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PAU INSTITUTE FOR BASIC SCIENCES, TECHNOLOGY AND INNOVATION

# OPTIMAL PLACEMENT AND SIZING OF SOLAR PHOTOVOLTAIC SYSTEM IN RADIAL DISTRIBUTION NETWORK FOR ACTIVE POWER LOSS REDUCTION

BY

MADJISSEMBAYE Nanghoguina

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# DECLARATION

This thesis is my original work, and I am the sole author of this work. It has not been presented for a degree in any other university and all the previous works used in this work were properly referred in the provided reference list.

Signature ________________________ Date ________________

Name: Madjissembaye Nanghoguina

Reg. Num.: EE300-0011/15

This thesis report is submitted for examination with our approval as University Supervisors

Signature ______________________________ Date ________________

Dr Christopher Maina Muriithi

Signature ________________________ Date ________________

Dr Cyrus Wekesa Wabuge

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# ABSTRACT

The integration of Distributed Generation into electric power systems has considerably increased to meet the increasing load requirements and provide environmental benefits. More attention has been given to Solar Photovoltaic (SPV) energy in the last decade because SPV technology provides the most direct way to convert solar energy into electrical energy without carbon dioxide emissions, or greenhouse effects; it also provides reliable, clean, efficient and continuous source of electrical energy to consumers. Optimal placement of SPV in the radial distribution system considerably reduces the active power loss and also improves the voltage profile. However, a limited study has been carried out on this. Therefore, the analysis of the optimal placement of SPV becomes mandatory to maximise the benefits of the DG integration. In this thesis, strategically siting and sizing of the SPV for loss reduction in a radial distribution network (RDN) were studied with various loading cases and tested on a standard IEEE 33-bus test RDN system, while considering constraints on the power generation capacity and the voltage limits of the SPV penetration. The technique used the branch current loss formula to evaluate the power loss and the size of the DG to be placed to reduce the power loss. The initial total power loss of the system was evaluated through the load flow analysis using Backward/Forward sweep method. The total power loss with the DGs injected was subtracted from the total initial losses to get the total loss saving for each DG placed at each node and the candidate node with the highest power loss saving was identified for the optimal placement of the DG. Furthermore, the optimal DG size was evaluated using the branch current injected at the optimal node. Results obtained in this analysis show a power loss reduction of 49% and a voltage improvement from 0.9134 p.u to 0.9507 p.u when injecting the SPV of 2.4752 MW at node 6. Clearly, optimal placement and sizing of SPV leads to reduced power losses and improved voltage profile.

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# LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ABC | Artificial bee colony algorithm |
| BFO | Bacterial Foraging Optimization |
| BFSM | Backward/Forward Sweep method |
| CAIDI | Customer average interruption duration index |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| DG | Distributed Generation |
| ELF | Exhaustive Load Flow |
| FACTS | Flexible AC transmission systems |
| GA | Genetic Algorithm |
| IA | Improved Analytic method |
| LSF | Loss Sensitive Factor index |
| NOx | Nitrogen oxide |
| p.u | per unit |
| PCC | point of common coupling |
| PF | Power factor |
| PFDG | Distributed Generation Power Factor |
| PSO | Particle Swarm Optimization |
| PV | Photovoltaic |
| RDN | Radial Distribution Network |
| RES | Renewable Energy Sources |
| SAIDI | System Average Interruption duration index |
| SNE | Societe Nationale d’Electricite |
| $SO_2$ | Sulphur dioxide |
| SPV | Solar Photovoltaics |
| THD | Total Harmonic Distortion |
| TS | Tabu Search |

## NOMENCLATURE

| | |
|---|---|
| A | cross-sectional area ($m^2$) |
| $I_{ay}$, $I_{ry}$ | real and imaginary components of current at branch y (A) |
| $I_{DGk}$ | The active component of injected DG current (A) |
| $I_y$ | current magnitude in branch y (A) |
| kWh/m2/d | Kilowatthour per square meter per day |
| m/s | meter per second |
| $P_{DGk}$ | active power injected at node k (MW) |
| $P_{LDGk}$, $Q_{LDGk}$ | total active and reactive power loss with DG injected (KW and KVAr) |
| $P_{TL}$, $Q_{TL}$ | total active and reactive power loss of the system (KW and KVAr) |
| $P_y$, $Q_y$ | active and reactive power flowing in branch y (KW and KVAr) |
| Ry, Xy | Resistance and reactance of branch y (Ω) |
| Price/E | The US dollars per kilowatt-hour ($/kWh) |
| $SS_k$ | total saving with DG injected at node k (MW) |
| $V_y$ | voltage magnitude at node y (V) |
| $V_{ymax}$, $V_{ymin}$ | maximum and minimum voltage magnitude at node y (V) |

# CHAPTER ONE: INTRODUCTION

## 1.1 BACKGROUND

Electricity is an ingredient for the development of any nation, and it has become a crucial commodity while the fossil fuels which are sources of conventional energy supply for several centuries are limited or exhauting. The fossils have also contributed to the pollution of the environment by the emission of carbon dioxide ($CO_2$), methane ($CH_4$) and other greenhouse gases ($NO_x$ and $SO_2$) [1]. These gases are causing the earth's temperature to rise, and this increase in greenhouse gases emission will lead to even greater global warming during this century, at the same time to meet the fast growth of the electric power demands of the world needs. To continually satisfy the electric power loads and to reduce the environmental pollution, many countries have invested in the renewable energy sources (RES) such as Photovoltaic systems, wind turbines, geothermal, biomass and hydropower as they are considered clean and environment-friendly [1].

Distributed Generation (DG) is a small source of electric power generation in the range from less than a kW to several tens of MW, which is not located in the central power plants but it is connected along the distribution network or directly connected to the loads. DG can be renewable or non-renewable energy sources. The non-renewable energy sources comprise of the combustion turbines, steam turbine, micro-turbines and fuel cell using the natural gases or petrol while the renewable DG energy sources are solar, wind turbine, small-hydro, biomass and the geothermal. DGs penetration into the power system has increased in the last decades because of some advantages namely power losses reduction, power quality enhancement, voltage deviation improvement, power generation cost reduction, reducing Total Harmonic Distortion (THD), and increasing the efficiency, with less pollution. The DGs are modular systems; their planning and time required for installation are shorter than other centralised power plants. Furthermore, it is easy to implement them in remote areas to supply electricity without requiring long transmission and distribution lines [2-3].

The losses in radial distribution networks are considered to be the highest in the electric power networks due to load unbalances and the losses in the conductors as the current is flowing through them. These losses can affect the operating conditions of the power system and may even lead to voltage collapse, thus the power blackout or the frequency instability which may destroy the users' equipment. The integration of DGs in the distribution systems enhances the power reliability by reducing the power losses if properly located in the system, the study of DGs allocation in the distribution networks becomes necessary as the penetration of DGs is increased in the power systems to achieve all the benefits above and also to mitigate the power loss and voltage profile challenges in the grid.

This research is an approach applied to standard radial distribution networks, to address the actual problem of electrification of Chad Republic, a country located in central Africa, with the mass land of 1,284,000 square kilometres, a distance of 2000 kilometres from South to the North; 1000 kilometres from East to West and a population of about 12 million people. The country is landlocked, and the total percentage of electrification is about 4% which consists of 80% electric power consumption in the capital city, the electric power source is exclusively thermal. The National Society of Electricity (SNE) which has a total integrated monopoly over electricity market, has a capacity less than 200MW of production.

The cost of electricity is very high despite the low income of an average Chadian; the electric bill is 0.15$/KWh for the consumption below 150KWh and 0.21$/KWh above 150KWh [32]. Apart from the cost, the reliability of the power supply is very low, and few people have access to this basic commodity considered to be sole of the development in the present era. The country has a good potential in the renewable energy especially the solar energy all over the country because it is located in the sub-Sahara. The research has shown that from South to North, the solar intensity varies between 4.5 to 6.5KWh/m2/d, a wind speed lies between 2.5 to 5m/s from South to North and a good potential of biomass in the South [33]. Therefore, there is a need to carry out research on the penetration of the SPV in the existing weak grid and the possible extension of the electrification of the country using the potential of solar which is uniformly distributed across the country and considered to be God given resources [33].

Several researches have been conducted to evaluate the effect of DG on the electric power system, and several methods were proposed to mitigate the losses and at the same time increasing the penetration of the DGs in the power system. Among these solutions, there is the strategic location and sizing of the DG sources in the distribution system. Although, many approaches were suggested to determine the optimal placement of the DG yet DG-units still have technical challenges to be effectively integrated into the electric power systems [4]. These methods namely, classical approaches, analytic approaches and meta-heuristic approaches, have their advantages, disadvantages and efficiency. In this research, an analytical approach was used for optimal placement and sizing of SPV in the RDN for maximum power loss reduction. An analytical method based on maximum power loss saving using the backwards/forward sweep method was employed for the optimal siting and sizing of the SPV in RDN. The current flowing in each branch was computed using the backwards/forward sweep method, and the branch current loss formula was adopted to optimally place and size the SPV.

## 1.2 PROBLEM STATEMENT

SPV systems integration in the distribution networks has led to some technical challenges such as reverse power flow and overvoltage as the power flows through the less resistible path. Moreover, keeping the voltage in the desired range has become a real challenge to the Distribution Network Operators (DNO) because the violation of the voltage profile may lead to the instability of the electric system [5]. The life span of the distribution equipment can also be shortened due to overvoltage operating conditions. On the other hand, the power losses in the distribution network which are reality because of the physics associated with various power system components, have to be reduced as well. Losses in the distribution systems are mainly due to low voltage feeders overloading and unbalanced loads connected to the lines. Therefore it is mandatory to contrive remedies to address these challenges mentioned above by increasing the integration of the SPV [3, 5, and 6].

Different methods were proposed to solve these challenges; some examples are the system level, plant level and interactive level [7]. The system level mainly deals with the grid side rather than PV plants or loads side. The interactive level includes solutions in-between, it has the communication facilities, fitted at different positions in the network. Plant level remedies focus on PV plants and are connected just before the point of common coupling (PCC). The voltage profile and power losses reductions management using these measures has shown efficiency but they are very expensive to implement, and they cannot reduce the global pollution challenges. Furthermore, research on the optimal location of the SPV in the distribution network is very crucial to minimise the power losses, to know the size of SPV to be integrated as they also provide sources of alternative power generation. Different objective functions were formulated based on active and reactive power branch loss formula to optimally place and size SPV in the radial distribution networks for voltage improvement and power loss reduction. Therefore, there is need to also evaluate the sizing and placement of SPV using the current branch loss formula and observe what is the voltage profile and the power loss reduction percentage.

## 1.3 JUSTIFICATION

The losses in the power system have led to the increasing cost of supplying electricity, the shortage of fuel with the ever-increasing cost to generate more power, and the global warming problems. Distribution losses also have a lot of effect on the power generation and consumers' equipment by reducing the life span and the stability of the power system is compromised. This research was intended to propose a solution to reduce these power losses. The reduction in the power losses leads to a real financial gain in energy production and reduced capital-intensive investments. This reduction will also encourage the increment in the penetration of the renewable energy resources hence improving the power quality and reducing the pollution of the environment. The results presented here may help the energy planners and Distribution Operator Networks to optimally place the SPV in the existing distribution system to reduce the losses. It provides a reliable power supply and relieves the transmission and distribution lines from the overloading during the peak load demand thus the results of the research can be used as a guideline for DG-units penetration.

## 1.4 OBJECTIVES OF THE STUDY

This section highlights the main objective and specific objectives of the study as follow.

### 1.4.1 MAIN OBJECTIVE

The objective of this research work is mainly to investigate the optimal placement and sizing of the solar Photovoltaic system in the radial distribution network for the active power losses reduction and to improve the voltage profile.

### 1.4.2 SPECIFIC OBJECTIVES

To achieve the main objective, the following specific objectives of the research are developed and outlined briefly.

1. Model the power distribution system with the solar PV at suitable bus,

2. Formulate the objective function and determine the constraints,
3. Determine the location, size of the SPV and the minimum active power losses,
4. Evaluate the performance of the proposed approach with the existing methods.

## 1.5 SCOPE OF THE STUDY

This research is limited to the following points:

1. Only the integration of the SPV is considered
2. The number of SPV integrated in the radial system is limited to 2;
3. Voltage constraints are within ±5% of the nominal value and the SPV capacity is limited between 20 to 80% of the total power load demands of the radial distribution networks to avoid the reverse power flow in the network.
4. Only three cases of the power factor variation were considered for the analysis namely 0.85PF lagging, 0.95PF lagging and unity PF respectively

## 1.6 THESIS OUTLINE

**The chapter one** gives the general view of the power loss problem in the radial distribution and the pollution challenges. The problem statement and the objective of the study was formulated with the specific objectives outlined. The scope of the study was described and finally the organization of the thesis was highlighted.

**In chapter two**, the background of the study on the integration of the DG in the radial distribution was discussed. The general topology of the grid was introduced followed by the power losses and their causes in the power systems were examined before naming the challenges of the radial distribution networks compared to the ring systems. Furthermore, the advantages and disadvantages of injecting DGs in the radial distribution systems were briefly mentioned before discussing the various techniques used for the power loss reduction including various algorithms. The survey on the objective function formulation for the placement of DGs and finally the load flow analysis methods were reviewed before the summary of the literature.

**Chapter three** started with the description of the proposed backwards/forward sweep method used for the load flow analysis of the radial distribution networks; this approach is a bridge over the formulation of the Jacobian matrix which leads to time and space consumption. The formulation of the power loss reduction problem for the optimisation purpose was related to the voltage and generation capacity constraints. The formula for evaluating the current flowing in each branch and the associated power losses were discussed, and this chapter lastly described the proposed maximum power loss saving technique used for the optimal placement and sizing of the SPV in the RDN.

Results from the basic load flow and integration of the SPV were discussed in **chapter four**. The analysis started with the various loadings of the IEEE 33 bus RDN for the initial load flow before injecting single SPV at the optimal nodes, and the power flow was carried out again to record the change in the total power losses and the voltage profile of the system. The effectiveness and performance of the proposed analytical method was compared with the existing methods found in the literature. Furthermore, the study went far by varying the power factor from 0.85 lag, 0.95 lag to unity PF and the results compared, and finally, the system with two DGs injected at various power factors was also studied at the end of this chapter.

**Chapter five** deals with the general conclusion of the study followed by the contribution of the research to the field and finally the the recommendation from the study. This section is followed by the appendix and the reference lists.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter highlights the overview of the DG placement and sizing in the radial distribution networks. It introduces the challenges of the distribution systems due to power losses and the impact of DG penetration in these systems. Then the overview of the research background on different approaches used for optimal siting of DG and the formulated objective functions to solve the optimisation problems are presented. Finally, the identification of gaps and limitations from the literature reviews are also highlighted in this chapter.

## 2.2 POWER SYSTEM TOPOLOGY AND POWER LOSSES

The losses in the distribution system have compromised the efficiency and the reliability of the power system while the electricity is a crucial commodity for the development and the improvement of the lifestyle of humanity [63]. Engineers and energy planners have investigated with different approaches to quantify the effect of the losses, and how to mitigate them, therefore, numerous tools and methods have been used to mitigate these challenges while considering the reduction of the pollution at the same time. Among the suggested solutions comes the penetration of the Distributed Generations (DG) to solve these power losses in the distribution network, to reduce the greenhouse gases emission and to provide alternative sources of electric energy [5-7]. The power system comprises of the generation, transmission, distribution and loads interconnected through the transformers and other ancillary and control services as shown in Figure 2.1 [7].

The centralized systems based on fossil fuels generate bulk electric power and transmit it through long distance lines to the consumers. These systems face the high power losses and pollution of the nature. The remedies to both problems have been the development of the techniques to integrate renewable energies namely wind turbines, PV modules, thermal concentrators, biomass, mini-hydro, and geothermal to provide an alternative power source to meet the exponential increasing load demands [64]. They generate power at a low or medium voltage rating which is stepped up by the transformers to high voltages for transmission lines.

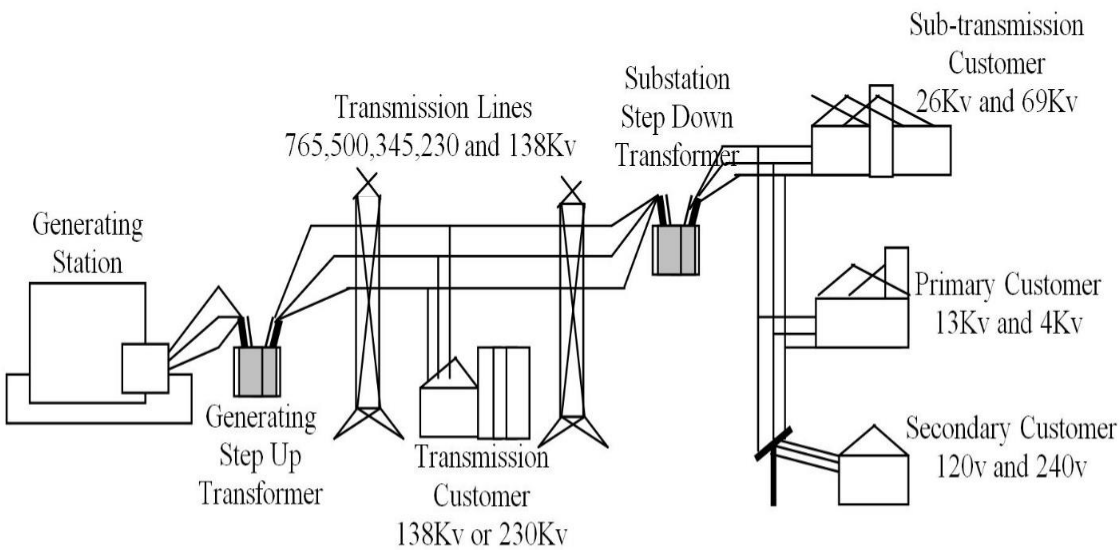


Figure 2.1 Traditional power topology

The lines and cables provide the means for the transmission and distribution from the generation point to the consumers' premises or load centres. They can be overhead lines and underground cables used in the transmission and distribution of the power system according to the rating they can carry high, medium or low voltages [13]. The knowledge of their characteristics helps in the design of the system to avoid overloading and heating which leads to further power losses in the power flow. The cross-sectional area of the conductors is a very important parameter in the selection of the transmission and distribution lines to avoid the power losses and overheating in the lines [7].

Transformers are essential elements in the power system because they enable to raise the voltage at a given sufficient level for the transmission and reduce it to a suitable level for the distribution purpose. They are static elements in the power system with fewer losses if properly selected and installed [10].

The consumers are end users of the power generated and the power system always has to be balanced that is the power generated has to be consumed [66]. There are different types of loads such as large consumers and small consumers; there are resistive, inductive and capacitive loads. The power loads connection and disconnection have an impact considerable on the operation of the power system, but they are difficult to predict or control [65]. The ancillary services and the control units are associated with the grid to have more control over the system operation and reliability. The compensating services such as capacitor banks, Flexible AC Transmission Systems (FACTS) and the integration of renewable energy resources are used to ensure the power flow runs smoothly in the required frequency and voltage profile ranges [36, 68].

With the penetration of intermittent energy sources, the configuration of the classical power system has changed, and the means of communication are incorporated in such a way that the consumers can also interact with the system [69-70]. The consumers can inject the excess of the small scale power generated into the grid during pick of their production. This system is called the Smart Grid which is the configuration of the future grid as shown in Figure 2 [5, 36-69].

