences from conventional generation [15]. Besides these important impacts of DG integrations, some other vital adverse impacts can be summarized as; reverse power flow, voltage and power fluctuations, voltage rise, frequency regulation and harmonics, unintentional islanding, fault currents and grounding issues [16]. Such negative impacts of DGs have highlighted the need of careful planning schemes for integration of DGs so that the useful environmental outcomes and advantages of them should not be reduced, whereby improving the power quality, system reliability, hosting capacity, congestion management and network stability.

1.1.3 Planning of Modern Power System for DG Integration

Intermittent nature, presumably large number and deregulated energy system has increased the challenges posed to the modern power systems. If it is understood and believed that (at least some percentage of) the problems are arising from penetration of DGs, a logical step is certainly to look thoroughly into the matter of DG installation while looking for their potential solutions.

The literature shows that a few of the major of the previously mentioned problems, like increased line flows, voltage profiles and need of additional equipment, can either be automatically reduced or completely mitigated by properly planning and forecasting the DGs penetration. It would, therefore, be interesting to investigate how big the benefits can be with such study and implementation. This can defer, or even eliminate, the investment on grid reinforcements like Flexible AC Transmission (FACT) controller, Phase Shift Transformers (PSTs) and any other of such methods. Furthermore, such study can help the consumer by providing an improved quality, low cost, reliable and clean energy. The environment gets the benefit due to clean energy and less greenhouse gas emission hence reducing the threats to global warming and pollution.

When considering the current scenario of DG penetration, it can be referred to as the "popping up like mushrooms" situation because the investors can make study on their own economic benefits and energy production only for installing a DG. If they abide by certain grid codes, these DGs must be connected to the system. Unfortunately, there are no detailed consideration of reducing power losses and other technical aspect those might support the consumer or Distribution Network Operator (DNO). The major motivation behind this study is to investigate the impact of a situation which is contrary to the current "popping up like mushrooms" scenario *i.e.*, to provide the DNO with a certain level of control for steering up the direction of DG penetration, while keeping the major interests of the investors under consideration. It is expected that the DNO can identify the location(s) and the desired generation patterns from DGs so that the system performance is improved, energy prices can be controlled and finally the grid reinforcements can be deferred or, preferably, completely removed. This, in turn, can make the DNO to float tenders in the market for inviting the potential investors in DGs. It is obvious that the proposed study enables DNO to control and manage the DG installation based on system improvement instead of lying on the investors' mercy. As the major points of consideration of investors are also kept into account, it is expected to have better acceptance from different stakeholders. This complete scenario is explained in Figure 1.2 and Figure 1.3.

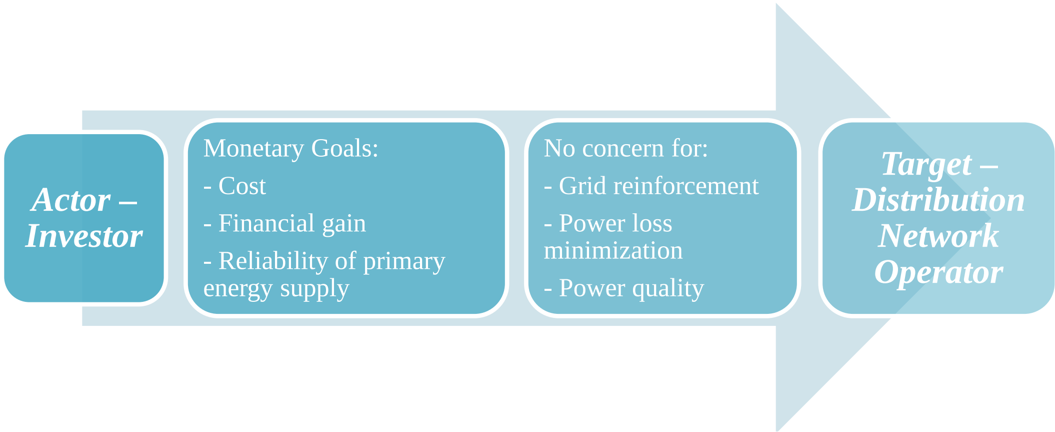


Figure 1.2: Current approach of DG penetration with DG owner(s) at controlling state and investors' benefits at priority

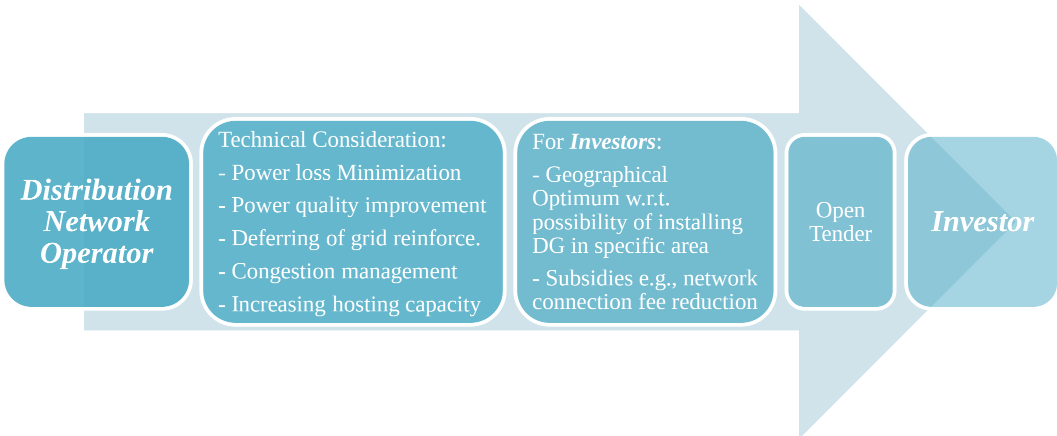


Figure 1.3: Proposed approach with DNO to have certain degree of control and expected benefits

1.1.4 Summarized Motivational Remarks

The challenges related to power quality and increased usability of existing distribution networks has been impeded by the increasing number of DGs placed without sufficient planning. It is an historical fact that the design of a distribution network is done for a unidirectional power flow. Similarly, the detailed controlling and monitoring of the distribution network is also not needed in thorough detail due to passive nature of the distribution networks. However, in the recent years, a motivational drive towards the generation from small sized generators, which are preferred to be of renewable nature, has increased the number of DGs significantly. In this changing paradigm from passive to active distribution networks, with ever increasing number of DGs, the challenges for all the participants (DG owners, network operators, regulatory bodies and consumers) have increased manifolds. The increased amount of local generation, with its volatile and uncertain nature, and a mix of variety of ranges of power being produced have made the operation and management of distribution network a complex task. The researches have identified the possibility of reducing these complexities and improving the performance of network along with improved power quality by many different ways.

As the distribution networks are not originally designed for the bidirectional power flows, it is a logical step to study the impact of any bidirectional flow before the implementation at mega levels. Moreover, if the challenges offered by increased penetration of DGs are clearly obvious and ever increasing, it is an easily justifiable step to perform necessary analysis and plan their penetration in order to minimize the harmful effects. This work is motivated from these two major reasons, and it attempts to provide a clear and detailed scientific reasoning for proper planning of DG penetration in distribution networks. The planning for placement of DGs is usually neglected with arguments such as: the methods available in literature do not offer sufficient openness to be modifiable to fit them in practical cases or they do not consider enough parameters which make the studies nearer to the practical scenario. To meet these challenges and address the issues raised, this work develops the methods which can be modified according to the requirements without losing their usefulness and performance quality. This work is motivated to develop a method which is open for improvements in future, and which can offer the possibilities of including as many factors as desired and needed.

1.2 Problems Addressed and Proposed Solutions

Due to ever increasing number of DGs being connected in the distribution network, the distribution network of future is prone to the serious issues such as the reliability, limited hosting capacity, network congestion and operating the lines near, or even beyond, their upper line flow limits. It is proved with the help of many researches that the reason for such a trend where the planning of a power distribution system for penetration of the DGs is not taken as primary concern is the absence of a complete and open method, and a set of mature and well defined regulations [17]. The existing trend in this regard does not allow the network operators to give their input for the DG placement as a commanding role. Instead, the network operators are left with the only options of network reinforcement and conventional methods to fulfill the regulatory requirements related to network operation, and customer rights and satisfaction. While there exist a lot of literature and studies related to the topic, their implementation is not yet fully possible due to different reasons. For example, the methods presented in the literature appear to be closed with respect to their applicability in real world scenario. Such as, the methods find an optimal location and size in single go but do not consider the objectives and constraints which cannot be modeled mathematically by a standard procedures. Under such scenario, it becomes inevitable to either ignore certain parameters set in the given method, or attempt the "fit and forget" type of procedure, as mostly done for placement of DGs in the distribution networks. As a result of such convention of DG connection, DGs are popping up randomly in the network, leading to the rise of serious issue of power quality, network congestion, increased losses, hosting capacity limitations and others. Consequently, the network operator is left only with the costly, time consuming and conventional methods of grid reinforcements in order to keep the network operational according to the legal and regulatory requirements.

It has been repeatedly reported in the literature that for any specific network location, there is an optimal size of DG which can produce best performance with respect to the considered objective such as active power loss minimization. Similarly, from all the available locations, certain location, or set of locations, may be preferred because of similar factors. This important conclusion help us to identify the need of splitting of the problem into respective parts. However, from thorough analysis of the available resources in the literature, it has been observed that the existing methods of optimal DG placement take the problem as a single unit, mostly. Such an approach leads to the limited access to an individual part of the optimization problem *i.e.*, location and size selection. Consequently, it becomes impossible to use the method under the conditions where an optimization of only one part is desired. Besides this, most of the presented methods rely on the mathematical formulation of the problem, their objectives and constraint which become tedious, or even impossible, in some real world scenario. On the contrary, if, in very few cases, the problem is being split into individual parts, standard optimization methods, which require detailed mathematical modeling, are used. As a consequence, the methods presented in the available literature do not offer the requisite openness to be shaped and modified according to the practical needs.

Another important problem with the available methods is their limited capability to include additional objectives and constraints. In the presented work, it is attempted to not only distribute the problem into logically separable and independent parts, but also provide the room for addition of any new factors (objectives and/or constraints). This target is achieved by suggesting an idea of individual factors for every variable that needs to be incorporated in optimal DG placement problem. As a starting example, the Load Concentration Factor (LCF) is designed to find out the location(s) for placement of DGs so that the maximum load can be driven by the local generation, which ultimately helps in reducing the power losses, managing the network congestion and increasing the hosting capacity along with reduced stress on fossil fuel based bulk generation plants. This ultimately helps in reducing the harmful effects on the environment due to the frequent emission of greenhouse gases. It is aimed that similar types of factors can be designed for other objectives. Ultimately, these factors can be combined together to choose the final optimal location(s). In this approach, it is obvious that the calculation of optimal sizes is not connected to the selection of optimal locations in any means. Moreover, the locations are not only chosen for the single objective, but multiple objectives can be taken into consideration by designing their respective factors. Similarly, the size calculation taken in this work are based to minimize the active power losses, hence the analytical expressions are derived from (exact) active power loss formula.

In the literature, the need of optimizing the power factor from a DG is usually not taken into account. The only available method of optimizing the power factor relies on the Combined Load Power Factor (CLPF). It has been proved during the course of this work that the CLPF is not always a suitable choice of the power factor from a DG because in some networks, the reactive power demand is too high as compared to the limit set for the DGs by the regulatory requirements. In such cases, the DGs operate at non-optimal power factor. Therefore, some realistic operational power factor is suggested. As for the earlier parts of this research, the care is taken to make the method open for any alteration as per requirements of the real networks and regulations.

Optimal DG placement is advantageous for improving the networks' voltage profile, however, a method to quantitatively find out the improvements is missing. For various conditions, which are different from each other and affect the network in many independently different ways, it becomes very cumbersome to identify the voltage status and respective changes. In this work, this problem is solved by proposing a Voltage Quality Index (VQI), which gives deep insight into the network's voltage status in the form of a lookup table. With the help of the results presented, its importance and usefulness is clearly highlighted. The information provided by this index is not only limited to the voltage level at the network's nodes but it also provides an information about the difference between maximum and minimum voltages appearing in the network at certain system condition. Centralized Voltage Control Algorithm (CVCA) is presented in order to mitigate any voltage problems in the network by controlling the reactive power from the installed DGs within their set capacity. The use of CVCA helps to explain the advantages of placing DGs optimally with the proposed method in comparison to the other methods available in the literature. It also justifies the usefulness of VQI by providing the quantitative comparison of the system's voltage condition before and after application of CVCA.

In summary, this work identifies and addresses the number of problems which hinder the applicability of existing optimal DG placement methods in practical implementation. This research aims to develop methods with openness and high possibility of interoperability with other methods. During the course of development of the methods in this work, it is targeted that the usefulness and applicability of the methods developed here should not be negatively affected if more objectives are needed and designed to operate with them. The only requirement is to develop a method of mixing any new method(s) with the proposed methods without affecting their results and shape in any respect. With such aims, it is expected that the proposed method not only provides justification of optimal DG placement and providing DNOs with certain level of steering role but also tries to reduce the number of hindrances in the practical implementability.

1.3 Methodology, Contributions and Justifications

The transition in power system due to an increasing number of DG units in the modern distribution networks has posed many challenges for different players of the system. The volatile and uncertain nature of the distributed generators along with their increasing number in distribution systems ask for detailed and timely planning by considering different aspects of their nature and functionality. Although the problems after installation of DGs with any (volatile or stable) form of primary energy requirements cannot be completely avoided, yet, these can be controlled and minimized by proper planning before installation. It has been thoroughly discussed in the literature [18, 19] that the location and size of DGs connected to the primary distribution networks affect the network parameters such as line flows, line losses, node voltages and network congestion. Moreover, the proper selection of the locations and sizes of the DGs can help in improving these network parameters significantly. This necessitates the need of serious addressing to the problem of optimal placement of DGs.

In order to highlight the importance of proper planning of DG placement in modern distribution system, many researches are done which have addressed this problem in due detail. The problem of optimal DG placement is solved to achieve *only* the technical benefits such as loss minimization in the network, voltage profile improvement and other of such benefits. While doing so, the only objective (or set of objectives) is to get the best of these benefits *e.g.*, to reduce the losses to the least possible value. Consideration of achieving the best values of technical benefit irrespective of taking different aspects about the practical network features and challenges to the implementability of a method into account make such methods only theoretically viable. These methods may not be useful in case of practical scenario due to such reasons. In this regard, it has been discussed in vast detail that the optimal DG placement methods should consider about their practical implementability as a primary focus. The methodological steps involved in this work are summarized here, along with the scientific contributions and respective justifications.

Optimal Location Selection. The optimal DG placement problem is of mixed nature; the selection of a location is done from a discrete set of values (nodes) and the selection of a size is performed from a considered continuous range (minimum to maximum sizes). In almost whole of the literature discussed in the chapter 2, the location selection is done only for getting technical benefits and the optimization problem is modeled as a single problem (for both location and size). Hence, if the location found by such methods appears to be infeasible in practical scenario, it seems impossible to get the optimal size on some other location which is practically feasible. In this work, it is focused that the individual parts of this optimization problem are independent of each other and can be separated without affecting the optimization problem in any respect. Rather, a separate part can be optimized in a better way and for a better practical implementation because the objectives and constraints of one part can be completely different from the other part. Both parts can be independently and separately optimized based on the selected objective function and respective constraints. Therefore, this work considers an approach of splitting the optimal DG placement problem into these separate and independent parts. While doing so, it is aimed to choose the optimal solution in respective part for as many practical factors as possible. To achieve this goal, an idea of proposing *factors* for respective objectives is proposed. As a starting example, LCF is proposed for selecting a node to place a DG. Another important fact about the placement of generation facilities in distribution network is their rapidly increasing number. Therefore, it is also important to design a method which should be able to find the locations of any number of DGs. The proposed method is also open in this respect because it provides a list of locations, set in the descending order with respect to the priority of selection for DG placement. Moreover, based on the discussed constraints and any other factors, the locations can be ignored even if they are at higher priority. This enables the method to be suitable for handling the objectives which cannot be modeled into mathematical formulation.

Optimal Size Calculation. The separation of this problem into independent parts creates an opportunity of using any method to get an optimal DG size that can be connected at preferred location. The openness provided by this separation of the parts help in choosing the size from the list of commercially manufactured DG sizes however, it has been proved that the DG size beyond certain range may adversely impact the distribution network. Therefore, some reference value should be found so that the DG size can be selected within the vicinity of that. In practical cases, a size found for a DG in theory may not be available commercially. As a consequence, some nearby size, which is commercially available, may be advised. While doing so, if the original DG size is not an exact optimal but a near optimal (as most of the heuristic and metaheuristic methods do) then the chances of getting poor results increase. Moreover, the method should be able to handle the calculation of sizes of multiple DGs. To achieve an accurate and precise value of DG sizes, an analytical method is proposed, which is also able to find the sizes of any number of DGs simultaneously, with reduced calculation burden and simulation time. The reason for choosing an analytical method for calculating the optimal DG size(s) is to get the precisely accurate value so that the chances of producing poor results (even if nearby size is chosen from commercially available list of DG sizes) get reduced.

Operational Power Factor. The increasing demand of energy has also lead to the increased need of reactive power. Different technologies being used for generating electrical energy at distribution level may have limited ability to produce reactive power. Increased number of DGs with limited reactive power capabilities have made the regulatory bodies think about forcing the generation facilities to provide certain amount of reactive power. Therefore, an optimal reactive power dispatch is also a hot topic in current research area, which is directly associated with the power factor requirements from a DG. In light of such factors, a method to find a power factor at which the system performance is further enhanced is also needed. To meet this challenge, an operational power factor is suggested, which is found by iterative method over the range of power factors which are allowed in considered grid codes.

Voltage Quality Index. The ability of proposed methods to be nearer to the practical implementation has been focused throughout the course of this work. In this regard, it is also needed to develop some method of quantifying the results and easy comparison. The loss reduction, which is one of the objectives, is measured by *loss reduction ratio*, as done in many studies presented in literature. However, a comprehensive method to quantify the improvement in the network's voltage status, which is also simple, straightforward and comprehensive, is not available already. A novel Voltage Quality Index (VQI) is proposed in this work. This index is not only able to present an information about the difference between maximum and minimum voltage appearing in the system but also their respective values. The importance of such an index becomes vital in case of bigger and complex systems where assessment of the voltage profile at different system conditions becomes a tedious task.

Centralized Voltage Control Algorithm. The justification about need of optimal DG placement with the proposed method is provided by quantitatively comparing with the other contemporary methods suggested in literature over the period of recent years. It is shown that the DGs placed optimally with the proposed method can help in reducing the chances of appearance of voltage problems in the network when the load is varied. Moreover, in case of a voltage problem, less amount of reactive power support is needed from the DGs placed with the method proposed in this work. To explain this, a Centralized Voltage Control Algorithm (CVCA) is suggested which is used to detect the voltage problem over the course of load variations. If a voltage problem is detected, it identifies the DG with highest sensitivity with respect to the node with voltage problem and varies the reactive power output from that DG until either the problem is resolved or the reactive power limit of that DG is exhausted. In case of later situation, the problem is tried to be mitigated from the next DG in the priority list with respect to the sensitivity.

As a result of implementing these methodological steps, it is expected that the method can provide a justification for planning the placement of DGs in real world scenario, and providing a DNO with certain level of control in steering the direction of DG placement process. Moreover, the proposed method is computationally efficient and produces better results in comparison to the methods available in the literature. It is also shown that the method is easily modifiable according to the specific needs of a DNO or any other participant in the system by adopting different steps such as designing and mixing of factors related to any specific objectives and constraints. Such features of the proposed methods help the method with a possibility to become a detailed and comprehensive mean of optimal DG placement in future by becoming acceptable to different stakeholders of the modern power system.

1.4 Organization of Thesis

The thesis is organized as follow:

- **Chapter 2: Distributed Generation, Optimal Placement Problems and Existing Methods**
  This chapter provides detailed insight into the various concepts related to the modern power system planning and involved stakeholders. Starting from types of generations, the chapter then focuses on the operation of an active distribution network. Furthermore, the advantages and challenges due to the placement of DGs are also explained in detail. The comparison of the cases with single and multiple DG integration is also provided. From the existing literature, the generalized formulation of the optimal DG placement problem along with conventionally considered objectives, variables, technologies and constraints are also included. A detailed classification of the optimization methods applied in the researches done so far is added too. A review about the limitations, barriers and challenges followed by the solutions proposed and, finally, by the core contributions of work are briefly presented.

- **Chapter 3: Analytical Method of Simultaneous Optimal DG Placement**
  This chapter details the method for optimal DG placement by splitting the selection of location and calculation of the size into two independent parts. For location selection, the LCF based method is presented. The LCF for all the nodes in considered networks along with their structure is included. For the sake of illustration and further explanation, the line flow in the networks considered in this network is also provided. In the next part of the chapter, detailed analytical steps are given which are used to find the optimal sizes of the DGs at locations found by LCF method. For this purpose, the minimization problem is formulated based on the exact active power loss formula, which is inherently a parabolic curve. Finally, a flowchart is given to explain the methodology of applying the method proposed until this point. Most parts of this chapter are published in the methods and methodology section of a research article enlisted in section 1.5.

- **Chapter 4: Methods for Assessments of Qualitative Improvements**
  The power quality can be improved by properly selecting the power factor of the DGs installed in any network. In order to get a suitable power factor, a method is discussed in this chapter. The power factor suggested and finalized with this method for operational phase of the system (after DG placement) is named as "operational power factor". Another index, named as voltage quality index, is also proposed. This index helps to assess the voltage quality of the network under different conditions. It is used to quantitatively present the voltage quality of the network, especially for the use cases with time varying loads at different loading conditions. To highlight the need of an *optimal* DG placement, another step is also introduced in this work. This is to use the reactive power based voltage control in case of voltage problem in the network due to any cause. A centralized voltage control algorithm is also presented in this chapter for said purpose. The operational power factor is part of the published article and results of CVCA on a simple use case are accepted for publication in conference proceeding. To compare the performance of the proposed method with the other contemporary methods, few methods are selected and briefed in this chapter along with their respective flowcharts in respective subsections.

- **Chapter 5: Results and Discussion**
  The methods and methodology proposed in this work is implemented on two different

standard IEEE networks *i.e.*, 37 node and 119 node, under three different use cases discussed in this chapter. The use cases are varying with respect to the type of load connected and if the voltage control action is being performed or not. The use case 1 is the one with static load whereas the load profile of a day (without voltage control) is considered in use case 2. The use case 3 is in general similar to use case 2 with only difference that the CVCA is applied to study the *need* and impact of corrective actions in case of voltage problems. The simulation set up and the chosen simulation tools along with the reasons of their selection are also detailed in a separate section in this chapter. The discussion on the results for every use case is then followed. Results are presented in the form of power and energy loss minimization, voltage profile and voltage quality improvements. The comparison of line flows before and after DG placement with different methods is also provided. Some of the results of use case 1 are presented in the published research article given in section 1.5.

- **Chapter 6: Conclusion and Future Recommendations**
  The major contributions of this work and the brief details of proposed methods are summarized in the conclusion section of this chapter. The recommendation and suggestions for the future extensions of the work are also proposed in second part of the chapter.

1.5 List of Publications

Following is the list of research papers published during the course of PhD.

Article:

- M. Shahzad, I. Ahmad, W. Gawlik, and P. Palensky, "Load concentration factor based analytical method for optimal placement of multiple distribution generators for loss minimization and voltage profile improvement," *Energies*, vol. 9, no. 4, p. 287, 2016.

Conference Proceedings:

- M. Shahzad, I. Ullah, P. Palensky, and W. Gawlik, "Analytical approach for simultaneous optimal sizing and placement of multiple distributed generators in primary distribution networks," in *2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE)*, pp. 2554–2559, 2014.
- M. Shahzad, A. Latif, P. Palensky, and W. Gawlik, "An alternate PowerFactory Matlab coupling approach," in *Smart Electric Distribution Systems and Technologies (EDST), 2015 International Symposium on*, pp. 486–491, 2015.
- M. Shahzad, I. Ahmad, W. Gawlik and P. Palensky, "Active power loss minimization in radial distribution networks with analytical method of simultaneous optimal DG sizing," in *2016 IEEE International Conference on Industrial Technology (ICIT)*, pp. 470–475, 2016.
- M. Shahzad, I. Ahmad, W. Gawlik and P. Palensky, "Voltage profile improvement in radial distribution networks with analytical method of simultaneous optimal DG sizing," in *2016 18th Mediterranean Electrotechnical Conference (MELECON)*, pp. 1–6, 2016.
- M. Shahzad, W. Gawlik and P. Palensky, "Voltage Quality Index Based Method to Quantify the Advantages of Optimal DG Placement," in *2016 The Eighteenth International Middle East Power Systems Conference*, *Accepted*, 2016.

2 Distributed Generation, Optimal Placement Problems and Existing Methods

2.1 Introduction

This chapter introduces the literature survey starting from explaining the available methods and technologies for power generation. A brief overview of the conventional power generation schemes and the modern trend of generation, *i.e.*, Distributed Generation (DG) is given. As the DG is mainly focused in this work, some details of modern DG technologies is provided. These include the wind and solar based technologies followed by a brief overview of other technologies. An overview of the trends in different regions of the world with increased wind and solar based power generation facilities is given too.

In conventional bundled power system, the role of Distribution Network Operator (DNO) is slightly limited whereas in modern power systems, with more focus on distributed generation, the role of a DNO is becoming increasingly vital. Unbundling of power system has also posed the DNO with extremely challenging situation. An overview about different aspects of operation of distribution system with and without DGs is discussed in this chapter. The subject of the placement of DGs is also introduced here along with their advantages and challenges. To highlight the impact of DGs, the study also includes the survey of a single and multiple DG integration scenarios with respect to their impacts, advantages and trends in modern research. The need of optimal placement is also justified with facts and figures from related literature.

After briefing the background information and trends, the generalized formulation of the problem, based on the used methods in different studies has been given. Generalized problem statement, objectives, variables, DG technologies, constraints and generalized algorithm for optimal DG placement is detailed in this chapter. Afterwards, a comprehensive overview of different optimization methods is given which are broadly categorized into four parts; classical, analytical, exhaustive and artificial intelligence. The critical review of the limitations of existing research is provided in order to highlight the need for this study and help setting targets for this work. This ultimately lead through the barriers in implementation of existing methods and challenges related to implementation for different agents of modern power system. The chapter concludes with the proposed solution and the contribution of this work.

2.2 Power Generation Methods and Technologies

Conventional methods of power generation are designed to produce bulk power which is then transmitted over the long transmission lines after being stepped up to higher voltage levels. Ultimately, the power is delivered to the consumers, at different voltage levels (lower than the level at transmission). It is noteworthy that most of such generation facilities are non-renewable based. Over the period of about last two decades, increasing interest in the renewable based generation has been observed and promoted by different governments and authorities. Similarly, due to many technical benefits, the generation in smaller quantity and near to the load centers is preferred in modern power systems. Such generation systems are commonly known as distributed generation (DG). Some other terms such as dispersed generation, decentralized generation or embedded generation are also used interchangeably in the literature [20]. A brief overview of different generation methods is given here.

2.2.1 Centralized Bulk Generation

Historically, the generation of electrical energy had been done in bulk at the stations away from population. Such generation stations are usually dispatchable units, with ability to produce at constant rate. The cost of energy generation varies among different technologies, but the capital investment on the installation of either type of bulk energy generation plants is higher. While these plants bear a disadvantage of high energy losses over the transmission network, the high cost of installation of transmission system appears as more discouraging factor. Moreover, in case of expansion in network, huge investment of time and money is needed for expanding the transmission network.

Fossils Fuel Based Generators (FFBGs) have been used widely to meet most of the world's energy demand. These generators rely on fuels like coal, oil and natural gas for energy generation. As a matter of fact, such resources are diminishing very rapidly; hence the FFBGs are usually termed as non-renewable generators. The cost of such fuels is increasing (or at least fluctuating) very rapidly, FFBGs are considered as an expensive or non-dependable sources of energy generation. Furthermore, the emission of pollutants, such as oxides of carbon, nitrogen and sulfur, from such generation plants is contributing towards the global warming. The trend given in Figure 2.1[1] about the level of CO_2 in environment is very alarming. Therefore, it is another among major drawbacks of FFBGs due to which the interest is decreasing in them. As an example, the most abundantly available and inexpensive fuel for FFBGs is coal, but coal-fired power generation is facing increasing pressure because of environmental regulations which are becoming more stringent than ever throughout the world [21]. Under such scenario of strong opposition, FFBGs can continue as a prime power generation source only if an affordable and sophisticated control scheme for reducing air pollution is developed and implemented. Due to such factors, the interest is rapidly shifting toward combined use of fossil fuels and cleaner sources so that the emission of pollutants are decreased yet satisfying certain reliability and cost margins. In restructured power market, generation on the small scale, preferably from renewable sources, is becoming more prominent. To attempt for diminishing the discrepancies of traditional power generation, such sources of energy are being connected to the utility grid at the distribution level. Along with cheaper energy, (renewable) distributed power sources are supposed to play a vital role in balancing the negative environmental impacts caused by FFBGs.

[1] `http://climate.nasa.gov/evidence/`

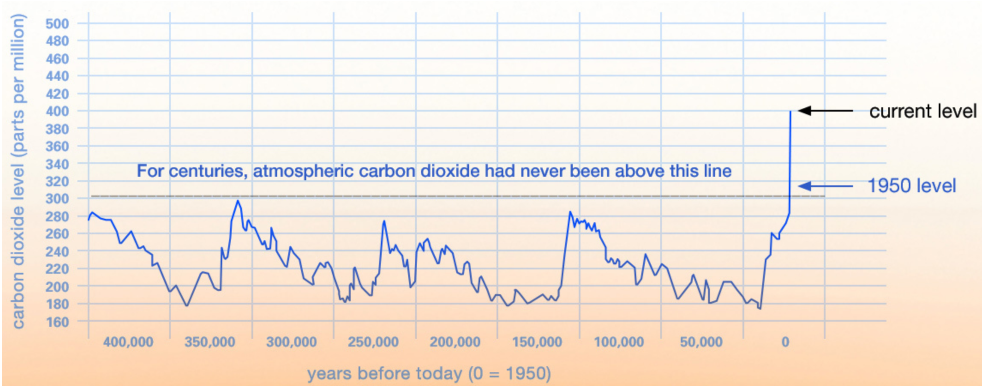


Figure 2.1: Carbon dioxide concentration in environment over the history

Along with these FFBGs, hydro power generation is another method used historically for generating electrical energy in bulk quantity. These are considered environmentally friendly as well as cheap source of energy generation, yet the cost of installation is high and other requirements such as land acquisition for making water reservoir are complex. It is important to mention that these power plants have advantage of water storage also, which can be used for different purposes like irrigation. Furthermore, in case of less demand, the water sluice gates can be closed to stop the electricity generation.

Another common method of electricity generation comes from nuclear power plants, which can produce cheap electrical energy. Unlike hydro power plants, nuclear power plant need less geographical space therefore, building these plants is comparatively easy. Another noteworthy feature of such power plants is that they should be built near a big water source to be used as coolant. Although these power plant do not have much greenhouse gas emission, yet these bear the disadvantage that efficient and safe disposal of nuclear wastes is a difficult task. Moreover, these power plants need high capital investment for installation along with danger of nuclear radiations.

2.2.2 Distributed Generation

Due to factors explained earlier, interest in centralized generation is decreasing quickly. In recent years, the generation of electrical energy is preferred near the load centers, and in smaller sizes. Building the generation facilities near the load centers make it efficient in terms of reduced energy loss in transmission networks as well as lesser demand of geographical space and binding of different factors such as availability of huge land in case of hydroelectric generation. The distributed generation is defined in number of ways in literature. For example, in [22], the distribution generation is said to be the one which is connected on the customer side of the meter or directly to the distribution network. Another definition is given on similar lines in [23] according to which any generation facility connected directly to the distribution network, instead of the transmission network is called distributed generation. International Council on Large Electricity Systems (CIGRE) defines the distributed generation with respect to their generation capacity, and dispatching and controlling mechanism. CIGRE defines the distributed generation as a generation of the range from few kilowatts (kW) to 100 Megawatts (MW), that is neither designed nor disptached centrally and is connected to the distribution network directly [20].

Distributed Generation (DG) can be either renewable based or nonrenewable based. However, the reduction of the emission of greenhouse cases and subsequent reduction in the global warming can only be achieved by one of the two ways; saving of the electrical energy or generation of electrical energy from renewable sources [21]. As a consequence, the most preferable DG technologies are renewable based. Other reasons for their preference also include low energy production cost and reduced dependency on fossil fuels. Wind turbine generation and Photovoltaic Cells are most common and major types of Renewable Based Generation (RBGs) which can be used at any level (small, medium or large) of power production. Whereas, small scale RBGs are based on biomass, tidal power, hydrogen and fuel cell, and geothermal energy are also in used. Some types of renewable based DGs, such as wind or solar based, bear a disadvantage of being non-dispatchable due to intermittent nature of primary energy. Some forms of non-renewable based DGs such as gas, combustion or micro turbines have the advantage of being dispatchable. Lastly, the energy storage systems are also used at distribution level. These include mechanical, electrical, chemical, thermal or electrochemical types of distributed generation which differ based on the technological grounds as well as the performance and structure. Different type of DG technologies [24] and a brief description about their capacities [25] are summarized in Figure 2.2.

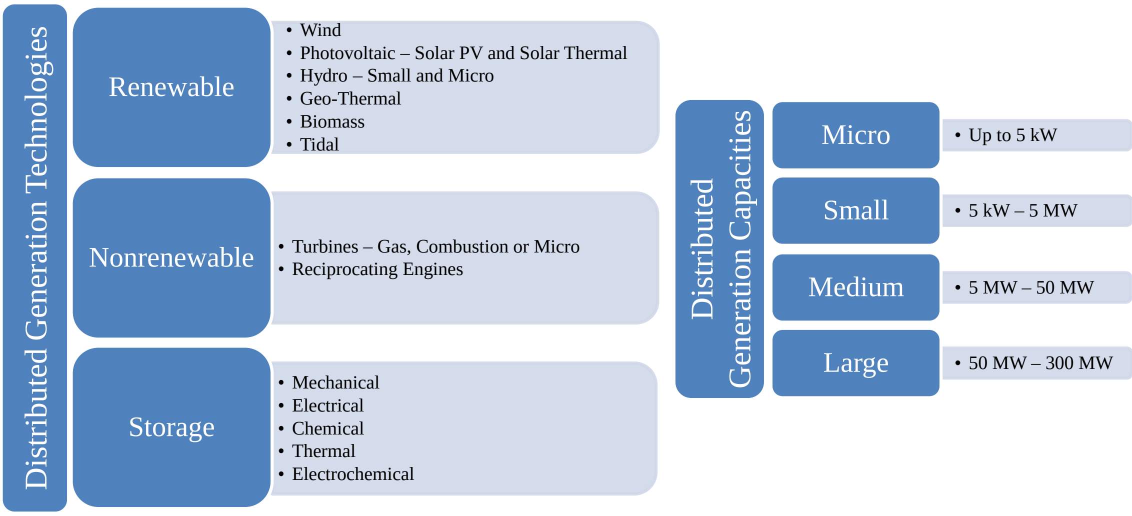


Figure 2.2: Brief summary of Distributed Generation Technologies

2.2.2.1 Wind Turbine Generators

Wind is a very convenient, frequently available and widely dispersed source of a primary energy, that can be used for generation of renewable electrical energy. Due to its widely dispersed and frequent availability, wind based generation can range from small scale wind turbines, subject to providing power to grid-isolated rural areas, up to the large scale on-shore and/or off-shore wind farms for generating electricity for national grid. The windmills, which are used to power the Wind Turbine Generators (WTGs), can be operated by Independent Power Producers (IPPs) or the utilities. The WTGs do not need any fossil or nuclear fuels, hence these are extremely environmentally friendly. Despite this fact, the WTGs bear a disadvantage of being non-dispatchable due to its dependency on weather conditions *i.e.*, intermittent nature of wind. The generation from WTGs is highly fluctuating over the period of a year or even a day or month, therefore it is highly recommended to design a control system for such generations which can handle their intermittent nature properly.

Global Wind Energy Council's (GWEC) statistics show that by 2015, china has the largest share with 114.604 GW of installed wind power capacity in the world. According to US department of energy statistics, total of 60 GW has been produced by 815 wind farms in 2012 which is enough to power 15 million homes [26]. Figure 2.3 shows the data for the producers of wind power, based on GWEC statistics with installed capacity of more than 1000 MW. As per the targets set by European Commission in 1997, 12 % of total energy demand had to be produced by renewables with share of wind energy production to be 6.9 % [27]. This target is revised and set to 20 % of total energy consumption from renewables [28]. It is believed that, in Europe, the half of total residential power demand will be fulfilled by wind power by 2020 [21].

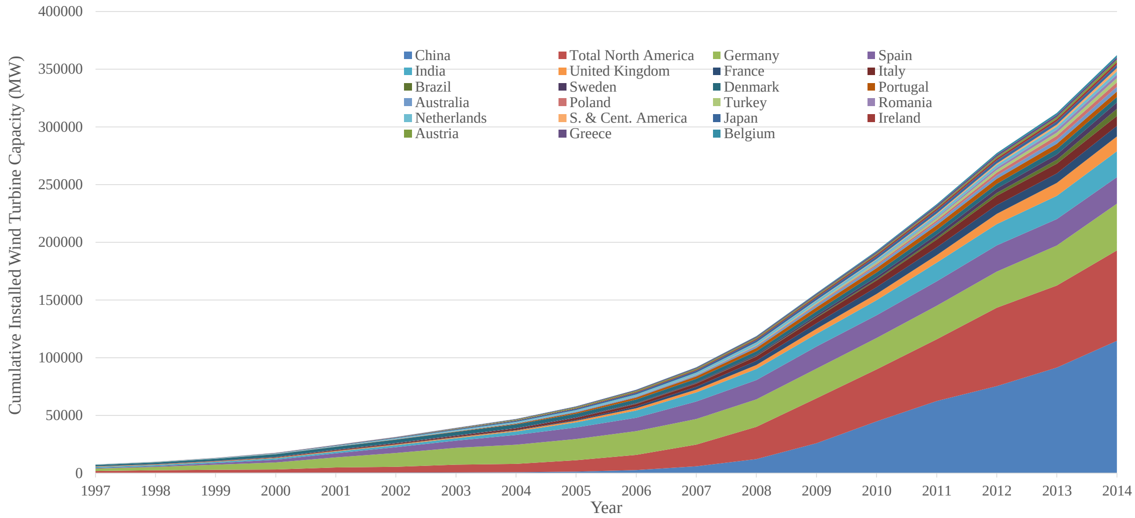


Figure 2.3: Cumulative installed wind turbine capacity

2.2.2.2 Photovoltaic Cells

With the use of photovoltaic effect of semiconductor materials, Photovoltaic (PV) cells convert sunlight into electrical energy. Sunlight is also a frequently available source, yet lesser than wind, but it is also highly impacted by the environmental and weather conditions. Therefore, the generation of electricity from solar PV panels is also of intermittent nature. This leads to the arising of various questions related to its reliability and continuous supply. On such grounds, the solar PV systems are also not considered as a preferred choice to be implemented independently. To handle these issues, there needs to be efficient control mechanism as well as an alternative system to either store the energy during peak generation times for use in peak load times or to hybridize the solar power generation parks with other forms of generation [29]. As a general observation about weather conditions of any area, it is seen that there is high amount of wind on the days without (or lesser) sunlight, therefore, hybridizing solar generation with wind generation can be a viable solution [30].

In comparison to WTGs, the interest in PV based generation is recorded to be very less but the energy generation from solar PV system has got a sharp rise over the period of last ten years. It is also worth mentioning that the energy generation from solar PV system is getting increasingly popular at both low and medium voltage levels, irrespective of their above mentioned shortcomings. Their environmentally friendly nature, rapid advancement for their technological improvements, subsequent reduction in their production and installation costs, and improvement in efficiency are the major drivers for their popularity. It can be seen from the Figure 2.4, that up to the year 2005, the total installed PV capacity was only 5 GW which has increased up to 174.23 GW in year 2014. This figure only combines the information about the countries with installed PV capacity of more than 1000 MW at the end of year 2014, based on the data given in 2015 annual report of International Energy Agency[2]. According to the data given in this report Germany is the leader in electricity production with 38.2 GW of installed capacity followed by China with installed capacity of 28.2 GW from solar by the end of 2014. The North American states produced 20.16 GW from solar in the same year.

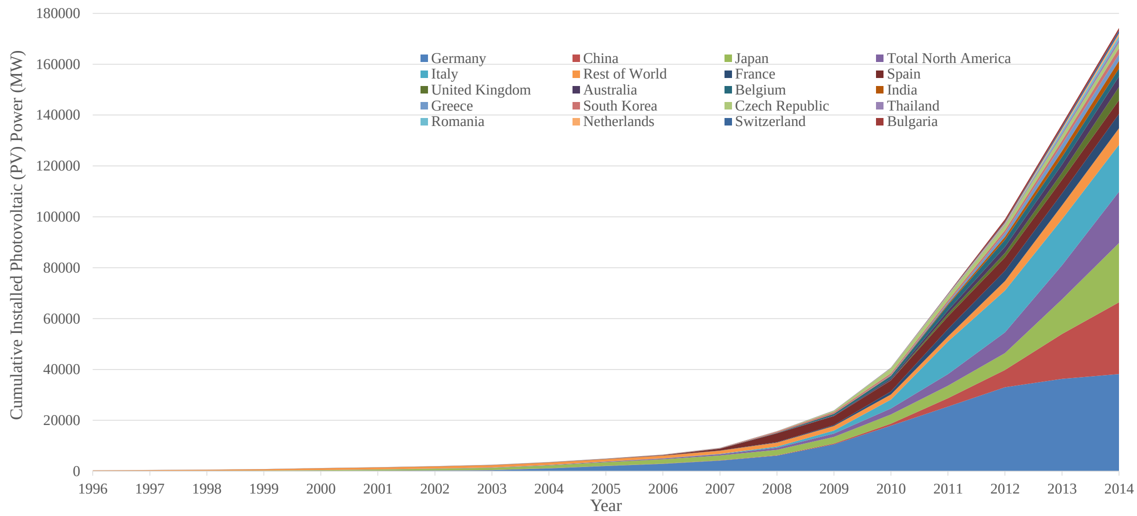


Figure 2.4: Cumulative installed solar capacity

2.2.2.3 Other Forms of Renewable Distributed Generation

As mentioned earlier that both the WTGs and PVs depend a lot on meteorological conditions which makes their generations highly sporadic. Therefore, for smoothing the fluctuations in wind or solar power, incorporation of energy storage systems is highly desired. *"Storage batteries"* can also provide additional advantage of storing surplus energy produced by WTGs or PVs which can be useful when the demand is higher than the generation from them. Hence storage batteries can be said as a sort of buffer for balancing the demand supply relationship, which is also helpful in improving the reliability of the system.

In recent years, the hunt for more and more renewable energy sources is increasing very rapidly. In this regard, a comparatively stable source of mechanical energy is contained in the moving water mass in the form of strong waves or tides. As per the theoretical estimates, 7400 EJ of energy can be extracted from worldwide oceans [31]. Interestingly, this is more than the total current energy demand. *"Tidal power"* is also considered as a costly solution, like other forms of renewables but it is also an immensely studied area. Therefore, their prices are expected to be reduced in near future. Due to such reasons, tidal power production is not very high. Tidal power is also considered important because it is a stable, predictable and continuous source of energy. Tidal power production bears the disadvantage of being geographically restricted than other renewable sources of energy production [32].

[2] `http://www.iea-pvps.org/fileadmin/dam/public/report/national/IEA-PVPS_-_Trends_2015_-_MedRes.pdf`

The combustion materials like solids, biofuels, biogas, landfill gas, and sewage treatment plant gas are usually termed as biomass. Although *"biomass plants"* are considered sustainable energy producer, they also contribute to the global warming due to combustion. To avoid the bad environmental effects of produced dangerous gases due to combustion, the proper filtering measures for emissions are highly required. Improvement in technologies is helping to meet such environmental requirements. By the year 2050, biomass is expected to contribute up to 50% of the world's primary energy consumption, as estimated in [33]. The biomass based distributed generation facilities can help in providing the access to the electricity in the areas with no or poor grid access [34].

"Fuel cells" are electrochemical devices which produce electrical energy during chemical reaction of hydrogen and oxygen to produce water. Fuel cells become important when their features of not using the fossil fuels, and hence no harmful emissions, are spoken. Fuel cells are preferred for producing energy in situations when it is needed on the go like spacecraft and hybrid vehicles. Various types of fuel cells include solid oxide type, proton exchange membrane type and molten carbonate type fuel cells. All these types are considered in Combined Heat and Power (CHP) applications [35]. Their small footprint size, ability to be dispatchable and capability of handling base-loads make them a preferable choice of electricity production.

