FEEDER VOLTAGE CONTROL IN THE PRESENCE OF DISTRIBUTED GENERATION

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Electrical Engineering.

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DEDICATION

To my parents and my sister
Thriambak Rao, Rajashree and Hiranmai

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Firstly, I would like to thank Wichita State University for giving me an opportunity to perform this thesis work, through which I gained a lot of experience academically. I am very fortunate to have Dr. Visvakumar Aravinthan as my Adviser and Committee chair, to whom I am deeply indebted for his unconditional support and guidance. I am grateful to him for believing in me and supervising me in the right direction during this work. I would like to extend my gratitude to the members of my committee, Dr. M. Edwin Sawan and Dr. Ehsan Salari for their valuable time and appreciation. I also want to thank the faculty and the students of Electrical Engineering Department at Wichita State University, for their extended support. Finally, I would like to thank my parents, my sister and my friends for their help and support during hard times.

ABSTRACT

Although integration of distributed generation (DG) with distribution system has many advantages, at the same time there are many challenges to be faced. One of the major challenges is voltage regulation. In traditional distribution system without distributed generation, step voltage regulators and capacitor banks are used to regulate voltage to maintain node voltages under required limits. When distributed generation is added to the distribution system, controlling node voltages will be a challenging task especially due to variable and uncontrolled nature of output of distributed generators. This thesis work studies the effects of distributed generation on voltage drop and node voltages, using Institute of Electrical and Electronics Engineers (IEEE) 13-node test feeder. Based on simulation results, reduction in voltage drop and rise of node voltages are identified.

With the presence of communication based control of distributed generators, voltage regulation can be done more efficiently. Therefore, this work focuses on developing a model to show the relationship between voltage drop and real and reactive powers, and developing a voltage optimization technique where real and reactive powers of distributed generators are controlled. The proposed technique is tested using IEEE 13-node test feeder and the results show that the proposed technique will control the feeder voltage under prescribed limits and minimize total voltage drop, real and reactive power losses.

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LIST OF ABBREVIATIONS

ANSI	American National Standards Institute
DG	Distributed Generation
IEEE	Institute of Electrical and Electronics Engineers
KKT	Karush-Kuhn-Tucker
LF	Load Factor
LTC	Load Tap Changer
PV	Photovoltaic
SMI	Smart Meter Infrastructure
VAR	Volt Ampere Reactive

CHAPTER 1

INTRODUCTION

1.1 Background

In recent years, research attention on smart grids in the presence of distributed power generators has increased. In fact, the world is now looking towards employing more percentage of distributed generation in power sector, keeping in mind about the recent advancements and improvements in the technology. Also, adding to the above statement, with the existing conventional centralized power generation where major percentage of generation is from non-renewable energy sources, there are problems related to the depletion of non-renewable energy sources, impact on environment and climatic conditions. On the other side, with ever increase in demand, the infrastructure maintenance and cost of transmission and distribution, energy security, reliability and efficiency becomes a challenging task, thereby creating a compulsion to go further towards adopting distributed generation [1].

Distributed renewable energy is one of the fastest growing sectors in the world. With the spread of markets for renewable energy to the developing countries and with better economies of scale, distributed generation has now become unlimited potential all around the world. Eight years back, the market growth was more in California and Germany, and recently it has spread to China, Chile and India, because electricity from the distributed generation is cheaper and reliable than from the utility grid [2]. With the advantages of ability to provide reliable power, flexibility and upgradability in the infrastructure, a better economy of scale, diversity to employ different varieties of power generating technologies, better efficiency, and improved quality of power, distributed generation will be the future of power system [3]. Figure 1 shows the benefits of distributed generation.

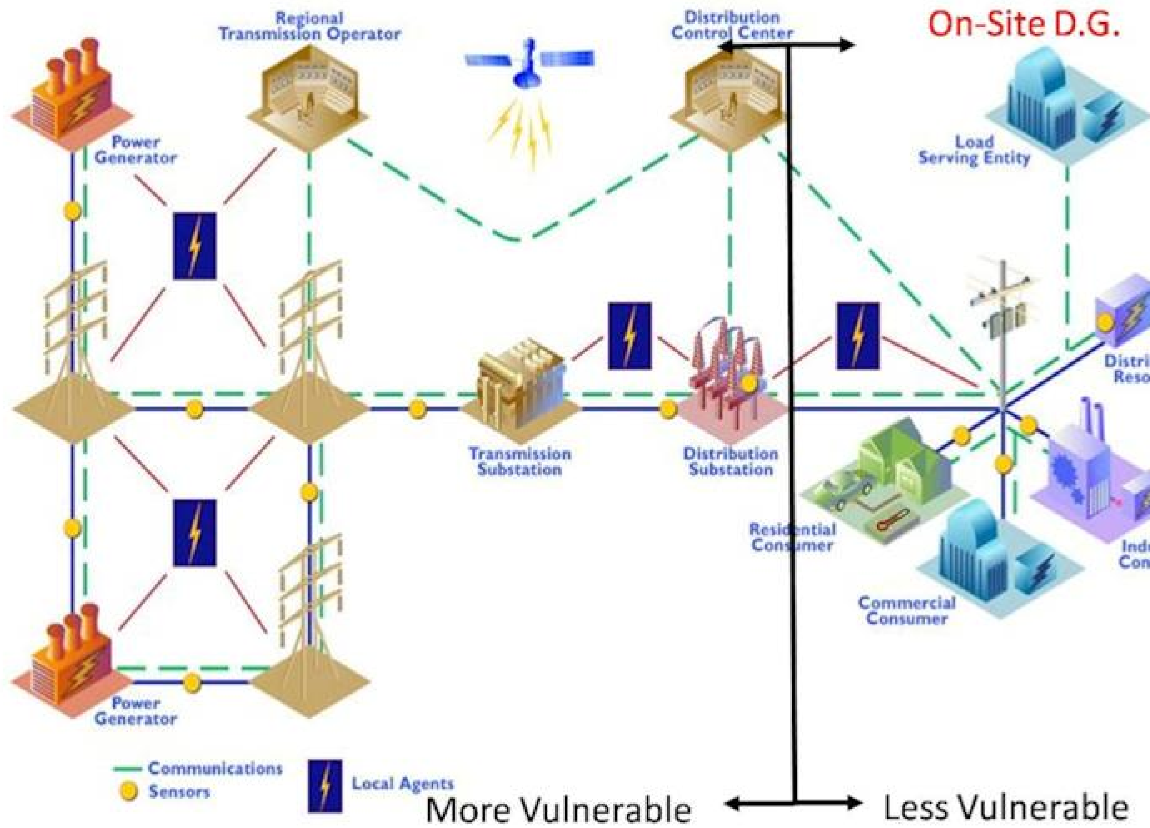

Figure 1 Benefits of distributed generation [3].

Although the integration of distributed generation has many advantages and is one of the biggest changes facing in the power industry, at the same time there are many challenges to be faced. Distributed generators which typically use different types of renewable energy sources including wind and solar photovoltaic (PV) sources, make system voltage regulation a challenging task. Generally, capacitor banks and step voltage regulators are used to regulate system voltage. Due to penetration of grid connected distributed generators, the capacitor banks and step voltage regulators may push the utilization voltages either above or below the adopted American National Standards Institute (ANSI) voltage limits. This is because of the variable nature of the sources used by the distributed generators. It will also have an adverse impact on reliability requirements of the utility and the life span of the voltage regulating equipment decreases [4].

Hence there is a requirement for the control of distributed generators. With the presence of communication infrastructure, storage system and power electronic devices, along with the application of proper control scheme, distributed generators could be more efficiently operated to perform voltage regulation [5,6,7,8,9,10,11,12].

1.2 Organization of Thesis

The content of this thesis has been divided into five chapters. Chapter 1 gives the introduction of present trends and future projection of distributed generation along with benefits and challenges. Chapter 2 is about the overview of the literature review and scope of this work. Chapter 3 provides a description of Effect of DG's on voltage drop and node voltage along with numerical analysis and results using IEEE 13 node test feeder. Chapter 4 provides the modeling of the distribution feeder for voltage drop analysis along with proposed optimization technique. Numerical analysis and results using IEEE 13 node test feeder are presented. Finally, the conclusion and possible future work are given in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Voltage Regulation Standards

In a distribution system, voltage regulation refers to maintaining the steady-state voltage within an acceptable or prescribed range always, with the help of an equipment. The voltage variation capacity varies from equipment to equipment, based on the standards for which it is designed. Generally, voltage regulation standards vary from utility to utility and from country to country. American National Standard for Electric Power Systems and Equipment Voltage Ratings ANSI C84.1 [13], which is shown in the Figure 2, is the national standard in USA, which is followed by most of the utilities. There are two categories mentioned in the above standard. Range A corresponds to normal operating conditions and Range B corresponds to short durations or unusual conditions.

