AGGREGATOR BASED OPTIMAL OPERATION OF RADIAL DISTRIBUTION SYSTEM

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 Lakshman and Chandrika, my sister Nuwanthi, and my husband Nipuna

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ABSTRACT

Due to the recent significant increase in Distribution Generation technologies and storage such as Solar, Wind and use of electric vehicle batteries improves and widely opens up the high penetration of renewable generation to the grid. The use of renewable distributed generation (DG) technologies and "green power" can provide a significant environmental benefit, and their costs continue to drop. Therefore, utilities try to get more injected renewable energy to our distribution network. However, the integration of such capacity of renewable generations are not beneficial if they are not coordinated properly to work with the prevailing power system grid. This thesis presents an aggregator based optimal power flow method to calculate optimal DG power output, necessary voltages at buses and to control the output of the DGs accordance to the grid behaviors in the distribution system. The proposed method is able to minimize the electricity cost by cutting the power transferred from the grid and to provide the co-optimized operation strategy for distribution system with residential photovoltaics (PVs). A Case study is also presented to demonstrate the feasibility of proposed method.

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LIST OF ABBREVATIONS

ANSI	American National Standards Institute
BOS	Balance of System
DG	Distributed Generation
DSM	Demand Side Management
IEEE	Institute of Electrical and Electronics Engineers
LCOE	Levelized Cost of Energy
LGC	Loss of Generation Cost
LMP	Locational Marginal Price
OPF	Optimal Power Flow
PV	Photovoltaics

CHAPTER 1

INTRODUCTION

1.1 Motivation/Background

The fast developing technological, environmental, economic and social trends encourage the prevailing use of distributed generation (DG) units in the electric utility system. Recent technological advances in the renewable energy sources such as wind, solar and mini hydro plants have made the "optimal power flow" concept a most interesting researched topic among the power community and there have been many discussions about enabling distributed generations to distribution network in order to reduce electricity cost [1].

In this era, distributed generation(DG) is one of the most popular subject in the power systems. Using many small plants located near end user level rather than using a one large generation plant located in the generation level would give many benefits. Earlier, combustion generators were used as distributed generation but they were not environmental friendly even though combustion generators are cheap. DGs provide environmental friendly, reliable and low cost option to produce electricity at end user level.

According to Bloom energy website [2], currently solar energy is the most popular distributed generation source as it is environmental friendly. Even though, connecting renewable energy to our distribution system could give us environmental and economic benefits, there are some limitations which would change that. One limitation of solar power is unpredictability of sudden cloud coverage. This could be a problem as DG will be need to be coordinated to get a benefit to the utility and end use customers. Because of this issue, Distribution Generations should be controlled according to the system requirements.

Currently DGs are not well optimized to meet the system requirements as the system becomes complex after connecting many DGs to the power system. This problem requires Demand Side Management or other controller to coordinate DGs operation. In Demand Side Management (DSM), to meet the electricity demand instead of increasing the generation it pays customers to reduce energy use at that time.

Voltage control of the system is very important as equipment in the power system and also at consumer ends are intended to work within a certain voltage range. At high voltage level equipment could be damaged by overheating and also at lower level of voltage that equipment will not have enough power to work properly [3].

In AC system, active power is used to supply the demand of the power system while reactive power controls the voltage to maintain the reliability of the system. If the voltage on the system is not high enough, active power cannot be supplied. When there is not enough reactive power, voltage decreases and efficient real power won't be provided. Reactive power is made when current and voltages are not in phase with each other. By predicting and correcting reactive power demand from loads voltages can be controlled [3].

Radial distribution systems, Loop distribution systems and Network distribution systems are three design types of the distribution systems. According to Kersting [4], only one power source is available in the radial system and all the customers are provided by this power source. In case of a power failure the entire line will be down until it is fixed. But this is the most common design as it is the cheapest design out of all three designs. This thesis only focuses on radial distribution system.

This thesis will present aggregator based optimal power flow method (OPF) [5] to find a solution in a way that is most cost effective and archives highest performance accordance to the given constrains. This thesis also proposes a model to calculate loss of generation cost for PV modules [6] [7] . Usually when optimizing the objective function itself restricted by the lack of full information because of assumptions made during the modeling of the objective equation. This work will include all the assumptions have made during its pre modeling the objective functions. Thus, this work will use optimal power flow to minimize the line loss, get minimal voltage deviation and most importantly to archive an active maximum optimal DG output. From the wide-ranging availability selections of renewable energy sources, this thesis only studies the solar (photovoltaic) DGs as there is no fuel cost but only the initial cost to start solar PVs, and also studies their fast accessibility and controllability [8] [9]. Also this thesis discusses how an optimal power flow between the generators and the loads is achieved from modeling the Line loss, Load modeling and AC power flow model. This thesis also uses the concept of Levelized Cost of Energy to model minimize the loss of generation cost of PVs according to system requirements.

1.2 Organization of Thesis

This thesis consists of six chapters. Chapter 1 introduces the background of the thesis. Chapter 2 is the literature review on Optimal Power Flow and Levelized Cost of Energy. Chapter 3 presents proposed feeder level modeling. Chapter 4 presents aggregator based optimal power flow, Chapter 5 illustrates case study, results and discussion. Chapter 6 ends with the conclusion and future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Optimal Power Flow

More than fifty plus years has already passed since the first optimal power flow problem was originally formulated by Carpentier in 1962, still we find it difficult to solve due the nonlinearity of the power flow problem [10]. Since then there are many potential mathematical tools and methods introduced to improve the speed and robustness of solving optimal power flow by including constraints and other linear approximations. In order to solve optimal power flow every day and save millions of dollars, the utility company's engineers analyze the network and based on their judgments they found out that there are three types of common problems that they identified in a normal optimization problem. Namely they are, Power flow, Economic dispatch and Optimal Power flow. Even though there are other problems to be considered, which are discussed on later part of the thesis, for now these three categories are given the first priority.

Many researchers have focused on this research and try to find a better strategic optimal solution/method to connect those DGs to the grid. [11]- [12] Davis, et al., proposed that distributed resources in power systems could provide significant advantages over traditional central station generations [11]. He also considered the factors of cost, efficiency and losses and presented the reliability evaluation for commercial, residential and remote load applications [13]. Hatziargyriou and Meliopoulos discussed the existing challenges related with distributed generations, which shows there are still many problems required to be addressed in the next few decades [14]. Smallwood talked about distributed generation in autonomous and non-autonomous micro grids in literature [15]. Katiraei, et al., covered another important topic with DGs and micro-grid, DGs autonomous operation during and subsequent to islanding process, which could provide a feasible way to implement DGs with micro-grid concept [16]. Zhang, et al., focused on design and operation of micro-grid with optimal energy management [17] [18]. Menon and Nehrir talked about the hybrid islanding detection by using voltage unbalance and frequency set point [19].