Along with above mentioned resources, there are many other power producing technologies. *Geothermal*, also known as earth heat, *biogas* (either from livestock or in form of natural gas), and *small hydro-power* are other useful means of clean energy production. Up to 8 GW of energy is being produced with geothermal and this figure is increasing due to high technological improvements. Similarly, the energy production from other means is also increasing. In this work, no specific type of the generation type is considered. Instead, the focus is put on the size and location to keep the solution easily implementable in real world scenario with an open choice of any type of generation selection.

2.3 Distribution Network Operation in Modern Power System

The DNO is the entity/company which is responsible for distributing the electrical power from transmission grid to the end consumers (residential, commercial or industrial), maintaining the cables, substations and equipment [36]. These companies are only allowed to operate the distribution system and are not allowed to generate electricity [17]. Distribution systems are originally designed and operated for unidirectional power flows, which used to be mostly predictable, hence easing the job of DNOs about maintaining, managing and monitoring of the system [37].

In regions, where whole system of electricity generation, transmission and distribution is owned and controlled by single entity or group of companies, planning the system for increased benefits becomes easier. It is comparatively easy for DNOs in bundled power systems to plan the location and generation capacity from DG plants in order to get certain benefits, whether technical or economical. Very few among many of such benefits include increasing of system reliability, delaying of investment for network reinforcement and increased capability of the system in power handling. While getting the benefits of environmentally friendly energy, less greenhouse gas emissions and increased system reliability, investments toward traditional methods for improving system performance in terms of reliability, ancillary services and other benefits can be either avoided or reduced. Moreover, from the viewpoint of the operation of power system, DGs can be very beneficial in the networks with high reactive power requirement (*e.g.*, rural networks with long distribution feeders), and DNO can encourage the DGs for providing such support.

In modern unbundled energy system, the consumers has an option and right to choose the electricity supplier (generating company) on their own, which are responsible to pay the DNO for the transport of their electricity to homes and businesses via wires. Among others, providing the cost-effective and reliable connection means to the (distributed) generation owners, irrespective of the technology or geographical location is also a key responsibility of a DNO [17] in modern era power system. In this regard, it is vital for a DNO to keep the network in properly working order, so that the consumers can be delivered with the power at good quality, and in a reliable and cost-efficient way. This ultimately necessitates the need of investment by the DNO on the network for its desired and required functionality because network performance is highly affected by many factors such as increasing load demands, various types of new generations being connected to the distribution system, possible network expansion and other such factors. The conventional regulatory environment does not provide enough benefits to a DNO for boosting the generation capacity at distribution system level [38]. Hence, the DNO continues to practice the traditional methods for network maintenance.

In modern power system, generation is being connected to the distribution grid also, resulting in an active distribution system. This has changed the network structure from traditional unidirectional to the bidirectional with its simplified outlook as shown in Figure 2.5[3]. Based on the region/country in which a DNO is operating, the rules applied to them for system operation are changed and a standardized set of rules is missing for DG connection [39]. There are few regions like European Union, where planning and siting of generation is totally beyond the control of a DNO due to liberalization of energy market [17] and a DNO has to connect DG(s) to their network without discrimination. The investors have liberty to plan and install generation units, either renewable based or conventional, independent of the system requirements, loads areas or any other bindings. Under this scenario of the markets with unbundled rules, an important challenge for DNOs is to decide about the location (where), time (when) and type (what) of the reinforcement to the system in order to deliver timely connections without the risk of standard assets. These opposing situations, where the investors in generating facilities and DNO have very different set of objectives and benefits, lead to uncertainty and lack of planning coordination. As a result, the DNOs are subjected to connect any DGs coming to the system turn-by-turn, with a “fit and forget” approach. Ultimately, the DNOs are left with only traditional reinforcement techniques like adding new lines or transformers. Unbundled DNOs can steer up the deployment of DGs in areas which are potentially capable of reducing power and energy losses, leading to increased hosting capacity, reduced congestion of the network and improved power quality as only very few of many advantages, if they are capable of determining the optimal locational connection charges.

It is vital to note that a DNO is facing new challenges, roles and responsibilities under the changing paradigm of modern power system where the slogans of carbon free economy and effective facilitation in the operation of an unbundled retail market are loudly spoken. Rapid changes on the demand (such as electric vehicles) and supply (*e.g.*, intermittent and decentralized generations) sides, and their connection to the distribution networks are also triggering for the increased role of a DNO [40]. The responsibilities of a DNO in active networks remains same as were in passive networks with unidirectional flows, *i.e.*, security of supply and quality of service, but with more challenges and efforts to ensure them. Based on such reasons, it seems inevitable

[3] `http://www.edsoforsmartgrids.eu/home/why-smart-grids/`

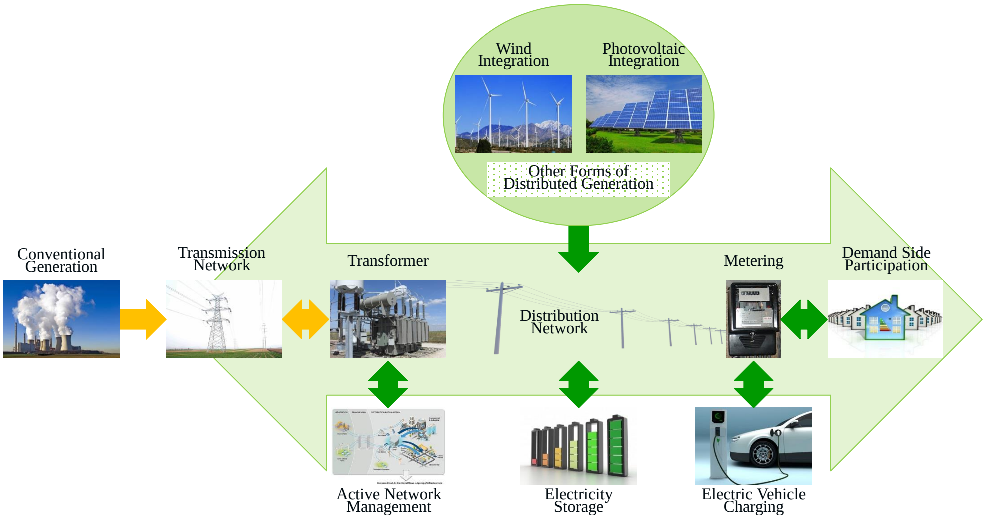


Figure 2.5: Modern distribution system operation: Active network with bidirectional flows

that the regulatory framework be modified in such a way to provide a DNOs with certain degree of control and liberty to steer up the direction of future distribution systems. Based on a survey from different operators of distribution systems/networks [40], it is concluded that the integration of distributed generations, management of electric vehicles in a significant quantity, encouraging the role of demand side management and other such activities must be done in a properly planned way. This will lead to the more smart distribution grid with ability to perform the regular operation efficiently and reliably.

2.4 Distributed Generation Placement

Due to many reasons such as liberalization of electricity markets and unbundling rules, the integration of DGs is increasing rapidly. About a decade ago, when the integration was started to increase rapidly, well defined regulations about DG integration were missing. The only constraint applied to the DG penetration was permissible limits of voltages, which means that the control voltage was considered as the highest influencing factor in regards to the DG integration at distribution system [41, 42]. Many incentives in the field of DG, especially in renewable based, have also fueled the rapid increase in the number and amount of energy generated from DGs. Such approaches facilitated the investors in DGs to be connected to the power system with very few requirements on power-purchase agreements [43]. As a consequence of such practices, the challenges for a DNO have increased to the maximum and they are subjected to the situation of connecting the DGs in a "fit and forget" style. DGs are connected to the network in case-by-case manner due to the lack of certainty and planning coordination, leading to the only option of conventional reinforcement methods.

In the recent years, when the problems due to the improper placement of DGs are becoming more obvious, the need of optimal placement is felt with great intensity. For example, in spain, where the renewable based DGs are given a lot of incentives and priority since 1997 under the slogan of "special regime", the situation is changing such that the DGs should adapt the technological developments as well as behave in accordance with the situation of the power system [44]. Similarly, there have been increasing interest in the recent researches which suggest for providing the advantages to the DG owners for building and connecting at certain locations in the network with desired capacity and type. The authors in [43] posed this in the form of an intriguing question as: *How can a DISCO*[4] *encourage the DG investors and operators into special contracts which can benefit the utility and enforce optimal overall grid performance?*. Similar concerns about the cost and investment in upgrading the existing network to meet the scenario with higher number of DG connections then ever are put forward by the P. Frías et al. in [45]. It is suggested in their work that the capacity of a network to accommodate the DGs can be significantly increased by adopting the active network management philosophy.

Reinforcement cost, energy losses and capacity replacement value are the three major factors where the DG affects a DNO in terms of costs [46]. The reinforcement cost becomes higher in case of high penetration of DGs. It becomes even more, if the conventional passive network management schemes are applied [45]. Energy losses are vital in case of high penetration level of DGs too. Lack of proper planning and network management can lead to the lowering of the DG penetration capacity of the network [47]. In case of load growth, the local generation from DGs can help reducing the power flows from high to medium voltage networks, hence, the need of grid reinforcement is deferred [48]. This also helps to reduce the investment required for the replacement of the equipment. It has been highlighted in many articles that with the current approaches, such as "fit and forget" or passive network management, the DNOs do not get any remarkable benefit until the DG penetration level is lower [49].

To address such issues, few recommendations are given in [45]. For example, it is recommended to compensate the DNO with high penetration level of DGs against their incremental costs (increased operational and capital expenditures). Similarly, formation of certain rules to regulate the DG connection charges is also recommended. Moreover, the costs of network reinforcement and upgrading should also be compensated for a DNO. Based on such recommendations and scenario, different DNOs have formulated different sets of procedures for the integration of DGs which can provide them with certain degree of control for steering up the direction of DG penetration, yet they cannot reject any connection offer. Despite their individual studies and efforts, the regulations at the higher levels (country or group of countries such as European Union etc.) bind them about proper control over the process.

European Distribution System Operators' Association also asks for the extreme rethinking in order to keep the infrastructure costs lower in the changing scenario of the energy systems[5]. The procedure adopted by Scottish and Southern Energy Power Distribution for connecting the DGs of capacity equal to or more than 10 MW [50] suggest that the investors in DGs should discuss about the proximity, 'spare' capacity and costs of connection with them prior to putting the application requesting for grid connection. Another such example is of Electro-Ljubljana which has clearly mentioned that all the technical conditions and prescription of the locations are provided by the system operator as a part of connection approval for the connection of DG in the network[6]. Similarly, guidelines provided by the Brazilian National Agency for Electric Energy mentions the selection of optimal locations for DG placement as an important aspect [51]. Moreover, e-control, the Austrian National Regulatory Authority also allows the network operators to identify a suitable connection points in case of a need of a new connections or modifications to the existing network, while ensuring the safety of an interests of network users[7].

[4]can be referred as DNO in this work

[5]`http://www.edsoforsmartgrids.eu/home/why-smart-grids/`

[6]`http://www.elektro-ljubljana.com/1/Renewable-Energy-Sources/Renewable-Energy-Sources/Network-Connection-Procedure.aspx`

[7]`http://www.e-control.at/industrie/strom/stromnetz/netzanschluss`

The variety of benefits that DGs can provide, has increased the interest of researchers and investors to explore system planning and operational aspects. A general procedure for determining DG location is considered compulsory for ensuring that the DG have positive impact on distribution systems in terms of minimizing the losses and maintaining the acceptable voltage profile [51]. DG planning tools must consider the essential network constraints like voltage and thermal limits, and stress over the lines etc. irrespective of the driving factor for a DNO. Variations in demand over the period of time or volatility of intermittent renewable generation sources (wind or PVs) must always be incorporated when such tools are being designed. For actively managed networks *i.e.*, networks with proper planning for DG placements, it is believed that control schemes are based on real-time control along with communication system for more effective management of different network parts. It is highly needed to account for voltage regulation devices, storage and demand in such actively managed networks.

2.4.1 Advantages of Distributed Generation

DGs are considered to be the solution of many problems along with their capabilities to provide additional advantages. It is worth mentioning that the advantages of DGs increase many folds if their placement is done strategically, while considering the network description, power demand, already connected generations, network structure and other similar factors. Impacts of DGs can be broadly categorized in one of these [52]:

a. Environmental

b. Technical

c. Economic

A generalized, yet comprehensive, list of advantages of DGs is given below.

- Voltage profile improvement can be significant if DGs are placed optimally in the distribution network [5, 53, 54]
- Optimal DG placement can help in power loss minimization [20, 55, 56]
- Up-gradation of transmission and distribution network is significantly delayed by DG placement at optimal location with optimal sizes [57, 58, 59]
- Overloading of feeders can be relieved by optimal placement and sizing of DGs [60]
- Significant improvement in power quality and system reliability is observed by optimal DG placement [61, 62]
- Proper planning for DG placement can help in better contribution of DGs in peak shaving. This also helps in operational cost of the system [20]
- Relieving the stress of transmission network by generating near the power demand centers [57, 63]
- Less emission of greenhouse gases in case of renewable based DGs [64, 65, 66]
- Health care cost also reduces due to environmentally friendly nature [9]

- In regions with long distribution feeders and need of electrification in rural areas, DGs become a very good and viable option [57, 67, 68, 69]
- DG units are improving technologically and becoming easily available in modular forms, hence easily installable by customers and utilities [57]
- Lead time and investment risk for DG is lower as they are modular [70, 71]
- A better tracking load variations is possible due to modular nature and small sizes of the DGs [9]
- Continued technological advancements over the recent years in DG technologies make them preferred and attractive choice of power generation [19]
- Installation of DGs near the load centers is easy due to their smaller sizes and hence smaller space requirement [9, 72]
- DGs can support in increasing the diversification of a energy resources of a country because variety of primary energy sources (wind, solar, biofuels etc.) are available for generation [63]
- Possibility of diverse deployment of energy resources helps in increased planning flexibility and structural rethinking of electric utility [51]
- Lessening the expenditure on fossil fuels can help in improving the economy, disruption of energy due to unavailability of such fuels and scarcity [9, 25, 73]
- Operational and maintenance cost of some of the DG technologies is less, hence economically beneficial. Moreover, peak shaving also helps in reducing the operating cost [52]
- With DGs, the protection of critical loads is increased [6, 74]

2.4.2 Challenges with Distributed Generation

While being beneficial in many ways, the DGs also pose certain challenges due to their very nature of being intermittent (*e.g.*, solar and wind based), inherent features of conventional power system and other such factors. Improper placement and sizing of DGs can also lead to number of challenging situations in the power system. However, these challenges can be efficiently met and adverse impacts of connecting generation at distribution system level can be considerably reduced by careful engineering and planning [75]. A detailed list of these challenges is given here:

- Overvoltage and excessive losses are observed in many studies due to improper sizing and location of DGs [30].
- Stability issues are also arisen when the DG sizing and location are not done properly [9].
- By virtue of the nature and methods of conventional generation, the traditional power systems were designed only for the unidirectional power flows. The bidirectional power flow, as a result of penetration of DGs, negatively impacts the conventional power system by disrupting the performance of protection relays [76].

- Short circuit current also increases due to bidirectional power flow, which is main outcome of installing generation in distribution networks [77].
- Local generation may cause the islanding of the network which can create safety issues for the crew and public. Moreover, it can also cause overvoltage problems [57, 78].
- Controlling the DGs being owned by the customers is highly challenging [30].
- Intermittent nature of various renewable based DGs makes them nondispatchable too. Both these properties create a challenging situation in modern power system with respect to control and forecasting of available resources.
- Voltage flickering is also a major feature of some DG types such as wind DGs where tower shades may affect the part of rotation leading to voltage flicker [79].
- Improperly placed DGs can cause harm to customer equipment [75].
- Restoration of the system in case of faults may get increased in the systems with improper placement of DGs.
- Protection issues become more obvious and difficult to handle in case of excessive penetration of DGs, specially without proper engineering and planning [75].
- Inability, or difficulty, of the utility to provide proper power quality in case of reconnection (system restoration) is another key challenge posed by the integration of DGs [75].
- The inverter interfaced DGs inject harmonics into the system.
- Due to bidirectional power flow caused by installing the generation at distribution level asks for implying new safety equipment as well as the network resizing [9].

2.4.3 Comparison of single- and multiple-DG integrations

As a matter of fact, the interest in generating power at distribution level was not very significant due to many economic and technical reasons. Under such scenario, DGs were only placed rarely and hence most of the researches focused on placement of single DG for achieving one or the other technical, economic or environmental benefits. Over the recent years, worldwide push towards the small scale generation, preferably but not necessarily renewable based, has provided considerable improvement to the DG technologies. Authorities in different regions of the world offered various benefits and advantages for the investors in DGs. This ultimately boosted the overall share of generation at local level. Subsequently, the modern day researches focused a lot on the placement of multiple DGs in distribution system for acquiring as many benefits as possible.

The numerous articles published over the recent years have explicitly approved the need of selecting the optimal size, location and type of DGs to placed in distribution system. Otherwise, their technical, economical and environmental benefits would be suppressed, leading to poor system performance [80, 81, 82]. It has been already mentioned that the improper DG placement would negatively affect the power quality and reliability of the power system. Moreover, the investment and operation cost would be controlled and harmful environmental impacts would be mitigated if the DGs are placed after proper planning.

In [45], it is said that the European Union tries to generate 20% of its total demand from renewable resources by the year 2020. Moreover, if the local generation is about 15–20% of total local demand, then it is considered as “high level” of DG penetration. A recent work in [5] tries to put forward the comparison of single and multiple DG cases in terms of power loss minimization, voltage problems and line flows in different standard test systems. Both cases (single and multiple DGs) produced similar results up to the 2–4% penetration levels in either network which is very low penetration level. Similarly, power losses reduced significantly in case of multiple DGs at penetration levels up to the considered 8% level. For the case of bus voltages, it is observed that the voltage problem becomes noticeable for bigger network in case of multiple DGs penetration. Finally, the number of lines with flows of 50% or more also increased in case of multiple DGs. Such studies provide a very clear insight into the need of planning the DGs penetration with utmost care for achieving one or more of the potential benefits.

2.5 Formulation of Optimal DG Placement Problem

The optimal DG placement problem is defined as the process of finding the optimal type, location and size for one or more DGs to be placed in a distribution system in order to obtain one or more of the technical, economical and/or environmental benefits. This optimization problem has number of difficulties due to various factors. Non-linear nature of power flow equation, mixed nature of DG related variables *e.g.*, continuous nature of the DG size and discrete nature of location, and non-linear nature of optimization objectives (*e.g.*, loss minimization, voltage profile improvement etc.) makes this problem a non-convex combinatorial problem which can have several acceptably good solutions (local optima) but a single global optimum [83].

The complex nature of the problem makes it hard to be solved by simple techniques. Therefore, two different approaches are frequently used. The first set of approaches use traditional mathematical programming methods for solving this problem. These methods try to simplify the problem formulation by relaxing the constraints and restrictions, linearisation of the objective functions or by simplifying the temporal variability of demand. The advantage of these methods is that they try to find exact solution but at the cost of complex mathematical modeling. The second set of approaches is focused on the heuristic optimization methods. These methods are appropriate for solving the non-convex combinatorial problems by trying many different combinations. Such methods allow the finding of an optimal solution for a non-differentiable complex objective functions. These methods bear the advantage of comparatively simple modeling and implementation of the problem, yet have a disadvantage that these can only find near optimal solution *i.e.*, good approximate of the global optimum solution [54, 83].

2.5.1 General Problem Statement

The optimal DG placement is a commonly addressed problem in recent researches due to many factors discussed already. The optimal location for installing a DG in the electrical network *i.e.*, the bus number and the optimal size *i.e.*, the output power of the DG are found in order to achieve one or several objectives – given in subsection 2.5.2 – subject to meeting the constraints such as electrical network operating constraints, DG operation constraints, and investment constraints [84]. Some other design variables for the DG placement problem are given in subsection 2.5.3. Over the period of two decades, increased interest in DGs due to different factors has also pushed the researchers to develop methods for optimal placement of multiple DGs. Moreover, a generalized methods which can be good for optimal placement of single as well as multiple DGs are also getting more focus. Similarly, the methods with openness to include as many objectives and constraints as desired or needed are also becoming increasingly popular as they can be improved according to the requirements with less effort of modeling from scratch.

2.5.2 Objectives

In literature, various researches are available with variety of objectives to be focused for optimal DG placement. However, during early days of interest in generation at distribution level, almost every research focused single-objective optimization. The considered objectives are usually the energy loss minimization, or the cost minimization, or the capacity maximization etc. The DG placement problem becomes even more cumbersome due to the involvement of different system players (agents) *i.e.*, DNO, promoter and regulator, who have their own objectives and interests. The operation of the distribution system varies a lot in different regions and under different regulations. Therefore, different researches have formulated the DG placement problem with respect to different agents. For example, a DNO can or cannot invest in promoting DGs, hence the problem formulation varies. In [85] and [86], single objective optimization is done from the perspective of a DNO that can invest in promoting the generation facilities at distribution system level. The optimization with respect to the minimization of investment in network for the contrary situation where the DNO cannot invest in DG is given in [70]. A comparatively simple formulation and optimization is given in [87] with respect to the DG promoter's perspective.

Based on these studies, the single-objective optimization can be considered as practical approach from any of the above mentioned perspectives, but it can lead to conflicting results because of the fact that all these agents can have opposing objectives. For example, maximization of DG capacity can be beneficial for the promoter as it can increase its income but it can increase losses and network congestion – an opposing situation for a DNO. Similarly, capacity maximization or loss minimization can be conflicting with the objective of network investments minimization. Renewable resources pose challenges of reliability, hence optimizing for maximizing the share of renewables can be conflicting with respect to the maximization of reliability. For such reasons, in today's research, the focus on optimizing multiple objectives, called multiobjective, is becoming more popular. Multiobjective optimization may not lead to the best solution with respect to any of the involved objectives but can find the best compromise among them, hence all the involved agents may get benefit.

Following is the list of commonly considered objectives in the literature. Any combination from the list can be used for the multiobjective optimization of the optimal DG placement problem.

- Minimization of the total power loss of the system.
- Minimization of energy losses.
- Minimization of system average interruption duration index (SAIDI).
- Minimization of cost.
- Minimization of voltage deviations.
- Maximization of DG capacity.
- Maximization of profit.

- Improvement of voltage profile.
- Reduction of energy purchased from the market.
- Reliability improvement.
- Market energy demand reduction.
- Maximizing the voltage stability.
- Maximization of profit of both the promoter and DNO (with active network management).
- Reduction of harmful environmental impacts *i.e.*, optimization for regulators' perspective.
- Maximization of a benefit/cost ratio.
- Maximization of voltage limit loadability (*i.e.*, the maximum loading that can be supplied by the power distribution system while the voltages at all nodes are kept within the limits).

In case of multiobjective optimization, it is common to have the naturally conflicting objectives. As a result, the chances of having a single solution to satisfy all the stockholders become minimal. The most commonly used formulations in case of multiobjective optimization of optimal DG placement problem are given as [84]:

- Weighted sum of Multiobjectives – A single objective function is formed based on the weighted sum of individual objectives.
- Goal multiobjective index – Goal programming method is used to form a single objective function from a multiobjective function.
- Pareto set – Compromise among multiple contrasting objectives and selecting the best among available feasible solutions.

For any of these formulations, there are number of ways available to find the exact solution. For instance, weights of different objectives can be taken as fixed or can be optimized with some method. Similarly, among all the solutions available in pareto set, a solution is chosen based on the different priority reasons. One such method of choosing the best solution utilizes multi-dimensional concept of "dominance" [88]. A solution x is said to be better than (dominate) the solution y if and only if x is no worse than y in all objectives and x is better than y in at least one objective.

2.5.3 Variables

For the optimal DG placement problem, the location and size are frequently used variables. However, there are some other design variables too, which are optimized for this problem. For instance, the type of DGs, which refers to the DG technology (primary energy input to the DG), is also becoming important due to the fact that the focus is shifting towards renewable based DGs. Another important variable considered in research is to optimize the number of DGs to be installed. It has been shown in various researches, such as in [89], that increasing the number of DGs beyond certain value cannot increase the benefits considerably. Moreover, contrary to the non-optimal placement of DGs, if the optimally sized DGs are placed at optimal locations, the network power quality, reliability and security indexes are improved, leading to the possibility of adding more number of DGs without a real need of the network reinforcement. It is worth mentioning that different combinations of these variables have been used in available literature.

The optimal placement based on one or several of the above mentioned variables strongly depends on the network structure, load and other generations connected. Therefore, different types of load models are considered in the research. The most common case is the one in which the load connected in a network remains constant *i.e.*, static load. Static load can be considered analogous to the average or peak load, in which cases the optimal placement becomes acceptable for most of the operational scenarios. To make such an approach more practical, multi-load levels are also considered as in [89]. In such approaches, the multiple load levels are considered as few percent higher and lower than the one for the static load. Similarly, the time varying loads, with different load level at different time instances is also considered. This is called time-varying load model and is supposed to be nearer to the real world scenario where the bidding in energy markets is being done at some regular intervals of minutes or hours. The probabilistic and fuzzy load models are also studied in few researches. Another important consideration in regards to the loads is their types such as distributed along the lines or concentrated on the network buses.

2.5.4 DG Technology

Conventionally, the electricity generation was done only by the rotating devices, either synchronous or asynchronous machines, which were used to be directly coupled with the network. The technological advancements have made it possible to generate electricity from static devices such as solar PVs or fuel cells. The electricity generated by such static devices is usually in the form of direct current therefore, a power electronic conversion is also needed. Some other DG technologies, such as wind power generation, also need power electronics converters due to variable nature of their energy production systems. So, the DGs can be of either of these types. Due to various factors, the DG technologies impact the power system with respect to the operation, control and stability [75, 90]. As an example the impact of harmonics on the power system due to the inverter based DGs is worse than the synchronous DGs, but they offer better voltage control capability. On the other side, protection coordination system is badly impacted by a directly coupled DG than inverter based DG. Such examples also highlight that the optimal DG placement is affected by the DG technology [91, 92]. However, it is worth-mentioning that the technological improvements and possibilities of hybridizing different DG technologies are helping to reduce these impacts significantly.

2.5.5 Constraints

Constraints are the variables which need to be met when finding the optimal solution in an optimization problem. For optimal DG placement problem, following constraints are usually considered [84]:

- Power flow equality (balance) constraints *i.e.*, $P_{gen} = P_{demand} + P_{loss}$;
- Bus voltage or voltage drop limits *i.e.*, $V_{i_{min}} \leq V_i \leq V_{i_{max}}$; and
- Line or transformer overloading or capacity limits

Along with these, some other constraints related to power quality, system reliability, and planning are also considered.

- Total harmonic voltage distortion limit;
- Short-circuit level limit;
- Reliability constraints, *e.g.*, max SAIDI;
- Power generation limits,
- Budget limit,
- DG with constant power factor;
- DG penetration limit;
- Maximum number of DGs;
- Limited buses for DG installation; and
- Discrete size of DG units

2.5.6 General Algorithm for Optimal DG Placement

The optimal DG placement problem is a complex multimodal combinatorial optimization problem which can be solved by a number of techniques. The objective function definition, the considered constraints and variables may differ according to the requirement. The complexity and specific requirements depend upon all the involved factors ranging from the selected optimization technique up to the considered constraints and variable. However, a generalized procedure for solving optimal DG placement problem is comparatively straightforward as illustrated in Figure 2.6. Starting from getting the information about entire system, the objective function is evaluated and it is checked whether the best solution is found. After confirming that the best solution has been found, other performance indexes are checked. If all the network parameters are within the permissible range, the results are finalized and the process stops.

2.6 Review of Optimization Techniques Used for Optimal DG Placement

As explained already that the penetration of DGs is increasing rapidly in existing power system but it is difficult to estimate how much DG capacity will be connected over the coming years. With such an increased DG penetration level, robust tools for assessing the capabilities and requirements of network to produce best planning and control strategies are highly needed. Despite the fact that there exist numerous studies to address the issue of power system planning by optimal placement of DGs, the presented methods do not take place in the implementation phase. The brief survey of the optimization techniques and methods used for the optimal DG placement problem is outlined here.

2.6.1 Classical Methods

There are various classical methods applied to the optimal DG placement problem. Gradient search, linear programming, nonlinear programming, sequential quadratic programming, dynamic programming and ordinal optimization are few among the commonly used methods. A brief descriptive survey of most common among these techniques is given below. Other mentioned techniques have not yet been frequently used for optimal DG placement problem.

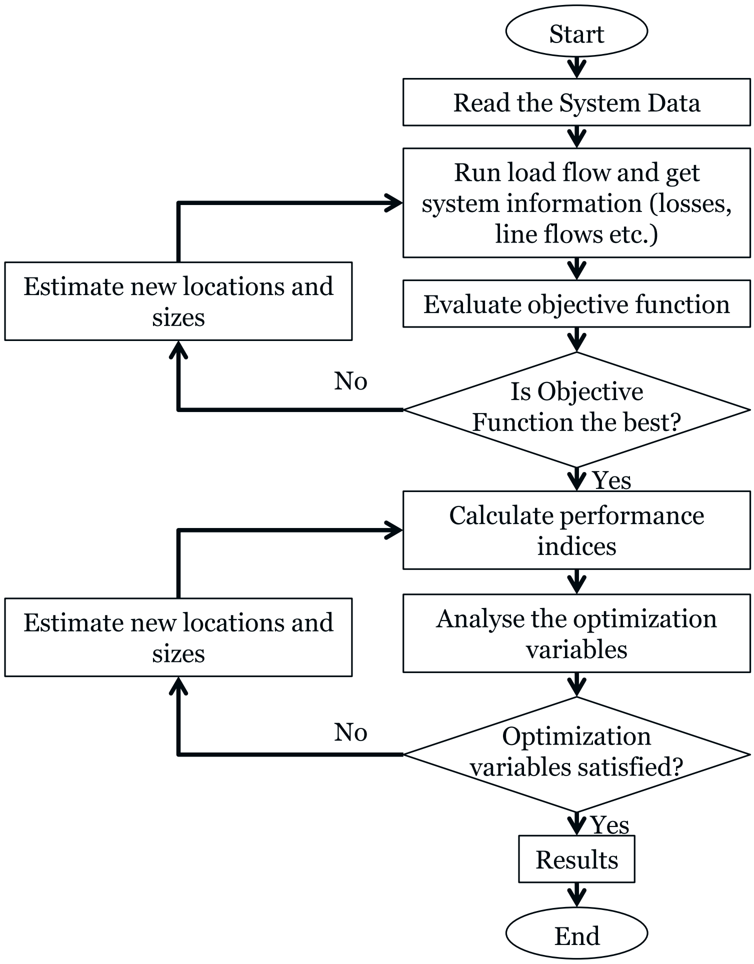


Figure 2.6: General Algorithm for Optimal DG placement

2.6.1.1 Linear Programming

Linear programming method is comparatively easy in implementation, offer high computational efficiency and good for solving the linear objective functions with linear constraints [9]. Some other advantages of linear programming method include its better ability to converge, quick identification of infeasibility, and its ability to incorporate large number of power system constraints [23]. The power flow equations are non-linear in nature, therefore, in linear programming method, either these equations or their results from AC power flow are linearized. As linearizion is process of approximation, certain amount of error in the results become unavoidable but it is shown by [93, 94] that such type of errors introduce negligible impact in context of discrete turbine sizes. Due to its advantage of offering significant potential for development of operational methods and robustness in optimizing, linear programming is considered as a preferred choice. However, AC optimal power flow approaches are considered better mean of optimizing at planning level [17]. Linear programming method is applied in [95, 96] to maximize the DG penetration and maximize the energy harvesting by the DG, respectively. A traditional urban network is optimized for maximizing the DG connection using the linear programming method in [97].

2.6.1.2 Non-Linear Programming

Non-linear programming can be defined as a process of solving an optimization problem for which some or all of the constraints and/or the objective function are nonlinear. Mixed integer non-linear programming is used to solve a complex problem that contains discrete probabilistic generation-load model along with all operating conditions for placement of wind DG [98] or various types of DGs [99]. In [100], an interesting study where nonlinear programming is used for minimizing the total number of DGs in order to minimize the losses in the network is given. The active power loss and generation cost from DGs have been optimized and DGs are placed optimally using mixed integer variant of nonlinear programming method in [101]. The optimal power flow (OPF) which is actually an example of nonlinear programming, is traditionally been used for solving the problem of economic dispatch. Optimal sitting and sizing of DGs in the system for minimization of transmission losses has been considered using OPF [102, 103, 104]. The OPF can be tailored to make it flexible for solving with extended objectives like voltage and thermal limits. Multiple periods can be incorporated in such tailored OPF to deal with variations and coincidence of demand and renewable generation. Various control strategies like coordinated voltage control, adaptive power factor and generation curtailment can also be incorporated to achieve maximum potential benefits, as done in [102]. Non-linear programming requires "closed" formulation of problem, which is usual with classical optimization techniques, hence significant limitations are put as to what can be accounted for.

2.6.2 Analytical Methods

A mathematical model representation of the system and subsequent computation leading to the direct numerical results is done in analytical methods. If a single snapshot of total system along with load demand and already connected generation is made available, the mathematical formulation for optimizing some specific technical aspect can be done to find the optimal DG sizes. The biggest advantage of these methods is their ability of producing very accurate results in considerably small computation time. The modeling is done to optimize any single objective such as voltage profile improvement or loss minimization in planning the power systems with DGs by considering only single load condition. This feature is usually termed as their biggest disadvantage, however, it can be addressed by splitting the problem into separate parts for optimal location selection and optimal size calculation [19]. These methods need to be modified for consideration of the intermittent nature of primary energy, which itself is a complex and demanding task. In fact, including such factors need further mathematical formulations. It is also important that the distribution networks with DGs require the assessment of energy losses which is, once again, needed due to variable nature of both demand and supply. For considering the impact of DGs on thermal overloads and voltage rise, analytical methods use the iterative method which reduces their versatility and time efficiency. Despite these facts, it has been shown in recent researches that analytical methods can outperform the other methods because of their ability to find exact results with direct calculations instead of repeated procedures and approximate solutions.

The earliest attempt to find the optimal DG sizes and location is know as "2/3" rule, presented in [105]. This is simple method which suggested to place the DG with capacity of 2/3 capacity of the incoming generation in radial distribution feeder at 2/3 of the length of the line. As uniformly distributed load is the main assumption in this method, it can be easily deduced that such method cannot perform well for non-uniformly distributed loads. In [106], the authors have primarily focused on finding the optimal location for placement of unity power factor DG. The optimal site and size of DG units in distribution system is calculated by an analytical method for static load models [72]. Due to the use of impedance and Jacobian matrices, the accuracy and speed of the method developed in [107] is improved. The optimal sizing of single DG is calculated for static load model in [18] in order to minimize the losses in a network. The method for selection of optimal location is iterative hence the increased time for acquiring the results. This method is improved in [108] where the similar assumptions are made with respect to the load model. In this work, the exact loss formula is used to find the optimal DG size that can ensure the minimum losses. The authors also suggest combined load power factor in this work, as a preferred choice of power factor in operation of DG. Different types of DGs, based on the output power and power factor, are considered. The same method is modified for placement of multiple DGs with iterative procedure in [109]. The concept of iteration for placing multiple DGs further increases the simulation time of this method due to increased computational burden. The authors in [110] propose analytical expression for optimal DG sizes based on three different methods *i.e.*, exact loss formula, current losses in branch and branch power loss. In this work, the authors use both dispatchable and nondipatchable generation types. Their considered generation types are biomass, wind and photovoltaic systems. Energy losses are also calculated in this work by considering the load profiles for a day.

As a general observation, such methods become complex if the number of involved variables is increased [52]. For instance, if the method is derived for placement of single DG, it cannot be generalized for multiple DGs with simple procedure. For doing so, iterative procedures are followed. Following the iterative procedures have a serious disadvantage of "sterilization of capacity" [17], multiple runs of load flow analysis and hence the increased computation burden. Sterilization of capacity means that the new oncoming DG(s) after placement of one or more will have reduced search space in terms of suitable size because the oncoming DG size can now vary not from zero to full load but from already installed DG capacity to full load. Moreover, inability of such techniques to handle/incorporate operational solutions like coordinated voltage control or generation curtailment is also a major drawback.

2.6.3 Exhaustive Methods

Exhaustive techniques are useful when single technical issue such as voltage rise or power losses needs to be addressed. Major advantage of such techniques is that they can search the whole (or at least the most of the) space of possible solutions to figure out the best one. While good in accuracy, the computation is extensive and highly dependent on the step size. As an example, if optimum DG size has to be computed, discrete values of DG sizes will be used and repeated runs of method will lead to the best solution. Hence, such methods are considered better choice when some specific limit, based on some technological issues *e.g.*, DG with specific capacity, is given. With exhaustive techniques, it is possible to find the solution for multiple objective and constraints without being involved in the sophisticated formulation of the objective function [17].

In [111] and [112], optimal DG site and size are found based on the objective function formulated with weighted sum technique for the technical benefits such as power and energy losses, voltage rise and short circuit levels. In [6], the quantitative approach to quantify the economic and environmental impact with and without DGs is presented and given in terms of performance indexes. In [113], the exhaustive method is used to maximize the system reliability and minimize the power loss of the system. Similarly, in [112], the exhaustive technique is used for finding the multiobjective performance index for a system with the time-varying load and generations. Such techniques are considered relatively straightforward in calculating individual indexes but finding the composite index is a complex task. Another point with exhaustive techniques is that they can be proved efficient with single objective and condition by some means but for variations in demand and generations, and multiple objectives, such techniques increase computation burden considerably.

2.6.4 Artificial Intelligent (Metaheuristic) Methods

In metaheuristic methods, the optimal or near-optimal solution is efficiently found by subordinate heuristics with the help of guidance provided by the iterative generation process [114]. Different artificial intelligence based methods are combined intelligently in metaheuristics for performance improvement. Metaheuristic methods have proved their ability to solve the complex optimization problems in many different research areas better than their subordinate heuristics. In comparison to the classical and analytical methods, metaheuristic methods do not need "closed" formulation of the problem, hence the complex power system optimization problems can be efficiently and easily modeled and included. The better ability of metaheuristics in solving the mixed integer problems make them very suitable choice for solving the power system optimization problems [17].

While being efficient with multiobjective problems and being able to solve objective function of any type, metaheuristics need careful tuning of optimization parameters so that a good solution can be found within reasonably shorter computation time. Hence, the algorithm parameters require more attention than the formulation of objective function and constraints, resulting in an inevitable compromise between quality of solution and computation time. Improper tuning of optimization parameters can lead to increased time for convergence while improper formulation of the objective function or the constraints can lead to an erroneous results. Another important point with metaheuristics, which is often considered a disadvantage too, is their inability to find the global optimum. These can provide reasonable solution but without any guarantee about the solution being the best, therefore, a lot of research is being carried out to reduce their chances of premature convergence [61]. Moreover, in some metaheuristic methods, there are some theoretical convergences which cannot be proven feasible/correct in real world [114]. Also, due to random search techniques, such methods yield different results when run several times. Hence, to get the best solution, metaheuristic based algorithms need several runs, which in turn increase the simulation time considerably.

Several metaheuristic algorithms have been developed and are used to solve the problem of optimizing the location and size of DGs. As a common practice, only one algorithm is used to solve the whole problem in most of the researches whereas in some cases, different methods have been used in combination for improving the quality of results as well as decreasing the simulation time. Table 2.1 summarizes the commonly used metaheuristic algorithms along with brief description of the problem and objectives used in different recent researches.

Table 2.1: Metaheuristic Algorithms used in Optimal DG placement problem along with their description

Metaheuristic Method	Description of optimal placement problem with reference
Genetic Algorithm (GA)	Optimal DG placement and maintenance scheduling for minimizing system cost and maximizing turbine reliability [115], Active power loss reduction by optimal sizing of DG [116], Optimal DG placement,for economic and technical benefits [117], Optimal DG placement,using PSO is done for optimizing the short circuit level, loss minimization,,voltage profile and intake of power from external grid by the distribution,network [118]
Particle Swarm Optimization (PSO)	Reduction in cost of losses and improvement in voltage profile by optimal DG placement [61], Long term planning,with optimal DG placement to help DNO [119], Fast variant of PSO,(*i.e.*, Rank Evolutionary PSO) is used to optimize multiple DGs output, for reducing network losses [120], Optimal size, location and power factor of different DG types is found with PSO for, minimizing distribution loss [55], Loss minimization and, loadability enhancement by optimal placement of multiple DGs using hybrid PSO,[121]
Fuzzy Logic (FL)	Optimal size of wind turbine based DGs [122], Loss reduction and voltage profile improvement [123]
Non-dominated Sorting GA-II (NSGA-II)	Optimal placement of DGs is done for objectives such as loss minimization, customer outage cost, absorbed private investment cost and total imposed cost, using NSGA-II [124], Optimal planning of,multiple DGs loss reduction, voltage deviation minimization and maximal,voltage stability margin [125]
Ant Colony Search Algorithm (ACS)	Optimal placement of DG and protection devices is done for reliability enhancement [126]
Artificial Bee Colony Algorithm (ABC)	Optimal size, location and power factor of DG unit is found by ABC for minimizing the power loss [127], Multiobjective performance index for enhancing voltage stability is done to get optimal size and location of real power output DG using ABC in [128]
Bellman-Zadeh Algorithm (BZA)	Optimal DG placement for loss reduction [129]
Monte Carlo Simulation (MCS)	Energy loss minimization in distribution system by estimating optimal DG allocation [130]
Clustering-based approach	By taking the time dependent evolution of generation and load, this method finds optimal DG sizes [131]
Tabu-Search Alogorithm (TS)	Minimization of cost and improvement of voltage profile is done by optimizing the DG sizes using Tabu Search method

(continued)

Metaheuristic Method	Description of optimal placement problem with reference
Bat Algorithm (BA)	Loss minimization and voltage profile improvement was done using BA by optimal DG placement in [132]
Big Bang Big Crunch Optimization Algorithm (BBBC)	Multiple voltage controlled DGs are placed for energy loss minimization [73]
Backtracking Search Optimization Algorithm (BSOA)	Voltage profile improvement and loss minimization are taken as objectives to find optimal placement of DG [133]
Modified Teaching Learning Based Optimization Algorithm (MTLBO)	Optimal sizes of multiple DGs have been found for minimizing the losses in [134]
Shuffled Frog Leaping Algorithm (SFLA)	cost optimization for placing DG optimally [135]
Cuckoo Search Method (CS)	Optimal DG allocation for voltage profile improvement and loss minimization [136, 137]
Modified Honey Bee Mating Optimization Algorithm (MHBMOA)	Optimal placement is done to minimize loss, cost and emission, and optimizing the voltage profile [66]
Hybrid	GA and PSO for reducing network losses, improving voltage stability and better voltage regulation [138] ACO and ABC are,hybridized to find optimal location and size of distributed energy resources, for minimizing power losses, emission, and total energy cost, and improving voltage stability,[65] Improved PSO and, Monte Carlo simulation method for placing DG optimally in order to minimize, the loss, improving voltage profile and reliability of distribution system,[61] GA and Monte Carlo,simulation based method is used for optimal DG placement to reduce, uncertainties due to intermittent nature of DGs [139] GA and TS methods arecombined to find optimal DG sizes and locations in order to minimize the losses [140]

2.7 Overall Review About Limitations of Existing Research

The optimal DG placement problem has been thoroughly investigated in recent years by many researchers and a brief overview of different aspects of the problem has already been discussed. Despite the fact that there exist numerous researches and this problem has been solved by many different aspects, there are still some serious shortcomings. These shortcomings range from the viewpoint of an optimization method used, the perspective (of any of the three agents involved in this whole process) from which the problem is being considered, and the number and type of DG variables considered. Some of these shortcomings are enlisted here.

- Distribution utilities in most of the regions in the world are unaware of the benefits of *optimal* DG placement. Likewise, in some (usually developing) countries, systems are still bundled hence no centralized power supply methods are used. This ultimately limits the benefits those can be acquired by placing the generation at distribution level, whether optimal or non-optimal. Moreover, the utilities mostly prefer the traditional experience-based strategies, usually "fit and forget" type, instead of modern methods. Hence, making these utilities aware of the benefits of modern methods as well as optimal DG placement techniques is highly needed.

- Huge amount of studies used the metaheuristic methods for optimization of optimal DG placement problem. As a matter of fact, such methods are efficient but have the problem to get stuck at local optima. Also, these bear higher time for finding the final result. Continual efforts for making these methods more efficient and improving their ability to find global optima are being done.

- Metaheuristic methods have certain control parameters, which have very strong influence on the quality of results. In almost every available research on optimal DG placement problem using metaheuristic methods, tuning of these control variables is either not done or not given.

- The methods which are able to find the optimal location and size of DGs in a single go, mostly the metaheuristics, are usually difficult to include any other design variables as well as the constraints and objectives. Such a "closed" approach should be modified so that the method become implementable for additional objectives, constraints and design parameters.

- Time varying nature of loads and generations demands for several runs of the method to get realistic picture of optimization results. For the metaheuristic based methods, this becomes problematic because their solutions are usually not consistent. Moreover, these methods are relatively slower than analytical or classical methods, repeated runs may cause significant increase in the simulation time and computational burden.