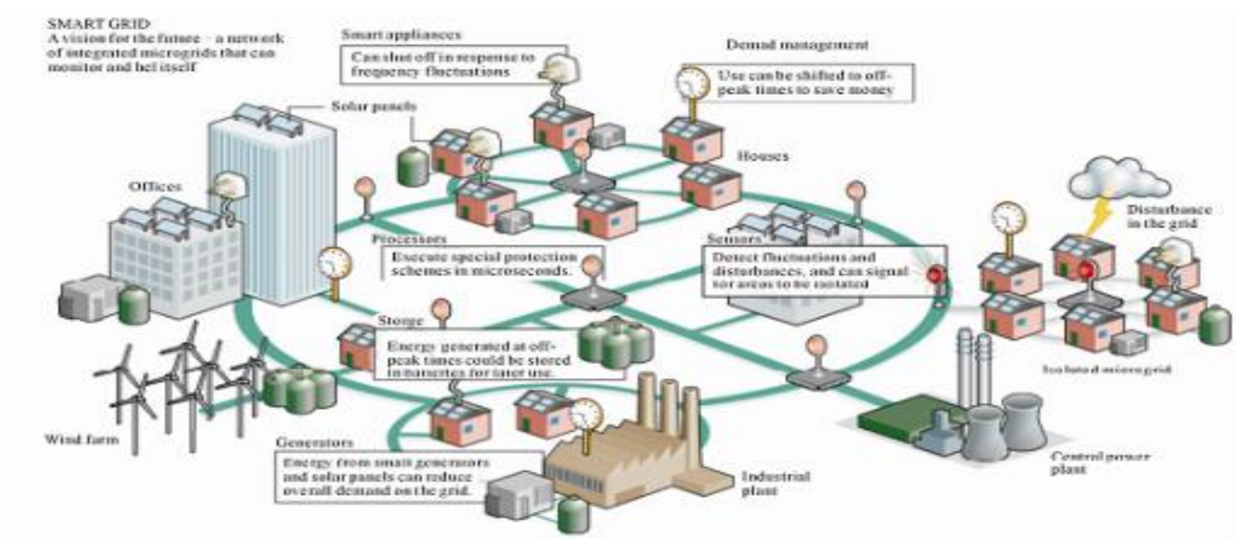


Figure 2.2 Smart grid power system topology

## 2.2.1 THE CHALLENGES OF RADIAL DISTRIBUTION NETWORKS

The distribution system is characterised by the primary distribution lines which supply power to heavy loads and the secondary distribution system which provides electricity to the low voltage consumers. Cabling can be overhead or underground depending on the area of the distribution. The distribution system configuration can be ring distribution systems which have different sources of electric power generation connected to the feeders, and they form a closed loop [5]. On the other hand, the radial distribution system is an open loop, and it depends only on the single feeder and single source of power generation for the simplicity of the coordination and control [37-43].

The latter configuration is mainly used in the existing centralised power generation system, and has many disadvantages [37-45]:

1. The consumers are dependent on the single feeder and single distribution line thus any fault found on the feeder or distributor failure, the consumers who are on the side of the fault away from the substation experience blackout,
2. The consumers very far from the supply feeder would be subjected to voltage fluctuation when the load changes and they also suffer low voltage profile,
3. No communication means for the control of the power flow and for the fault identification thus it takes time to fix any small fault in the lines.

### 2.2.2. OVERVIEW OF THE LOSSES IN ELECTRIC POWER SYSTEM

The increase in the loads changes the structure of the electric power system to be very complex, the complexity of the electric power systems has brought some technical challenges in operation especially the power losses due to the equipment used in transporting the bulk power from generation to the load centres [15]. The system power losses cause a voltage instability and disturbance in the power system; the losses occur in the transmission and distribution systems, substation transformers [10], and the connection extension of the power system [70].

The losses in the transmission lines are mainly due to electric energy dissipation in the conductor used for the transmission caused by the high current flowing through the conductors. The transmission line losses include conductor loss, radiation loss, dielectric heating, coupling loss and the corona [9]. Thus reducing the current from the sending end will reduce the power losses in the transmission lines and at the same time it is important to prevent the corona discharges losses due to high voltage that may also offset the lower resistance losses.

Distribution power losses can be subdivided into two groups: technical and non-technical power losses [2]. The technical losses in the distribution systems are mainly caused by the aluminium used in the overhead lines and cables, the current flowing through the line causes heat or power dissipation. Another factor of losses in the distribution network is unbalanced loadings when the three-phase current are not balanced, the neutral line can be affected, and more leakage current is produced thus the losses become severe in unbalanced loads. The research has shown that the temperature rise also participates to the increase in power consumption, where the loading can rise by 3.75% for 1ºC temperature rise [7].

The challenge is that the power losses in the system are unavoidable because of some factors such as electric energy cannot be stored thus the generated power must match with the load at any time. Moreover, the integration of DGs-units in the grid is one of the solution of reducing the system power losses as described in the next section [2].

### 2.2.3 OVERVIEW OF THE LOSSES REDUCTION APPROACHES

The power losses from the generations to the consumer's premises are estimated to be 13% of the total power generated [3], [11] and the researchers have tried different approaches to address the power loss issues, and some of the techniques are outlined below:

According to the approach given in [3], to reduce or eliminate the non-technical losses in the distribution, the following measures can be taken:

1. Regular inspection can be carried out randomly to check any suspected connected load,
2. Provide and install new meters at the primary substation to control the internal consumption to avoid considering substation consumption as losses,
3. Appraise and locate the default-meters and replace them for the accuracy of measurement,
4. Awareness and power factor penalties should be increased to the consumers for the efficient use of electricity.

For the technical losses, the following approaches were suggested for the effective operation of the power system [3], [5], [8], [12], [16].

1. Install capacitor banks to support the voltage profile in RDN [5], [9].
2. Replace overloaded lines with new bigger conductors, avoid any overloading of the system and monitor the progress in losses reduction.
3. Remove unloaded transformers to avoid no-load losses and balancing the loading of the transformer to reduce the neutral current flowing thus reducing the power losses [10], [11].
4. Upgrade transformers to match the load and the installed capacity, and to replace old/damaged transformers.

5. Perform regular preventive maintenance and ensure the frequent live-line washing to reduce the leakage current.
6. The most effective are the placement of the DG optimally in the distribution network and the network reconfiguration

The other loss reduction techniques used are feeder reconfiguration, VAR compensation, Distributed Generation Integration and the installation of the smart metering for non-technical losses [8, 34, and 48]

Wu, Y.K. et al. [8] developed the reconfiguration method used for the loss reduction by using optimisation techniques and heuristics to determine the configuration with minimal loss power. From their result, many other techniques have been suggested such as Baran and Wu's method [2, 8] on feeder reconfigurations for loss reduction based on branch exchange. This approach started with a feasible configuration of the network; then one of the switches was closed, and others were opened based on heuristics and approximate formulas for change in system losses. Zhu, Ji Ngong [3] presented another heuristic approach for the reconfiguration using genetic algorithm, but this search technique also did not necessarily guarantee global optimisation. These techniques suffer the different optimisation issues, but they were efficient in reducing the power losses in the electric system. The main challenge is that the system still depends on a single source of power supply also the transmission and distribution lines are not relieved from overloading.

VAR compensation or shunt compensators are in the family of Flexible AC Transmission Systems and they are used mainly to control reactive power and provide support to the voltage profile by injecting or absorbing the reactive power to/from the power system [16]. The challenge is when there is voltage collapse, instead of compensating they tend to worsen the situation because the voltage profile further decreased and they require harmonic filters to inject the current into the power system [19]. Another approach for the losses reduction is integration of the Distributed Generation which will be described in the next section.

### 2.2.4 TYPES OF THE DISTRIBUTED GENERATIONS

Distributed or embedded Generations are small-scale electric power sources connected near the load centre or across the distribution systems to support the centralised power plants by supplying electric power near the consumers [2, 14]. They effectively participate to the power loss reduction and the voltage profile improvement. Furthermore, they provide an alternative source of energy with considerable pollution reduction. They can be subdivided into renewable or non-renewable sources. There are different types of the DGs according to the power they feed into the grid and the role they play in compensation [16]:

*First type*: DGs that can only supply reactive power (PF=0) such as synchronous condensers which mainly support the voltage profile in the network.

*Second type*: they can only generate and supply active power (PF=1). The solar energy sources are most popular in this category along with their battery backup.

*Third type*: in this category, DGs generate and supply both active and reactive power to the system ($0 \leq PF \leq 1$). The induction machines/generators are used to produce electric power including wind turbines.

*Fourth type*: DGs act like the slack bus regulating the voltage at the bus, thus they generate and absorb reactive power in/from the network to maintain the balance in the voltage buses ($-1 < PF < 1$).

In this research work, the second and third type will be used for investigation of optimal placement of the DG in the Distribution systems for active power loss reduction, the improvement of voltage profile and environmental pollution reduction as well [58]. The types 2 and 3 have direct impact on the active power loss improvement and also they provide an alternative power supply to the consumers [14-16].

## 2.3 THE EFFECT OF INTEGRATING SPV IN THE POWER SYSTEM.

The climate change or the global warming has become a real problem faced by the humankind, and the technological revolution has made humanity, to be quasi-dependent of the electricity for the improved lifestyle. The clean energy has become part of the political debate i.e. conference of parties (COP21-Paris) [71]. Moreover, the increase in the integration of renewable energy resources has introduced some technical challenges which slow down or prevent the efficient injection or deployment of these resources along with the availability and intermittency of these resources which are located in privileged areas. The integrations of the distributed energies are considered in this thesis with a particular focus on the solar photovoltaic in the radial distribution networks for the ultimate aim of maximum active power loss reduction and improved voltage profile [14, 15].

The integration of the Solar Photovoltaics (SPV) to the grid has its pros and cons on the existing power systems since the traditional power systems were designed without taking into account the penetration of the intermittent energy resources [20]. Apart from the fact that SPV provides clean and interminable power to the consumers, the systems can lead to the maximum reduction of the power losses and improvement of the voltage profile in the system. The proper placement of the PV can also free the transmission lines, and they impact both the active and reactive power unlike the capacitor banks which only affect the reactive power flow [2, 12, 13]. Distributed generators are beneficial in reducing the power losses effectively compared to other methods employed for the power loss reduction.

On the other hand, the integration of the PV systems can lead to some unexpected conditions such as voltage and power fluctuation issues, harmonic distortions, high transmission and distribution losses, over/under loading of the feeders and the malfunctioning of the protection systems. Therefore, there is a need to critically investigate the effects of SPV systems integration level which is increasing daily to meet the demand of the consumers [13].

Researchers have evaluated the effect of SPV and have shown that small scale of SPV is considered as negative load and may not affect the operation of the power system while the large penetration of SPV into the grid can affect the stability of the power system [14]. In [15], the authors showed that the SPV penetration beyond 20% of the total power generated will degrade the frequency stability of the power system but they have not considered the optimal placement of the PSV in their study. The dynamic analysis of SPV integration showed that change in the temperature and irradiance can affect the performance of the grid and may lead to the voltage collapse due to the sudden change or fluctuation if there is no proper reserve to peak up the load [13-15]. So many works have proved that the non-optimal and sizing of the SPV or non-sizing and optimal placement of the SPV can degrade the quality of the power system thus it is important to study the optimal placement under the constraints of active power capacity and voltage limits of the SPV in the distribution system [21].

Facing these two challenges namely, the power losses in the distribution systems, and the effect of the DG penetration into the electric system, some research works have been conducted to mitigate them [12-21]. Different approaches and algorithms investigating the penetration of the renewable energy sources into the power system are increasing daily with these challenges mentioned above [15-29]. Some of the techniques used in analysing the optimal placement of the DGs are highlighted in the following section.

## 2.4 DIFFERENT APPROACHES USED IN SOLVING THE SITING AND SIZING OF DG.

The challenges due to the integration of DG have received considerable attention and many works have been done up to now to mitigate the effect of DG penetration. These techniques include classical approach, the analytical approach and the meta-heuristics approach such as the Genetic Algorithm (GA), Tabu Search (TS), Simulated Annealing, Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO) [15-20]. These methods have their pros and cons given the estimate of how the power losses can be minimised. The results showed different voltage profile improvement and level of DG integration.

The metaheuristic approaches are mainly based on the systematic random exploration of the space solutions augmenting the probability of getting the global optimal and avoiding the premature convergence. The optimisation technique in heuristic methods are the Genetic Algorithm which uses the strings instead of manipulating the objects themselves to get the results, but the principal challenge is coding of these objects into strings which may take a long time [17]. Many techniques were applied to place the DGs in the power system to reduce the losses, and besides, many optimisation tools including the artificial intelligence approaches like a Genetic Algorithm, Direct Search Algorithm, Tabu Search, particle swarm optimisation (PSO) were also used to achieve the same objective.

N. Acharya et al. in [18,] suggested the analytical method for minimising the power loss in the primary distribution system. In [16] S.A.H. Zadeh et al. have suggested the smart method comprising of Binary Genetic Algorithm (BGA) and Bacteria Foraging Algorithm (BFA) for DG placement in the distribution network, their approach was the bridge by combining two different algorithms. In [22], the thumb rule technique was presented for the optimal location of the capacitor for reactive power support. This method is easy and efficient, but it failed to analyse the other types of loads or the unbalanced loading systems. In [23], the authors used Direct Search Algorithm for optimal placement of SPV in the distribution systems with three DGs connected.

In [24] optimal placement and sizing of DGs for active loss and total harmonics distortion (THD), reduction and voltage profile improvement using sensitivity analysis and PSO have been presented. The authors in [25] presented based on the heuristic approaches, a novel optimal placement of Photovoltaic system for loss reduction and the improvement of voltage profile. Srinivasa R. et al. [26] have proposed ABC algorithm for the reconfiguration of the system power loss reduction. The results were compared with the existing algorithm, and they concluded that the ABC had a better performance than others such as Tabu search, GA and Simulated Annealing (SA). In [27], the authors used the metaheuristic method ABC for the optimal placement and sizing of DG for power loss reduction and improved voltage profile. The power branch loss formula was used to formulate the objective function, and the results were compared to the grid search method.

The maximum power loss saving technique was introduced in [43] to identify the placement and optimal sizing of the DG. Although the results were satisfactory, only the unity power factor was considered throughout the study. The authors in [44] proposed a simple analytical method based on iterative search technique and Newton-Raphson method for the optimal sizing and allocation of DG in a network to lower the cost and loss effectively. They used the weight factors between the loss and cost in the study. In [61], the authors also proposed an analytical method to place and size DG in the RDN based on sensitivity index which was the combination of the exact loss formula and voltage sensitivity coefficient to achieve the active power loss reduction and improved voltage profile.

As mentioned earlier, different researchers have investigated on the optimal placement of DG with different algorithms but the main difference is how those problems were formulated and the assumptions made with the constraints. Moreover, each approach has its efficiency, advantages and limitations in solving the effect of the integration of the Distributed Generation in the electric systems. The metaheuristic population-based algorithms are to be fast and required less storage, but they are probability based so their results can not be guaranteed due to so many manipulations of parameters and they depend on the analytical equations. They used the analytical methods as benchmark methods. The analytical methods are more accurate than the meta-heuristic methods for the smooth objective functions. The next section will deal briefly with the formulation of the objective functions used in the location of the DG in the distribution systems.

### 2.4.1 REVIEW ON THE OBJECTIVE FUNCTION FORMULATION

Many approaches have been used to quantify the power losses in the distribution systems which are due to the current flowing through the conductors. Some of the formulations are highlighted briefly below:

In [31], the consideration of the characteristics of the resistance due to the temperature was investigated as factor of losses, the power loss formulated considering the current flowing in the conductors, and the objective function of the study was:

$$P_{loss} = I^2 \times R \tag{2.1}$$

The line resistance R depends on many factors, including the length of the line, the effective cross-sectional area A, and the resistivity of the metal of which the line is made.

$$R = \rho \frac{L}{A} \tag{2.2}$$

The current can be expressed in terms of the apparent power.

$$I^2 = \frac{P^2 + jQ^2}{|V|^2} \tag{2.3}$$

where I is current flowing in the branch, P is active power, Q is reactive power and V is the magnitude of the voltage at the node.

Parizad et al. in [17] used the Harmony Search heuristic algorithm to optimally site and size DG to reduce losses, improve voltage profile, improve system security and reduce THD. The objective function they used is described as follow:

$$F = a_1.J_P + a_2.J_V + a_3.J_{LOSSES} + a_4.J_{THD} \tag{2.4}$$

The trial and error optimisation coefficients $a_1$ to $a_4$. The objective functions are given by

$$J_V = \sum_i w_i \left|V_i - V_{ref,i}\right|^2 \tag{2.5}$$

$$J_p = \sum_j w_j \langle \frac{S_j}{S_{j,max}} \rangle^2 \tag{2.6}$$

Where $V_i$ is the voltage amplitude at bus i, $S_j$ is the apparent power for line j, $V_{ref,\,i}$ is the nominal voltage, $S_j$, max is the apparent nominal power of the line jth and $w_i$, $w_j$ are weighting factors.

$$J_{losses} = \sum_{j=1}^{nb} a_j . \mathrm{Max}(0, (P_j^{DG} - P_j^{Base})) \quad (2.7)$$

where $P_j^{DG}$ is the loss in j[th] branch after DG installation, $P_j^{Base}$ is the loss in the j[th] branch without DG connected and *nb* is the total number of nodes. The power loss is calculated in terms of the bus current injection as described below:

$$J_{THD} = \sum_{j=1}^{nb} a_j . \mathrm{Max}(0, (THD_j - THD_{max})) \quad (2.8)$$

where $THD_j$ is the total harmonic distortion in the jth bus with DG and $THD_{max}$ without DG injected and $a_j$ is the trial and error optimisation coefficients. The loads consist of the harmonic current sources and the impedance using the backwards and forward sweep method to compute the load flow; the limitation is that the current absorbed by the shunt capacitor were not known [17, 20].

Hung et al. in [27] proposed the improved analytical (AI) method to size all the four types of the DGs optimally, and the results of their work were compared to the Exhaustive Load Flow (ELF) method and the Loss Sensitivity Factor (LSF). The results showed that AI method achieved a loss reduction of 61.62% which is less that of the ELF at 64.83% while the LSF is said to be the worst of the three methods with 59.72% of power reduction. [20, 27]. The test was carried on the IEEE test systems (16, 33, 69 bus). Different types of objective functions to fit each category of DGs are summarised below:

1. Type 1 DG ($0<PF_{DG}<1$) it injects active and reactive power and the size of DG is defined by:

$$P_{DGi} = \frac{\propto_{ii}(P_{Di} + aQ_{Di}) - X_i - aY_i}{a^2 \propto_{ii} + \propto_{ii}} \quad (2.9)$$

$$Q_{DGi} = aP_{DGi} \quad (2.10)$$

Where $a = (sign)\tan(\cos^{-1} PF_{DG})$ and sign = +1 (DG injecting reactive power), $P_{DGi}$ is the total active power generated by the distributed generator at node i; $P_{Di}$ and $Q_{Di}$ are active and reactive power demands at node i respectively.

$$X_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} (\propto_{ij} P_j - \beta_{ij} Q_j) \quad (2.11)$$

$$Y_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} (\propto_{ij} Q_j + \beta_{ij} P_j) \qquad (2.12)$$

The loss coefficients $\propto$ and $\beta$ are obtained from the base case load flow and they are updated at each load flow step. $P_j$ and $Q_j$ are active and reactive power flowing in node *j*.