Even though the utilities have installed DGs connected to the distribution network system, they are not well optimized to meet requirements from system. After connecting a large number of DGs into the grid, the network itself becomes complex. Therefore, it needs a demand side management and other automated operation and control to coordinate the DGs operation and the consumers (load side). Also the output of the DGs is going to change from time to time with weather changes. For an example, a power output between solar PVs and wind DGs will affect the optimal output of the system because of reduced power generation depending on availability of solar and wind. Both will never produce constant power to the grid, unless it is being controlled according to system requirements. Therefore, most of the radial distributed system could not get benefits from the DGs. These unanticipated factors have made the optimization of power flow be an active research topic.

2.2 Levelized Cost of Energy

Emerging technologies in renewable energy sources such as solar and wind have encouraged society to use Distributed generation in the electric system. Usage of DG’s will reduce the electricity cost if it is used efficiently.

Cameron proposed the Levelized Cost of Energy concept(LCOE). This can be used to develop an appropriate model of loss of generation cost for solar PV’s to improve optimal the power flow of a radial distribution system model. The author has only considered about the calculation of LCOE of Solar PV in his work [20].

According to Cameron, the cost of energy generated from roof-top solar panels have decreased due to better efficiency, life cycle improvement of PVs and reduction of the initial cost spent on PVs [20].

LCOE is used to compare costs of different types of PVs [21]. According to Baker, there are mainly six types of commercial and near commercial PV technologies, which are thick film silicon low, thick film silicon high, thin film inorganic low, thin film inorganic high, thin film organic low and thin film organic high [21]. Out of all six technologies, thick film silicon low and thick film silicon high have 30 years' life span each [21].

LCOE is used to compute the precise cost of energy produced using solar PV [21] [20]. LCOE measures dollars per kilowatt-hour generated over the life cycle of the system [20]-[22]Installation cost, financing factors, cost of operation and maintenance costs etc. accounts for LCOE [20] [21]. Goal of PV is to obtain a LCOE in a given location to be equal to or lower than the current price of the market [21]. According to Baker, LCOE can be represented using the following equation [21].

$$LCOE = \frac{\sum_{t=0}^{L} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{L} \frac{E_t}{(1+i)^t}} \tag{2.1}$$

L is the life span of the technology. i is the discount rate. C_t is the installation and operating costs occurred in the time period t. E_t is the energy output in the period of time t [21]. In the above equation, the numerator measures the total value of cost occurred to initiate and control the generation of the technology [21] . Energy output produced by a solar PV also depends on many parameters such as tilt of solar panels, time of year and system capacity [21] [23].

Kang developed a model to analyze the LCOE on the impact of combined and individual efficiency of module, cost of a module, system lifespan, total system loss rate and balance of system (BOS) cost [24].The author uses parameters such as Daily insolation, Temperature coefficient, Module operating temperature, Installed system cost, Operation and maintenance cost, Mortgage loan rate, Loan fraction, tax rate, weighted average cost of capital and Annual system output degradation etc. to calculate LCOE and how it is going to change with the parameters [24]. The author was able to achieve a target LCOE by choosing right arrangement of the parameters [24]. Cameron also discusses the impact of various parameters in the LCOE [20]. The author states that financial parameters (tax rates, Interest rate on borrowed money etc.) have a significant impact on LCOE while the lifetime of the solar inverter has only a small impact on large commercial networks and a large effect on smaller systems [20].

CHAPTER 3

PROPOSED FEEDER LEVEL MODELING

A simple model in presence of aggregators is presented as shown in Figure 1 and is used in this work to introduce the proposed optimal radial distribution level power flow.

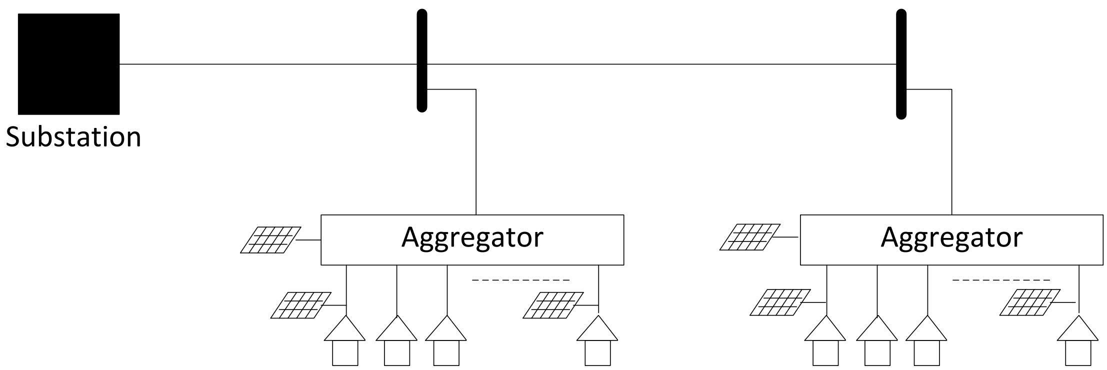

Figure 3.1:Aggregator Based Radial Distribution System with Co-Located PV

A shown in the Figure 3.1, the several residential customers and co-located solar PV generation is managed by aggregators. Solar PVs considered in this work can be either roof-top solar panels that are connected at the residential level or small PV farms that are located independently and managed by the aggregator. Since the proposed model envisions that the aggregator would use a real time power management scheme, it is necessary to reduce the complexity of computation. The following needs to be modeled to reduce the computational complexity,

For real time computation of power flow in the lines it is necessary to eliminate the iterative process associated with the power flow analysis. The standard forward and backward sweep power flow analysis [4]is computation intensive method. At distribution level the assumption of 1.0 pu voltage magnitude at all the nodes will reduce the accuracy of computation and thus standard DC power flow assumptions will not be valid. With the presence of aggregators more sensors will be placed at the aggregator nodes to measure the bus voltage. Therefore, a AC power flow model is developed for radial feeders in this work.

