INTEGRATING DISTRIBUTED GENERATION IN POWER DISTRIBUTION NETWORKS USING FUZZY LOGIC

by

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Dedicated

To my caring parents, and inspiring brother for their unconditional love and support

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ABSTRACT

In this research simulations have been carried out on a 10 kV and IEEE 13 node test distribution feeder to show the impact of adding distributed generations (DG) in the medium voltage distribution network. Equations of power line loss coefficients have been derived for both test feeders in order to determine the best possible case. A fuzzy logic controller has been proposed in the IEEE13 node test distribution feeder to determine the amount of DG output to be added in the network on the basis of power supply-demand gap and time of the day. Another fuzzy logic controller is proposed to select the bus where the DG need to be connected using the input of DG amount needed to be installed and distance of generation from the distribution transformer in the power distribution network.

LIST OF ABBREVIATIONS USED

DG Distributed Generation

DN Distribution Network

DSM Demand Side Management

FIS Fuzzy Interference System

FLC Fuzzy Logic Controller

HC Hosting Capacity

kcmil Thousands Circular Mils

kW kilo Watt

kV kilo Volt

kVA kilo Volt Ampere

LTC Load Tap Changer

mi Mile

MVA Mega Volt Ampere

MV Medium Voltage

OLTC On Load Tap Changer

PFC Power Factor Correction

ACKNOWLEDGEMENTS

First of all I would like praise Almighty Allah for creating human beings and granting so many blessings in life. I would also like to mention the holy verses (96.1-5) of Qur'an from 96. Surah Al- Alaq (The Clot): 96.1 Recite in the name of your Lord who created- 96.2 Created man from a clot(a piece of thick coagulated blood), 96.3 Recite, and your Lord is the most Generous- 96.4 Who taught by the pen- 96.5 Taught man that which he knew not.

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CHAPTER 1 INTRODUCTION

Power consumption is one of the daily resources without which we can't imagine our life. According to BP Energy Outlook 2030 report the power sector is the key driver of global energy growth where all the primary fuels compete and in 2030 total electricity consumption will be 61% higher than in 2011. Due to increasing depletion of primary energy sources, supply and demand gap of electrical energy is also rising. Global proven reserve of oil and natural gas at end of 2011 were about 54 years and 64 years respectively. Moreover, the total population growth of the world is also increasing energy demand. Following the study of the World Energy Outlook 2011 world's total population will increase by 26% in 2035. Establishing new power plants requires longer time and huge investment along while increasing the possibility of emitting greenhouse gases. Therefore optimal consumption of energy resources is an interesting area of research to mitigate potential shortages in power distribution network.

Immense development of modern technology is also increasing the demand of electricity which enforces the integration of available renewable energy sources in existing power system infrastructure because of depletion of available energy sources such as coal, oil, natural gas etc. Basically distribution system was developed to carry the electricity from transmission network to customer premises. However, increasing demand of electricity leads the modern distribution network to work as generation network for renewable energy sources. Consequently control technique of these distribution networks for on-site generation has become an important issue to balance network stability and performance.

1.1 Objective

The intention of this research is to assist the energy consumers by preserving same level of comfort without changing energy consumption practice. To follow up on this thought distributed generation (DG) at customer's site can play an important role. DG is the process of generating power at the distribution network level. But distribution network is usually designed as a loop where power flow is one directional with no or very little redundancy compared to mesh designed transmission network. Moreover, low voltage distribution network has higher resistance than high voltage transmission lines which cause significant voltage drop along lines. Hence the connection of DG can have a noticeable influence on local voltage level. The objective of the thesis is to perform the analysis to observe how the connection of distributed generations in medium voltage distribution network can influence the voltage level at buses, loss coefficient of power line, total active and reactive power loss. To find out the prime factors while connecting distributed generation in the network. Finally to determine the controlling technique to integrate distributed generations in the network. Fuzzy logic controllers are proposed in this study to integrate DG with distribution network by observing the supply and demand gap of energy consumption to maintain the expected voltage level.

1.2 Motivation

Renewable energy technology has always been an exciting area of research which directed human being to challenge the most critical problem of this century for energy crisis. If we look around the current political and economical issues of the world we would observe that most of crises lead because of energy insecurity which arises from limited reserve of coal, oil and natural gas. Most of the developed countries want to secure their energy reserve for future and developing countries are already facing the inconsistent energy system for rapid infrastructure development. Researcher has already developed exciting 5G technology, high speed fiber optic communication, and physical representation of 3D data in real time, but all of these exciting branches of innovation will be futile if power system infrastructure collapse due to shortage of world's primary energy sources. Therefore available alternate sources such as wind, solar, hydro, biomass are sources of energy which must have feasibly added in the power distribution network to create an alternate of existing energy sources. Hence the analysis of technical challenges to integrate distributed generation in distribution network is an important and interesting area of research.

1.3 Thesis Outline

This thesis paper is divided into six chapters, references and appendix. Chapter one includes the introduction of the paper. Chapter two discuss about the background of the thesis which includes the idea of power distribution network, distributed generation, demand side power management and fuzzy logic controller. Chapter three includes all literature review of the thesis .Chapter four includes case study of two types of test distribution feeder to show the affect of adding distributed generation in the network. Chapter five discusses the integration of distributed generation using fuzzy logic controller. Chapter six includes the research outcome, contribution and limitation summary. In the end it includes all references and appendix.

CHAPTER 2 BACKGROUND

In this research four key terms are highlighted: power distribution system, distributed generation, demand side power management, fuzzy logic controller. Detail explanation of these terms is highly important for understanding the formation the thesis work.

2.1 Power Distribution Network:

Distribution network is integral part of power system. There are three major parts of power system such as generation, transmission and distribution of power to end users. In this research distribution network is considered as the heart of the study. Generated power is transmitted from meshed and high voltage transmission line of 35-230 kV to primary distribution line of 600V-35kV or, using LV/MV circuits by step down operation of substation transformer at a distribution substation. At customer's end primary distribution voltage is further step down to a low voltage secondary circuits of 120/240 V [1].

Distribution circuits are available almost in all streets and road in which urban utilities provide 50ft of distribution circuit of underground construction and rural utilities provide 300ft primary circuit of overhead construction for each customer. Feeders are important part of distribution circuits which is formed in substation. The main feeder, three phase backbone of the circuit which is also called the main or mainline is a larger conductor of 500-700 kcmil [1kcmil=0.5067 mm^2] aluminum of 400A rating and in case of emergency 600A rating. The branching from the feeders are called laterals or taps/lateral taps/ branches/branch lines which may be one/two/three phase and have switches to separate them from mainline if fault occurs. The most common distribution primaries are four wire multi grounded system: three phase conductors and multi grounded neutral, where a single phase line has one phase conductor and neutral; two phase line has two phase conductor and neutral. Neutral act as a return conductor and equipment safety ground. A single phase load is served by a transformer connected between one phase and neutral [1].

A distribution networks are often radial which has advantage of easier fault current protection, lower fault current, easier voltage and power flow control and minimum cost. A radial distribution network might have different types of feeder such as single main line, branch main line, very brunched main line and express feeder.

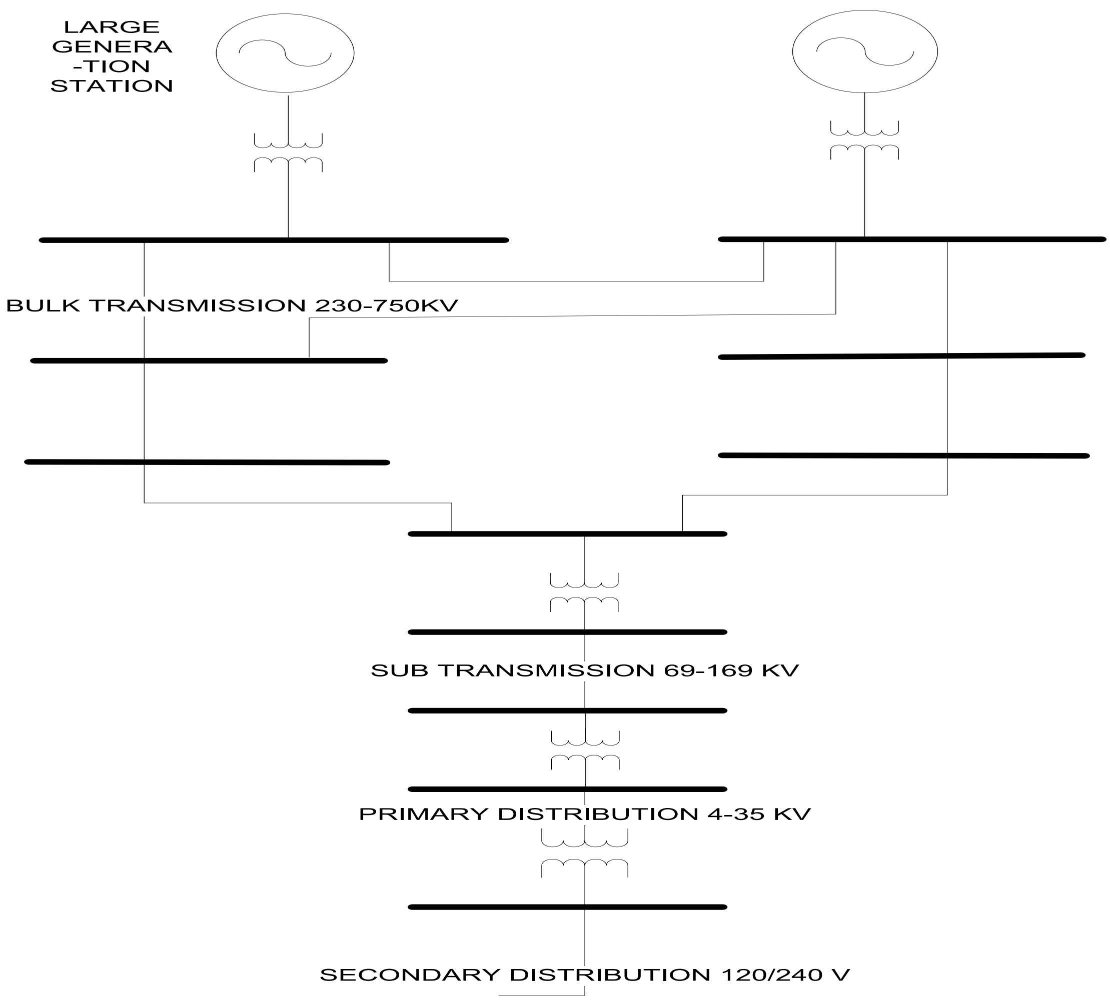

Figure 2.1 Electricity Infrastructures [1]

Many circuits derive from one substation and among those circuits one circuit may have different type of feeders. Most of the feeders cover area near the substation whereas express feeder covers area from distance of the substation. Radial circuits are equipped with open tie points to connect with other circuits for reliability issues for limiting the time of interruption. If fault occurs in any of the circuits the tie switch restore the part of the faulted circuit. These switches are manually operated but some utilities offer automated switch or recloser. Primary Loop scheme offers reliable service for critical load to ensure highest reliability where the circuit is routed through each critical customer transformer and if any part is found faulted then all critical customers can still be served by reconfiguring transformer switches.

Table 2.1 Typical Distribution Circuits Parameter [1]

	Most Common/ Other Values
Substation Characteristics	
1. Voltage	**12.47 kV**/ 4.16, 4.8, 13,2, 13.8,24.94,34.5 kV
2. Number of station transformer	**2**/ 1-6
3. Substation transformer size	**21 MVA**/ 5-60 MVA
4. Number of feeders per bus	**4**/ 1-8
Feeder Characteristics	
1. Peak current	**400 A**/ 100-600 A
2. Peak load	**7 MVA**/ 1-15 MVA
3. Power factor	**0.98 lagging**/0.8 lagging-0.95 leading
4. Number of customers	**400**/ 50-50000
5. Length of feeder mains	**4 mi**/ 2-15 mi
6. Length including laterals	**8 mi**/ 4-25 mi
7. Area covered	**25 mi^2**/ 0.5-500 mi^2
8. Mains wire size	**500 kcmil**/ 0-795 kcmil
9. Lateral tap wire size	**#1/0** / #4-2/0
10. Lateral tap peak current	**25 A**/ 5-50 A

11. Lateral tap length 12. Distribution transformer size(1 ph)	**0.5 mi**/ 0.2-5 mi **25 kVA**/ 10-150 KVA

The distribution voltage ranges from 4-35 kV range among which 5, 15, 25, 35 are most common voltage level. 15 kV insulators are applicable for using any 15 kV class voltages such as 12.47, 13.2, 13.8 and these voltages are not actual system voltage. Most utilities use 15 kV voltages in North America among which 12.47 kV is widely used and it has line to ground voltage of 7.2 kV. Higher voltage primary distribution was widely used in the later part of twentieth century which carry more power for certain amount of current which in turns reduce the voltage drop, power loss. Higher voltage system needs fewer voltage regulators and capacitors for voltage support and more power or smaller currents can be carried for higher voltage for longer distribution circuits which reduce the number of distribution transformer [1].

The basic relation of power, current indicates that for same amount of current power changes linearly with voltage [$P_2= (\frac{V_2}{V_1})P_1$, when $I_1=I_2$]; for the same amount of power, increasing the voltage decreases the current linearly [$I_2=(\frac{V_1}{V_2})\ I_1$, when $P_1=P_2$]; for the same power delivered the percentage of voltage drop changes as the ratio of the voltages squared, which means the voltage drop is four times for 12.47 kV circuit than that of 24.94 kV circuit supporting the same load [$V_{\%2}= (\frac{V_1}{V_2})^{2*}(V_{\%1})$, when $P_1=P_2$]; for the same load density the area coverage increases linearly with voltages, which means that the 24.94 kV system can cover the twice the area of the 12.47 kV system and 34.5 kV can cover 2.8 times of 12.47 kV system [$A_2= (\frac{V_2}{V_1})\ A_1$] [1].

Table 2.2 Power Supplied by Each Distribution Voltage for a Current of 400A [1]

System Voltage (kV)	Total Power(MVA)
4.8	3.3
12.47	8.6
22.9	15.9
34.5	23.9

The higher voltage system has less resistive line loss for voltage limited circuit. The major disadvantage of a higher voltage line is lack of reliability due to longer lines which are more prone to environmental changes, ferroresonance, radio interference and more switches, automation are needed than that of lower voltage. For an example a 34.5 kV, 30 mi mainline has more interruption than 12.5 kV, 8 mi mainline [1]. The higher voltage equipment costly but it needs less number of substation. Higher voltage conversion is beneficial when there is growth of load and substations are not available especially in rural lines. On the other hand 15 kV class voltages provide good balance of cost, reliability and safety where with the support of voltage regulators and feeder capacitors it can reach the line up to 20 mi or more. Many utilities have multiple voltages; even one circuit might have multiple voltages. A utility may install 12.47 kV where 4.16 kV is installed through using 12.47/4.16 kV step down transformer.