2. Type 2 DG (0<PFDG<1) which inject the active power but absorb reactive power (sign = -1) and they have the same formula as type 1.
3. Type 3 DG (PFDG=1) DG injects only the active power sign=0, thus the optimal DG size at bus *i* is given by:

$$P_{DGi} = P_{Di} - \frac{1}{\propto_{ii}} \sum_{\substack{j=1 \\ j \neq i}}^{n} (\propto_{ij} P_j - \beta_{ij} Q_j) \qquad (2.13)$$

4. Type 4 DG (PFDG=0) DGs inject only the reactive power in the system with sign = ∞ , and the optimal DG size is calculated as follow:

$$Q_{DGi} = Q_{Di} - \frac{1}{\propto_{ii}} \sum_{\substack{j=1 \\ j \neq i}}^{n} (\propto_{ij} Q_j + \beta_{ij} P_j) \qquad (2.14)$$

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

where $P_i$ and $P_j$ are active power injected at *ith* and *jth* buses respectively; $Q_i$ and $Q_j$ are reactive power injected at *ith* and *jth* buses. $V_i < \delta_i \; and \; V_j < \delta_j$, they are complex voltages at buses *ith* and *jth*; $R_{ij} + jX_{ij}$ is the *ijth* element of the impedance matrix [$Z_{bus}$] and *n* is the total number of the buses.

The challenge is the need of means of communication for the control of reactive power, yet the small DG are not equipped with these means, and the combination of the four types of DG in the same network is practically difficult to be implemented in reality. Furthermore, the authors run the type 1 and type 3 only for the analysis with the software they developed. Thus the unity power factor is best practice for the DG penetration [20, 27].

Paliwal et al. in [28] proposed the analytical method for the distributed generator placement for loss reduction and improvement in reliability based on the reliability indices: SAIDI, CAIDI and EANS, which are defined as follow:

SAIDI defines the System Average Interruption Duration Index i.e. the customers' downtime

$$\text{SAIDI} = \frac{\sum V_i.N_i}{\sum N_i} \tag{2.15}$$

Where $V_i$ is the annual outage time and $N_i$ is the number of customer of lateral *i*.

CAIDI stands for the Customer Average Interruption Duration Index i.e. average time needed to restore service to the average customers per sustained interruption defined by

$$\text{CAIDI} = \frac{\sum V_i.N_i}{\sum \beta_i N_i} \tag{2.16}$$

AENS is the Average Energy Not Supplied which is the total energy not supplied to the total number of the customers

$$\text{AENS} = \frac{\sum V_i.La_i}{\sum N_i} \tag{2.17}$$

where *La(i)* is the average load connected at load point *i*; this analysis was based on the consumer side and the effect of not supplying power to the consumers. The authors considered the consumers' downtime to size the DG. Therefore, the generator capacity was studied in this case, the power loss experienced by the lines during the operation was not taken into consideration.

The authors used the current phasor to formulate the objective function considering the distance *Xo* to place the DG optimally as illustrated in Figure 3 below.

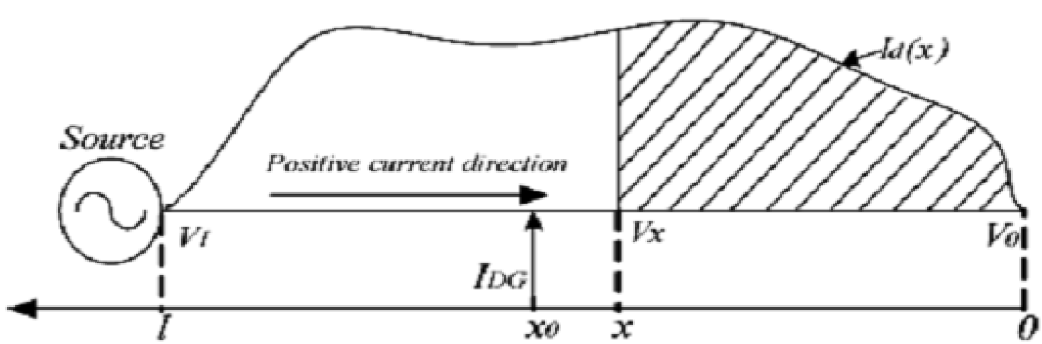


Figure 2.3. Current direction along the distribution line

Considering one DG is injected into the distribution feeder at the distance *Xo*, the feeder phasor current is derived as:

$$I(x) = \int_0^x Id(x)dx \qquad 0 \le x \le x_0 \tag{2.18}$$

$$I(x) = \int_0^x Id(x)dx - I_{DG} \qquad x_0 \le x \le l \tag{2.19}$$

where $I_d(x)$ is the current phasor density. *Xo* is the distance from the source.

The power loss and voltage drop in the feeder are calculated as follow

$$P_{loss}(x0) = \int_0^{x0} (I_d(x).dx)^2.Rdx + \int_{x0}^{l} (\int_0^x |I_d(x)dx - I_{DG}|^2.Rdx) \tag{2.20}$$

$$V_{drop}(x) = \int_0^x \int_0^x I_d(x)dx.Zdx, \quad 0 \le x \le x0 \tag{2.21}$$

$$V_{drop}(x) = \int_0^x \int_0^x I_d(x)dx.Zdx + \int_{x0}^{l} (\int_0^x I_d(x)dx - I_{DG}).Zdx\,, \;\; x_0 \le x \le l \tag{2.22}$$

The objective function is defined as DG place at point *X* and $V_x$ along the feeder should be acceptable thus the solution $X_0$ will give the optimal placement of DG for maximum loss reduction.

$$\frac{dP_{loss}(x0)}{dx} = 0 \tag{2.23}$$

The authors assumed fixed DG value and fixed power factor for the analysis and they noticed that this location could not guarantee that all the voltage along the feeder is in the acceptable range. The DG can be located around *Xo* to satisfy the voltage regulation while decreasing the power loss which is calculated by placing the DG at each node. The problem with this method is on the lateral branches of the power system, because only main branch was considered in the analysis and the change of the power factor could also affect the current phasor consisdered to be constant.

In [29] Jayavarma1 et al. used the exact loss formula as objective function based on the power losses at various nodes to find the optimal placement of PV DG based with constraints described as follow:

$$F = \sum_{k=1}^{nb} P_{LK} \tag{2.24}$$

Where *nb* is total number of nodes and $P_{LK}$ is the active power loss at node *k*.

The objective function F is subjected the following equality constraints,

$$P_i = P_{Gi} - P_{Di} - \sum_{j=1}^{nb} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \tag{2.25}$$

$$Q_i = Q_{Gi} - Q_{Di} - \sum_{j=1}^{nb} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \tag{2.26}$$

Also the inequality constraints

$$Q_{Gi,min} \le Q_{Gi} \le Q_{Gi,max} \qquad i = 1,2 \dots \dots \dots \dots N_G$$

$$V_{i,min} \le V \le V_{i,max} \qquad i = 1,2 \dots \dots \dots \dots N_b$$

$$|P_{ij}| \le P_{ij}^{max}, \qquad ij = 1,2 \dots \dots \dots \dots \dots \dots \dots \dots N_l$$

Where $P_i$ and $Q_i$ are active and reactive power flowing in branch *i*, $P_{Gi}$ and $Q_{Gi}$ are active and reactive power generated at node *i, Vi, Vj* are voltages magnitude at node *i* and *j* respectively. $Y_{ij}$ is the admittance of the line between node *i* and *j*. $\delta_i$ $\delta_j$ and $\theta_{ij}$ are phase angles of the voltage at node *i, j*, and the admittance respectively.

This study was intended to investigate the losses improvement and the effect of high-level penetration of the SPV using the heuristic algorithm. This objective function was tested on standard IEEE 14 bus non-radial network and the active power loss minimization was 34.46%.

Another research presented by H. Nasiraghdam [30], using the Bacterial Foraging optimisation (BFO) algorithm has proposed the following objective function for the power loss reduction

$$\text{PLRI} = \frac{P_{loss-Base} - \text{Ploss}_{\text{DGi}}}{P_{loss-Base}} \tag{2.27}$$

where *PLRI* is the Power Loss Reduction Index, $P_{\text{loss Base}}$ is the power loss without DG and $Ploss_{DG}$ is the power loss with the DG integrated. The complex power loss between bus *i* and *j* is computed as follow:

$$S_{ij} = V_i . I_{ij}^* \tag{2.28}$$

$$S_{ji} = V_j . I_{ji}^* \tag{2.29}$$

Where $S_{ij}$ is the complex power loss from node *i* to *j* and $S_{ji}$ is the complex power loss from node *j* to *i*. $V_i$ and $V_j$ are voltage magnitude at node *i* and *j* respectively. $I_{ij}$ and $I_{ji}$ is the current value at each node. *Re* is the equivalent resistance of the lines.

The total power loss is the summation of all power losses in different lines.

$$P_{loss} = \sum_{i=1}^{N} \sum_{j=1}^{N} R_e(S_{ij} + S_{ji}) \tag{2.30}$$

Along with the BFO, the optimisation equation was tested on the IEEE 33-bus test system, and the results are satisfactory. Thus various objective functions were formulated to fit with the algorithm used for the optimisation, and each approach has its merits and limitations.

## 2. 5 REVIEW OF LOAD FLOW ANALYSIS METHODS

The power flow or load flow analysis is essential for planning, operation, optimisation and control of power systems. It is called the heart of decision making in the electric power systems [46]. The information provided by the load flow analysis consists of the active and reactive power flow in each branch and associated line losses, the magnitude and phase angles of voltages at each bus and the current magnitude in the various branches under steady state condition. The load flow analysis is highly complex, and it involves hundreds of buses and several distribution links, therefore resulting in the extensive calculations [35, 47].

The load flow analysis in the electric power systems consists of primary evaluating the voltage magnitudes and phase angles at each node. Using the obtained values to compute the current at each branch and also the power flowing in various branches along with the system power losses associated with the current flowing in these lines [2]. The same principle is applied to the single wire earth return analysis, underground cables or overhead distribution systems for the optimisation, upgrading the existing system equipment or installing a new distribution system.

There are mainly two topologies of the electric power distribution systems namely the ring loop and the radial distribution systems. The ring distribution systems are more reliable and robust but very expensive thus many existing electric grids adopted the radial distribution systems which have the following characteristics [48]:

- Radial or weakly meshed networks (source supplied at one side only),
- Low X/R ratios, due to high resistance and low reactance of the line,
- Unbalanced operation, Unbalanced distributed load and multi-phase,
- Distributed generation not easily dispatchable,
- Less expensive but least reliable network configuration.

These features make the radial distribution networks to be known as ill-conditioned systems, and they become challenging for the conventional, Gauss-Seidel method, Newton-Raphson, Fast Decoupled and their variants to effectively analyse them [47].

The Newton-Raphson algorithm is the most widely used methods in the electric power industries for the strongly meshed transmission lines with several redundant paths and parallel lines. But it failed in the radial distribution network due to the reasons mentioned above and the convergence challenges though it could be effective and robust in the voltage convergence [47]. It could not be effective for the optimal power flow computation due to the time consumption, and large storage memory required [35, 48].

Authors in [49] proposed a Newton-Raphson method for solving ill-conditioned power systems. Their work demonstrated voltage convergence but could not be effectively applied for large power flow calculations.

In this thesis, the proposed backwards and forward sweep method is used to calculate branch currents, nodal voltages and power losses in each branch using the Kirchhoff's current and voltage laws [43, 50, and 51].

The backwards and forward sweep method is used to solve the power flow analysis of the radial distribution systems with recursive equations. W.H. Kersting et al. proposed the method known as the modified Ladder iterative technique [52, 53] and R. Berg et al. [54], the convergence of the method explained in [51,55]. The backwards and forward sweep method is based on the Kirchhoff's voltage and current laws and in each iteration, two computation stages occur, the forward path and the backwards walk. The BFSM has the advantage over the counterpart methods in the load flow analysis due to the fast convergence and taking into account each branch of the network thus more accurate. Unlike other methods that used the admittance matrix and the Jacobean inverse matrix to evaluate the power losses, the BFSM used each branch resistance and reactance to evaluate the power losses in that specific branch.

## 2.6 SUMMARY OF THE LITERATURE REVIEW

Each of the methods described in this review has its merits and gaps. Moreover, there is still need to emphasize more on technical effects of DGs especially the solar photovoltaic integration in the radial distribution systems characterized by the high R/X ratio and the unbalanced loads connected [43]. It was observed from the litterature review that metaheuristic methods are fast, robust, and reliable but they are probabilistic approaches and their control parameters required expertise. Therefore, any mistake in the manipulation can compromise the final output, and they are all based on the analytic formula.

All these methods have a common point which is the problem formulation; they used the exact loss formula or the power branch formula to define the objective functions and apply different optimization techniques [62]. From the review on the objective functions, it is clear and obvious that active and reactive power components were mainly used to formulate the objective functions and other optimization tools were used to allocate and size the DG to reduce the power losses and improve the voltage profile of the radial distribution networks. Moreover, the power loss in the system can be also evaluated using the branch current components i.e. $I^2R$. The current flowing through the distribution lines causes the power loss in the system. Therefore the optimal placement and sizing of the DG in RDN using this approach is mandatory and necessary. However, the current branch loss used as objective function for the optimal placement is quasi-inexistent.

Furthermore, the purpose and the novelty of this research is to propose a simple and effective analytical method based on the current branch loss formula and equivalent current injection to optimally place and size DG in the radial distribution systems. The current flowing in various branches and the equivalent current injected at different nodes were explored to evaluate the total power loss, the power saving for the current injected at each node, and the size of the SPV associated to these power savings. The backward and forward sweep method was proposed to run the load flow analysis to achieve the bridge over high R/X ratio and unbalanced loadings of the systems [47]. The method did not use the admittance matrix, the Jacobian matrix which is shown to be problematic for the radial distribution systems.

# CHAPTER THREE: METHODOLOGY

## 3.1 INTRODUCTION

This chapter highlights the methodology proposed for the optimal placement and sizing of SPV in RDN. The chapter introduces the formulation of the objective function along with different constraints followed by the proposed method used for the load flow analysis. Finally, the proposed optimization algorithm named maximum power loss saving technique is discussed in details at the end of this chapter.

## 3.2 FORMULATION OF THE OBJECTIVE FUNCTION

This part deals with the analytical method of formulating the optimisation problem and defines the constraints attached to the objective function to achieve the optimal siting and sizing of the SPV for maximum loss reduction and voltage improvement.

Consider a two buses radial network shown in Figure 3.1 with the active and reactive loads connected the impedance of the lines given in ohms.

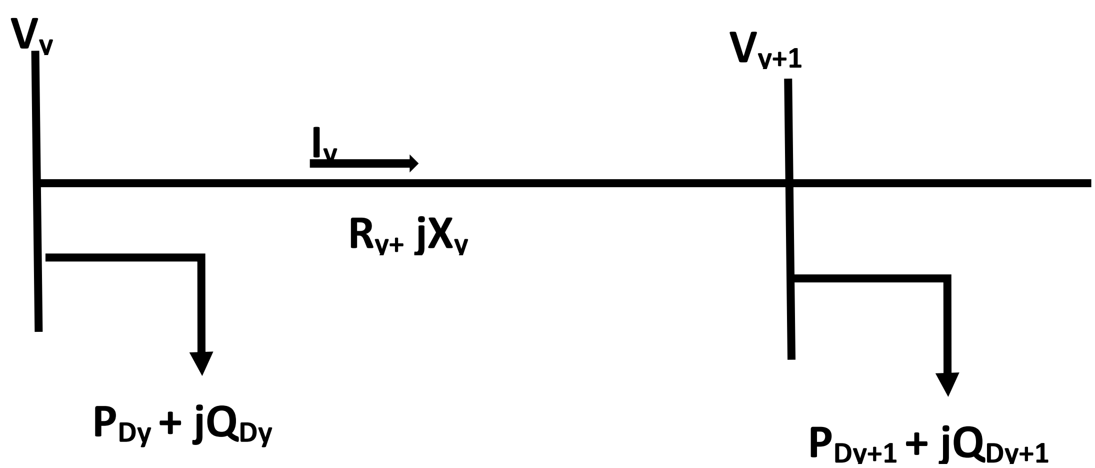


*Figure 3.1 Two buses network configuration*

The per-unit of the network which is used throughout this analysis is evaluated as follow:

$$Z_{base} = \frac{KV_{base}^2}{MVA_{base}} \tag{3.1}$$

$$R_{pu} = \frac{R_{actual}}{Z_{base}} \tag{3.2}$$

$$X_{pu} = \frac{X_{actual}}{Z_{base}} \tag{3.3}$$

$$P_{pu} = \frac{P_{actual}}{1000 \times MVA_{base}} \tag{3.4}$$

$$Q_{pu} = \frac{Q_{actual}}{1000 \times MVA_{base}} \tag{3.5}$$

Where $Z_{base}$ is the base impedance of the line;

$R_{pu}$ is the per unit value of the resistance; $R_{actual}$ is the actual value of the resistance;

$X_{pu}$ is the per unit value of the resistance; $X_{actual}$ is the actual value of the reactance;

$P_{pu}$ is the per unit value of the active power; $P_{actual}$ is the actual value of the active power;

$Q_{pu}$ is the per unit value of the reactive power; $Q_{actual}$ is the actual value of the reactive power;

$MVA_{base}$ is the base value of the Megawatt; $KV_{base}$ is the base value of kilovolt.

The initial current flowing through each branch of the network can be obtained using the active and reactive power and assuming 1.0 p.u. voltage at node 1 as shown in Equation (3.6).

$$I_y = \text{conj}\left\{\frac{P_y + jQ_y}{V_y}\right\} \tag{3.6}$$

where $P_y$ and $Q_y$ are the active and reactive power flowing from bus $y$ to bus $y+1$ respectively.

Updating the voltage at every node, the value of the current flowing in each branch can be evaluated using the following formula;

$$I_y = \left\{\frac{\mathbf{V_{y<\delta_y} - V_{y+1<\delta_{y+1}}}}{\mathbf{R_y + X_y}}\right\} \tag{3.7}$$

Where $V_y$, $V_{y+1}$ voltage magnitude at node y and y+1 respectively. $\delta_y$, $\delta_{y+1}$ voltage angle at node $y$ and $y+1$. $R_y$ and $X_y$ are the resistance and reactance of the line.

Similarly, the voltage at each node is calculated using the value of the branch current obtained previously.

$$V_{y+1} = V_y - I_y\left(R_y + jX_y\right) \tag{3.8}$$

where $V_y$ and $V_{y+1}$ are the voltage magnitude at node $y$ and $y+1$ respectively, $I_y$ is the current flowing the branch $y$ and the impedance of the line is $R_y+jX_y$ .

The equations 3.7 and 3.8 are repeated and the convergence conditions are checked with an accuracy of ε=0.001 between the previous voltage calculated and the value of voltage in the current iteration.

$$\boldsymbol{\varepsilon = V_{y\_old} - V_{y\_new}} \tag{3.9}$$

Where $V_{y\_old}$ is the voltage magnitude in the previous iteration, $V_{y\_new}$ is the actual voltage magnitude, and ε is the accuracy set for the stopping criteria.

After the convergence, the current values obtained are used to evaluate the power losses in the network as described in the next section.