At distribution level power loss neglecting power losses will reduce the accuracy significantly. Therefore, a model to determine the feeder segment power loss is developed and a simple model is presented to evaluate the net power consumption of each aggregator. Finally, a model is presented to obtain loss of generation cost for PV modules. Each subsection (3.1-3.4) describe the modeling of each model.

3.1 Modified Radial AC Power Flow Model

AC power flow model for a radial distribution network in the presence of aggregator is investigated. This thesis limits its scope to managing the power flow between the substation and the aggregator bus. It is assumed that the connections between the customers who are connected to the aggregator is strong and has the capability to direct the power flow locally. Figure 3.2 shows a bus connection that is used for radial power flow computation.

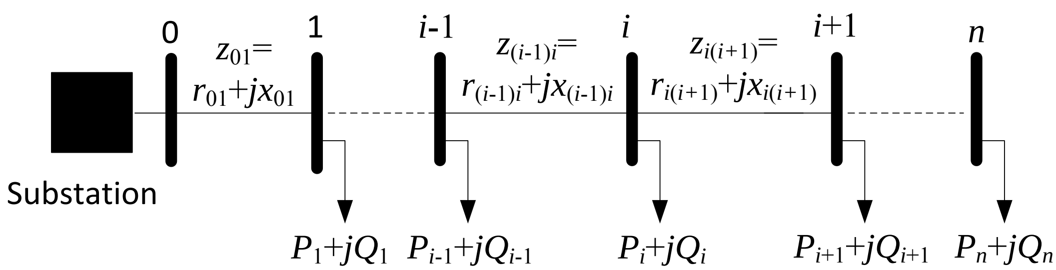

Figure 3.2: Radial Distribution System

The i[th] node in Figure 3.2 is used for the illustration purpose, the admittance of the line connecting the node (i-1) and i is given by,

$$y_{(i-1)i} = g_{(i-1)i} - jb_{(i-1)i} \tag{3.1}$$

where

$$g_{(i-1)i} = \frac{r_{(i-1)i}}{\left(r_{(i-1)i}\right)^2 + \left(x_{(i-1)i}\right)^2} \tag{3.2}$$

and

$$b_{(i-1)i} = \frac{x_{(i-1)i}}{\left(r_{(i-1)i}\right)^2 + \left(x_{(i-1)i}\right)^2} \tag{3.3}$$

where, $r_{(i-1)i}$ is the resistance in the line between buses $(i-1)$ and i, and $x_{(i-1)i}$ is the reactance in the line between buses $(i-1)$ and i.

Distribution lines can be modeled as short lines and this work assumes that the aggregators will balance the three phases to reduce the unbalanced operation of the distribution system by appropriate system modeling and demand response schemes. Since the short line model is used the capacitance is neglected [4], therefore line charging is not considered. The complex power flow in the feeder segment $(i-1)$ and i flowing from node i to $(i-1)$ is computed through ohms' law [3] as,

$$\mathbf{S}_{(i-1)i} = \mathbf{V}_{(i-1)i}\mathbf{I}^*_{i(i-1)} \tag{3.4}$$

where, $\mathbf{V}_{(i-1)i}$ is the voltage drop vector across feeder segment $(i-1)$ and i; and $\mathbf{I}_{(i-1)i}$ current flowing from node i to node $(i-1)$. Using the node voltages, the above relationship could be rewritten as,

$$\mathbf{S}_{(i-1)i} = \left(y_{(i-1)i}\right)^* \left(V_i^2 - V_i V_{(i-1)} \left(\cos\left(\theta_i - \theta_{(i-1)}\right) + j\sin\left(\theta_i - \theta_{(i-1)i}\right)\right)\right) \tag{3.5}$$

where, V_x is the voltage magnitude at bus x and θ_x is the voltage angle at bus x. The voltage angle difference is very small between two segments of distribution feeder during steady state operating conditions. Since the aim of this thesis is to develop an optimal power flow model for the steady state operating conditions the following assumption for two adjacent busses are used in this work.

$$\cos\left(\theta_i - \theta_{(i-1)}\right) = 1 \tag{3.5}$$

and

$$\sin\left(\theta_i - \theta_{(i-1)}\right) = \left(\theta_i - \theta_{(i-1)}\right)_{rad} = \theta_{i(i-1)} \tag{3.6}$$

where, $\theta_{i(i-1)}$ is the angle difference between the node i to node $(i-1)$ measured in radians. Using the above relationship, the power flow from node i to node $(i-1)$ is given by:

$$S_{i(i-1)} = \left(g_{(i-1)i} + jb_{(i-1)i}\right)\left(V_i^2 - V_iV_{(i-1)} - jV_iV_{(i-1)}\theta_{i(i-1)}\right) \tag{3.7}$$

Using the above relationship, the real power flow from node i to node $(i-1)$ can be computed as,

$$P_{i(i-1)} = g_{i(i-1)}\left(V_i^2 - V_iV_{(i-1)}\right) + b_{i(i-1)}V_iV_{(i-1)}\theta_{i(i-1)} \tag{3.8}$$

and the reactive power flow from node i to node $(i-1)$ can be computed as,

$$Q_{i(i-1)} = b_{i(i-1)}\left(V_i^2 - V_iV_{(i-1)}\right) - g_{i(i-1)}V_iV_{(i-1)}\theta_{i(i-1)} \tag{3.9}$$

These two equations are used in the optimization algorithm to determine feeder section power flow.

3.2 Feeder Section Power Loss Model

Line loss between nodes is considered in this work. This work assumes the sectionalizes and switches and protection devices connected in series to the feeder section would have negligible impedance compared to the feeder section impedance. Therefore, real power lost in the distribution system is due to the copper losses in the conductors. Power loss in a feeder section is computed with the assumption that the line impedance doesn't change within a day during steady state operations [25], The line loss can be given by,

$$P_{i(i-1)}^{Loss} = r_{i(i-1)}\left|\mathbf{I}_{i(i-1)}\right|^2 \tag{3.10}$$

By using the ohms law the power loss in the line segment is given by,

$$P_{i(i-1)}^{Loss} = g_{i(i-1)}\left|(V_i\cos\theta_i + jV_i\sin\theta_i) - (V_{(i-1)}\cos\theta_{(i-1)} + jV_{(i-1)}\sin\theta_{(i-1)})\right|^2 \tag{3.11}$$

The above equation is expanded and rewritten as,

$$P_{i(i-1)}^{Loss} = g_{i(i-1)}\left(V_i^2(\cos^2\theta_i + \sin^2\theta_i) + V_{i-1}^2(\cos^2\theta_{i-1} + \sin^2\theta_{i-1}) - 2V_iV_{i-1}(\cos\theta_i\cos\theta_{i-1} + \sin\theta_i\sin\theta_{i-1})\right) \tag{3.12}$$

Using the same assumption for node angle difference the power flow and the trigonometric identities,

$$P_{i(i-1)}^{Loss} = g_{i(i-1)}(V_i^2 + V_{i-1}^2 - 2V_iV_{i-1}) \tag{3.13}$$

This relationship is used as an objective to minimize the power loss in the feeder section.