- Being complex multimodal combinatorial problem, it is very difficult to design and implement the solution of optimal DG placement problem that satisfies all the requirements. Most of the researches, therefore, simply ignore one or the other objectives or constraints when formulating the problem. Hence, it is necessary to design a method which can be open for incorporating as many objectives and constraints as possible.

- Similarly, the storage devices have been recognized as a very suitable counterpart of distributed generation which can help in smoothing the output power and solving the intermittency related problems of renewable based DGs, but these have not been given enough focus in research.

- Uncertainties due to intermittent nature of some renewable based generation technologies should be considered in the problem formulation to achieve a realistic solution for optimal DG placement problem but most of the recent method do not do so.

- As a matter of fact, it is desired that the results should be reproducible which forces the researches to test their methods on standard systems. However, the standard systems are comparatively smaller with respect to the number of buses and branches. Therefore, implementation of these methods in real world distribution system becomes a big question.

- Most of the recent researches focus mostly on finding the optimal size and location whereas the type is also an important variable when it comes to the generation at distribution system level. Although, increasing interest in hybrid generation facilities can help in reducing the strength of this variable because any combination of different DG types can be mixed to get the desired size, yet it is important.

- Load models play an important role in finding the optimal DG placement. Most of the researches have considered only one type of the load model which limits their usefulness. Therefore, the results and discussion about using any single method for different load models should be given in order to increase the usability.

- Methods should be developed to optimally place the DGs while considering the transients/dynamic characteristics of the system. This is still missing in recent researches because most of them optimize for the steady state conditions of the system.

- Different types of DGs, based on their produced output characteristics should be considered. This means that not only the DGs with only active power output should be considered but also the DGs with reactive power output only or the mix of both active and reactive power output should be considered.

- Mostly, the optimal placement of DGs is done for one of two cases, the grid connected or standalone. However, DGs usually face both of these situations therefore, the studies should include results for both of these cases.

- The DGs are usually preferred due to one of these three benefits; technical, economical or environmental. Most researches consider either one or two of these important objectives and environmental objectives are usually ignored. Similarly, the geographical constraints are also not being considered usually.

It is very clear and accepted reality that non-optimal placement of DGs can lead to many economics as well as technical problems such as increased losses, difficulty in controlling the voltage or reactive power, and reliability or stability related issues [141]. Most of the factors must be simultaneously considered in order to make these methods practically implementable. This ultimately results in further increase in computational cost as well as complexity of the problem. Some authors have suggested the “clustering” based optimization methods in order to reduce the number of power flows [142, 143, 144]. Such limitations ultimately force the researchers to split the problem into smaller parts and solve them instead of solving for the whole bunch of objectives, constraints and variables. As a result, despite the fact that there exist huge range of optimization methods those are proposed for solving optimal DG placement problem, the systematic principles is still an unsolved problem.

2.8 Obstacles in Effectuation

In recent years, numerous researches have been carried out to outline the various challenges about integration of DGs into the power system [47, 75, 145]. Not all, but many of these methods derive the solutions which are viable for application in the real world scenarios, hence implemented in different parts of the world. As an example, updating the grid connection standards in order to overcome the barrier in connection and integration of DGs was very initial, but a major, step [146, 147]. The challenges related to DGs do not only relate to their technology and economics but also to the complexities related to the “planning” and “operational control” of them. It has already been highlighted that DNOs are usually not used to the custom optimization codes, if any, as well as the techniques proposed for DG integration do not consider enough set of scenarios and variables to accommodate the real world problems.

A detailed overview of the optimal DG placement have been provided in previous sections with respect to the problem formulation, design variables, objective and constraints, and various optimization methods. However, adequate and economical planning of the distribution network for connecting a DG is also a challenging and demanding task. This is because of the fact that methods for controlling and managing the operation of connected DG also have critical influence in evaluating the needed capability of the distribution network. In many early researches related to this specific case, which focus mostly on the bundled and regulated energy systems, the potential benefits and costs of DGs have been compensated in a simplified way where the through year operation is represented for the DG [148].

For the optimal DG placement problem, being the complex multimodal combinatorial problem, full representation of all of their physical and operational features and constraints, and incorporation of various conflicting objectives is not a trivial task. Furthermore, complications increase to the maximum due to the extremely uncertain nature of modern technologies (such as demand response, energy storage, and electric heating and transportation), selection of their point of connection and method for managing them. Some researches such as [149, 150, 151], have proved that the curtailment from DG output increases the opportunities for DG to access network, both with respect to the network operator and the DG developers. A stochastic programming approach is used in [152] to enlighten the uncertainty of operational characteristics of DG along with the suitability of DG constraint management.

In modern power system, increased use of data sources and recording tools at distribution system seems to create new opportunities as well as challenges. A challenging situation for the network planners is arising due to huge amount of, hopefully, meaningful information which is easily available from smart meter roll out programs because of, for instance, their aggregation issues. However, the same provides huge opportunities due to the possibilities of better insight about happenings in the system and hence the DG connection and network access. Such improvements in the system will lead to the substantial developments in near future. In the coming years, the optimal DG placement and network integration seems to be getting more importance and focus due to the increased interest and availability of data capture, processing, modeling, estimation and forecasting [17]. Consequently, the usability of existing methods seems to become more limited, resulting as another impeding factor in implementation.

During the operational phase of DGs, their control and management is also a challenging task. In recent year, the term “active network management” has become vital in relation to the operation of DGs. Active network management can further increase the network capacity and improve the power quality related issues however it requires the secondary control and communication infrastructure to be properly represented. This creates new challenges *i.e.*, the cost of such infrastructure needs to be considered into the formulation of the problem and their impact onto the system (such as in terms of reliability and safety etc.) needs to be considered. Most of the studies related to the optimal DG placement ignore the evaluation of the operational optimization of DGs. The maturing of active network management approaches and possible maximization of the network access for DGs are considered as the possible reasons for considering the operational optimization of DGs. Although few researches exist related to the optimization of DG control [153, 154, 155, 156], these have certain issues such as robustness, scalability and finding the solution in dynamic scenario.

Lastly, the capability of DNO to adopt the modern methods of DG placement has also been projected as a new challenge. A very slow progress has been observed on projects related to the deployment of DGs (and other new devices) due to extremely complex nature of the planning and design process for the networks, and the incorporation of new operational approaches. Ultimately, "DNO adoption" is highlighted as major problem for whole lot of researches related to DG placement and planning [17]. DNOs have now different options to chose from *i.e.*, advanced and sophisticated planning tools, models developed on their own, or tools and techniques resulting from research. Along with various other challenges, choosing from the different available options of DG planning has also turned out to be a significantly difficult task. Consequently, along with all other reasons, DNO adoption can be said as a big barrier in implementation of existing research.

2.9 Issues and Challenges for Different Agents in Power System

In the recent years, the share of DGs in overall generation mix has increased considerably due to the strong move towards higher DG penetration. This results in a challenging situation, specially in the networks with few interconnections. Rapid increase in generation from distributed energy resources has already been explained in previous sections. For example, approximately 10 GW, which correspond to about 25% of the total new generation capacity, increase in distributed generation was speculated by [157] in the U.K. by 2015. Due to such and many already explained reasons, the need of considering DG in the planning and operation of distribution as well as transmission systems is becoming unavoidable. In fact, it is not a trivial task to address this issue to each and every details, resulting in the inability of the methods developed until now to be fully implementable. Consequently, more detailed and integrated transmission and distribution models for the challenges and opportunities to be properly assessed. This whole scenario highlights the need of considering the wider system requirements.

In literature, the services such as reserve, reactive power support and inertial response are continually termed as "ancillary" services however, these are expected to become vital in the near future. This is because, these have to be acquired from alternative sources instead of the conventional bulk synchronous generation plants as had been traditionally done. In many recent researches, such as [158, 159, 160, 161], a strong focus about provision of these services from DGs along with impact of DGs on the transmission system has been observed. From such efforts in recent researches, the capabilities of DGs are expected to be enhanced significantly but additional support for the transmission network may also be required [162].

To have multiple integration schemes in order to facilitate the DG owners in terms of economic benefits is also possible however it mainly depends on the particular DG development circumstances *e.g.*, planning consents, resource availability or declared net capacity. For example, the operation strategy and/or selection of connection point can be considered as a DG integration scheme along with economics of different locations. In fact, if distribution connection charges are also involved along with the infrastructure costs, selection of optimal locations and their economics becomes even more relevant and important. With such an approach, it may become possible for DNOs to control the direction of DG projects towards specific areas in the network where it can achieve technical and economical benefits. Recent developments in the regulations also provide the possibility of providing certain degree of control to the DNOs in this regards. Moreover, bilateral agreements between DG owners and DNOs can also provide another win-win alternative but to do this, DNOs need to put some effort in determining the appropriate locational signals. Similarly, they also need to investigate about the DG integration capability (limits) of their network. In most cases, the DNOs are not allowed to invest in generation facilities, it can only specify whether to connect an oncoming DG or not based on their capacity. This results in an inability of the DG owner to control the overall DG placement process. Consequent to this, entering into commercial arrangements with DG owner appear to be the only option available with DNOs to get certain degree of control over the process. An alternative to this scenario can be the case of regulatory modifications and improvements to allow DNOs with certain, whether limited, degree of control for steering the direction of DG placement.

2.10 Proposed Solution

The major issues which are put forward as a consequence of the detailed discussion up to this point cannot be combined into a single statement. The reason for complexity of the problem have their roots in variety of factors which can be extremely opposing but highly dependent on each other. Some of such factors include contradicting objectives of different agents in the power system, the intermittent nature of some types of (renewable) generations, and regulatory requirements which bind the DNOs with a limited control over the planning for DG placement in order to get technical, economical or environmental benefits. Under this scenario with extreme diversity of objectives, targets and ambitions; solving the optimal DG placement problem to fit most of the power system scenario and requirements is a challenging task. Despite these facts, there have been numerous researches related to the field which have posed us in front of an important question: *who will benefit from such studies when there are many challenges toward their implementation?* Moreover, how existing methods can be improved and/or modified to extract maximum benefits for different agents *e.g.*, DNOs and DG owners etc., in the whole power system, is an interesting query. It is also important to note that most of presented studies in literature do not consider some non-conventional – yet very important – design variables, such as geographical location, that affect the whole process of DG placement starting from its planning up to the final implementation.

The optimization methods applied to the optimal DG placement problem are mostly metaheuristic based, which make the quality of the solution slightly doubtful due to their inherent nature. Such methods are also computationally expensive as well as time consuming. On the other hand, analytical methods are comparatively fast and accurate but they also bear a demerit of being complex in formulation. Moreover, most of the analytical methods available in the literature are only designed/formulated to find the optimal DG sizes. Choosing the optimal location or modifying such methods for other benefits such as voltage profile improvement or reactive power support etc. is beyond the scope of such methods. As an example, the optimal location is selected in some analytical methods by finding the optimal size of DG at each bus of the system, then connecting the respective DG on the buses in one by one manner and calculating losses. In the end, the optimal location would be the one at which least losses are observed. Such iterative procedure do produce good results but it clearly speaks about closeness of the methods so adding other variables becomes more difficult or even impossible. Hence, to make the solutions provided by conventional studies practically implementable, these need to incorporate the consideration of many parameters. The observations based on the literature survey can be briefly summarized as:

- Studies justifying the need of providing the DNOs with a control to steer the penetration of DGs are negligibly less in number.
- To provide the DNO a steering control, concerns and issues related to the DG(s) investors should also be incorporated. For example, the geographical maps for availability of land and primary energy should be considered when identifying the optimal location.
- As a matter of fact and practice, it is not possible to connect a DG on every bus in the system because of some network features and conditions. Considering this point as a useful information, the search space, and hence the simulation burden and time, can be significantly reduced.
- Excessive computational burden and considerable error in calculation of DG sizes results due to considering the loss coefficients as constants throughout the iterative process of placing multiple DGs, especially in analytical methods.
- The methods are in some respect hard coded. This means, if finding the size on some predefined location is needed, it cannot be done in a simple straightforward way. This problem stands especially with methods using the metaheuristic or hybrid metaheuristic methods.
- The loss minimization from few methods is so small that the optimal placement of DGs to get technical advantages sounds like a costly solution as compared to the other grid reinforcement techniques. Therefore, DG placement should not only reduce the losses to reasonably higher value but also provide other benefits in order to get better justified for the optimal placement studies.
- DG technologies and motivational measures for shifting from fossil fuel based bulk generations to the renewable based DGs are growing very fast. Under such scenario, considering really small DG sizes at low voltage level may appear non-practical approach. Moreover, without properly planned approach for DG penetration, the DGs are expected be appearing in the system as "popping up like mushrooms" which may lead to serious issues related to the power system safety, security, reliability and quality.

In this study, above mentioned targets are approached by distributing the problem into logically separable and independent sub-parts *i.e.*, location and size. In this way, the method developed here is expected to be able to include any factor(s) being designed in future. This study benefits from the idea of distributed designing and computation of various factors with respect to all of the specific requirements of respective variable (for which this factor is being designed). In the end, all these factors can be combined within a single final factor which can be used for finding the final solution. In this way, the optimal locations are selected, not only based on single objective such as loss reduction or voltage profile improvement but based on as many factors as needed. With this approach, it is attempted to ensure that different agents in the system can have their own factors, independent of each other, for choosing the suitable locations which can be combined together to find the final optimal locations. The method of combining these factors can be simple such as binary logic based or complex such as based on different weighting factors. Afterwards, the DG sizes can be found independent of the selected locations. A method based on the analytical expression to find the sizes of any number of DGs simultaneously is proposed here. Analytical approach is preferred due to its advantages mentioned earlier. As a consequence of this approach, a win-win situation for all the agents of a power system is expected with more openness for incorporation of as many factors as possible in future.

The factor designed to select the optimal location in order to minimize the losses of the system is called "Load Concentration Factor". This factors identifies the buses with maximum load concentration hence it has proved to be equally good for the improvement of voltage profile and voltage quality which is explained with the respective "Voltage Quality Index" proposed in this study. The selection of geographical location has been done based on the binary type factor. Afterwards, both these factors are combined to make the final list for selecting the buses to place DGs. The method of finding optimal sizes of DGs is not used during the process of finding optimal locations, which is contrary to the most of the existing literature. This means that the location selection has been considered completely independent of the size calculations hence, any method, even other then the proposed one, can also be used. On the similar grounds, if in future, the selection of the type (based on primary energy) of DG is also desired, some factor can be designed for that too. As the method is neither metaheuristic based nor it uses the iterative procedure for selection of location(s), simulation time and computational burden become very less. This big advantage of the method helps to be used for different load profiles and hence, the optimal generation profiles from DGs, which can ensure best performance for the selected objectives, can also be achieved.

2.11 Contributions of the Work

This thesis attempts to formulate a standard procedure for power system planning with DGs of different types based on some conventional objectives like loss minimization and voltage profile improvement, and some non-traditional objectives like geographical location as input to the system. It is worth mentioning that the objectives considered here are important because they contribute to increasing the hosting capacity of a network, reducing its congestion and the line flows along with many other potential advantages. Also, to accelerate the computation, the analytical expressions for calculating the optimum DG sizes simultaneously are derived. In fact, the problem has been modified by splitting it into two logical parts; selection of optimal location for achieving desired benefits and finding optimal size to minimize the losses. Each part is addressed in a way that the solution becomes more practical and implementable.

Selection of location has been given key importance because not all or any bus in the system is practically feasible of installation of DG, as being done in conventional studies. It is, therefore, considered that the optimal location should be chosen for reducing the network power losses and improving the voltage profile of the system. Moreover, the selected locations should not be geographically unfeasible. Once, the optimal candidate locations are finalized, the sizes can be calculated, by any method, with relatively less effort because now the search space is logically reduced and hence, the calculations are minimized. In this work, the exact loss formula based analytical expressions are derived by using the derivative based method. The sizes can be calculated for any number of DGs simultaneously, which is contrary to previous iterative methods. This helps to further reduce the computation time considerably along with improving the accuracy. In previous methods of optimal size calculation based on similar principle did not update some co-efficients which introduced some degree of error in calculation (this is further explained in chapter 3).

Unlike the most of the conventional studies, the method has been applied to the static as well as time varying load profiles in order to have better impression about the usefulness of the method. Furthermore, a comparison of network's voltage quality by different methods of optimal DG placement, the proposed and few other available in the literature, is presented too. In this regard, voltage problems are corrected in both these cases and voltage quality, voltage profile and the losses are compared to provide another valuable reason for optimal placement.

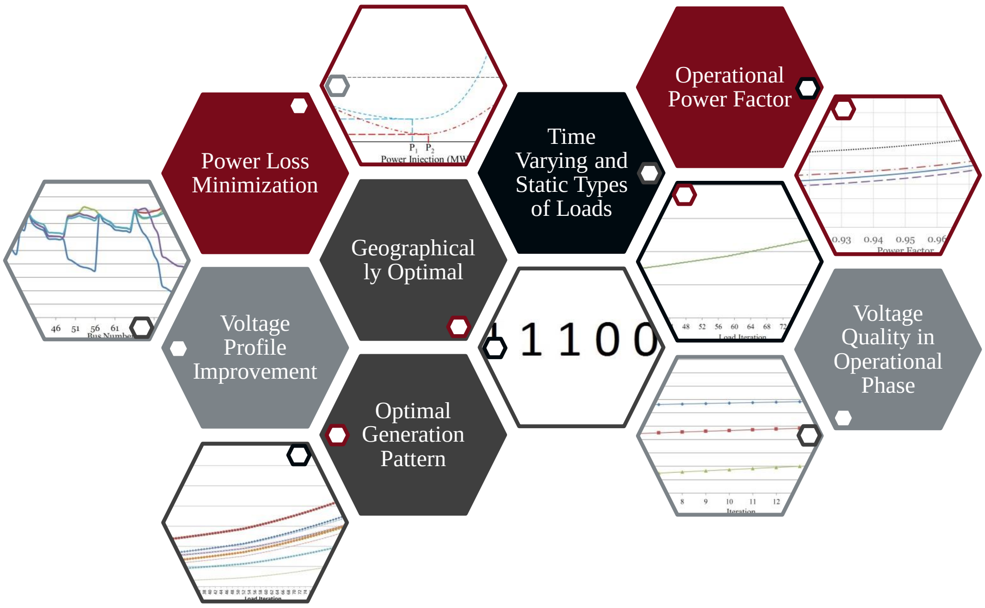


Figure 2.7: Variable considered for optimal DG placement

3 Analytical Method of Simultaneous Optimal DG Placement

3.1 Introduction

This chapter explains the analytical methods for selecting the optimal location(s) for placing the Distributed Generations (DGs) which can ensure the minimization of active power loss as well as the improvement of voltage profile. In this context, a very brief overview of already existing approaches for the optimal location selection is provided. Along with this, an overview about their merits and demerits is also given to explain the need of introducing new approach. On the contrary to existing approaches, which mostly prefer to choose the optimal location as a part of finding optimal sizes, the method of selecting optimal locations presented here is completely independent of the size calculation. Due to this feature, it is expected that the method becomes open for the inclusion of other factors so that the optimal location selection can be made more practically implementable.

The optimal location selection is based on the factor introduced in this work which is named as "Load Concentration Factor (LCF)". As the name implies, this factor prioritize the locations (buses) with high concentration of load for connecting the DGs. In this way, the loads are supplied with the local generation, leading the benefits of reduced transmission congestion and line flows. This ultimately helps in reducing the transmission loss and improve the hosting capacity of the network. As a matter of fact, the voltage dips in the distribution network at either the far end of long feeders (due to excessive inductive impedance of the lines) or at the regions with high loads (and subsequent high reactive power demand). As the LCF gives priority to the locations with high concentration of load, it is expected to be useful in improving the voltage profile also.

Afterwards, the analytical method for simultaneous optimal sizing of multiple DGs is used to find optimal sizes of multiple DGs which is based on the exact power loss formula. The method is based on partial derivative based technique of finding the DG sizes at minimum value of losses. With this analytical method, it is possible to calculate the sizes of as many generators as needed ranging in number from one to the maximum number of buses. It is worth mentioning that active power losses can be minimized to approximately zero by placing the DG of size equal to the load connected at respective buses. However, such an approach may not be considered practically implementable due to many obvious reasons. Simultaneous optimal sizing is preferred as it finds the sizes of all the DGs within the full range of available search space. Moreover, several iterations of analytical methods to find the sizes of multiple DGs can increase computation cost and the simulation time.

Finally, the general algorithm for optimal DG placement is presented. In this section, the problem is formulated in the form of conventional optimization problem and a systematic procedure for using the proposed method to finally achieve the solution is presented. The optimization problem is formulated as minimization problem and the usual power system constraints *i.e.*, active power balance, reactive power balance, voltage limit constraints and line flows constraints are taken into account. A flowchart for this algorithm is also presented in this section.

3.2 Optimal Location Selection

In this work, the optimal location selection is kept completely independent of the optimal size calculation for DG placement. This is done in order to create an opportunity for incorporating different variables and objectives in this process so that the method can be made realistic as well as practically implementable. The objectives considered in this work are minimization of active power loss of the distribution network and improvement of voltage profile. Along with these, it is attempted that the chosen locations should be feasible with respect to the optimal geographical location which means that the locations are not only electrically optimal but these must also be suitable for installation of DGs in real network too. The selection of electrical optimal has been done based on the loads connected to the network and its structure whereas the geography related variable is considered as a binary variable which can reject some of the available locations where the installation of DGs is either not possible or not permissible.

3.2.1 Existing Approaches of Optimal Location Selection

Due to several already mentioned reasons, it is very obvious that the number of DGs is increasing considerably in the distribution networks. For this reason, the selection of optimal locations for multiple DGs is also important. In literature, there are different methods to find multiple optimal locations. For example, in many metaheuristic based methods, the number of DGs to be placed is given as a part of the problem formulation. Some researches, usually analytical based methods, use the iterative procedure which not only increases the chances of error because these do not update the loss co-efficient according to the new working conditions (*i.e.*, after placing a DG [163]. Moreover, iterative procedure of DG placement also bear a disadvantage of limiting the search space for finding the optimal size of next oncoming DGs because the optimal size of a DG is function of existing system loads and generations. So, if there already exists a generation, there is less need of the more “local” generation as increased generation may increase the line flows and flow of power back to the main grid (reverse power flow), which *may* cause subsequent increase in the network losses. Another approach in the literature is of sectioning the given distribution network into regions [164, 165]. Such approaches appear useful in avoiding the densely concentrated installation of the DGs in one region. However, such methods may not guarantee the minimization of losses to the maximum because the most suitable locations may appear in single region. For all these approaches, the optimal locations are selected based on the electrical parameters and not on the basis of geographical factors of real network. This is important to note that incorporation of such non-conventional factors may result is slight variation in the losses due to deviation from electrical optimal location. The strategically decided regions in region-wise selection of optimal location(s) can also be useful in finding the optimal location(s) based on the geographical space.

3.2.2 Essence of Location Selection

The main reason for the power loss in the power system is resistance (R) and impedance (X) of the lines over which the power is being transmitted from generation to the load. As repeatedly mentioned, the bulk power was generated conventionally and was transmitted over the long transmission lines. These long transmission lines had higher values of R and X, leading to higher power loss across the transmission lines. It is worthy to mention that the R and X of these lines increases as function of their length along with other factors. Along with the length of lines, and values of R and X, the losses also increase due to the amount of power being transmitted. From this explanation, it can be easily concluded that reduction of losses is possible either by reducing the values of R and X, which ultimately necessitate reducing the length of transmission lines, or by reducing the amount of power being transmitted over these lines. The DGs serve both these purposes by generating near the load center and hence reducing the lengths of transmission lines, which is contrary to the conventional power system approach. Supplying the demand locally can ideally reduce the losses to zero if every load is powered by local generation of equal size, however, it is not possible due to many technical and economical reasons. Consequently, supplying a group of loads with comparable size of local generation seems to have better impact in this regards. Reduction in stress of conventional power plants, improved reliability of supply system and reduction of transmission system stress are very few among many benefits of supplying the local loads with local generation.

In standard power distribution system, various buses contain loads connected to them whereas, historically, there had not been any generation connected. Based on the principle mentioned above, if the group of loads is served with generation connected nearby, a considerable loss reduction is expected because it reduces the line flows by serving the loads locally and, ultimately, reducing the power loss across the long transmission lines (with high R and X). In this regards, the selection of a location for connecting the generation becomes vital. The buses in a power system with higher concentration of the connected loads get higher priority for connecting DG due to this principle. To formulate this, Load Concentration Factor (LCF) has been introduced here which arranges all the buses in the system in sequence to set their priority level for connecting the DGs. The LCF is a simple measure of the amount of the load being faced by certain bus in the distribution system. If the connection of multiple DGs is desired, the topmost buses in this LCF list can be taken as the candidate locations.

It has been observed in power systems that the voltage (drop) problem becomes prominent when the length of certain feeder becomes very high and/or the power demand increases beyond certain level. As usual practice, it is seen that the voltage at the far end from the external grid drops significantly in radial distribution systems. By choosing the locations for connection of DGs on the basis of LCF, it is expected that the voltage problem can also be mitigated to the considerable extent because supplying the highly concentrated load with local generation reduces the line flows. This ultimately reduce the voltage drop across the lines due the line parameters and ultimately, the voltage profile improves. In regards to the voltage rise issue, the tap setting of the transformers at distribution system are set in such a way that the voltage at the connection point to the external grid is kept at the highest permissible voltage limit. Moreover, this (slack) bus is a voltage control bus, hence, no extra equipment is needed for controlling the voltage.

Finally, if the DG sizes are calculated optimally, the chances of getting voltage rise problem due to DGs becomes even lower.

3.2.3 Types of buses

In a standard power system, usually represented by IEEE systems of various sizes and complexity, it is not compulsory to have the load connected to every available bus. Also, every bus in the system is usually connected to at least one other bus. As the selection of buses for connecting the DGs is linked with the amount of "concentrated" load to be served, the buses are categorized as "directly connected" and "loaded" buses in this work. The definition used here for each of these types are given as:

Directly Connected Bus: For any bus "i" in the system, any other bus will be said the directly connected bus if both these are directly connected without any other bus is appearing/connected in between them. As a direct consequence of this definition, it can be inferred that, for a bus "i", the number of directly connected buses is equal to the number of lines connected to that bus. To simplify the mathematical formulation and to aid easy understanding, the set "C_i" for a bus "i" is given as a set which contains the bus numbers of all the directly connected buses to the bus "i" and the bus "i" itself.

Loaded Bus: As the name infers, it is the type of bus which has some load connected to it. For the buses without load, zero load can be considered in any mathematical expressions for the purpose of generalizing.

In this work, two different IEEE standard systems viz a viz 37 node and 119 node, given in Figure 3.1 and 3.2, have been used for implementation and validation of proposed method. The data for these systems is given in Table 1 and 2 (in Appendix section), which is slightly modified based on the one given in [166, 167], respectively. In the given system data, the loads are always connected to the sending nodes, represented by "Sn. Nd.". In 37 node test system, every bus except 1, 3, 4, 6, 7, 8, 12, 16, 18, 25, 29 and 34 has load connected with it therefore termed as loaded bus. Similarly, It is obvious that the buses 21, 23, and 24 are connected directly to the bus 22 in 37 node network hence the set "C_{22}" is given as $\{21, 22, 23, 24\}$. Using similar approach, "C_{10}" can be given as $\{8, 10\}$ for bus 10 in same network.

3.2.4 Load Concentration Factor

The optimal buses are selected completely independent of the selection of the the optimal size of DGs. The method is equally suitable for choosing single as well as multiple locations simultaneously. In this method, the complete list of buses in the network is arranged in a sequence so that the topmost bus(es) are selected for placement of DG(s). It has been highlighted earlier that the DGs can help in reducing the losses because these help in supplying the loads locally, hence, reducing the flow of power over the lines. However, if the location is not selected strategically, these line flows, and hence the losses, may increase. This may be, for example, due to the connection of DGs at the locations where the demand is less in comparison to the size of connected DGs. To address such problems and to help in selecting the location for optimal DG placement that can ensure loss reduction, LCF is proposed. The LCF of an "i_{th}" bus of the system is the

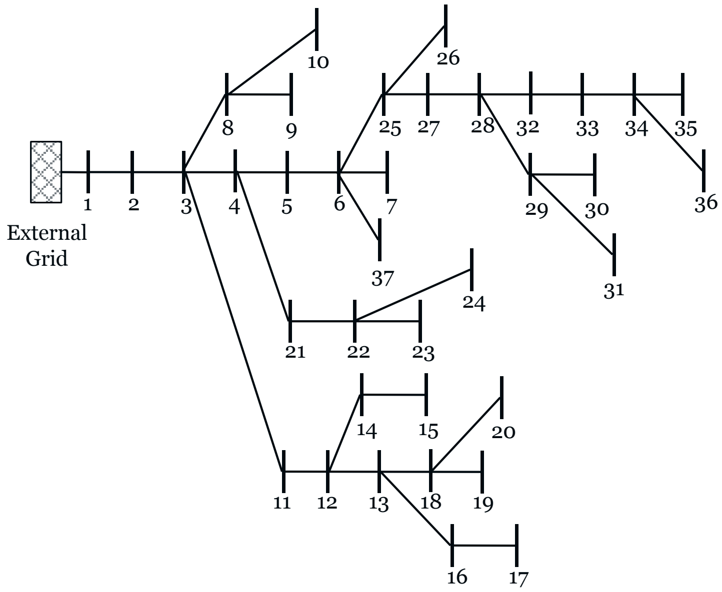


Figure 3.1: IEEE 37 node network.

sum of all the loads connected to the directly connected buses *i.e.*, the buses represented by the set "C_i". Mathematically,

$$LCF_i = \sum_{j \in C_i} P_{Dj} \tag{3.1}$$

where P_{Dj} is the power demand *i.e.*, load connected at bus "j". If, there is no load connected to some bus(es), the respective P_{Dj} is considered as zero.

3.2.5 Selection of Optimal Locations with LCF

The LCF_i for the IEEE 37 and 119 node systems are calculated using the Equation 3.1 and are given in Figure 3.3 and 3.4, respectively. The power networks have different structure and specifications. For example, in radial networks, the power flows over the main line originating from the main (slack) bus connected to the external grid can be extremely high because of it being the supplier of the total network demand through it. It can be observed from the line flows information provided in the Figure 3.5 and 3.6 for the IEEE 37 and 119 node systems, respectively. If the DG is connected to the bus connected to such lines, the losses may increase due to still increased line flows. Under such scenarios, the optimal location selection is not done by simple straightforward selection of the buses with the topmost LCF_i, as it should ideally be done. By performing several experiments, it has been observed that connecting the DGs to the directly connected buses is not suitable due to the chances of increased line flows and chances of voltage rise. Although the optimal number of DGs is also important, the number of DGs to be placed are taken as user input in this work. Total of four and five DGs are considered for placing in IEEE 37 and 119 node systems. As a result of such considerations, the finalized selection of the buses for IEEE 37 and 119 node systems become (12, 18, 22, 32) and (43, 52, 74, 82, 115) with considered static load, respectively. For this work, the whole network has been considered as single region, instead of using the region-wise splitting of the network as done in [164, 165]. However, similar method and steps can be applied to every region if region-wise optimal location selection is desired.

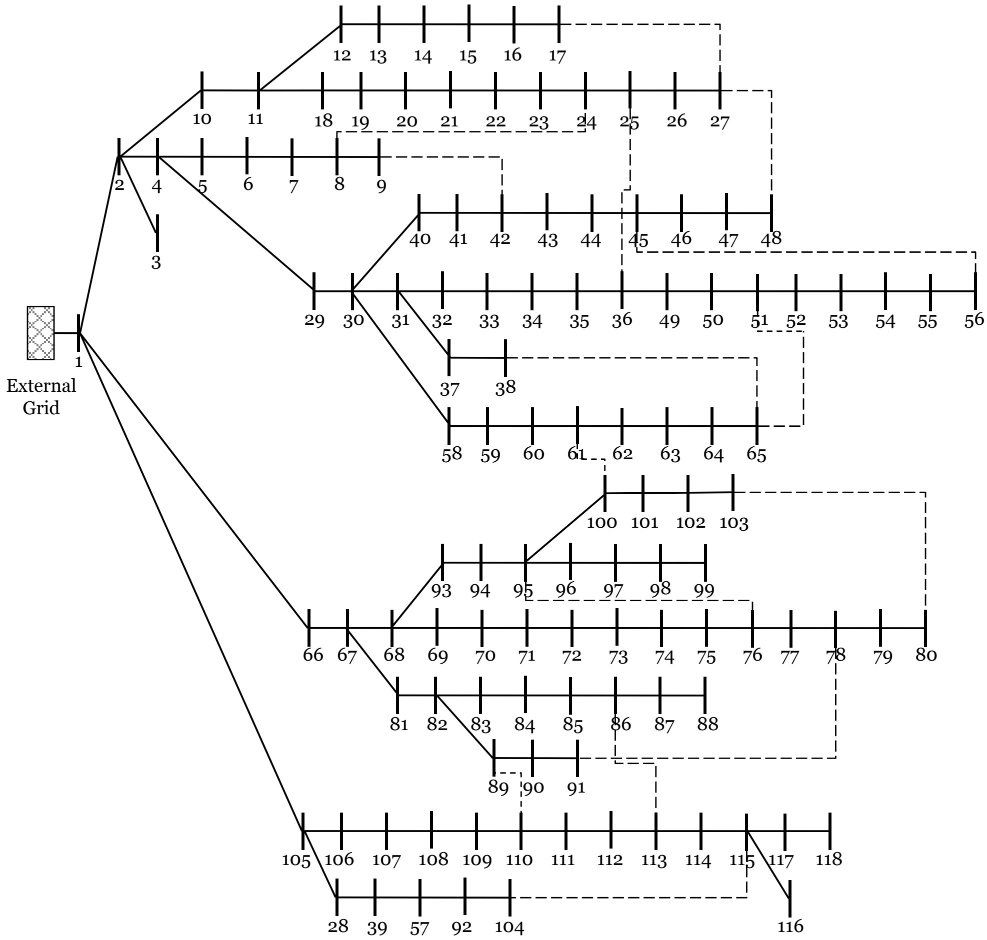


Figure 3.2: IEEE 119 node network.

3.2.6 Location Selection for Geographical Factor

In this work, selection of location is not only intended to be optimal for the electrical parameters (such as power loss minimization and voltage profile improvement, as done with LCF) in the system but also for the some nontraditional factors too. Geographical factor is considered in this regard in order to have the impression of such variables in location selection. Availability of land and the primary energy, and legal requirements are the most prominent factors which influence the installation of DG in certain area/region. The legal requirements may include the factors such as restrictions due to will of the population in a region, some strategic and political influences/guidelines or constraints such as environment protection. There can be many other of such factors, with extremely diverse impacts and influence on the planning and placement of DGs. It is worth mentioning that the number and nature of all such factors vary from region to region and country to country. The relationship and influence of such factors on each other can also be unpredictable due to the preferences and requirements of different entities (population, legal, political, or geographical etc.) in some specific region.

Due to all these reasons, formulation of the geographical factor becomes more complex and complicated task, making it hard to come up with a straightforward method even for some very specific region. Under such scenario, it is not possible to have a geographical factor that can

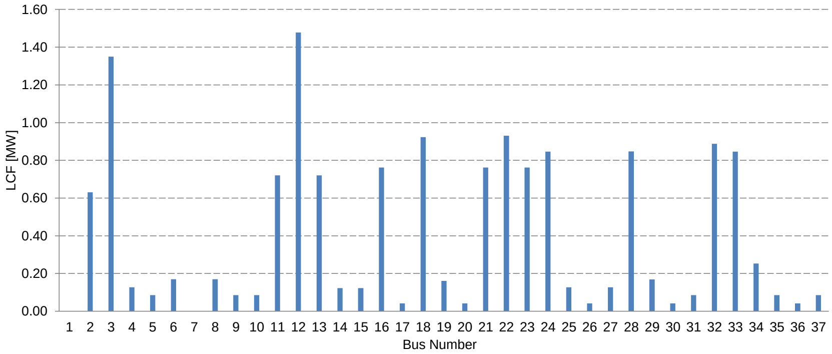


Figure 3.3: Load concentration factors for 37 node system.

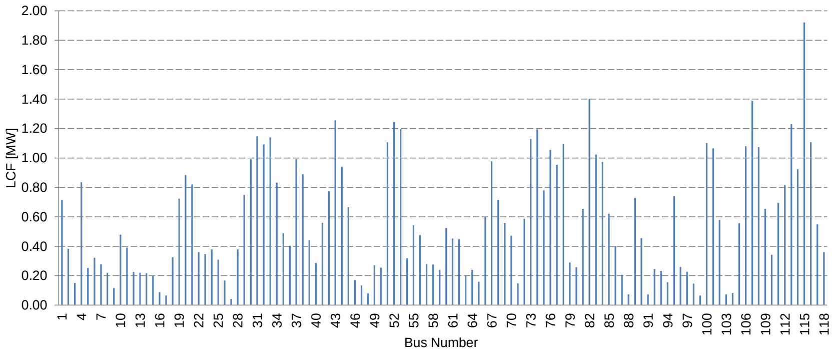


Figure 3.4: Load concentration factor for 119 node system.

be generalized for every region across the globe. Moreover, designing the geographical factor for single region includes many variables, for which information and knowledge of different fields is highly demanded. Considering such reasons and facts, the geographical factor in this factor is taken as a binary variable, which gives the status of logical "1" or "0" for the buses where DG can or cannot be installed based on any variables of "non-electrical" nature, respectively. For the purpose of simplicity, all the locations selected in the LCF are taken to be "1" in geographical factor. From the remaining locations (not selected in final LCF selection), some can have "0" status as well, which can show its influence when the already chosen location is dropped due to aforementioned reasons.

3.3 Analytical Expressions for Optimal Sizing

In this section, the analytical expressions for calculating the optimal sizes of given number of DGs simultaneously are given. As mentioned earlier, the number of DGs and the bus numbers at with the DGs are to be placed is taken as input for these expression. The method explained here is generalized for finding optimal sizes of "N" DGs simultaneously. This method is based on the exact power loss formula, also known as Elgerd's loss formula [168]. The method is useful in finding the optimal active power which can ensure the minimization of the active power losses in the network. The steps to find the generalized method for calculating the output of other types of generations *i.e.*, which can also produce reactive power based on different power factor, are also explained.

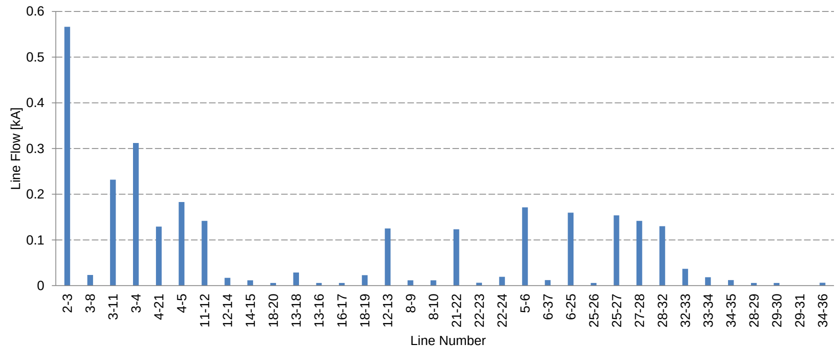


Figure 3.5: Line flows for 37 node system.

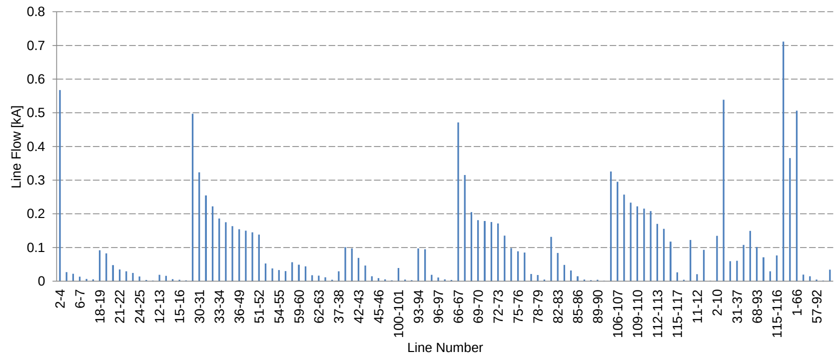


Figure 3.6: Line flows for 119 node system.

3.3.1 Distribution System Power Losses

According the Elgerd's exact loss formula, the total real power loss is given as a function of real and reactive power function as:

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} [\alpha_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j - P_i Q_j)], \tag{3.2}$$

where

$$\alpha_{ij} = \frac{R_{ij}}{|V_i|\,|V_j|} \cos(\delta_i - \delta_j); \qquad \textit{and} \qquad \beta_{ij} = \frac{R_{ij}}{|V_i|\,|V_j|} \sin(\delta_i - \delta_j),$$

P_i, P_j: Active power injections at the ith and jth buses, respectively; Q_i, Q_j: Reactive power injections at the ith and jth buses, respectively; $V_i\angle\delta_i$,$V_i\angle\delta_j$: Complex voltages at the ith and jth buses, respectively; $R_{ij} + jX_{ij}$: ijth element of impedance matrix $[Zbus]$; n: Total number of buses in the system. α_{ij} and β_{ij} are known as loss coefficients in Equation 3.2.

3.3.2 Proposed Method

For any (distributed) generator, the relationship between its active and reactive power output can be given by the Equation 3.3 [108]. As, this work is mostly focused on DGs, the subscripts *DG* are used in this equation to highlight this fact.

$$Q_{DGi} = aP_{DGi}, \tag{3.3}$$

where

$$a = (sign)\tan(\cos^{-1}(PF_{DG})),$$

and $sign = +1$ or -1 for DG injecting or consuming reactive power. PF_{DG} is the power factor of the DG.

The net active and reactive power injections at the bus where a DG has to be installed are given, in terms of active and reactive power demands P_{D_i} and Q_{D_i}, as:

$$P_i = P_{DGi} - P_{Di}, \tag{3.4}$$

$$Q_i = Q_{DGi} - Q_{Di} = aP_{DGi} - Q_{Di}. \tag{3.5}$$

By substituting Equation 3.4 and 3.5 in Equation 3.2, the active power loss becomes:

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n}[\alpha_{ij}\{(P_{DGi} - P_{Di})P_j + (aP_{DGi} - Q_{Di})Q_j)\} + \beta_{ij}\{(aP_{DGi} - Q_{Di})P_j - (P_{DGi} - P_{Di})Q_j\}] \tag{3.6}$$

The relationship between the active power loss and power injection at certain bus of a power system follow the parabolic relationship as given in Figure 3.7 [18]. From this, three important conclusions can be drawn:

- The active power loss after placement of DG can be even more that of no DG case if sizes are not calculated properly.
- The location plays an important role to get the least possible losses as given by red curve in the system where P_2 has reduced the losses more than P_1.
- Derivative based approach can be used in order to find the minimum value of losses for specific value of power injection from DG at given bus.