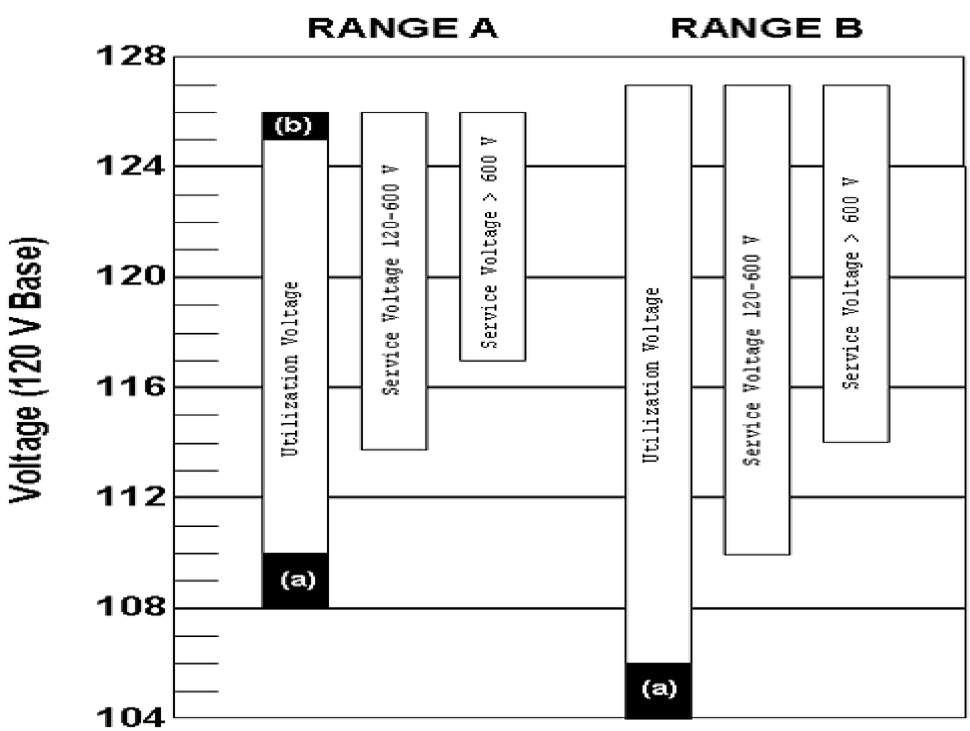

Figure 2 ANSI C84.1 voltage standards [13].

2.2 Voltage Control with DG

In a distribution system, fluctuations in voltages occur mainly due to variations in the load. Change in the load corresponds to change in the current drawn from the substation. As product of impedance and line current constitute voltage drop, variation of line current is directly proportional to the voltage drop. Bus voltage depends on the voltage drop and any changes in the voltage drop affects the bus voltage. Therefore, voltage regulation needs to be done all the time. Voltage regulation is done using substation transformer load tap changers (LTC's) with voltage regulators, line voltage regulators, fixed and switched capacitor banks. Figure 3 shows a typical example of voltage ranges for primary feeder and secondary customer service points.

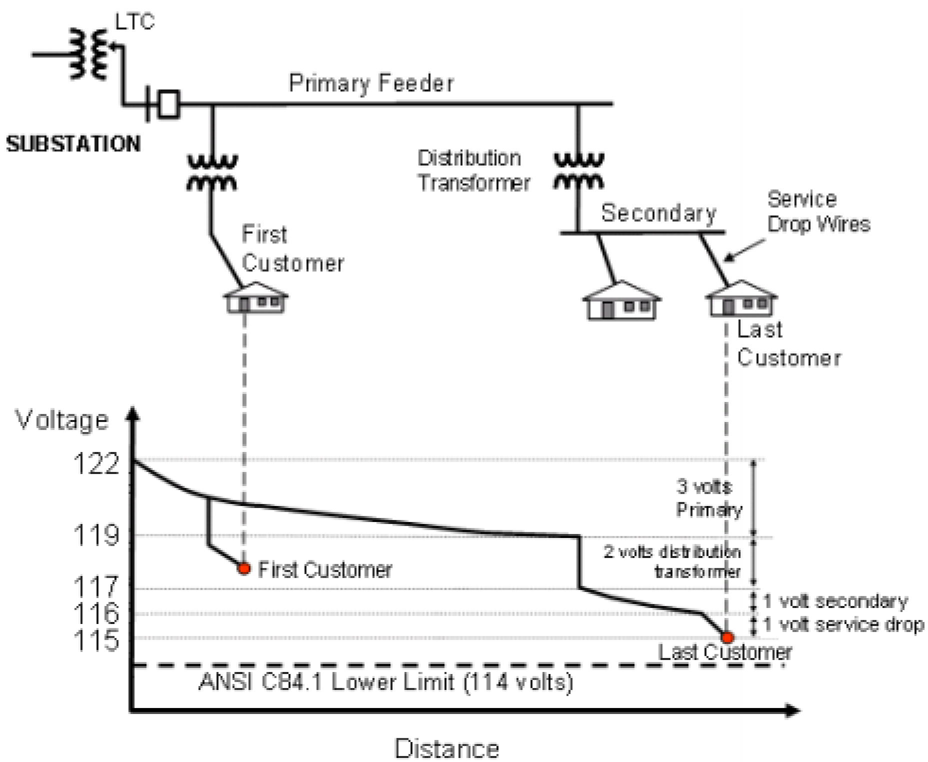

Figure 3 Distribution feeder first and last customer voltages [4].

Figure 4 shows an example of a distribution system with voltage regulating devices and communication based control infrastructure, where voltage load tap changer, voltage regulators and capacitor banks are operating together for voltage regulation.

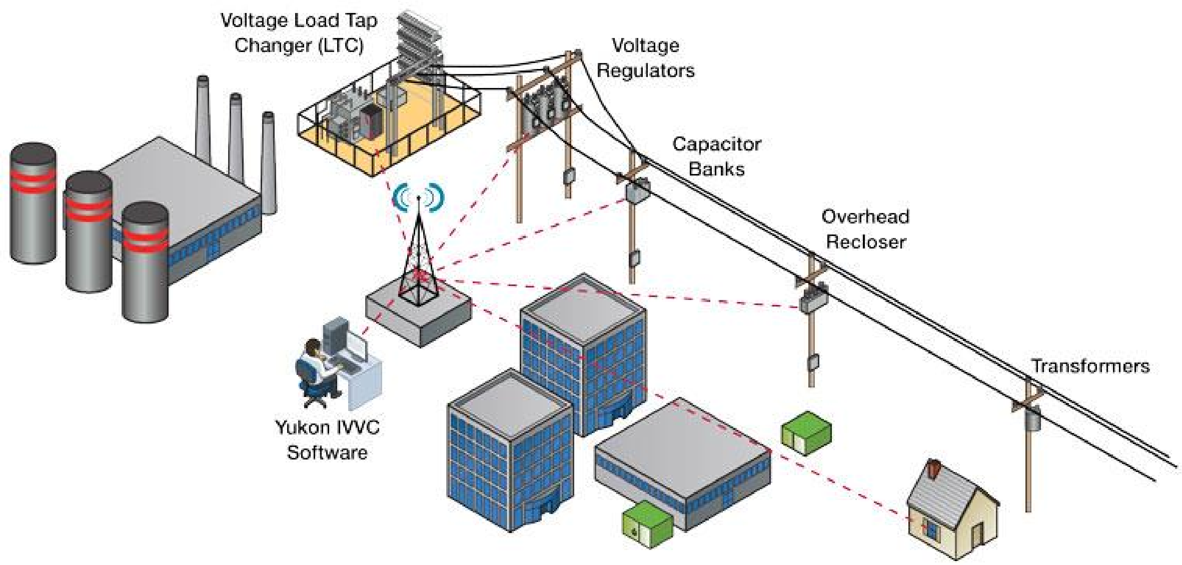

Figure 4 Distribution system voltage regulating devices [14].

Integration of distributed generation with power system

The addition of grid connected distributed generators will have both good and bad impacts on power system. In distribution system, due to injection of distributed generator current into the system, substantial reduction in power losses, voltage drop and rise in the feeder voltage takes place. Excessive switching of voltage regulating equipment and power quality problems like flickering problem and harmonics occurs [15]. In transmission system, transient and dynamic stability issues and impact on efficiency of the fossil fuel plants by sudden ramping takes place [16]. Hence, these problems need to be solved properly for efficient and reliable operation of distributed generators.

Significant work has been done on optimal placement of distributed generators for voltage regulation [17]. Reactive power injected by the distributed generators contribute in reduction of reactive power losses and increase node voltage [18]. By controlling the reactive power injected, voltage deviation can be controlled [19, 20]. A local controller on the bus can be used to sense the voltage and reactive power injected by the distributed generation can be controlled accordingly when there is voltage violation [21]. Decentralized Volt/VAR control can be done with offline coordination and with reactive power exchange between distribution networks and DG's [22, 23]. When transformer load tap changer and DG are in coordination, voltage deviation can be avoided [24, 25] and tap operation can be reduced [26]. Communication based coordinated control between capacitors and DG's can perform better Volt/VAR control [27], [28]. A collective control of all the regulating devices along with DG's can be more effective in terms of reliable voltage regulation [29, 30, 31]. Effective voltage regulation is achieved when there is communication based control architecture. Figure 5 shows a distribution feeder with DG's, communication, smart meter and control infrastructure.