### 3.2.1 Objective function

The objective function of this study is formulated based on the current branch loss formula as follows [36]

$$P_{TL} = \sum_{y=1}^{N} I_y^2 \times R_y \tag{3.10}$$

$$Q_{TL} = \sum_{y=1}^{N} I_y^2 \times X_y \tag{3.11}$$

Where $P_{TL}$ and $Q_{TL}$ are total active and reactive power losses in the system respectively,

$I_y$ is the current magnitude flowing from node *y* to node *y+1*.

$R_y$ and $X_y$ are the resistance and reactance of the line respectively with *N* number of branches.

The current magnitude in Equations (3.10) and (3.11) has two components which are active component *Ia* and imaginary component *Ir*, therefore the total active and reactive power loss in the system in Equations (3.10) and (3.11) can be rewritten as:

$$P_{TL} = \sum_{y=1}^{N} I_{ay}^2 \times R_y + \sum_{y=1}^{N} I_{ry}^2 \times R_y \tag{3.12}$$

$$Q_{TL} = \sum_{y=1}^{N} I_{ay}^2 \times X_y + \sum_{y=1}^{N} I_{ry}^2 \times X_y \tag{3.13}$$

Where $I_{ay}$, $I_{ry}$ are real and imaginary components of current at node *y*

### 3.2.2 Constraints

The main objective function is subjected to equality constraints and inequality constraints described below:

**1. Bus Voltage constraints**

The voltage at each node must be within its operating conditions of ±5% of the nominal value [43].

$| V_{y\,min} | \leq | V_y | \leq | V_{y\,max} |$

**2. Feeder capacity limits**

The current flowing through each branch must be less than its maximum capacity rating to avoid overloading of the feeder lines [5].

$| I_y | \leq | I_{ymax}, |$ $y=1, 2, 3\ldots\ldots N$

**3. Power flow equation constraints**

The total active power generated ($P_{y\,Gen}$) must be equal to the sum of total real power losses in the line ($P_{loss}$) and the total active nodal loads ($P_{y\,loads}$).

$$\sum P_{yGen} = P_{Loss} + \sum P_{yloads} \tag{3.14}$$

Where $P_{yGen}$ active power injected at node $y$, $P_{loss}$ is the total real power loss, and $P_{yload}$ is the active load connected to bus $y$.

## 3.3 BACKWARD AND FORWARD SWEEP METHOD

Power flow analysis is a necessary basic tool for any electrical power system under steady state condition for determining the exact electrical performance. It helps to determine the real and reactive power losses, the amount of current flowing through the lines, and the voltage magnitude and phase angle at different nodes. It is important in the planning of the new power installation and upgrading or extension of the existing power system. The stability analysis and protection designs based on the load flow calculation, similarly the selection of the equipment and their rating such as generator capacity, switch gear for protection, transformers and the cable sizes; thus the results of the load flow is the starting point for other analyses of the electric power system. In this section, the backwards/forward sweep method for radial distribution system load flow analysis is explained and the flowchart is provided in Figure 3.2.

The Backward/Forward Sweep method (BFSM) for load flow computation is an iterative method in which, at each iteration two calculation steps are performed. The first set of equations for calculating the power flow through the branches starting from the last branch and proceeding in the backwards direction towards the root node. The other set of equations is for calculating the voltage magnitude and angle at each node starting from the root node and continuing in the forward direction till the last node [34, 35, 43, 51]. This method is useful in the radial distribution network where the classical methods for load flow analysis failed to compute the power losses in each branch accurately.

**Backwards path:** the purpose is to find the current flowing in each branch in the tree by considering the constant value of voltages found in the previous iteration while a flat voltage value assumed at the initial iteration. The backwards path starts from the last node to the source node.

**The forward path** which starts from the source node to the far end node aims to calculate the voltages at each bus while keeping the current obtained from the previous walk constant meaning that the current obtained in the backwards walk will be held constant during the forward propagation. The calculated voltages are compared with specified voltages, and if the error is within tolerance limits, the process is stopped, and the power line losses are computed otherwise; the process is repeated until criteria conditions are met. The pseudo code and the flowchart of the backwards /forward sweep method are shown below.

### Pseudo code of Backward/forward sweep algorithm

**Step 1:** Read bus data, line resistance and reactance data,

**Step 2**: Read base MVA and base KV and calculate the per unit values of the data loaded using Equations (3.1) to (3.5).

**Step 3:** Backwards walk from end node to source node to find all branch currents by using Equation (3.6) while keeping constant flat initial voltages for the initial walk else Equation (3.7)

**Step 4**: Forward walk from the source node to the far end node, to find all voltages using Equation (3.8) while updating the constant current values obtained in the previous iteration and check for convergence criterion.

**Step 5**: Check if the mismatch of the specified and calculated voltages at the substation is less than the convergence tolerance using equation (3.9). If yes, go to next step. Otherwise, repeat step 3 and step 4.

**Step 6:** calculate the total active and reactive line losses using Equations (3.10) and (3.11) with the currents and voltages obtained from the backwards and forward sweep method.

**Step 7**: Print the results of all bus voltage, branch currents and total power losses in the system,

**Step 9:** Stop.

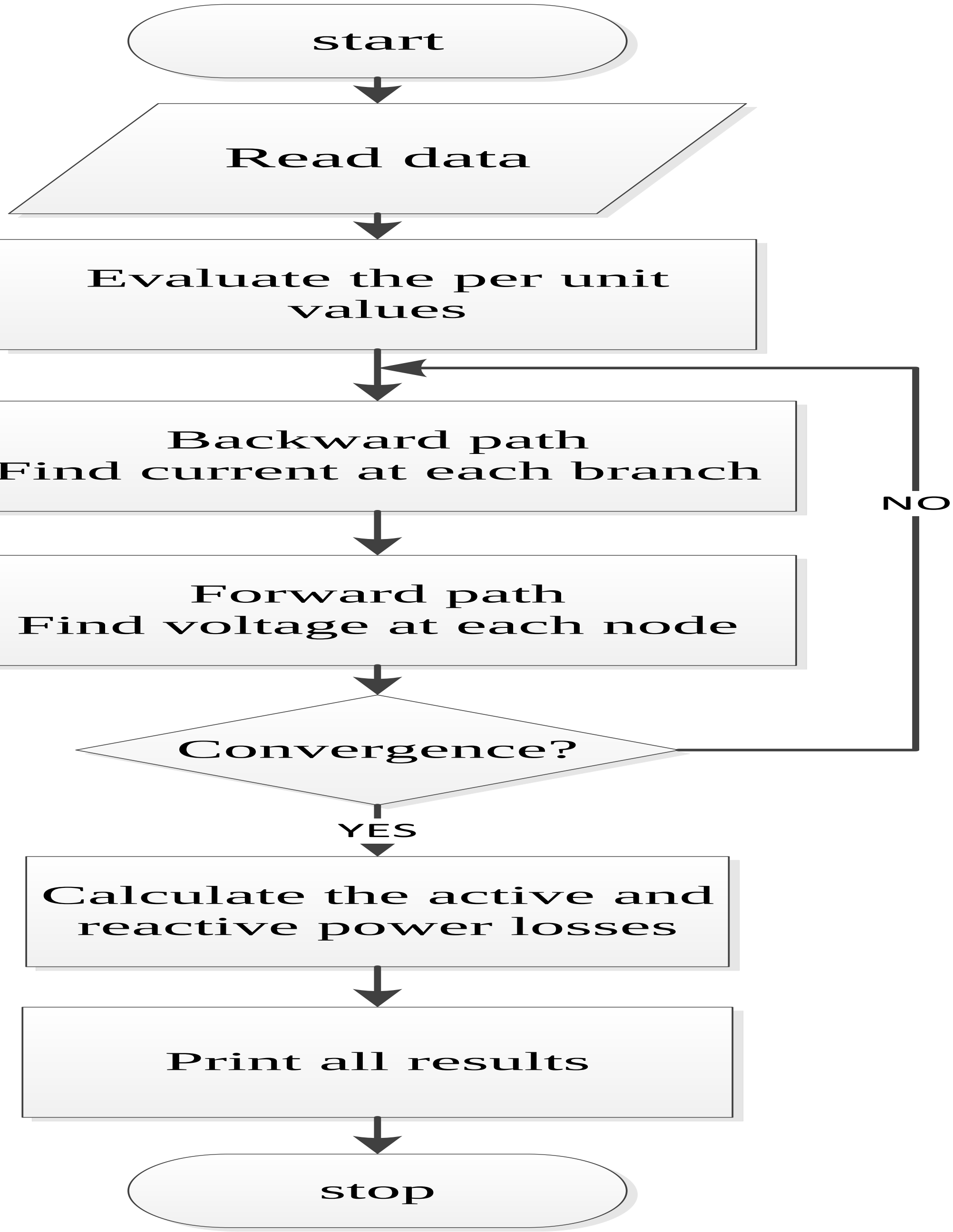


*Figure 3.2 Flowchart of Backward and forward sweep method*

## 3.4 MAXIMUM POWER LOSS SAVING TECHNIQUE

Now let consider a network of N branches, if DG is placed at node k and β set branches are branches located between the source node and the node at which DG is placed as illustrated in Figure 3.3.

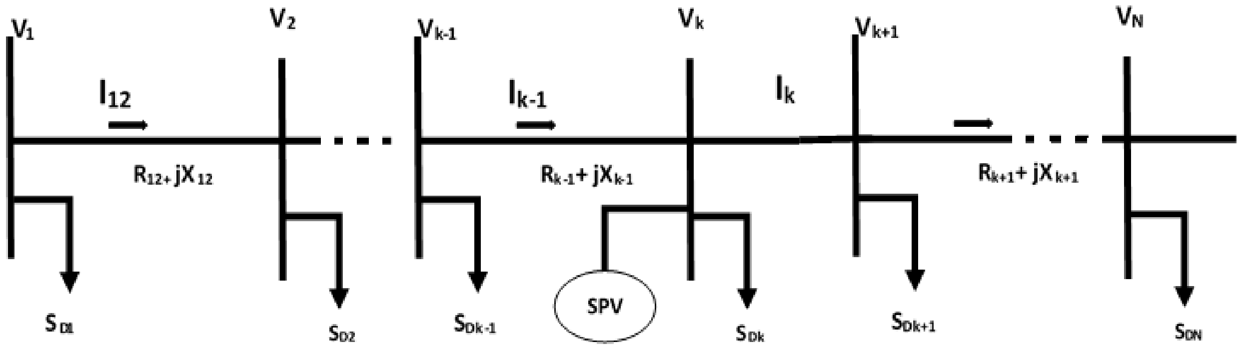


*Figure 3.3 Radial distribution network with SPV integrated*

The current flow in β branch set will be uttered by the DG current injected while the current flowing in the rest of the network remains unaffected. Furthermore, the total loss in the system with the integration of the DG in the radial distribution network can be evaluated as follow:

$$P_{LDGk} = \sum_{y=1}^{k}[(I_{ay} + I_{DGk})^2 \times R_y] + \sum_{y=k+1}^{N}(I_{ay}^2 \times R_y) + \sum_{y=1}^{k}[(I_{ry} + a_k I_{DGk})^2 \times R_y] + \sum_{y=k+1}^{N}(I_{ry}^2 \times R_y) \quad (3.15)$$

$$Q_{LDGk} = \sum_{y=1}^{k}[(I_{ay} + I_{DGk})^2 \times X_y] + \sum_{y=k+1}^{N}(I_{ay}^2 \times X_y) + \sum_{y=1}^{k}[(I_{ry} + a_k I_{DGk})^2 \times X_y] + \sum_{y=k+1}^{N}(I_{ry}^2 \times X_y) \quad (3.16)$$

Where $P_{LDGk}$, $Q_{LDGk}$ are active and reactive power loss with DG injected in the network.

$I_{ay}$, $I_{ry}$ are the real and imaginary components of the current obtained from the initial load flow analysis and $I_{DGk}$ is the active current component injected by the SPV at node $k$. $R_y$, $X_y$ are resistance and reactance of the lines respectively.

The imaginary part of the injected current is $\boldsymbol{I_{rk} = a_k I_{DGk}}$ , $I_{DGk}$ is the SPV real current injected at node k. $a_k = (sign)\tan(\cos^{-1}(PF_{dg}))$, sign =+1 if DG producing the reactive power and sign= -1 if DG is absorbing the reactive power from the network.

The maximum power loss saving technique evaluates the current injected at each node and calculates the power losses when this current is injected at that node. The saving for each DG injected is saved and compared, the bus with the maximum power loss saving is identified as the optimal node for the placement of the DG and the size of the DG is evaluated accordingly.

The power loss saving is the subtraction of the total losses with DG integrated from the initial power loss; we consider integrating the real current component from the solar photovoltaic i.e. $a_k = 0$. Thus subtracting Equation (3.15) from Equation (3.12), we will have:

$$SS_k = -2I_{DGk} \times \sum_{y=1}^{k}(I_{ay} \times R_y) - I_{DGk}^2 \times \sum_{y=1}^{k} R_y - 2a_k \times I_{DGk} \times \sum_{y=1}^{k}(I_{ry} \times R_y) - a_k^2 \times I_{DGk}^2 \times \sum_{y=1}^{k} R_y \qquad (3.17)$$

Where $SS_k$ is the power saving for DG current injected at each node.

Differentiating the Equation (3.17) with respect to the current injected at node *k*, and equating the result to zero will give the maximum power loss saving for the DG integrated at each node.

$$\frac{\partial SSk}{\partial I_{DGk}} = 0 \cong -2\sum_{y=1}^{k} I_{ay} \times R_y - 2I_{DGk}\sum_{y=1}^{k} R_y \qquad (3.18)$$

The Equation (3.18) will allow the computation of the current injected at each node. Therefore this equation is used to compute the value of the current to be injected at each candidate node for the maximum power loss reduction. Furthermore, the computed current values are replaced in Equation (3.17) for all the nodes to evaluate the saving for the injected current at each node respectively. The results are compared, then the node with highest power loss saving is identified and selected as a candidate for SPV placement. The expression for the SPV current injected at each node is given by:

$$I_{DGk} = -\frac{\sum_{y=1}^{k} I_{ay} \times R_y}{\sum_{y=1}^{k} R_y} \qquad (3.19)$$

In the analytical method, the identification of the node with maximum power loss saving defined the optimal location of the DG in the radial system and once the optimal node is identified. The size of the DG injected at that node can be evaluated using constant voltage values obtained in the initial load flow analysis multiplied by the value of current injected. The optimal size of power injected at selected node k will be the optimal branch current from Equation (3.19) with its corresponding nodal voltage magnitude as given by:

$$P_{DGk} = I_{DGk} \times |V_k| = -|V_k| \frac{\sum_{y=1}^{k} I_{ay} \times R_y}{\sum_{y=1}^{k} R_y} \qquad (3.20)$$

Where $P_{DGk}$ is the optimal active power injected at node $k$, $I_{DGk}$ is the current magnitude, and the DG voltage magnitude is $V_k$. This process is repeated for multiple integrations of the DG in the systems till power loss becomes negligible as specified in Equation (3.9). The flowchart of maximum power loss saving method is shown in figure 3.4 below.

The comparison was done based on the percentage reduction of the active power loss reduction for each method and also the voltage profile improvement of the proposed method was compared with the results found in the provided literatures.

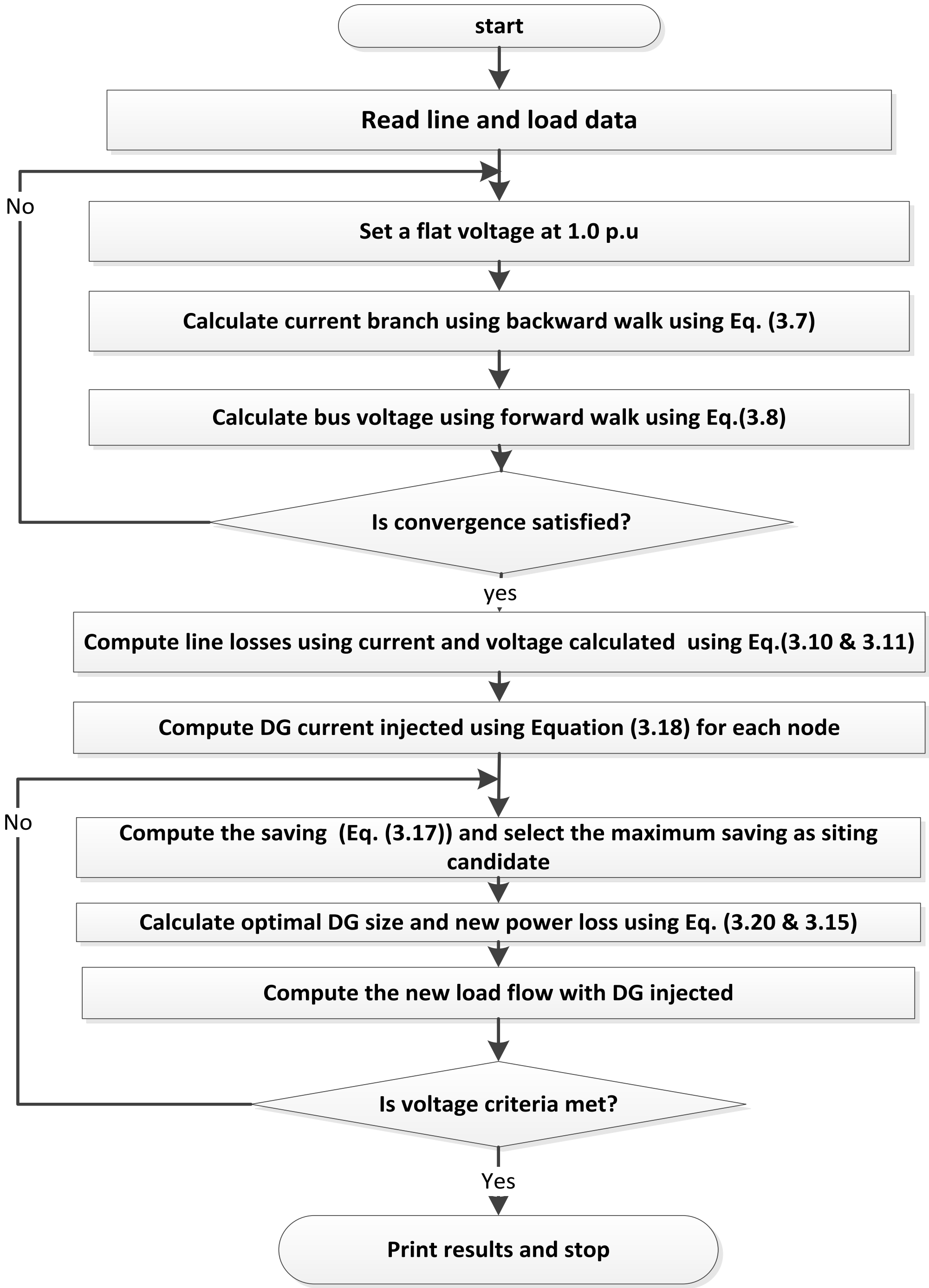


*Figure 3.4 Flowchart of load flow for DG analytical allocation*

# CHAPTER FOUR: RESULTS AND DISCUSSIONS

## 4.1 INTRODUCTION

The maximum power loss saving was tested on IEEE 33-bus with different loading scenarios and results were reported in this chapter. The analysis starts with the based load flow with 90%, 100%, and 130% of the total real and reactive power demands, and initial power losses and voltage profiles of the system were reported respectively. The results analysis of single SPV optimal placement and sizing were carried out, and the comparisons were made with the existing methods. Finally, the power factor variation was considered in the DG-units penetration in the radial distribution systems before concluding with the integration of two DGs for maximum power loss reduction and improved voltage profile using the same technique. Similarly, the results were also compared to the existing methods in the provided references.