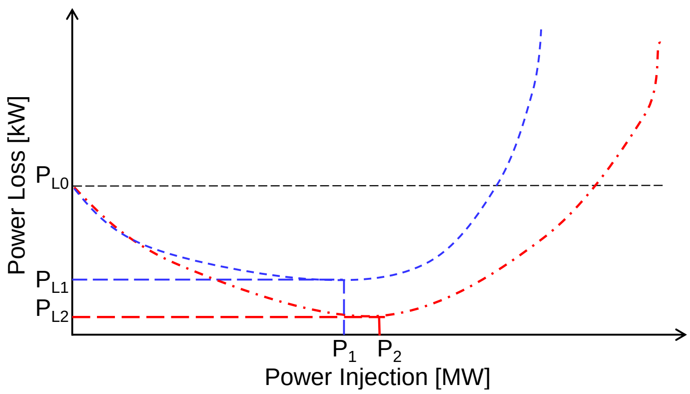


Figure 3.7: Power loss as a function of power injection at a bus

Hence, the partial derivative of Equation 3.6 is given as:

$$\frac{\partial P_L}{\partial P_{DGi}} = 2\sum_{j=1}^{n}[\alpha_{ij}(P_j + aQ_j) + \beta_{ij}(aP_j - Q_j)] = 0. \tag{3.7}$$

To generalize the method for finding optimal sizes of "N" DGs, x_1","x_2", ... ,"x_n" are taken as the potential locations (bus numbers) for DG placement. It should be noted that "x_n" cannot exceed the total number of buses *i.e.*, "n". For given potential DG locations, the Equation 3.7 can get the form:

$$\frac{\partial P_L}{\partial P_{DGx_1}} = \alpha_{x_1x_1}(P_{x_1} + aQ_{x_1}) + \beta_{x_1x_1}(aP_{x_1} - Q_{x_1}) + \alpha_{x_1x_2}(P_{x_2} + aQ_{x_2}) + \beta_{x_1x_2}(aP_{x_2} - Q_{x_2}) + ...+$$

$$\alpha_{x_1x_n}(P_{x_n} + aQ_{x_n}) + \beta_{x_1x_n}(aP_{x_n} - Q_{x_n}) + \sum_{j=1, j\neq 1,2...n}^{n}(\alpha_{x_1x_j}P_j - \beta_{x_1x_j}Q_j) +$$

$$a\sum_{j=1, j\neq 1,2...n}^{n}(\alpha_{x_1x_j}Q_j + \beta_{x_1x_j}P_j) = 0$$

$$\frac{\partial P_L}{\partial P_{DGx_2}} = \alpha_{x_2x_1}(P_{x_1} + aQ_{x_1}) + \beta_{x_2x_1}(aP_{x_1} - Q_{x_1}) + \alpha_{x_2x_2}(P_{x_2} + aQ_{x_2}) + \beta_{x_2x_2}(aP_{x_2} - Q_{x_2}) + ...+$$

$$\alpha_{x_2x_n}(P_{x_n} + aQ_{x_n}) + \beta_{x_1x_n}(aP_{x_n} - Q_{x_n}) + \sum_{j=1, j\neq 1,2...n}^{n}(\alpha_{x_2x_j}P_j - \beta_{x_2x_j}Q_j) +$$

$$a\sum_{j=1, j\neq 1,2...n}^{n}(\alpha_{x_2x_j}Q_j + \beta_{x_2x_j}P_j) = 0$$

$$\vdots$$

$$\frac{\partial P_L}{\partial P_{DGx_n}} = \alpha_{x_nx_1}(P_{x_1} + aQ_{x_1}) + \beta_{x_nx_1}(aP_{x_1} - Q_{x_1}) + \alpha_{x_nx_2}(P_{x_2} + aQ_{x_2}) + \beta_{x_nx_2}(aP_{x_2} - Q_{x_2}) + ...+$$

$$\alpha_{x_nx_n}(P_{x_n} + aQ_{x_n}) + \beta_{x_nx_n}(aP_{x_n} - Q_{x_n}) + \sum_{j=1, j\neq 1,2...n}^{n}(\alpha_{x_nx_j}P_j - \beta_{x_nx_j}Q_j) +$$

$$a\sum_{j=1, j\neq 1,2...n}^{n}(\alpha_{x_nx_j}Q_j + \beta_{x_nx_j}P_j) = 0. \tag{3.8}$$

$$\text{Let}\begin{cases} X_{x_1} = \sum_{j=1, j\neq x_1,x_2...x_n}^{n}(\alpha_{x_1x_j}P_j - \beta_{x_1x_j}Q_j) + a\sum_{j=1, j\neq x_1,x_2...x_n}^{n}(\alpha_{x_1x_j}Q_j + \beta_{x_1x_j}P_j) \\ X_{x_2} = \sum_{j=1, j\neq x_1,x_2...x_n}^{n}(\alpha_{x_2x_j}P_j - \beta_{x_2x_j}Q_j) + a\sum_{j=1, j\neq x_1,x_2...x_n}^{n}(\alpha_{x_2x_j}Q_j + \beta_{x_2x_j}P_j) \\ \vdots \\ X_{x_n} = \sum_{j=1, j\neq x_1,x_2...x_n}^{n}(\alpha_{x_nx_j}P_j - \beta_{x_nx_j}Q_j) + a\sum_{j=1, j\neq x_1,x_2...x_n}^{n}(\alpha_{x_nx_j}Q_j + \beta_{x_nx_j}P_j). \end{cases}$$

In addition, $\beta_{ii} = 0$, $\alpha_{ij} = \alpha_{ji}$ and $\beta_{ij} = -\beta_{ji}$. Thus, by substituting Equation 3.4 and 3.5 in set of Equation 3.8, and arranging for P_{DGx_i},

$$(1+a^2)\sum_{i=1}^{n}(P_{DGx_i}\alpha_{x_1x_i})-\sum_{i=1}^{n}[P_{Dx_i}(\alpha_{x_1x_i}+\beta_{x_1x_i}a)+Q_{Dx_i}(\alpha_{x_1x_i}a-\beta_{x_1x_i})]+X_{x_1}=0,$$
$$(1+a^2)\sum_{i=1}^{n}(P_{DGx_i}\alpha_{x_2x_i})-\sum_{i=1}^{n}[P_{Dx_i}(\alpha_{x_2x_i}+\beta_{x_2x_i}a)+Q_{Dx_i}(\alpha_{x_2x_i}a-\beta_{x_2x_i})]+X_{x_1}=0,$$
$$\vdots$$
$$(1+a^2)\sum_{i=1}^{n}(P_{DGx_i}\alpha_{x_nx_i})-\sum_{i=1}^{n}[P_{Dx_i}(\alpha_{x_nx_i}+\beta_{x_nx_i}a)+Q_{Dx_i}(\alpha_{x_nx_i}a-\beta_{x_nx_i})]+X_{x_1}=0. \quad (3.9)$$

Writing in the form of matrices to solve using Cramer's rule:

$$AX=B, \quad (3.10)$$

where

$$A=(1+a^2)\begin{bmatrix}\alpha_{x_1x_1} & \alpha_{x_1x_2} & \cdots & \alpha_{x_1x_n}\\ \alpha_{x_2x_1} & \alpha_{x_2x_2} & \cdots & \alpha_{x_2x_n}\\ \vdots & \vdots & \ddots & \vdots\\ \alpha_{x_nx_1} & \alpha_{x_nx_2} & \cdots & \alpha_{x_nx_n}\end{bmatrix}, X=\begin{bmatrix}P_{DG_1}\\ P_{DG_2}\\ \vdots\\ P_{DG_n}\end{bmatrix}, B=\begin{bmatrix}B_{x_1}\\ B_{x_2}\\ \vdots\\ B_{x_n}\end{bmatrix},$$

and

$$B_{x_1}=\sum_{i=1}^{n}[P_{Dx_i}(\alpha_{x_1x_i}+\beta_{x_1x_i}a)+Q_{Dx_i}(\alpha_{x_1x_i}a-\beta_{x_1x_i})]-X_{x_1},$$
$$B_{x_2}=\sum_{i=1}^{n}[P_{Dx_i}(\alpha_{x_2x_i}+\beta_{x_2x_i}a)+Q_{Dx_i}(\alpha_{x_2x_i}a-\beta_{x_2x_i})]-X_{x_2},$$
$$\vdots$$
$$B_{x_n}=\sum_{i=1}^{n}[P_{Dx_i}(\alpha_{x_nx_i}+\beta_{x_nx_i}a)+Q_{Dx_i}(\alpha_{x_nx_i}a-\beta_{x_nx_i})]-X_{x_n}. \quad (3.11)$$

The order of matrices A, B and X when placement of "n" DGs is desired, is as $n\times n$, $n\times 1$ and $n\times 1$, respectively.

It can be noted from the finalized mathematical expressions for simultaneous optimal DG sizing that these expressions only provide the amount of active power output to minimize the active power loss. If the sizes for the other types of DGs is desired, their reactive power can be calculated using the Equation 3.5. The four types of DGs are:

1. DGs which can only produce active power output.
2. DGs which can produce both active and reactive power output.

3. DGs which can produce active power output and are able to consume the reactive power.
4. DGs which can only produce reactive power output.

The selection of power factor is, however, made by the user, which ultimately selects the type of DG. Moreover, the DG size calculations depend upon any generation or load, represented as active and/or reactive power, already connected to the system. This fact helps in generalizing the derived expressions to be useful for the case of a system with other equivalent equipment such as storage *etc.* that can be represented in the form of active and reactive power. However, the care about the sign convention should be taken depending upon the type and functionality of the considered equipment. In this way, similar to the method presented in [169], this method can be generalized to include already existing generations.

3.4 Algorithm for Optimal DG Placement

3.4.1 Formulation of Optimization Problem

The optimal DG placement problem is an optimization problem which can be formulated in different ways, based on the objective of optimization. In this work, the minimization of active power losses is the main objective subject to the network power balance constraints as well as the line flows and bus voltage limits. The active power losses by Elgerd's formula are given as:

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n}[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j - P_iQ_j)], \tag{3.12}$$

where

$$\alpha_{ij} = \frac{R_{ij}}{|V_i|\,|V_j|}\cos(\delta_i - \delta_j); \qquad \mathit{and} \qquad \beta_{ij} = \frac{R_{ij}}{|V_i|\,|V_j|}\sin(\delta_i - \delta_j),$$

P_i, P_j: Active power injections at the ith and jth buses, respectively; Q_i, Q_j: Reactive power injections at the ith and jth buses, respectively; $V_i\angle\delta_i$,$V_i\angle\delta_j$: Complex voltages at the ith and jth buses, respectively; $R_{ij} + jX_{ij}$: ijth element of impedance matrix $[Zbus]$; n: Total number of buses in the system.

The optimization problem is formally defined as:

$$Minimize(P_L). \tag{3.13}$$

Subject to the following power, voltage and line flow constraints:

$$\begin{aligned}
\sum_{dg=1}^{n} P_{DG_{dg}} &\leq \sum_{i=1}^{N} P_{D_i}, \\
\sum_{dg=1}^{n} Q_{DG_{dg}} &\leq \sum_{i=1}^{N} Q_{D_i}, \\
V_{min} < &V_i < V_{max}, \\
I_i &< I_{max},
\end{aligned}$$

$P_{DG_{dg}}$ and $Q_{DG_{dg}}$: real and reactive power output from DGs; n: total number of DGs to be installed; P_{D_i} and Q_{D_i}: the active and reactive power demands on ith bus; N: the total number of buses in the system; V_{min} and V_{max}: the lower and upper bus voltage bounds; V_i: the ith bus voltage; I_i: flow on the ith line; I_{max}: the maximum loading limit of ith line. In this work, line loading is taken in form line currents.

3.4.2 Methodological Steps

Figure 3.8 illustrates the flow chart of the computational steps needed to find the results based on proposed analytical expressions. The power of the slack bus is kept positive in order to limit the chances of increasing the losses.

1. Enter the base case network.
2. Enter the desired number of DGs to be placed.
3. Run base case load flow and calculate losses using Equation 3.2.
4. For all the buses in a region, calculate the LCF_i and arrange the buses in descending order with respect to this.
5. Choose "N" buses for placing "N" DGs. The initial set of bus numbers will contain the bus(es) with highest LCF in each region.
6. Based on input data in step (4), find the optimal size of DGs using the expression given in Equation 3.10.
7. Stop if:

    a. The sum of power of DGs to be installed is less than the total power demand plus losses.

    b. The bus voltages are within a permissible limit.

    c. The lines are not overloaded.

    Else, look for new locations by using these steps.

    i. Try to change only one bus in the region from the set of bus numbers chosen in step (4) *i.e.*, for placing n DGs, $(n-1)$ buses will remain the same.

    ii. The most suitable candidate for the changed bus will be the one which has the least difference in LCF from the LCF of a previously selected bus, while staying in the same region.

    iii. In case of a clash between any two or more regions for the selection of the second highest LCF bus, priority will be given to the bus which carries the highest load.

    Go to step (6)
8. Place sized DGs in the system and calculate losses using Equation 3.2.
9. To check for better sizes, optimal sizes in nearest proximity can also be checked.

10. To check for even better solutions, next candidate buses in the list of LCF can also be checked.

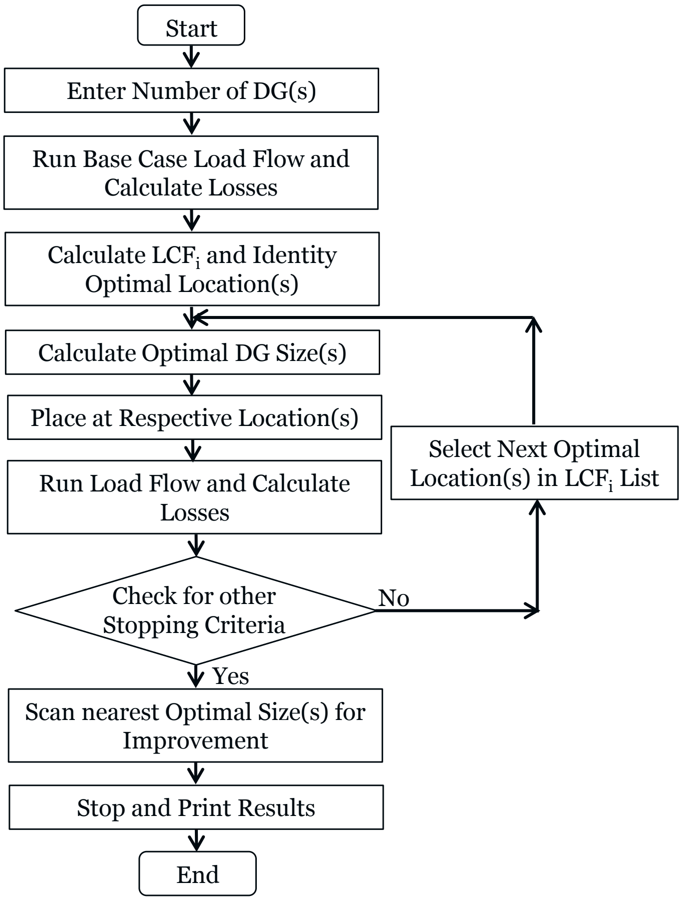


Figure 3.8: Flowchart of optimal DG placement with proposed method without selecting operational power factor

To further improve the sizes calculated in this method, an exhaustive approach is also added to the presented method. The DG sizes are slightly changed to look for finding any possible sizes which can further improve the loss reduction ratio. As the locations are already fixed, the computation burden only increases slightly by using this approach, however this helps in improving the losses in some cases. Another important consideration for improving the optimal sizes for reducing the losses further is use of suitable power factor. This is important due to regulatory reasons as well, which bind the owners of generation facilities to provide the power at certain predefined power factor range. The detailed discussion in regard to selection of suitable power factor and respective method is included in chapter 4.

4 Methods for Assessments of Qualitative Improvements

4.1 Introduction

The placement of DGs in power system plays an important role in achieving certain technical and economical benefits. Most of these advantages are closely linked with each other. For example, reduction in active power loss also helps to reduce the line flows and congestion. Similarly, deferring the investment on the grid reinforcement due reduced line flows is a huge economical benefit for a DNOs. It has been observed in wide range of literature studies that the optimal DG placement problem is mostly solved for the sake of planning phase and no real quantification of its benefits is done in operational phase *i.e.*, when the DGs are installed in the system and it starts operating. It is strongly believed that suitable selection of certain variables can further improve the performance of a power system with optimally placed DGs.

In order to focus such benefits and highlight the usefulness of optimal DG placement in operational phase, some methods are presented in this work. The optimization of power factor is considered at the first stage because fulfilling the power factor guidelines is compulsory for most of the generation units, especially at distribution level. In most of the optimal DG placement studies, selection of optimal power factor has been ignored. To the best of literature research done in this work, Combined Load Power Factor (CLPF) is the only method presented in order to choose an optimal power factor. This method is relatively fast but sometimes, the load power factor is too low, and operation at such a low power factor is not possible from certain DG types. Moreover, grid codes also bind the generators to operate within predefined power factor range. Hence, usability of this method becomes limited. To handle this limitation, operational power factor is suggested here, range for which can be adjusted as per specific grid code requirements, resulting in the power factor which cannot be out the permissible range.

Another important impact of DGs in the power system is on the network voltage. In distributions systems with low voltage issues, DGs have very supporting impact in boosting the voltage. However, DGs can create high voltages in the system with comparatively better voltage profile. Along with this, the variation of load also has a strong relationship with the voltage variation. This can be said in two different ways; day-to-day variation of voltage and increase of load over the course of long periods (*i.e.*, years). In order to study the impact of DGs on the voltage quality in either case of load variations, a voltage quality index (VQI) is proposed in here. The proposed VQI is advantageous because it not only gives the information about the difference between maximum and minimum voltage appearing at any nodes in the system but also about the exact values of the voltage. The case where the system has lower least voltage value produces lower value of VQI in comparison to the case of comparatively higher least voltage value. To quantify the need and ease of voltage corrective action in case of optimal DG placement with proposed method in comparison to the other methods available in literature, the Centralized Voltage Control Algorithm (CVCA) is also proposed in this work.

Finally, the methods used to validate and compare the proposed methods, whether planning phase or operational phase, are also given. These comparative studies include the Loss Sensitivity Factor (LSF) method, exhaustive method and Improved Analytical (IA) method. All these methods are chosen due to their logical connection with the proposed methods *i.e.*, these methods are also based on analytical approach. The complete algorithms for each of these methods are given in detail too. In the last section, a brief overview of the algorithm for implementing the proposed methods is discussed briefly.

4.2 Optimization of DG Power Factor

In most of the optimal DG placement studies, optimizing the power factor is either not considered at all or if considered, it is not considered as a main variable. However, in recent years, few researches have proved that power factor is not only useful in managing the voltage and reactive power related issues, but also in reducing the system losses, which ultimately help in improving the hosting capacity and managing the congestion in the network along with other benefits. It has been discussed earlier that the power loss can be reduced to zero if load connected to every bus in the system is supplied by an equal amount of generation. However, it is important to note that this is not only possible by equating the active power demand and generation only but reactive power demand and generation must also be balanced in order to reduce the line flows to zero. As a result of this balance of both active and reactive power demand and generation at every bus in the system, the active power loss can be reduced to zero. This implies that the power factor of load and generation at the respective bus should also be similar, which is only possible in ideal cases. In practical power systems, connecting the DGs at every bus is not a feasible option due to many reasons. Moreover, some of the loads may have very absurd power factor demand therefore such an approach is not usually considered practical.

4.2.1 Combined Load Power Factor

Using similar approach of finding the optimal power factor which is related to the power factor of connected loads, combined load power factor (CLPF) is suggested in [108]. In this method, the total active and reactive power demand in the system, given by Equation 4.1, is considered to find out the net power factor of the load, given by Equation 4.2. Afterwards, the same power factor is considered equal to the optimal power factor requirement from DG. This is termed as "fast approach" of finding optimal power factor of DG, that corresponds to the least losses and is given in by Equation 4.3 as given below.

$$P_D = \sum_{i=1}^{N} P_{D_i}; \qquad and \qquad Q_D = \sum_{i=1}^{N} Q_{D_i} \tag{4.1}$$

$$PF_D = \frac{P_D}{\sqrt{P_D^2 + Q_D^2}} \tag{4.2}$$

$$PF_{DG} = PF_D \tag{4.3}$$

P_D and Q_D are total active and reactive power demands in the network, respectively; PF_D is the net power factor of the total system demand; N is the total number of loads connected in the system.

In the fast approach of finding the optimal power factor, presented in [108], power factor is computed by Equation 4.2. This approach has produced good results but the power factor suggestions are not always practical. For instance, in the IEEE 119 node system being considered in this study, the power factor requirement using this approach is about 0.79. Such a low value of power factor requires high amount of reactive power generation, hence these are not preferred in most of the distribution grid codes [19].

4.2.2 Operational Power Factor

In power systems, there are several loads which have extremely low power factor. Similarly, long distribution lines also consume high reactive power to deliver power reliably and with good quality. In such case, it is not possible to maintain the generator's power factor at the CLPF level, hence such methods have limited practical implementability. In many grid codes, the power factor requirement at distribution level vary in the range of 0.90 or 0.95 and higher. Some distribution grid codes also allow 0.85 power factor but such low power factors are upgraded to a bit higher values. As an ideal practice, higher the power factor, preferably near or equal to unity, better is for the generator.

Keeping such important points in view, the operational power factor is suggested in this work. For optimally sized DGs connected in the system, the best possible power factor, which can ensure least losses along with being suitable for distribution grid code requirements, is calculated by an iterative procedure. Although the range for this iterative procedure is defined by the user but according to the usual grid codes, it is taken to be 0.90–1.00 with the step size of 0.01 in this work. The step size of 0.01 is a logically suitable choice because power factor is usually mentioned up to two decimal places in common practice. It is worthy to highlight that the analytical methods for selecting optimal location and calculating optimal sizing are significantly faster than other contemporary methods, this iterative procedure is expected to have no significant adverse impact with respect to the computational cost and simulation time. To further improve the computational efficiency, the iterative procedure stops as soon as it finds that the losses have increased in comparison to the previous iteration. This is done based on an interesting trend found in several experiments which suggested that the power factor follows the concave curve with active power loss. This is also given in the section 5.3 where the results for complete range of considered power factors are presented.

4.3 Quantification of Voltage Quality

It has been repeatedly mentioned that the voltage should be maintained within the permissible limits on every bus in the system. Distribution system operators use different methods and equipment in order meet this fundamental requirement of the power system. The permissible range of voltage usually lies between ±6 % of nominal voltage at distribution system level [170]. This implies that keeping the voltage within this limit is compulsory. Along with this, maintaining the voltage variation as low as possible is also an important and desired feature in power system. The variation of load and generation are among the major causes of voltage variations.

In real power system, the loads are not only varying continuously but also increasing over the period of time. As a result, the variation of voltage is also very common, mitigation of which is a continuous effort. Besides improving the overall system voltage (voltage profile improvement), the planning scheme of optimal DG placement can also help in reducing the chances of voltage variation due to load variation as well as load growth. There have been few attempts in the literature which try to represent the status of the system with respect to its voltage. Each of these methods have some very useful mechanism about quantification of the system status in terms of voltage however a comprehensive method is still unavailable. Some of the available methods are presented here, followed by related discussion about their merits and limitations.

4.3.1 Available Indices about Voltage Quality

Keeping in view the importance of voltage related issues and requirement, there are different studies which proposed various indices and methods for quantifying them. An early approach proposed the voltage stability index [171] that identifies the buses in the radial system which are most sensitive and are considered as possible causes of the voltage collapse of the system. This index is based on the transfer of active and reactive power over the distribution lines. A major shortcoming of this useful index is that it does not take the variation in system conditions, such as changes in load and generation, into account.

Another such index is proposed in [6] with the name of voltage profile improvement index, where the authors actually attempted to quantify the benefits of DGs. As the main focus of this work is to highlight the advantages of DGs, the proposed index is the ratio of system voltage profile for the cases of with and without DG, while keeping the load condition of the system similar in both cases. The usefulness of this method appears to be limited because of well known feature of the ratio based indexes that these cannot provide information about the actual numbers. Ultimately, important information about the actual system voltage is completely lost, leading to the difficulty about drawing any concrete conclusion about the system voltage conditions.

A comparatively older form of voltages stability index proposed in [172] is useful in identifying the buses of the system which are near the voltage collapse. The magnitude of the voltage of directly connected buses through a line with certain resistance (R) and impedance (X) values is the basis of this index. In this way, the method is good in providing the information about specific region of the network. However, it is required to calculate the value of this index for every bus in the system in order to get the overall information about the system voltage condition. This method does not provide any mechanism to get the voltage related information of the system over the variation of load and/or generation. Hence, if a simple load growth scenario needs to be considered, such methods need several iterations to get a clear picture of the system voltage. The situation becomes even more complicated and cumbersome for the system with high number of buses, loads and generations.

In general, it can be concluded that the available methods have the property of showing the system's voltage stability but information about whole system is not provided. Moreover, the variation of loads and generations may cause considerable changes in the system stability as well as performance but that is also missing in these methods. Finally, the *only* ratio based methods cannot be useful in providing enough information about system conditions. Therefore, a comprehensive and detailed index should be introduced in order to enlighten the system performance and condition over different scenarios such as incorporation of new generations, variations in loads and other similar factors.

4.3.2 Voltage Quality Index

Maintaining the voltage at different buses in the power system at permissible level (±6 % of nominal voltage in this work) is not the only important requirement. The power system should also be able to minimize the variations of the voltage at various parts of the system under different circumstances, such as load or generation variation. In this work, a novel Voltage Quality Index (VQI) is introduced to quantify the system condition over different load growth and voltage control action scenarios. The VQI at the i_{th} load condition is given as:

$$VQI_i = \left[V_{nom} - \frac{V_{max_i} - V_{min_i}}{V_{max_i}} \right] 100\% \tag{4.4}$$

V_{nom} is the nominal bus voltage in p.u. and is taken to be unity in our case; V_{max_i} and V_{min_i} are the respective maximum and minimum voltages in the network (at any bus) at ith load condition in the system.

Keeping the difference between V_{max_i} and V_{min_i} to the minimum possible value is always desired in real power systems, because it is indicative of better voltage quality and healthy network. The second term in Equation 4.4 is related to showing this specific feature. The difference of this factor from nominal voltage value shows the overall condition of the system with respect to the permissible voltage range. Therefore, the VQI_i is not only useful in providing information about the voltage level of the system but also the voltage stability. Hence, with only single index *i.e.*, VQI_i, it is possible to get a better insight into the system performance with discrete numeric values. The quantification of useful system information is also helpful in providing the possibility of comparing the system conditions in various cases.

Unlike the previous ratio based methods, this method provides straightforward information about the system current voltage status of the system because for a similar difference between V_{max_i} and V_{min_i}, it gives higher value output for higher value of these variables. For example, if V_{max_i} and V_{min_i} are 1.01 and 0.98 respectively, the resulted VQI_i would be 97.03% whereas, for a similar difference in case of 0.95 and 0.92 respectively, the resulted VQI_i would be 96.84%. On basis of this, the VQI_i is also helpful in giving information about the actual bus voltages in a system for specific load condition. To explain the usefulness of the proposed VQI_i, following different cases are taken.

1. $V_{max_i} - V_{min_i} = 0.03$. This correspond to VQI_1
2. $V_{max_i} - V_{min_i} = 0.05$. This correspond to VQI_2
3. $V_{max_i} - V_{min_i} = 0.08$. This correspond to VQI_3

The importance of these three cases is that the difference between maximum and minimum bus voltages at any specific condition is taken irrespective of their exact values. Despite this fact, the results provide the possibility of identifying the better conditions of the system among all three case by simple pick-up approach. To explain these important points, different sets of values are given in Table 4.1. The *"iter"* column contains 21 different possible levels of the system voltages, which are given by the V_{min_i} and three different variants of V_{max_i}. Each of these variants correspond the three different cases proposed above (along each row in this table). Down in the column are the cases when the overall system's voltage condition is improving (due to any reasons) but the net difference between V_{max_i} and V_{min_i} remains uniform according to the considered cases. The last three columns contain the values of VQI_i respective to every case in each row.

From this table, it can be easily seen that, for every iteration, VQI_1 has the highest value whereas the VQI_3 has the lowest. This is because of the fact that the difference between V_{max_i} and V_{min_i} is increasing in this specific range. On the other hand, while looking down in any specific column of VQI_i, for example VQI_1, the value is increasing too. This increase in the value of VQI_i indicates the better overall system voltage quality because the V_{min_i} has increased from 0.8 p.u up to the 1 p.u. It should be noted as a final remark that the difference in VQI_i values corresponding to the difference of 0.3, 0.5 and 0.8 is more as compared to the difference of specific VQI_i, for example VQI_1, at different values of V_{min_i} (down the specific VQI_i column). On the basis of this explanation, following important conclusions about the system's voltage condition can be drawn:

i. Lower the difference between the V_{max_i} and V_{min_i}, higher will be the value of VQI_i,

ii. Higher value of V_{min_i} produces higher VQI_i.

Such useful information makes the proposed VQI_i as a versatile tool for quantifying and understanding the system voltage performance in a better way, even with a single overview. All these details can also be extracted from the Figure 4.1. To summarize, the voltage quality index quantifies the system's bus voltage condition at given load condition. In this way, it also helps in providing useful guess about system's bus voltage conditions at future load level, either higher or lower than the current value of load.

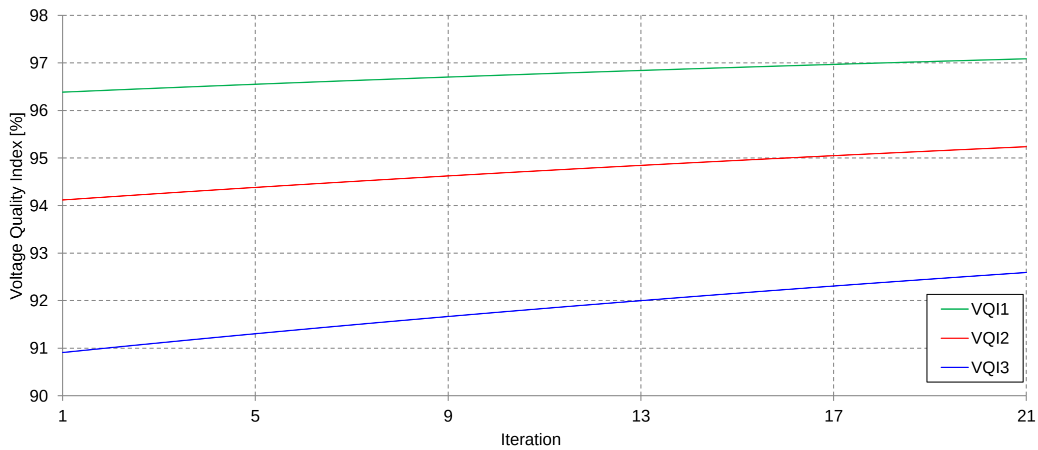


Figure 4.1: Evaluation of voltage quality index at different system voltage conditions

Table 4.1: Comparison of different voltage quality index values

Iter	V_{min_i}	V_{max_1}	V_{max_2}	V_{max_3}	VQI_1	VQI_2	VQI_3
1	0.8	0.83	0.85	0.88	96.39	94.12	90.91
2	0.81	0.84	0.86	0.89	96.43	94.19	91.01
3	0.82	0.85	0.87	0.9	96.47	94.25	91.11
4	0.83	0.86	0.88	0.91	96.51	94.32	91.21
5	0.84	0.87	0.89	0.92	96.55	94.38	91.30
6	0.85	0.88	0.9	0.93	96.59	94.44	91.40
7	0.86	0.89	0.91	0.94	96.63	94.51	91.49
8	0.87	0.9	0.92	0.95	96.67	94.57	91.58
9	0.88	0.91	0.93	0.96	96.70	94.62	91.67
10	0.89	0.92	0.94	0.97	96.74	94.68	91.75
11	0.9	0.93	0.95	0.98	96.77	94.74	91.84
12	0.91	0.94	0.96	0.99	96.81	94.79	91.92
13	0.92	0.95	0.97	1	96.84	94.85	92.00
14	0.93	0.96	0.98	1.01	96.88	94.90	92.08
15	0.94	0.97	0.99	1.02	96.91	94.95	92.16
16	0.95	0.98	1	1.03	96.94	95.00	92.23
17	0.96	0.99	1.01	1.04	96.97	95.05	92.31
18	0.97	1	1.02	1.05	97.00	95.10	92.38
19	0.98	1.01	1.03	1.06	97.03	95.15	92.45
20	0.99	1.02	1.04	1.07	97.06	95.19	92.52
21	1	1.03	1.05	1.08	97.09	95.24	92.59

4.4 Load Variation and Voltage Control

During the operation of a power system, controlling the system voltage and maintaining it within permissible limits is a continuous process in order to maintain the power quality and meet regulatory requirements. The voltage in the system varies as soon as the system's active and reactive power demand and/or supply varies. The voltage control in distribution systems with enough penetration of DGs becomes more complicated. However, if properly sized DGs are placed strategically by considering the load distribution in the network and network structure, the voltage problems can be reduced. In order to justify this, different scenarios of voltage problems in the network with and without DGs, during the operation of a power system are studied.

From the discussion until this point, it is clear that the selection of optimal location and calculation of optimal size is based on some static system condition *i.e.*, some specific load and generation levels as well as the network configuration. This asserts that the optimal DG placement is suitable for that specific system condition because both the location selection and size calculation are function of system parameters. Hence, changing these parameters affects the *"optimality"* of the DG placement results directly. However, it is an interesting study to know about the impact of variation in system conditions and parameters in presence of the DGs on the system voltage. Moreover, response of the system to the corrective action taken by some voltage control system is also important.

A scenario of load variation is also included in this work to explain the usefulness and effectiveness of the proposed optimal DG placement method. Load variation is defined here as a scenario of varying the total demand in the system over the certain time range. This variation may also be beyond the conditions (loads and generations) of the system for which the optimal locations and sizes of DGs are found. As the optimal DG sizes found in optimal DG placement problem are the function of system variable such as power demand and network losses, the found sizes no longer remain optimal for case with changed system variables. Despite the fact that variation in the network power generation or demand adversely affect the results of the optimal DG placement, the proposed method has been proved advantageous in different use cases and scenarios, details of which are given in the chapter 5.

It has also been observed in power system that the system load can decrease considerably during different seasons or time of day. Significant decrease in the load demands for respective reduction of the generation otherwise voltage problem and huge rise in line flow, leading to increased losses and stress on the lines, may appear. The load profile considered in different use cases also caters to highlight the the impact of optimal DG placement under such scenario. Details of these use cases and features of the profiles considered can be found in chapter 5.

4.4.1 Centralized Voltage Control Algorithm

The essence of designing this specific control is to assess the capabilities of the proposed optimal DG placement method beyond the planning phase. It is intended to highlight the usefulness of placing the DGs optimally during the operational phase with respect to their ability to reduce the chances of occurrence of the voltage problems on one side, and efficient handling and mitigation in case if the voltage problem do appear on the other side. Interestingly, in some cases of optimal DG placement with method proposed here, no voltage problem is observed. In fact, the voltage profile is improved significantly in comparison to the base case. In comparison to the other methods of optimal DG placement, the voltage problem is not only delayed but is not as severe.

In real power networks, there exists a control loop at different levels (primary, secondary and tertiary) which attempts to maintain the system's voltage at various points within the permissible limits in case of any problem. Due to any reasons (*e.g.*, load variation), if there appears any voltage problem, the control actions at respective level attempts to nullify it accordingly. In this work, a simple centralized voltage control algorithm is also considered in order to study the usefulness of the optimal DG placement problem in operational phase. This algorithm tries to adjust the voltage by varying the reactive power from DGs as per their specifications. In case of a voltage problem at certain bus i, the sensitivity of every bus with DGs j is calculated with respect to the bus with voltage problem *i.e.*, i. This is mathematically given as:

$$S_{ij} = \frac{\partial V_i}{\partial Q_j} \tag{4.5}$$

The sensitivity can be found using the power flow solution of the system. Higher the sensitivity of a bus with DG, higher is the chance to vary its reactive power for attempting to mitigate the voltage problem. If the voltage problem persists even after the maximum permissible variation of reactive power from a DG, corrective action is taken from the next DG in the sensitivity based list and the process continues until either the problem is resolved or the total reactive power support capacity of all the DGs is fully exhausted. In real power flow calculations, The partial derivative given in Equation 4.5 can be replaced with delta (Δ) for simplification of calculations and easy assessment of the required value of reactive power [173]. The value of reactive power needed in case of voltage problem can be calculated, as shown below:

$$\Delta Q_j = \frac{\Delta V_i}{S_{ij}} \tag{4.6}$$

$$\left.\begin{aligned} \Delta V_i &= |V_{i_{current}} - V_{min}| \\ \Delta V_i &= |V_{i_{current}} - V_{max}| \end{aligned}\right\} \tag{4.7}$$

$$\Delta Q_j = Q_{j_{current}} - Q_{j_{desired}}$$

$$Q_{j_{desired}} = Q_{j_{current}} - \frac{\Delta V_i}{S_{ij}} \tag{4.8}$$

The value of reactive power needed from DG can be computed using Equation 4.8, where the current value of reactive power output from DG ($Q_{j_{current}}$) is already known. However, it should be noted that if the required value of reactive power exceeds the limits of the DGs, the remaining part is provided by the next DG in the priority list. Moreover, the direction of reactive power flow (into or out of the DG) depends on the nature of voltage problem *i.e.*, voltage rise or fall. The complete procedure for correcting voltage rise or fall problem by providing reactive power support from DG is summarized in algorithm 4.1.

The purpose of implementing the voltage control algorithm is to show the ease and efficiency of performing corrective actions in case of voltage problem in different considered cases. Results and detailed discussion about this are given in section 5.7.

Algorithm 4.1: Centralized voltage control algorithm

Initialization;
Calculate load flow sensitivity;
Build sensitivity table for buses with DGs ($Sen[]$) using Equation 4.5;
Sort descending $Sen[]$;
Run Load Flow;
$Vmin = \text{Min}(V_{bus_1}, V_{bus_2}, V_{bus_3}...V_{bus_n})$;
$Vmax = \text{Max}(V_{bus_1}, V_{bus_2}, V_{bus_3}...V_{bus_n})$;
$V_{min} = 0.94p.u$;
$V_{max} = 1.06p.u$;
j =1;
$j_{max} = N_{DG}$;
while $(Vmin < V_{min})$ *or* $(Vmax > V_{max})$ *and* $i \leq i_{max}$ **do**
    Get $Sen(j)$;
    Calculate $Q(j)_{new}$ from DG using Equation 4.8;
    if $(Q(j)_{new} => Q(j)_{max})$ **then**
        $j = j + 1$;
    else
        set $Q_{DG} = Q(j)_{new}$;
        calculate load flow, get V_{new};
        $V = V_{new}$;
    end
end

4.5 Comparative Studies

There are different methods used to solve the optimal DG placement problem. To validate and compare the method proposed in this work, some of the available methods have been chosen. Among many methods mentioned in the detailed survey given in chapter 2, analytical based approaches are selected for the purpose of comparison and validation here. An exhaustive method, which is considered to be very accurate method for optimal placement of DGs, is also taken for the said purpose. The reason for selecting the analytical and exhaustive methods is their closeness to the proposed approach because after calculating the the exact size, the proposed method searches for any possible better size in the vicinity of the calculated size, and calculates the operational power factor using exhaustive approach. On these grounds, the methods selected for the comparison and validation appear to be the logically feasible choices. A brief overview about the selected methods is also provided here for the purpose of clarity and understanding.

4.5.1 Loss Sensitivity Factor Method

The original exact loss formula is a non-linear function. In Loss Sensitivity Factor (LSF) method, sensitivity factors are calculated by linearization of exact loss formula. Similar approach has been widely used for solving the capacitor allocation problem [174]. The earliest use of such an approach for optimal DG placement problem is reported in [175]. It is worth mentioning that by linearization, this method ignores a considerable amount of search space. As a general rule, first order derivative based linearization of a function make it biased towards the function with higher slope at initial condition. This may lead to the possibility of missing some good solutions due to reduced capability of finding the global optimum.

The sensitivity factor are calculated on the basis of exact power loss formula as an ultimate objective is minimization of active power loss. Also, the loss minimization is desired by placing optimally sized DGs which are capable of injecting only active power (type 1 as given in subsection 3.3.2. The sensitivity factor is found by taking partial derivative of real power loss with respect to real power injection from DG. Based on Equation 3.2, the LSF of ith bus is given as:

$$LSF_i = \frac{\partial P_L}{\partial P_i} = 2\sum_{j=1}^{n}(\alpha_{ij}P_j - \beta_{ij}Q_j). \tag{4.9}$$

In base case power system (without any DGs), the LSF for every bus in the system is evaluated. Next, a priority list is formed by arranging the buses in descending order with respect to their LSF values. Higher the order of the bus in this priority list, higher is its chance to be taken as a suitable location for placing the DG. Scanning every bus for placement of DGs makes this method time consuming and and computationally demanding. However, it has been mentioned in the literature that only some predefined percentage of the total buses can be considered. In this work, top 20% of the buses in the complete sorted list of LSF are selected for DG placement. On every selected bus, the DG is placed and its value is varied from some minimum value (*e.g.*, zero) up to the maximum value (*e.g.*, total system load) and the bus number and DG size for which the losses of system are the lowest is finalized. The detailed computational procedure is given in algorithm 4.2.

It can be concluded from this algorithm that it follows an iterative procedure for finding the optimal sizes and locations for placing DGs, where load flow is needed to run in every iteration.

Also, only predefined number of buses are checked for optimal size and location calculation. Due to both these features of this method, it is attempted to limit the extensive computational burden and the simulation time. However, it is already mentioned that linearization of a non-linear equation can lead to the possibility of missing good solutions, checking for optimal sizes only at the few number of buses may also multiply the chances of having poor results. Another major concern about this method is that the procedure given in algorithm 4.2 is only for placing single DG. If placement of multiple DGs are required, same procedure needs to be repeated for the number of times equal to the number of DGs to be placed, which increases the simulation time and computational burden even more. The stopping criteria in case of multiple DG placement can be set as any of the following:

- Violation of bus voltage limit.
- Installed DG capacity is equal to or greater than the total demand and network losses.
- The maximum number of DG units is reached.
- Losses are increased after placing the nth DG. In this case, only $n-1$ DGs will be placed.

As a last comment about the *LSF* method, it should be noted that if the loss coefficients (*i.e.*, α and β in Equation 3.2 are not updated when finding the optimal DG size by increasing in step of size equal to "step size", certain amount of error is introduced. To nullify this error, these coefficients can be calculated in every iteration, leading to further increase in the computational burden and simulation time.

4.5.2 Exhaustive Method

Exhaustive method, as the name asserts, tries to exhaust whole of the search space within prescribed limits to figure out the optimal location and size of the DG. Unlike *LSF* method, no limitations are applied on the number of buses to be selected for optimal DG placement, hence the method is very extensive and computationally demanding. As a result, the simulation time for this method also increases considerably. This method is first introduced in [108] where it is used to place only a single DG. This method originally finds the optimal active power output *i.e.*, type 1 DG only. Later, the method is thoroughly explained, with some modifications, in [176] where placement of multiple DGs is also considered along with optimizing the power factor from DG as well. The method used for optimal power factor calculation is similar as explained in subsection 4.2.1. Starting from bus 2 (because bus 1 is taken as slack bus, with connection to external power grid), the method places a DG of type 1 with minimum size (usually zero) and increases its size in "small" steps. Then, the losses are calculated and the best size (which correspond to the least losses) is stored. In this way, all the buses in the network are scanned and finally a location for placing the DG corresponding to the least losses is selected. In order to place multiple DGs, similar process is repeated. The complete procedure is explained in the algorithm 4.3. The stopping criteria used for this method is similar to that used for the *LSF* method in subsection 4.5.1.

Algorithm 4.2: Loss sensitivity factor method

Initialization;
Run base case load flow;
Calculated losses of base system using Equation 3.2;
Calculate LSF at each bus using Equation 4.9;
Create priority list of buses by sorting their respective LSF in descending order;
Set $P_{List} = 20\% \times N_{Bus}$ *#In this way, only top 20% of the total buses in the system are considered for DG placement*;
Set $i = 1$;
Set $P_{DG_{min}}$ = Starting value of DG size;
Set $P_{DG_{max}}$ = Maximum permissible value of DG size;
Set $Step$ = step size;
while P_{List} *is NOT exhausted completely* **do**
    Place DG at the bus $P_{List}(i)$ *i.e.*, bus with highest priority in P_{List};
    Set $P_{DG} = P_{DG_{min}}$;
    while $P_{DG} =< P_{DG_{max}}$ **do**
        Run load flow;
        Calculated losses using Equation 3.2;
        if $Loss_{new} =< Loss_{old}$ **then**
            $Loss_{min} = Loss_{new}$;
            $P_{DG_{best}} = P_{DG_{new}}$;
            Set $P_{DG} = P_{DG} + Step$;
        else
            Set $P_{DG} = P_{DG} + Step$;
        end
    end
    i = i + 1;
end

4.5.3 Improved Analytical Method

Recently, an improved analytical (IA) method is proposed in [108] which is based on the exact loss formula. This method identifies the optimal location and size of single DG in order to minimize the loss. The method is useful in finding the optimal sizes of any type of DGs, as it uses a combined load power factor based "fast" approach, given by Equation 4.3, to find optimal or near optimal power factor of a DG too. The analytical expressions used for finding the optimal sizes of different DG types are given below.

1. The DG with only active power output. In this type of DGs, the power factor is unity *i.e.*, $PF_{DG} = 1$ and $a = (sign)\tan(\cos^{-1}(PF_{DG})) = 0$. The optimal size of DG to be connected at ith bus for minimizing the active power loss can be calculated using Equation 4.10:

$$P_{DG_i} = P_{D_i} - \frac{1}{\alpha_{ii}} \left[\beta_{ii} Q_{D_i} + \sum_{j=1, j \neq i}^{N} (\alpha_{ij} P_j - \beta_{ij} Q_j) \right] \tag{4.10}$$

Algorithm 4.3: Exhaustive method

```
Initialization;
Run base case load flow;
Calculated losses of base system (Loss_Base) using Equation 3.2;
Calculate power factor of DG (PF_DG) using Equation 4.3;
for Stopping Criteria = False do
    Set P_DG_min = Starting value of DG size;
    Set P_DG_max = Maximum permissible value of DG size;
    Set Step = step size;
    Set Loss = 0;
    for BusNumb: 2 to N do
        P_DG(BusNumb) = P_DG_min;
        Calculate Q_DG(BusNumb) using Equation 3.3;
        while P_DG(BusNumb) =< P_DG_max do
            Run load flow;
            Store α and β;
            Calculated losses Loss using Equation 3.2;
            if Loss_new =< Loss_old then
                Loss_min(BusNumb) = Loss_new;
                P_DG_best(BusNumb) = P_DG(BusNumb);
                Set P_DG(BusNumb) = P_DG(BusNumb) + Step;
                Set Q_DG(BusNumb) using Equation 3.3;
            else
                Set P_DG(BusNumb) = P_DG(BusNumb) + Step;
                Set Q_DG(BusNumb) using Equation 3.3;
            end
        end
        P_DG(BusNumb) = 0;
        Q_DG(BusNumb) = 0;
    end
    opt_Loc = Index of Min(Loss_min(x));
    opt_Size = P_DG_best(opt_Loc);
    P_G(opt_Loc) = opt_Size;
end
```

2. DG with both active and reactive power output. In this case, the power factor can be in range of 0 and 1. For a predefined value of PF_{DG}, the value of constant a can be calculated by putting $sign = +1$. Finally, Equation 4.11 and 3.3 can be used to find the optimal DG size of this type.

$$P_{DG_i} = \frac{\alpha_{ii}(P_{D_i} + aQ_{D_i}) + \beta_{ii}(aP_{D_i} - Q_{D_i}) - X_i - aY_i}{a^2\alpha_{ii} + \alpha_{ii}} \tag{4.11}$$

where,

$$X_i = \sum_{j=1, j\neq i}^{N} (\alpha_{ij}P_j - \beta_{ij}Q_j); \qquad and \qquad Y_i = \sum_{j=1, j\neq i}^{N} (\alpha_{ij}Q_j + \beta_{ij}P_j)$$

3. DG with active power output but reactive power absorption capability. For this case, same procedure as in item 2 can be used except the modification of $sign = -1$ to represent the flow of reactive power. DG power factor has the same range and value of constant a can be found in a similar way. Afterwards, the optimal DG size are calculated using Equation 4.11 and 3.3.