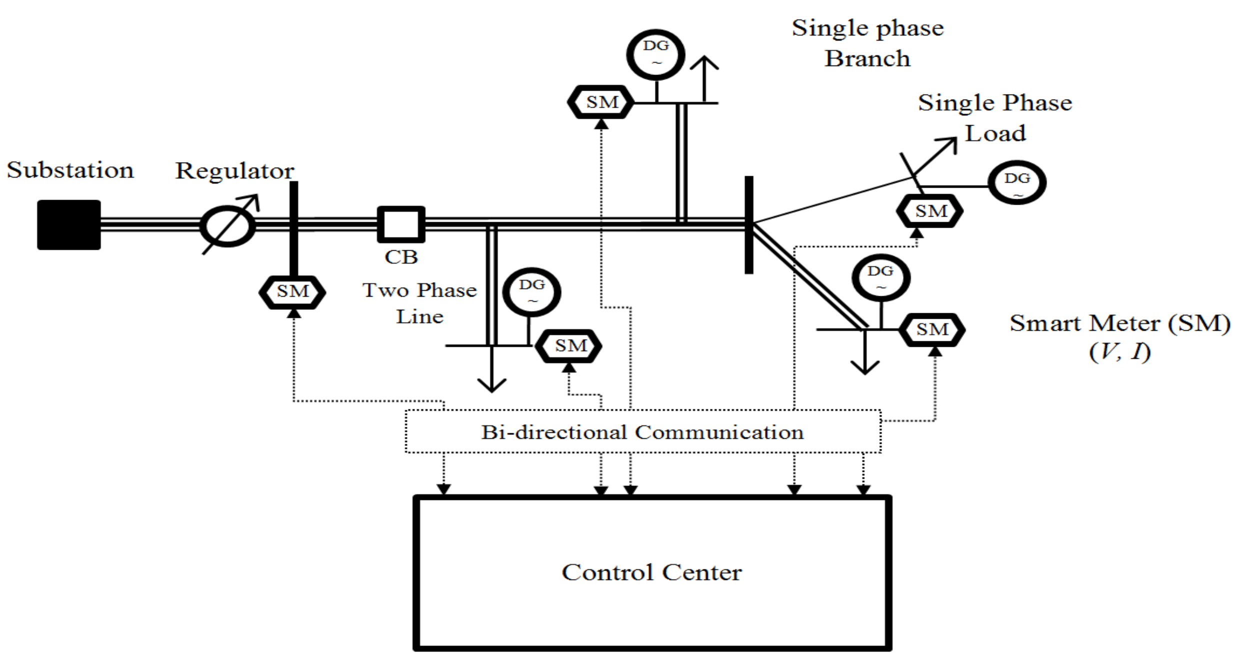

Figure 5 Distribution feeder with DG's, communication and control center [32].

2.3 Scope of This Work

This study evaluates the effect of distributed generation on voltage drop and node voltage on a single phase equivalent radial distribution feeder and identification voltage rise based on output current of distributed generator. Further, the distribution feeder is modeled with voltage drop model, by assigning fixed weights to the feeder lines, to find linear relationship between voltage drop and apparent power flowing through the line. Also, distributed generation control scheme with optimization approach to minimize of feeder voltage is presented. Finally, the validity of the proposed optimization technique is tested using IEEE 13-node test feeder.

CHAPTER 3

EFFECT OF DG'S ON VOLTAGE DROP AND NODE VOLTAGE

3.1 Voltage Drop

A distribution system voltage drop can be computed by sum of primary and lateral feeder voltage drops. Figure 6 shows single phase equivalent of a generalized distribution system with n buses, showing substation voltage, loads, load currents and line impedances.

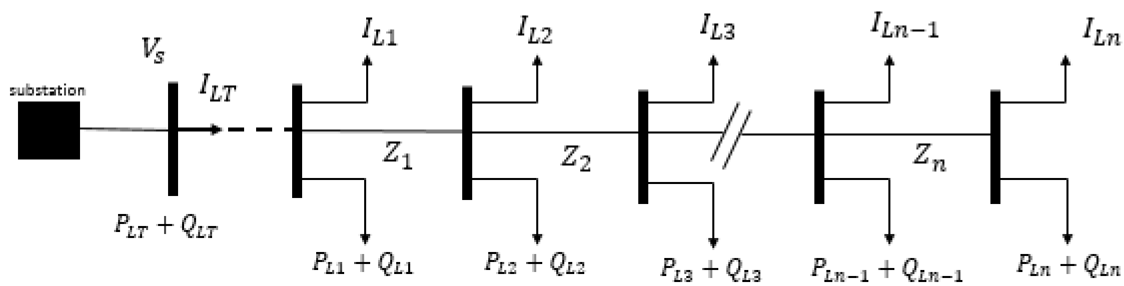

Figure 6 Radial distribution feeder 1.

Individual line voltage drops are computed initially for primary and lateral feeders. Voltage drop for each line is computed using line current (I_k) and line impedance (Z_k). Line current (I_k) is calculated using approximate load factor method with total current (I_{LT}) calculated at substation and load factor (Lf_k) calculated for each line. Total current calculated at substation is given by

$$I_{LT} = \frac{(P_{LT}+jQ_{LT})}{V_s} \tag{1}$$

where $(P_{LT} + jQ_{LT})$ for a given time t, is the total load power delivered by the substation to the distribution system, (V_s) for a given time t, is substation voltage. Load factor for a line is given by

$$Lf_k = \frac{(P_k+jQ_k)}{(P_{LT}+jQ_{LT})} \tag{2}$$

where $(P_k + jQ_k)$ for a given time t, is the sum of all the primary and lateral feeder loads that contribute to line current, which is given by

$$P_k + jQ_k = (P_{Lk} + jQ_{Lk}) + (P_{Lk+1} + jQ_{Lk+1}) + \cdots + (P_{Ln} + jQ_{Ln}) \tag{3}$$

It is assumed that load demand could be obtained based on measurement with smart meter infrastructure (SMI). Line current is given by

$$I_k = Lf_k \times I_{LT} \tag{4}$$

Finally, individual line voltage drop is given by

$$\Delta V_k = I_k \times Z_k \tag{5}$$

Voltage drops for two identical distribution systems with and without DG's are computed and compared to identify the effect of DG's on voltage drop.

Voltage drop for a line without DG's

$$\Delta V_k = I_k \times Z_k \tag{6}$$

Total system voltage drop without DG's

$$\Delta V_{total} = (I_1)Z_1 + (I_2)Z_2 + \cdots + (I_n)Z_n \tag{7}$$

Voltage drop for a line with DG's

$$\Delta V_k{}^{DG} = (I_k - I_{Gk})Z_k \tag{8}$$

$$\Delta V_k{}^{DG} = \Delta V_k - (I_{Gk})Z_k \tag{9}$$

where I_{Gk} is the sum of all the individual DG currents that influence the line, which is given by

$$I_{Gk} = I_{gk} + I_{gk+1} + \cdots + I_{gn} \tag{10}$$

Total system voltage drop with DG's

$$\Delta V_{total}{}^{DG} = (I_1 - I_{G1})Z_1 + (I_2 - I_{G2})Z_2 + \cdots + (I_n - I_{Gn})Z_n \tag{11}$$

$$\Delta V_{total}{}^{DG} = \Delta V_{total} - [(I_{G1})Z_1 + (I_{G2})Z_2 + \cdots + (I_{Gn})Z_n] \tag{12}$$

From the above computations, when equations (6) and (9), (7) and (12) are compared, it is evident that there is significant reduction in voltage drop because of DG's. It can be concluded that voltage drop for each line reduces by $I_{Gk}Z_k$ and for total system by $[(I_{G1})Z_1 + (I_{G2})Z_2 + \cdots + (I_{Gn})Z_n]$.

3.2 Node Voltage

Individual node voltages for a distribution system can be computed using substation voltage V_s and individual line voltage drops.

Node voltage without DG's

$$V_k = V_s - \sum_{a=1}^{k} \Delta V_a \tag{13}$$

Node voltage with DG's

$$V_k{}^{DG} = V_s - \sum_{a=1}^{k} \Delta V_a{}^{DG} \tag{14}$$

$$V_k{}^{DG} = (V_s - \sum_{a=1}^{k} \Delta V_a) + [(I_{G1})Z_1 + (I_{G2})Z_2 + \cdots + (I_{Gk})Z_k] \tag{15}$$

From the above computations, when equations (13) and (15) are compared, it is evident that there is significant node voltage rise because of DG's. It can be concluded that voltage rise for a node is given by $[(I_{G1})Z_1 + (I_{G2})Z_2 + \cdots + (I_{Gk})Z_k]$.

3.3 Numerical Analysis

The approximate load factor method of analysis of line current was verified with IEEE 13-node test feeder, using the data of single phase spot load shown in the Figure 7, [33]. The analysis was done by using a software Milsoft Engineering Analysis tool Windmil [34], by simulation. The analytically calculated and software simulated values of the line currents were compared and were found to be equal with negligible error, shown in the Figure 8.