3.3 Aggregator Load Model

Load at the aggregator level is assumed to be the difference between the sum of all the customer loads and the sum of all distributed generation output. The aggregator will have access to the historic load profile for different consumers and the load schedule of demand response through the smart meters. The expected PV output would be computed using the weather forecast. Since developing a demand response model is out of the scope of this work and demand forecasting models are available through literature [26], the real and reactive load at the aggregator is given by:

$$P_i^L = \sum_{k=1}^{N} P_k^{L_i}, \quad P_i^{DG} = \sum_{l=1}^{M} P_l^{DG_i} \tag{3.14}$$

and

$$Q_i^L = \sum_{k=1}^{N} Q_k^{L_i}, \quad Q_i^{DG} = \sum_{l=1}^{M} Q_l^{DG_i} \tag{3.15}$$

where, $P_k^{L_i}$ is the real power consumption of k^{th} (out of N total users) customer connected to the aggregator, $Q_k^{L_i}$ is the reactive power consumption of k^{th} (out of N total users) customer connected to the aggregator, $P_l^{DG_i}$ is the real power supplied byl^{th} (out of M total DGs) PV panel connected to the aggregator, and $Q_l^{DG_i}$ is the reactive power supplied by l^{th} (out of N total DGs) PV panel connected to the aggregator. This load model is used in this work to represent the net load at the aggregator bus.

3.4 Loss of Generation cost for PV modules

It is customary to use the full rated energy output generated from Solar PV DGs. As power hungry consumers we tend to accumulate all the free power and then use it to run day-to-day appliances as we please. It is acceptable as long as the solar PVs are not connected to the national grid that is not controlled over the renewable DGs. As soon as you connect the grid, that has a capability of controlling DGs, the use of renewable DGs are limited by on or below their rated output. For example, since controlled DGs means that they are under Optimal Power flow and constrained, one's output of solar energy could be less than its actual output at a given time because of aforementioned satisfactory conditions to be met. Therefore, the loss of generation is occurred. This gap between constrained solar output, or rather controlled DG output and uncontrolled DG output, produces a lost cost by not using the extra generation.

Levelized Cost of Energy measures dollars per kilowatt-hour generated over the life cycle of the system. However, there is a major concern that should be addressed properly when using a solar panel on optimized conditions. Initial and operation cost of solar panels will not be compensated just from the revenue over the life cycle of the PV. In optimal conditions, the controller will not always allow the PV to produce its maximum value as it is bounded by system constraints. Therefore, in optimal conditions, there will be a loss of revenue. So the concept of Lost of Generation Cost (LGC) is introduced.

Levelized cost of energy is defined as,

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{L} \frac{C_i}{(1+i)^t}}{\sum_{t=1}^{L} \frac{E_t}{(1+i)^t}} \tag{3.16}$$

L is the life span of the technology. i is the discount rate. C_t is the installation and operating costs occurred in the time period t. E_t is the energy output in the period of time t [21].

Then, we could use this concept to generate the loss of generation cost(LCE) for solar PVs.

$$\mathrm{LGC} = \frac{\sum_{t=1}^{L} \frac{C_i}{(1+i)^t}}{\sum_{t=1}^{L} \frac{E_t}{(1+i)^t} - \frac{\Delta E}{(1+i)^{t1}}} \tag{3.17}$$

E_t is the energy output in the period of t. ΔE will be the energy difference between optimal DG output and uncontrolled DG output. t1 is the operating time period of the PV module.

Equation 3.17 could be simplified as,

$$\mathrm{LGC} = \frac{C}{E - \frac{\Delta E}{(1+i)^{t1}}} \tag{3.18}$$

Using equation 3.16, we could simplify the above equation to be,

$$\mathrm{LGC} = \mathrm{LCOE}\left(\frac{1}{1 - \frac{\Delta E}{E(1+i)^{t1}}}\right) \tag{3.19}$$

Using taylor series and neglecting higher order terms, loss of generation cost can be presented as,

$$\mathrm{LGC} = \mathrm{LCOE}\left(1 + \frac{\Delta E}{E(1+i)^{t1}}\right) \tag{3.20}$$

By using LGC concept on the objective function will minimize the loss of generation cost. This will allow the PV to maximize its PV output according to system requirement.

CHAPTER 4

Aggregator Based Optimal Power Flow

Aggregator level optimal power flow requires a balance between the consumer benefits, distribution system provider benefits and aggregator benefits. Therefore, a multi-objective power flow optimization model is developed with a simplified power-flow model to eliminate iterative computation process.

4.1 Objective function

The following are considered as the objective of the aggregator when the power flow is managed:

I. Overall cost of power supplied from the substation is minimized. It is assumed that with the implementation of smart grid distribution level locational marginal price would be determined by the distribution system operators [6]. By minimizing the total cost of real power supplied from the substation using the distribution level locational marginal price will optimize the monthly energy consumption cost for each residential consumer. The real power flow from the substation is equal to the power flow from the 0^{th} node to the 1^{st} node. Therefore, the real power flow from the substation is given by,

$$\min_{V_1, \theta_{01}} P_{ss} = g_{01}(V_0^2 - V_0 V_1) + b_{01} V_0 V_1 \theta_{01} \tag{4.1}$$

Since the real power flow could be in either direction the square of real power supplied by the substation is used as the objective function. The substation voltage V_0 is assumed to be known in advance, and its voltage angle is used as the reference. The node voltage and their angles are unknown and will be determined through the optimal power flow.

II. The operating voltage magnitude at the aggregator bus is controlled. One of the objectives of reactive power supply from the distributed generation is to control the voltage in real time. The local voltage control approach will limit the impacts on sub-transmission and transmission systems and limit sudden voltage collapse during cloud cover. An objective function to minimize the difference between the reference voltage magnitude and the operating voltage magnitude excluding the substation bus is given by,

$$\min_{V_i}(\Delta V_i)^2 = (V_i - \overline{V_l})^2 \tag{4.2}$$

Where, $\overline{V_l}$ is the preferred operating voltage.