Rural and urban distribution substations have nominal rating of 5 MVA and 200 MVA respectively. Bus configuration of distribution substations is simple with limited redundancy. Transformer smaller than 10 MVA is protected with fuse and larger transformer. Differential protection and sudden pressure relays detect internal failures and clear the circuit to limit additional damage to transformers. Utilities also use recloser in small substation instead of circuit breakers. Usually utilities size the transformer so that if one transformer fails other can support the entire load of the transformer.

Usually utilities use split bus where a bus tie between two buses is left open in distribution substation so that it can lower the fault current and obstruct the circulation of the current in a two bank station of transformer as well as to make simple the bus voltage regulation. A closed bus tie has some advantage where feeders from each bus spot or grid secondary networks it prevents circulating current through the secondary network. It also helps to balance the unequal loading of the transformer.

Subtransmission system is also an integral part of distribution system as it supply to distribution substation. Most common subtransmission voltages are 34.5, 69, 115 and 138 kV and subtransmission circuits are supplied by bulk transmission lines at subtransmission substation. To some extent one transmission system can work both as subtransmission function by feeding distribution substation and transmission function by distributing power from bulk generators. Radial subtransmission circuits are simple but unreliable because a fault in the subtransmisison circuits can force an interruption of several distribution substations. To compensate this problem a subtransmission circuits can be dual, looped or meshed circuits and the configuration design depends on the present and future load demand, availability of bulk transmission and distribution circuit voltages [1].

Most of the subtransmisison lines are overhead and some lines are undergrounded using some solid insulation cable. Higher voltage subtransmisison circuit uses a private right of way such as bulk transmission lines use. Lower voltage such as 23, 34.5 and 69 kV subtransmisison lines are also used as distribution lines with radial or simple loop construction along with over current protection, reclosers, regulators and often with unshielded wire. Higher voltage subtransmisison lines such as 115, 138 and 230 kV are designed like bulk transmission line with loop or mesh arrangements with lightening protection wires, pilot wire relaying from two ends and with shielded wire.

There are some basic difference between European and North American power distribution system. Although the basic structure of both distribution systems is similar in case of voltages, power carrying capabilities, conductors, cables, insulators, regulators, transformers, but both systems are different in case of layouts, configuration and applications.

European distribution system has three phase transformer rating of 300-1000 kVA which supports more customers compare to one phase North American transformer of 25 or 50 kVA. European system offers secondary voltage of 220, 230, or 240 V which is twice of North American secondary voltage of 120 V. Higher secondary voltage of European distribution system allow to travel around 1 mi where North American secondary voltage allow to run up to 250 ft only [1]. For a given load and voltage drop a European secondary can reach eight times the length of an American secondary. In European design secondary is used as like primary laterals of American; primary levels fuses and recloser are not even used as frequently as American distribution system.

Comparatively European primary equipment is more costly especially for the areas which can be served with single phase circuits. North American system is more reliable than European system or in other words European system is 35% more prone to interruption as the system has less primary circuits and hugely distributed on main feeder; any loss in main feeder will interrupt all customers in the circuit. Multi grounded neutral provides more safety for American system than that of European system. In European system high impedance faults are easier to notify.

European system has the flexible secondary which can support urban system and American system has flexible primary circuit for supporting rural area.

2.2 Distributed Generation:

Electric Power Research Institute (EPRI) defines the distributed generation as a generation from 'a few kilowatts up to 50 MW' [2]. The international conference on Large High Voltage Electric System (CIGRE) defines DG as 'smaller than 50 to 100 MW' [2]. Distribution network is basically designed to supply generated power from transmission network to customer end. In other words distribution system provides real (P) and reactive power (Q) flows from high voltage network to lower voltage network and not suitable for generating power in this network. Due to installation of DG in the distribution network power not only flows in one way but both ways where the voltage in the network is determined by both generators and loads [3].

It is important to adjust ratio of MV/LV transformer using off circuit taps so that during minimum load situation the voltage received by all customers is just below the maximum permitted voltage and in case of maximum load the most remote customer will receive at least acceptable minimum voltage. The voltage profile and power flow both change when a distributed generation is added to the distribution network. There are three worst situations while connecting distributed generation: (a) maximum generation and maximum system demand (b) no generation and maximum system demand (c) maximum generation and minimum system demand.

The voltage rise in the network is $\Delta V = \frac{RP+XQ}{V}$ where P and Q are the active and reactive power output of the generator respectively; R and X are the resistance and inductive reactance of the circuit; V is the nominal voltage of the circuit [3]. The voltage rise can be limited by reversing the reactive power (Q) which can be achieved either by an induction generator, under-exciting synchronous machine or operating an inverter to absorb reactive power in MV distribution network which tend to have higher $\frac{X}{R}$ ratio. In case of low voltage distribution circuit the effect of real power (P) and resistance (R) are more prominent and $\frac{X}{R}$ is lower in such resistive circuit as resistance is higher than that of reactive circuit and current carrying capacity is also higher which makes difficult situation for a protective device to clear the fault as protective device clear the fault in zero current situation.

Low voltage distribution network has higher resistance than high voltage transmission network which causes significant voltage drop. The higher resistance of low voltage network occurs due to the smaller cross sectional area of the cable as we know distribution cables are thinner than that of transmission cable line and resistance inversely proportional to that cross sectional area of the cable [$R = \frac{\rho L}{A}$ where A and L are the cross section and length of the cable respectively]. Consequently, to maintain the voltage within the limit while connecting distributed generation in the distributed network is one of the major challenges.

Distribution network faces the problem of higher power loss too. As we know that distribution network carry smaller voltage than transmission network. Hence to transmit the same amount of power through distribution network very large current is required compare to that of transmission network. Increasing the current has significant drawback as it increase the power loss[$P = I^2R$] when supplying to customer ends.

2.3 Demand Side Power Management:

Demand side power management is a process carried out by most of the utilities for reducing peak hour demand to avoid expensive generation only for short period of time. In this case peak hour demand is encouraged to be shifted when the demand profile is comparatively lower so that customer demand can be met without adding any extra generation. Most of the utilities encourage customers to consume their energy efficiently by following demand side power management program such as reducing peak hour demand, using energy efficient bulb, changing energy consumption period for an example using heavy loads before or after peak hours, using alternate sources of power to supply peak demand load such as generator or cogeneration, installing power factor correction capacitor bank to improve load's power factor, changing some electrical load to other type of fuels such as natural gas[4].

Another way is to use direct load control technique to reduce the heavy load household appliances such as water pump, electric oven, washing machine, dish washer etc especially in peak hours. According to the reference [5] saving 1 unit of electricity at consumer end reduce 2.5 times of capacity addition. Moreover 1 MW capacity addition of thermal power requires the cost of 6 crores rupees equivalent to 1.1 million CAD installation cost and another 3 crores equivalent to 0.54 million CAD of transmission and distribution cost. DSM basically encourages customers to use the available resources efficiently for meeting peak demand by changing energy consumption periods.

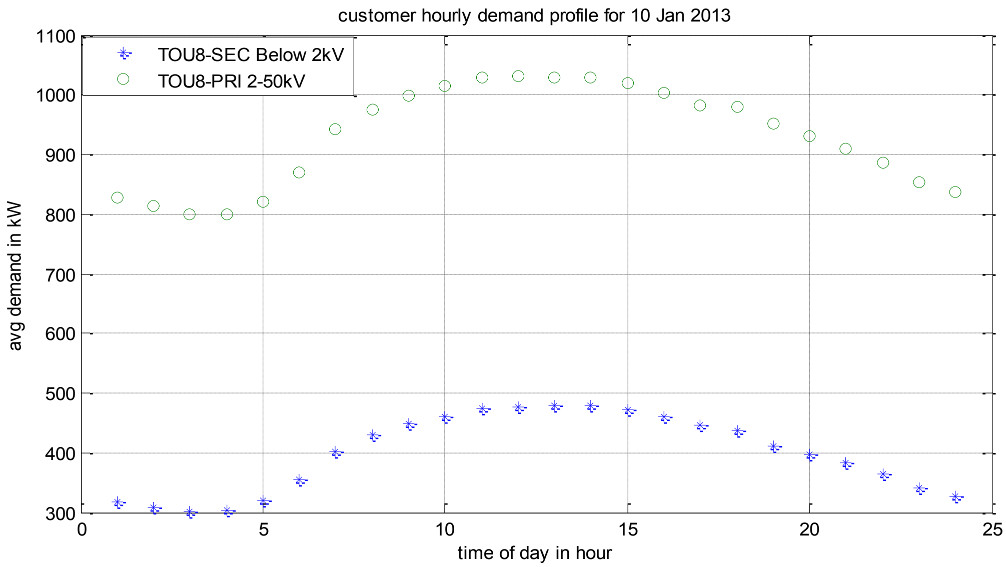

Figure 2.2 Load Profile of Southern California Edison (SCE) Utility [6-7]

In above fig the load profiles of SCE utility is shown for large power greater than 500 kW and data is given in the reference [6-7]. The bottom and upper line shows the time of use (TOU) of secondary voltage level below 2 kV and primary voltage level between 2-50 kV respectively for general service [6][7]. In both case the peak demand is formed between 0007 to 2000 hours in the day. For the secondary voltage level the peak demand of 0.479 MW occurs at 1400 hours whereas peak demand of 1.03 MW occurs for primary voltage level at 1200 hours.

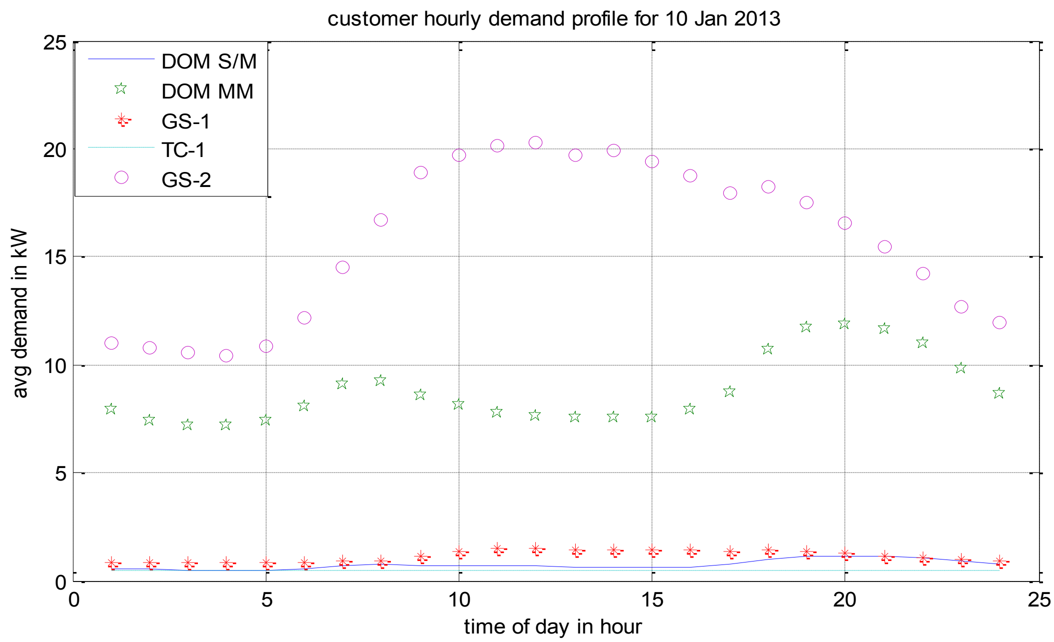

Figure 2.3 Load Profile for SCE Utility [8-12]

In the above fig the load profile of different types of customers has been shown and data for the demand profile is given in the reference [8-12]. The second most bottom lines shows the load profile of domestic single/ multiple metered (DOM- S/M) customers in which the peak demand of 1.129 kW occurs at 2000 hour of the day [8]. There are two peak demand hours for domestic master metered (DOM- MM) in which the first peak occurs between 0006 and 1000 hours and other one occurs between 1700 and 2300 hours with peak demand of 9.268 kW at 0008 hours and 11.87 kW at 2000 hours respectively [9]. For GS-1 which combines the customers of general service, small commercial or non demand metered, peak demand of 1.503 kW occur at 1200 hours [9]. The TC-1 refers to traffic control in which the demand profile of 0.474 kW remains same throughout the whole day [11]. The GS-2 includes general service, medium commercial/ industrial or demand metered customers in which the peak demand occurs between 0008 and 2100 hours [12]. The peak demand of 20.28 kW occurs at 1200 hours.

2.4 Fuzzy Logic:

Fuzzy logic is an intelligent controlling method developed by Lotfi Zadeh in 1960. According to professor Zadeh it is not required to know exact numerical input value to make highly adaptive control. Instead of knowing exact mathematical formulation it is possible to develop an easy controlling technique using common human linguistic terms. In other words it can be said the success of this controlling method depends more on experience rather than technical understanding of the system. One of the biggest advantages of fuzzy controller is that it can deal with imprecise inputs while comparing with conventional feedback controller. Fuzzy logic controllers have been hugely implemented in consumer's industrial products of Asia and Europe especially in Japan and Germany rather than in America.

One of the interesting characteristics of fuzzy logic is that it can deal with partial true-false value between "completely true" and "completely false". According to Zadeh statement [13] "The notion of a fuzzy set provides a convenient point of departure for the construction of a conceptual framework which parallels in many respects the framework used in the case of ordinary sets, but is more general than latter and, potentially, may prove to have a much wider scope of applicability. Essentially, such a framework provides a natural way of dealing with problems in which the source of impression is the absence of sharply defined criteria of class membership rather than the presence of random variables."

A typical crisp set separates the universe of discourse into two groups such as members and non-members. Let assume that U is the universe of discourse. For a crisp set A, the characteristics or membership function μ_A (x) includes the value [0, 1]. If x is a member of set A or in other words if x belongs to A then μ_A (x)= 1, otherwise μ_A (x) = 0. Here the boundary of the crisp set A is rigid and sharp. For an example in crisp set where $-1 \leq x \leq 1$, the membership function is $\mu_A(x) = 1$ otherwise 0. Here Y and X axis represent the membership function $\mu_A(x)$ and elements of universe of discourse where $x \in U$ respectively.