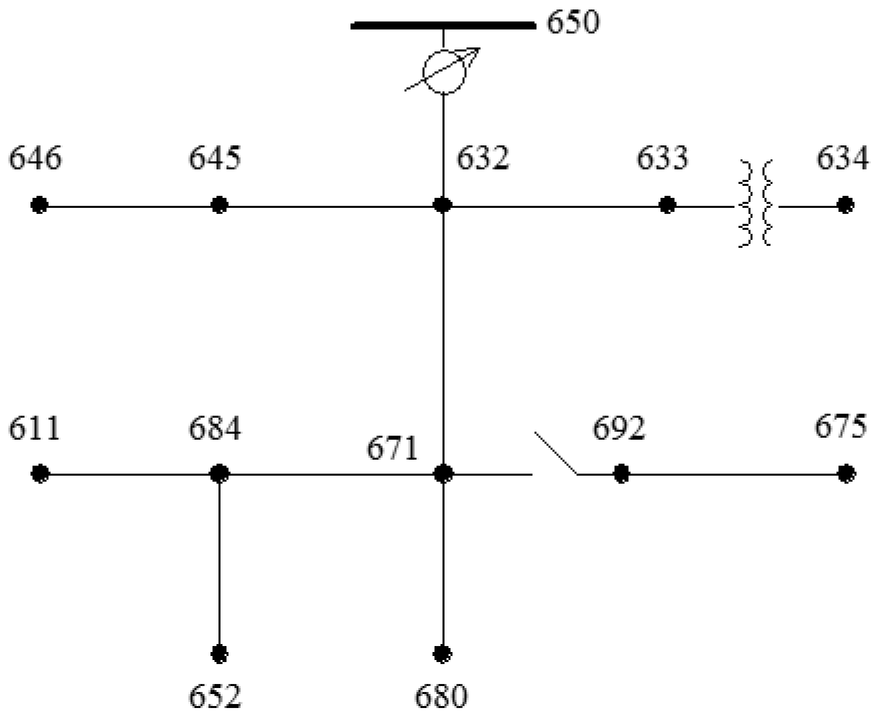

Figure 7 IEEE 13 node test feeder 1 [33].

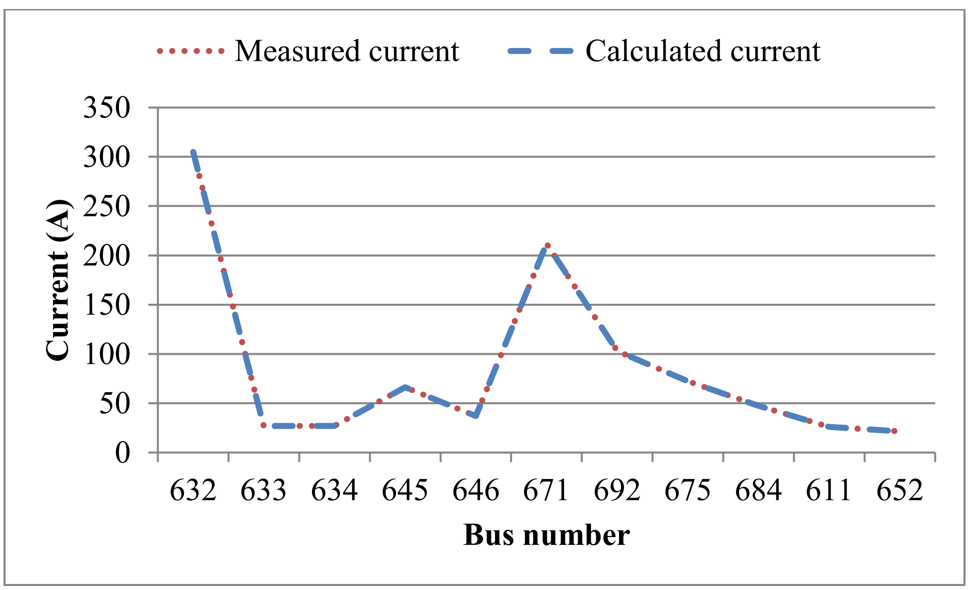

Figure 8 Line current analytical vs simulation.

Voltage drop and node voltages were tested with IEEE 13-node test feeder with spot loads for single phase feeder. Distributed generators were connected to nodes 671 and 675. The maximum available generation for DG's were taken 30% of the substation load. The output of the DG placed at the node 671 was considered to be 70% of the total available DG output and the output of the DG placed at the node 675 was considered to be 30%. The power factors for the DG's were taken randomly. By comparing the values with and without DG's, it was proved that voltage drop reduces and there was rise in node voltages because of the effect of injected current from the DG's. Figure 9 shows the voltage drop comparison with and without DG's, Figure 10 shows the comparison of node voltages with and without DG's for IEEE 13 node test feeder.

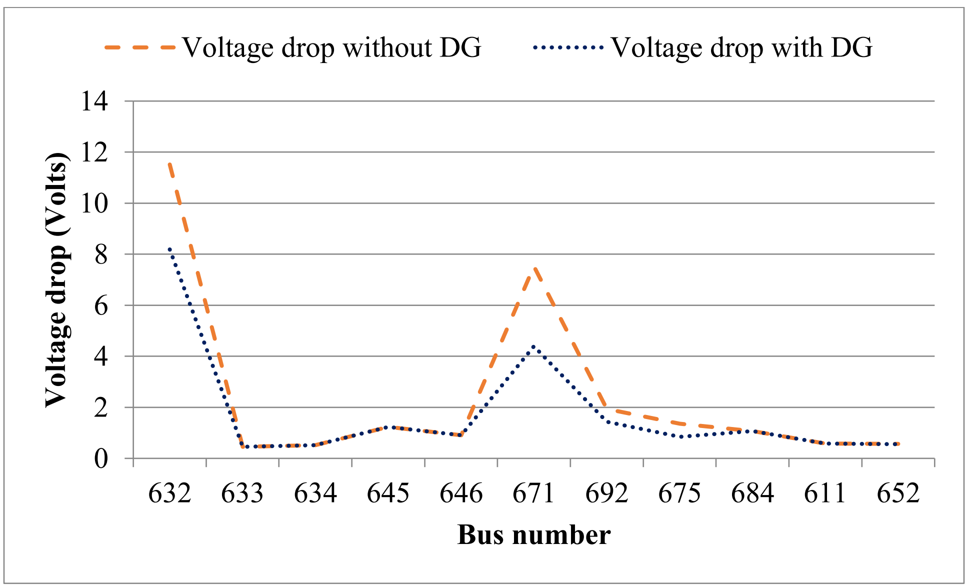

Figure 9 Voltage drop analytical vs simulation.

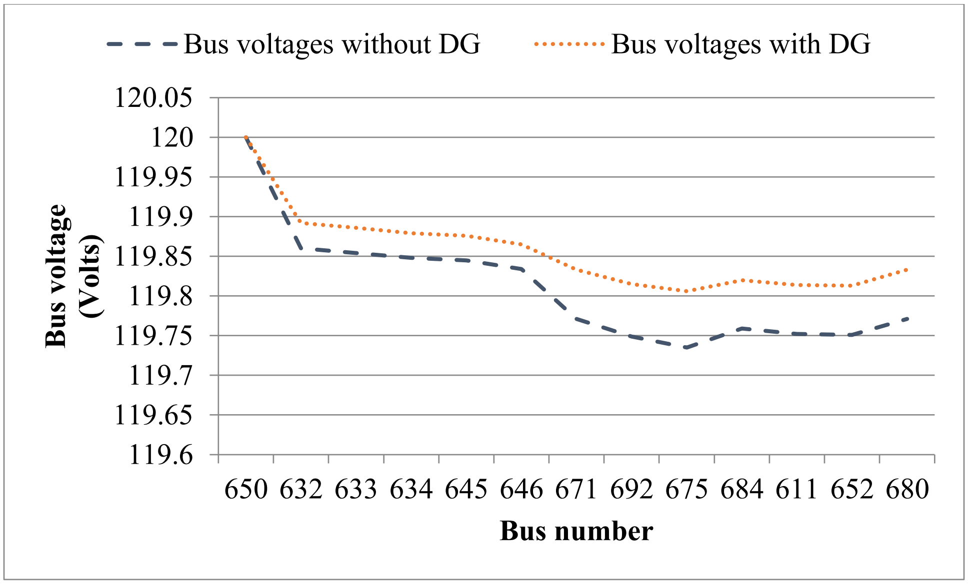

Figure 10 Node voltage analytical vs simulation.

CHAPTER 4

DG REAL AND REACTIVE POWER CONTROL SCHEME

4.1 Approximate Voltage Drop Model

The main objective is to reduce the voltage drop of a distribution system by controlling real and reactive power output of the distributed generation. Figure 11 shows a single-phase equivalent of a generalized distribution system with n buses, showing substation voltage, loads, distributed generation output powers and line impedances.

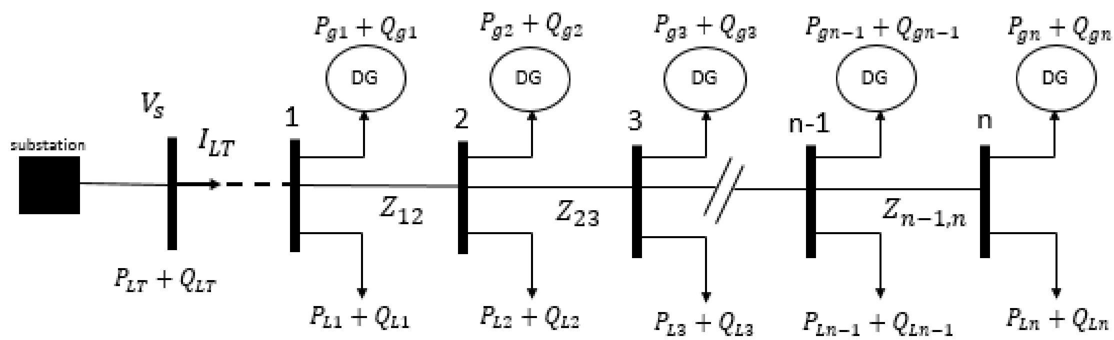

Figure 11 Radial distribution feeder 2.