III. Since each aggregator is responsible for their bus voltage management, the aggregator should ensure that the total active power generated by the distributed generators should at least support the local real power load. Therefore, an objective is introduced at aggregator level to minimize the difference between the real power demand and the real power generation at aggregator level. Using the aggregator load model the real power net flow is minimized. To ensure the dimensions of this objective is the same as the first objective, the square of consumed and supplied power at the aggregator bus is minimized, and the objective function is given by,

$$\min_{V_i,\, \theta_{(i-1)i},\, P_i^{DG}} P_{ag}^2 = \sum_{i=1}^{n} P_{ag-i}^2 = \sum_{i=1}^{n}\left(\left(P_i^L\right)^2 - \left(P_i^{DG}\right)^2\right) \tag{4.3}$$

IV. Since there are two entities are operating to minimize their cost of operation, namely distribution system operator and collection of aggregators, it is important to minimize the total real power loss at the feeder level. Using the developed feeder section power loss model the objective function to minimize the total feeder loss is developed as,

$$\min_{V_i,\ \theta_{(i-1)i},\ P_i^{DG}} (P_{Loss})^2 = \sum_{i=1}^{n} \left(P_{i(i-1)}^{Loss}\right)^2 \tag{4.4}$$

V. Loss of generation cost is minimized. If the optimized DG output values are not closed to maximum DG output for a given time period, there will be real power loss. This real power loss will lead to a generation cost. So to minimize the loss of generation cost is considered.

A multi-objective function is developed incorporating all the objectives as shown below,

$$\min_{V_i,\ \theta_{(i-1)i},\ P_i^{DG}} (\lambda_{LMP} P_{ss})^2 + (\lambda_A)^2 P_{ag}^2 + (\lambda_V)^2 (V_i - 1)^2 + \lambda_{LMP}^2 P_{loss}^2 + \lambda_{LGC}^2 \Delta P^2 \tag{4.5}$$

Where, λ_{LMP} is the distribution level locational marginal price at the substation for the time period under consideration. Locational Marginal Price is the marginal cost to generate the next Mega Watt hour(MWh). LMP is useful to calculate the day ahead pricing and to manage congestion in the transmission lines. LMP defers from the location due to line losses and transmission congestion in the system. LMP at each node is calculated by adding a fixed load of 1MW to the node and determining the minimum change to the total system cost while fulfilling all the constraints. Market participant's bids determines the prices. On real-time market LMP is calculated every 5 minutes for every bus in the system above certain voltage [27]. λ_A is the cost of the aggregator not meeting the total demand, typically this value can be determined as a function of LMP and the penalty and λ_V is the penalty cost for not supplying the load at the predetermined voltage. λ_{LGC} is the loss of generation cost of PV over its life cycle.

4.2 Constraints

The following constrains are used in this work to ensure the power flow limits and standard operating voltage requirements are met.

1. Node Power Constraints:

All node power flows should abide by the Kirchoff's Current Law (KVL). In other words, the net power injected to the node is zero. Figure 4.1 is used to illustrate the node power injection,

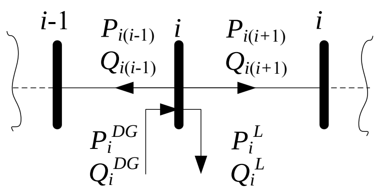

Figure 4.1: feeder sections connected to node i

The net real power consumed from the node i is given by

$$P_i^L - P_i^{DG} = \sum_{m=i-1\ \&\ i+1} g_{im}(V_i^2 - V_iV_m) + b_{im}V_iV_m\theta_{im} \quad i = 1 \dots N \tag{4.6}$$

The net reactive power consumed from node i is given by

$$Q_i^L - Q_i^{DG} = \sum_{m=i-1\ \&\ i+1} b_{im}(V_i^2 - V_iV_m) - g_{im}V_iV_m\theta_{im} \quad i = 1 \dots N \tag{4.7}$$

Above set of constraints need to be included for all nodes.

2. Voltage Limits:

Voltage limits at the aggregator bus needs to be kept within a range to ensure that the consumer voltage is within the American National Standard Institute (ANSI) voltage limits [28].

$$V_i^{min} \leq V_i \leq V_i^{max} \quad i = 1 \dots N \tag{4.8}$$

3. Reactive Power Limits:

Based on the current standard practice, residential consumers are compensated for the real power generated by the solar PV modules. Therefore, this work limits the maximum reactive power that could be generated as a function of real power. In case the customers are rearward for reactive power supplied by their solar PV units, this constraint can be relaxed as per the operating standards. The reactive power limit is defined by,

$$Q_i^{DG} = \varepsilon_i P_i^{DG} \tag{4.9}$$

where, ε is the limiting factor of the reactive power generation. In other words, $\varepsilon = \tan(\theta_i^{DG})$ - θ_i^{DG} is the power angle of the distributed generators. The ε_i is a variable in this algorithm which would be optimized for every aggregator in this work.

4. Total Power Output Limit

DG power output is limited by the available solar irradiation. Therefore, for a given period the maximum power that could be generated at the aggregator level is given by,

$$(P_i^{DG})^2 + (Q_i^{DG})^2 = (S_i^{DG})^2 \leq S_i^{max} \tag{4.10}$$

where, S_i^{max} is the maximum possible apparent power that could be supplied by the solar PVs at the aggregator level. Using the reactive power limits,

$$((1 + \varepsilon^2)(P_i^{DG})^2 \leq S_i^{max} \tag{4.11}$$

5. Maximum Real Power Output:

The maximum real power that could be supplied by each aggregator is limited to the maximum possible apparent power using the following relationship,

$$P_i^{DG,min} \leq P_i^{DG} \leq P_i^{DG,max} \tag{4.12}$$

Developed optimization problem is a convex problem. A unique solution technique needs to be developed or a robust optimization tool needs to be used to evaluate the results.

6. Transmission line limits

The maximum real power that could be transferred in each line segment is limited to the maximum possible apparent power of the line using the following relationship,

$$f_{ij} \leq f_{ij}^{max} \tag{4.13}$$

CHAPTER 5

CASE STUDY, RESULTS AND DISCUSSION

IEEE four node test feeder [29] is used to as a numerical example to perform the proposed model. In Figure 5.1, each node is assumed to be controlled by an aggregator. Aggregators at nodes 1 and 3 are equipped with distributed generations and participate in the active voltage control. However, aggregator at node 2 does not participate in the active voltage management.