4. The DG with only reactive power output. In this case, DG's power factor is zero and $a = \inf$. The optimal DG size can be calculated using the Equation 4.12.

$$Q_{DG_i} = Q_{D_i} - \frac{1}{\alpha_{ii}} \left[\beta_{ii} P_{D_i} - \sum_{j=1, j \neq i}^{N} (\alpha_{ij} Q_j - \beta_{ij} P_j) \right] \tag{4.12}$$

Same method is extended in [109] to optimally place the multiple DGs for minimization of the active power loss. In either of these methods, the optimal location is selected using the iterative approach, similar to that of LSF based or exhaustive method. This method is computationally better because it has straightforward procedure for finding the optimal size, hence reducing the computational burden and simulation time significantly. However, this method does not update the values of loss coefficients *i.e.*, α and β to further quicken the simulation. Although this has negligible impact on the selection of optimal location selection, it affects the optimal size calculations considerably. The complete method is presented in algorithm 4.4. The stopping criteria is same as the previous two methods.

Algorithm 4.4: Improved analytical method

Initialization;
Run base case load flow;
Calculated losses of base system ($Loss_{Base}$) using Equation 3.2;
for *Stopping Criteria = False* **do**
    Get PF_{DG} from user or Calculate using Equation 4.3;
    for *BusNumb: 2 to N* **do**
        Calculate $P_{DG}(BusNumb)$ using respective Equation 4.10, 4.11 or 4.12;
        Calculate $Q_{DG}(BusNumb)$ using Equation 3.3;
        Set $P_G(BusNumb) = P_{DG}(BusNumb)$;
        Set $Q_G(BusNumb) = Q_{DG}(BusNumb)$;
        Calculate approximate loss with α and β of base case using Equation 3.2;
        if $Loss_{new} =< Loss_{old}$ **then**
            $Loss_{min}(BusNumb) = Loss_{new}$;
            $P_{DG_{best}}(BusNumb) = P_{DG}(BusNumb)$;
        end
        $P_G(BusNumb) = 0$;
        $Q_G(BusNumb) = 0$;
    end
    $opt_{Loc} =$ Index of Min($Loss_{min}(x)$);
    $opt_{Size} = P_{DG_{best}}(opt_{Loc})$;
    $P_G(opt_{Loc}) = opt_{Size}$;
end

4.6 Algorithms for Qualitative Assessment

In previous chapter, the methodological steps for finding optimal locations and placing DGs at them is given. These steps are related to the finding of optimal locations and active power output from DGs to correspond to the most minimum active power losses. However, it is clear from the discussion until this point that the modern power system regulations bind the power generation facilities to abide by certain other requirements. Keeping the power factor within permissible limits is one such important requirement. Therefore, the final algorithm for DG placement also includes the steps for selecting the operational power factor. The detailed steps are similar as have already been given in section 3.4, except an additional step of finding the operational power factor, as given in Figure 4.2. This method computes the operational power factor after finding the optimal active power of DG that correspond to the least power loss. It should be noted that the operational power factor is only desired for the DG type which can generate or absorb the reactive power. For DGs with capability of generating either active or reactive power only, operational power factor calculations become insignificant.

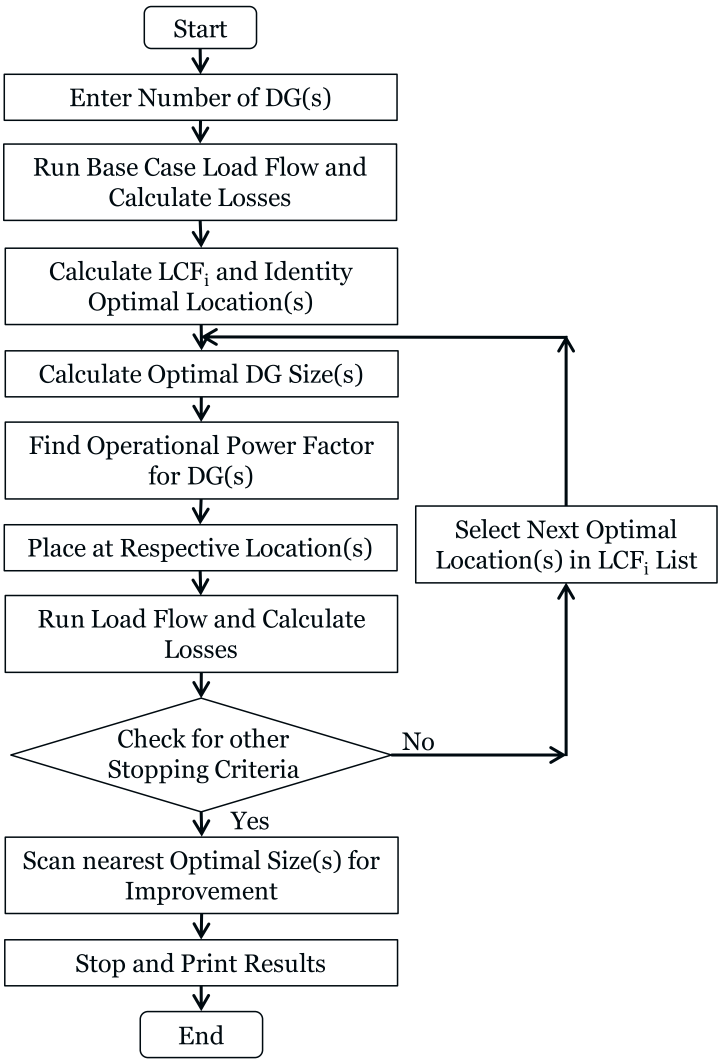


Figure 4.2: Flowchart of optimal DG placement with operational power factor selection

The voltage profile is monitored and voltage quality improvement is also studied for case of load variation. Load variations are considered as an analogous phenomenon to the operational phase of distribution system with DGs. In case of any voltage problems during the operational phase, the CVCA takes corrective action and tries to mitigate the problem. The complete algorithm for this is given in Figure 4.3. In this algorithm, it is considered that the system is stable and there exist no voltage problem in the network prior to the application of load variation and voltage control algorithm. In chapter 5, the results of voltage problem are also compared with the different scenarios where the DGs are placed optimally with other contemporary methods.

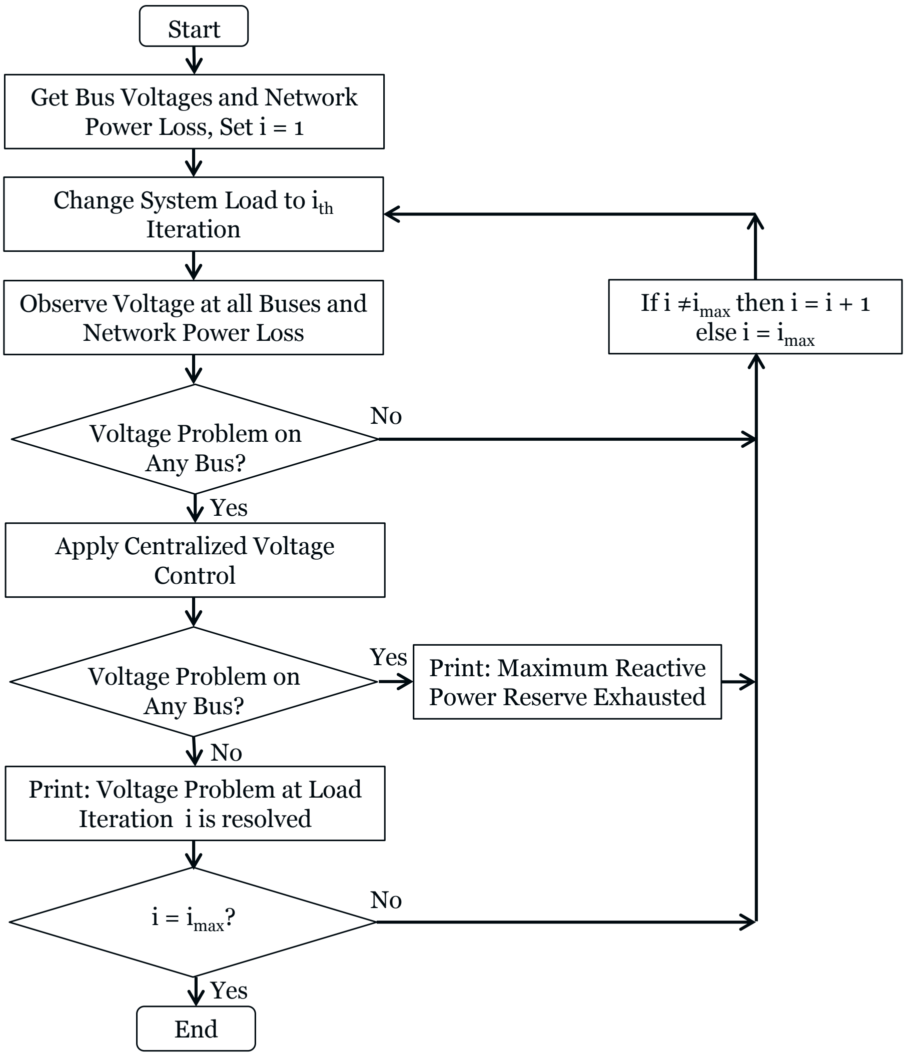


Figure 4.3: Flowchart of operational phase scenario; time varying loads and actions taken by centralized voltage control algorithm in case of voltage problem

5 Results and Discussion

5.1 Introduction

The advantages of the optimal DG placement can be explained by translating them into different forms such as power loss minimization, voltage profile improvement, congestion management, hosting capacity enhancement, line flow reduction or any other such factors. In order to provide different stakeholders with a strong and valid reason to consider optimal DG placement in real world scenario, it is vital to have useful results for the methods proposed. Such an approach help to justify the usefulness and applicability of the proposed methods in a well quantifiable way.

The active power loss minimization is the most important factor considered in this work because minimization of losses can be argued in favor of other advantages such as increasing hosting capacity. Therefore, the results are presented and discussed here for this important variable. Moreover, the operational power factor, voltage quality and voltage profile improvement, and impact of DGs on line flows is also discussed. Total of three use cases are considered; one with static loads, second with time varying load and third with time varying load and voltage control algorithm. The third use case is designed to put emphasis on the usefulness of optimal DG placement with proposed method during operational phase *i.e.*, what are the chances of having voltage problem if the DGs are installed by using the proposed method and how easy is to correct that voltage problem? The results showed that if the DGs are placed with set of locations and sizes proposed in this work, the voltage problem arises at very later stage in comparison to the case of DG placement with other methods available in literature.

Some results are given for the static load case where the power factor of DG is changed sequentially. This is done in order to find the operational power factor, as suggested in chapter 4. Results for the voltage variation are also presented for different power factors cases. It has been concluded based on these results that the losses as well as the voltage variation are reduced at operational power factor for either of the considered networks. Therefore, it is suggested to use the operational power factor in order to further improve the performance of network.

The voltage related results are presented in the form of voltage quality index (VQI) because the voltage quality index provides an easy way of knowing the network's voltage status. It is cumbersome to look into the voltage profile of the system for every load condition, when the time varying loads are considered (use case 2 and 3). Under such circumstances, the VQI is proved to be very simple, clear and detailed index. Despite the usefulness of the VQI, the voltage profiles are given for the results of use case 3 so that the impact of the corrective action taken by Centralized Voltage Control Algorithm (CVCA) can be easily identified.

5.2 Experiments/ Use Cases

It has been highlighted in chapter 2 that the type of loads considered in most of existing studies do not focus much on various types of loads. This reduces the versatility of such methods and creates an ambiguity about their usefulness in the real world power systems. In order to explore the capabilities of the methods proposed here, different load types *i.e.*, static and time varying loads are considered in this work. For the sake of easy understanding, these are termed as use case 1, 2 and 3, respectively.

5.2.1 Use Case 1: Networks with Static Loads

The power system with static loads is not a practical case in any study however it is used repeatedly in many researches and literature because these help to check the usefulness of any new methods applied for some specific system conditions. Afterwards, these methods can be applied to the more realistic networks and upgraded accordingly to make them useful in practical scenarios. On the similar lines, the first use case presented in this work is also with static loads, and hence with static generation and other system parameters.

5.2.2 Use Case 2: Networks with Dynamic (Time Varying) Loads

In use case 2, a load profile of a day, at 15 minutes interval is considered for a typical load with its peak value near the static case load considered in use case 1. It is worthy to highlight that the optimal locations and sizes corresponding to the least losses vary as soon as the loads connected to the system nodes changes however, it is not practically feasible. Therefore, the locations and sizes are kept fixed corresponding the static load case of DG. The power factor is kept at optimal level also. DG size and location are fixed corresponding to the peak load level to help the system perform better in case of load growth. This means that, in future, when the load is increased, the same sizes and locations can remain, at least, near optimal.

5.2.3 Use Case 3: Networks with Dynamic (Time Varying) Loads and Centralized Voltage Control

Among many others, the possibility of improving the voltage profile of the system and helping the system to maintain the voltage nearer to the nominal voltage limit is also important. A system with optimal locations and sizes of DGs should inherently be strong enough to withstand the network disturbances. Moreover, in case of any network voltage problem, system with optimally placed DGs is expected to be able to recover quickly then the system with non-optimally placed DGs. To study such impacts of optimally placed DGs, use case 3 is designed where the centralized voltage control becomes active in case of any voltage problems. In this use case, the comparison of different optimal DG placement methods in case of voltage problem is studied.

5.3 Operational Power Factor Test Results

The DGs considered throughout this work are capable of injecting both real and reactive power. Hence, the impact of power factor is also important. To get the best power factor within the considered range, an iterative procedure has been proposed in subsection 4.2.2. Considering the static load conditions (as in use case 1), the power factor of optimally sized DGs has been varied, and the losses and voltage characteristics of the system are studied to finalize the operational power factor.

For the results shown in Figure 5.1 and 5.3, it can be clearly seen that the operation beyond the operational power factor increases the losses, with either of the methods discussed here. The Loss Sensitivity Factor (LSF) method appears to be the least efficient method, whereas the Exhaustive Load Flow (ELF) and Mohsin Method (MM) produced very similar as well as the best results. The Improved Analytical (IA) method also produces good results in comparison to the LSF but is outperformed by the ELF and MM methods. Similar trends of loss reduction is observed for both test systems studied in this work. From these figures, the operational power factor is finalized to be 0.97 for 37 node network and 0.90 for 119 node network. Based on the fact that the power factor is low for 119 node network, it can be said that this network demands high reactive power, which is in coincidence with the actual facts about this network.

It is important to set the power factor in accordance with the network's features and requirements because operating at optimal or nearly optimal power factor can not only reduce the losses but also improve the voltage performance of the network. This is clearly depicted in the Figure 5.2 and 5.4. As stated in the discussion about the voltage quality index that the difference between maximum and minimum voltage levels in the network should be kept as low as possible in order to have uniform voltage profile. Therefore, the difference between maximum and minimum voltage appearing in the network at any given power factor is considered here and is taken along y–axis in these figures. For the MM method, the voltage variation (difference between maximum and minimum node voltage at given power factor) is the minimum over most of the considered range of power factors. From this, it is clear that the operational power factor is also useful in reducing the voltage variation along with helping in minimizing the losses. Further discussion about improvement of voltage quality is given for the results presented in respective sections.

Based on the results of this section, it is proven that the power factor selection is also important which should be properly addressed while optimizing the size and location for placement of DGs.

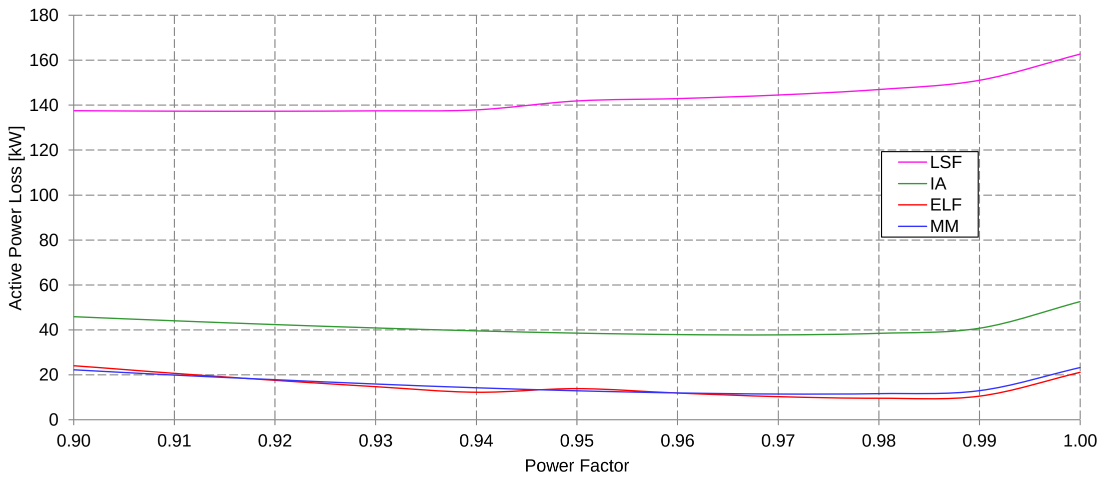


Figure 5.1: Power Factor *vs.* Active Power Loss - 37 Node

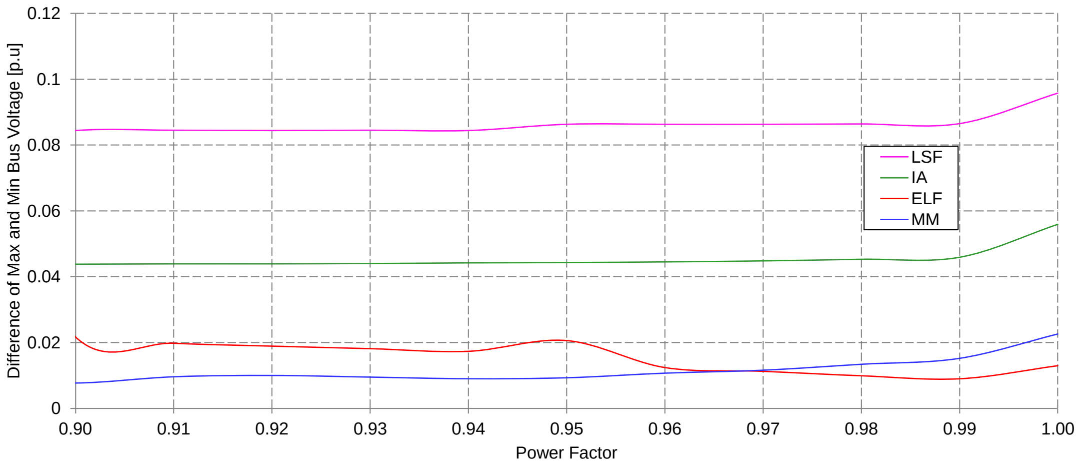


Figure 5.2: Power Factor *vs.* Voltage Variation - 37 Node

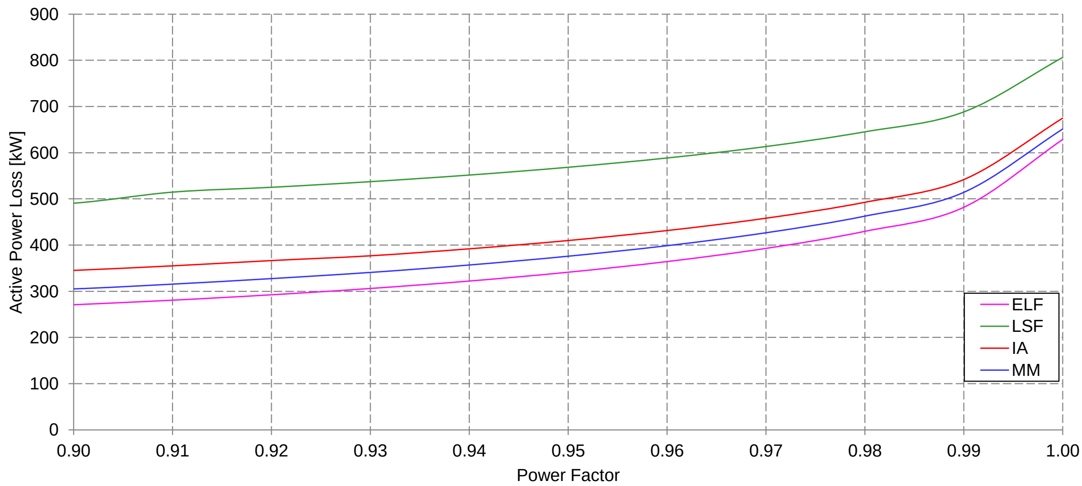


Figure 5.3: Power Factor *vs.* Active Power Loss - 119 Node

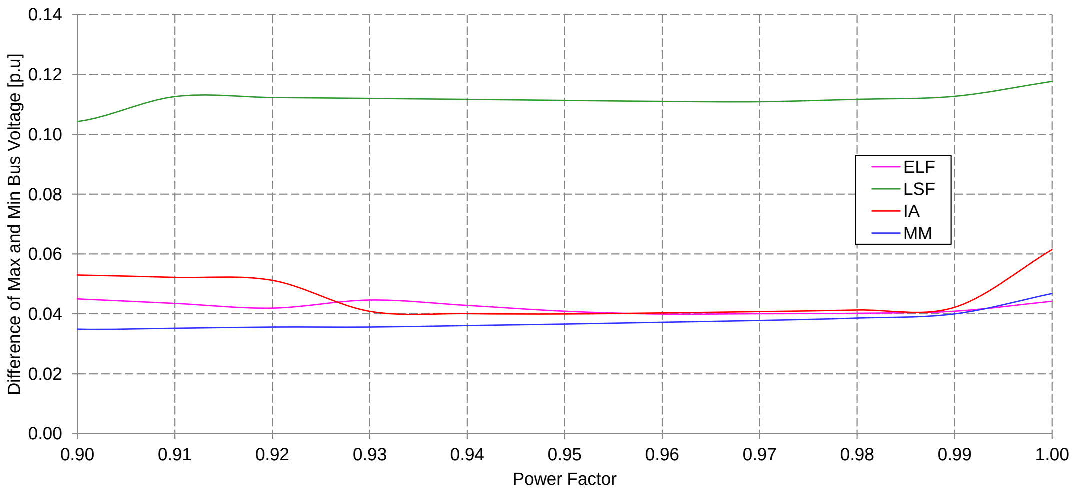


Figure 5.4: Power Factor *vs.* Voltage Variation - 119 Node

5.3.1 Power Factor Cases

There are different types of DGs explained earlier in subsection 3.3.2, based on the active and reactive power of DGs. The analytical expressions derived in this work to find optimal DG sizes are based on the minimization of active power losses by placing optimally sized active power sources. However, already established relationship between active and reactive power output of the DG helps to generalize these expressions for any type of the DGs. In this work, the simulation results for the cases where DGs have different power factor are given and explained here. For each network, following are the considered power factor cases:

- PF-Case 1: Power factor = 0
- PF-Case 2: Power factor = 0.95 Lagging
- PF-Case 3: Power factor = 0.95 Leading
- PF-Case 4: Power factor = 1
- PF-Case 5: Power factor = operational power factor, *i.e.,* 0.97 for 37 node network and 0.90 for 119 node network

5.4 Simulation Setup

There are two major parts of this work for implementation and validation of the proposed method in simulation; power system implementation and analytical method implementation. The first part is the implementation of the electrical power network with ability to run power flow algorithm in order to calculate the network status of bus voltages, line flows, the power losses and any other required variables related to power system. The system data is then stored for being used in the other part. The second major part is comprised of implementation of the proposed analytical methods for selection of optimal locations and calculation of optimal sizes on them. This part needs the information of all the variables used in the analytical expressions for location and size calculation *i.e.*, network data including net power injections at the buses, bus voltages and impedance of all the lines in the network. Once the network data is available, a platform which is able to compute the respective formula of DG location and size calculation is only needed.

There are different software tools available for the said purpose, using various interesting approaches for implementation of similar types of work. For example, in [177], the power flow algorithm is coded by the authors in MathWorks® MATLAB command line. This is a good approach because it can provide better insight into the implemented methods and algorithms however, it incurs extensive laborious efforts with the possibilities of human errors in programming complex differential equations. Moreover, optimal setting of the power flow algorithm for the best performance is not guaranteed. The code can be written for the proposed analytical method to get the complete picture of the this project. However, such an approach of writing codes for everything from scratch becomes extremely tedious and cumbersome when it comes to the study of various other factors such as line flows or thermal limits of the lines etc. There are variety of software tools dedicated for the detailed analysis of electrical power networks. However, most of such tools have limited capability of being programmed for specific purpose, hence implementation of analaytical part of the proposed method becomes difficult or even impossible.

To cope with such situations where the extensive programming needs to be done, coupling of different software is an efficient and viable option. In recent years, such approaches are becoming increasingly popular as they extremely enhance the capabilities of resulting coupled software. There are numerous possibilities about coupling different software. In this work, DIgSILENT PowerFactory is used for implementation of the power system and performing power flow and other related studies. It contains important features like network models, data management and reporting the results. This software is a very detailed power system modeling, analysis and simulation tool with capability of performing various calculations and methods such as steady-state analysis, transient analysis, voltage stability analysis, load flow sensitivities calculations, contingency analysis and number of fault related studies. Some advanced features such as distribution network optimization, harmonic and power quality analysis, techno-economic calculations, optimal power flow, reliability analysis, state estimation, quasi dynamic simulation and protection function make PowerFactory as even more preferred choice to be taken as power system simulation tool. A detailed list of different loads and generators, whether traditional or renewable based types, are also available. Moreover, DIgSILENT Programming Language (DPL) is also included in the package which makes the programming possible. However, it is comparatively complex tools for programming with limited capability.

To address this issue and expand the functionality of the PowerFactory, it is now possible to couple it with a very efficient and versatile programming tool *i.e.*, Python using Application Programming Interface (API). PowerFactory provides number of interfaces such as MATLAB, external C++ functions, OPC, RCOM, API and DGS is given in [178]. For co-simulation with MATLAB, PowerFactory has a built-in interface *i.e.*, DSL. An alternative and comparatively new approach for MATLAB PowerFactory co-simulation is presented in [179]. Similarly, external dynamic link library (DLL) can be used in DSL components *e.g.*, TCP/IP sockets and DPL scripts. To make use with multi-agent system, PowerFactory can be coupled with the industrial standard interface *i.e.*, OPC client. PowerFactory can be used in engine mode by remote communication (RCOM) with remote procedure call interface. A comparatively advanced but direct control of internal objects/data models of PowerFactory can be done using Application Programming Interface (API). Geographical information and data models can be exchanged using DGS file format. All these possible method of coupling PowerFactory are briefed in Figure 5.5.

Among all these options, coupling with Python using API is the latest and most powerful which allows accessing the PowerFactory from Python as an object with all the control possibilities of its models and system as from inside PowerFactory. The main program is written in Python command line environment, which computes the base case losses and get respective data of the power network implemented in PowerFactory. Based on this information, the script then finds the Load Concentration Factor $LCFs$ of all the buses, rank them and finalize the locations for placement of DGs. Afterwards, the optimal DG sizes are calculated and placed on these locations using the proposed method. After placement of DGs at optimal locations, the power flow calculation is done again to find the losses and check for violation of any parameters. The Newton–Raphson method of power flow solution has been used in this work. Simulations are performed on a standard PC with Intel® Xeon Processor W3505 and 12 GB RAM.

5.5 Test Results for Use Case 1

For each use case, two different systems with different sizes and complexity *i.e.*, IEEE 37 node and 119 node radial networks, have been studied in this work. Table 5.1 summarizes the information

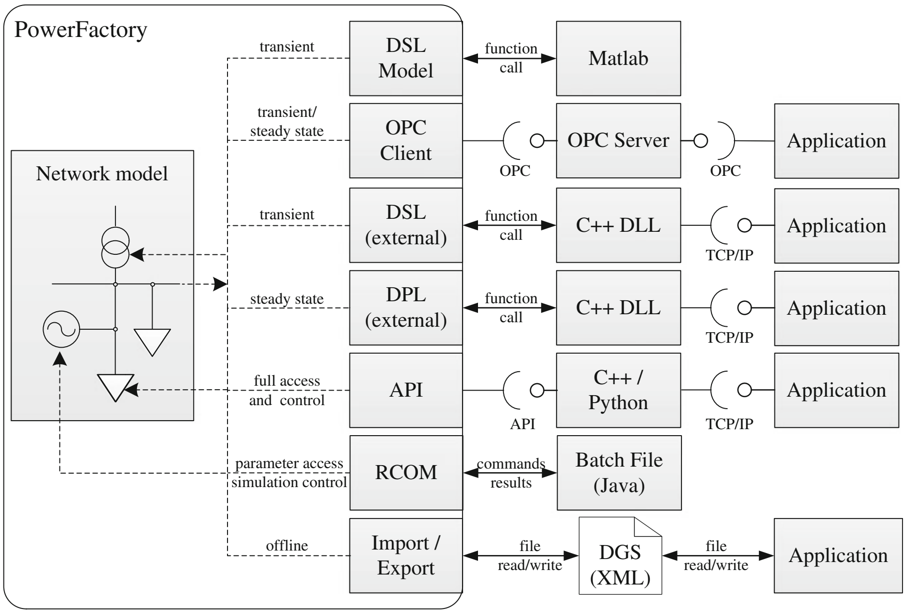


Figure 5.5: Possible options for coupling DIgSILENT PowerFactory [178]

about power demand, power losses and system voltage status of these networks when no DGs are placed *i.e.*, for base case. The results for these systems with static loads, after optimal placement of DGs, are summarized as use case 1a and 1b, respectively. The key objective of the presented study is to minimize the active power losses, thereby increasing the systems' hosting capacity and managing network congestion, and improve voltage profile by placing the optimally sized DGs at optimal locations while maintaining the operational constraints of the system within limits. All these results are presented and discussed here.

Table 5.1: Base case system information

Parameters	37 Node System	119 Node System
Active Power Demand	4.98 MW	22.71 MW
Reactive Power Demand	1.35 MVar	17.04 MVar
Active Power Loss without DGs	281.77 kW	1440.9 kW
Min Voltage in Network	0.878 p.u	0.869 p.u
Max Voltage in Network	1.000 p.u	1.000 p.u

It is worth mentioning that finding the optimal number of DGs for a specific network is also a separate study which is not considered in this work. Therefore, as given in subsection 3.2.5, this study considers placement of only 4 DGs in IEEE 37 node network and 5 DGs in IEEE 119 node network. However, it must be clearly understood that these are not the only possibilities for number of DGs or their size calculations that can be found by the proposed method. The main objective in this work is to minimize the active power losses and improve the voltage profile by optimal DG placement, hence, the method provides the reference values for the network and data considered. If, for example in operational phase of the network, the sizes are needed to be varied due to any reasons, it is not only possible but also recommended to achieve best system performance. However, it is important to note that such practice, either changing the network parameters and keeping DG sizes similar (to those calculated before changes in network parameters) or changing the DG sizes and keeping the network parameters similar, leads to non-optimal sizes. This may change the system losses and voltage profile because of obvious reasons.

The flow of power back to the external grid is also possible when the generation facilities are connected to the distribution grids. The conventional power system has been designed to have limited capabilities of handling reverse power flow so excessive reverse power flow is not recommended. As already stated in previous chapters that both the power loss minimization and voltage profile improvement are useful outcome of reduced line flows due to supply of power locally by DGs. The reverse power flow can increase the line flows due to flow of power back to the external grid, resulting in *possibility* of increased losses as compared to the case with no or less reverse power flow. On these grounds, the total power supplied from DGs is not taken more than the total demand in the given network as also suggested in [109]. However, it must be noted that such an assumption might not be considered practical for real networks, hence it can easily be altered to allow certain amount of reverse power flow. Moreover, the care must be taken in proper handling of reverse power flow in such cases.

5.5.1 Use Case 1a: IEEE 37 Node System – Results

It has been thoroughly discussed that the optimal DG placement offers many advantages over the "fit and forget" strategy of DG placement which lead to DGs "popping up like mushrooms". These advantages can be measured and quantified in the form of different power system variables. In this study, the main objective is to place the DGs optimally for minimizing active power losses and thereby increasing the hosting capacity as well as managing the congestion of the network. Therefore, the results are mainly presented in terms of the loss minimization. The factor for location selection *i.e.*, LCF inherently helps in voltage profile improvement which is also presented here. Finally, an insight into the line flow in the system with different methods is given. The nominal voltage of this network is 4.8 kV.

5.5.1.1 Power Loss Minimization

The simulation results of active power loss minimization, at different power factors considered, with the proposed method and other techniques mentioned earlier for the purpose of comparison and validation have been summarized in Table 5.2 – 5.6 for the IEEE 37 node system. The losses for no DG case are also given. For these results, the location selection with proposed method depends upon the active power demand in the network (predicted by LCF), hence remains same for all power factor cases. Whereas for all the other methods, location is chosen iteratively for ensuring least losses hence they are changing in different power factor cases. Although changing the DG locations in different operational scenarios is not possible in practical networks, these locations are considered to compare them with proposed method in their best/exact form available in literature.

It should be noted that the method proposed in this work for finding optimal sizes is based on the active power loss formula, hence it ensures finding the optimal DG sizes for the given set of locations. Due to this fact, active power loss reduction ratio in different cases varies significantly. For example, in power factor case 1, least active power loss reduction is observed because no active power is being supplied by the DGs. The DGs only provide small amount of reactive power, which is neither optimal nor enough to reduce active power losses significantly. Other methods also suffer from similar type of limitations. However, for any given power factory case, a uniform relationship can be observed easily which shows that the MM method is the nearest to the ELF method, which is able to find the best possible sizes and locations by thoroughly searching the whole search space. The nearest competitor method is the IA method, which is also based on the exact power loss formula but uses iterative technique for selecting the optimal location. As the LSF method reduces the search space by testing only the top 20% of buses in sorted LSF list as potential candidate location for placing DGs, it has produced the least loss reduction. It may also be worth mentioning that the highly recommended and most often used power factor cases are 2 (in many grid codes) and 5 (suggested in this work) because they provide both active and reactive power to the network. Both these power factor cases produce almost comparable results, which are better then the results for other power factor cases too. The comparison of the power loss reduction ratio results also highlights that operating the system at operational power factor is better in comparison to any other power factor case. Ultimately, the importance of selecting the power factor with respect to the system requirements and ability of operational power factor in fulfilling this criteria are also spotlighted by these results.

Optimal placement of DG is a planning phase issue where the computational time of a few minutes may not be very important but is presented here for the sake of comparison among different methods. Comparing the computational time for placement of four DGs with different techniques discussed here shows an additional advantage of our proposed methodology. The nearest competitor in terms of simulation time taken is the IA method, which took about 33% more time than the proposed method. Similarly, the LSF method, being iterative over the limited number of buses, took a considerably high amount of time (about more than five times higher) for placing four DGs. Despite being slightly better at reducing the losses, the ELF method is computationally highly demanding, as can be seen from the simulation time taken by it. The time taken by the ELF method to reach the final solution is approximately 33 times more than that of the MM method. It is important to note that the ELF method could be made faster by making the step size of DG size bigger, which would have ultimately adversely affected the optimal sizes and hence the loss reduction. Hence, the proposed method appears to be the best in respect to both the loss reduction and computational time. Based on this fact, it can be concluded that the presented method can be efficiently implemented for the systems with bigger sizes *i.e.*, the scalability of presented method is significantly higher then other contemporary methods. External infeed for this system was reported to be 5.40 MVA in the base case, which was reduced to 1.46 MVA after optimal placement of DGs.

Table 5.2: DG placement by all methods for IEEE 37 node system with PF case – 1 (use case 1a)

Case	**Method**	**Installed DG Schedule (MVar)**					**DG (MVar)**	**Ploss (kW)**	**Loss Red (%)**	**Time (s)**
No DG		Total Real Load = 4.98 MW					-	281.85	-	-
4 DGs	LSF	Bus	2	5	37	26	6	251.15	10.89	169.6
		Size	5	1	0	0				
	IA	Bus	27	24	11	36	0.93	261.19	7.33	84.2
		Size	0.45	0.24	0.11	0.13				
	ELF	Bus	2	4	12	28	7	248.41	11.86	765.8
		Size	5	1	0.50	0.50				
	MM	Bus	12	18	22	32	0.93	261.49	7.22	48.4
		Size	0.33	0.18	0.15	0.27				

Table 5.3: DG placement by all methods for IEEE 37 node system with PF case – 2 (use case 1a)

Case	Method	Installed DG Schedule (MW)					DG (MW)	Ploss (kW)	Loss Red (%)	Time (s)
No DG		Total Real Load = 4.98 MW					-	281.85	-	-
4 DGs	LSF	Bus Size	25 2.5	2 5	7 0	7 0	7.5	150.07	46.76	169.6
	IA	Bus Size	33 1.0	24 0.5	19 1.0	5 0.7	3.2	38.57	86.32	84.2
	ELF	Bus Size	22 1	32 1.5	13 1.5	2 5	9	13.87	95.08	765.8
	MM	Bus Size	12 0.6	18 0.6	22 0.9	32 1.3	3.4	12.92	95.42	48.4

Table 5.4: DG placement by all methods for IEEE 37 node system with PF case – 3 (use case 1a)

Case	Method	Installed DG Schedule (MW)					DG (MW)	Ploss (kW)	Loss Red (%)	Time (s)
No DG		Total Real Load = 4.98 MW					-	281.85	-	-
4 DGs	LSF	Bus Size	25 2	7 0	7 0	7 0	2	193.09	31.49	169.6
	IA	Bus Size	33 0.7	24 0.4	19 0.8	27 0.7	2.6	105.67	62.51	84.2
	ELF	Bus Size	22 1	32 1	13 1	11 0.5	3.5	74.51	73.56	765.8
	MM	Bus Size	12 0.4	18 0.5	22 0.8	32 1.1	2.8	78.35	72.20	48.4

Table 5.5: DG placement by all methods for IEEE 37 node system with PF case – 4 (use case 1a)

Case	Method	Installed DG Schedule (MW)					DG (MW)	Ploss (kW)	Loss Red (%)	Time (s)
No DG		Total Real Load = 4.98 MW					-	281.85	-	-
4 DGs	LSF	Bus Size	25 2.5	2 2.5	26 0	37 0	5	162.72	42.27	169.6
	IA	Bus Size	33 0.9	24 0.5	19 1.0	5 0.6	3.1	52.60	81.34	84.2
	ELF	Bus Size	22 1	32 1.5	13 1.5	11 0.5	4.5	21.13	92.50	765.8
	MM	Bus Size	12 0.6	18 0.6	22 0.9	32 1.4	3.5	23.27	91.74	48.4

Table 5.6: DG placement by all methods for IEEE 37 node system with PF case – 5 (use case 1a)

Case	Method	Installed DG Schedule (MW)					DG (MW)	Ploss (kW)	Loss Red (%)	Time (s)
No DG	Total Real Load = 4.98 MW						-	281.85	-	-
4 DGs	LSF	Bus	25	2	37	7	7.5	150.47	46.61	169.6
		Size	2.5	5	0	0				
	IA	Bus	33	24	19	5	3.2	37.81	86.59	84.2
		Size	1.0	0.5	1.1	0.7				
	ELF	Bus	22	32	13	11	4.5	10.32	96.34	765.8
		Size	1	1.5	1.5	0.5				
	MM	Bus	12	18	22	32	3.5	11.49	95.92	48.4
		Size	0.6	0.6	0.9	1.4				

5.5.1.2 Voltage Profile and Quality Improvement

Optimally placed DGs not only help in reducing active power loss in the network but also improve the system's voltage profile. The comparison of bus voltages in the network when the DGs are placed by different mentioned methods are given in Figure 5.6 – 5.10. It has been repeatedly explained that for a stable system, the bus voltage should not only remain within the permissible limits (±6 % in this work) but it should also remain close to each other in magnitude for all network buses. As mentioned in the Table 5.1 and can also be seen in related figures, the minimum voltage in either network is about 0.87 p.u. approximately, whereas the maximum voltage is 1.000 p.u., which appeared at the node where the external grid is connected and is a voltage regulated node. After DG placement, all the methods improved the voltage in the network; however, the voltage improvement is varying.

From these figures, it can be seen that the buses 22, 23 and 24 have the least voltage in the network. When comparing the performance of different methods in improving the bus voltages, LSF method is not able to significantly improve the network voltage, specially at the critical buses (22 – 24). For all power factor cases, the voltage at these buses with LSF method remained below the lowest permissible limit. On the contrary, the voltage improvement is very good with ELF and MM methods. Another important observation for the voltage profile with these methods is that the network voltage remains very close to the nominal value for every bus in the network. Also, the bus voltage at the critical buses is improved a lot and reached near the nominal value. Improved analytical method showed intermediate results between two extremes marked by ELF and MM methods, and LSF method. This method cannot improve the bus voltage for given network and parameters to more than minimum permissible limit at the critical buses in power factor case 3. This may be because of the fact the DGs in this power factor case also require the reactive power hence the network voltage dropped. However, such problem was not observed for the ELF and MM methods and the voltage was improved and kept within the permissible band. For the similar reasons as mentioned for active power loss minimization, no significant improvement in the network voltage is observed in power factor case 1.

For the 37 node network, the minimum voltage observed after optimal DG placement was 0.998 p.u. with the ELF method, whereas with the proposed method (MM), the voltage was 0.988 p.u. Moreover, the highest voltage observed with ELF method of optimal DG placement was 1.009 p.u., and, with the proposed method, it was 1.000 p.u. The IA method also brought the minimum voltage to the permissible limit of 0.961 p.u. and maximum voltage to 1.005 p.u. Although the voltage improvement by IA method is within the allowed band, it is closer to the minimum level, which makes it prone to falling below with small variation in loads or generations. The LSF method was unable to increase the minimum voltage to the permissible level.

As a final comment, it is mentioned that, for a network, it is not only required to keep maximum and minimum voltages within the limits, but the difference between these two should also be kept closer to zero to make the system more stable with respect to the voltage. Based on these values, the MM method is proved in very close coincidence with the ELF method, which is supposed to be the most accurate method of optimal DG placement.