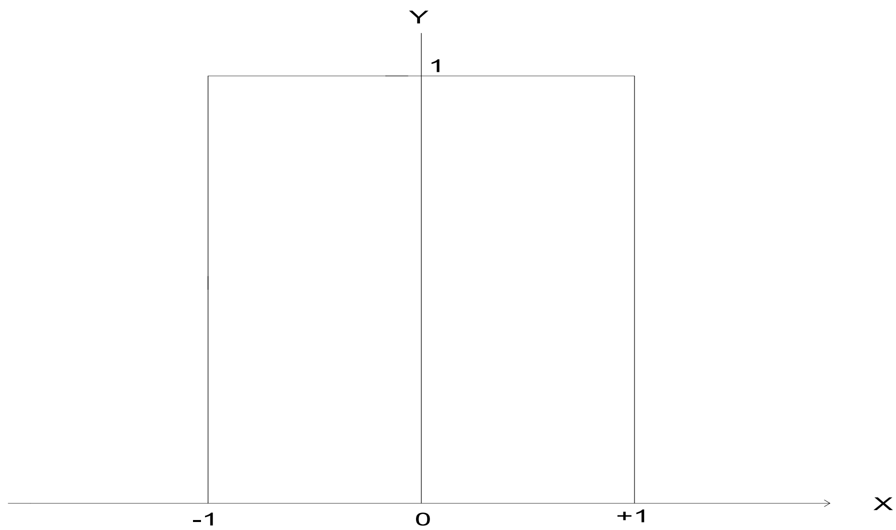

Figure 2.4 Membership Function of Crisp Set A

On the other hand in fuzzy sets professor Zadeh introduced the degree of membership to different elements of the universe of discourse on a continuous interval [0, 1] rather than mentioning only member and non-member elements. On continuous interval 0 and 1 refer to no membership and full membership respectively. Membership function is basically dimensionless. In fuzzy set the boundary between member and non-member elements is gradual rather than sharp which introduces vagueness too. Let assume that B is a fuzzy set in the universe of discourse U where $B = \{(x, \mu_B(x)) \mid x \in U\}$. Here $\mu_B(x)$ represents the degree of membership of element x in set B.

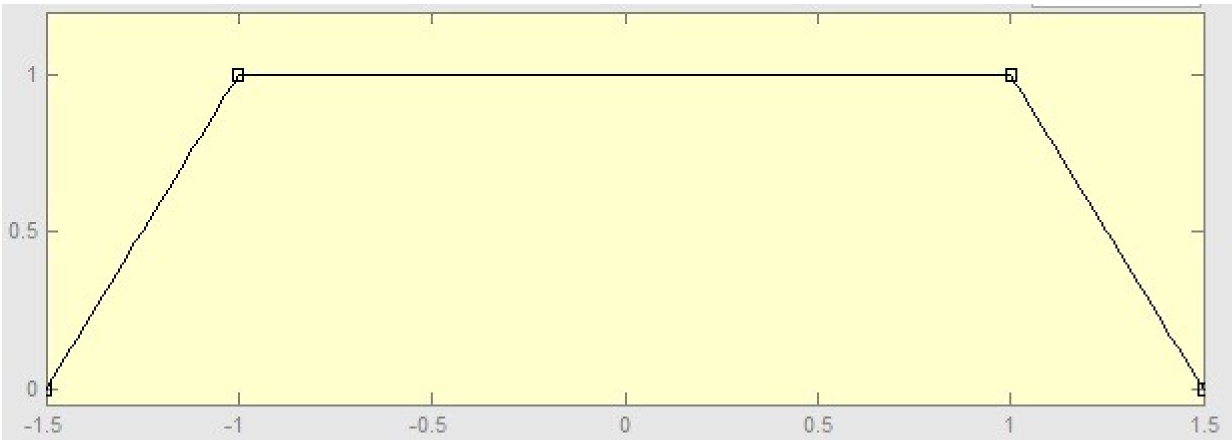

Figure 2.5 Membership Function of Fuzzy Set B

While comparing above two figures of membership function of crisp and fuzzy set, it is quite easy to observe the difference of boundaries between two sets. Some properties such as support, singleton, crossover point, kernel, height of fuzzy set, normalization, α-cuts, resolution principle, convexity, fuzzy numbers, and cardinality of fuzzy set are essential to know for further understanding of fuzzy set theory. The support of a fuzzy set B is supp(B) which contains all the elements of universe of discourse (U) where the membership functions are greater than zero. In other words supp(B)= $\{ x \in U \mid \mu_B(x) > 0\}$. If the support is a single point in U with $\mu_B(x) = 1$ is called fuzzy singleton.

Crossover or break-even point is set of all the elements x in U whose membership function is 0.50. The kernel of fuzzy set B includes all the elements x in U where $\mu_B(x) = 1$, in other words ker(B)= $\{x \in U \mid \mu_B(x) = 1 \}$. The height of fuzzy set B is the supremum or maximum of membership function of elements x in U. In other words, Height (B) = $\sup_{x \in U} \mu_B(x)$. Fuzzy set B is called normalized when height of the set is 1, otherwise it is called subnormal. A non empty fuzzy set can be normalized by dividing membership function by the height of the fuzzy set. An α-cut of a fuzzy set B includes all the elements in U where membership function of the elements are greater than equal to α, or it can be expressed as $B_\alpha = \{x \in U \mid \mu_B \geq \alpha\}$. B_α is called strong α –cut if $\mu_B > \alpha$. The set of all level $\alpha \in (0, 1]$ that represents all distinct alpha cut of a fuzzy set B is called the level set of B. The level set of B is expressed as $\pi_B = \{\alpha \mid \mu_B = \alpha \text{ for some } x \in U\}$.

According to resolution principle the fuzzy set B can be expressed as $B = \bigcup_{a \in \pi_B} \alpha B_\alpha$. Otherwise it can be stated that in resolution principle of the fuzzy set B can be decomposed into αB_α where α ∈ (0, 1], or fuzzy set can be expressed as union of its αB_α which is also called representation theory. A fuzzy set is convex if and only if $\mu_B\{\lambda x_1 + (1-\lambda)x_2\} \geq \min\{\mu_B(x_1), \mu_B(x_2)\}$ where x_1 and x_2 are elements in U and λ ∈ (0, 1].

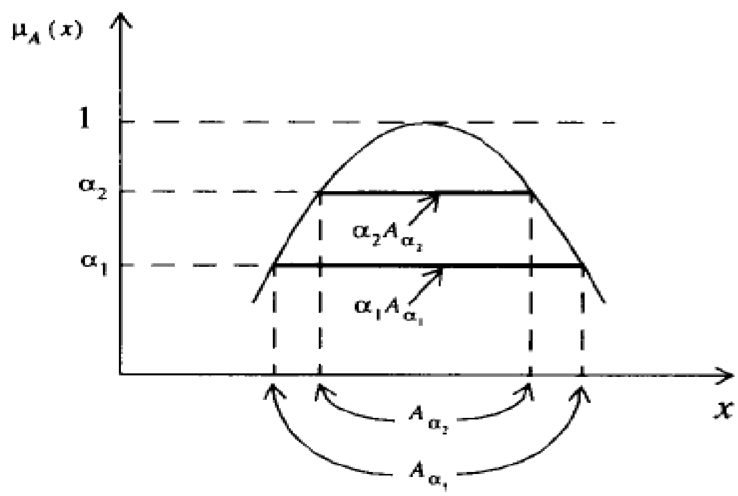

Figure 2.6 Decomposition of Fuzzy Set [13]

The condition of convex means that if we draw a connecting straight line between x_1 and x_2 then all the membership function of the points in the line is equal or greater than minimum of the membership function of the both elements. The fuzzy numbers are those convex and normalized fuzzy sets on real line R which have continuous membership function or alpha cut is in a closed interval. In the following expression and figure two fuzzy numbers S and π function are shown.

$$S(x: a, b) = \begin{cases} 0 & \text{for } x < a \\ 2\left(\frac{x-a}{b-a}\right)^2 & \text{for } a \le x < \frac{a+b}{2} \\ 1 - 2\left(\frac{x-b}{b-a}\right)^2 & \text{for } \frac{a+b}{2} \le x < b \\ 1 & \text{for } x \ge b \end{cases} \tag{2.1}$$

$$\Pi(x: a, b) = \begin{cases} S(x\,; b-a, b) & \text{for } x < b \\ 1 - S(x\,; b, b+a) & \text{for } x > b \end{cases} \tag{2.2}$$

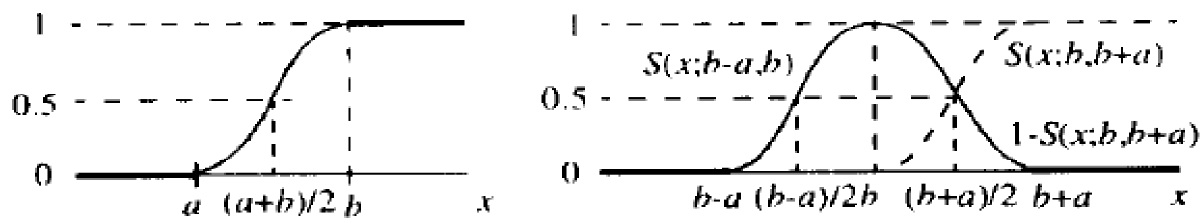

Figure 2.7 (a) S and (b) π Fuzzy Number Shapes [13]

The crossover and unity point of S function are at $\frac{a+b}{2}$ and b respectively. There are two such as $\frac{b-a}{2}$ and $\frac{b+a}{2}$ crossover points in π function and bandwidth is a. The unity point of π function is at point b. The cardinality of the fuzzy set B is the summation of membership function of all elements of x in U or, $|B| = \sum_{x \in U} \mu_B(x)$. The relative cardinality of fuzzy set B is $|B|_{rel} = \frac{|B|}{|U|}$, where |U| is finite.

There are some other basic operations of fuzzy set A and B such as union, intersection, complement, commutative, associative, distributive, absorption, idempotence etc. Let us assume that A and B are fuzzy sets. In the following figures the intersection and the union of the fuzzy sets A and B are shown.

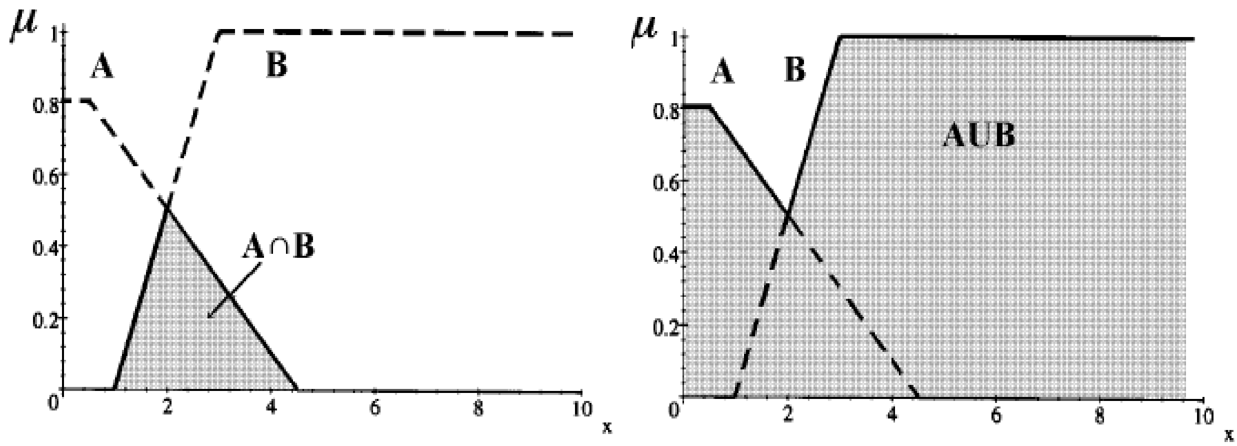

Figure 2.8 (a) Intersection of Fuzzy Set (b) Union of Fuzzy Set [13]

Let the intersection and union of the fuzzy sets are respectively C and D, where $C = A \cap B$ and $D = A \cup B$. The membership function of intersection and union of fuzzy sets A and B are $\mu_C(x)$ and $\mu_D(x)$ respectively. The intersection $\mu_c(x) = \min\{\mu_A(x), \mu_B(x)\} = \mu_A(x)\ \ \mu_B(x)$, where '' refers to minimum operator. In case of intersection $A \cap B \in A$ and $A \cap B \in B$. On the other hand $\mu_D(x) = \max\{\mu_A(x), \mu_B(x)\} = \mu_A(x)\ \ \mu_B(x)$, where '' refers to maximum operator. Here fuzzy sets are A and B, where $A \in A \cup B$ and $B \in A \cup B$.

The complement of fuzzy set A is $\overline{A}$, where the membership function of the fuzzy set $\overline{A}$ is $\mu_{\overline{A}}(x) = 1 - \mu_A(x)$. According to the DeMorgan law fuzzy set A and B can be written as $\overline{A \cup B} = \overline{A} \cup \overline{B}$ and $\overline{A \cap B} = \overline{A} \cap \overline{B}$. Unlike the crisp sets the fuzzy set A and its complement set $\overline{A}$ represents $A \cup \overline{A} \neq U$ and $A \cap \overline{A} \neq \emptyset$. Since fuzzy set does not have precise boundary as like crisp set. The union or intersection does not represent respectively the universe of discourse U or empty set $\emptyset$ completely. There are some other properties of fuzzy sets similar to that of crisp set are mentioned in below table.

Table 2.3 Properties of Fuzzy Operation Sets [13]

Commutativity	$A \cup B = B \cup A, A \cap B = B \cap A$
Associativity	$(A \cup B) \cup C = A \cup (B \cup C)$ $(A \cap B) \cap C = A \cap (B \cap C)$
Distributivity	$A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$ $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$
Absorption	$A \cup (A \cap B) = A$ $A \cap (A \cup B) = A$
Idempotence	$A \cup A = A, A \cap A = A$

The membership function of algebraic and bounded sum of two fuzzy sets A and B are respectively $\mu_{A+B}(x) = \mu_A(x) + \mu_B(x) - \mu_A(x).\mu_B(x)$ and $\mu_{A\oplus B}(x) = \min\{ 1, \ \mu_A(x) + \mu_B(x)\}$ .The product of fuzzy sets A and B is $\mu_{A.B}(x) = \mu_A(x).\mu_B\ (x)$. The bounded difference of the two fuzzy sets A and B is $\mu_{A\ominus B}(x) = \min\{ 0, \mu_A(x) - \mu_B(x)\}$.

Chapter 3 Literature Review

In reference [14] a fuzzy logic controller is proposed to control DSM techniques using seven controlling rules to run only the vital or most important load during peak hours when the feedback signal is greater than the reference to mitigate supply-demand gap. There are two inputs and four outputs for the fuzzy logic controller. One of the inputs is comparator which compares the power consumption with a reference and another input is timer which differentiates the peak and off-peak hours. In this study a demand limiter is used to control the load while designing the fuzzy logic controller. It is observed from the study that power consumption with FLC is restricted during peak hours and encouraged in off-peak hours. Here peak hour is considered 0006-1000 hours and 1800-2200 hours interval for 24 hours period. The limitation of this study involves the curtailment of load consumption to compensate the supply-demand gap in peak hours.