## 4.2 LOAD FLOW ANALYSIS WITH THE BACKWARD AND FORWARD SWEEP ALGORITHM

In this section, the performance and validity of the proposed methods were tested on IEEE 33-bus radial distribution networks [36, 41], the data of the test system is shown in Appendix A, and Figure 4.1 shows the network structure. Different peak loadings were studies from the minimum loading to the medium loading then the maximum peak demand as shown in the data.

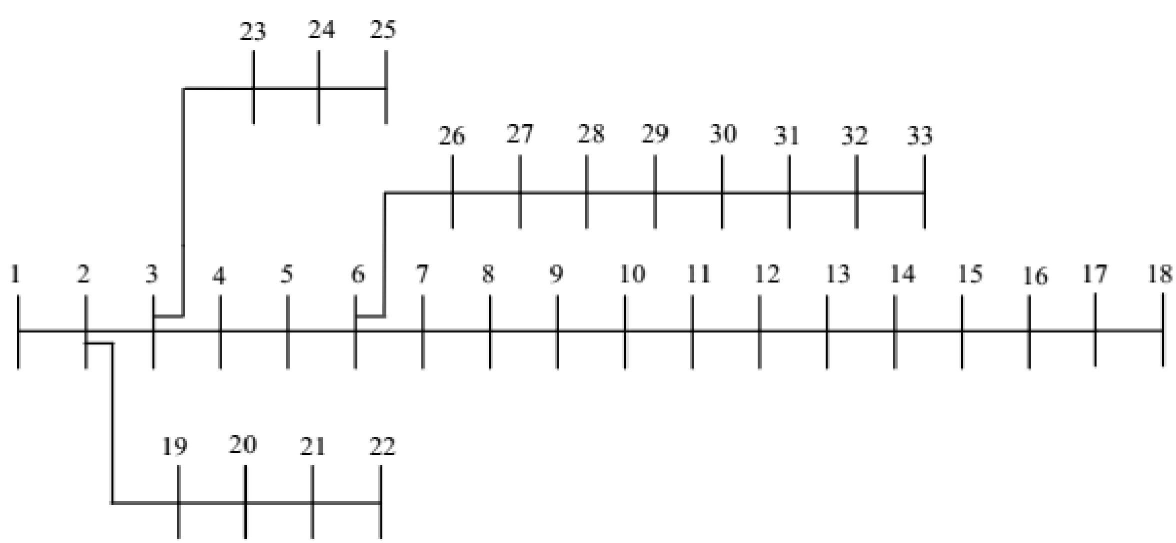


*Figure 4.1 IEEE 33 bus radial distribution network*

The test system fed on a single side, and it has a serially connected active and reactive power loads at different scenarios which are minimum, medium and maximum loading. The characteristics of the test system are given below:

Total number of nodes: 33 and Total number of branches: 32,

Kilovolt base: 12.66 KV and MVA base are 100MVA,

In this simulation, three case scenarios with different power demands corresponding to different peak loads are considered as described below:

**Case 1 Minimum Loading:** The total minimum active and reactive power loadings connected to the system are 3343.5 KW and 2070 KVAr which represent 90% of normal system loading.

**Case 2 Medium loading**: The total medium active and reactive power loadings are 3715 KW and 2300 KVAr respectively which represent the normal system loading or 100%.

**Case 3 Maximum loading:** The total maximum active and reactive power loadings are 4829.5 KW and 2990 KVAr respectively which represent 130% of the normal system loading.

The initial load flow simulation was carried out under MATLAB using the backwards and forward sweep method, and the summary of the result was presented in Table 4.1 below. The active and reactive power losses in the system represent 4.82%, and 5.19% of the total load demands respectively for the low loading, 5.44% and 5.86% of the demand for the medium loading while for the maximum loading, it represents 7.41% and 7.99% respectively thus the system losses increase proportionally with the increase in the loading.

Table 4.1 Based load flow result of the test systems

| **Loading** | **Minimum** | **Medium** | **Maximum** |
|---|---|---|---|
| Total load (KVA) | 3343.5+j2070 | 3715+j2300 | 4829.5 +j2990 |
| Total active loss (KW) | 161.1077 | 201.9057 | 357.8295 |
| Total reactive loss (kVAr) | 107.4235 | 134.6618 | 238.8545 |
| Min voltage (p.u) | 0.9227 | 0.9134 | 0.8845 |
| Bus | 18 | 18 | 18 |

Figures 4.2, 4.3 and 4.4 illustrate the nodal voltage profile, active and reactive power losses for the different loading scenarios using the backwards and forward sweep algorithm based on the branch current loss formula given in Equations (3.10) and (3.11). RDN are supplied from a single side which is the centralized generation, and the end users receive power through this passive network making the direction of the power flow to be unidirectional, thus a large amount of current flowing. The high resistance to reactance ratio explains the high power loss and the large voltage drop across the lines. Under heavy loading, the voltage is degraded further which explain a very low voltage profile of the maximum loading shown in Figures 4.2 and 4.3.

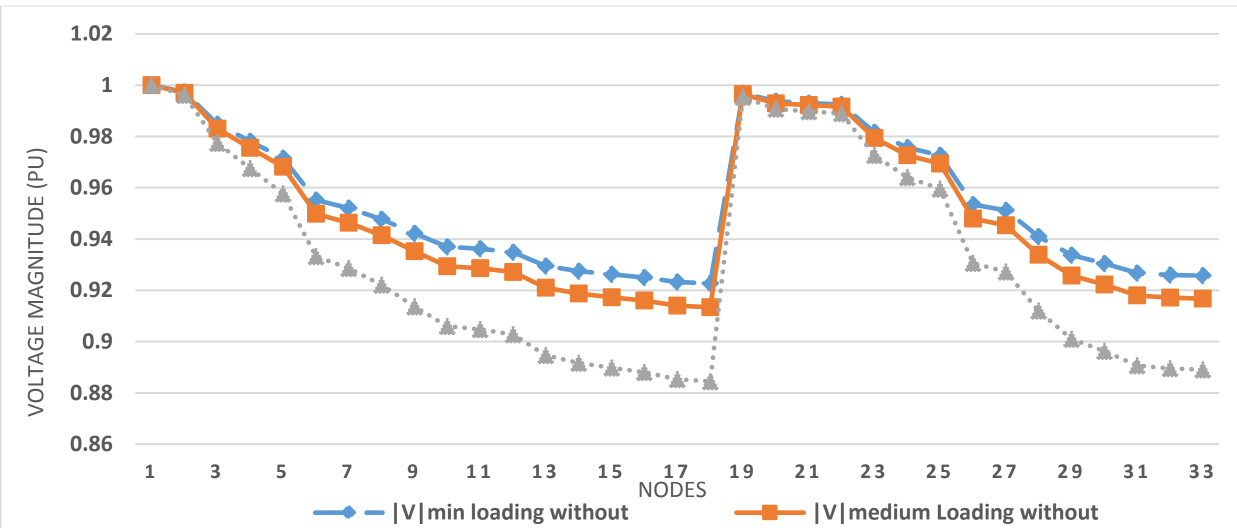


Figure 4.2 Voltage profile for different loading of 33 bus

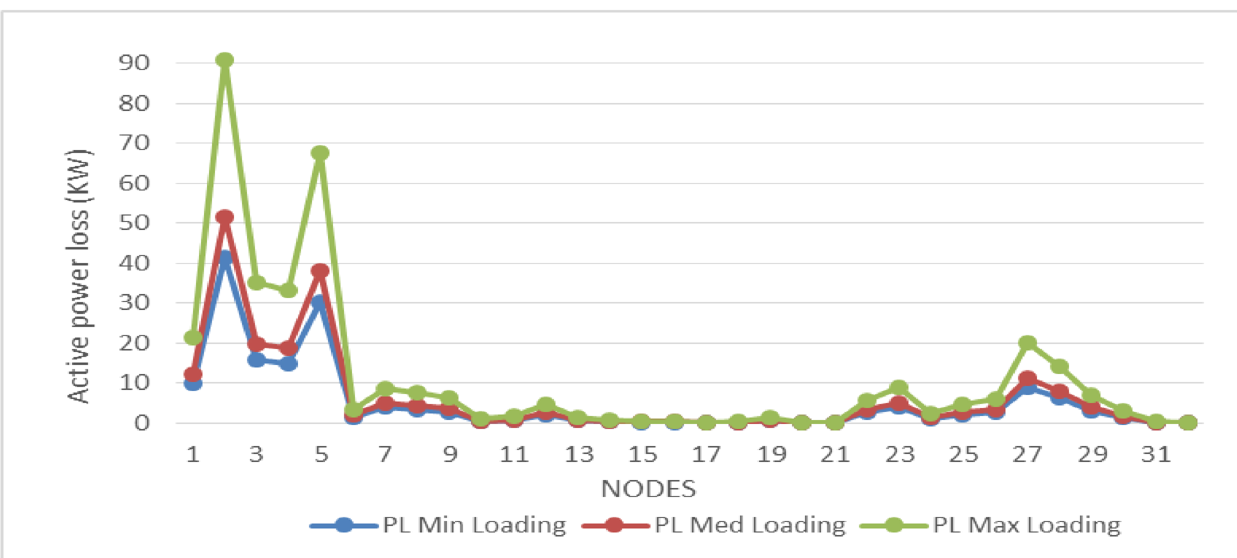


*Figure 4.3 Active power loss in different branches for three scenarios.*

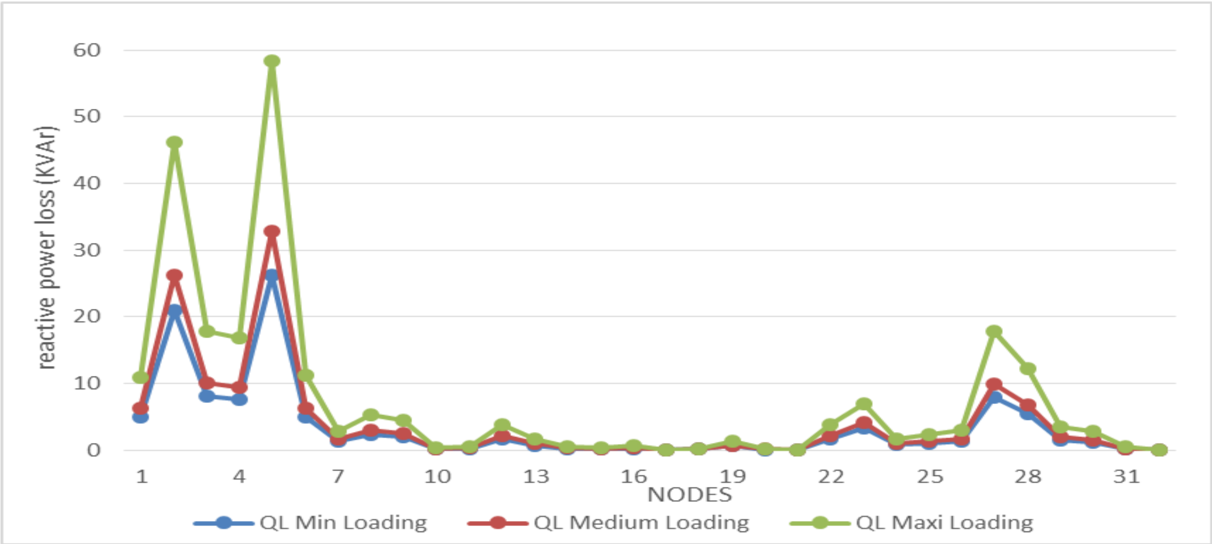


Figure 4.4 Reactive power loss in different branches for the three scenarios.

Table 4.2 shows the voltage profile for the three scenarios with the comparison with the result obtained in the provided references, for the three cases, the minimum voltage occurs at node 18 i.e. **0.9038 p.u. 0.9134 p.u. 0.9227 p.u and 0.8845 p.u.** for the minimum, medium and maximum loadings respectively. The results of the medium loading were compared to existing results [56], but the proposed method has shown better results; the total power loss for the proposed method is **201.91 KW and 134.66 KVAr**.

Table 4.2 Voltage profile (p.u) for IEEE 33 bus Radial Distribution system and the total power

| | Medium Loading | | Min Loading | Max Loading |
|---|---|---|---|---|
| nodes | ref [56] | Proposed method | proposed method | |
| 1 | 1 | 1 | 1 | 1 |
| 2 | 0.997 | 0.997 | 0.9974 | 0.9961 |
| 3 | 0.9829 | 0.983 | 0.9848 | 0.9774 |
| 4 | 0.9754 | 0.9755 | 0.9781 | 0.9675 |
| 5 | 0.968 | 0.9682 | 0.9715 | 0.9577 |
| 6 | 0.9495 | 0.9498 | 0.9552 | 0.9332 |
| 7 | 0.946 | 0.9463 | 0.9521 | 0.9286 |
| 8 | 0.9323 | 0.9415 | 0.9477 | 0.9221 |
| 9 | 0.926 | 0.9352 | 0.9422 | 0.9137 |
| 10 | 0.9201 | 0.9294 | 0.937 | 0.906 |
| 11 | 0.9192 | 0.9286 | 0.9362 | 0.9048 |
| 12 | 0.9177 | 0.9271 | 0.9349 | 0.9028 |
| 13 | 0.9115 | 0.921 | 0.9295 | 0.8947 |

| | | | | |
|---|---|---|---|---|
| 14 | 0.9092 | 0.9187 | 0.9275 | 0.8917 |
| 15 | 0.9078 | 0.9173 | 0.9262 | 0.8898 |
| 16 | 0.9064 | 0.916 | 0.925 | 0.888 |
| 17 | 0.9044 | 0.914 | 0.9232 | 0.8853 |
| **18** | **0.9038** | **0.9134** | **0.9227** | **0.8845** |
| 19 | 0.9965 | 0.9965 | 0.9969 | 0.9954 |
| 20 | 0.9929 | 0.9929 | 0.9937 | 0.9907 |
| 21 | 0.9922 | 0.9922 | 0.993 | 0.9898 |
| 22 | 0.9916 | 0.9916 | 0.9925 | 0.989 |
| 23 | 0.9793 | 0.9794 | 0.9816 | 0.9727 |
| 24 | 0.9726 | 0.9727 | 0.9756 | 0.964 |
| 25 | 0.9693 | 0.9694 | 0.9726 | 0.9596 |
| 26 | 0.9476 | 0.9479 | 0.9534 | 0.9306 |
| 27 | 0.945 | 0.9453 | 0.9512 | 0.9272 |
| 28 | 0.9335 | 0.9339 | 0.941 | 0.912 |
| 29 | 0.9253 | 0.9257 | 0.9337 | 0.901 |
| 30 | 0.9218 | 0.9222 | 0.9305 | 0.8963 |
| 31 | 0.9176 | 0.918 | 0.9268 | 0.8907 |
| 32 | 0.9167 | 0.9171 | 0.926 | 0.8895 |
| 33 | 0.9164 | 0.9168 | 0.9258 | 0.8891 |
| **Minimum voltage** | **0.9038** | **0.9134** | **0.9227** | **0.8845** |
| **bus** | **18** | **18** | **18** | **18** |
| **PTL (KW)** | **210.9824** | **201.91** | **161.108** | **357.8295** |
| **QTL (KVAr)** | **143.0219** | **134.66** | **107.424** | **238.8545** |

Table 4.3 shows the branch active and reactive power loss of the system. The maximum active loss occurs at branch 2 for the three scenarios **41.2383 KW, 51.5711 KW, and 90.7723** KW respectively while the maximum reactive power loss occurs at branch 5 which are **26.1544 KVAr, 32.826 KVAr,** and **58.442 KVAr** for the three scenarios respectively.

Table 4.3 Numerical results of the active and reactive power losses in the IEEE 33 bus RDN

| **branches** | **Active power loss in KW** | | | **Reactive power loss in KVAr** | | |
|---|---|---|---|---|---|---|
| | **Min load** | **Med load** | **Max load** | **Min load** | **Med load** | **Max load** |
| 1--2 | 9.7625 | 12.1927 | 21.3729 | 4.9766 | 6.2154 | 10.8951 |
| 2--3 | **41.2383** | **51.5711** | **90.7723** | 21.004 | 26.267 | 46.2331 |
| 3--4 | 15.7831 | 19.7934 | 35.1528 | 8.0382 | 10.081 | 17.903 |
| 4--5 | 14.8178 | 18.5931 | 33.0784 | 7.5469 | 9.4697 | 16.8473 |
| 5--6 | 30.2977 | 38.0256 | 67.7001 | **26.1544** | **32.826** | **58.442** |
| 6--7 | 1.5248 | 1.9131 | 3.4027 | 5.0402 | 6.3238 | 11.2478 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7--8 | 3.8493 | 4.8342 | 8.6241 | 1.2721 | 1.5976 | 2.85 |
| 8--9 | 3.3225 | 4.1773 | 7.4799 | 2.387 | 3.0012 | 5.3739 |
| 9--10 | 2.8287 | 3.5575 | 6.3764 | 2.005 | 2.5216 | 4.5197 |
| 10--11 | 0.4397 | 0.5531 | 0.992 | 0.1454 | 0.1829 | 0.328 |
| 11--12 | 0.6996 | 0.8802 | 1.5801 | 0.2313 | 0.2911 | 0.5225 |
| 12--13 | 2.1163 | 2.6638 | 4.7866 | 1.6651 | 2.0958 | 3.766 |
| 13--14 | 0.5787 | 0.7286 | 1.3099 | 0.7618 | 0.959 | 1.7242 |
| 14--15 | 0.2834 | 0.3569 | 0.6424 | 0.2522 | 0.3176 | 0.5717 |
| 15--16 | 0.2234 | 0.2813 | 0.5066 | 0.1631 | 0.2054 | 0.37 |
| 16--17 | 0.1996 | 0.2515 | 0.4532 | 0.2665 | 0.3358 | 0.605 |
| 17--18 | 0.0422 | 0.0531 | 0.0957 | 0.0331 | 0.0416 | 0.075 |
| 2--19 | 0.1302 | 0.161 | 0.2732 | 0.1242 | 0.1536 | 0.2607 |
| 19--20 | 0.673 | 0.8322 | 1.4132 | 0.6064 | 0.7498 | 1.2734 |
| 20--21 | 0.0815 | 0.1008 | 0.1711 | 0.0952 | 0.1177 | 0.1999 |
| 21--22 | 0.0353 | 0.0436 | 0.0741 | 0.0466 | 0.0577 | 0.098 |
| 3--23 | 2.5613 | 3.1812 | 5.4774 | 1.7501 | 2.1737 | 3.7426 |
| 23--24 | 4.1402 | 5.1432 | 8.8605 | 3.2693 | 4.0613 | 6.9966 |
| 24--25 | 1.0359 | 1.2873 | 2.2202 | 0.8106 | 1.0073 | 1.7373 |
| 6--26 | 2.0646 | 2.594 | 4.6342 | 1.0516 | 1.3213 | 2.3605 |
| 26--27 | 2.6425 | 3.3211 | 5.9387 | 1.3454 | 1.6909 | 3.0237 |
| 27--28 | 8.9701 | 11.2766 | 20.1834 | 7.9088 | 9.9424 | 17.7953 |
| 28--29 | 6.2179 | 7.818 | 14.00 | 5.4169 | 6.8108 | 12.1965 |
| 29--30 | 3.0919 | 3.8881 | 6.9661 | 1.5749 | 1.9805 | 3.5482 |
| 30--31 | 1.2656 | 1.5928 | 2.8611 | 1.2508 | 1.5742 | 2.8277 |
| 31--32 | 0.1693 | 0.2131 | 0.3829 | 0.1973 | 0.2484 | 0.4462 |
| 32--33 | 0.0105 | 0.0132 | 0.0237 | 0.0163 | 0.0205 | 0.0368 |

## 4.2 MAXIMUM LOSS SAVING TECHNIQUE RESULTS

This section discusses the results of the maximum power loss saving in the identification of optimal location and calculation of the size of SPV to reduce losses in the system. The single SPV and two DG are discussed respectively considering different loading conditions.