Basic power flow between two nodes $i - j$, where i is outgoing node and j is incoming node, is given by power flow equations

$$P_{ij} = \frac{V_i V_j Cos(\partial_j - \partial_i + \theta_{ij})}{Z_{ij}} - \frac{{V_j}^2 Cos(\theta_{ij})}{Z_{ij}} \tag{16}$$

$$Q_{ij} = \frac{V_i V_j Sin(\partial_j - \partial_i + \theta_{ij})}{Z_{ij}} - \frac{{V_j}^2 Sin(\theta_{ij})}{Z_{ij}} \tag{17}$$

where P_{ij}, Q_{ij} are real and reactive power flows, V_i, V_j are node voltage magnitudes, ∂_i, ∂_j are load angles of the node voltages, Z_{ij} is the magnitude of line impedance, θ_{ij} is the angle between resistance and reactance. The above two equations (16) and (17) are modified into the following equation by squaring and adding and applying trigonometric Pythagorean identities

$$P_{ij}^{2} + Q_{ij}^{2} = \frac{V_j^{2}}{Z_{ij}^{2}}(V_i^{2} + V_j^{2} - 2V_iV_jCos(\partial_j - \partial_i)) \tag{18}$$

where voltage drop square can be represented by

$$\Delta V_{ij}^{2} = (V_i^{2} + V_j^{2} - 2V_iV_jCos(\partial_j - \partial_i)) \tag{19}$$

By solving the above equations (18) and (19), apparent power flow is given by

$$S_{ij} = \frac{V_j \Delta V_{ij}}{Z_{ij}} \tag{20}$$

The node voltage V_j can be represented in terms of substation voltage V_s which is given by

$$S_{ij} = \frac{(V_s - \left(\sum_{k=1}^{j} \Delta V_k\right))\Delta V_{ij}}{Z_{ij}} \tag{21}$$

where $\left(\sum_{k=1}^{j} \Delta V_k\right)$ is the sum of voltage drops. The value $\Delta V_{ij}\left(\sum_{k=1}^{j} \Delta V_k\right)$ is neglected as the value is very small and negligible. A linear relationship between absolute value of voltage drop and absolute value of apparent power is found for each individual line which is given by

$$|\Delta V_{ij}| = K_{ij} \times |S_{ij}| \tag{22}$$

where $|\Delta V_{ij}|$ is the absolute value of voltage drop for the line $(i - j)$ for a given time t. K_{ij} is the fixed weight assigned to the line $(i - j)$ which is given by

$$K_{ij} = \frac{|Z_{ij}|}{V_s} \tag{23}$$

where $|Z_{ij}|$ is the absolute value of impedance for the line $(i - j)$, V_s is the substation voltage for a given time t. The voltage tap is set to a fixed value. $|S_{ij}|$ is the absolute value of apparent power flowing through the line $(i - j)$ for a given time t which is given by

$$|S_{ij}| = \sqrt{P_{ij}^{2} + Q_{ij}^{2}} \tag{24}$$

where P_{ij} is the real power flow though the line $(i-j)$, Q_{ij} is the reactive power flow through the line $(i-j)$. The real and reactive power flows can be represented by

$$P_{ij} = \left(\sum_{j=1}^{n} P_{Lj} + \sum_{i=0,j=i+1}^{n} P_{ij}{}^{Loss}\right) \tag{25}$$

$$Q_{ij} = \left(\sum_{j=1}^{n} Q_{Lj} + \sum_{i=0,j=i+1}^{n} Q_{ij}{}^{Loss}\right) \tag{26}$$

where $\sum_{j=1}^{n} P_{Lj}$, $\sum_{j=1}^{n} Q_{Lj}$ are summation of real and reactive load powers respectively, $\sum_{i=0,j=i+1}^{n} P_{ij}{}^{Loss}$, $\sum_{i=0,j=i+1}^{n} Q_{ij}{}^{Loss}$, are summation of real and reactive power line losses respectively. Line losses can be represented in terms of line drops which is given by

$$P_{ij}{}^{Loss} = \left(\frac{R_{ij}}{Z_{ij}{}^{2}}\right)\times\Delta V_{ij}{}^{2} \tag{27}$$

$$Q_{ij}{}^{Loss} = \left(\frac{X_{ij}}{Z_{ij}{}^{2}}\right)\times\Delta V_{ij}{}^{2} \tag{28}$$

where R_{ij} and X_{ij} are resistance and reactance for the line $(i-j)$ respectively. Therefore, real and reactive power flows are given by,

$$P_{ij} = \left(\sum_{j=1}^{n} P_{Lj} + \sum_{i=0,j=i+1}^{n} \left(\frac{R_{ij}}{Z_{ij}{}^{2}}\right)\times\Delta V_{ij}{}^{2}\right) \tag{29}$$

$$Q_{ij} = \left(\sum_{j=1}^{n} Q_{Lj} + \sum_{i=0,j=i+1}^{n} \left(\frac{X_{ij}}{Z_{ij}{}^{2}}\right)\times\Delta V_{ij}{}^{2}\right) \tag{30}$$

When distributed generators are connected to the distribution system, the apparent power is given by

$$|S_{ij}| = \sqrt{(P_{ij}-P_{Gj})^2 + (Q_{ij}-Q_{Gj})^2} \tag{31}$$

where $P_{Gj} = \sum_{k=j}^{n} P_{gk}$ and $Q_{Gj} = \sum_{k=j}^{n} Q_{gk}$ are summation of real and reactive power outputs of distributed generators. Voltage drop for a single line is finally given by

$$|\Delta V_{ij}| = \left[K_{ij}\times\sqrt{\left(P_{ij}-P_{Gj}\right)^2 + \left(Q_{ij}-Q_{Gj}\right)^2}\right] \tag{32}$$

Total distribution system voltage drop is obtained by summation of voltage drops of all the lines which is given by

$$|\Delta V_{total}| = \sum_{i=0,j=i+1}^{n}\left[K_{ij}\times\sqrt{\left(P_{ij}-P_{Gj}\right)^2+\left(Q_{ij}-Q_{Gj}\right)^2}\right] \quad (33)$$

4.2 Problem Formulation

4.2.1 Objective

The optimization of the equation (33) is done by decomposing all the feeder lines from the last node to the first node of primary and lateral feeders for a distribution system. This is done since the optimization of each feeder line is dependent on the succeeding feeder line. Therefore, the calculated voltage drop value for the last node can be used to calculate voltage drop for the preceding line and this process continues so on until the first node. The optimization procedure is same for every line. Hence the procedure for a single line is explained below.

The objective in the problem formulation is to minimize voltage drop for a time t, by utilizing the voltage drop equation (32). A generalized solution for the controlled output of real and reactive powers of distributed generation must be found. Hence a nonlinear optimization problem, square of voltage drop equation is considered as an objective function.

It is assumed that the hourly available generation from the distributed generators could be predicted at least one day in advance. Furthermore, the expected demand for consumers could be determined a day ahead based on smart meter infrastructure and active consumer participation. The length of the period is taken for a day. The objective function is given by

$$J\left(P_{gj},Q_{gj}\right) = min\ \Delta V_{ij}^{\ 2} = k_{ij}\left[\left(P_{ij}-P_{gj}\right)^2+\left(Q_{ij}-Q_{gj}\right)^2\right] \quad (34)$$

where $k_{ij} = K_{ij}^{\ 2}$. The constraints and computation process is given below.

4.2.2 Constraints

Limiting Power Generated: The absolute value of the apparent power generated by an individual distributed generator should be always less than or equal to its corresponding maximum available generation limit ($|S_{gj}{}^{max}|$) for a given time t. This work assumed that the distributed generators were integrated with some storage, in order to make sure that they could supply power to the available capacity. Since the main purpose of this work is only to control the real and reactive power output, it is assumed that the generation is available enough for the control. Therefore, the capacity constraint is given by

$$(P_{gj})^2 + (Q_{gj})^2 \leq (|S_{gj}{}^{max}|)^2 \tag{35}$$

Reactive Power Generation Limit: Since the distributed generators are expected to maximize the real power generation, this work assumed a limit on the maximum reactive power that could be generated by the distributed generator. This was considered based on the current practice where the distributed generators are paid based on the net real power injected into the system. Also, this work assumed that distributed generators would compensate for reactive power supply. The reactive power limiter constraint could be given by

$$Q_{gj} \leq \tau P_{gj} \tag{36}$$

where τ is the maximum allowed percentage for the distributed generators, which is determined using maximum allowed power factor angle. This would be determined based on the contract between the utility and the DG operators (customers).

Voltage Drop Limit: The output of the distributed generators should be controlled such that the voltage drop of a line should be within the prescribed limits, which is determined by the utility. The square of voltage drop of line should be less than or equal to square of maximum allowed voltage drop. The voltage limit constraint is given by

$$k_{ij}\left[\left(P_{ij}-P_{gj}\right)^2+\left(Q_{ij}-Q_{gj}\right)^2\right]\leq \Delta V_{max}{}^2 \tag{37}$$

where ΔV_{max} is the maximum allowed voltage drop.