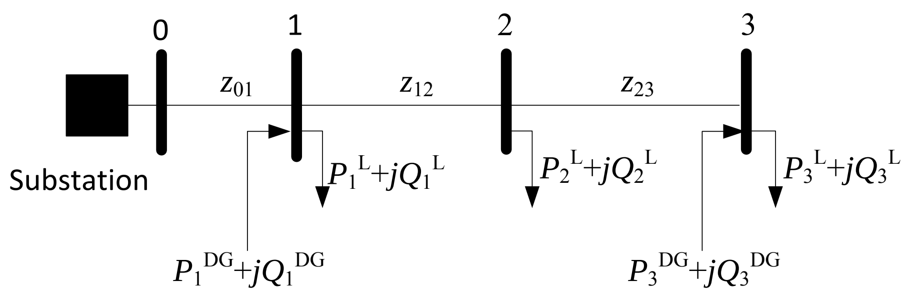

Figure 5.1: IEEE four node distribution test feeder

Based on the IEEE 4 bus feeder data system rated voltage is taken as 4.16kV line to line and the transformer between node 1 and 2 is neglected. System maximum load data, line impedance are taken from the IEEE 4 bus test feeder and tabulated in Table 5.1 and Table 5.2 respectively.

Table 5.1

Load data for four bus system

	1	2	3
P_i^L	180 kW	180 kW	180 kW
Q_i^L	87.2 kVAr	87.2 kVAr	87.2 kVAr

Table 5.2

Line Impedance data

	1	2	3
z_{ij}	0.087+j0.20	0.088+j0.20	0.13+j0.30

Since the single load value is provided in the datasheet load shape curve from a utility is used to generate a 24-hour load period. Using the weather data from GridLabD [30] solar power output curves for node 1 (DG1) and node 3 (DG2) are generated and shown in Figure 5.2.

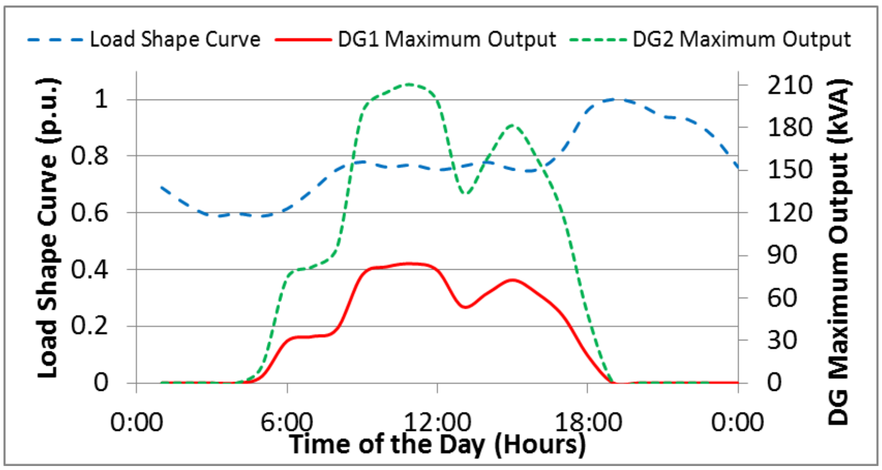

Figure 5.2: Load shape and DG output curves for 24 hours

From Figure 5.2, it could be seen that DG1 produces less power than the DG2 as the number of houses used in each node is not the same. Limits for the developed optimization model are given in Table 5.3. For all nodes the same limits are imposed and the limits are kept constant for the whole day. The maximum real power output is kept as same as the apparent power maximum from Figure 5.2 for each node and the minimum real power output is fixed at 0 for all time.

Table 5.3

Optimization Limits and Data

V_i^{min}	V_i^{max}	$\|\varepsilon\|$
0.9 p.u.	1.1 p.u.	2

The substation voltage was kept at 1.00 p.u. and the preferred voltage or the target voltage at each node was chosen as 1p.u. The locational marginal price available from ComEd Chicago for a particular day in summer, as shown in Figure 5.3, is used and PV generation and load were synchronized for the same day same location.

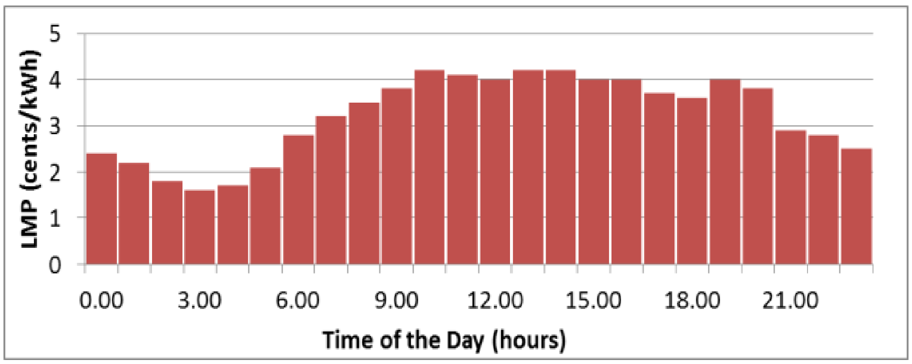

Figure 5.3: Locational Marginal Prices of the day

Table 5.4 provides the Levelized costs of Energy for selected photovoltaic technologies [21] which is used to calculate the loss of generation cost for PV modules.

Table 5.4

Module costs for commercial photovoltaic technologies

	Technology	Lifetime(years)	Discounted rate(i)	LCOE module($/kWh)
DG1	Thick-film silicon:low	180 kW	3%	0.02
DG2	Thick-film silicon:high	87.2 kVAr	15%	0.17

Using MATLAB optimization tool the optimal solution was obtained [23]. All the outputs are given for the time in which DGs were operational (from 5.00 am to 7 pm).

Figure 5.4 shows the real power output for both maximum generation case without control and optimal case.