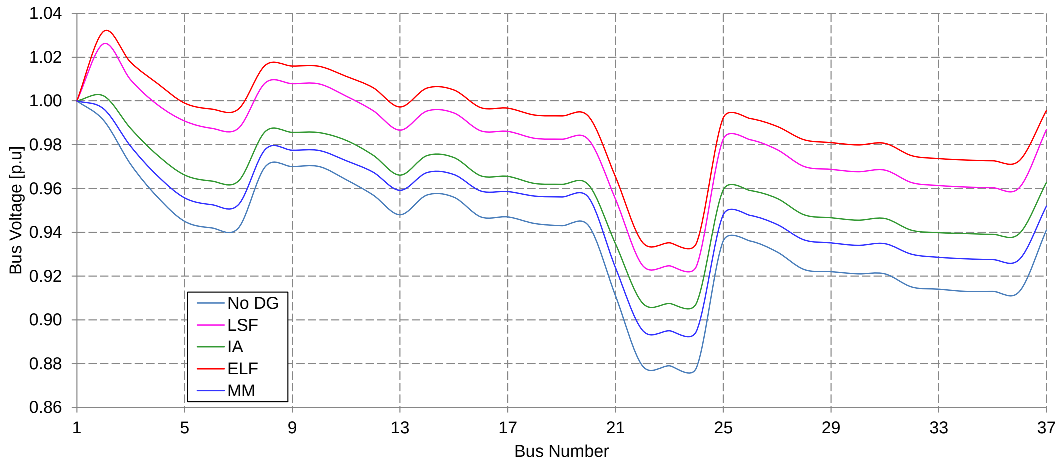


Figure 5.6: Voltage profile for 37 node system with all methods with PF case – 1 (use case 1a)

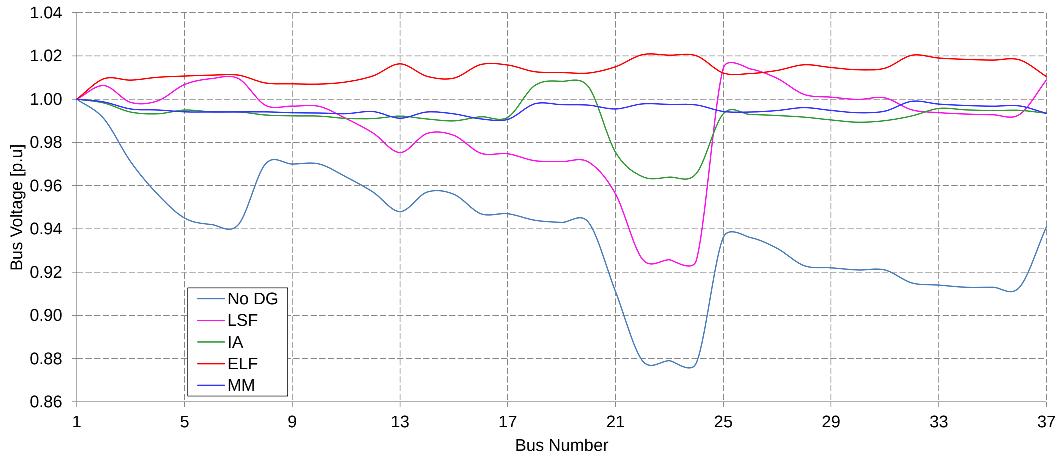


Figure 5.7: Voltage profile for 37 node system with all methods with PF case – 2 (use case 1a)

The voltage quality index introduced earlier is also utilized to provided a simple and clear method of identifying the voltage status of the network. From Figure 5.11, the VQI can be observed for different power factor cases with different methods. It is clear that the best voltage quality is observed in power cases 2, 4 and 5. The ELF method produced best voltage quality results (approximately 99 % in PF case 2 and 5) whereas the results produced by the MM methods are either better than or the nearest to the ELF method in most cases. As as general trend, the performance of IA method is again nearer but slightly behind the MM and ELF methods. Moreover, the VQI is improved significantly in comparison to the case of No DG.

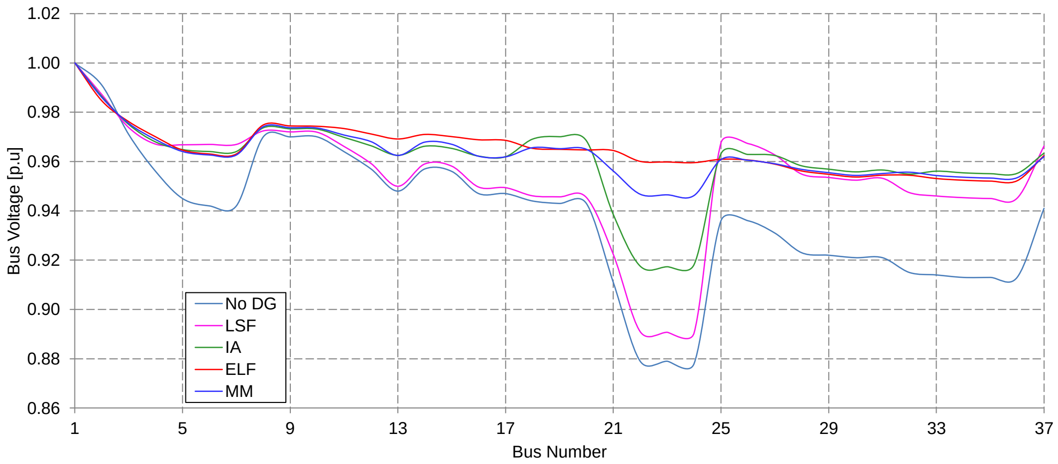


Figure 5.8: Voltage profile for 37 node system with all methods with PF case – 3 (use case 1a)

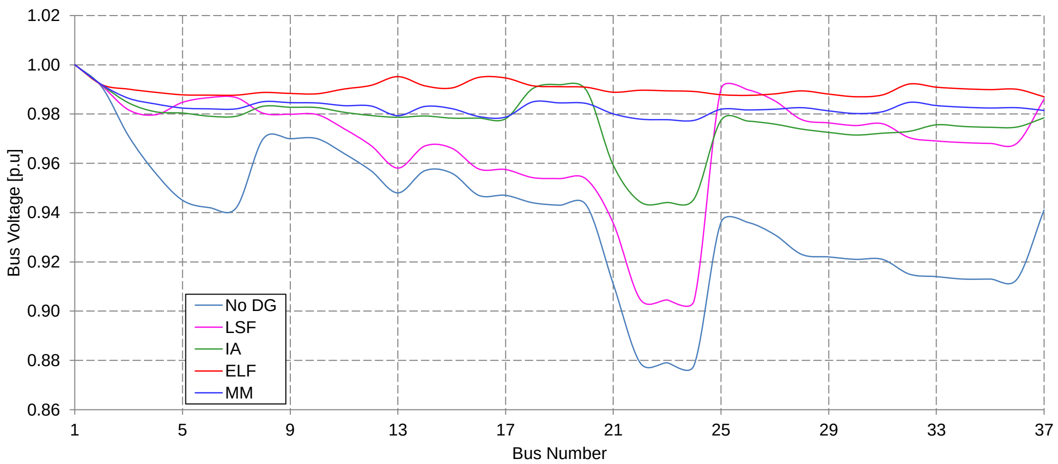


Figure 5.9: Voltage profile for 37 node system with all methods with PF case – 4 (use case 1a)

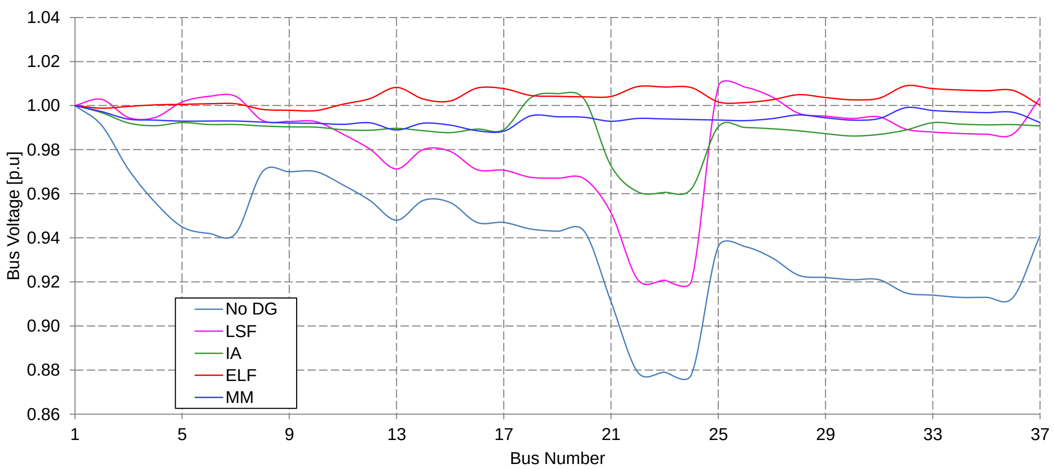


Figure 5.10: Voltage profile for 37 node system with all methods with PF case – 5 (use case 1a)

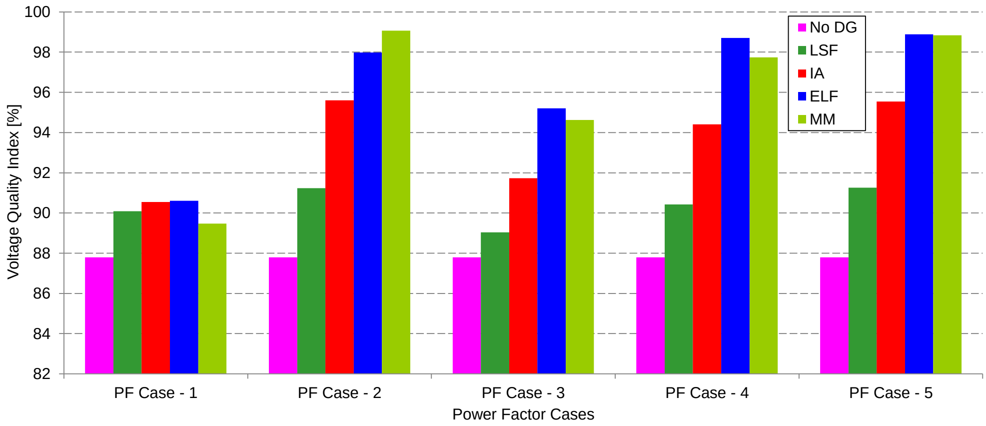


Figure 5.11: Voltage quality index for 37 node system with all methods with PF case – 5 (use case 1a)

5.5.1.3 Line Flows

As a matter of fact, the line losses in the network depend directly on the line parameters and the amount of current flowing through them. Moreover, these parameters have strong impact on the network's voltage levels. The flow of the current over different network lines is summarized in Figure 5.12 for the power factor case 5. It is obvious that the line(s) emerging directly from the bus connected to external grid have high line flow because they carry the total amount of network's demand, specially in case of no DG case. In cases with DGs, the line flow on such lines may also be higher if the total power demand is not fulfilled by the installed DGs. From the Figure 5.12, significant reduction in line flow throughout the network lines is observed with DGs, where the best line reduction is either with MM method or with ELF method. For some lines, such as line 12 – 13 or 28 – 32, the line flow is significantly low with IA method, as compared to MM or ELF however, the number of such lines is lower.

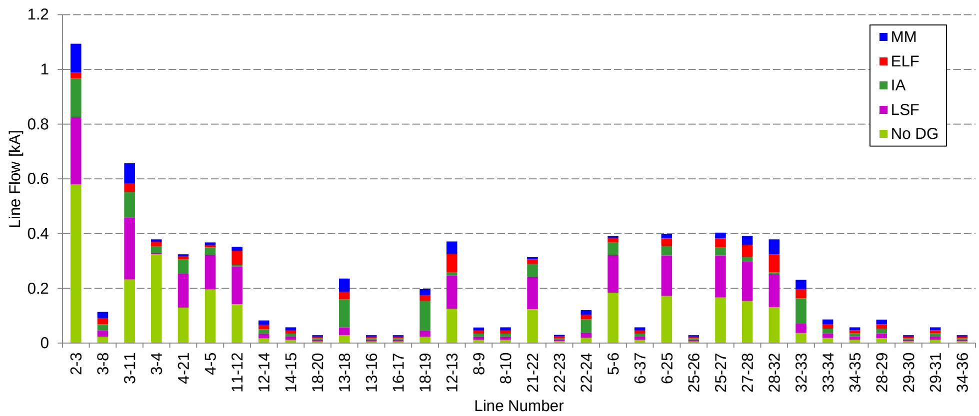


Figure 5.12: Line Flow for 37 node system with all methods with PF case – 5 (use case 1a)

5.5.2 Use Case 1b: IEEE 119 Node System – Results

In order to further investigate the outcome of placing DGs optimally with the proposed methods, the results are also gathered for a bigger and more complex network. IEEE 119 bus system is used for the sake of this purpose. This system contains 118 sectioning switches, 15 tie lines and

119 nodes with operating voltage of 11 kV. This system has higher reactive power demand and more number of weak buses. Therefore, it is comparatively difficult to optimize and control this network. The placement of 5 DGs is considered in this network and results are present in a similar fashion and for similar variables as has been done in use case 1a.

5.5.2.1 Power Loss Minimization Results

Table 5.7 – 5.11 presents the simulation results for the IEEE 119 node system in the same fashion as they are done for the 37 node system. It can be seen that the proposed methodology could find the optimum sizes for reduction of losses in the system considerably faster. In addition, the sizes found depict the effectiveness of the proposed analytical expression for simultaneous sizing of DGs because the loss reduction is higher among all the presented techniques except the ELF method for some power factor cases. Similar to the trend found in IEEE 37 node system, the proposed method is found to be less efficient in case where the DGs are generating only reactive power output. This is because of the fact that the analytical expressions for the DG sizes are based on the active power loss minimization and find optimal active power output of the DGs. If, for certain power factor case, the active power output of the DG is reduced to zero, adverse impact is observed on the active loss minimization.

Despite the impact of such factors, it is clear from the results presented in these tables that the proposed method is an efficient and a better method than the other methods taken for comparison and validation. The LSF method is resulted to be the least efficient in terms of simulation time and optimum sizes that can reduce losses to the lowest level. Reducing the search space in LSF method for available number of buses to only top 20% of total number of buses seems to be the prominent reason for the lower grade output of this method. Moreover, an interesting comparison of the loss reduction ratio at different power factors studied in this work can be made. For instance, the power factor case 2, which is commonly studied in the literature and taken in many different grid codes, does not appear as good as the operational power factor proposed in this work. The comparison of the loss reduction ratio in Table 5.8 and 5.11 clearly highlights this important conclusion, where the loss reduction with, for example, ELF and MM methods is improved from 76.31% and 73.91% respectively in power factor case 2 to 81.20% and 78.82% respectively with operational power factor. For other methods, similar trend is also observed. Such comparison highlights the need of optimizing the power factor as well as the usefulness of proposed method of finding operational power factor.

As mentioned before, the size, structure and condition of 119 node network is complex in comparison the 37 node network. From the Table 5.1, it is clear that the total active power demand for 119 node network is about 4.5 times more than that of 37 node network. As the optimal number of DGs is not the subject of this work, only 5 DGs are placed and this is a random selection of number of DGs. However, considering only 5 DGs in 119 node network appears to be insufficient due to bigger size, higher power demand and higher number of loads. This is also depicted by the fact that the highest loss reduction ratio observed in this network (with any method and at any power factor) is 81.2% which is considerably lower than value of 96.3% found in 37 node network.

The proposed methodology can find the optimum size for five DGs in the 119 node system approximately 3.5 times faster than by the IA method. The LSF method, being an iterative technique for finding the optimum size, consumes 6.4 times more time as compared to the proposed method. Although slightly better in loss reduction, the ELF method consumed approximately 35.6 times more time than the proposed method. Based on these important observations, the proposed method outperformed the other methods considered here. In this system, external infeed of 30.16 MVA in the base case and 15.05 MVA after optimal placement of DGs is recorded.

Table 5.7: DG placement by all methods for IEEE 119 node system with PF case – 1 (use case 1b)

Case	Method	Installed DG Schedule (MVar)						DG (MVar)	Ploss (kW)	Loss Red. (%)	Time (s)
No DG		Total Real Load = 22.71 MW						-	1440.89	-	-
5 DGs	LSF	Bus Size	114 2.5	52 2.5	94 2	82 2	31 3	12	1029.20	28.57	169.6
	IA	Bus Size	112 2.9	77 3.3	53 3.8	116 1.8	82 1.5	13	978.05	32.12	84.2
	ELF	Bus Size	115 2.5	74 2	52 2.5	82 2	30 4.5	13.5	947.13	34.27	765.8
	MM	Bus Size	43 0	52 0	74 0	82 0	115 0	0	1440.89	0	48.4

Table 5.8: DG placement by all methods for IEEE 119 node system with PF case – 2 (use case 1b)

Case	Method	Installed DG Schedule (MW)						DG (MW)	Ploss (kW)	Loss Red. (%)	Time (s)
No DG		Total Real Load = 22.71 MW						-	1440.89	-	-
5 DGs	LSF	Bus Size	114 3.5	52 3.5	95 3	82 3	46 1	14	568.48	60.55	189.4
	IA	Bus Size	74 2.7	112 2.4	53 3.7	117 1.7	82 1.8	12.3	409.90	71.55	100.7
	ELF	Bus Size	114 3.5	75 3	52 3.5	83 2.5	100 1.5	14	341.29	76.31	734.2
	MM	Bus Size	43 0.4	52 3.3	74 3	82 2.8	115 3.5	13	375.96	73.91	61.7

Table 5.9: DG placement by all methods for IEEE 119 node system with PF case – 3 (use case 1b)

Case	Method	Installed DG Schedule (MW)						DG (MW)	Ploss (kW)	Loss Red (%)	Time (s)
No DG		Total Real Load = 22.71 MW						-	1440.89	-	-
5 DGs	LSF	Bus Size	114 2.5	52 2	95 2	83 1.5	41 1.5	9.5	1114.87	22.63	169.6
	IA	Bus Size	74 2.1	117 1.1	29 6.4	112 1.3	36 2.0	12.9	1003.19	30.38	84.2
	ELF	Bus Size	74 2	114 2.5	52 2	100 1.5	83 1.5	9.5	1000.73	30.55	765.8
	MM	Bus Size	43 0.4	52 1.8	74 2	82 1.7	115 2.1	8.0	1014.54	29.59	48.4

Table 5.10: DG placement by all methods for IEEE 119 node system with PF case – 4 (use case 1b)

Case	Method	Installed DG Schedule (MW)						DG (MW)	Ploss (kW)	Loss Red. (%)	Time (s)
No DG	Total Real Load = 22.71 MW							-	1440.89	-	-
5 DGs	LSF	Bus Size	114 3.5	52 3	95 2.5	82 2.5	41 2	13.5	806.25	44.04	169.6
	IA	Bus Size	74 2.6	112 2.1	36 2.9	117 1.6	82 1.7	10.9	674.73	53.17	84.2
	ELF	Bus Size	114 3.5	74 3	52 3	82 2.5	100 1.5	13.5	628.64	56.37	765.8
	MM	Bus Size	43 0.5	52 2.9	74 2.8	82 2.5	115 3.1	11.8	651.20	54.81	48.4

Table 5.11: DG placement by all methods for IEEE 119 node system with PF case – 5 (use case 1b)

Case	Method	Installed DG Schedule (MW)						DG (MW)	Ploss (kW)	Loss Red (%)	Time (s)
No DG	Total Real Load = 22.71 MW							-	1440.9	-	-
5 DGs	LSF	Bus Size	52 3.5	69 3	83 2.5	95 3	114 3.5	15.5	490.73	65.94	619.01
	IA	Bus Size	53 3.6	77 3.1	82 1.7	112 2.4	116 1.3	12.1	345.24	76.04	106.59
	ELF	Bus Size	52 3.5	74 3	83 2.5	100 1.5	114 3.5	14	270.9	81.20	3077.71
	MM	Bus Size	43 0.4	52 3.3	74 2.9	82 2.8	115 3.4	12.8	305.2	78.82	42.95

5.5.2.2 Voltage Profile and Quality Improvement

Optimally placed DGs help in improving the system's voltage profile because of the injection of active and reactive power. However, inappropriate amount of injected active and reactive power may cause voltage disturbances leading the poor voltage quality as well as causing the stability issues. Due to such an importance, the voltage conditions of the system are also studied after placement of DGs with different methods and are presented in terms of voltage profile in Figure 5.13 – 5.17. Node 1, which connects the system under study to the external grid, is regulated at 1.000 p.u. whereas the least voltage in the system is 0.869 p.u. observed at node 80. Nodes 49 – 56, 73 – 80 and 110 – 118 in the system have the voltage level below 0.94 p.u. in the no DG case. Different level of improvement in node voltages is observed after placement of DGs in by different methods and at different power factor cases.

In all these figures of voltage profile, it is clear that the LSF method has been least efficient in improving the voltage profile. The ELF method improveD the voltage profile to the best value with the MM method as the nearest competitor. IA method produced good results as well, however, the voltage difference between minimum and maximum voltage in the network is found to be higher. This lead IA method to have lower voltage quality index in comparison to the ELF and MM methods. It is worth-noting that voltage in the network is improved and becomes higher than the lower permissible limit of 0.94 p.u. in power factor case 2, 4 and 5 with every method except LSF method. For case 1, as mentioned in earlier discussion, the reactive power output of DGs cannot be termed as optimal due to different factors. Similarly, for case 3, the reactive power is being demanded by the DGs, hence, voltage level in the network is not within the allowed range.

Comparing the exact values of voltages in this network, the least voltage appeared with ELF method is 0.961 p.u. in power factor case 5. For all other power factor cases, this value is lower, which highlights the usefulness of the operating at operational power factor. At operational power factor, the maximum voltage with ELF method is 1.006 p.u. approximately. With proposed method, these values are 0.965 p.u. and 1.001 p.u., respectively. The IA method has been able to limit the node voltage between allowed range too, whereas the DG placement with LSF method could not help in reducing the (low) voltage problems.

The voltage quality index appears to be a useful parameter to closely observe and study the network's voltage status, especially in bigger networks like 119 node system studied here. The VQI for this network with different methods at different power factors is summarized in Figure 5.18. In commonly used power factor case (*i.e.*, case 2) and the case suggested here (with operational power factor), the best voltage quality index value is observed with MM method with values of 96.34% and 96.51%, respectively. At unity power factor (case 4), the value for VQI is slightly lower. The possible reason for this is zero reactive power being supplied by the DGs to the network with extremely high reactive power demand. In all these cases, the ELF and IA methods have very close values of VQI to the values produced by MM method. However, the VQI is not improved significantly by placing DG with LSF method, yet it is improved to some extent in comparison to the no DG case. Finally, it must be noted that for the power factor cases and the methods where the voltage cannot be brought within the permissible range, the value of VQI is also considerably low. This also presents the merits of using VQI for studying system's voltage performance and status.

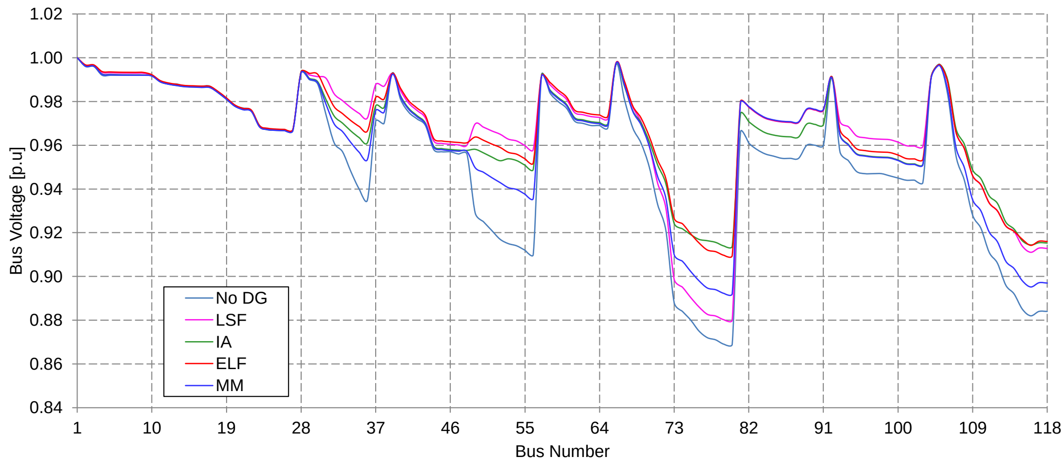


Figure 5.13: Voltage profile for 119 node system with all methods with PF case – 1 (use case 1b)

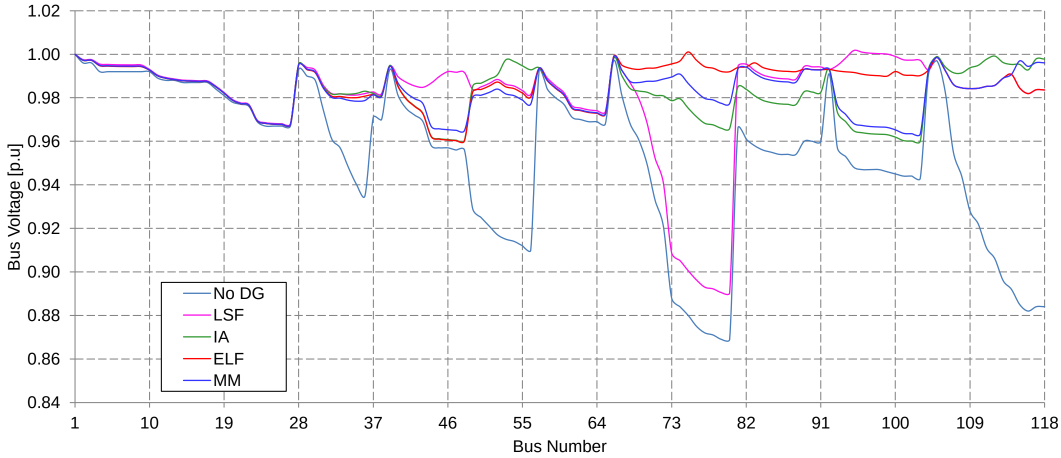


Figure 5.14: Voltage profile for 119 node system with all methods with PF case – 2 (use case 1b)

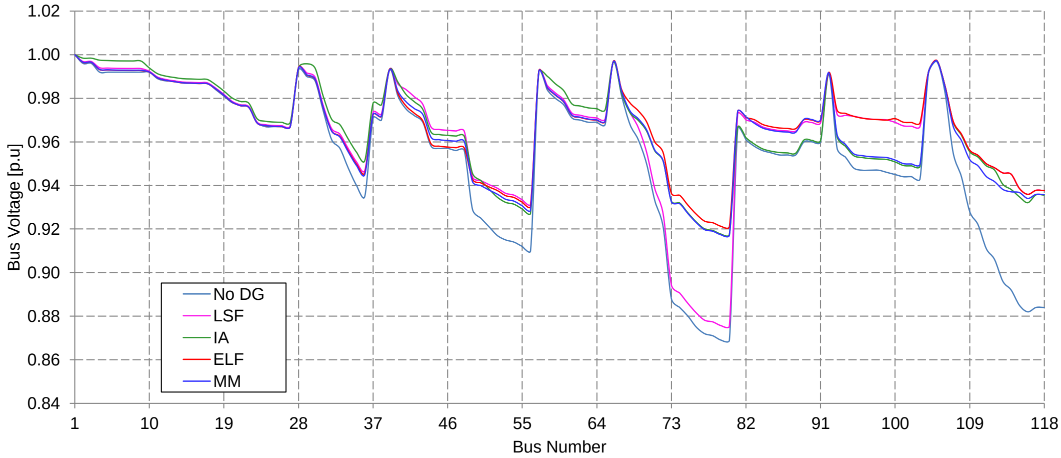


Figure 5.15: Voltage profile for 119 node system with all methods with PF case – 3 (use case 1b)

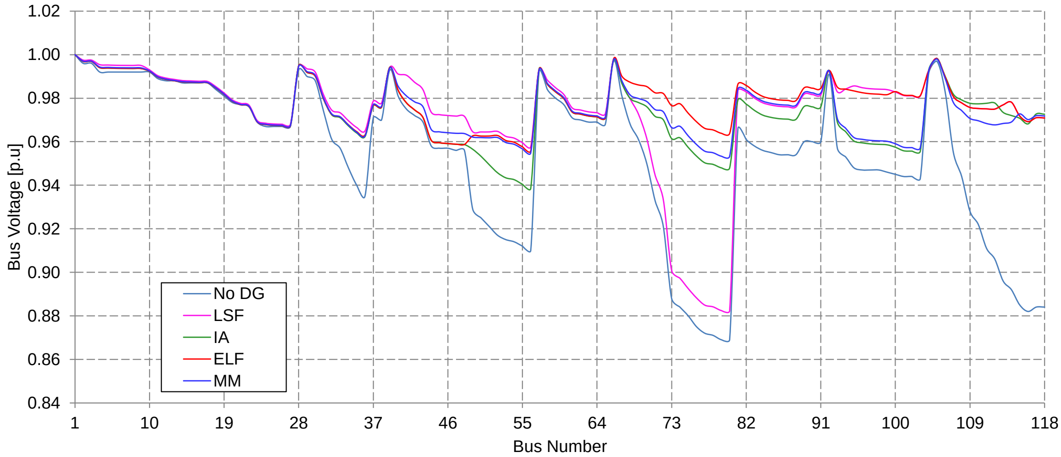


Figure 5.16: Voltage profile for 119 node system with all methods with PF case – 4 (use case 1b)

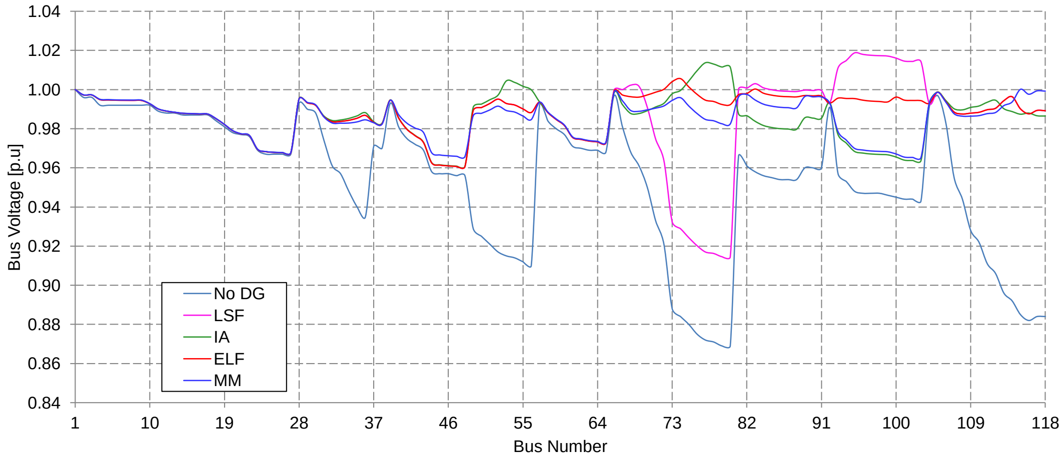


Figure 5.17: Voltage profile for 119 node system with all methods with PF case – 5 (use case 1b)

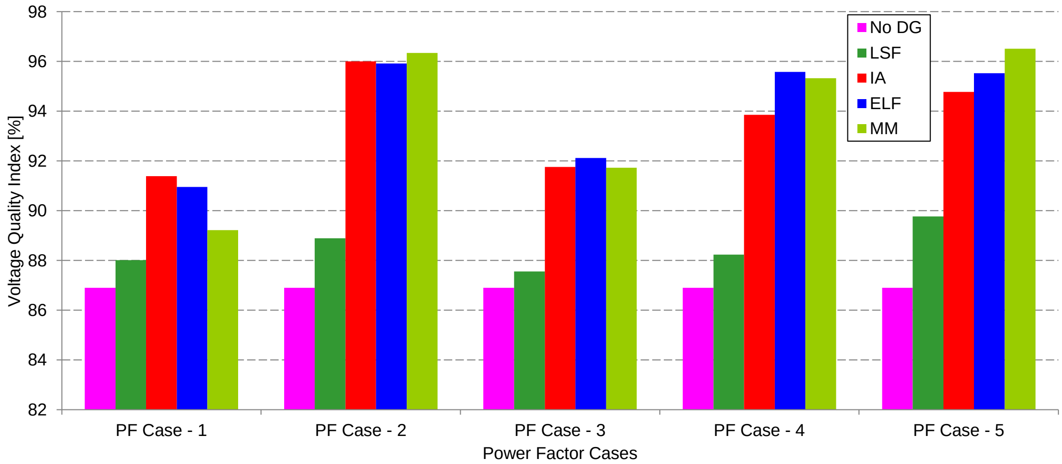


Figure 5.18: Voltage quality index for 119 node system with all methods with PF case – 5 (use case 1b)

5.5.2.3 Line Flows

The placement of DGs is important in reducing the line losses and hence increasing the hosting capacity of the network. The optimal placement can help in significant reduction in line flow and hence the power loss. Figure 5.19 presents the line flow for different methods at the operational power factor. The line flow is reduced after DG placement with all the methods, however, the ELF and MM methods reduced line flow more than the LSF and IA methods. The main lines to the different groups of loads have higher line flow than the subsequent branches due to obvious reasons. The line flows are higher as compared to the use case 1a because of higher net demand of the network.

5.6 Test Results for Use Case 2

The static case, discussed as use case 1, is useful for the purpose of estimation of the optimal DG placement under single load condition which is contrary to the case which appears most often in real world. To make the presented methods applicable to the practical scenario, it is important

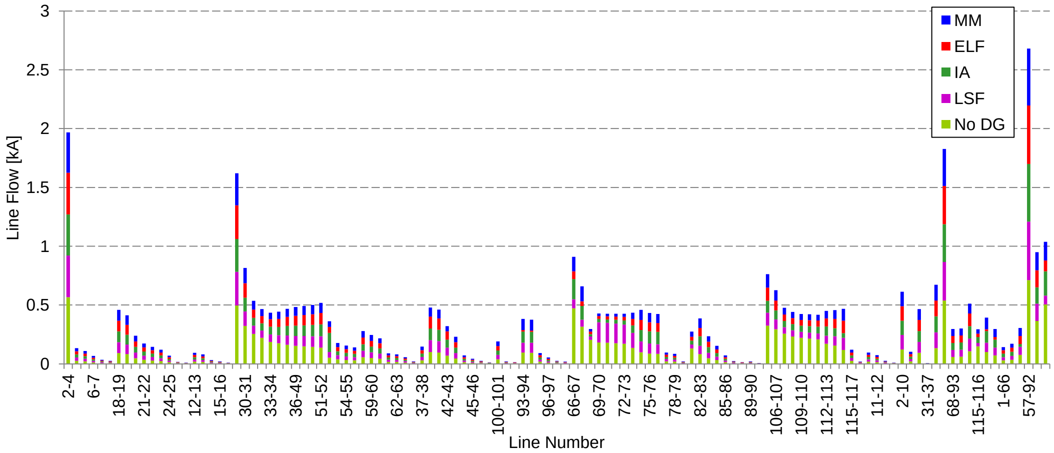
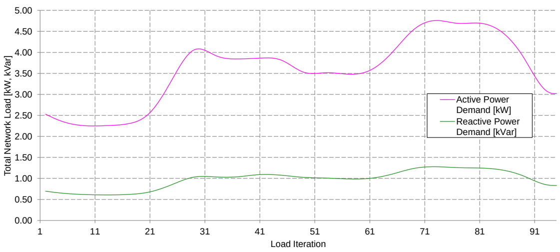
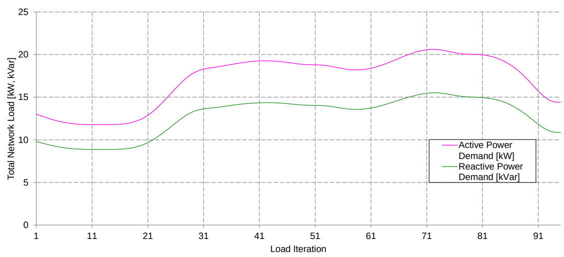


Figure 5.19: Line Flow for 119 node system with all methods with PF case – 5 (use case 1b)

to implement them on some practical cases such as time varying loads. In this regards, the use case 2 is designed where the load profile of a day is considered for a typical load. It is worth mentioning that the total load connected to the network is updated every 15 minutes over the period of a day, hence resulting in 96 iterations in total, presented as "load iteration" in the graphs given in this section. use case 2a and 2b are defined as before, for IEEE 37 and 119 node systems, respectively. The total load connected to the system in each iteration is presented in Figure 5.20(a) and 5.20(b) for IEEE 37 and 119 node networks, respectively. In the following sections, the results for these use cases are presented in detail. The number of DGs to be placed are taken to be similar to the case of use case 1.



(a) for use case 2a and 3a



(b) for use case 2b and 3a

Figure 5.20: Load profile considered in use cases 2 and 3

5.6.1 Use Case 2a: 37 Node System – Results

As before, the use case 2 is also split in 2a and 2b for 37 node and 119 node networks, respectively. In use case 1, the load was consistent, hence the locations found by any method remained fixed for a specific power factor case. However, in case of varying loads, each method produces different set of locations and sizes at each load iteration for a given power factor case. This is because the location and size depends mainly on the network parameters. Hence, if the load varies, the location and size do also. Varying system conditions also changed the set of optimal locations chosen for static case of load because the load variation considered is not uniform for all the network loads. In fact, the load variation is random *i.e.*, some load may increase to different value with different percentage of the base load value than any other load's percentage. However, the total load of the considered system in any load iteration will remain similar to the one shown in Figure 5.20 and **??**, respectively. As a consequence, the LCF method produced different set of locations for different load iterations. Also, as stated in subsection 3.4.2, the nearest locations can be tested for any improved results in MM method. In this regard, three different sets of locations are considered in MM method, named as MM − 1, MM − 2 and MM − 3. Similarly, for other methods (LSF, IA and ELF), the locations are also kept fixed throughout the simulation time (a day) because it is not practical to have DG locations varying during the day. DGs are connected once and only, at some specific location. The finalized sets of locations taken in each of these sets are:

- MM − 1 = [12, 18, 22, 32]
- MM − 2 = [12, 16, 22, 32]
- MM − 3 = [12, 16, 22, 34]
- LSF = [2, 7, 25, 37]
- IA = [5, 19, 24, 33]
- ELF = [11, 13, 22, 32]

As thoroughly discussed in the literature survey that the output from DGs can be made dispatchable by hybridizing the different types and forms of DGs. In this work, the DG sizes are considered fixed due to such reasons in all the different methods. These fixed sizes are found for the static load case at DG locations given above. Moreover, it has already been concluded from the results of use case 1, that the loss reduction and voltage profile improvement are maximum at operational power factor, hence, the results for use case 2 are only taken for the operational power factor. The active power output from DGs in MW is given here. These optimal sizes correspond to the peak load conditions keeping in view that the load may increase in future hence these sizes will appear as an intermediate choice and will be able to cater for the increased load scenario. If the sizes would have been calculated for medium or low load levels, better results might be expected for the current case, but as the load is ever increasing, this may not be advisable to choose optimal sizes for smaller load conditions. The reactive power demand can be calculated according the power factor case considered using Equation 3.3.

- MM − 1 = [0.6, 0.6, 0.9, 1.4]
- MM − 2 = [0.4, 0.8, 0.9, 1.3]
- MM − 3 = [0.4, 0.8, 0.9, 1.1]
- LSF = [5, 0, 2.5, 0]
- IA = [0.67, 1.05, 0.5, 1]
- ELF = [0.5, 1.5, 1, 1.5]

The results presented in the sections below are for these data.

5.6.1.1 Power Loss Minimization Results

The simulation results for use case 2a are given in Figure 5.21 - 5.25, for active power loss at each iteration of load. As no active power is being injected in the network, the results are not very impressive in power factor case 1. Instead, the losses followed almost similar trend as the load variation because the losses increase proportional to the increased load when the generation is kept fixed. In all other power factor cases, the losses are reduced significantly by each of the methods, their reduction ratio differs though. The loss reduction is minimum with the LSF method, especially at the higher load levels. For ELF method, the loss reduction is good as compared to the LSF method, but at the starting load conditions, the loss reduction is comparatively lower than at the higher load levels. This may be because of the fact that the DG sizes are taken equal to the one found in static case which correspond to the peak load conditions. The best results are observed with the IA and different variants of MM method. An important observation from these figures of active power loss minimization is that the losses remained nearly uniform irrespective of the load variation when the DGs are placed with MM method. The IA method also followed the same trend but MM method produced slightly better results. For all the power factor cases, only minor differences are observed in the loss reduction with these methods.

In case of time varying loads, it is also very useful and important to know the amount of energy lost over the period of mentioned time. The energy loss information provide an easy and straightforward method of choosing the best method. Therefore, the energy loss for different power factor cases are summarized in Figure 5.26. The energy loss is significantly reduced for power factor case 2, 4 and 5. Although the energy loss is much lower in power factor case 3 than the case of no DG or power factor case 1, yet it is almost double than other power factor cases. The energy loss without any DGs is 5158.7 kWh which is reduced to the 771 kWh and 720.5 kWh in use cases 2 and 5, respectively with the MM – 1 set of DG locations and sizes. The second best set of energy loss values is found with MM – 3 method whereas the IA method is placed at number 3 in this regards. Such a comparison clearly speaks about the performance of the proposed method. Among the methods for comparison and validation, the LSF has been very inefficient because of the limited search space (reduced to only 20% of the total buses present in the system), however, this method is still able to reduce to energy loss to 36% of the losses without any DGs approximately.

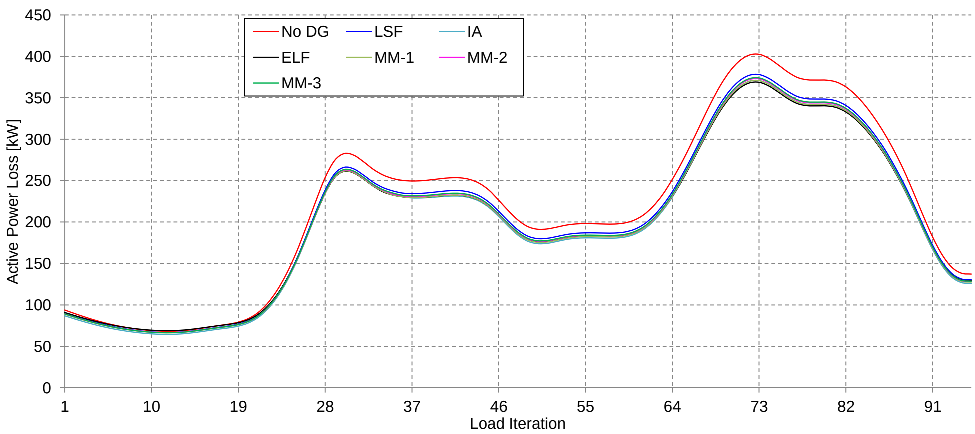


Figure 5.21: Active power loss for 37 node system with all methods with PF case – 1 (use case 2a)

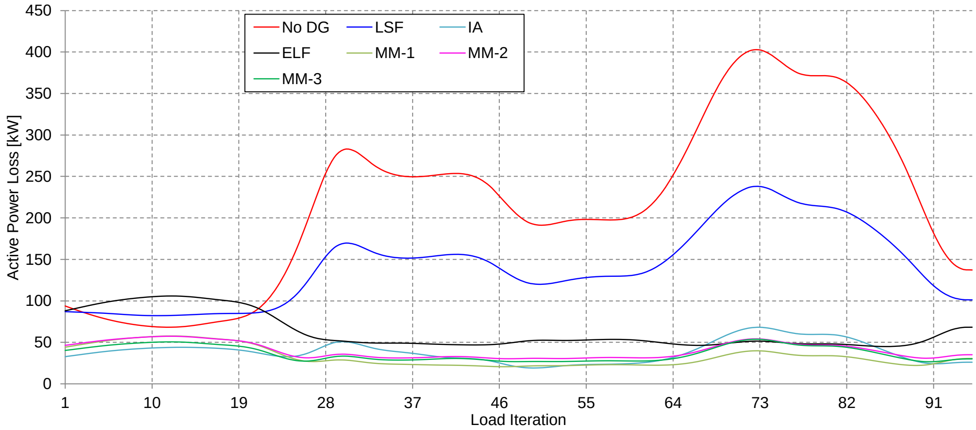


Figure 5.22: Active power loss for 37 node system with all methods with PF case – 2 (use case 2a)

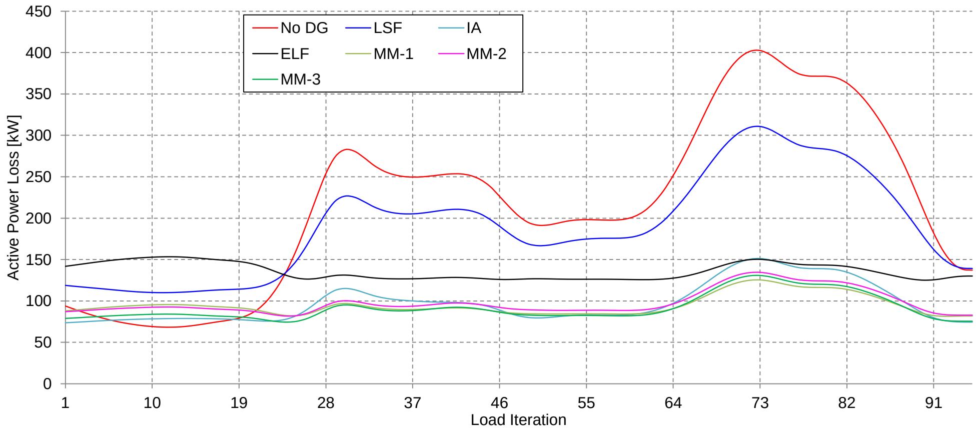


Figure 5.23: Active power loss for 37 node system with all methods with PF case – 3 (use case 2a)

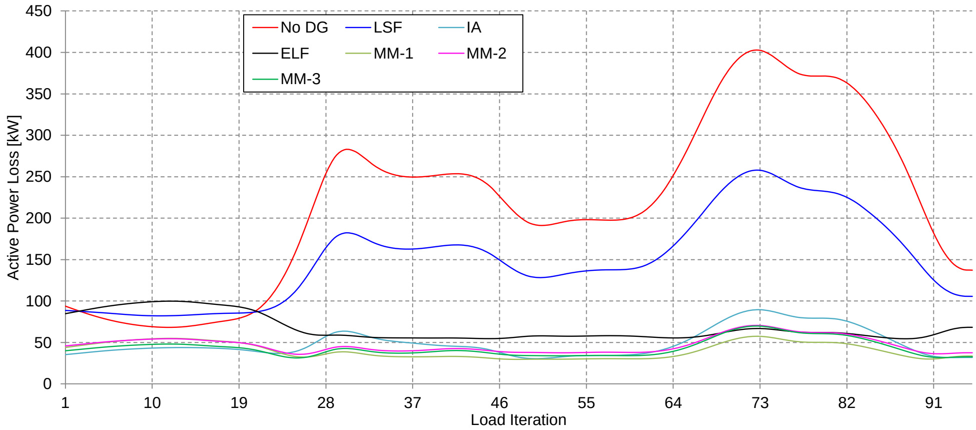


Figure 5.24: Active power loss for 37 node system with all methods with PF case – 4 (use case 2a)

5.6.1.2 Voltage Profile and Quality Improvement

In case of time varying loads, it is not very efficient to present the system's voltage profile at every load iteration, as it may lead to the huge amount of the data to be analyzed. This lead to the chances of difficulty in viewing and focusing any chances in the system's voltage conditions.