4.2.3 Computation

To compute the final objective function for the optimization problem the lagrange-multiplier approach was used. Therefore, the lagrangian function, which includes square of voltage drop and inequality constraints for a single line is given by

$$\mathcal{L}\left(P_{gj},Q_{gj},\lambda_1,\lambda_2,\lambda_3\right)=k_{ij}\left[\left(P_{ij}-P_{gj}\right)^2+\left(Q_{ij}-Q_{gj}\right)^2\right]-\lambda_1\left(\left(\left|S_{gj}{}^{max}\right|\right)^2-\left(P_{gj}\right)^2-\left(Q_{gj}\right)^2\right)-\lambda_2\left(\tau P_{gj}-Q_{gj}\right)-\lambda_3\left(\Delta V_{max}{}^2-k_{ij}\left[\left(P_{ij}-P_{gj}\right)^2+\left(Q_{ij}-Q_{gj}\right)^2\right]\right) \tag{38}$$

The inequality constraints are multiplied by variables $\lambda_1, \lambda_2, \lambda_3$, called the Lagrange multipliers. The final objective function can have a stationary point, which can be a local minimum or maximum. To check whether the developed constrained optimization problem is a convex function or not, the bordered Hessian matrix was constructed for the equation (38) is given by

$$H=\begin{pmatrix}2\left(k_{ij}(1+\lambda_3)+\lambda_1\right) & 0\\ 0 & 2\left(k_{ij}(1+\lambda_3)+\lambda_1\right)\end{pmatrix} \tag{39}$$

Since the determinant of the Hessian matrix is positive definite, the critical point would be a local minimum. To solve this nonlinear programming problem the Karush-Kuhn-Tucker (KKT) conditions were utilized. Therefore, the KKT conditions for the above Lagrangian function, which would minimize voltage drop is given by

Stationary Conditions:

$$-2k_{ij}\left(P_{ij}-P_{gj}\right)+2\lambda_1 P_{gj}-\lambda_2\tau-2k_{ij}\lambda_3\left(P_{ij}-P_{gj}\right)=0 \tag{40}$$

$$-2k_{ij}\left(Q_{ij}-Q_{gj}\right)+2\lambda_1 Q_{gj}+\lambda_2-2k_{ij}\lambda_3\left(Q_{ij}-Q_{gj}\right)=0 \tag{41}$$

Complimentary Slackness:

$$\lambda_1\left(\left(\left|S_{gj}{}^{max}\right|\right)^2-\left(P_{gj}\right)^2-\left(Q_{gj}\right)^2\right)=0 \quad (42)$$

$$\lambda_2\left(\tau P_{gj}-Q_{gj}\right)=0 \quad (43)$$

$$\lambda_3\left(\Delta V_{max}{}^2-k_{ij}\left[\left(P_{ij}-P_{gj}\right)^2+\left(Q_{ij}-Q_{gj}\right)^2\right]\right)=0 \quad (44)$$

Primary Feasibility:

$$\left(\left(\left|S_{gj}{}^{max}\right|\right)^2-\left(P_{gj}\right)^2-\left(Q_{gj}\right)^2\right)\geq 0 \quad (45)$$

$$\left(\tau P_{gj}-Q_{gj}\right)\geq 0 \quad (46)$$

$$\left(\Delta V_{max}{}^2-k_{ij}\left[\left(P_{ij}-P_{gj}\right)^2+\left(Q_{ij}-Q_{gj}\right)^2\right]\right)\geq 0 \quad (47)$$

Dual Feasibility:

$$\lambda_1\geq 0 \quad (48)$$

$$\lambda_2\geq 0 \quad (49)$$

$$\lambda_3\geq 0 \quad (50)$$

The convergence for the above problem can be achieved for any combination of slack variables ($\lambda_1, \lambda_2, \lambda_3$). There are 8 possible combinations out of which only 4 combinations were found to be feasible. Table 1 shows global optimal solutions obtained for the possible combinations of slacks variables.

TABLE 1

OPTIMAL SOLUTIONS FOR VOLTAGE DROP MINIMIZATION PROBLEM

Combinations	(P_{gj})	(Q_{gj})
$\lambda_1 = \lambda_2 = \lambda_3 = 0$	P_{ij}	Q_{ij}
$\lambda_1 \neq 0, \lambda_2 = \lambda_3 = 0$	$\frac{P_{ij} \lvert S_{gj}{}^{max} \rvert}{\sqrt{P_{ij}{}^2 + Q_{ij}{}^2}}$	$\frac{Q_{ij} \lvert S_{gj}{}^{max} \rvert}{\sqrt{P_{ij}{}^2 + Q_{ij}{}^2}}$
$\lambda_1 = \lambda_3 = 0, \lambda_2 \neq 0$	$\frac{P_{ij} + \tau Q_{ij}}{(1+\tau^2)}$	$\tau \times \left(\frac{P_{ij} + \tau Q_{ij}}{(1+\tau^2)}\right)$
$\lambda_1 = \lambda_2 \neq 0, \lambda_3 = 0$	$\frac{\lvert S_{gj}{}^{max} \rvert}{\sqrt{1+\tau^2}}$	$\frac{\tau \lvert S_{gj}{}^{max} \rvert}{\sqrt{1+\tau^2}}$

Each condition for the slack variable is valid only under certain limitations. The limitations for the corresponding KKT conditions are given below in Table 2.

TABLE 2

CORRESPONDING KKT CONDITIONS

Combinations	Limitations
$\lambda_1 = \lambda_2 = \lambda_3 = 0$	$a = \tau P_{gj} - Q_{gj} \geq 0$ $b = \left(\lvert S_{gj}{}^{max} \rvert\right)^2 - \left(P_{gj}\right)^2 - \left(Q_{gj}\right)^2 \geq 0$ $d = \Delta V_{max}{}^2 \geq 0$

TABLE 2 (continued)

Combinations	Limitations
$\lambda_1 \neq 0, \lambda_2 = \lambda_3 = 0$	$a = \tau P_{gj} - Q_{gj} \geq 0$ $b = \left(\left\lvert S_{gj}{}^{max} \right\rvert\right)^2 - \left(P_{gj}\right)^2 - \left(Q_{gj}\right)^2 < 0$ $e = \Delta V_{max}{}^2 - \left(k_{ij}\right)\left(\sqrt{P_{ij}{}^2 + Q_{ij}{}^2} - \left\lvert S_{gj}{}^{max} \right\rvert\right)^2 \geq 0$
$\lambda_1 = \lambda_3 = 0, \lambda_2 \neq 0$	$a = \tau P_{gj} - Q_{gj} < 0$ $c = \left(P_{ij} + \tau Q_{ij}\right) - \left\lvert S_{gj}{}^{max} \right\rvert (\sqrt{1 + \tau^2}) \leq 0$ $f = \Delta V_{max}{}^2 - (k_{ij}) \frac{(Q_{ij} - \tau P_{ij})^2}{(1 + \tau^2)} \geq 0$
$\lambda_1 = \lambda_2 \neq 0, \lambda_3 = 0$	$a = \tau P_{gj} - Q_{gj} < 0$ $c = \left(P_{ij} + \tau Q_{ij}\right) - \left\lvert S_{gj}{}^{max} \right\rvert (\sqrt{1 + \tau^2}) > 0$ $g = \Delta V_{max}{}^2 - \left(k_{ij}\right)\left(\left(P_{ij} - \frac{\left\lvert S_{gj}{}^{max} \right\rvert}{\sqrt{1 + \tau^2}}\right)^2 + \left(Q_{ij} - \frac{\tau \left\lvert S_{gj}{}^{max} \right\rvert}{\sqrt{1 + \tau^2}}\right)^2\right) \geq 0$

Since the function is strictly convex, the solution is unique. An algorithm to solve the above optimization problem was developed. This is shown in Figure 12.