In reference [15] a multi agent based which means different system control units such as on-load tap changer or LTC agent, DG agent and load agent are proposed to regulate the voltage in smart distribution grid through communication infrastructure to exchange the message among different agents. Interior structure of the agent is based on fuzzy logic control theory in which received data from local measurement sensors is fuzzified by converting crisp values into linguistic labels. The interference engine of the interior structure depends on the predefined rules to achieve the objective of each agent and finally the output of the agent is defuzzified using center of gravity method to derive a crisp value. The LTC agent has three inputs such as voltage deviation from load agents, permission messages from DG units and average tap operation and two outputs are tap and reply. The LTC agent maintains the feeder’s voltage within permitted limit by minimum number of tap changing operation of transformer. The DG unit has three inputs called voltage deviation, reply, available Q and three outputs such as permission, Q_{set} and P_{set}. The idea of DG unit is to keep the voltage in permitted limit while keeping the maximum generation of DGs. Finally the load agent measures bus voltage of load point through a sensor and compares with maximum and minimum voltage limit to detect voltage deviation from a reference. In this paper 16 bus distribution feeder has been studied to implement the fuzzy multi agent based voltage control procedure in MATLAB Simulink. The system has two DG units and a LTC transformer in substation where a 69/13.8 kV transformer with 32 taps is modified as LTC transformer. Dispatchable DG unit of 1.5 MVA synchronous machines is connected to bus 6 where as another unpredictable renewable DG unit of 6 MVA DFIG wind turbine is connected to bus 4. The minimum value of load is 2 MW between 0000-0006, 2100-2400 hours and maximum is 8 MW between 1200-1800 hours over 24 hours. It is also shown in this paper that when the system work on traditional control techniques three buses have overvoltage situation during first nine hours. The proposed multi agent fuzzy logic controller keeps the voltage level within limit.

In reference [16] a fuzzy logic control technique is used to coordinate power factor control, on load tap changer and generation curtailment method to keep the voltage level within limit while adding distributed generation in IEEE 13 node test distribution feeder. If the voltage is violated in any load bus of the network then fuzzy logic control will be activated to correct the voltage level. In this control technique, first the power flow simulation of distributed network with DGs is performed. There are two inputs in the system such as load voltages and DG input power. Load voltages are categorized by low, medium, high and very high voltages ranges from 0.90 to 0.95 p.u, 0.96 to 1.05 p.u, 1.51 to 1.069 p.u, and 1.071 to 1.100 p.u respectively. The DG inputs of the system are categorized by low, medium and high which range of 1MW, 2MW and 3MW respectively.

Three control methods such as PFC, OLTC and generation curtailment are coordinated using fuzzy logic so that depending on the different circumstances in the system the right method can be chosen. The power factor control is firstly implemented as PFC indicates the reactive power output of the generating unit to maintain the proportion of the real power output to keep the power factor constant. The reactive capability of typical generator at full load normally ranges between 0.85 lagging and 0.95 leading. Operating DG in leading power factor is used to decrease voltage rise and lagging power factor is used to increase the voltage level at load bus. For low, medium and high, very high range of voltages 0.85 lagging, 0.95 leading and 0.90 leading power factor are used respectively. Once the PFC is failed to achieve the permitted voltage range then OLTC is implemented. For very high range of voltage and medium, high voltage range OLTC is chosen as 1.02 p.u and 1.05 p.u respectively. The least preferred voltage control option is the curtailment of generators. 0% curtailment of active power is done for low, medium and high voltage range, where 40% of curtailment is done for very high voltage range. Some fuzzy rules are mentioned in the paper such as (1) if voltage is low and power is low then PFC is 0.85 lag, (2) if voltage is medium and power is high then PFC is 0.95 lead, (3) if voltage is high and power demand is medium then PFC is 0.90 lead, OLTC is 1.02 p.u and generation curtailment 0%, (4) if voltage is very high and power is very high then PFC 0.90 lead, OLTC 1.02 p.u and generation curtailment 40%. The results in the reference shows that the voltage at the load bus without fuzzy logic control exceeds the permitted limit while with the coordination of three control techniques in fuzzy logic keep the voltage at the load bus within limit.

In reference [17] FLC is used to reduce the total reactive power injection in the medium voltage Italian distribution network while producing maximum active power without disconnecting distributed generations from the network. The control action is performed by changing reactive power according to a designed FLC which allows maintaining voltage level within limit. In this paper the control method uses local regulation of voltage level by modulation of active and reactive power produced by DGs at the connection bus. The generator capability curve constrains the variation of active reactive power production. Wind DGs are connected to network by means electronic interface. The converter voltage (V_c) depends on the dc link voltage (V_{dc}), modulation technique and amplitude of the modulation index. The reactance (X_c) of the wind turbine transformer adapt with the WDG's medium voltage to grid's voltage and filters. The maximum voltage and current which limit the active-reactive power capability curve of the wind turbine also limits the converter. Only considering reactive power capability it corresponds to Q_{DG}=min $\{Q_{DG}^c , Q_{DG}^v\}$, where Q_{DG}^c and Q_{DG}^v are maximum amount of reactive power limited by current and voltage respectively.

There are two inputs and one output in FLC. The voltage (V_{DG}) is one input calculated at time t_k at bus connected to DG and its variation (ΔV_{DG}) is other inputs of the FLC. The output of the FLC is represented by the variation of reactive power (ΔQ_{DG}) at time t_k which depends on voltage V_{DG} , on load active power $P_L(t_k)$, on load reactive power $Q_L(t_k)$, and active power at the node where generation $P_{DG}(t_k)$ is connected. Both V_{DG} and ΔV_{DG} have the three membership function of low (L), optimum (O), high (H) and negative (N), zero (Z), positive (P) respectively. The output ΔQ_{DG} has five membership function such as large negative (LN) and negative (N) mean it absorbs reactive power; positive (P) and large positive (LP) define it produces reactive power; zero (Z) means it works with unitary power factor. According to the fuzzy rules (1) if V_{DG} is low and ΔV_{DG} is negative then ΔQ_{DG} large positive; (2) V_{DG} is optimum and ΔV_{DG} is negative then ΔQ_{DG} zero; (3) V_{DG} is high and ΔV_{DG} is negative then ΔQ_{DG} negative; (4) if V_{DG} is low and ΔV_{DG} is zero then ΔQ_{DG} positive, (5) if V_{DG} is optimum and ΔV_{DG} is zero then ΔQ_{DG} zero;(6) if

V_{DG} is high and ΔV_{DG} is zero then ΔQ_{DG} negative; (7) if V_{DG} is low and ΔV_{DG} is positive then ΔQ_{DG} positive (8) if V_{DG} is optimum and ΔV_{DG} is positive then ΔQ_{DG} zero and (9) if V_{DG} is negative and ΔV_{DG} is positive then ΔQ_{DG} large negative.

Here optimization process is used to maintain the voltage level at WDG connection within limits and this problem is solved by PSO (Particle Swam Optimization) algorithm. Through minimizing the reactive power injection or absorption from WDG's in distribution network the paper also shows the potential of increasing reactive power support from distributed generations. The optimization problem is defined as minimum of fitness function $f_{Q_{DG}}$ where this function is the summation of Q_k^{DG}, k= 1 to N_c. N_c is the number of control cycle for which optimization process is performed. There are two sets of free threshold point of FLC membership functions which are defined as $x^v = \{x_1^v, x_2^v, x_3^v, x_4^v\}$ and $x^{\Delta v} = \{x_1^{\Delta v}, x_2^{\Delta v}, x_3^{\Delta v}, x_4^{\Delta v}\}$. The optimization problem constrain defined as $V_{DG_{min}} \leq V_{DG}(t_k) \leq V_{DG_{min}}$, $PF_{DG_{min}} \leq PF(t_k) \leq PF_{DG_{min}}$, $|P_{ij}^{line}|\hat{}t_k \leq |P_{ij}^{line}|$, $0.95 \leq x_1^v \leq x_2^v \leq 1 \leq x_3^v \leq x_4^v \leq 1.05$, $-0.01 \leq x_1^{\Delta v} \leq x_2^{\Delta v} \leq 0 \leq x_3^{\Delta v} \leq x_4^{\Delta v} \leq 0.01$.

The optimization process continues up to reaching fitness minimum where daily load demand profile and generation are used to run power flow simulation. In the Italian test distribution network the primary substation 's tap is fixed at 1.006 p.u and four WDGs of same active power generation have been added to the bus 31,46,53, and 54 by power electronic converter with starting power factor of 1 along with 5% variation. The simulation result without any control signal shows the subsequent voltage rise in the bus 54 at third operation hour. Hence the bus 54 is chosen to apply optimization procedure and the result of objective function $f_{Q_{DG},min}$= 10.68 MVAR is obtained from the simulation. The result of this study shows that reactive power injected by the FLC PSO is less than that of KKT (Karush Kuhn Tucker) optimization. Since capability curves constraints are not violate, thus maximum active power production is possible without disconnecting distributed generation.

In reference [18] a fuzzy logic based load balancing is proposed in order to implement the load change decision. If average unbalance per phase is less than the threshold then there is no change needed in the load, otherwise fuzzy logic based load balancing is implemented to find the load change value for each phase. Negative value for the load change indicates the phase has additional load and need to reduce that amount of load and vice versa for positive value of load change. The load change value is an input to the system to optimally shift the specific number of load points. In this paper it is assumed that average per phase capacity of the system is 150kW with 50 load points connection and maximum overload capacity per phase is 300kW. Hence beyond 300 kW instead of using fuzzy logic controller for load balancing that specific phase supposed to be cut off from the service to prevent power breakdown and severe overloading of the transformer.

In FLC the input is the total phase load for each of the three phases and output is the change of load for each phase. Both input and output are divided into eight categories of membership function such as very less loaded, less loaded, medium less loaded, perfectly loaded, slightly overloaded, medium overloaded, overloaded, heavily overloaded for inputs and high subtraction, subtraction, medium subtraction, slight subtraction, perfect addition, medium addition, large addition, very large addition for outputs. The fuzzy rules are as following: (1) if load is very less loaded then change is very large addition; (2) if load is less loaded then change is large addition; (3) if load is medium less loaded then change is medium addition; (4) if load is perfectly loaded then change is perfect addition; (5) if load is slightly overload then change is slight subtraction;

(6) if load is medium overload then change is medium subtraction; (7) if load is overloaded then change is subtraction; (8) if load is heavily overloaded then change is high subtraction.

For an example if the inputs load data is P_{in} (kW)= $\begin{bmatrix} 245 \\ 120 \\ 82 \end{bmatrix}$ for three phases. Mamdani (centroid) defuzzification technique is used to get the output load change configuration using eight fuzzy rules described above. Hence the output is ΔP_{fuzzy} (kW) $= \begin{bmatrix} -104 \\ 25 \\ 65 \end{bmatrix}$, but the summation of the fuzzy output or in other words the error of the output is -14 which not equal to zero and this output will result reduction of 14kW of total load. Since this is not acceptable as it is important to keep the total load constant and only changing the load points among the three phases. An average error is given as AE= round ($\sum \frac{\Delta P_{fuzzy}}{3}$). To evaluate the error matrix ΔP_{error} average error is used where $\Delta P_{error}(kW) = \begin{bmatrix} AE \\ AE \\ \sum \Delta P_{fuzzy} - 2AE \end{bmatrix}$. So the final load change output is $\Delta P\ (kW) = \Delta P_{fuzzy} - \Delta P_{error}$ where the summation of $\sum \Delta P = 0$. The final output is $P_{final}\ (kW) = P_{in}\ (kW) + \Delta P\ (kW) = \begin{bmatrix} 146 \\ 150 \\ 151 \end{bmatrix}$. Using the formula of absolute average unbalance per phase it is showed that the initial absolute average unbalance per phase is 108.67 kW where the final absolute average unbalance per phase is 3.33 kW. Hence by showing the reduction of unbalance per phase it shows the improvement in load balancing.

In reference [19] a comparison study between mamdani and sugeno type fuzzy interference system (FIS) is showed while designing fuzzy rules for air conditioning system. According to the study mamdani method gives the opportunity to present the situation more spontaneously, but it also initializes computational burden than that of sugeno method. One of the basic differences between two methods lies within how it generates the crisp output. The mamdani type FIS method uses the technique of defuzzification of a fuzzy output whereas the sugeno method uses the weighted average to compute crisp output. Hence the sugeno method has better processing time than mamdani method.

Another difference is that sugeno FIS method has no output membership function like mamdani FIS method. Mamdani FIS can be used widely in decision support application whereas sugeno method best suits for integration in neural network, genetic algorithm or other optimization technique. In this study air conditioning is first developed using mamdani FIS. It has two inputs namely temperature and humidity which are ranged from 0 to 45 degree celsius and 0 to 100% respectively with four triangular memberships function each. The output is named compressor speed also consists of four triangular membership function which ranges from 0 to 100%. The membership function for two inputs 'temperature' and 'humidity' are described as very low, low, high, very high and dry, comfortable, humid, and sticky respectively. The membership function for output 'compressor speed' is defined as off, low, medium, fast.

The fuzzy rules are as following: (1) if temperature is very low and humidity is dry then compressor speed is off; (2) if temperature is very low and humidity is comfortable then compressor speed is off; (3) if temperature is very low and humidity is humid then compressor speed is off; (4) if temperature is very low and humidity is sticky then compressor speed is low; (5) if temperature is low and humidity is dry then compressor speed is off; (6) if temperature is low and humidity is comfortable then compressor speed is off; (7) if temperature is low and humidity is humid then compressor speed is low; (8) if temperature is low and humidity is sticky then compressor speed is medium; (9) if temperature is high and humidity is dry then compressor speed is low; (10) if temperature is high and humidity is comfortable then compressor speed is medium; (11) if temperature is high and humidity is humid then compressor speed is fast; (12) if temperature is high and humidity is sticky then compressor speed is fast; (13) if temperature is very high and humidity is dry then compressor speed is medium; (14) if temperature is very high and humidity is comfortable then compressor speed is fast; (15) if temperature is very high and humidity is humid then compressor speed is fast; (16) if temperature is very high and humidity is sticky then compressor speed is fast. In case of sugeno method the paper uses the same inputs from both temperature and humidity sensors to generate the signal to control output. In this case the output compressor speed does not have any membership function but has constant value which can range only between 0-1. For the compressor speed off, low, medium and fast, it has four constants value of 0, 0.3333, 0.6667, and 1 respectively. Results of the study show that both methods for air conditioning works similarly but in sugeno method the air condition system works upto its full capacity compare to mamdani method.

In reference [20] the technical challenges to connect distributed generation in low and medium voltage network is shown. According to the paper the increasing size of wind turbine in distribution network is also encouraging to connect them in medium and high voltage grids. Power generation from independent power producers (IPP) or nonutility generators (NUG) creates new challenges for utilities on voltage control, power quality, grid protection and etc. Varying loads along the grid create varying currents through the resistance and reactance of the feeder resulting frequent change of voltage drop in the line. If injected power from distributed generation is slightly greater than or equal to the loads connected to the feeder, then frequent change in voltage drop decreases. In that case powers supplied by the grid and current through the feeder are decreasing which reduce voltage drop. But when the generating power from the DGs goes much above the load demand of the feeder, it stimulate voltage rise in the point of connection of DGs. Voltage rise occurs because of the reverse power flow from the DGs and short circuit power of the grid at point of connection. In this study voltage rise is shown in 10kV distribution test feeder while adding distributed generation ranging from 1MW to 3.2 MW at substation four around 12 km away from the distribution transformer. The study shows that if there is no DG added to any substation then voltage decreases from substation one to six. But adding 1MW generation in the substation four increases the voltage slightly, while adding 3.2MW generation at the same substation significantly increase the voltage profile. The study also mention several ways to keep the voltage profile within limit by reducing primary substation voltage, increasing conductor diameter in which DG is connected, controlling the reactive power flow by STATCOM device with sufficient $\frac{X}{R}$ ratio.