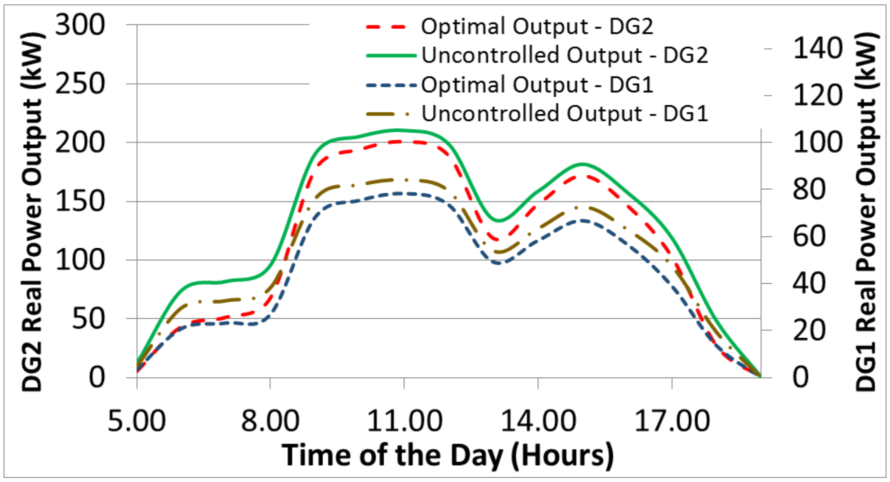

Figure 5.4: Real Power Outputs for node 1 and node 3

From Figure 5.4 it could be seen that the optimal solution reduces the real power generation from DGs. The difference in the real power generated is used for voltage support.

Voltage magnitudes at nodes 1 to 3 are evaluated in Figure 5.5- Figure 5.7. They are evaluated in three different cases (i) without any Distributed Generation, (ii) DGs are operated without any control and (iii) DGs operated based on the proposed optimal power flow algorithm.

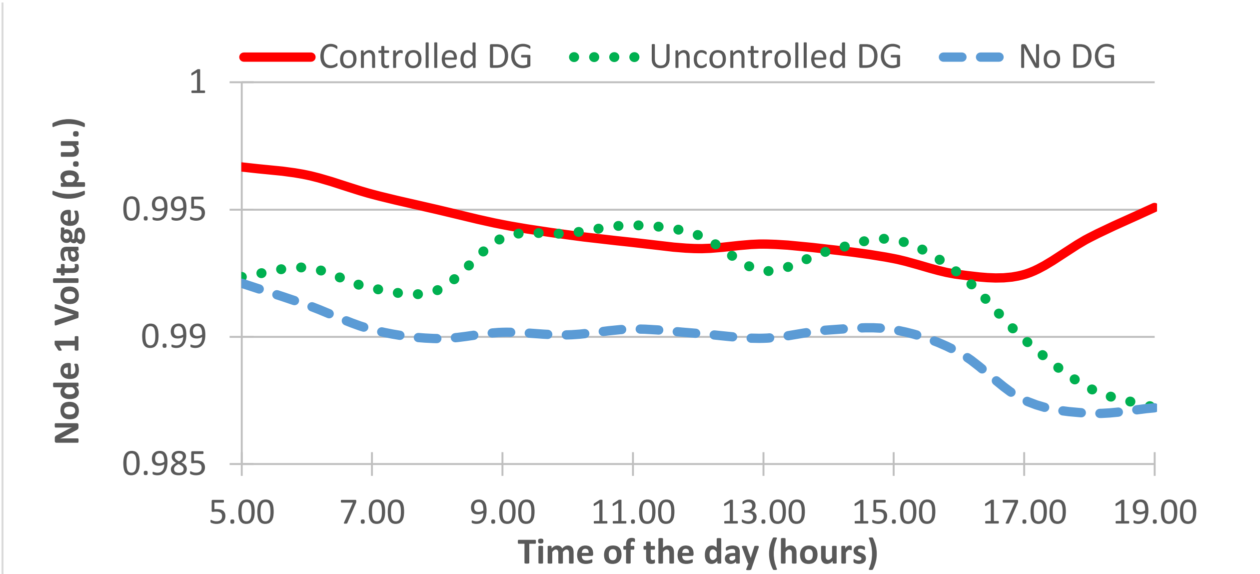

Figure 5.5:Node 1 voltage magnitude

From Figure 5.5 it could be seen that the when DGs are operated without voltage control the bus voltage rises significantly when compared to the system operations without DG, however the proposed algorithm will increase the node voltage which would be closer to the preferred voltage for each node.

Figure 5.6 shows the node 2 voltages for the same case as node 1. The node 2 voltage behaves similar to that of node 1.

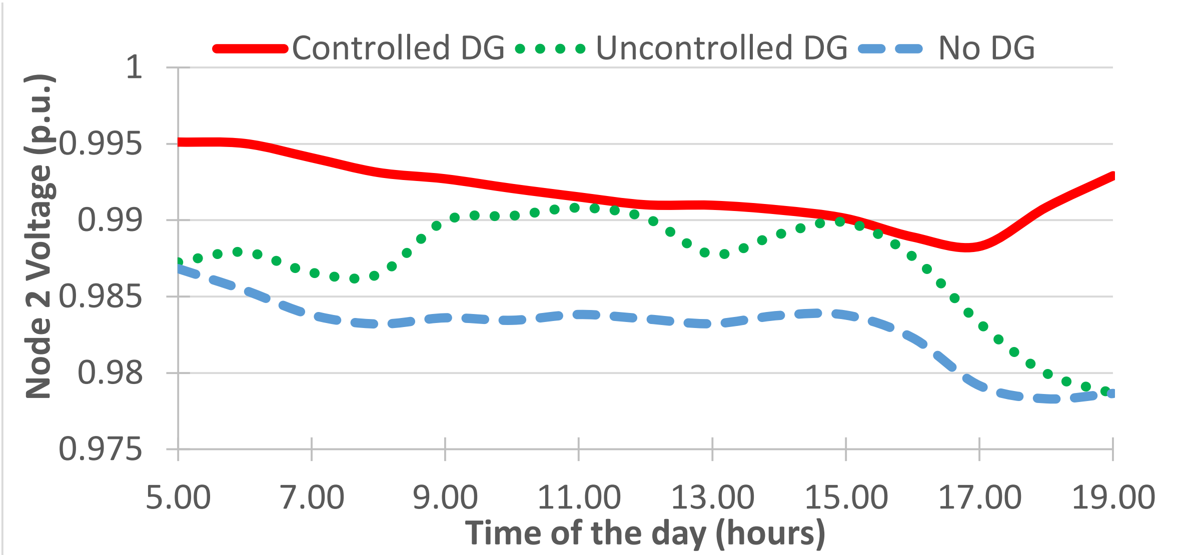

Figure 5.6:Node 2 voltage magnitude

Finally, the node 3 voltage profile for the same cases as other two nodes are evaluated and plotted in Figure 5.7. The general observation is same as pervious two nodes. Since this is the node at the far end the voltage is the lowest. From the voltage plots it could be observed that the node voltages are better managed when the optimal power flow is utilized.