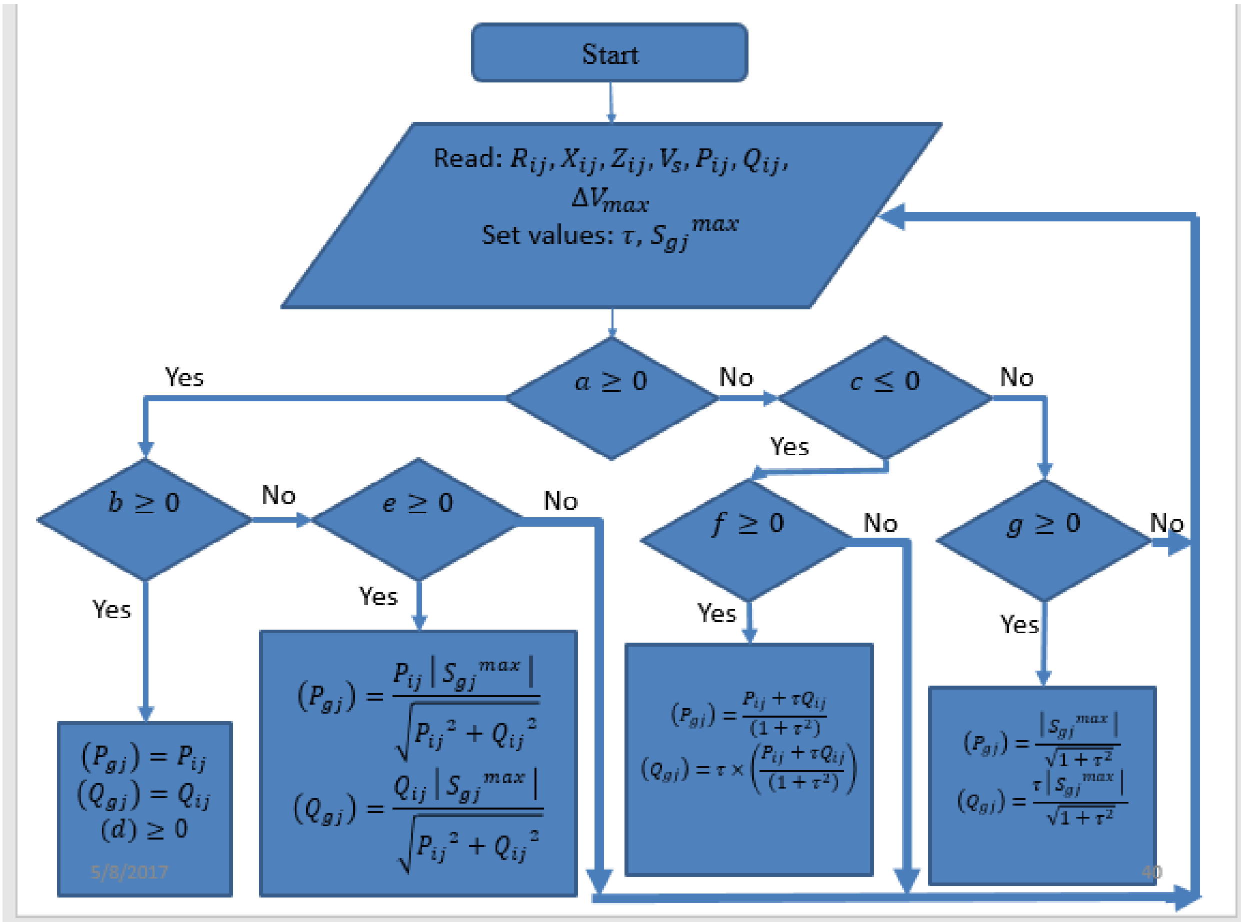

Figure 12 Flowchart algorithm for DG output.

4.3 Numerical Analysis

IEEE 13 node test feeder was used in this work to illustrate the validity of the above optimization algorithm [33]. The demand curve was developed by taking random hourly load data for 24 hours. The load data was considered as total apparent power (substation load) consumed at different nodes for each hour and was randomly distributed among different nodes. Figure 13 shows IEEE 13 node test feeder.

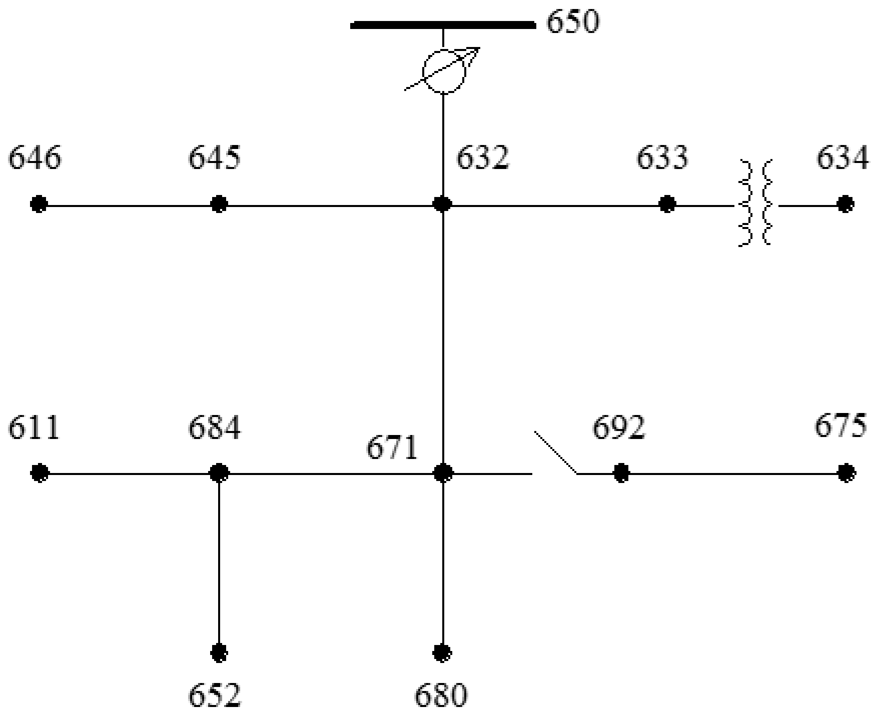

Figure 13 IEEE 13 node test feeder 2 [33].

Two solar PV distributed generators were considered at nodes 675 (DG1) and 671 (DG2). The output generation curve for PV generators were taken from solar PV power generation data source [35]. Maximum available generation for DG1 was considered to be 10% of the maximum substation load and for DG2 was considered to be 42% of the substation load. Figure 14 shows Load curve along with generation output curves of DG1 and DG2.

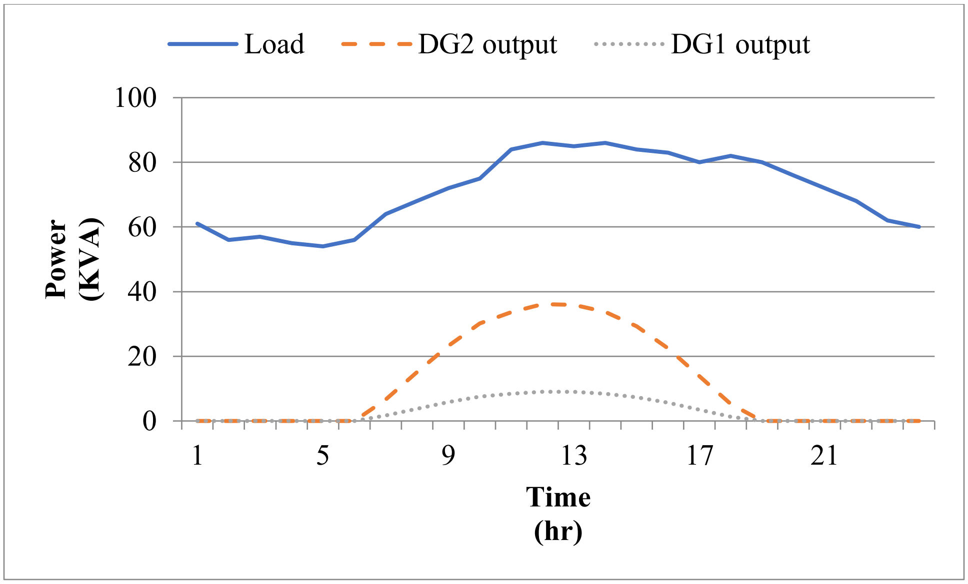

Figure 14 Load and PV generator profiles.

Since the distributed generation availability is only for 12 hours, voltage drops for the lines 632-671 and 692-675, total feeder voltage drop, total real and reactive power losses were calculated for 13 node feeder for 12-hour duration. Because the main objective of this work is to minimize the voltage drop, a comparison with DG control and without DG control was done. The controlled real and reactive power output for DG1 and DG2 was computed using MATLAB [36] and the voltage drop and power loss values were obtained using Milsoft Windmil [34]. Based on the values taken for computation in the optimization algorithm, the maximum voltage drop for a line was set to be 0.0872 volts. Figure 15 and Figure 16 shows comparison of voltage drops for the lines 632-671 and 692-675 respectively with and without DG control, and the results show that voltage drop was kept within the set range. Similarly, the results shown in Figures 17, 18 and 19 indicate that total feeder voltage drop, real and reactive power losses were reduced with DG control scheme.

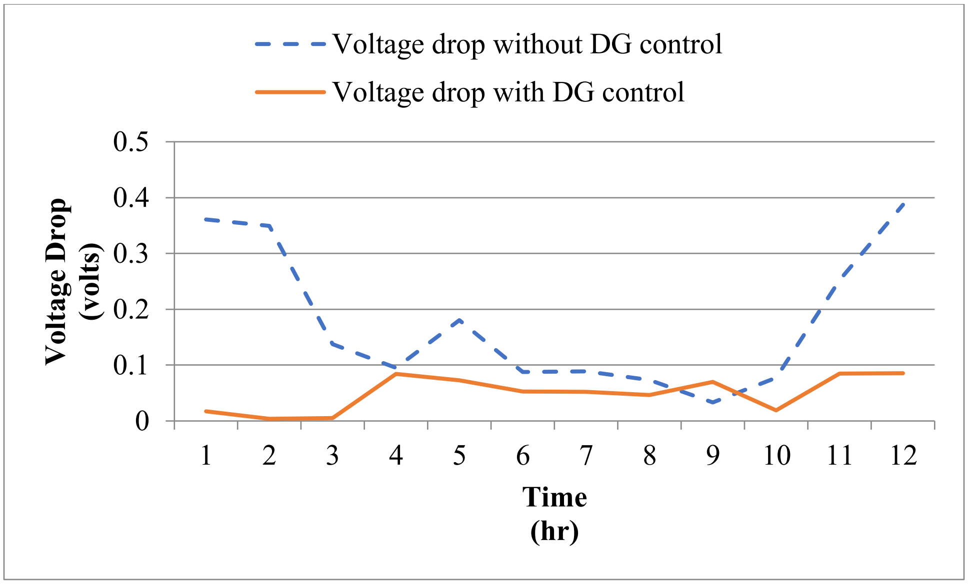

Figure 15 Voltage drop comparison for the line 632-671.