According to the paper integration of DG has impact on power quality in terms of voltage rise, voltage flicker, and harmonics. Voltage rises when DG is connected to a lightly loaded feeder. Voltage rise issue basically depends on the $\frac{X}{R}$ ratio, feeder load, and injected power by DGs. Similarly frequent load current variation of a DG unit causes a sudden increase or decrease of the feeder current which affects on feeder voltage. Voltage flicker also happen due to the large load change in the distribution network. DG connected to the network contributes towards fault level and eventually reduce network impedance. Hence changing load currents results small voltage variation which improve power quality. DGs which are connected with an inverter to the grid can cause harmonic currents and magnitude of the harmonic currents depends on the technology used in converter and mode of the operation. Harmonic currents can alter the voltage waveform and similarly small voltage alteration can cause large harmonic currents. One way to reduce harmonic current is to filter the output current using modern grid connected converters.

The study of the paper states about few problems in grid protection while adding DGs. Grid protection is basically over current protection method. But connection of several DG units in the network generates multiple sources of fault currents which is difficult to determine in case of disturbances. Generation of fault currents from DGs depends on the type and the connection pattern of DG to the distribution grid. DGs which are connected through converter to grid do not contribute to introduce fault currents in the network. But the grid protection problem such as reclosing problem, blinding of protection, false tripping etc occur when DGs are connected directly to grid. An automatic recloser is a protection device which turns off any faulty overhead line connected to the grid for short period of time to allow the arc to extinguish before energizing the line again. Otherwise the recloser will turn off the line permanently if the line's fault is not restored within successive few attempts of reconnection of the line by recloser. DGs can still energize the line which is isolated by automatic recloser resulting a permanent fault and equipment damage in the network. At the same time coordination between fuse and recloser can be lost. Hence DGs units must be disconnected from the network before recloser process starts. Due to integration of DGs in the network total fault current increases in case of any short circuit, but the contribution of grid to increase of fault current decreases. As a result it becomes hard to detect the short circuit because the contribution of fault current by grid never reaches the pick up current of protective relay. This phenomenon is called blinding of protection. The study shows that integrating DGs in a strong grid of moderate length of feeders can avoid blinding of protection.

False tripping occurs when DG unit contributes towards fault of its nearer feeder which is also connected to the same substation. However, the contribution to fault current of DGs can surpass the pickup level of the over current protection resulting trip of the healthy feeder than clearing actual fault. This problem mostly occurs in the weak grid with long feeder which is protected by over current relays of specific time. Hence the fault at the end feeder must be detected by protection relays which may lead to low pickup current. So according to the study of Kauhaniemi and Kumpulainen it is important to find suitable relay setting which indicate to increase the fault clearing time rather than increasing pick up current [21]. The faulted feeder will be disconnected first and consequently, false tripping of healthy feeder is avoided.

3.1 Literature Review Summary and Research Queries:

From the literature review it is observed that comparative studies have not been considered in order to determine the effect of adding DG in power distribution networks. No studies have been performed to evaluate the prime factor to find out the best or worst case while connecting DG in different distribution networks. Most of the studies refer to load balancing or load curtailment technique especially in peak hours to avoid power outage. No controlling techniques have been developed to compensate power supply-demand gap in peak hours. Finally most of the studies have selected the bus arbitrarily in which DG will be connected. There might have scope to determine the parameters on basis of which bus will be selected logically. Hence the research queries involve the following questions:

1. How to study and compare the effect of adding DG on DN in terms of voltage profile, power line loss coefficient, and real-reactive power loss while considering several cases?
2. What is the prime factor to be considered in order to identify the best case?
3. How to integrate DG in DN in order to compensate supply-demand gap of power in peak hour to avoid load curtailment and load change technique?
4. How to select the bus to add DG in DN?

Chapter 4 Case Studies on 10kV and IEEE 13 Node Distribution Test Feeders

In this chapter 10kV and IEEE 13 node distribution test feeder have been chosen to perform several case studies. In order to determine how the distribution feeder can be influenced by adding distributed generation in medium voltage distribution network, the Power World Simulator 17 has been used to perform several case studies.

4.1 Simulation of 10 kV Distribution Test Feeders

There are six substations connected to the 10 kV distribution feeder. Network data of 10 kV distribution test feeder is given in reference [20].

Table 4.1 Network Data of 10kV distribution feeder [20]

Cable XLPE 400 mm^2 Al	R= 0.13 ohm/km	X=0.124 ohm/km
Load	P_L=0.5 MW	PF=0.9
$S_{k,grid}$	200 MVA	U1= 10 kV
$S_{k,gen}$	4 MVA	P_{DG} = 1/2/5.5 MW, PF=0.8

The following case studies are performed on 10kV distribution feeder:

Case 1: Generation at slack bus only

Case 2: DG of 1 MW is added at substation four

Case 3: DG of 2 MW is added at substation four

Case 4: DG of 5.5 MW is added at substation four

Case 5: DG of 5.5 MW is added at substation four while under loading

Case 6: DG of 5.5 MW is added at substation four without load

Generation is only added at slack bus in case 1. In case 2, DG of 1MW has been added at power factor 0.80 with substation four for same load and branch input connected in case 1. In case 3, 2 MW DG is connected to the substation and all other inputs remain the same as case 2. DG is further increased to 5.5 MW in case 4 along with other input same as case 2. In case 5 and 6 DG are remained same as case 4, but loading of the both networks are changed. Under load and no load situations have been tested for case 5 and 6 respectively with same branch input as case 2.

Case 1: Generation at slack bus only

I have shown the simulation of ideal 10 kV distribution test feeder in case 1. The following figures show the screenshots of various inputs and outputs data for cases 1 to 6. In fig 4.1 branch input data such as resistance, reactance, conductance etc are mentioned for case 1. For an example the resistance, reactance between substations one and two are 0.52 and 0.496 in per unit respectively and so on between others substations. In fig 4.2 loads input data of the each substation is given for detail understanding of the test feeder network. In this case each of the substations has the equal amount of demand of 0.5 MW and total demand of 3 MW has been considered.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	R	X	B	Lim A MVA	Lim B MVA	Lim C MVA
1	Sub1	2	Sub2	1	Closed	Line	NO	0.52000	0.49600	0.00000	0.0	0.0	0.0
2	Sub2	3	Sub3	1	Closed	Line	NO	0.52000	0.49600	0.00000	0.0	0.0	0.0
3	Sub3	4	Sub4	1	Closed	Line	NO	0.52000	0.49600	0.00000	0.0	0.0	0.0
4	Sub4	5	Sub5	1	Closed	Line	NO	0.52000	0.49600	0.00000	0.0	0.0	0.0
5	Sub5	6	Sub6	1	Closed	Line	NO	0.52000	0.49600	0.00000	0.0	0.0	0.0

Figure 4.1 Branch Input of Simulation Case 1

Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar
1	Sub1	1	1	1	Closed	0.50	0.00	0.50	0.50	0.00
2	Sub2	1	1	1	Closed	0.50	0.00	0.50	0.50	0.00
3	Sub3	1	1	1	Closed	0.50	0.00	0.50	0.50	0.00
4	Sub4	1	1	1	Closed	0.50	0.00	0.50	0.50	0.00
5	Sub5	1	1	1	Closed	0.50	0.00	0.50	0.50	0.00
6	Sub6	1	1	1	Closed	0.50	0.00	0.50	0.50	0.00

Figure 4.2 Load Input of Simulation Case 1

In fig 4.3 graphical presentation of simulation of 10 kV ideal distribution feeder has been shown using power world simulator 17 using above mentioned branch and load inputs data.

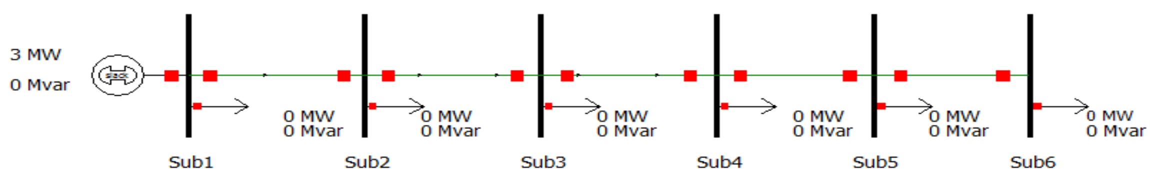

Figure 4.3 Simulation of 10kV Distribution Test Feeder (Case 1)

In fig 4.4 the slack generator output of 3.08 MW has been observed from simulation to supply total 3 MW load demand by the all substations.

	Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	1	Sub1	1	Closed	3.08	0.07	1.00000	YES	YES	0.00	1000.00	-9900.00	9900.00	None	10.00

Figure 4.4 Generator Output of Simulation Case 1

In fig 4.5 real and reactive power flow and loss between substations are shown. For an example the real and reactive power flow between substations one and two are 2.6 MW and 0.1 Mvar respectively. The total real and reactive power loss between substations one and two is 0.03 MW and 0.03 Mvar respectively. Similarly the real and reactive power loss between other substations can be obtained from this fig. To obtain the values of real power loss coefficients between substations, the real power losses values between substations are used in later part of this chapter.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Sub1	2	Sub2	1	Closed	Line	NO	2.6	0.1	2.6	0.0	0.0	0.03	0.03
2	Sub2	3	Sub3	1	Closed	Line	NO	2.0	0.0	2.0	0.0	0.0	0.02	0.02
3	Sub3	4	Sub4	1	Closed	Line	NO	1.5	0.0	1.5	0.0	0.0	0.01	0.01
4	Sub4	5	Sub5	1	Closed	Line	NO	1.0	0.0	1.0	0.0	0.0	0.01	0.01
5	Sub5	6	Sub6	1	Closed	Line	NO	0.5	-0.0	0.5	0.0	0.0	0.00	0.00

Figure 4.5 Branch State Output of Simulation Case 1

In fig 4.6 the load flow information of all substations are obtained. For an example for the substations 2, 3, 4, 5, 6 voltage drops of 0.137, 0.246, 0.327, 0.382, and 0.409 in kV are observed.

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num
1	Sub1	1	10.00	1.00000	10.000	0.00	0.50	0.00	3.08	0.07		0.00	0.00	1
2	Sub2	1	10.00	0.98633	9.863	-0.72	0.50	0.00				0.00	0.00	1
3	Sub3	1	10.00	0.97542	9.754	-1.31	0.50	0.00				0.00	0.00	1
4	Sub4	1	10.00	0.96727	9.673	-1.76	0.50	0.00				0.00	0.00	1
5	Sub5	1	10.00	0.96184	9.618	-2.07	0.50	0.00				0.00	0.00	1
6	Sub6	1	10.00	0.95914	9.591	-2.23	0.50	0.00				0.00	0.00	1

Figure 4.6 Load Flow of Simulation Case 1

<u>Case 2: DG of 1 MW is added on substation four</u>

To observe the effect of adding distributed generation with 10 kV test distribution feeder, a DG output of 1 MW is added to the substation four at power factor 0.80 using with same branch and load inputs as case 1 in fig 4.7.

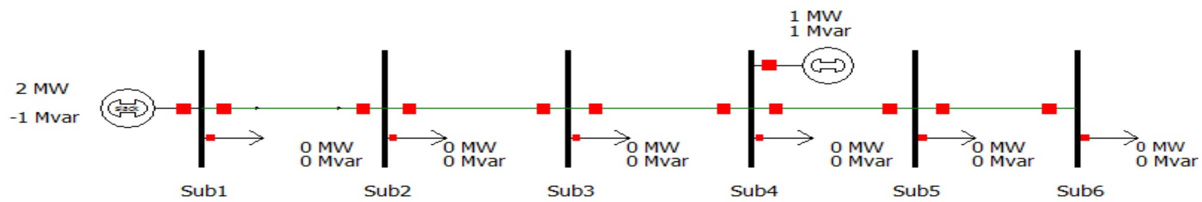

Figure 4.7 Simulation of 10kV Distribution Test Feeder (Case 2)

The fig 4.8 shows that the slack generator outputs 2.04 MW, while the DG produces 1 MW real power approximately. Hence it is observed that real power is generating locally to reduce the slack generation.

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	Sub1	1	Closed	2.04	-0.72	1.00000	YES	YES	0.00	1000.00	-9900.00	9900.00	None	10.00
4	Sub4	1	Closed	1.00	0.75	1.00000	YES	YES	0.00	1000.00	0.75	0.75	None	10.00

Figure 4.8 Generator Output of Simulation Case 2

From fig 4.9 it is observed that the complex power flow between substations 1 and 2 has been reduced from 2.6 MVA to 1.7 MVA in case 2 while comparing with case 1.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Sub1	2	Sub2	1	Closed	Line	NO	1.5	-0.7	1.7	0.0	0.0	0.01	0.01
2	Sub2	3	Sub3	1	Closed	Line	NO	1.0	-0.7	1.3	0.0	0.0	0.01	0.01
3	Sub3	4	Sub4	1	Closed	Line	NO	0.5	-0.7	0.9	0.0	0.0	0.00	0.00
4	Sub4	5	Sub5	1	Closed	Line	NO	1.0	0.0	1.0	0.0	0.0	0.01	0.01
5	Sub5	6	Sub6	1	Closed	Line	NO	0.5	0.0	0.5	0.0	0.0	0.00	0.00

Figure 4.9 Branch State Output of Simulation Case 2

In fig 4.10 it is observed that the voltage drops of substations 2, 3, 4, 5, 6 are 0.043, 0.06, 0.049, 0.102, and 0.128 in kV respectively, which is comparatively lower than case 1.

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num
1	Sub1	1	10.00	1.00000	10.000	0.00	0.50	0.00	2.04	-0.72		0.00	0.00	1
2	Sub2	1	10.00	0.99566	9.957	-0.65	0.50	0.00				0.00	0.00	1
3	Sub3	1	10.00	0.99403	9.940	-1.17	0.50	0.00				0.00	0.00	1
4	Sub4	1	10.00	0.99508	9.951	-1.54	0.50	0.00	1.00	0.75		0.00	0.00	1
5	Sub5	1	10.00	0.98980	9.898	-1.83	0.50	0.00				0.00	0.00	1
6	Sub6	1	10.00	0.98717	9.872	-1.97	0.50	0.00				0.00	0.00	1

Figure 4.10 Load Flow of Simulation Case 2

<u>Case 3: DG of 2 MW is added on substation four</u>

Similarly in case 3 a DG output of 2 MW is added to the substation four at power factor 0.80 using same branch and load inputs as case 1 in fig 4.11.