### 4.2.1 OPTIMAL PLACEMENT OF SINGLE DG WITH UNITY POWER FACTOR

The validity of the proposed method discussed in section 3.3 was tested on the standard IEEE 33-bus RDN considering different scenarios of the loadings using results obtained from the basic load flow calculation above. It is assumed that all nodes in the network are candidates for the SPV placement except slack bus. The currents flowing in each branch were calculated first with the nodal voltage then the algorithm was used to identify the node with maximum power loss saving which becomes the optimal candidate for SPV placement, and the optimal SPV size was calculated using the injected current value. In this study, node six is identified as the optimal SPV location for maximum active power loss reduction as shown in Table 4.4. The active power reduction percentage of the medium loading, was compared to references [41, 57 and 58] but the results of the proposed method gave a better result of 48.99% of loss reduction compared to a decrease of 48.19%, 47.33% and 44.83% for [41, 57 and 58] respectively.

Table 4.4 Summary of SPV placement impact on loss and voltage improvement

| Loading | low | Medium | | Maximum |
|---|---|---|---|---|
| | | [57] | proposed method | |
| optimal siting | 6 | 6 | 6 | 6 |
| optimal size (MW) at 1PF | 2.2243 | 2.601 | 2.4752 | 3.2337 |
| Initial Active losses (KW) | 161.1077 | 211.2 | 201.9057 | 357.8295 |
| Total active loss (KW) | 82.8181 | 111.1 | 102.9785 | 177.83 |
| % of MW loss reduction | 48.60% | 47.33% | 48.99% | 50.30% |
| Total reactive loss (KVAr) | 59.6041 | -- | 74.1179 | 128.05 |
| Min voltage (p.u) at node 18 | 0.9558 | 0.9425 | 0.9507 | 0.9352 |

Figures 4.5, 4.6, and 4.7 show the comparison of the real power branch losses with and without SPV integration for the minimum, medium and maximum loading scenarios respectively. The active power losses in the branches located between the source node and the optimal node at which the SPV was placed have drastically reduced. It is three times lesser than the initial losses. However, beyond the optimal node, there was only a slight power loss reduction.

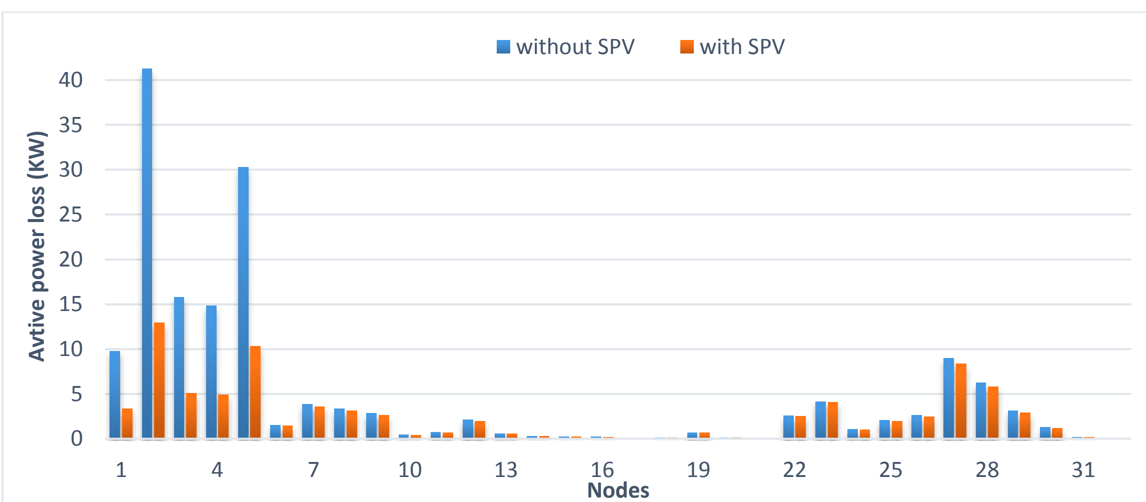


Figure 4.5. Active power loss comparison for the minimum loading

The drastic power loss reduction is caused by the active power injected at the optimal node 6, the injected power supplied part of the total loads thus reducing the amount of current flowing in the line between the source and node 6.

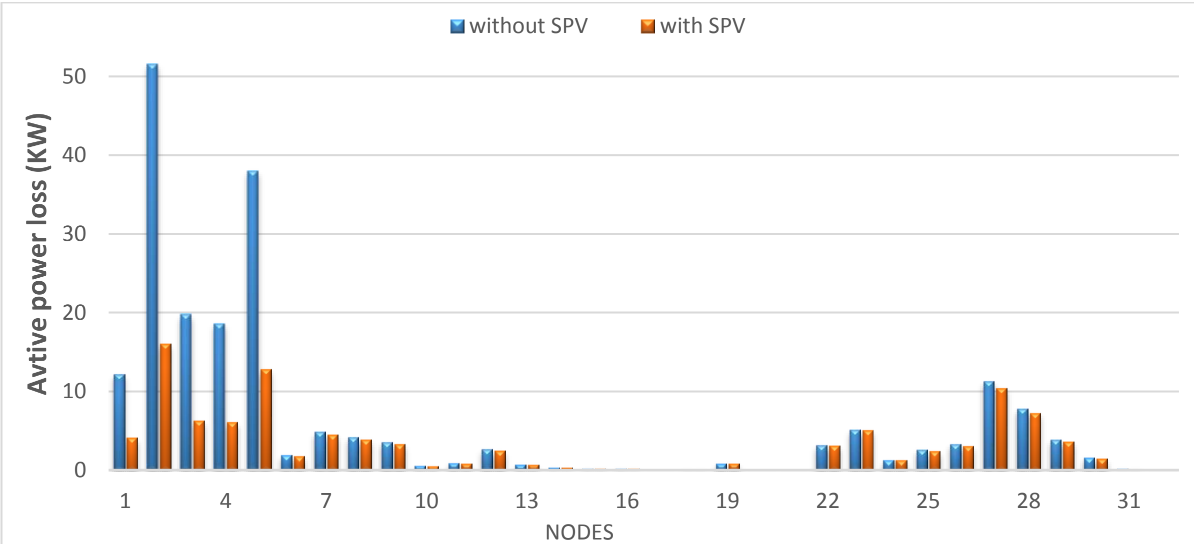


Figure 4.6. Active power loss comparison for the medium loading

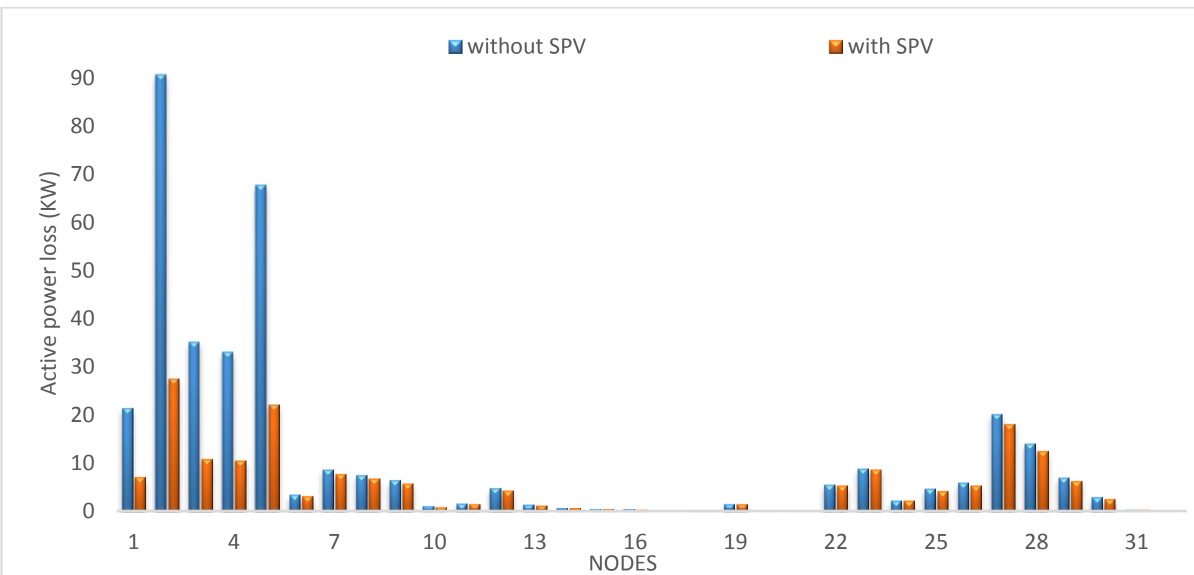


Figure 4.7. Active power loss comparison for the maximum loading

Table 4.5 provides the branch active and reactive power losses with solar photovoltaic system penetration for the different loading scenarios. The maximum branch loss occurs at the same branch 2 for the real power loss and branch 5 for the reactive power loss, but the loss values have drastically reduced with the integration of SPV. The percentage of active power loss reduction are

48.60% for case 1, 48.99% for case 2 and 50.66% for case 3 respectively. The SPV integrated has supplied the total or part of that particular zone load demand, hence reducing the current flow from the source to a load of a given location.

*Table 4.5 Real and Reactive power loss at each branch with the SPV integration for the 33 bus RDN*

| branch | Active power loss in KW | | | Reactive power loss KVAr | | |
|---|---|---|---|---|---|---|
| | case 1 | case 2 | case 3 | case 1 | case 2 | case 3 |
| 1--2 | 3.3202 | 4.1214 | 7.0429 | 1.6925 | 2.1009 | 3.5902 |
| 2--3 | **12.9281** | **16.0621** | **27.5398** | 6.5847 | 8.1809 | 14.0269 |
| 3--4 | 5.0467 | 6.2715 | 10.8364 | 2.5702 | 3.194 | 5.5189 |
| 4--5 | 4.893 | 6.0796 | 10.5165 | 2.4921 | 3.0965 | 5.3562 |
| 5--6 | 10.3155 | 12.8149 | 22.1729 | **8.9049** | **11.0624** | **19.1407** |
| 6--7 | 1.4234 | 1.77 | 3.0566 | 4.7052 | 5.8509 | 10.1037 |
| 7--8 | 3.5919 | 4.4701 | 7.7386 | 1.187 | 1.4773 | 2.5574 |
| 8--9 | 3.0987 | 3.8601 | 6.7034 | 2.2262 | 2.7733 | 4.816 |
| 9--10 | 2.6378 | 3.2869 | 5.7128 | 1.8697 | 2.3298 | 4.0493 |
| 10--11 | 0.4099 | 0.5109 | 0.8886 | 0.1355 | 0.1689 | 0.2938 |
| 11--12 | 0.6522 | 0.813 | 1.4149 | 0.2157 | 0.2688 | 0.4679 |
| 12--13 | 1.9728 | 2.46 | 4.2849 | 1.5522 | 1.9355 | 3.3713 |
| 13-14 | 0.5395 | 0.6728 | 1.1724 | 0.7101 | 0.8856 | 1.5432 |
| 14-15 | 0.2641 | 0.3295 | 0.5747 | 0.235 | 0.2932 | 0.5115 |
| 15-16 | 0.2082 | 0.2597 | 0.4532 | 0.152 | 0.1897 | 0.331 |
| 16-17 | 0.186 | 0.2321 | 0.4053 | 0.2484 | 0.3099 | 0.5412 |
| 17-18 | 0.0393 | 0.049 | 0.0856 | 0.0308 | 0.0384 | 0.0671 |
| 2--19 | 0.1298 | 0.1604 | 0.272 | 0.1239 | 0.1531 | 0.2596 |
| 19-20 | 0.6711 | 0.8296 | 1.4073 | 0.6047 | 0.7475 | 1.268 |
| 20-21 | 0.0812 | 0.1004 | 0.1704 | 0.0949 | 0.1173 | 0.1991 |
| 21-22 | 0.0352 | 0.0435 | 0.0738 | 0.0465 | 0.0575 | 0.0976 |
| 3--23 | 2.5155 | 3.1173 | 5.3283 | 1.7188 | 2.13 | 3.6408 |
| 23-24 | 4.066 | 5.0397 | 8.6188 | 3.2107 | 3.9795 | 6.8057 |
| 24-25 | 1.0173 | 1.2613 | 2.1594 | 0.796 | 0.987 | 1.6897 |
| 6--26 | 1.9243 | 2.395 | 4.147 | 0.9801 | 1.2199 | 2.1123 |
| 26-27 | 2.4625 | 3.0658 | 5.3126 | 1.2538 | 1.561 | 2.7049 |
| 27-28 | 8.3581 | 10.4083 | 18.0501 | 7.3692 | 9.1768 | 15.9144 |
| 28-29 | 5.7934 | 7.2154 | 12.5184 | 5.047 | 6.2859 | 10.9057 |
| 29-30 | 2.8806 | 3.5881 | 6.2278 | 1.4673 | 1.8276 | 3.1722 |
| 30-31 | 1.1786 | 1.4691 | 2.5553 | 1.1648 | 1.4519 | 2.5254 |
| 31-32 | 0.1577 | 0.1965 | 0.3419 | 0.1838 | 0.2291 | 0.3985 |
| 32-33 | 0.0097 | 0.0121 | 0.0211 | 0.0151 | 0.0189 | 0.0328 |

The voltage profile of the three cases with the integration of SPV is given in Table 4.6, and Figures 4.8, 4.9, and 4.10 provide the voltage profile before and after the SPV integration for the three cases respectively.

*Table 4.6 Voltage profile with and without SPV for the three cases of 33 bus RDN*

| without SPV injected | | | | with SPV injected at node 6 | | |
|---|---|---|---|---|---|---|
| Buses | \|V\| min loading | \|V\| medium Loading | \|V\| Max Loading | \|V\| min loading | \|V\| medium Loading | \|V\| Max Loading |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0.9974 | 0.997 | 0.9961 | 0.9987 | 0.9986 | 0.9982 |
| 3 | 0.9848 | 0.983 | 0.9774 | 0.9935 | 0.9928 | 0.9906 |
| 4 | 0.9781 | 0.9755 | 0.9675 | 0.9924 | 0.9915 | 0.989 |
| 5 | 0.9715 | 0.9682 | 0.9577 | 0.9915 | 0.9905 | 0.9877 |
| 6 | 0.9552 | 0.9498 | 0.9332 | 0.9875 | 0.9861 | 0.9821 |
| 7 | 0.9521 | 0.9463 | 0.9286 | 0.9844 | 0.9826 | 0.9775 |
| 8 | 0.9477 | 0.9415 | 0.9221 | 0.9803 | 0.978 | 0.9714 |
| 9 | 0.9422 | 0.9352 | 0.9137 | 0.9748 | 0.9719 | 0.9634 |
| 10 | 0.937 | 0.9294 | 0.906 | 0.9698 | 0.9663 | 0.956 |
| 11 | 0.9362 | 0.9286 | 0.9048 | 0.9691 | 0.9655 | 0.9549 |
| 12 | 0.9349 | 0.9271 | 0.9028 | 0.9678 | 0.9641 | 0.953 |
| 13 | 0.9295 | 0.921 | 0.8947 | 0.9625 | 0.9582 | 0.9452 |
| 14 | 0.9275 | 0.9187 | 0.8917 | 0.9605 | 0.9559 | 0.9422 |
| 15 | 0.9262 | 0.9173 | 0.8898 | 0.9593 | 0.9546 | 0.9404 |
| 16 | 0.925 | 0.916 | 0.888 | 0.9581 | 0.9532 | 0.9386 |
| 17 | 0.9232 | 0.914 | 0.8853 | 0.9563 | 0.9513 | 0.936 |
| 18 | 0.9227 | 0.9134 | 0.8845 | 0.9558 | 0.9507 | 0.9352 |
| 19 | 0.9969 | 0.9965 | 0.9954 | 0.9983 | 0.9981 | 0.9975 |
| 20 | 0.9937 | 0.9929 | 0.9907 | 0.995 | 0.9945 | 0.9928 |
| 21 | 0.993 | 0.9922 | 0.9898 | 0.9944 | 0.9938 | 0.9919 |
| 22 | 0.9925 | 0.9916 | 0.989 | 0.9938 | 0.9931 | 0.9911 |
| 23 | 0.9816 | 0.9794 | 0.9727 | 0.9903 | 0.9893 | 0.986 |
| 24 | 0.9756 | 0.9727 | 0.964 | 0.9844 | 0.9826 | 0.9773 |
| 25 | 0.9726 | 0.9694 | 0.9596 | 0.9814 | 0.9793 | 0.973 |
| 26 | 0.9534 | 0.9479 | 0.9306 | 0.9859 | 0.9843 | 0.9798 |
| 27 | 0.9512 | 0.9453 | 0.9272 | 0.9838 | 0.9819 | 0.9766 |
| 28 | 0.941 | 0.9339 | 0.912 | 0.974 | 0.971 | 0.9623 |
| 29 | 0.9337 | 0.9257 | 0.901 | 0.967 | 0.9632 | 0.9521 |
| 30 | 0.9305 | 0.9222 | 0.8963 | 0.964 | 0.9599 | 0.9478 |
| 31 | 0.9268 | 0.918 | 0.8907 | 0.9604 | 0.9559 | 0.9424 |
| 32 | 0.926 | 0.9171 | 0.8895 | 0.9596 | 0.955 | 0.9412 |
| 33 | 0.9258 | 0.9168 | 0.8891 | 0.9593 | 0.9547 | 0.9409 |

It was observed that despite the compensation, the minimum voltage profile uniformly occurred at node 18 for all the loading operations but the correction of the voltage magnitude varied from one case to another. The voltage at node 18 improved from 0.9227 p.u. to 0.9558 p.u., 0.9134 p.u. to 0.9507 p.u., and 0.8845 p.u. to 0.9352 p.u. for the minimum, medium, and maximum loadings respectively. The minimum loading presented a better voltage profile than the medium and maximum loading respectively. The placement of SPV at node 6 has improved the whole network voltage profile.

The injection of SPV has reduced the overall current magnitude flowing in the network and also decreases the voltage drop across the distribution lines. Therefore the far end users experience the voltage profile improvement. In this study, the remote node is identified to be node 18 and it experiences the lowest voltage profile which has been improved after injecting a SPV. Moreover, to improve the voltage profile, voltage stability index study for the optimal placement of DG or the reactive power compensation to support the voltage are recommended instead of the power loss index as considered in this study.