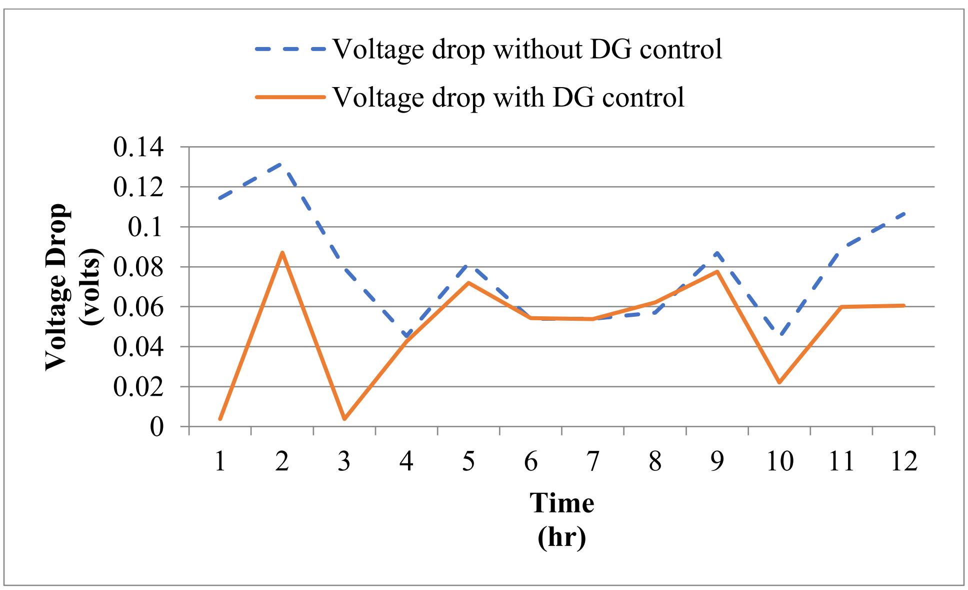

Figure 16 Voltage drop comparison for the line 692-675.

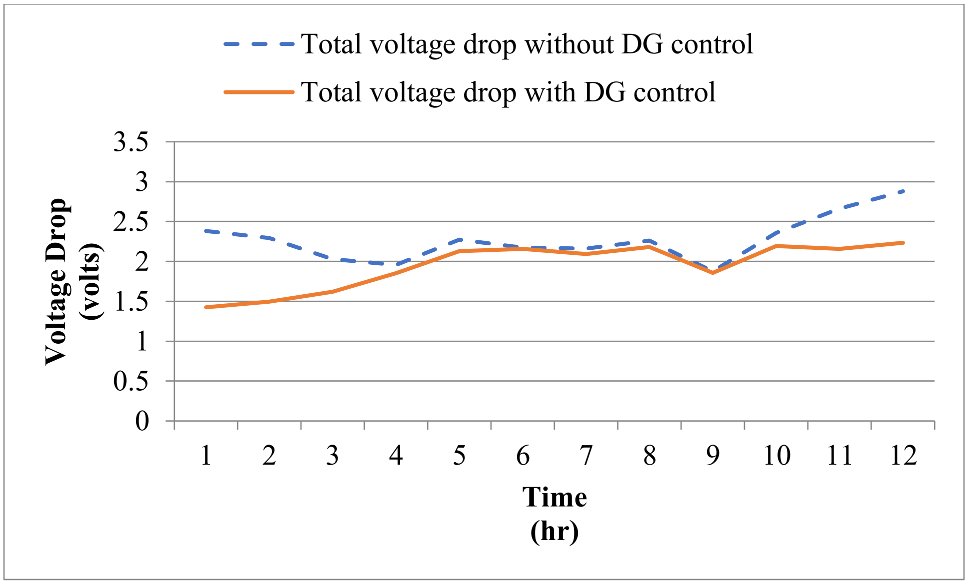

Figure 17 Total feeder voltage drop comparison.

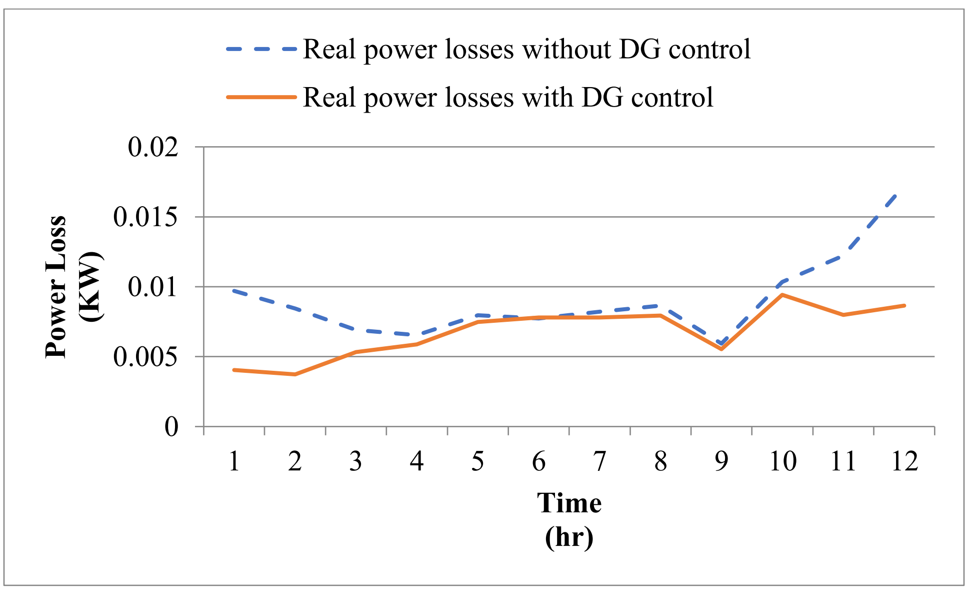

Figure 18 Real power losses comparison.

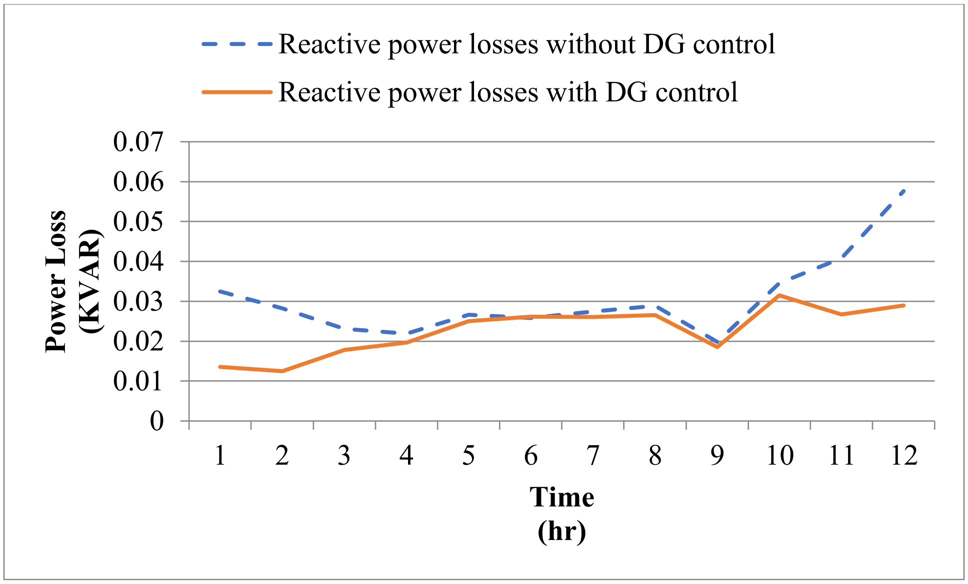

Figure 19 Reactive power losses comparison.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The first part of this work focused on impact of distributed generators on voltage drop and node voltage. For a single phase radial distribution feeder, line currents were calculated using approximate load factor method. After testing the proposed method on IEEE 13-node test feeder using Milsoft Engineering Analysis tool Windmil, the error between simulated value and analytically calculated value was negligible. Similarly, voltage drop and node voltage was verified with IEEE 13-node test feeder with and without DG's and found that, reduction in feeder voltage drop and rise in the node voltage due to the penetration of DG power.

In the second part of this work, a voltage drop model was developed for the radial distribution feeder and a constraint optimization approach was proposed to minimize feeder voltage by DG control. After testing the proposed method with IEEE 13-node test feeder, the voltage drop was minimized within the set maximum allowable range. There was a significant reduction of total system voltage drop, real and reactive power losses.

5.2 Future Work

In this work, the substation voltage was considered to be a fixed value in the voltage drop model. As a part of future work the substation voltage tap setting has be determined using dynamic programming. Objective function of voltage drop has to be further developed so that optimization can be done including capacitor banks.

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