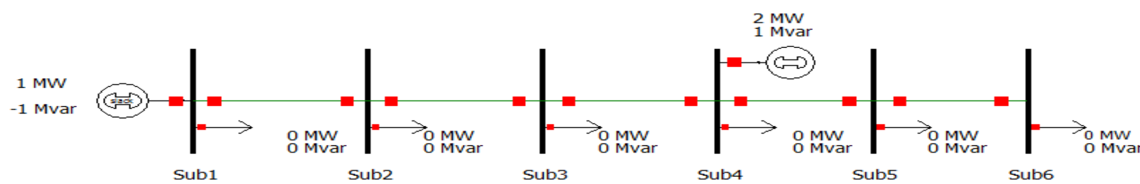

Figure 4.11 Simulation of 10kV Distribution Test Feeder (Case 3)

The fig 4.12 shows that the slack generator produces 1.04 MW, while the DG outputs 2 MW real power approximately. There is a reverse reactive power flow of 1.46 Mvar from the slack bus or substation 1.

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	Sub1	1	Closed	1.04	-1.46	1.00000	YES	YES	0.00	1000.00	-9900.00	9900.00	None	10.00
4	Sub4	1	Closed	2.00	1.50	1.00000	NO	YES	0.00	1000.00	1.50	1.50	None	10.00

Figure 4.12 Generator Output of Simulation Case 3

The branch state of the simulation in fig 4.13 shows that there are reverse reactive power flows between the first three pair of substations. Reverse real power flow is observed between the substations three and four. The reactive power losses between the substations are lower than case 1, but higher than case 2.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Sub1	2	Sub2	1	Closed	Line	NO	0.5	-1.5	1.6	0.0	0.0	0.01	0.01
2	Sub2	3	Sub3	1	Closed	Line	NO	0.0	-1.5	1.5	0.0	0.0	0.01	0.01
3	Sub3	4	Sub4	1	Closed	Line	NO	-0.5	-1.5	1.6	0.0	0.0	0.01	0.01
4	Sub4	5	Sub5	1	Closed	Line	NO	1.0	0.0	1.0	0.0	0.0	0.01	0.00
5	Sub5	6	Sub6	1	Closed	Line	NO	0.5	0.0	0.5	0.0	0.0	0.00	0.00

Figure 4.13 Branch State of Simulation Case 3

In fig 4.14 it is observed that the voltage profile in case 3 significantly improves at all the substation than that of case 1 and 2.

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num
1	Sub1	1	10.00	1.00000	10.000	0.00	0.50	0.00	1.04	-1.46		0.00	0.00	1
2	Sub2	1	10.00	1.00448	10.045	-0.59	0.50	0.00				0.00	0.00	1
3	Sub3	1	10.00	1.01163	10.116	-1.03	0.50	0.00				0.00	0.00	1
4	Sub4	1	10.00	1.02139	10.214	-1.33	0.50	0.00	2.00	1.50		0.00	0.00	1
5	Sub5	1	10.00	1.01626	10.163	-1.60	0.50	0.00				0.00	0.00	1
6	Sub6	1	10.00	1.01369	10.137	-1.74	0.50	0.00				0.00	0.00	1

Figure 4.14 Load Flow of Simulation Case 3

<u>Case 4: DG of 5.5 MW is added on substation four</u>

In fig 4.15 DG is further increased to 5.5 MW while adding with substation four at power factor 0.80 for the same load and branch input connected in case 1.

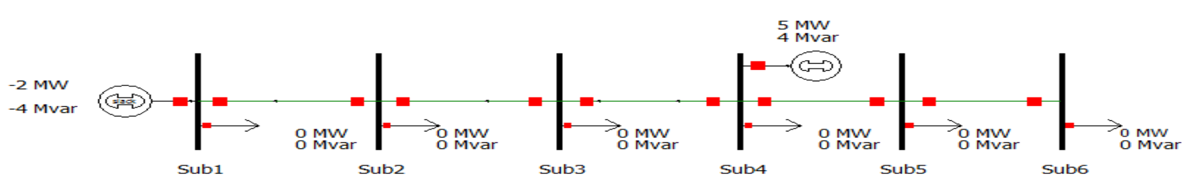

Figure 4.15 Simulation of 10kV Distribution Test Feeder (Case 4)

In fig 4.16 shows that the slack generator produces reverse real and reactive power of 2.12 MW and 3.76 Mvar, while the DG produces real and reactive power of 5.50 MW and 4.12 Mvar respectively.

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	Sub1	1	Closed	-2.12	-3.76	1.00000	YES	YES	0.00	1000.00	-9900.00	9900.00	None	10.00
4	Sub4	1	Closed	5.50	4.12	1.00000	NO	YES	0.00	1000.00	4.12	4.12	None	10.00

Figure 4.16 Generator Output of Simulation Case 4

In fig 4.17 shows that the large reverse real and reactive power flow between the substations and at the same time it is observed that the real and reactive power losses between the substation increases significantly while comparing with other cases.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Sub1	2	Sub2	1	Closed	Line	NO	-2.6	-3.8	4.6	0.0	0.0	0.11	0.10
2	Sub2	3	Sub3	1	Closed	Line	NO	-3.2	-3.9	5.0	0.0	0.0	0.12	0.12
3	Sub3	4	Sub4	1	Closed	Line	NO	-3.9	-4.0	5.5	0.0	0.0	0.14	0.13
4	Sub4	5	Sub5	1	Closed	Line	NO	1.0	0.0	1.0	0.0	0.0	0.00	0.00
5	Sub5	6	Sub6	1	Closed	Line	NO	0.5	0.0	0.5	0.0	0.0	0.00	0.00

Figure 4.17 Branch State Output of Simulation Case 4

Fig 4.18 shows that the substation four has voltage profile of 1.105 per unit (p.u), which exceeds the maximum excepted upper limit of 1.1p.u considered for this case study. The voltage profiles in other substation are significantly higher than compare to previous case studies.

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num
1	Sub1	1	10.00	1.00000	10.000	0.00	0.50	0.00	-2.12	-3.76		0.00	0.00	1
2	Sub2	1	10.00	1.03232	10.323	-0.36	0.50	0.00				0.00	0.00	1
3	Sub3	1	10.00	1.06718	10.672	-0.58	0.50	0.00				0.00	0.00	1
4	Sub4	1	10.00	1.10449	11.045	-0.66	0.50	0.00	5.50	4.12		0.00	0.00	1
5	Sub5	1	10.00	1.09974	10.997	-0.89	0.50	0.00				0.00	0.00	1
6	Sub6	1	10.00	1.09737	10.974	-1.01	0.50	0.00				0.00	0.00	1

Figure 4.18 Load Flow of Simulation Case 4

<u>Case 5: DG of 5.5 MW is added on substation four while under loading</u>

In fig 4.19 the load input for the case 5 has been shown. In this case the network has been under loaded to observe the changes in simulation.

Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar
1	Sub1	1	1	1	Open	0.00	0.00	0.00	0.50	0.00
2	Sub2	1	1	1	Closed	0.50	0.00	0.50	0.50	0.00
3	Sub3	1	1	1	Open	0.00	0.00	0.00	0.50	0.00
4	Sub4	1	1	1	Closed	0.50	0.00	0.50	0.50	0.00
5	Sub5	1	1	1	Closed	0.50	0.00	0.50	0.50	0.00
6	Sub6	1	1	1	Open	0.00	0.00	0.00	0.50	0.00

Figure 4.19 Load Input of Simulation Case 5

In fig 4.20 the DG generates the same as case 4 but the only difference is under loading the network to show the affect on 10 kV distribution network.

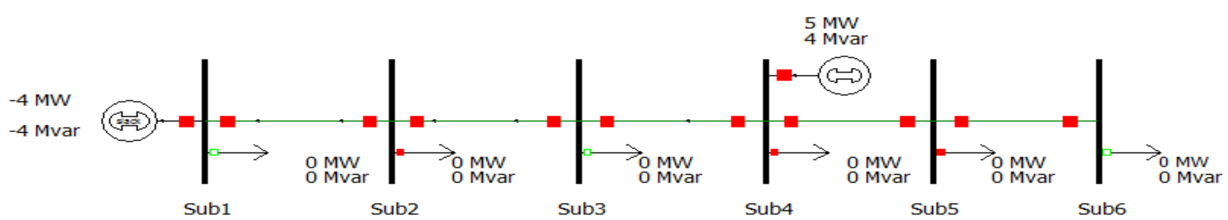

Figure 4.20 Simulation of 10kV Distribution Test Feeder (Case 5)

In fig 4.21 the slack generator produces reverse real and reactive power flow of 3.55 MW and 3.70 MW respectively. The DG produces real and reactive power of 5.50 MW and 4.12 Mvar respectively.

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	Sub1	1	Closed	-3.55	-3.70	1.00000	YES	YES	0.00	1000.00	-9900.00	9900.00	None	10.00
4	Sub4	1	Closed	5.50	4.12	1.00000	NO	YES	0.00	1000.00	4.12	4.12	None	10.00

Figure 4.21 Generator Output of Simulation Case 5

In fig 4.22 shows that case 5 has larger reverse real and reactive power output at each substation. Both real and reactive power losses are higher at substations one, two and three.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Sub1	2	Sub2	1	Closed	Line	NO	-3.6	-3.7	5.1	0.0	0.0	0.14	0.13
2	Sub2	3	Sub3	1	Closed	Line	NO	-4.2	-3.8	5.7	0.0	0.0	0.16	0.15
3	Sub3	4	Sub4	1	Closed	Line	NO	-4.3	-4.0	5.9	0.0	0.0	0.16	0.15
4	Sub4	5	Sub5	1	Closed	Line	NO	0.5	0.0	0.5	0.0	0.0	0.00	0.00
5	Sub5	6	Sub6	1	Closed	Line	NO	-0.0	-0.0	0.0	0.0	0.0	0.00	0.00

Figure 4.22 Branch State Output of Simulation Case 5

In fig 4.23 shows the violation of maximum upper limit of voltage profile at substation four, five and six. The voltage at substation four, five and six are 1.116, 1.113, and 1.113 in p.u respectively which clearly exceeds the limit of 1.1 p.u.

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num
1	Sub1	1	10.00	1.00000	10.000	0.00	0.00	0.00	-3.55	-3.70		0.00	0.00	1
2	Sub2	1	10.00	1.03681	10.368	-0.09	0.50	0.00				0.00	0.00	1
3	Sub3	1	10.00	1.07613	10.761	-0.05	0.00	0.00				0.00	0.00	1
4	Sub4	1	10.00	1.11545	11.154	-0.00	0.50	0.00	5.50	4.12		0.00	0.00	1
5	Sub5	1	10.00	1.11311	11.131	-0.12	0.50	0.00				0.00	0.00	1
6	Sub6	1	10.00	1.11311	11.131	-0.12	0.00	0.00				0.00	0.00	1

Figure 4.23 Load Flow of Simulation Case 5

Case 6: DG of 5.5 MW is added on substation four without load

Fig 4.24 shows that no load has been added with any substations in case 6 to show the affect while performing simulation.

Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar
1	Sub1	1	1	1	Open	0.00	0.00	0.00	0.50	0.00
2	Sub2	1	1	1	Open	0.00	0.00	0.00	0.50	0.00
3	Sub3	1	1	1	Open	0.00	0.00	0.00	0.50	0.00
4	Sub4	1	1	1	Open	0.00	0.00	0.00	0.50	0.00
5	Sub5	1	1	1	Open	0.00	0.00	0.00	0.50	0.00
6	Sub6	1	1	1	Open	0.00	0.00	0.00	0.50	0.00

Figure 4.24 Load Input of Simulation Case 6

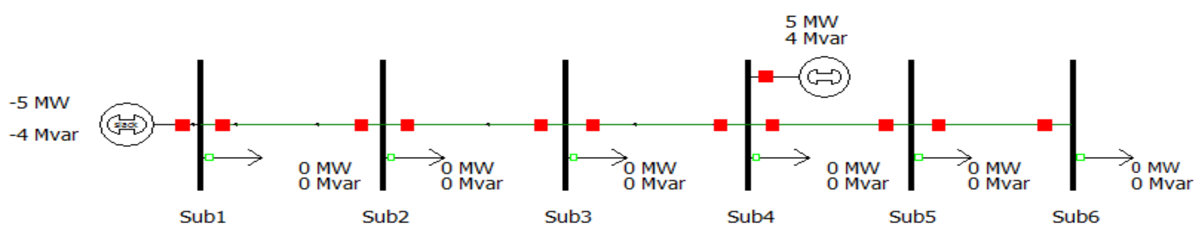

Figure 4.25 Simulation of 10kV Distribution Test Feeder (Case 6)

The slack generator in fig 4.26 shows the reverse real and reactive power of 4.92 MW and 3.58 Mvar, whereas the DG generates the real and reactive power of 5.50 MW and 4.12 Mvar respectively.

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	Sub1	1	Closed	-4.92	-3.58	1.00000	YES	YES	0.00	1000.00	-9900.00	9900.00	None	10.00
4	Sub4	1	Closed	5.50	4.12	1.00000	NO	YES	0.00	1000.00	4.12	4.12	None	10.00

Figure 4.26 Generator Output of Simulation Case 6

The branch state of case 6 in fig 4.27 shows the largest reverse power flow occurs between substations while comparing with all the cases. Both the real and reactive power losses are highest in this case.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Sub1	2	Sub2	1	Closed	Line	NO	-4.9	-3.6	6.1	0.0	0.0	0.19	0.18
2	Sub2	3	Sub3	1	Closed	Line	NO	-5.1	-3.8	6.3	0.0	0.0	0.19	0.18
3	Sub3	4	Sub4	1	Closed	Line	NO	-5.3	-3.9	6.6	0.0	0.0	0.19	0.18
4	Sub4	5	Sub5	1	Closed	Line	NO	0.0	-0.0	0.0	0.0	0.0	0.00	0.00
5	Sub5	6	Sub6	1	Closed	Line	NO	0.0	0.0	0.0	0.0	0.0	0.00	0.00

Figure 4.27 Branch State Output of Simulation Case 6

The voltage profile of case 6 at substation 4, 5 and 6 in fig 4.28 exceeds the maximum permitted voltage of 1.1 p.u. The voltage profile at substation four, five and six are approximately equal to the value of 1.13 p.u.

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num
1	Sub1	1	10.00	1.00000	10.000	0.00	0.00	0.00	-4.92	-3.58		0.00	0.00	1
2	Sub2	1	10.00	1.04336	10.434	0.32	0.00	0.00				0.00	0.00	1
3	Sub3	1	10.00	1.08675	10.867	0.61	0.00	0.00				0.00	0.00	1
4	Sub4	1	10.00	1.13017	11.302	0.88	0.00	0.00	5.50	4.12		0.00	0.00	1
5	Sub5	1	10.00	1.13018	11.302	0.88	0.00	0.00				0.00	0.00	1
6	Sub6	1	10.00	1.13018	11.302	0.88	0.00	0.00				0.00	0.00	1

Figure 4.28 Load Flow of Simulation Case 6

4.2 Simulation Result Discussion of 10 kV Distribution Test Feeders

In this section the summary of the above case studies has been performed in order to simplify the findings of the study. The following observations have been performed on the basis of i) Voltage profile ii) Hosting capacity iii) Real and reactive power loss iv) Power line loss coefficients determination.

4.2-1 Voltage Profile of 10 kV Distribution Test Feeder:

The following table 4.2 shows how the connection of DG affects the voltage profile at substations in varying situations. Case 1 shows the voltage profile at substations without any DG connected to the 10 kV distribution network and generator is only added to the slack bus.