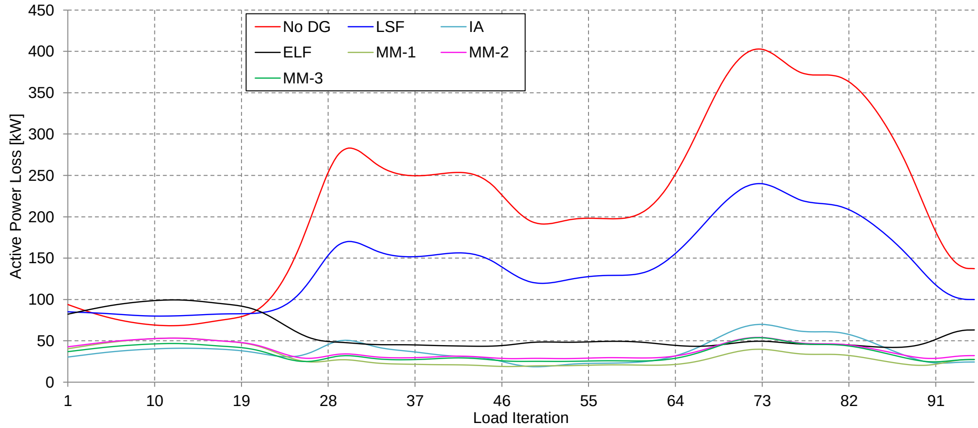


Figure 5.25: Active power loss for 37 node system with all methods with PF case – 5 (use case 2a)

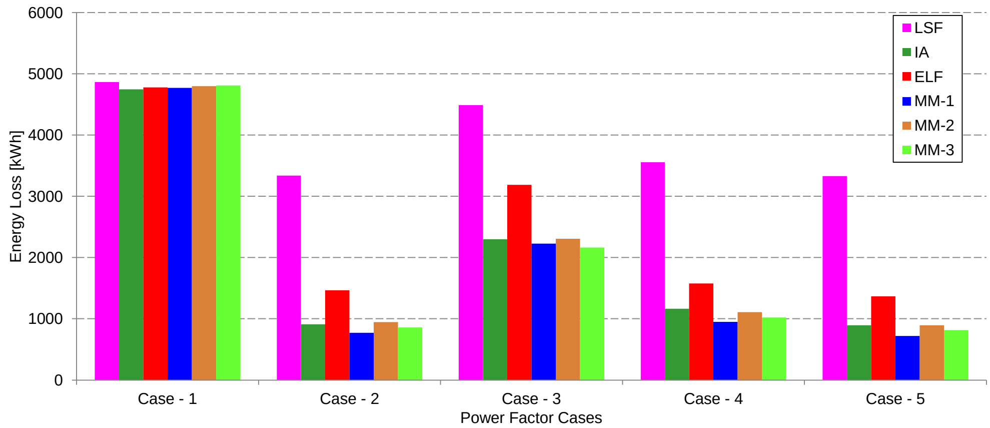


Figure 5.26: Energy loss for 37 node system with all methods (use case 2a)

Under such circumstances, the voltage quality index proposed in this work becomes even more useful as it provides clear look up type of information. To explain the voltage performance after optimal placement of DGs with different methods, the voltage quality index is calculated at each load iteration and summed up in the Figure 5.27 – 5.31. It is very clear from all these figures that the voltage quality of the network is improved a lot as compared to the no DG case by any of the methods, this means that the placement of DGs at reasonably good locations can have positive impact on the system performance. However, by selecting the location to the best, can improve the performance even more.

A very consistent voltage profile, with the bus voltage level very close to the nominal value means the consistent and higher values of the VQI. Also, the consistent values of VQI over the range of load variation show that the system is stable with respect to the voltage. This ultimately projects the system's ability to handle even more loads without sufficient voltage problems. From Figure 5.28, 5.30 and 5.31, it is very clear that the value of voltage quality with either of the sets of DG locations proposed by MM method is not only very consistent but also much higher than those produced with other methods. Although ELF method is not so good in reducing energy losses but it has produced very good voltage quality. The IA method also produced good voltage quality but lower than either of MM method or the ELF method. Moreover, the VQI values with IA methods are not as consistent as are with any of the variants of MM method. Similarly, the VQI values are lower with IA method in different power factor cases. The LSF method is only able to improve the voltage quality to some extent in comparison to the no DG case. Also, the VQI values followed similar pattern to the no DG case. Besides showing the limitation of improvements after DG placement with LSF method, the need of *true* optimal placement for maximizing the benefits is explained from these figures. In summary, the highest value of VQI is observed with MM – 1 method in power factor case 4 with a value of 98.60% whereas the best VQI value for power factor case 5 is observed to be 98.42% with MM – 1 method. The VQI value for all the other methods is lower than these values, in either of the power factor cases. A difference in VQI at operational power factor is very low as compared to the improvement in losses, hence operational power factor should be preferred in practical implementation.

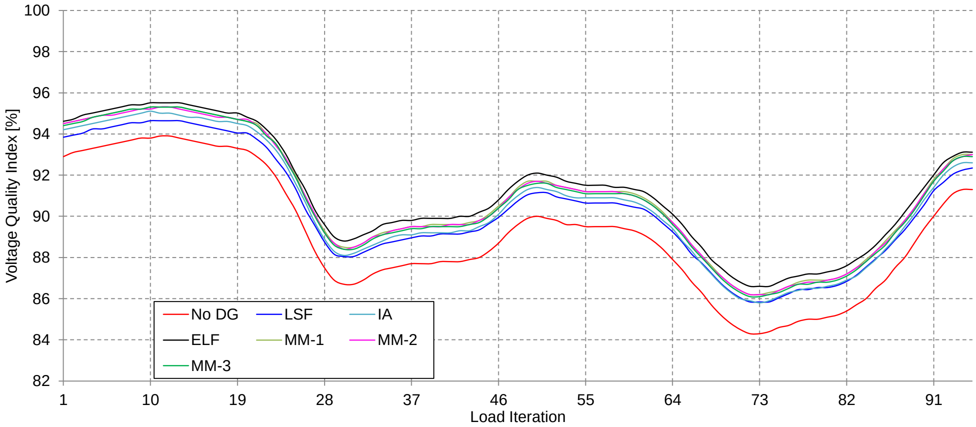


Figure 5.27: Voltage Quality Index for 37 node system with all methods with PF case – 1 (use case 2a)

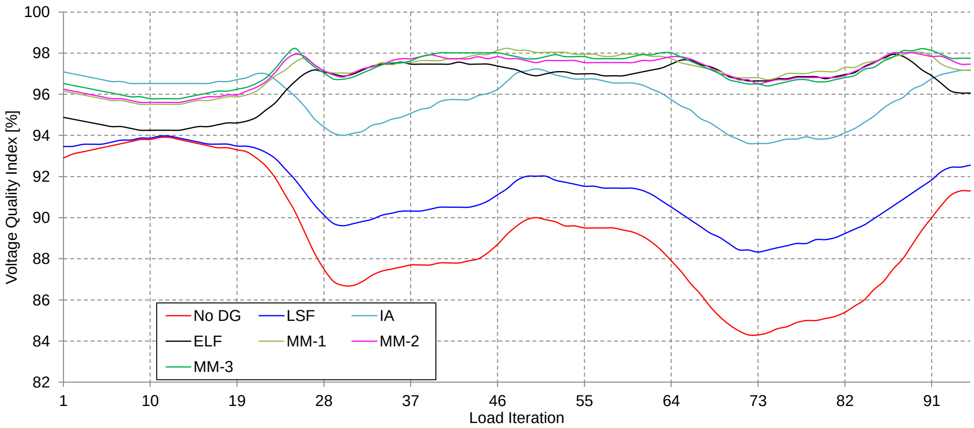


Figure 5.28: Voltage Quality Index for 37 node system with all methods with PF case – 2 (use case 2a)

5.6.2 Use Case 2b: 119 Node System – Results

Similar to the use case 2a, the locations and sizes are also kept fixed here, corresponding the static load case (use case 1b). Also, two more sets of locations are taken for MM method because, in MM method, the nearest locations can also be tested get even better set of locations. Moreover, the load variation lead to the different set of locations in LCF method proposed in this work. This is due to the fact that the optimal locations in case of MM are function of the exact load connected at certain time and due to load iteration, the optimal locations are also changing.

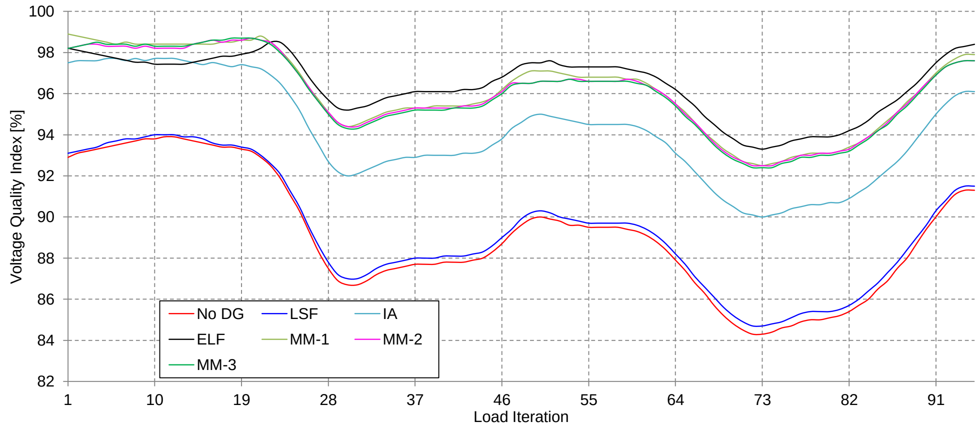


Figure 5.29: Voltage Quality Index for 37 node system with all methods with PF case – 3 (use case 2a)

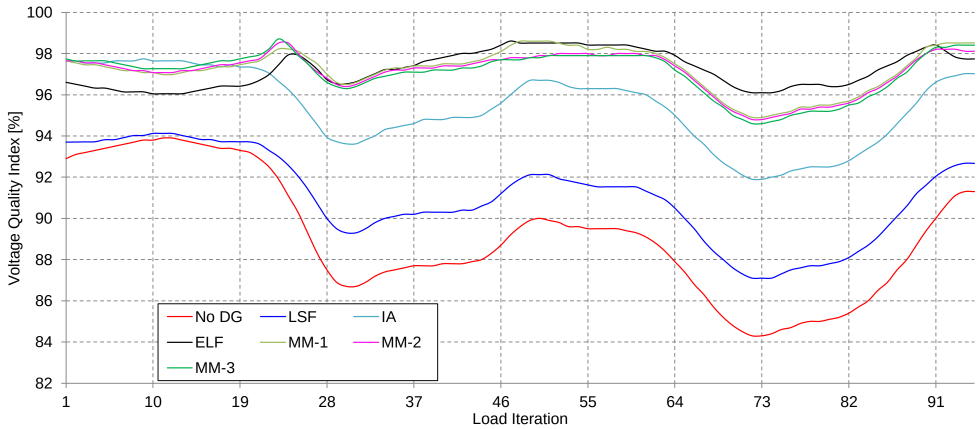


Figure 5.30: Voltage Quality Index for 37 node system with all methods with PF case – 4 (use case 2a)

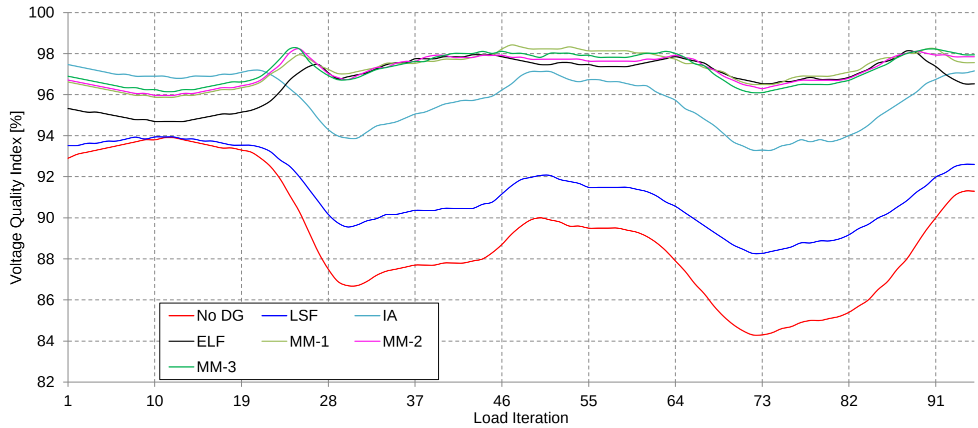


Figure 5.31: Voltage Quality Index for 37 node system with all methods with PF case – 5 (use case 2a)

Therefore, it appears to be logically valid to test other good sets of locations as well. As a result, MM – 1, MM – 2 and MM – 3 are the three different sets of locations considered in this work. In a similar fashion as done for use case 2a, the details of locations and active power output (in term of MW) from the DGs connected to these locations for all the methods considered in this work is given here:

- MM – 1 = [43, 52, 74, 82, 115]
- MM – 2 = [25, 35, 74, 82, 115]
- MM – 3 = [25, 52, 74, 82, 115]
- LSF = [52, 69, 83, 95, 114]
- IA = [53, 77, 82, 112, 116]
- ELF = [52, 74, 83, 100, 114]

The corresponding DG sizes are given as:

- MM – 1 = [0.4, 3.3, 2.9, 2.8, 3.4]
- MM – 2 = [0.9, 4.4, 3, 2.8, 3.5]
- MM – 3 = [0.9, 3.3, 3, 2.8, 3.5]
- LSF = [3.5, 3, 2.5, 3, 3.5]
- IA = [3.6, 3.1, 1.7, 2.4, 1.3]
- ELF = [3.5, 3, 2.5, 1.5, 3.4]

For power factor cases where the reactive power output is also needed, it is calculated using the Equation 3.3, as mentioned in previous section too. It is also worthy to mention that the sizes considered here are similar to those taken for the static case due to already mentioned reasons.

5.6.2.1 Power Loss Minimization Results

The power loss minimization results for the use case 2b are presented in Figure 5.32 – 5.36, in a similar fashion as has been done for use case 2a. It is worth mentioning that the 119 node system is complex as compared to the 37 node system with high reactive power demand, increased number of branches and more number of weak buses. Moreover, the considered number of DGs to be installed is only 5. Hence, in some power factor cases, the power loss minimization results are only nearer to, or even higher than, the case of no DG. For example, in power factor case 3, none of the considered methods produced any better results in comparison to the no DG case. The main reason for these unusual results is exceptionally high reactive power demand which increases further in power factor case 3 due to leading power factor. As a result, the power loss in the system increased beyond the value of no DG case. Another important point is that the DG sizes are taken as are taken in the static load case, which correspond to peak load demand or even slightly higher demand. This consideration has lead to have more losses during the time when the power demand is lower. However, after certain level of load, the power loss starts decreasing. In power factor cases 2, 4 and 5, the loss reduction is better as it remained higher for most of the load iterations. Among these three cases, the best results are produced in case 5 *i.e.*, at the power factor suggested in this work with maximum loss of 644.47 kW at the peak load condition, produced by the MM – 2 method. With this, the locations given by MM – 2 and the respective sizes calculated by the proposed analytical expressions, are supposed to be the best among all the considered sets of locations and sizes.

It is obvious from the results of the active power loss minimization that a very clear information about the best method is a bit difficult to acquire. To get a better insight into the improvement of the system performance in terms of losses, energy loss is also calculated over the considered period of time and is given in Figure 5.37. As explained above, the energy loss is higher in power factor case 3, because the reactive power is being taken by the DGs as well. For no DG case, the energy loss is recorded to be 17513.6 kWh. The least energy loss is found with MM – 2 set of locations and sizes, in power factor case 5 with a value of 12132.1 kWh. With MM – 1 set of locations and sizes, the energy loss is slightly higher than MM – 2 and MM – 3. The reason for increased energy loss is that the set of location does not correspond to the load level in most of the iterations. However, MM – 1 has produced better results in comparison to the IA method. The results by MM – 1 set of locations and sizes are comparable with ELF method too. In power factor case 1, the energy loss is reduced considerably as the DGs are providing reactive power to the network, hence fulfilling the network's reactive power demand to large extent. The ultimate conclusion is that, for any specific power factor case, the energy loss is reduced with the proposed method in comparison to any of the considered methods. However, due to complexity of the network, its bigger size, higher reactive power demand and lower number of DGs (in comparison to the power demand of the network), slightly poor power and energy loss reduction is produced in comparison to the 37 node network.

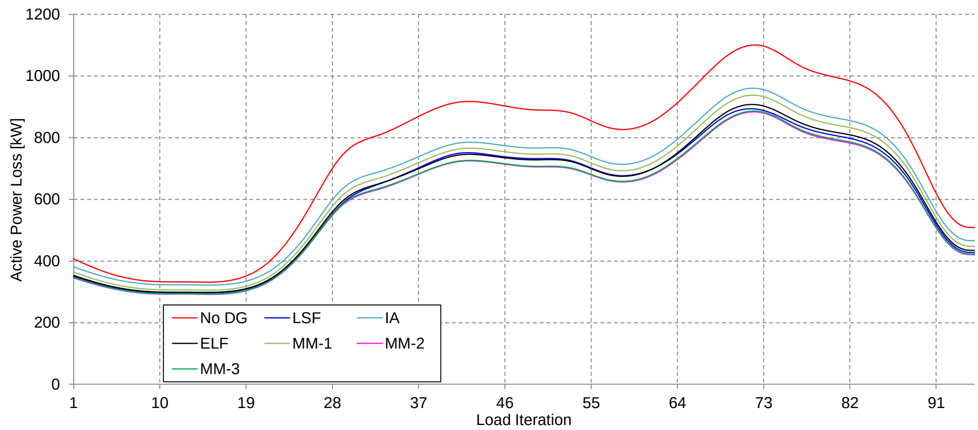


Figure 5.32: Active power loss for 119 node system with all methods with PF case – 1 (use case 2b)

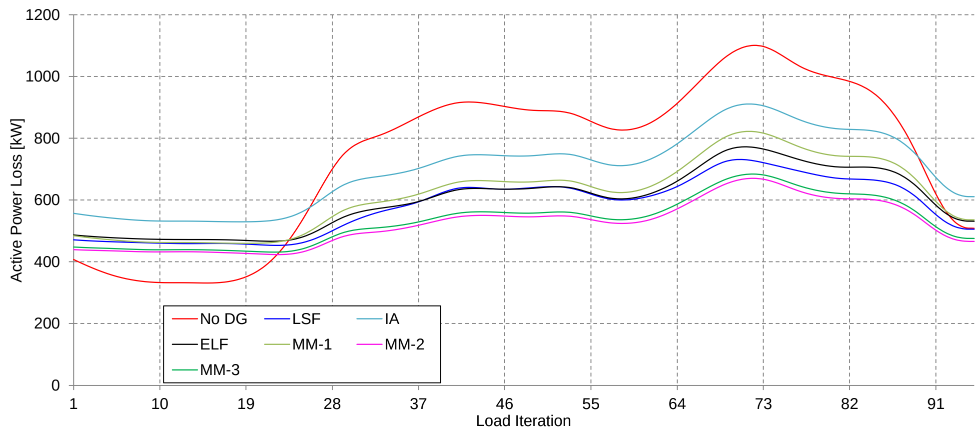


Figure 5.33: Active power loss for 119 node system with all methods with PF case – 2 (use case 2b)

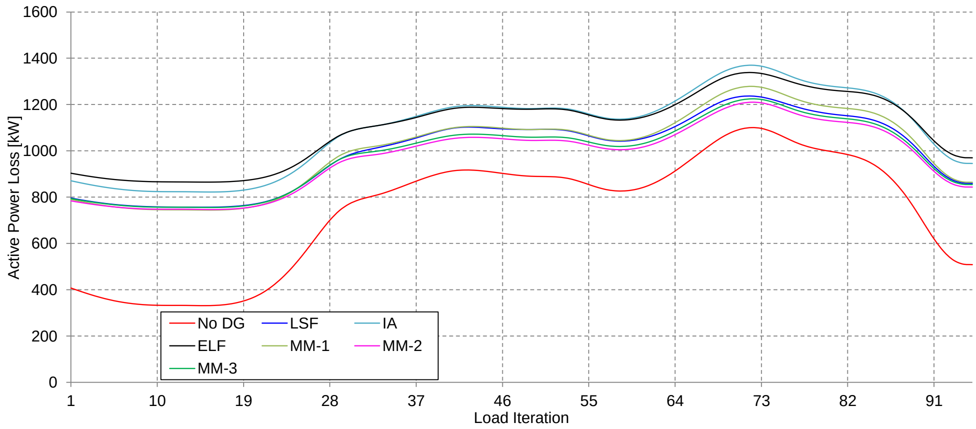


Figure 5.34: Active power loss for 119 node system with all methods with PF case – 3 (use case 2b)

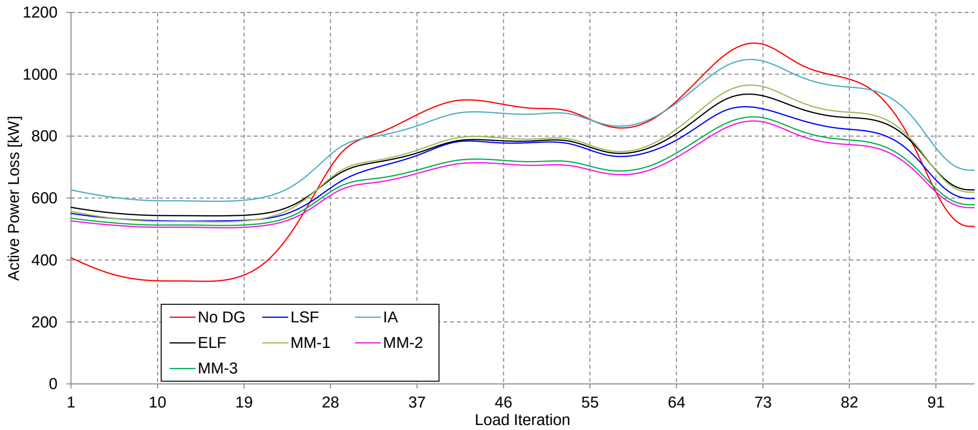


Figure 5.35: Active power loss for 119 node system with all methods with PF case – 4 (use case 2b)

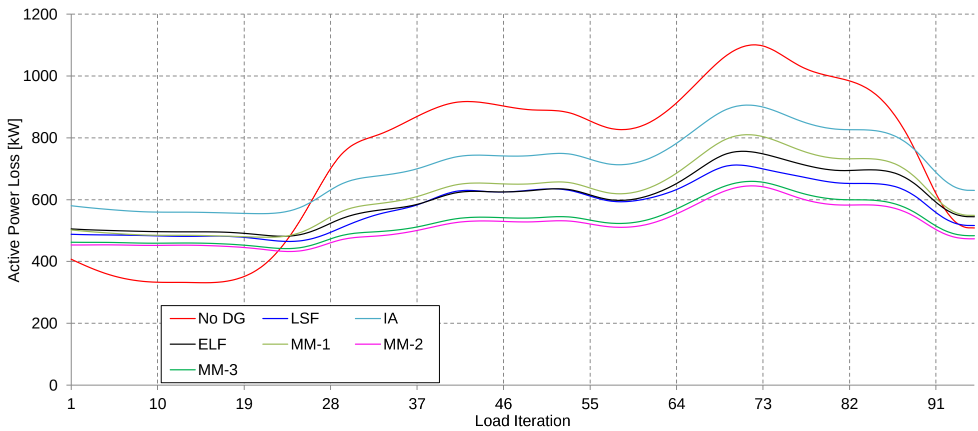


Figure 5.36: Active power loss for 119 node system with all methods with PF case – 5 (use case 2b)

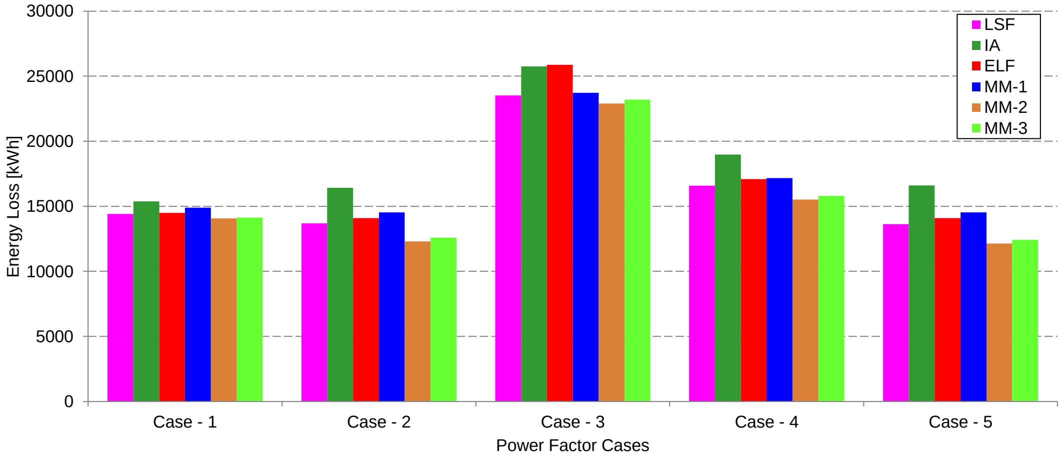


Figure 5.37: Energy loss for 119 node system with all methods (use case 2b)

5.6.2.2 Voltage Profile and Quality Improvement

For 119 node system, it is not a easy to look into the system's voltage performance by looking at the node voltage profile due to large number of nodes and load iterations. Therefore, the VQI is utilized once again to explain the voltage performance of the network with and without DGs. Figure 5.38 – 5.42 provide the VQI for all the power factor cases considered in this work. In general, for all power factor cases, the best voltage quality is produced with the MM – 2 and MM – 3 methods, as was expected because the power and energy loss reductions are better in these cases. Whereas the voltage quality for all other methods of DG placement is nearly identical, with small differences at some load iterations. However, the voltage quality is slightly reduced in comparison to the no DG case. After placement of optimally sized DGs with either of the methods, the maximum voltage in the system increased very much, *i.e.*, to the level of 1.2 p.u. or more on buses 73 – 80, being the weakest nodes in the system. Due to this reason, the voltage quality is decreased significantly. However, as previously explained, the energy and active power loss are reduced with similar sizes and locations of DGs, voltage control should be applied in order to achieve the stable voltage characteristics of the system with permissible voltage magnitudes. The exceptionally larger size, high active and reactive power demand and more number of weak nodes may also be taken as the reasons for such behavior of the system.

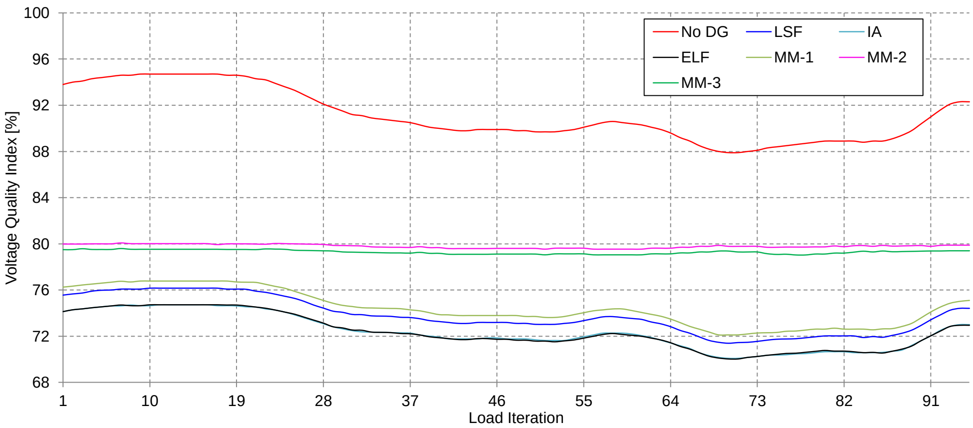


Figure 5.38: Voltage quality index for 119 node system with all methods with PF case – 1 (use case 2b)

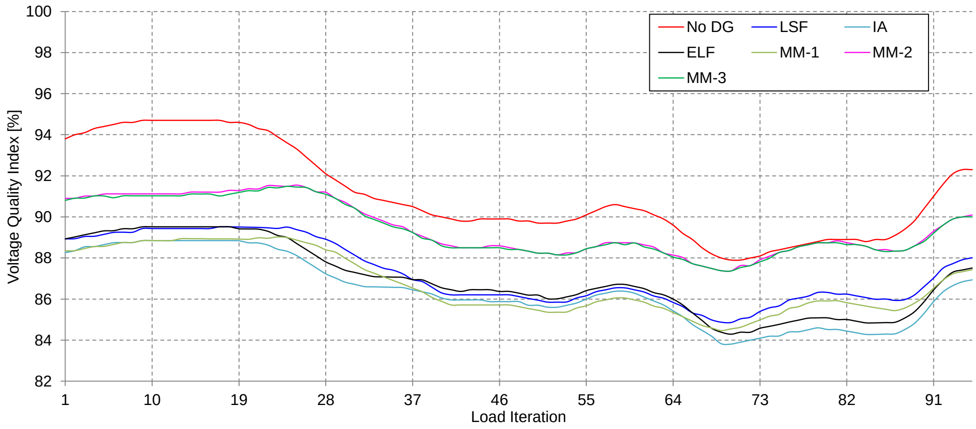


Figure 5.39: Voltage quality index for 119 node system with all methods with PF case – 2 (use case 2b)

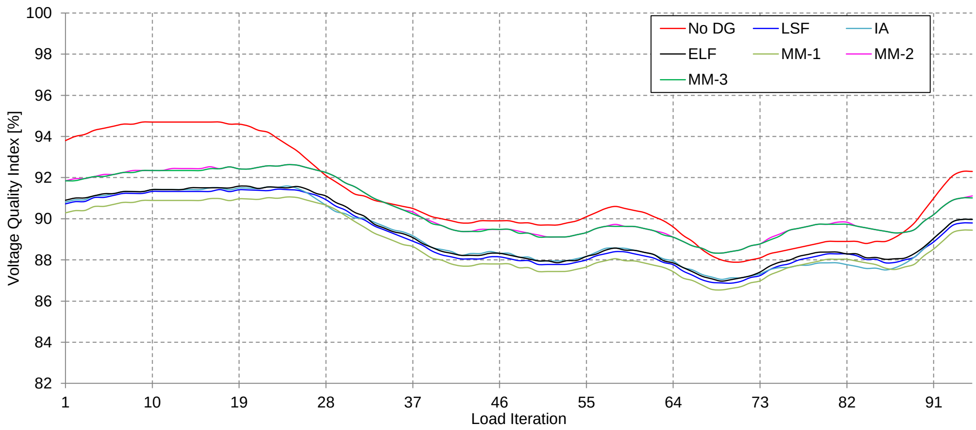


Figure 5.40: Voltage quality index for 37 node system with all methods with PF case – 3 (use case 2b)

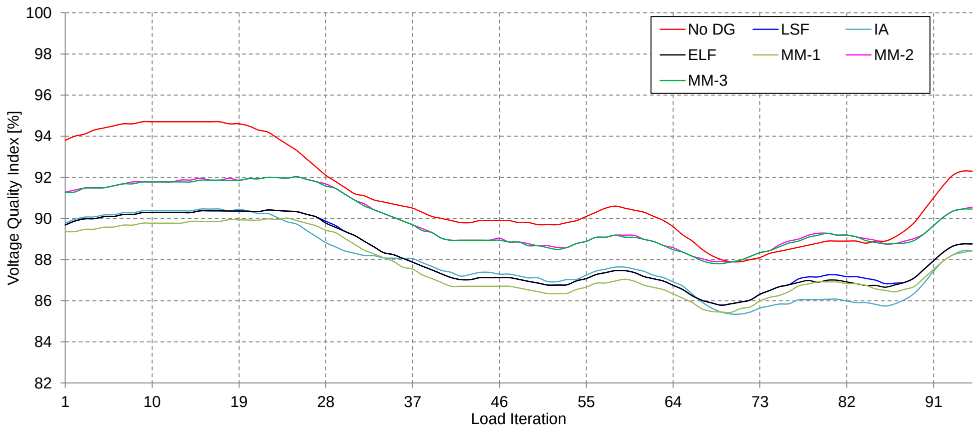


Figure 5.41: Voltage quality index for 119 node system with all methods with PF case – 4 (use case 2b)

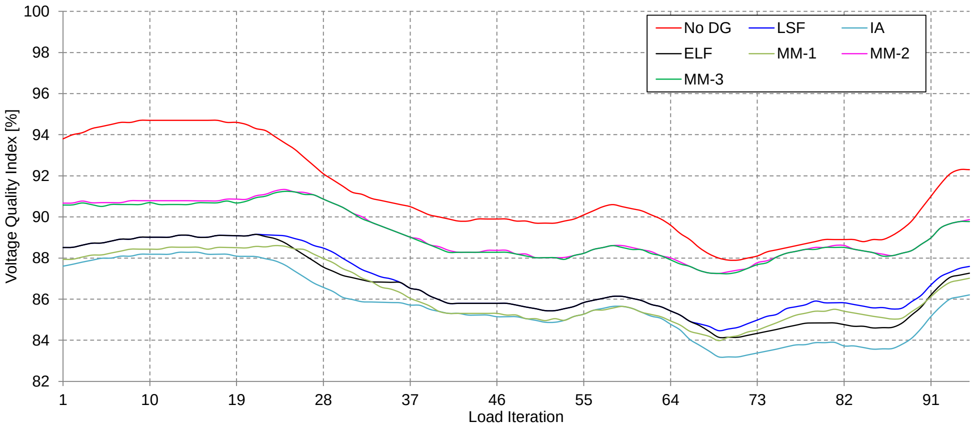


Figure 5.42: Voltage quality index for 119 node system with all methods with PF case – 5 (use case 2b)

5.7 Test Results for Use Case 3

In previous use case, it is observed that the voltage problems appeared in some cases of 119 node network after variation of the load. Under such conditions, the control scheme in the power system takes necessary corrective action(s) in order to keep it operational within the permissible limits, safely and securely. Such a scenario is presented in use case 3, where the time varying load is considered, similar to the use case 2 but with the centralized voltage control algorithm (CVCA). The CVCA tries to mitigate the voltage problem by changing the reactive power output from the DGs according the nature of the voltage problem. In previous use cases, an argument has been built with facts and figures that the operational power factor should be preferred for better system performance. Therefore, the results for use case 3 are only taken at this power factor. Another reason for presenting the results only for the operational power factor is that the only difference between use case 2 and 3 is of the CVCA. So, for studying the impact of CVCA on same system under similar conditions, only one power factor case should suffice.

For the 37 and 119 node networks, the results are summarized as use case 3a and 3b, respectively. As for other use cases, the active power loss and voltage quality index are presented to explain the results. The voltage profiles are also presented here in order to show the exact points where the impact of CVCA appeared, in terms of variation in bus voltage. The load profile used in this use case is similar to the one used in use case 2. The sets of DG locations and and sizes are also similar. However, the reactive power output of the DGs, during the operation may vary according to the requirements of the corrective action needed to keep the node voltage within the permissible limits. It is worthy to mention that the minimum power factor, even after the CVCA, is taken to be 0.80. If the CVCA is unable to correct the voltage problem by supplying the reactive power from DGs corresponding to the 0.80 power factor, no further corrective action is taken and voltage problem in the system may persist.

5.7.1 Use Case 3a: 37 Node System – Results

5.7.1.1 Power Loss Minimization Results

Active power loss minimization results with operational power factor are given in Figure 5.43. These results show that the power loss is not different from that of use case 2a, at operational power factor. Such response is observed only because every aspect of the network is similar except only marginal difference in the reactive power output from DGs, if the voltage correction is needed. The active power output remains same throughout the simulation. Moreover, the difference in the reactive power is only made when a voltage at certain node is out of the permissible bounds of ±6%. For example, as discussed in the subsubsection 5.7.1.2, the voltage problem appears only for the DG placement with IA and LSF methods. This means that, for all other methods, the output from DGs remains same as for use case 2a, leading the same output for these methods.

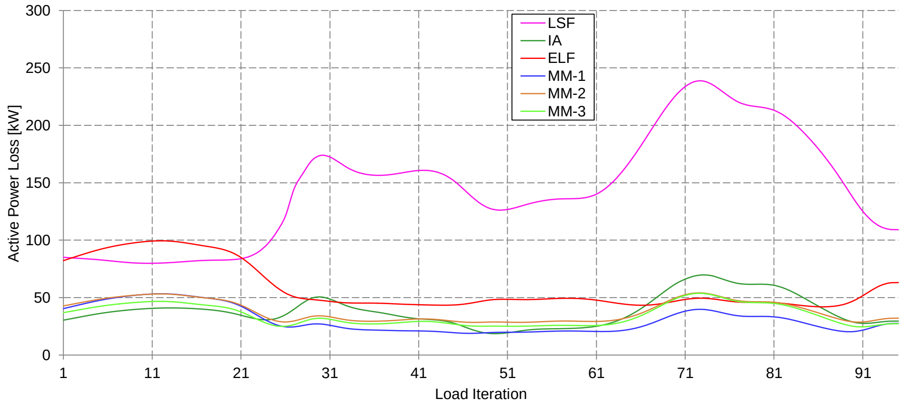


Figure 5.43: Active power loss with voltage control algorithm in 37 node network at operational power factor (use case 3a)

5.7.1.2 Voltage Profile and Quality Improvement

The voltage profiles for the 37 node network where the DGs are placed with different methods are given in the Figure 5.44 – 5.49. As a general comment, it can be seen from these figures that the voltage remained within the permissible range for all the methods except the LSF and IA methods. In LSF method, the voltage level decreased below the 0.94 p.u. at the load iteration 26 on the buses 23 and 24. Hence the CVCA tries to alter the reactive power output from the DG with highest sensitivity corresponding to these buses and brings the voltage level back to the allowed level. This variation of reactive power from the DG influences the voltage at other nodes too, resulting in the increase in voltage at other regions of the network. After further increase in the load, the voltage problem at same nodes appear again, but as the maximum reactive power limit has already been exhausted from the DGs, the CVCA cannot improve the voltage further. For DGs placed with IA method, the voltage at the same two buses decreased below the 0.94 p.u. however this happened at higher load level *i.e.*, at load iteration number 69. Also, the CVCA could improve the voltage back to the permissible limit without fully exhausting the reactive power limit of all DGs. This consequently means that the IA method is better than the LSF in terms of the creating voltage stability in the network.

For all the other methods, the optimal locations and sizes of the DGs are set in such a way that the voltage problem did not appear. Based on this, it can be concluded that these methods of DG placement are comparatively better, not only for loss minimization but also for the voltage stability and better voltage profile.

The impact of the voltage profile is also be presented in form of VQI. In the Figure 5.50, slight increase in VQI value is clearly observed at the load iteration instances where the CVCA attempts to correct the voltage problem for LSF and IA methods, marked by the arrows in the figure. As the voltage was not fully corrected in case of LSF method, only slight variation in the VQI value is observed. On the other hand, the voltage correction was complete in IA method, the improvement in VQI values is also very clear. For the other methods, the VQI remains similar to the use case 2a as no change of active or reactive power output from DGs is required.