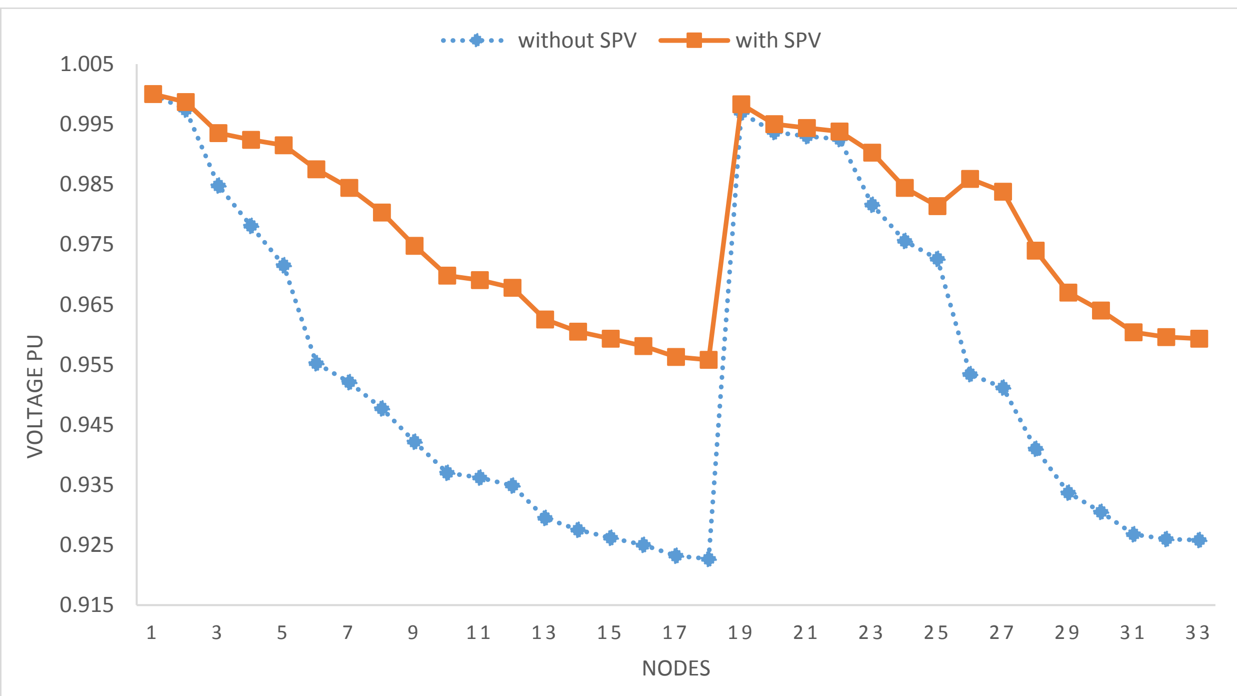


Figure 4.8 Comparison of the voltage profile with and without SPV for minimum loading

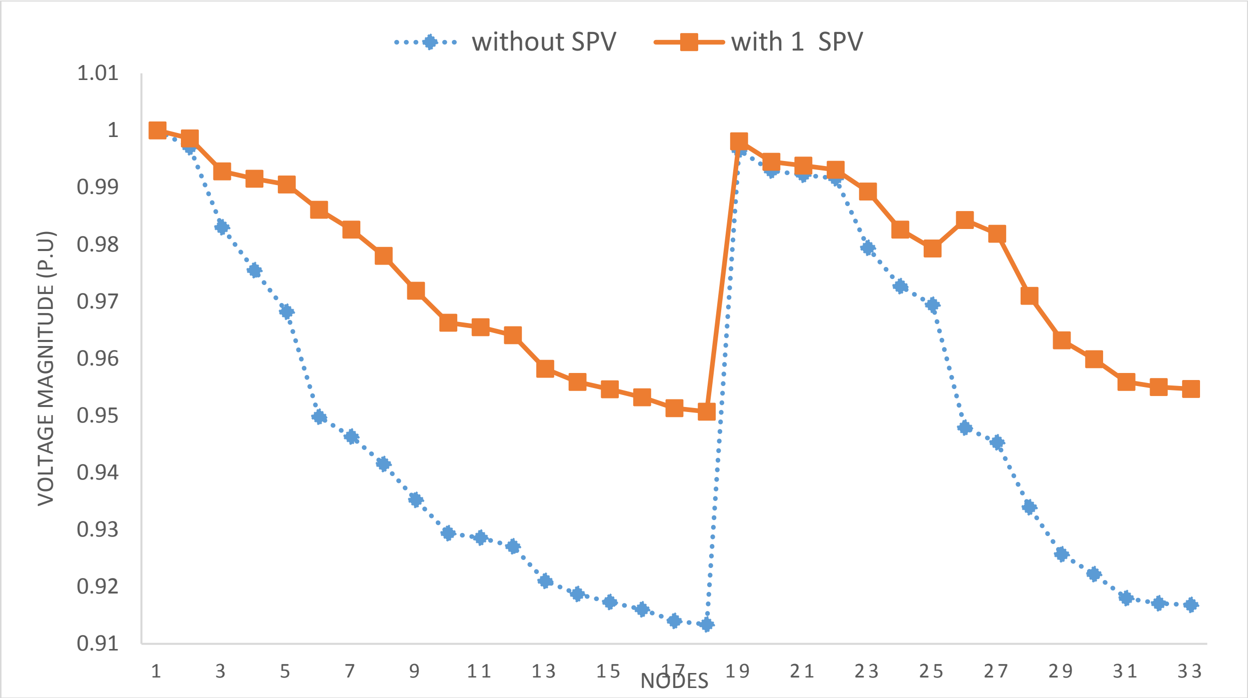


Figure 4.9 Comparison of the voltage profile with and without SPV for Medium loading

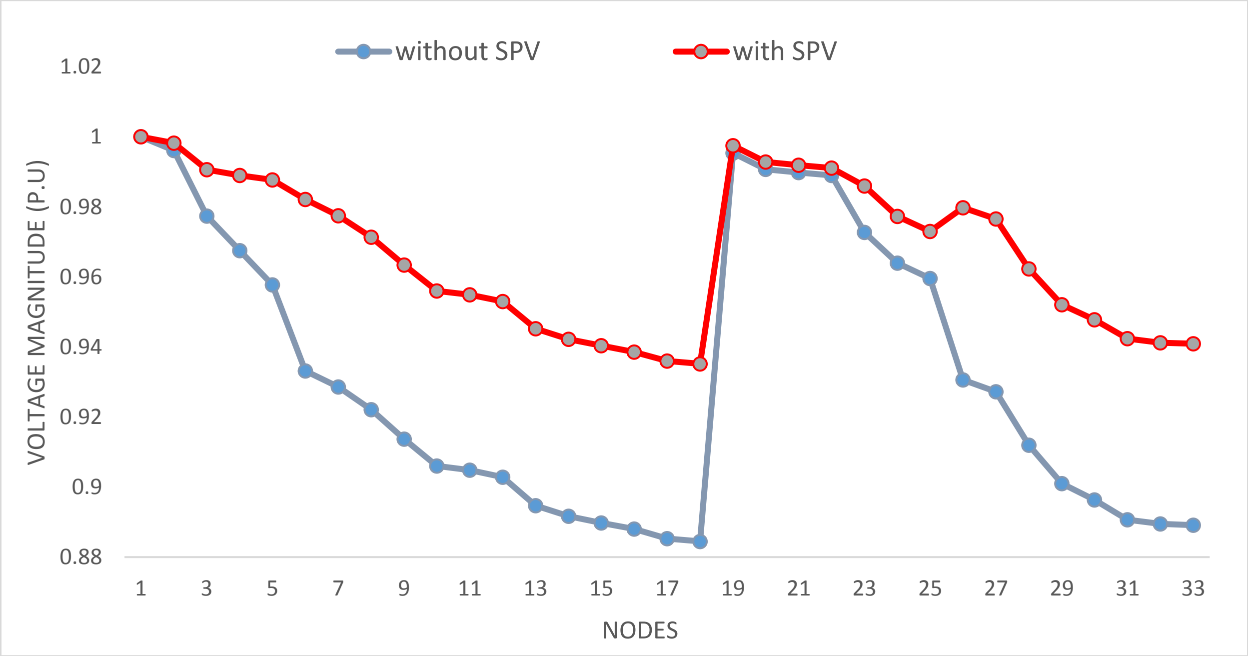


Figure 4.10 Comparison of the voltage profile with and without SPV for maximum loading

The variation of the voltage profile due to the effect of SPV penetration was compared to the Firefly Algorithm [59], and the proposed method gives a better voltage profile. It is observed that the size of the SPV integrated increases with the increase in loading but the location remains the same despite the loading variations. Similarly, the node at which the minimum voltage occurs is the same for the different cases and even after compensation. Figure 4.11 gives the comparison of the voltage profile for the three cases with and without SPV injected. The minimum voltage profile at 18, had improved by 0.0331pu, 0.0373pu and 0.0507pu when the SPV was optimally inserted at node 6 for low, medium, and maximum loadings respectively.

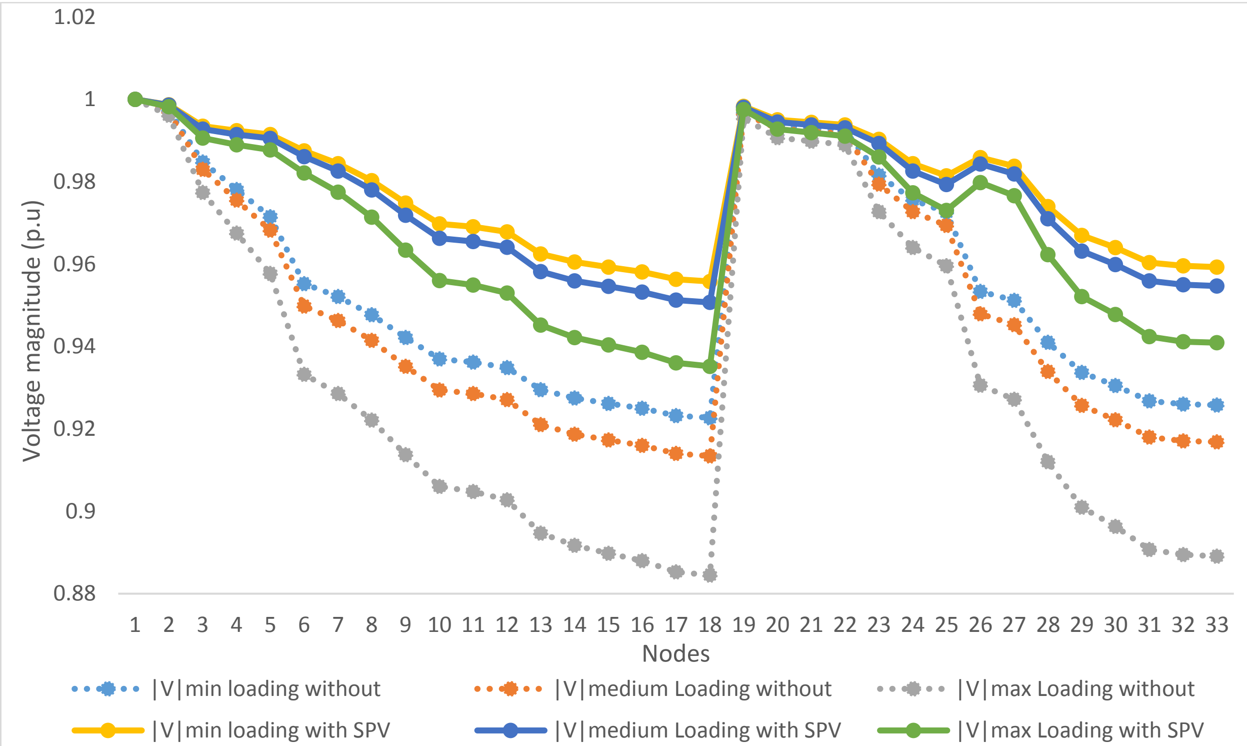


Figure 4.11 Comparison of the voltage profile for different loadings with and without SPV penetration at unity PF

### 4.2.2 PLACEMENT OF TWO DG WITH VARIATION OF POWER FACTOR

Table 4.7 shows the DG integration at different power factor and the effect on real power loss and voltage profile were observed for the three cases. The power factor set at 0.95 lagging has shown better active power loss reduction compared to unity PF and 0.85 lagging while the best voltage profile was found with unity power factor for all the cases followed by 0.95 PF lagging and 0.85 PF lagging respectively. The role of the power factor is vital in the stability of the electric power system. Therefore, a careful design is required when injecting SPV in the grid at a power factor different from unity.

Table 4.7. Results of the DG injected at node 6 with different power factor for the three cases

| Power factor | **0.85 PF lagging** | | | **0.95 PF lagging** | | | **unity PF** | | |
|---|---|---|---|---|---|---|---|---|---|
| Loading | low | Medium | Maximum | low | Medium | Maximum | low | Medium | Maximum |
| Optimal size (MW) | 0.91845 | 1.0213 | 1.3311 | 1.5512 | 1.7257 | 2.2524 | 2.2243 | 2.4752 | 3.2337 |
| Initial Active loss (KW) | 161.1077 | 201.9057 | 357.8295 | 161.108 | 201.9057 | 357.8295 | 161.1077 | 201.9057 | 357.8295 |
| Total active loss (KW) | 92.4154 | 115.89 | 205.8447 | 75.7351 | 94.9765 | 168.7016 | 82.8181 | 102.9785 | 177.83 |
| % of MW loss reduction | **42.64%** | **42.60%** | **42.47%** | **52.99** | **52.96%** | **52.85%** | **48.60%** | **48.99%** | **50.30%** |
| Total reactive loss (KVAr) | 107.424 | 134.662 | 238.855 | 107.43 | 134.662 | 238.855 | 59.6041 | 74.1179 | 128.05 |
| Min voltage (p.u) at bus18 | **0.9418** | **0.935** | **0.9139** | **0.9504** | **0.9446** | **0.9253** | **0.9558** | **0.9507** | **0.9352** |

The medium loading in case 2 was used for the optimal successive placement of DGs using the maximum power loss saving technique with different power factors. The placement of two DGs in the radial distribution networks allows the maximum reduction of real power loss and a net improvement of voltage profile as shown in Table 4.8. The results compared to the Exhaustive load flow [57], and it was observed that the locations are different. Furthermore, the power loss reduction of the proposed method was better than that of [57] and [60].

Table 4. 8. Optimal placement of two DGs in the radial distribution system

| Power factor | **unity PF** | | | | **0.95 PF lag** | | **0.85 PF lag** | |
|---|---|---|---|---|---|---|---|---|
| comparison | [57] | | Proposed method | | Proposed method | | Proposed method | |
| Number of DG | First DG | second DG | First DG | second DG | First DG | second DG | First DG | second DG |
| Optimal location | 6 | 14 | 6 | 32 | 6 | 32 | 6 | 31 |
| Optimal size (KW) | 1800 | 720 | 2475.2 | 41.9487 | 1725.7 | 336.674 | 1.0213 | 247.052 |
| Initial Active loss | - | 211.2 | 201.91 | 201.906 | 201.91 | 201.906 | 201.91 | 201.906 |
| Total active loss (KW) after | - | 91.63 | 102.979 | 78.806 | 94.9765 | 47.79 | 115.89 | 66.355 |
| % of MW loss reduction | - | **56.61%** | 48.99% | **60.97%** | **52.96%** | **76.33%** | 42.61% | **67.13%** |
| Min voltage (p.u) at bus 18 | - | 0.9539 at 33 | 0.9507 | 0.9515 | 0.9446 | 0.9465 | 0.935 | 0.9403 |

Figure 4.12 shows a comparison between the voltage profile before and after injecting two DGs in the radial distribution network for normal loading. The minimum voltage which occurred at node 18 was 0.9134 p.u. for base load flow of the medium loading, and it had improved to 0.9507 p.u. when single DG was integrated at unity power factor. There was a further voltage improvement for the second DG injected in the system to 0.9515 p.u. Furthermore, there was a significant improvement in voltage profile of 0.0311 p.u, 0.0373 p.u, and 0.0507 p.u for low, medium, and maximum loading conditions at the minimum node when a single SPV was optimally injected at node 6. After integrating the second SPV, there was a slight voltage improvement from the single SPV penetration as shown in Figure 4.12 and Table 4.8.

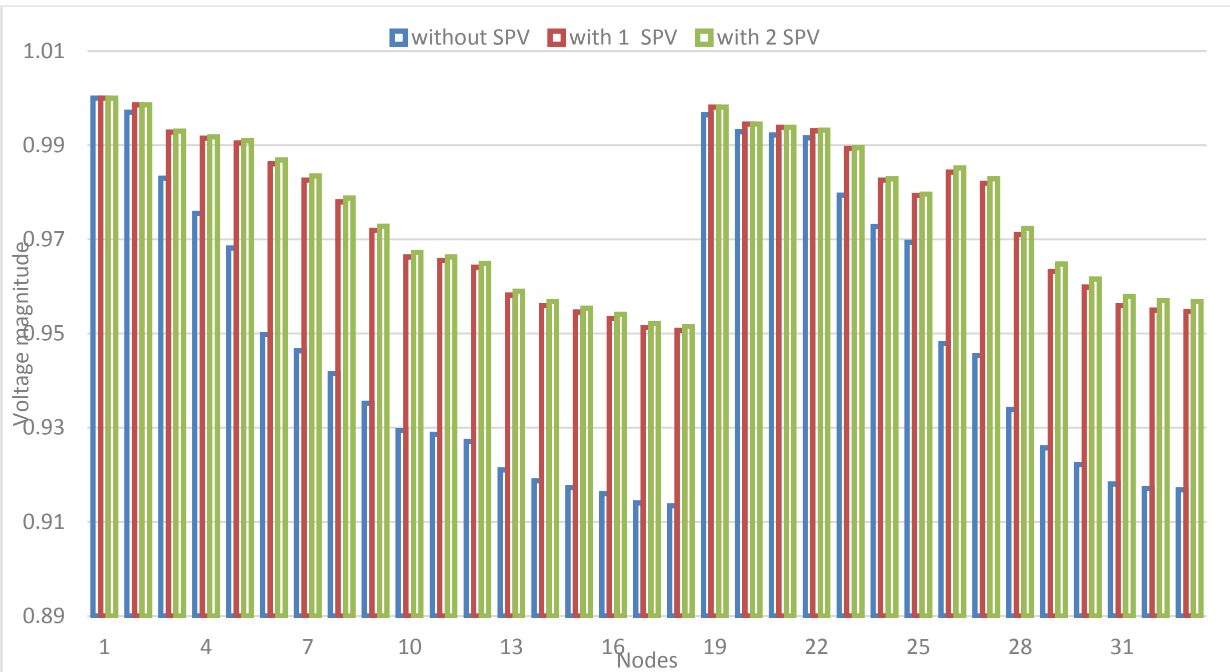


Figure 4.12 Comparison of the voltage profile for base load flow, with one DG, and two DGs injected.

The performance of the proposed method in optimally placing single DG in the radial distribution system for effective active power loss reduction and improved voltage profile on IEEE 33-bus test system was compared to metaheuristic methods [45, 59], and improved analytical method [57]. The method has optimally identified the same location of DG in RDN as other methods and the size of the placed DG varied from one method to another. The maximum active power reduction of the proposed analytical method has outperformed those methods provided in the reference as shown in Table 4.9. The minimum voltage magnitude occurred at the same node 18 for all the algorithms. The proposed maximum power loss saving technique has shown better voltage profile than improved analytical method [57] and Firefly method [59] respectively. Therefore, the proposed approach of using the branch current loss formula along with the maximum power loss saving could be effectively used for the optimal placement and sizing of DGs in radial distribution systems.