Table 4.2 Voltage Profiles at substations of Case 1-6

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Sub1	1.0	1.0	1.0	1.0	1.0	1.0
Sub2	0.986	0.996	1.004	1.032	1.037	1.043
Sub3	0.975	0.994	1.011	1.067	1.076	1.087
Sub4	0.967	0.995	1.021	**1.104**	**1.115**	**1.130**
Sub5	0.962	0.989	1.016	1.099	**1.113**	**1.130**
Sub6	0.959	0.987	1.014	1.097	**1.113**	**1.130**

Case 2 shows that adding DG of 1 MW improves the voltage profiles at substations.Since more loads are supplied locally thus both the power flow from the grid or slack bus and voltage drop are reduced in first part of the feeders. Incresing the DG output to 2 MW in case 3 significantly improves the voltage profile. In case 4 DG output of 5.5 MW further increases the voltage profile and exceeds the maximum permitted limit of 1.1 p.u at substation four. Case 5 shows the affect of adding DG while underloading the network. In which voltage profile rises not only at the substations where DG is connected but also at the following substations connected to the netwok. The voltage profile in case 6 shows one of the worst cases in which no load is connected to the network and consequently voltage profile reached to it's peak in this situation. Fig 4.29 shows the visual representation of the effects of adding DGs at substaions more precisely.

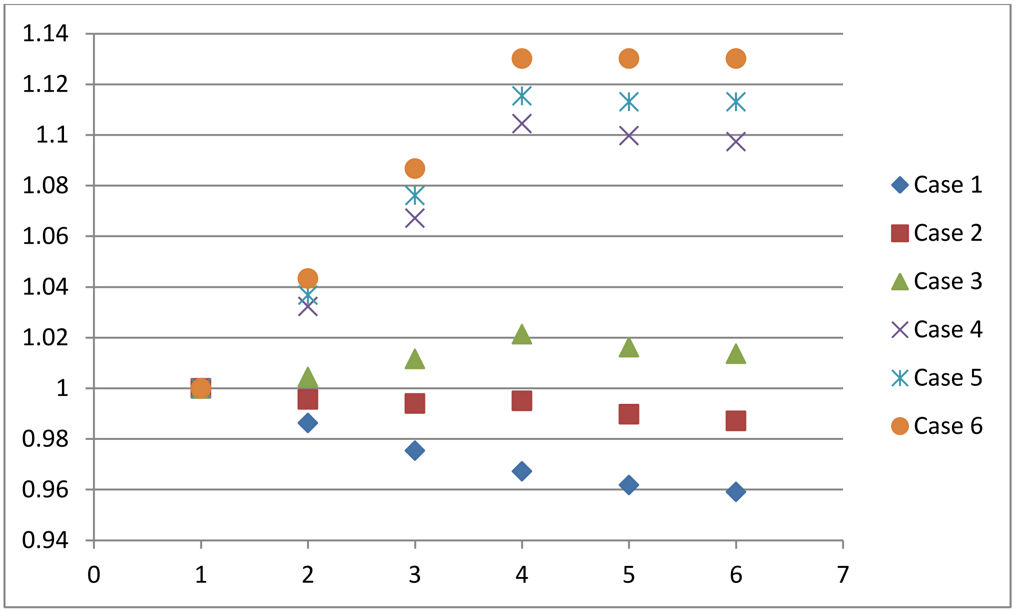

Figure 4.29 Voltage Profiles at Substations of Case 1-6

The fig 4.30 shows how the voltage profiles in each case are changing with the distance from the substations. For all the cases the voltage profile is unity at substation one. The distance among all the substations is equal which about 4 km and the total length of the distribution network is 20 km. The fig clearly shows that for case 1 voltage profile decreases gradually from the substation one to six. For case 2 the voltage profile at 12 km away from the distribution transformer increases as the DG is connected to the substation four and at the following substations five and six the voltage profile again decreases comparing to that of substation four. Similar type of observation has been noticed for case 3.

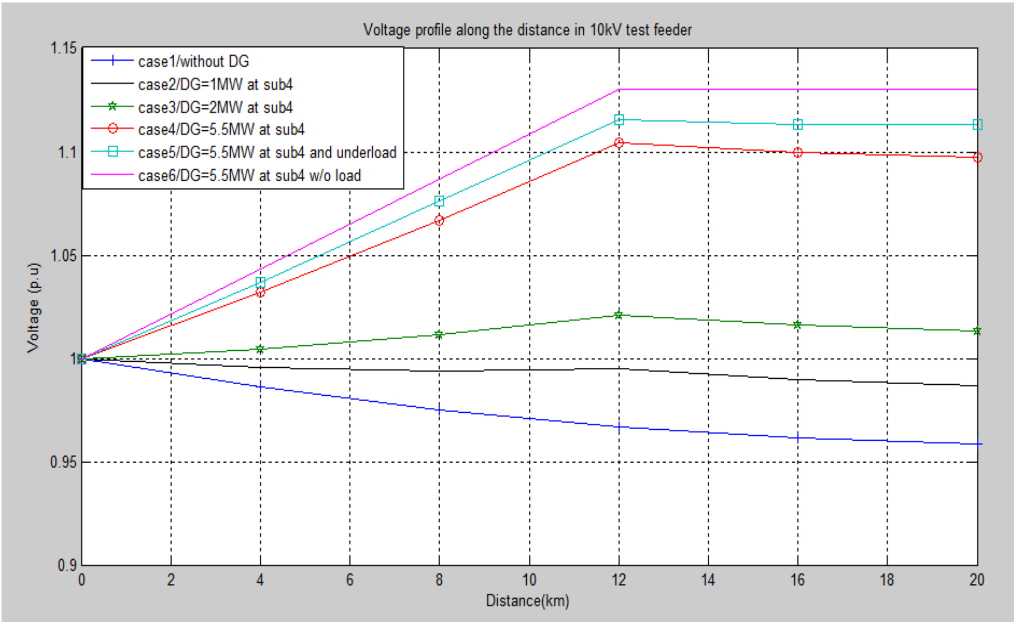

Figure 4.30 Voltage Profiles vs. Distance of Case 1-6

For case 4 DG output is increased to 5.5 MW which is 12 km away from the distribution transformer at substation four and voltage profile exceeds the maximum permitted limit. It is interesting to notice that in case 3 and 4 the voltage profile at substation one, two and three steadily increases with distance which is contrary to case 1. Similar observations have been made for case 4 and 5 where the maximum permitted limit of voltage profile exceeds at substation four which is 12 km away from the distribution transformer.

4.2-2 Hosting Capacity of 10 kV Distribution Test Feeder:

The hosting capacity (HC) is the maximum amount of generation that can be added to any bus or substation which may increase the voltage equal to the overvoltage margin [22]. Overvoltage margin is the difference between the overvoltage limit and the maximum voltage magnitude before connection of the generation. In this case the resistance of the distribution transformer can be neglected. The hosting capacity can be expressed as $P_{max} = \frac{{U_{nom}}^2}{R}\delta_{max}$, where U_{nom} is the nominal voltage of the network; R is the source resistance; δ_{max} is the overvoltage margin and

P_{max} is the hosting capacity for the three phase network. For per phase, the hosting capacity is the one sixth of the three phase network.

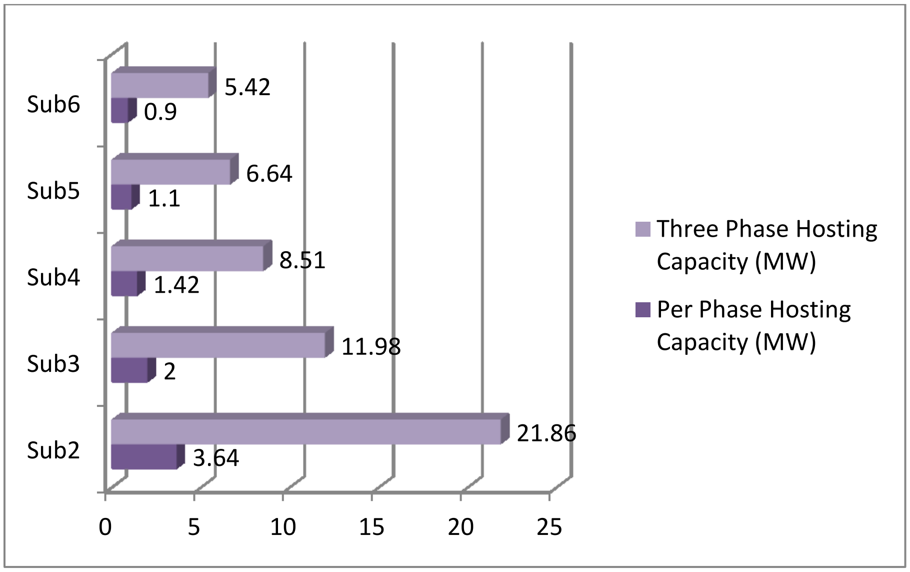

Figure 4.31 Hosting Capacity at Substations of Ideal 10 kV Distribution Test Feeder

From the fig 4.31 it is visible that hosting capacity of the three phase network is almost six times higher than per phase network. The nominal voltage of network is 10 kV for three phase and 5.77kV for per phase approximately. Fig 4.32 again shows that the hosting capacity for both one and three phase of the network, which decreases with the increase of the distance. Or, in other words hosting capacity is the highest for the bus or substation nearer to the distribution transformer and decreases with the increase of the distance.

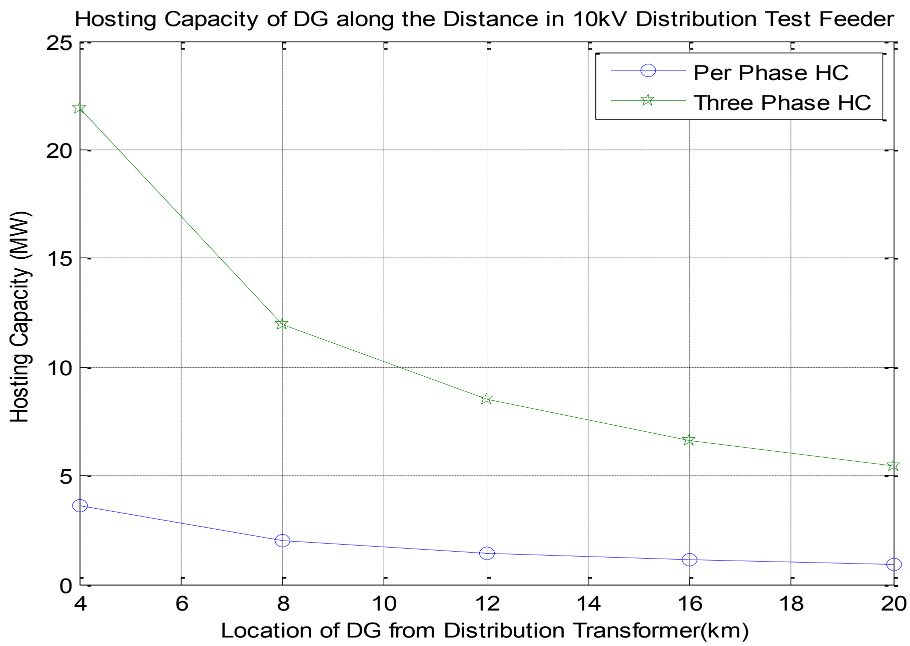

Figure 4.32 Hosting Capacity vs. Distance

4.2-3 Real and Reactive Power Loss of 10 kV Distribution Test Feeder:

The real and reactive power losses of the above cases are shown in table 4.3 and fig 4.33. From the following table it can be said that the case 2 has the lowest both real and reactive power loss whereas case 6 has the highest real and reactive power losses. In case 2 distributed generation of 1 MW is added to the network with 3 MW load demand where in case 6, DG of 5.5 MW is added without any load connected to the network.

Table 4.3 Real and Reactive Power Loss of Case 1-6

	MW Loss	Mvar Loss
Case 1	0.07	0.07
Case 2	0.03	0.03
Case 3	0.04	0.03

Case 4	0.37	0.35
Case 5	0.46	0.43
Case 6	0.57	0.54

Fig 4.33 also shows the same interpretation of the table from which it can easily be concluded that case 2 is the best case whereas case 6 is the worst case in terms of both real and reactive power losses in the distribution network.

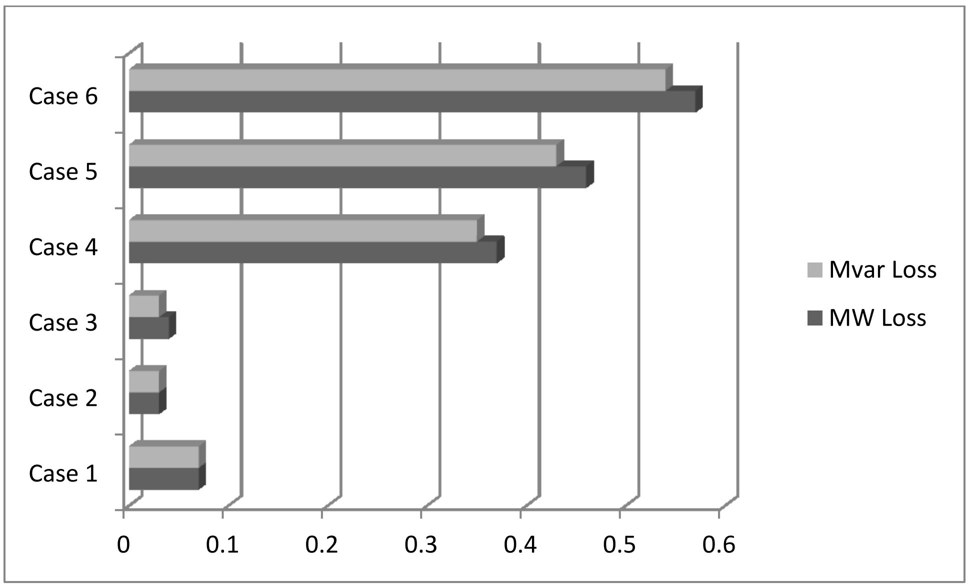

Figure 4.33 Real and Reactive Power Loss of Case 1-6

<u>4.2-4 Power Line Loss Coefficient Determination of 10kV Distribution Test Node:</u>

Power line loss coefficients of each line have been determined for 10 kV distribution test feeder. The power line loss between two buses m and k is approximately proportional to the square of the power flow through the line. Let us consider the one line diagram for the two bus system shown in fig 4.34.