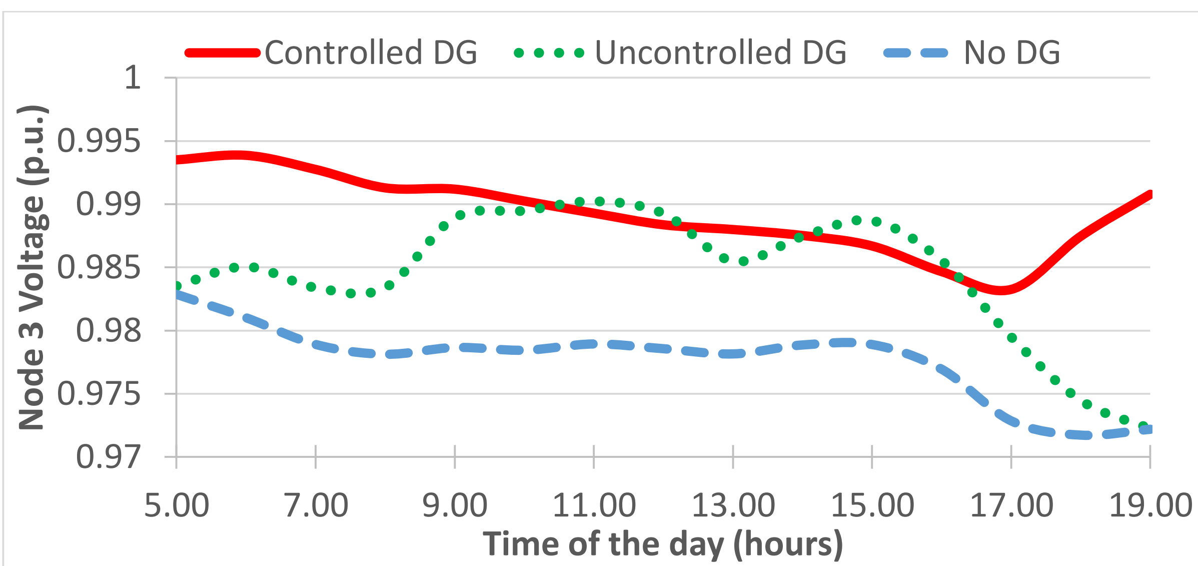

Figure 5.7:Node 3 voltage magnitude

Finally, the power loss in in the system is analyzed in this work. Figure 5.8 shows the power loss of the system with the three cases used for voltage analysis.

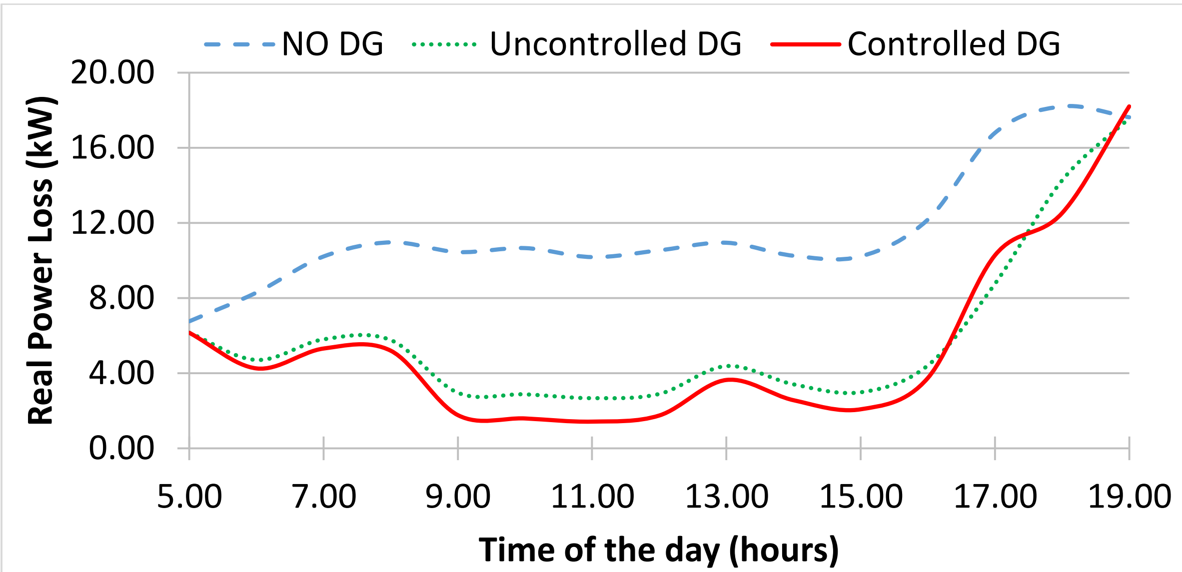

Figure 5.8:Total Real Power loss

From Figure 5.8 it could be observed that when the system is operated with optimal control, power loss is minimized. Since the total feeder load is higher than the total. The proposed optimal power flow has the potential to manage the power loss based on imposed penalty. Minimizing the real power loss in the system we could increase the efficiency of the system.

CHAPTER 6

CONCLUSION AND FUTURE WORKS

6.1 Conclusion

The energy situation in the world asks for major improvements in the efficiency of generation, transmission and conversion of the electricity, the most frequently used energy carrier. It is widely accepted that the use of electricity is not the most efficient today and better efficiency is expected in the future.

This thesis shows a feasible way for an optimal power flow analysis of a distributed network with large scale of integrated DGs. It has proved from case study results that optimal power flow can be archived to minimized the power loss. The modeled objective function discussed in this thesis is modeled by considering minimizing the injected power to the system and keeping the bus voltages close to 1.0 p.u. The modeled system has a low capacity DG collocated with a Load in a bus, the DG itself will act as a parent to the load so that instead of feeding voltage to the whole gird, it will continue supply the demand for that Load it's collocating.

This thesis archived its optimal results when the geographical locations of the system are known and this work is yet to be extended to a level when the locations of the DGs are unknown and when they are available. The results could further optimized and modified in to different scenarios with DGs and Loads by loosening the constraints.

6.2 Future Work

As future work, storages can be used to store excess loss of generations and which can be used towards the next optimal power flow run/iteration. Also develop an Optimal Power Flow method considering cost as a variable which would make the modeling more accurate.

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