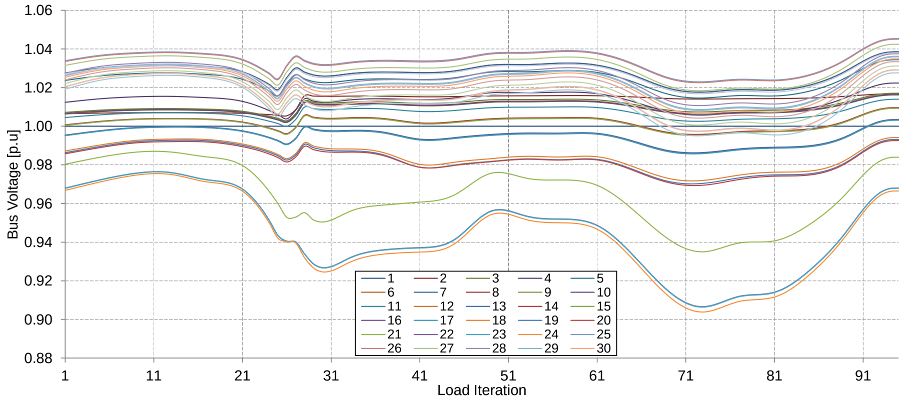


Figure 5.44: Voltage profile when DGs are placed according to LSF method in 37 node network with voltage control algorithm at operational power factor (use case 3a)

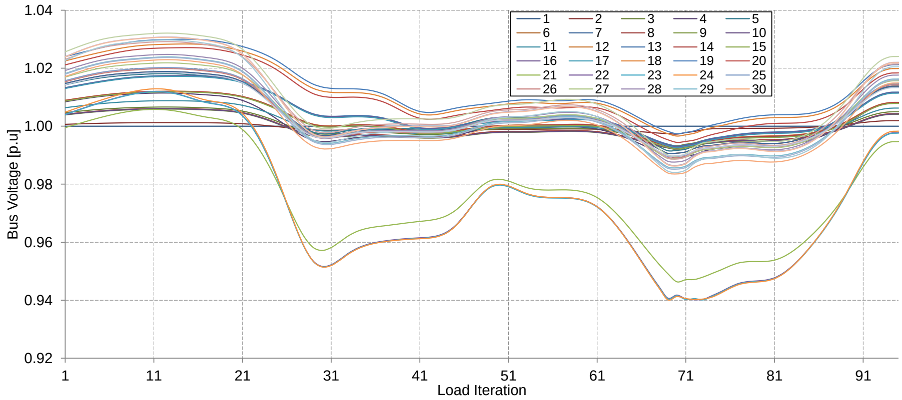


Figure 5.45: Voltage profile when DGs are placed according to IA method in 37 node network with voltage control algorithm at operational power factor (use case 3a)

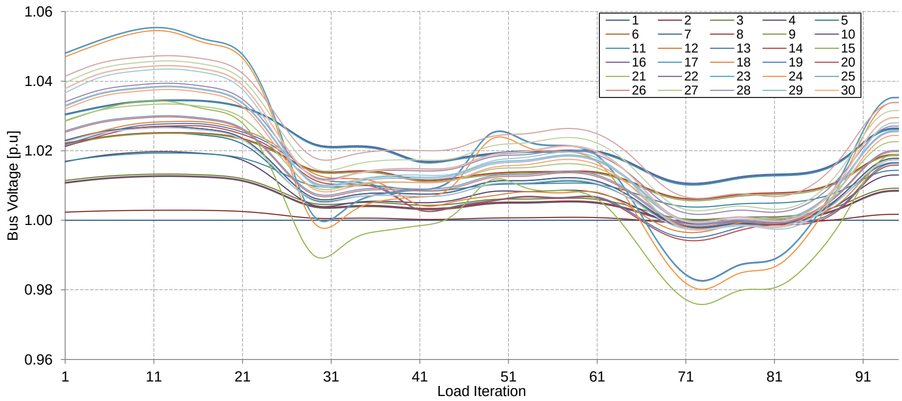


Figure 5.46: Voltage profile when DGs are placed according to ELF method in 37 node network with voltage control algorithm at operational power factor (use case 3a)

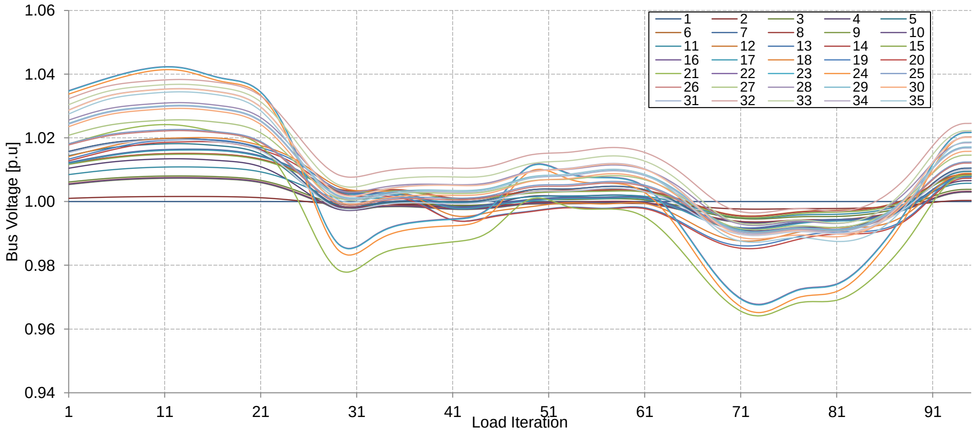


Figure 5.47: Voltage profile when DGs are placed according to MM-1 method in 37 node network with voltage control algorithm at operational power factor (use case 3a)

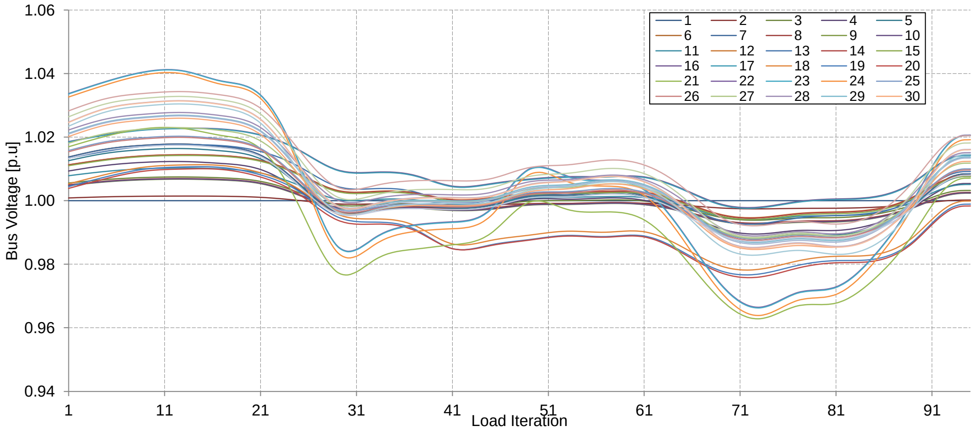


Figure 5.48: Voltage profile when DGs are placed according to MM-2 method in 37 node network with voltage control algorithm at operational power factor (use case 3a)

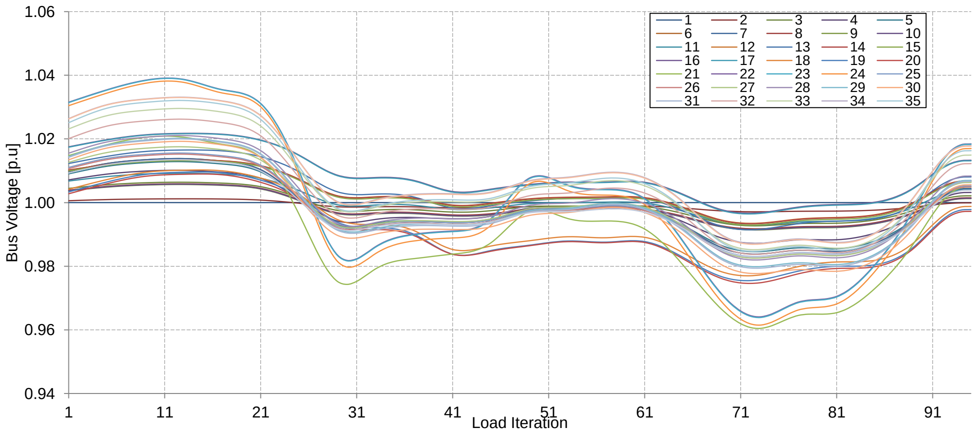


Figure 5.49: Voltage profile when DGs are placed according to MM-3 method in 37 node network with voltage control algorithm at operational power factor (use case 3a)

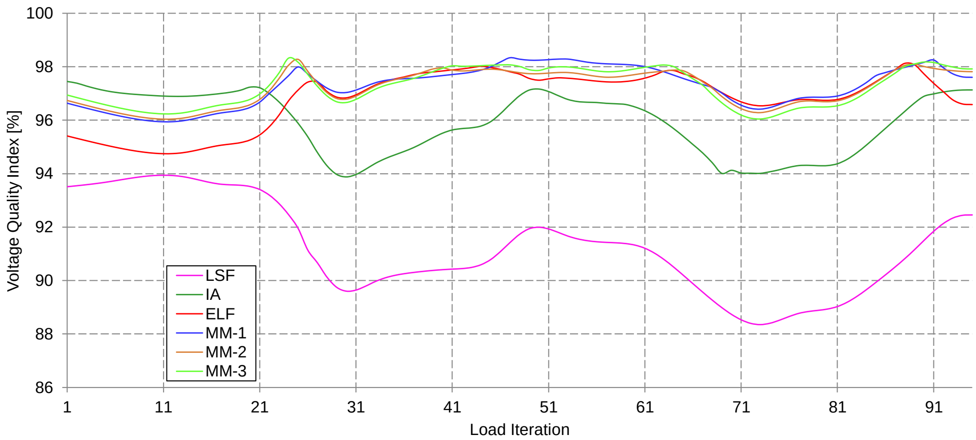


Figure 5.50: Voltage quality index with voltage control algorithm in 37 node network at operational power factor (use case 3a)

5.7.2 Use Case 3b: 119 Node System – Results

5.7.2.1 Power Loss Minimization Results

Figure 5.51 presents the results for active power loss for 119 node system with operational power factor. As mentioned in discussion of previous use cases, that the 119 node system is complex as compared to 37 node system, it appears to be difficult to mitigate the voltage problem by only adjusting the reactive power output of the DGs. The amount of reactive power that can be supplied by the DGs is much less than the required amount. Moreover, the number of DGs is also very few, resulting in the very low voltage sensitivity of the buses with DG with respect to the buses where the voltage problem is appearing. On such grounds, it has been observed with consistency that the voltage problem in this use case cannot be completely rectified. However, the reactive power output is changed within the limits defined by the minimum power factor. Such variation of reactive power produced some variation in the losses, as shown in this figure. Despite such opposing factors, it is an important observation from these results that MM – 2 and MM – 3 produced the least amount of active power losses.

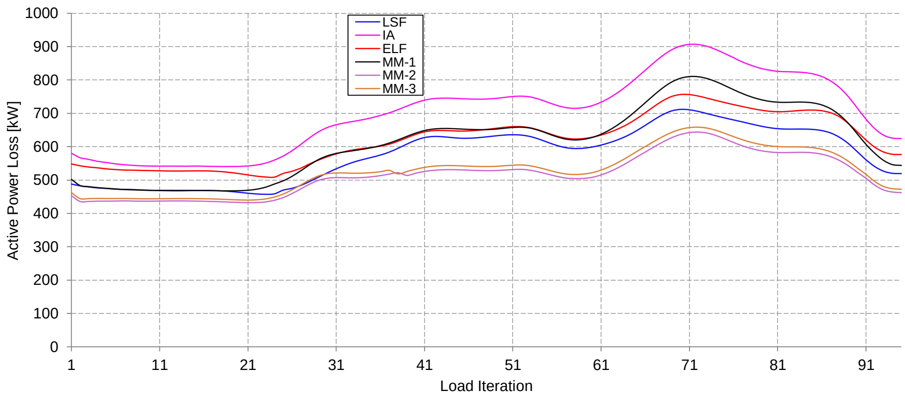


Figure 5.51: Active power loss with Voltage Control Algorithm in 119 node network at operational power factor (use case 3b)

5.7.2.2 Voltage Profile and Quality Improvement

To clearly show the impact of CVCA, the voltage profiles for the 119 node network are given in Figure 5.52 – 5.57. The node 23 – 27 have been identified as the nodes with lowest voltage level and the voltage level at 118 bus is detected to be the highest. Despite this fact, the MM – 2 and MM – 3 methods are proved to be the best in terms of controlling the voltage and keeping it within the limits for the maximum number of load iteration (which correspond to the higher load level too). For DG placement with both these methods, the voltage is reduced below the 0.94 p.u. level only after about 63 load iterations whereas for all other methods, the voltage level is below the lower bound after 23 load iterations. Moreover, for none of the methods, the voltage could be more than 1.06 p.u. on any of the nodes.

In the system without CVCA (use case 2b), the maximum voltage of 1.2 p.u. was observed which has been controlled and taken down to the permissible range. This highlights the usefulness and proficiency of the CVCA. As a consequence of limiting the voltage within the upper bound, the VQI is improved significantly and can be seen from Figure 5.58. For all the methods, the voltage quality is improved by about 1 or more percent. Also, the VQI for MM – 2 and MM – 3 cases is considerably higher than those of the other methods. In VQI curves, sharp variation in the voltage quality at the point where the CVCA takes corrective actions can be observed. This means that the changes in the network voltage, due to any means and reasons, is directly translated into the VQI value, highlighting the significance as well as the usefulness of this index.

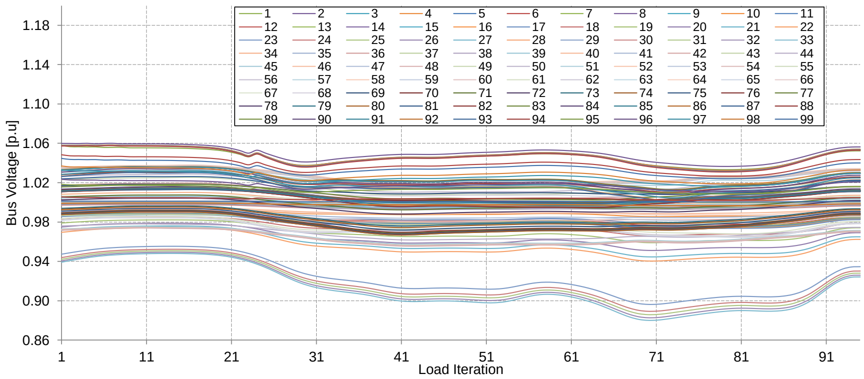


Figure 5.52: Voltage profile when DGs are placed according to LSF method in 119 node network with voltage control algorithm at operational power factor (use case 3b)

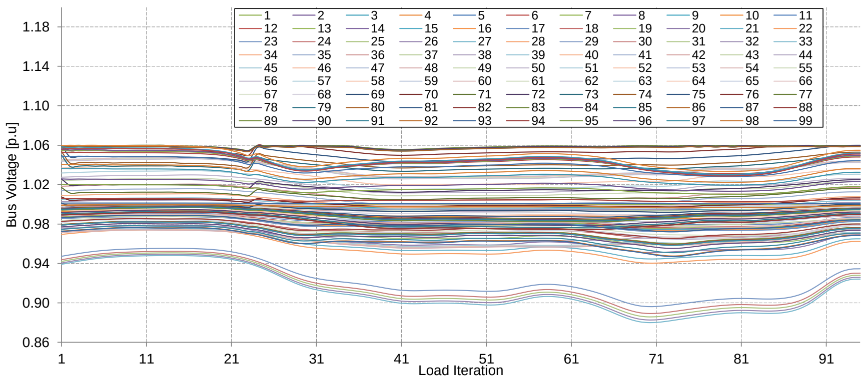


Figure 5.53: Voltage profile when DGs are placed according to IA method in 119 node network with voltage control algorithm at operational power factor (use case 3b)

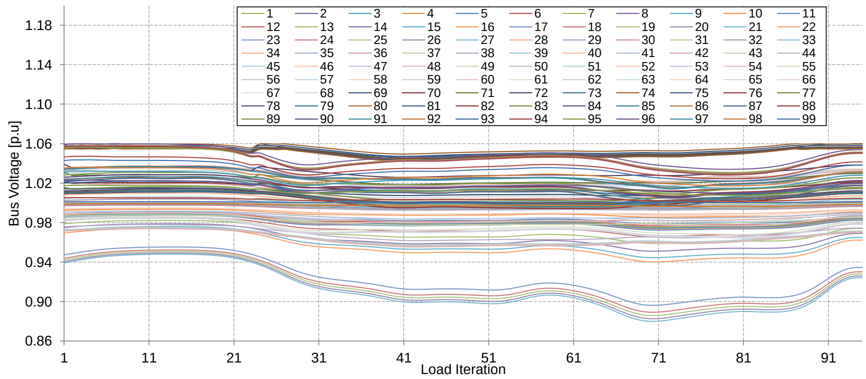


Figure 5.54: Voltage profile when DGs are placed according to ELF method in 119 node network with voltage control algorithm at operational power factor (use case 3b)

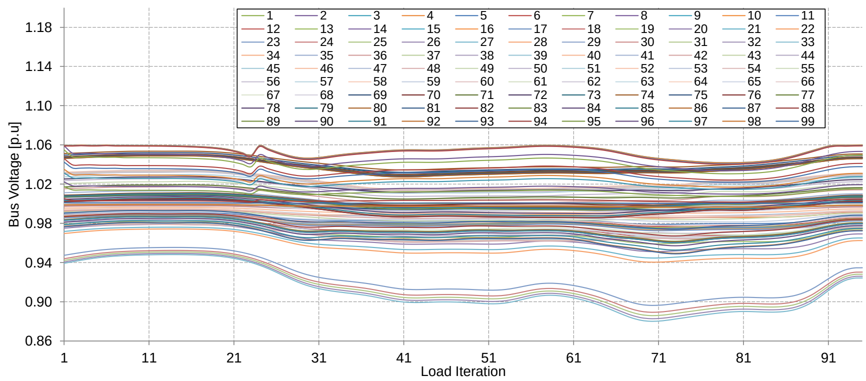


Figure 5.55: Voltage profile when DGs are placed according to MM – 1 method in 119 node network with voltage control algorithm at operational power factor (use case 3b)

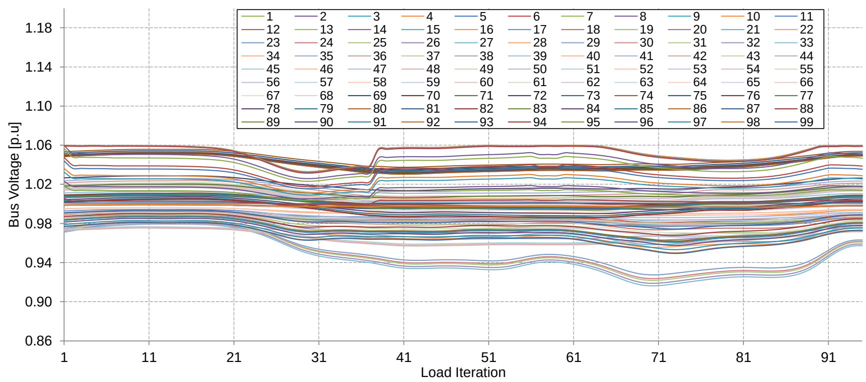


Figure 5.56: Voltage profile when DGs are placed according to MM – 2 method in 119 node network with voltage control algorithm at operational power factor (use case 3b)

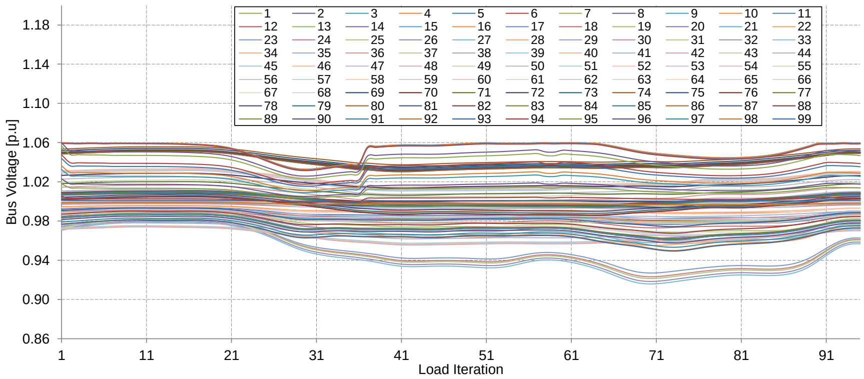


Figure 5.57: Voltage profile when DGs are placed according to MM − 3 method in 119 node network with voltage control algorithm at operational power factor (use case 3b)

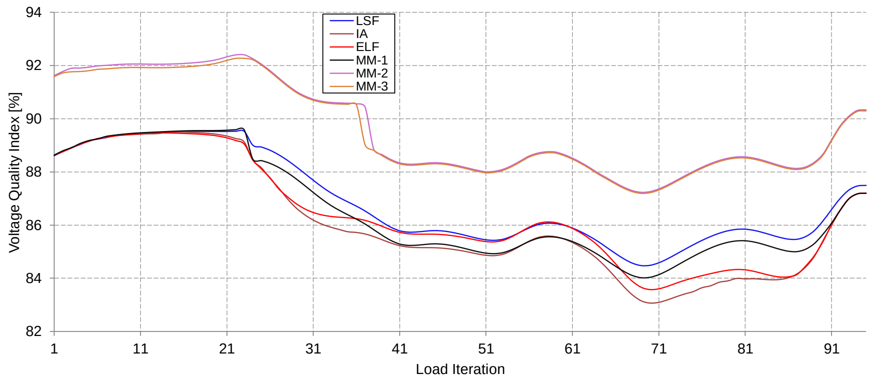


Figure 5.58: Voltage quality index with voltage control algorithm in 119 node network at operational power factor (use case 3b)

6 Conclusion and Future Recommendations

6.1 Conclusion

Over the period of last two decades, the electrical power system has been reshaped to incorporate many different systems which have never been the part of it, nor the system is originally designed to include such systems and parts. Generation of electricity by many different means which were not used in early era of modern power system also contributed significantly in reshaping of the power system. In recent years, the generation of electricity is preferred to be done near the load centers in order to reduce the transmission overhead as well as reducing the cost and time needed to install bulk generation power plants. Such power plants are installed at distribution system level, hence termed as “Distributed Generator (DG)”. As a result of this whole process, certain advantages are aimed at, such as reducing the environmental pollution, reducing the dependence on the conventional technologies and fuels used for power generation, increasing the system reliability and performance, reducing the network losses, managing the congestion in the electrical network and increasing its hosting (of more generation facilities) capacity, and many other of such benefits.

Despite the fact that the environmental and reliability related concerns are the major drivers behind this paradigm shift in the power system, there have been several other issues observed in the modern power system. The motivational drivers set by many different governments and bodies around the globe have remarkably increased the number of distributed energy resources, mostly in the form of DGs. As a result of this continuously increasing penetration of DGs, the modern power system is now facing many new challenges which either never existed before or were of minimal importance and impact. Ever increasing power demand also contributed in increasing the number and severity of the challenges being faced by the power system of today. For instance, the power system with bulk generation had almost no chances of reverse power flow. However, with increased amount and number of generation at the distribution level, reverse power flow, reduced hosting capacity, increased congestion and over voltage are only few among the many challenges being faced.

In order to cope with the situation posed by such rapid and vital changes in the modern power system, it becomes compulsory to address them timely and in due detail so that the power system of tomorrow should be more efficient, reliable and improved. If the nature of the problems occurring due to the DGs is seen in detail, the improper placement of DGs appears to be an important and significant reason behind all these. In the literature available so far, it has been focused very thoroughly and with detailed reasoning that the optimal placement of DGs can help in reducing the network losses, thereby improving the hosting capacity and managing the congestion along with improving the voltage quality being supplied to the consumers. However, optimal DG placement is always considered as a theoretical problem because of the limitations of the available methods. The available methods mostly consider the problem from the perspective of a Distribution Network Operator (DNO) who does not have enough control to steer the direction of DG placement due to existing regulatory bindings applied in most parts of the world. Subsequently, it appears that such studies do not offer enough reasons to be implemented in practical networks. However, there have been several references available, where the needs of optimal DG placement and making/updating the regulations in order to provide a DNO with certain level of control to steer the direction of DG placement are thoroughly discussed and asserted. It is important to mention that the literature available for solving the optimal DG placement problem ignores or does not care completely for the practical network scenarios. For example, nearly all the studies consider the optimal location selection and optimal size calculation as single problem, with closed problem formulation, leading to very limited or even no possibility of including any of the extra objectives or factors. Considering the practical scenario, one of these two objectives (location and size) may not be available for optimization or it may be desired to formulated that specific part differently by including different variables. For instance, in some cases, the DG sizes cannot be fixed whereas some DG investors may require to install at certain fixed location(s).

The presented work tries to argument in favor of such voices (which ask for giving certain level of control to DNOs) by proposing a method where the idealistic assumptions should be minimized to make the solution practically implementable. Also, the method of location and the size selection must not be rigid and hard-coded. Rather it should be flexible in order to provide different stakeholders of the modern power system with a chance to easily conciliate at certain point. In this regards, it is important to place the DGs at the locations where they are highly needed *i.e.*, near the load centers. This is due to the fact that the generated power should be locally consumed, which helps definitely to reduce the transmission as well as distribution overhead and losses, leading to help in the congestion management. Moreover, it is observed that the network regions where the load concentration is higher, the (low) voltage problem becomes prominent. Therefore, placing DGs near the load centers is also helpful in reducing such problems due to either providing local active power or a chance of voltage control by reactive power variation. These factors are summed up in the form of a "Load Concentration Factor (LCF)", which prioritize the locations/nodes in the system for placing the DG(s). In this work, the selection of location with LCF has been proved significantly better or, at least, comparable to the other high quality contemporary methods available in literature.

Despite such logically valid and sound reasons, such methods of selecting DG locations might not be acceptable for the owners/investors in DGs because their aim in investing capital is to increase their profit, which is function of availability of primary energy and cost of land available along with many other factors. As the wind and solar energy profiles or any other types of primary energy resources are not the subject of the presented study, the geographically optimal (to increasing the usability of primary energy and hence the profit of the DG owners) is also taken as a factor. This factor is included to provide a chance of considering non-conventional factors as well as an example of combining them to get final locations. It is worth mentioning the method of selecting the location for DGs is flexible, so as many factors as desired can be formulated and mixed with the proposed factors of location selection. By keeping the location selection method open for incorporating as many factors as desired, it becomes easy for the DNOs, the investors in DGs and the regulatory bodies to come up with factors of their desired variable, mix them with each other and conclude a set of locations which are acceptable for all the players. It is expected that with such efforts, the presented study is a leap forward toward the practical usability of optimal DG placement studies. In this way, the proposed method differs and, in fact, supersedes the existing studies related to this topic.

On the other hand, the optimal size selection is the problem, which is not under the control of any of the players in the system due to many factors. Few among them are:

- In case of high renewable primary energy, limiting the DG sizes may not be environmentally friendly.
- Optimal size found by any method may not be available in the DGs manufactured.
- The land available for installing the DG may not comply with the amount of land required to install the DG of proposed size.

Although an analytical method for simultaneously calculating the optimal DG sizes of multiple DGs is presented in this work, the final algorithm also includes a stage where the DG sizes can be checked in the vicinity of the calculated sizes. This helps in ensuring any further reduction in the active power losses, thereby further increasing the hosting capacity of the network and managing the network congestion. With such a feature, the final algorithm proposed in this work can be considered open for taking any sizes other than the one calculated with the proposed method.

Along with proposing the methods for optimal location and size calculations, the role of selecting a suitable power factor for operation of a DG is also presented. By operating at different power factors, it is shown that at operational power factor, the network losses are further reduced with similar location and active power output from DGs. Also, it is shown with the help of presented results that the voltage problems are considerably lower by operating the DGs at operational power factor. Moreover, in some networks, the DGs are placed at such locations with such sizes that they cannot help in reducing the voltage problems, if there occurs any due to any reason(s), *e.g.*, the load variation. In such cases of any voltage problem in the network, a Centralized Voltage Control Algorithm (CVCA) is used in order to adjust reactive power output of the DGs with respect the voltage sensitivity of the node at which the voltage problem appeared. By use of CVCA in the networks where the DGs are placed with different methods (proposed and other available in literature), a comparison of the network's performance is also presented. Such analysis suggested that the proposed method of selecting optimal location and sizes of the DGs also helps in minimizing the chances of appearance of the voltage problem in comparison to the other methods under similar conditions. Moreover, in the network where the DGs are placed with the proposed method, it is easier to resolve the voltage problems if there appears any *i.e.*, with less of reactive power support from the DGs.

For the purpose of testing and validation of proposed methods, the experimental use cases are designed in such a way that optimization for a simple and brief system (with static loads) is done as use case 1. Then, for same networks taken in use case 1, the practical scenario with one day power demand profile is taken and the results are presented as use case 2. In this use case, the energy losses are also calculated and the Voltage Quality Index (VQI) is also computed. In final use case (3), the comparison of different methods of optimal DG placement is performed in terms of the reactive power support needed from optimally placed DGs in case of any voltage problem due to variation of load over the period of a day. In this use case, CVCA is applied and it is observed that the amount and frequency of appearing the voltage problem is significantly lower in the system with proposed method of optimal DG placement. These results are also explained in terms of VQI. The VQI for the optimal DG placement case with proposed method is higher in comparison to other comparative methods, which is further improved after the voltage problems are eliminated by the CVCA. By applying the proposed methods on the variety of the use cases, the usability, applicability and advantages of the proposed methods are highlighted.

Based on the discussion given until here, the major research targets are summarized as:

- To design a method of optimal DG placement which can be improved in future by incorporating as many factors as needed by different network players so that the method should not be treated as only theoretical.
- To develop an optimal DG placement method to benefit all the network players in terms of their own objectives.
- To justify the need of providing certain degree of control in steering the direction of DG penetration to the DNO.
- A suggestion for including unusual design variable *e.g.*, geographical factor is also given in order to make the proposed method a step nearer to the practically implementable.

These targets have been achieved by designing a novel methods which are open for working with any other methods and factors targeted to address the similar sort of problems. For instance, the proposed LCF can be combined with any other factor(s) for selecting optimal locations. Similarly, the method of sizes calculation is completely independent from the method of locations selection, leading to the possibility of installing any DG sizes at the locations found by proposed method. Hence, additions to the methods presented in this work are straightforward and can help in making optimal DG placement problem acceptable for implementation by all the players.

The summary of the proposed method is given as in Figure 6.1. This figure shows that if there is an electrical network given, along with the geographical information and number of DGs to be placed, the proposed method identifies the locations for placing DGs, their respective sizes and operation power factor in order to minimize the active power (and hence the energy) losses, improve the voltage profile and reactive power support of the system.

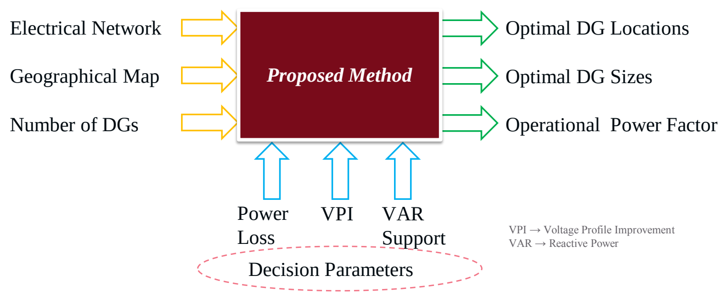


Figure 6.1: Outline of the proposed method

6.2 Directions for Future Extension

It has been repeatedly mentioned and discussed that the optimal placement of DGs appears to be only the theoretical study due to the fact that many factors which affect the planning of distribution system with DGs are usually ignored or not properly addressed. In order to make the optimal DG placement problem implementable in real world scenarios, a lot more needs to be done. However, it should be done by keeping in view a contribution made by this work *i.e.*, each part should be open for independent incorporation of as many factors as needed over the period of time. This means that the *method* should adopt the plug and play type of strategy so that it can be easily be combined/mixed with existing method(s) to make them more and more detailed and comprehensive, leading to increased chances of them to become practically implementable. For example, there should be some more factors like LCF for weather forecast, primary energy availability, some law related restrictions, any other regulatory requirement and other of such factors. Although the geographical factor is taken into account in this work, the detailed formulation is still needed so that the ideal assumptions should be minimized or, preferably, completely removed and the method steps forward toward the practical implementation.

While considering the improvement in sizes offered by the considered method, it is important to note that these sizes are only for the purpose of loss minimization. The analytical method is suggested for optimal size calculation in order to get more accurate results in comparatively less time with less computation burden. However, being the planning phase task, factors such as reducing the computation burden may not be vital. Therefore, it may be suggested for the future studies that the complete list of available DG sizes with all types and features should be summed up in the form of a database so that the sizes found by any method can be the only which are available by different DG manufacturers. This will help in making the optimal size calculation more practical. Moreover, better results can also be ensured if the sizes are not only calculated with respect to the minimization of the losses to the least possible level. In fact, size calculation should also be done according to the different factors such as size of land available in certain region for installation of DG, the amount and nature of the primary energy available, and the type of DG to be installed for not only fulfilling the energy needs but also to improve network's performance in terms of technical as well as economical factors.

It should also be noted that the optimization of power factor is an important factor which is neglected in most of the existing studies. Two networks considered in this network have different reactive power demands, leading to very different loss reduction ratios, voltage profile improvements and voltage quality indexes. The values of operational power factors for both these networks differ a lot. Such a comparison enlightens the need of careful selection of the power factor from the DGs. In this work, only single power factor for all the DGs has been considered but different power factors from DGs, according to the reactive power demand in their vicinity may also produce some interesting results. It is suggested for future studies to develop some method with which the power factor from all the DGs may not be kept constant but according to their own specific requirements. Another important point in the discussion of power factor is that there is a move to fix the range for the power factor from DGs irrespective of the networks' demand of reactive power and its very nature. Such an approach may lead to increased losses, high network congestion and reduced hosting capacity along with the voltage problems. This can be justified from the results and discussion in use case 2b and 3b, where the voltage level was above the upper bound with poor VQI values, which is then controlled by proposed CVCA algorithm and the VQI values are improved.

The voltage quality index proposed in this work is a useful index. It provide very clear, simple and straightforward method of identifying the voltage status of the system. Its usefulness becomes more prominent in the systems with many number of nodes and for larger set of load and/or other variations. The impact of any changes, whether due to load variation or due to any other factors, can be seen just as a look up table without much difficulty. Such indexes for other system parameters and variable can also be formulated in order to get clearer insight into the systems' performance and status. An important impact of such factors is the amount of ease they provide when comparing two or more systems or methods which differ in size, complexity, amount of load and other parameters. The discrete nature of information provided by these indexes is helpful in quantifying the systems' performance. Moreover, justifying certain steps taken by some system player(s) for system performance improvements becomes easier due to quantifiable results of such factors. Based on these and many other such reasons, it can be good move to formulate such indexes for quantification of other system variables.

The amount of power being flowing into the external grid is also important because excessive reverse flow can put adverse impact on the system performance if not handled properly. Therefore, the reverse power flow should also be taken into account for the studies related to planning of power system with DGs. Moreover, the impact of connecting the DGs in a network which is connected together with some other network(s) should also be studied, because in such case excessive power may also travel to the neighboring network(s). Hence, the performance of that may also be affected in terms of voltage profile, losses, line flows and other such variables. Scaling this scenario to completed grid, with transmission as well as the other distribution and connected grids may also be useful, however, it become more cumbersome to deal with such a big network. Yet, the importance to different indexes, as discussed above, may become more prominent in bigger and complex systems.

To sum up, it is an ongoing study, which can be enhanced and increased to any level, in order to make it nearer to the real world scenario. It can also be helpful in providing guidelines for the different players of the modern power systems, especially for the regulatory bodies by arguing in favor of proper planning of DG placement problem instead of current "fit and forget" and "popping up like mushrooms" approach. The optimal number of DGs is also important. If there is no control over the type, number and amount of energy being provided by the DGs, future power system may face serious quality issues. Moreover, excessive energy generation may lead to very low, or even negative, energy prices which is good for the energy consumers but may reduce the interest of investors in this sector. Therefore, some balance needs to be maintained in order to continue the flourishing of green energy initiatives.

Appendix

IEEE 37 Node System Data

Branch Number	Branch Rc. Nd.	Branch Sn. Nd.	Branch Impedance r (Ω)	Branch Impedance x (Ω)	Loads PL (kW)	Loads QL (kVar)
1	0	1	0	0	0	0
2	3	2	0.08374	0.05238	630	315
3	4	3	0.11514	0.07201	0	0
4	8	3	0.15372	0.05697	0	0
5	11	3	0.08548	0.04432	0	0
6	5	4	0.14244	0.07385	0	0
7	6	5	0.04753	0.02464	85	40
8	8	9	0.09198	0.03409	85	40
9	8	10	0.12222	0.04530	85	40
10	12	11	0.12343	0.06399	85	40
11	13	12	0.18935	0.09817	0	0
12	16	13	0.14026	0.07272	85	40
13	12	14	0.03024	0.01121	38	18
14	14	15	0.19908	0.07379	85	40
15	16	17	0.10710	0.03970	42	21
16	13	18	0.35280	0.13076	0	0
17	18	19	0.04662	0.01728	161	80
18	18	20	0.28980	0.10741	42	21
19	4	21	0.92106	0.34138	42	21
20	21	22	0.66232	0.34340	42	21
21	22	23	0.10710	0.03970	42	21
22	22	24	0.07686	0.02849	126	63
23	6	25	0.07636	0.03959	0	0
24	27	25	0.07636	0.03959	0	0
25	25	26	0.12348	0.04577	42	21
26	28	27	0.13246	0.06868	85	40
27	29	28	0.19908	0.07379	0	0
28	32	28	0.15194	0.07878	42	21
29	29	30	0.49140	0.18213	42	21
30	29	31	0.07686	0.02849	85	40

(continued)

Branch Number	Branch Rc. Nd.	Branch Sn. Nd.	Branch Impedance R (Ω)	Branch Impedance X (Ω)	Connected Load PL (kW)	Connected Load QL(kVar)
31	33	32	0.09350	0.04848	140	70
32	34	33	0.09350	0.04848	126	62
33	34	35	0.07686	0.02849	85	40
34	34	36	0.09350	0.04848	42	21
35	6	37	0.14026	0.07272	85	40

IEEE 119 Node System Data

Branch	Branch		Branch Impedance		Connected Load	
Number	Rc. Nd.	Sn. Nd.	R (Ω)	X (Ω)	PL (kW)	QL(kVar)
1	0	1	0	0	0	0
2	1	2	0.036	0.01296	133.84	101.14
3	2	3	0.033	0.01188	16.214	11.292
4	2	4	0.045	0.0162	34.315	21.845
5	4	5	0.015	0.054	73.016	63.602
6	5	6	0.015	0.054	144.2	68.604
7	6	7	0.015	0.0125	104.47	61.725
8	7	8	0.018	0.014	28.547	11.503
9	8	9	0.021	0.063	87.56	51.073
10	2	10	0.166	0.1344	198.2	106.77
11	10	11	0.112	0.0789	146.8	75.995
12	11	12	0.187	0.313	26.04	18.687
13	12	13	0.142	0.1512	52.1	23.22
14	13	14	0.18	0.118	141.9	117.5
15	14	15	0.15	0.045	21.87	28.79
16	15	16	0.16	0.18	33.37	26.45
17	16	17	0.157	0.171	32.43	25.23
18	11	18	0.218	0.285	20.234	11.906
19	18	19	0.118	0.185	156.94	78.523
20	19	20	0.16	0.196	546.29	351.4
21	20	21	0.12	0.189	180.31	164.2
22	21	22	0.12	0.0789	93.167	54.594
23	22	23	1.41	0.723	85.18	39.65
24	23	24	0.293	0.1348	168.1	95.178
25	24	25	0.133	0.104	125.11	150.22
26	25	26	0.178	0.134	16.03	24.62
27	26	27	0.178	0.134	26.03	24.62
28	4	29	0.015	0.0296	594.56	522.62
29	29	30	0.012	0.0276	120.62	59.117
30	30	31	0.12	0.2766	102.38	99.554
31	31	32	0.21	0.243	513.4	318.5
32	32	33	0.12	0.054	475.25	456.14
33	33	34	0.178	0.234	151.43	136.79
34	34	35	0.178	0.234	205.38	83.302
35	35	36	0.154	0.162	131.6	93.082
36	31	37	0.187	0.261	448.4	369.79
37	37	38	0.133	0.099	440.52	321.64
38	30	40	0.33	0.194	112.54	55.134
39	40	41	0.31	0.194	53.963	38.998
40	41	42	0.13	0.194	393.05	342.6
41	42	43	0.28	0.15	326.74	278.56
42	43	44	1.18	0.85	536.26	240.24
43	44	45	0.42	0.2436	76.247	66.562

(continued)

Branch Number	Branch Rc. Nd.	Sn. Nd.	Branch Impedance R (Ω)	X (Ω)	Connected Load PL (kW)	QL(kVar)
44	45	46	0.27	0.0972	53.52	39.76
45	46	47	0.339	0.1221	40.328	31.964
46	47	48	0.27	0.1779	39.653	20.758
47	36	49	0.21	0.1383	66.195	42.361
48	49	50	0.12	0.0789	73.904	51.653
49	50	51	0.15	0.0987	114.77	57.965
50	51	52	0.15	0.0987	918.37	1205.1
51	52	53	0.24	0.1581	210.3	146.66
52	53	54	0.12	0.0789	66.68	56.608
53	54	55	0.405	0.1458	42.207	40.184
54	55	56	0.405	0.1458	433.74	283.41
55	30	58	0.391	0.141	62.1	26.86
56	58	59	0.406	0.1461	92.46	88.38
57	59	60	0.406	0.1461	85.188	55.436
58	60	61	0.706	0.5461	345.3	332.4
59	61	62	0.338	0.1218	22.5	16.83
60	62	63	0.338	0.1218	80.551	49.156
61	63	64	0.207	0.0747	95.86	90.758
62	64	65	0.247	0.8922	62.92	47.7
63	1	66	0.028	0.0418	478.8	463.74
64	66	67	0.117	0.2016	120.94	52.006
65	67	68	0.255	0.0918	139.11	100.34
66	68	69	0.21	0.0759	391.78	193.5
67	69	70	0.383	0.138	27.741	26.713
68	70	71	0.504	0.3303	52.814	25.257
69	71	72	0.406	0.1461	66.89	38.713
70	72	73	0.962	0.761	467.5	395.14
71	73	74	0.165	0.06	594.85	239.74
72	74	75	0.303	0.1092	132.5	84.363
73	75	76	0.303	0.1092	52.699	22.482
74	76	77	0.206	0.144	869.79	614.775
75	77	78	0.233	0.084	31.349	29.817
76	78	79	0.591	0.1773	192.39	122.43
77	79	80	0.126	0.0453	65.75	45.37
78	67	81	0.559	0.3687	238.15	223.22
79	81	82	0.186	0.1227	294.55	162.47
80	82	83	0.186	0.1227	485.57	437.92
81	83	84	0.26	0.139	243.53	183.03
82	84	85	0.154	0.148	243.53	183.03
83	85	86	0.23	0.128	134.25	119.29
84	86	87	0.252	0.106	22.71	27.96
85	87	88	0.18	0.148	49.513	26.515
86	82	89	0.16	0.182	383.78	257.16

(continued)

Branch Number	Branch Rc. Nd.	Sn. Nd.	Branch Impedance R (Ω)	X (Ω)	Connected Load PL (kW)	QL(kVar)
87	89	90	0.2	0.23	49.64	20.6
88	90	91	0.16	0.393	22.473	11.806
89	68	93	0.669	0.2412	62.93	42.96
90	93	94	0.266	0.1227	30.67	34.93
91	94	95	0.266	0.1227	62.53	66.79
92	95	96	0.266	0.1227	114.57	81.748
93	96	97	0.266	0.1227	81.292	66.526
94	97	98	0.233	0.115	31.733	15.96
95	98	99	0.496	0.138	33.32	60.48
96	95	100	0.196	0.18	531.28	224.85
97	100	101	0.196	0.18	507.03	367.42
98	101	102	0.1866	0.122	26.39	11.7
99	102	103	0.0746	0.318	45.99	30.392
100	1	105	0.0625	0.0265	100.66	47.572
101	105	106	0.1501	0.234	456.48	350.3
102	106	107	0.1347	0.0888	522.56	449.29
103	107	108	0.2307	0.1203	408.43	168.46
104	108	109	0.447	0.1608	141.48	134.25
105	109	110	0.1632	0.0588	104.43	66.024
106	110	111	0.33	0.099	96.793	83.647
107	111	112	0.156	0.0561	493.92	419.34
108	112	113	0.3819	0.1374	225.38	135.88
109	113	114	0.1626	0.0585	509.21	387.21
110	114	115	0.3819	0.1374	188.5	173.46
111	115	116	0.2445	0.0879	918.03	898.55
112	115	117	0.2088	0.0753	305.08	215.37
113	117	118	0.2301	0.0828	54.38	40.97
114	105	28	0.6102	0.2196	211.14	192.9
115	28	39	0.1866	0.127	67.009	53.336
116	39	57	0.3732	0.246	162.07	90.321
117	57	92	0.405	0.367	48.785	29.156
118	92	104	0.489	0.438	33.9	18.98

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Curriculum Vitae

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Education

Since 2013	Doctoral student at Faculty of Electrical Engineering and Information Technology, Technische Universität Wien, Vienna, Austria, supervised by Prof. Wolfgang Gawlik.
2008 – 2009	M.Sc. (Eng.) Avionic Systems at The University of Sheffield, Sheffield, United Kingdom.
2003 – 2006	B.E. Industrial Electronics Engineering at Institute of Industrial Electronics Engineering, N.E.D University of Engineering and Technology, Karachi, Pakistan.

Professional History

Since 2013	PhD Student at Complex Energy Systems, Energy Department, Austrian Institute of Technology GmbH, Vienna, Austria.
2010 – 2013	Lecturer at Department of Electrical Engineering, COMSATS Institute of Information Technology (CIIT) , Abbottabad, Pakistan.
2007 – 2008	Lecturer at Department of Electrical Engineering, COMSATS Institute of Information Technology , Abbottabad, Pakistan.
2007	Trainee Engineering at Al-Badeey Technologies, Karachi, Pakistan.
2005	Internee Engineer at Bestway Cement (Pvt) Limited, Haripur, Pakistan.

Journal Articles

- M. Shahzad, I. Ahmad, W. Gawlik, and P. Palensky, "Load concentration factor based analytical method for optimal placement of multiple distribution generators for loss minimization and voltage profile improvement," *Energies*, vol. 9, no. 4, p. 287, 2016.
- H. Ali, I. Ullah, M. Irfan, M. Shahzad, M. Aftab, "Genetic Algorithm Based PID tuning for Controlling Paraplegic Humanoid Walking Movement," in *International Journal of Computer Science Issues*, vol. 9, no. , pp. 275–285, 2012.
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- M. Shahzad, I. Ahmad, W. Gawlik and P. Palensky, "Voltage profile improvement in radial distribution networks with analytical method of simultaneous optimal DG sizing," in *2016 18th Mediterranean Electrotechnical Conference (MELECON)*, pp. 1–6, 2016.
- M. Shahzad, I. Ahmad, W. Gawlik and P. Palensky, "Active power loss minimization in radial distribution networks with analytical method of simultaneous optimal DG sizing," in *2016 IEEE International Conference on Industrial Technology (ICIT)*, pp. 470–475, 2016.
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- I. Ahmad, J. Kazmi, M. Shahzad, P. Palensky, and W. Gawlik, "Cosimulation framework based on power system, AI and communication tools for evaluating smart grid applications," in *Smart Grid Technologies-Asia (ISGT ASIA), 2015 IEEE Innovative*, pp. 1–6, 2015
- M. Shahzad, A. Latif, P. Palensky, and W. Gawlik, "An alternate PowerFactory Matlab coupling approach," in *Smart Electric Distribution Systems and Technologies (EDST), 2015 International Symposium on*, pp. 486–491, 2015.
- I. Ahmad, M. Shahzad, and P. Palensky, "Optimal PID Control of Magnetic Levitation System Using Genetic Algorithm," in *Energy Conference (ENERGYCON), 2014 IEEE International on*, pp. 1429–1433, 2014.
- M. Shahzad, I. Ullah, P. Palensky, and W. Gawlik, "Analytical approach for simultaneous optimal sizing and placement of multiple distributed generators in primary distribution networks," in *2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE)*, pp. 2554–2559, 2014.
- S. Khan, M. Shahzad, P. Palensky, and K. Jahangir, "Dynamics of wind-turbine driven Self-Excited Induction Generator with online parameter calculation," in *39th Annual Conference of the Industrial Electronics Society, IEEE, IECON 2013*, vol., no., pp.5271-5275, 2013.

- M. Jamil, S. P. Shaikh, M. Shahzad, and Q. Awais, “4G: The future mobile technology,” in *TENCON 2008-2008 IEEE Region 10 Conference*, pp. 1–6, 2008.

Engineering Tools and Programming Skills

- MATLAB (Command line, Simulink)
- DIgSILENT PowerFactory (Comprehensive Power Systems Simulation package)
- Power System Analysis Tool (PSAT)
- Programming Languages (Python, Assembly, Visual BASIC, C++)
- Programmable Logic Controllers (PLC) programming (Siemens and LG PLCs)
- National Instruments Multisim (Electronic Circuit simulation package)

Achievements

- Secured scholarship to pursue PhD studies from Vienna University of Technology, Austria.
- Conducted 3 days Professional Development Workshop on “Matlab based Power Engineering” under Pakistan Engineering Council.
- Won Scholarship for MSc Studies at University of Sheffield, United Kingdom.
- Developed state of the art Control Lab at Department of Electrical Engineering, CIIT, Abbottabad.
- Among Top Three Position holders in B.E. semester exams.

Professional Memberships

- Student Member Institute of Electrical and Electronics Engineers (IEEE), USA
- Registered Engineer (Pakistan Engineering Council)