Table 4.9 Comparison of different approaches for optimal DGs in IEEE 33-bus RDN

| Method used | ABC [45] | Firefly [59] | IA [57] | Proposed method |
|---|---|---|---|---|
| optimal bus | 6 | 30 | 6 | 6 |
| Optimal size (KW) | 2400 | 1190.4 | 2601 | 2475.2 |
| loss reduction percentage | 48.20% | 48.74% | 47.39% | 48.99% |
| voltage profile p.u at 18 | 0.964 | 0.9398 | 0.9425 | 0.9507 |

# CHAPTER FIVE: CONCLUSION AND RECOMMANDATIONS

## 5.1 CONCLUSION

The impact of power losses and the low voltage profile in the radial distribution networks are among the critical issues in the electric power systems. It affects especially the planning and operation conditions of the distribution networks. Numerous approaches have been used to address the power loss reduction including the network reconfiguration, capacitor banks and FACTs to support the voltage profile, and DGs integration. Each approach has specific techniques for the integration with their merits and disadvantages. The integration of SPV has both advantages of power loss reduction and the greenhouse gases reduction.

Maximum power loss saving technique was proposed to optimally place and size SPV in the RDN and it has been tested on the standard IEEE 33 bus and from the results discussed, the proposed method has given better results in terms of power loss reduction and voltage profile improvement.

The proposed analytical method has been used to identify the optimal node candidate for the SPV placement and to compute the size of the SPV at that node to achieve the maximum power loss reduction. Further investigation was done on 3 different discrete power factor to achieve the maximum power loss reduction follow by the placement of 2 DGs which has further improved the voltage profile and also maximum power loss reduction.

## 5.2 CONTRIBUTION

This research has proposed a simple, easy and efficient analytical method based on branch current loss formula for optimal location and sizing of DG in the Radial distribution networks for maximum loss reduction.

The proposed method could be used as a guideline by the power planners and distribution system operators to optimally place and size the DGs in the radial distribution systems for the reliable and stable power systems.

This research work has provided a clear impact of the solar photovoltaic penetration in improving the voltage profile and drastically reducing the system real power loss.

This research work suggests the use of current branch loss formula to explore the optimal location and sizing of DG in the radial system or weakly meshed systems as an alternative option to the common exact loss formula and power branch formula.

## 5.3 RECOMMENDATIONS

Following points are worthy of further research to optimally reduce the losses and improve the voltage profile:

1. This research work suggests the use of current branch loss formula to explore the optimal location and sizing of DG in the radial system or weakly meshed systems as an alternative option to the common exact loss formula and power branch formula. Furthermore, other optimization techniques can be applied for the loss reduction and the method can be applied to a large network to test its robustness and efficiency.
2. The study done on the uniformly distributed loads, but the allocation of the SPV could be done with the network reconfiguration simultaneously using the same technique.
3. The study has been carried out on balanced distribution networks. The DGs placement problem could be extended to unbalanced distribution systems.
4. The economic dispatch of SPV injection could be included in the study to establish the impact of the cost function in the penetration of the SPV.
5. Study considering the intermittency of the solar irradiance and the load's variation uncertainties.

# Appendix A

**Table A.1. System data of 33-bus test radial distribution system [56]**

| Serial Number | Sending Node | Receiving Node | Low loading | | Medium loading | | Maximum loading | | R(ohms) | X(ohms) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | P (KW) | Q (KVAr) | P (KW) | Q KVAr | P (KW) | Q (KVAr) | | |
| 1 | 1 | 2 | 90 | 54 | 100 | 60 | 130 | 78 | 0.0922 | 0.047 |
| 2 | 2 | 3 | 81 | 36 | 90 | 40 | 117 | 52 | 0.493 | 0.2511 |
| 3 | 3 | 4 | 108 | 72 | 120 | 80 | 156 | 104 | 0.366 | 0.1864 |
| 4 | 4 | 5 | 54 | 27 | 60 | 30 | 78 | 39 | 0.3811 | 0.1941 |
| 5 | 5 | 6 | 54 | 18 | 60 | 20 | 78 | 26 | 0.819 | 0.707 |
| 6 | 6 | 7 | 180 | 90 | 200 | 100 | 260 | 130 | 0.1872 | 0.6188 |
| 7 | 7 | 8 | 180 | 90 | 200 | 100 | 260 | 130 | 0.7114 | 0.2351 |
| 8 | 8 | 9 | 54 | 18 | 60 | 20 | 78 | 26 | 1.03 | 0.74 |
| 9 | 9 | 10 | 54 | 18 | 60 | 20 | 78 | 26 | 1.044 | 0.74 |
| 10 | 10 | 11 | 40.5 | 27 | 45 | 30 | 58.5 | 39 | 0.1966 | 0.065 |
| 11 | 11 | 12 | 54 | 31.5 | 60 | 35 | 78 | 45.5 | 0.3744 | 0.1238 |
| 12 | 12 | 13 | 54 | 31.5 | 60 | 35 | 78 | 45.5 | 1.468 | 1.155 |
| 13 | 13 | 14 | 108 | 72 | 120 | 80 | 156 | 104 | 0.5416 | 0.7129 |
| 14 | 14 | 15 | 54 | 9 | 60 | 10 | 78 | 13 | 0.591 | 0.526 |
| 15 | 15 | 16 | 54 | 18 | 60 | 20 | 78 | 26 | 0.7463 | 0.545 |
| 16 | 16 | 17 | 54 | 18 | 60 | 20 | 78 | 26 | 1.289 | 1.721 |
| 17 | 17 | 18 | 81 | 36 | 90 | 40 | 117 | 52 | 0.732 | 0.574 |
| 18 | 2 | 19 | 81 | 36 | 90 | 40 | 117 | 52 | 0.164 | 0.1565 |
| 19 | 19 | 20 | 81 | 36 | 90 | 40 | 117 | 52 | 1.5042 | 1.3554 |
| 20 | 20 | 21 | 81 | 36 | 90 | 40 | 117 | 52 | 0.4095 | 0.4784 |
| 21 | 21 | 22 | 81 | 36 | 90 | 40 | 117 | 52 | 0.7089 | 0.9373 |
| 22 | 3 | 23 | 81 | 45 | 90 | 50 | 117 | 65 | 0.4512 | 0.3083 |
| 23 | 23 | 24 | 378 | 180 | 420 | 200 | 546 | 260 | 0.898 | 0.7091 |
| 24 | 24 | 25 | 378 | 180 | 420 | 200 | 546 | 260 | 0.896 | 0.7011 |
| 25 | 6 | 26 | 54 | 22.5 | 60 | 25 | 78 | 32.5 | 0.203 | 0.1034 |
| 26 | 26 | 27 | 54 | 22.5 | 60 | 25 | 78 | 32.5 | 0.2842 | 0.1447 |
| 27 | 27 | 28 | 54 | 18 | 60 | 20 | 78 | 26 | 1.059 | 0.9337 |
| 28 | 28 | 29 | 108 | 63 | 120 | 70 | 156 | 91 | 0.8042 | 0.7006 |
| 29 | 29 | 30 | 180 | 540 | 200 | 600 | 260 | 780 | 0.5075 | 0.2585 |
| 30 | 30 | 31 | 135 | 63 | 150 | 70 | 195 | 91 | 0.9744 | 0.963 |
| 31 | 31 | 32 | 189 | 90 | 210 | 100 | 273 | 130 | 0.3105 | 0.3619 |
| 32 | 32 | 33 | 54 | 36 | 60 | 40 | 78 | 52 | 0.341 | 0.5302 |
| **Total loading** | | | **3344** | **2070** | **3715** | **2300** | **4830** | **2990** | | |

**Substation voltage KV base= 12.66 KV and MVA base = 100 MVA.**

## Per unit values calculation.

$$Z_{base} = \frac{KV_{base}^2}{MVA_{base}}\ \mathbf{;}$$

$$R_{pu} = \frac{R_{actual}}{Z_{base}}\ \mathbf{;}$$

$$X_{pu} = \frac{X_{actual}}{Z_{base}}\ ;$$

$$P_{pu} = \frac{P_{actual}}{1000 \times MVA_{base}}\ ;$$

$$Q_{pu} = \frac{Q_{actual}}{1000 \times MVA_{base}}.$$

Where $Z_{base}$ is the base impedance of the line;

$R_{pu}$ is the per unit value of the resistance;

$R_{actual}$ is the actual value of the resistance;

$X_{pu}$ is the per unit value of the resistance;

$X_{actual}$ is the actual value of the reactance;

$P_{pu}$ is the per unit value of the active power;

$P_{actual}$ is the actual value of the active power;

$Q_{pu}$ is the per unit value of the reactive power;

$Q_{actual}$ is the actual value of the reactive power;

$MVA_{base}$ is the base value of the Megawatt;

$KV_{base}$ is the base value of kilovolt.

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# LIST OF PUBLICATIONS

1. N. Madjissembaye, L. Thiaw, C. M. Muriithi, C. W. Wekesa, "Optimal siting and sizing of single SPV system in radial distribution systems for loss reduction based on maximum power saving technique." International Journal of Modern Engineering Research (IJMER) Vol 6, Issue 7, July 2016.

2. N. Madjissembaye, C. M. Muriithi, C. W. Wekesa, "Load Flow Analysis for Radial Distribution Networks Using Backward/Forward Sweep Method" Journal of Sustainable Research in Engineering (SRI) (pending)

3. N. Madjissembaye, V.Siyoi, C. M. Muriithi, C. W. Wekesa, "Optimal Siting and Sizing of Distributed Generation in Radial Distribution System for Active Power Loss Reduction." Journal of Sustainable Research in Engineering (SRI) (pending)

OPEN ACCESS

International Journal Of Modern Engineering Research (IJMER)

**Optimal Siting and Sizing of Single SPV System in Radial Distribution Network for Loss Reduction Based on Maximum Power Saving Technique**

N. Madjissembaye [1*], L. Thiaw[2], C. M. Muriithi[3], C. W. Wekesa[4]

[1]*Department Of Electrical Engineering, Pan African University, Institute For Basic Sciences, Technology and Innovations (Pauisti/Jkuat), Nairobi, Kenya (Student),* ***smadjissembaye@gmail.com**

[2]*Departement de Genie Electric Ecole Superieure Polytechnique, ESP Check Anta Diop de Dakar, Senegal*

[3]*Department of Electrical & Power Engineering, Technical University Of Kenya, Nairobi, Kenya.*

[4]*Department of Electrical and Information Engineering, University Of Nairobi, Nairobi, Kenya.*

***ABSTRACT:*** *This paper presents the optimal placement of a SPV (Solar Photovoltaic) system in the distribution system using the backward and forward sweep method based on the analytical maximum power saving technique for the maximum power loss reduction and voltage profile improvement. The integration of the DG in the distribution network has several advantages such as the power line losses reduction and the improvement of the voltage profile thus the reliability of the system and the reduction of the environment's pollution due the greenhouse gases. On the other hand, the non-strategic location of DG can lead to a serious disturbance in the power network; therefore the research for the optimal siting and sizing of the DG in the radial network becomes crucial. The validity and performance the proposed method was tested on the IEEE 33 and 69 bus test systems and the results were satisfactory.*

***Keywords:-*** *radial distribution network, power loss reduction, Solar Photovoltaic (SPV), Backward and Forward Sweep Method (BFSM).*

## MATLAB CODE

```
%======ESSAY FOR THE RADIAL DISTRIBUTION NETWORK LOAD FLOW USING BFSM=====%
%********* LOAD CALCULATION WITH ACTIVE POWER DG PENETRATION*********
clc;
clear all;
format short;
tic
sn=load('loaddata33bus2.m');
ln=load('linedata33bus.m');
%-----------------------------------------------------------------------%
je=length(ln);
tu=length(sn);
MVAb=100;
KVb=12.66;
ak=tan(acos(1));
Zb=(KVb^2)/MVAb;
% Per unit Values
for i=1:je
    R(i,1)=(ln(i,4))/Zb;
    X(i,1)=(ln(i,5))/Zb;
end
for i=1:tu
    P(i,1)=((sn(i,4))/(1000*MVAb));
    Q(i,1)=((sn(i,5))/(1000*MVAb));
end
%-----------------------------------------------------------------------%
R;
X;
P;
Q;
D=zeros(je,tu);
for i=1:je
    f=ln(i,2);
    g=ln(i,3);
    for j=1:tu
        if f==j
            D(i,j)=-1;
        end
        if g==j
            D(i,j)=1;
        end
    end
end
D;
b=1;
for i=1:tu
    a=0;
    for j=1:je
        if D(j,i)==-1
            a=1;
        end
    end
    if a==0
        endnote(b,1)=i;
        b=b+1;
    end
```

```
end
endnote;
%------------------------------------------------------------------------%
c=length(endnote);
for j=1:c
    b=2;

    d=endnote(j,1);
   % while (f~=1)
   for s=1:tu
     if (d~=1)
       k=1;
       for i=1:je
           if ((D(i,d)==1)&&(k==1))
                d=i;
                k=2;
           end
       end
       k=1;
       for i=1:tu
           if ((D(d,i)==-1)&&(k==1));
                d=i;
                e(j,b)=i;
                b=b+1;
                k=3;
           end
       end
     end
   end
end
for i=1:c
    e(i,1)=endnote(i,1);
end
e;
h=length(e(1,:));
for i=1:c
    j=1;
    for k=1:tu
        for l=1:h
            if e(i,l)==k
                e(i,l)=e(i,j);
                e(i,j)=k;
                j=j+1;
             end
         end
    end
end
e;
%------------------------------------------------------------------------%
for k=1:je
    b=1;
    for i=1:c
        for j=1:h-1
            if (e(i,j)==k)
                if e(i,j+1)~=0
                    Sam(k,b)=e(i,j+1);
                    b=b+1;
```

```
                    else
                        Sam(k,1)=0;
                    end
                end
            end
        end
    end
     Sam;
    for i=1:je-1
        for j=c:-1:1
            for k=j:-1:2
                if Sam(i,j)==Sam(i,k-1)
                    Sam(i,j)=0;
                end
            end
        end
    end
    Sam;
    m=length(Sam(:,1));
    n=length(Sam(1,:));
    for i=1:m
        for j=1:n
            if Sam(i,j)==0 && j~=n
                if Sam(i,j+1)~=0
                    Sam(i,j)=Sam(i,j+1);
                    Sam(i,j+1)=0;
                end
            end
            if Sam(i,j)~=0
                Sam(i,j)=Sam(i,j)-1;
            end
        end
    end
    Sam;
    for i=1:m-1
        for j=1:n
            samy(i,j)=Sam(i+1,j);
        end
    end
    g=length(samy);
    %-----------------------------------------------------------------------%
    %evaluation of the branche currents and the node voltages
    for i=1:tu
        vb(i,1)=1;
    end
    for s=1:10
        for i=1:tu
            Icp(i,1)=conj(complex(P(i,1),Q(i,1)))/(vb(i,1));
        end
        Icp;
        for i=1:je
            Ibr(i,1)=Icp(i+1,1);
        end
        Ibr;
        xx=length(samy(1,:));
        for i=je-1:-1:1
            for k=1:xx
```

```
            if samy(i,k)~=0
                xy=samy(i,k);
                Ibr(i,1)=Ibr(i,1)+Ibr(xy,1);
                %Ibr(i,1)=Icp(i+1,1)+Ibr(k,1);
            end
        end
end
Ibr;
for i=2:tu
    e=0;
    for f=1:g
        if xy>1
            if samy(f,2)==i-1
                xy=samy(f,1);
                vb(i,1)=((vb(xy,1))-((Ibr(i-1,1))*(complex((R(i-1,1)),X(i-
1,1)))));
                e=1;
            end
            if samy(f,3)==i-1
                xy=samy(f,1);
                vb(i,1)=((vb(xy,1))-((Ibr(i-1,1))*(complex((R(i-1,1)),X(i-
1,1)))));
                e=1;
            end
        end
    end
    if e==0
        vb(i,1)=((vb(i-1,1))-((Ibr(i-1,1))*(complex((R(i-1,1)),X(i-1,1)))));
    end
end
 s=s+1;
end
Icp;
Ibr
vb;
Vbp=[abs(vb) angle(vb)*180/pi]

%toc;
for i=1:tu
    va(i,2:3)=Vbp(i,1:2);
end
for i=1:tu
    va(i,1)=i;
end
va;
Ibrp=[abs(Ibr) angle(Ibr)*180/pi];
PL(1,1)=0;
QL(1,1)=0;
%-----------------------------------------------------------------------%
%evaluation of the line losses
for d=1:je
    Pl(d,1)=(Ibrp(d,1)^2)*R(d,1);
    Ql(d,1)=(Ibrp(d,1)^2)*X(d,1);
    PL=PL(1,1)+Pl(d,1);
    QL=QL(1,1)+ Ql(d,1);
end
%print the answers
```

```
Pkwloss=(Pl)*1e5;
Qkvarloss=(Ql)*1e5;
PTL=(PL)*1e5;
QTL=(QL)*1e5;
voltage=Vbp(:,1);
angle=Vbp(:,2)*(pi/180);
%-------------------------------------------------------------------------%
%evaluating the power losses using the current real and imaginary component
Ibrr=real(Ibr);Ibri=imag(Ibr);
IL=[Ibrr Ibri];
for d=1:je
    PLL(d,1)=(Ibrr(d,1)^2)*R(d,1)+(Ibri(d,1)^2)*R(d,1);
    QLL(d,1)=(Ibrr(d,1)^2)*X(d,1)+(Ibri(d,1)^2)*X(d,1);
    Ptl=PL(1,1)+PLL(d,1);
    Qtl=QL(1,1)+QLL(d,1);
end
PTl=Ptl*1e5
QTl=Qtl*1e5
%==========================================================================%
%in this portion, we will calculate the value of the DG current injected
%at each node and evaluate the power saving using these values once the bus
%with highest power savingis loacated it will be candidate to the DG
penetration thus the
%load flow will be done using these node to minimize the loss.
for i=1:je
    Iy(i,1)=IL(i,1)*R(i,1);%Evaluating the I^2.R of the branches/active cpmt
    Ir(i,1)=IL(i,2)*R(i,1);%Evaluating the I^2.R of the branches/reactive
cpmt
end
for j=1:je
    Ipv(j,1)=-(sum(Iy(1:j,1))-ak*sum(Ir(1:j,1)))/((ak^2+1)*sum(R(1:j,1)));%DG
current for maximum saving
end
for i=2:je
    SS(i,1)= -2*Ipv(i,1)*sum(Iy(1:i,1))-(Ipv(i,1)^2)*sum(R(1:i,1))-
2*ak*Ipv(i,1)*sum(Ir(1:i,1))-(Ipv(i,1)^2)*ak^2*sum(R(1:i,1));%the saving....
    %calculated using the maximum value of the Pv current
end

  [sav,branch]= max(abs(SS(1:i,1))) %selecting the maximum saving branch
which will be
  %the candidate for the DG placement
%   for j=1:je
%
PDDloss=sum((IL(1:6,1)+Ipv(6,1)).^2)*sum(R(1:6,1))+(sum(IL(7:je,1).^2))...
%           *sum(R(7:je,1))+(sum(IL(1:je,2)))*sum(R(1:je,1));
%   end
% %
%the power loss can be calculated using the Ploss without DG minus the
%maximum saving when injecting the DG.
PLDG=Ptl-max(abs(SS));PLDG61=PLDG*1e5, PDG=-
Vbp(branch+1,1)*Ipv(branch,1)*1e5, QDG=ak*PDG
toc

% toc;
```