Figure 4.34 One Line Diagram for Two Bus System

$$P_{L_{mk}} = a_{mk}(P_{mk}{}^2)$$

Where m and k are the bus numbers and a_{mk} is the line loss coefficient which depends on the voltage and resistance of the line. P_{mk} is the power flow through line m and k. In other words $P_{mk} = P_{k_{in}}$, where $P_{k_{in}}$ is the injected power in the bus k. The power line loss between bus m and k is denoted by $P_{L_{mk}}$.

$$P_{L_{mk}} = a_{mk}(P_{k_{in}}{}^2)$$

Let us now consider the 10 kV distribution test feeder. To evaluate the value of power line loss coefficients for all the case studies performed above, following equations have been determined. In order to obtain the approximate value of the power line loss coefficients a_{mk} , the value of the line loss $P_{L_{mk}}$ has been obtained from the branch state outputs of the performed simulations. For an example, the power line loss between bus 1 and 2 ($P_{L_{12}}$) is proportional to the square of the power flow through line 1 and 2 (P_{12}) or injected power to the bus 2($P_{2_{in}}$).

$$P_{L_{12}} = a_{12}(P_{2_{in}}{}^2)$$

$$\text{Therofore power line}(1-2)\text{ loss coefficient}, a_{12} = \frac{P_{L_{12}}}{(P_{2_{in}}{}^2)} \quad 4.1$$

$$\text{where}, P_{2_{in}} = P_{D_2} + P_{L_{23}} + P_{D_3} + P_{L_{34}} + P_{D_4} + P_{L_{45}} + P_{D_5} + P_{L_{56}} + P_{D_6}$$

The values of load demand such as $P_{D_2}, P_{D_3}, P_{D_4}, P_{D_5}, P_{D_6}$ are known and values of power line losses such as $P_{L_{23}}, P_{L_{34}}, P_{L_{45}}, P_{L_{56}}$ have been determined from the simulations for each of the cases. Similarly, the line loss coefficients such as a_{23}, a_{34}, a_{45} and a_{56} are determined and shown in equations from 3.2 to 3.5.

$$\text{The power line } (2-3)\text{loss}, P_{L_{23}} = a_{23}\left(P_{3_{in}}{}^2\right)$$

$$\text{Therefore power line}(2-3)\text{loss coefficient}, a_{23} = \frac{P_{L_{23}}}{(P_{3_{in}}{}^2)} \quad 4.2$$

$$\text{where}, P_{3_{in}} = P_{D_3} + P_{L_{34}} + P_{D_4} + P_{L_{45}} + P_{D_5} + P_{L_{56}} + P_{D_6}$$

$$P_{L_{34}} = a_{34}\left(P_{4_{in}}{}^2\right)$$

$$\text{Power Line}(3-4)\text{Loss Coefficient}, a_{34} = \frac{P_{L_{34}}}{(P_{4_{in}}{}^2)} \quad 4.3$$

$$\text{where } P_{4_{in}} = P_{D_4} + P_{L_{45}} + P_{D_5} + P_{L_{56}} + P_{D_6}$$

$$P_{L_{45}} = a_{45}\left(P_{5_{in}}{}^2\right)$$

$$\text{Power Line}(4-5)\text{Loss Coefficient}, a_{45} = \frac{P_{L_{45}}}{(P_{5_{in}}{}^2)} \quad 4.4$$

$$\text{where } P_{5_{in}} = P_{D_5} + P_{L_{56}} + P_{D_6}$$

$$P_{L_{56}} = a_{56}\left(P_{D_6}{}^2\right)$$

$$\text{Power Line}(5-6)\text{Loss Coefficient}, a_{56} = \frac{P_{L_{56}}}{(P_{D_6}{}^2)} \quad 4.5$$

In table 4.4-1 the approximate values of power line loss coefficient for the cases 1 to 6 have been shown using equations 4.1 to 4.6. Following table shows that the case 2 has the lowest line loss coefficient among all the cases whereas case 6 has the highest line loss coefficient values. Line loss coefficient value of case 1 is much higher comparing to that of case 2 in which 1 MW DG is added to the network to feed loads locally. Hence it is proved from this value that line losses decrease while DGs are added in the medium voltage distribution network.

Table 4.4-1 Power Line Loss Coefficients of Case (1-6)

Power Line Loss Coefficient a_{jk}	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
a_{12}	$4.650 * 10^{-9}$	$1.60 * 10^{-9}$	$1.60 * 10^{-9}$	$1.44 * 10^{-8}$	$4.23 * 10^{-8}$	$1.32 * 10^{-6}$
a_{23}	$4.902 * 10^{-9}$	$2.480 * 10^{-9}$	$4.902 * 10^{-9}$	$2.62 * 10^{-8}$	$11.89 * 10^{-8}$	$5.26 * 10^{-6}$
a_{34}	$4.390 * 10^{-9}$	0	$4.390 * 10^{-9}$	$6.22 * 10^{-8}$	$16.0 * 10^{-8}$	Undefined
a_{45}	10^{-8}	10^{-8}	10^{-8}	0	0	0
a_{56}	0	0	0	0	0	0

The line loss coefficient value increases eventually in case 3, 4, 5 and 6. In case 3 the line loss coefficient values increase compare to that of case 2 because to feed the same amount of loads DG output of 2 MW has been added to the distribution network. When the DG output is increased to 5.5 MW in case 4 while the loads connected to the network are same as previous cases causes significant increase in power line loss coefficients too. Under loading the network in case 5 further increases the line loss coefficients and finally the line loss coefficients reached to its peak while no load is connected to the network in case 6. It can be concluded by observing the line loss coefficient value that case 2 is one of the best cases and case 6 is one of the worst cases.

Table 4.4-2 Average of Power Line Loss Coefficients Case (1-6)

Power Line Loss Coefficient, a_{jk}	**Average of Power Line Loss Coefficients Case (1-6), a_{jk}**
a_{12}	$2.307 * 10^{-7}$
a_{23}	$2.623 * 10^{-8}$
a_{34}	Undefined
a_{45}	$5 * 10^{-9}$
a_{56}	0

In above table 4.4-2 the average of all cases (1-6) the power line loss coefficients have been determined. The average of power line loss coefficient is the lowest for the line between 5 and 6 and highest for the line between 1 and 2. The average of the power line loss coefficient is undefined for the line between 3 and 4.

4.3 Simulation of IEEE 13 Node Distribution Test Feeder

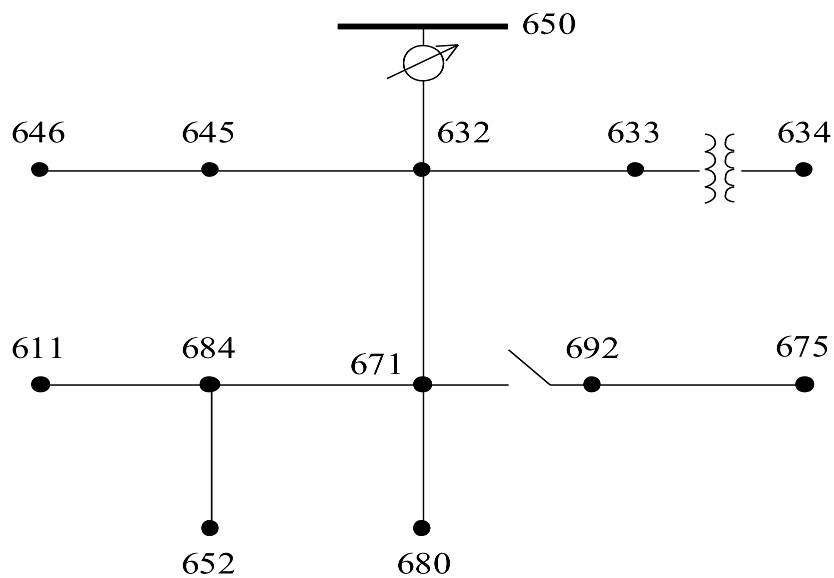

Figure 4.35 IEEE 13 Node Test Feeder [23]

Network data of IEEE 13 node test feeder is given in reference [23]. The following case studies have been performed on IEEE 13 node distribution test feeder:

Case 1: Generation at slack bus only

Case 2: Over loading the network by turning on the switch between node 671 and 692

Case 3: DG addition at node 684 for same loads and branch input as case 2

Case 4: Under loading with additional DG for same branches input in case 2

In case 1, generation is only added at slack bus. In case 2, the switch between node 671 and 692 is turned on which creates overloading situation. To improve the overloading situation of case 2, distributed generation has been added at node 684 in case 3. In case 4, under loading situation has been created by turning off several loads connected to the feeder along with supplementary distributed generation. Branch input for both case 3 and 4 are as same as case 2.

Case 1: Generation at slack bus only

I have shown the simulation of ideal IEEE 13 node test feeder in case 1.The following figures show various inputs and outputs data for case 1. In fig 4.36 branch input data such as resistance, reactance, conductance etc of the distribution line are mentioned. For an example the resistance and reactance between node 632 and node 633 are 0.404 and 0.624 in per unit respectively and so on between others nodes. In fig 4.37 loads input data of the each node is given for information. For an example, the node 632 has the real and reactive load demand of 0.20 MW and 0.12 Mvar respectively.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	R	X	B	Lim A MVA	Lim B MVA	Lim C MVA
1	Substation	14	650	1	Closed	Transformer	YES	0.01000	0.08000	0.00000	0.0	0.0	0.0
2	632	3	633	1	Closed	Line	NO	0.40402	0.63421	0.00000	0.0	0.0	0.0
2	632	5	645	1	Closed	Line	NO	0.71216	0.72580	0.00000	0.0	0.0	0.0
2	632	7	671	1	Closed	Line	NO	0.74405	2.21926	0.00000	0.0	0.0	0.0
14	650	2	632	1	Closed	Line	NO	0.74405	2.21926	0.00000	0.0	0.0	0.0
3	633	4	634	1	Closed	Transformer	YES	0.01100	0.02000	0.00000	0.0	0.0	0.0
5	645	6	646	1	Closed	Line	NO	0.42729	0.43548	0.00000	0.0	0.0	0.0
7	671	8	684	1	Closed	Line	NO	0.42729	0.43548	0.00000	0.0	0.0	0.0
7	671	11	692	1	Open	Line	NO	0.00000	0.00001	0.00000	0.0	0.0	0.0
7	671	13	680	1	Closed	Line	NO	0.37125	1.10732	0.00000	0.0	0.0	0.0
8	684	9	611	1	Closed	Line	NO	0.43641	0.44241	0.00000	0.0	0.0	0.0
8	684	10	652	1	Closed	Line	NO	1.17539	0.44862	0.00000	0.0	0.0	0.0
11	692	12	675	1	Closed	Line	NO	0.43514	0.23650	0.00000	0.0	0.0	0.0

Figure 4.36 Branch Input of Simulation Case 1

Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar
632	1	1	1	Closed	0.20	0.12	0.23	0.20	0.12
634	1	1	1	Closed	0.40	0.29	0.49	0.40	0.29
645	1	1	1	Closed	0.17	0.12	0.21	0.17	0.12
646	1	1	1	Closed	0.20	0.12	0.23	0.00	0.00
671	1	1	1	Closed	1.15	0.66	1.33	1.15	0.66
611	1	1	1	Closed	0.16	0.07	0.17	0.00	0.00
652	1	1	1	Closed	0.11	0.07	0.13	0.00	0.00
692	1	1	1	Closed	0.00	0.00	0.00	0.00	0.00
675	1	1	1	Closed	0.00	0.00	0.00	0.84	0.46

Figure 4.37 Load Input of Simulation Case 1

In the following fig 4.38 the graphical representation of simulation of ideal IEEE 13 node distribution test feeder has been shown using power world simulator 17 using above mentioned branch and load inputs data.

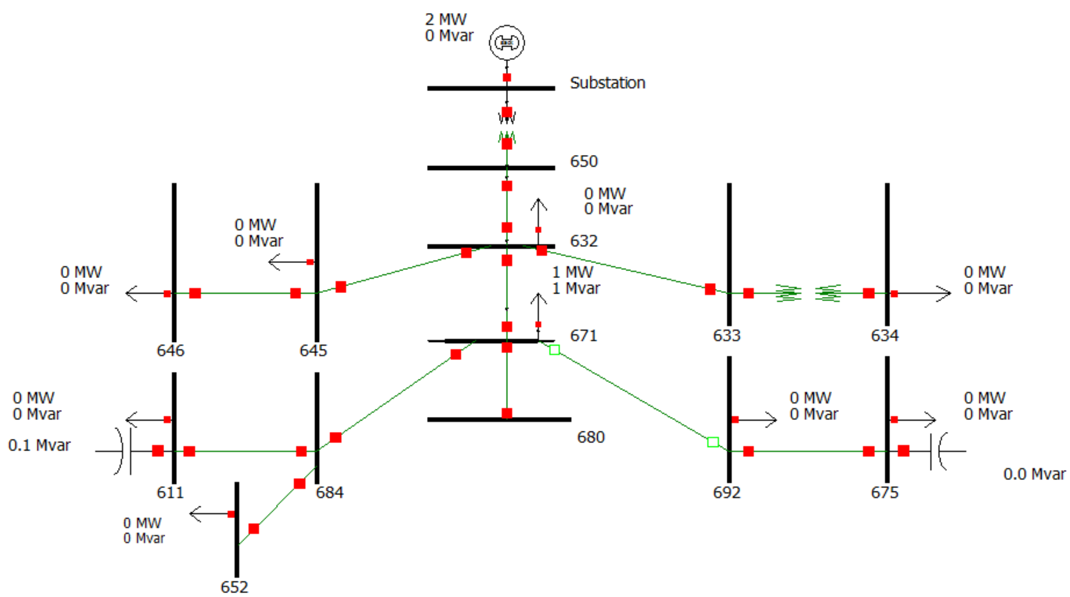

Figure 4.38 Simulation of IEEE 13 Node Test Distribution Feeder (Case 1)

In fig 4.39 the slack generator output of 2.49 MW has been observed from the simulation to supply the total 2.39 MW load demand by the all the nodes. In fig 4.40 and 4.41 the switched shunts and transformer control data of the simulation have been given respectively.

Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
Substation	1	Closed	2.49	0.00	1.00000	NO	YES	0.00	1000.00	0.00	0.00	None	10.00

Figure 4.39 Generator Output of Simulation Case 1

Number of Bus	Name of Bus	ID	Reg Bus Num	Status	Control Mode	Regulates	Actual Mvar	Volt High	Volt Low	Reg Volt	Deviation	Nominal Mvar	Max Mvar	Min Mvar
9	611	1	9	Closed	Fixed	Volt	0.08	1.0000	0.9900	0.9157	-0.0743	0.10	0.10	0.00
12	675	1	12	Closed	Fixed	Volt	0.00	1.0000	0.9900	0.0000	-0.9900	0.75	0.60	0.00

Figure 4.40 Switched Shunts of Simulation Case 1

To Number	To Name	Circuit	Type	Status	Tap Ratio	Phase (Deg)	XF Auto	Reg Bus	Reg Value	Reg Error	Reg Min	Reg Max	Tap Min	Tap Max	Step Size
14	650	1	Fixed	Closed	1.00000	0.00000	No	0	0.00000	-0.51000	0.51000	1.50000	0.51000	1.50000	0.00625
4	634	1	Fixed	Closed	1.00000	0.00000	No	0	0.00000	-0.51000	0.51000	1.50000	0.51000	1.50000	0.00625

Figure 4.41 Transformer Control of Simulation Case 1

In fig 4.42 real and reactive power flow and loss between nodes are shown. For an example the real and reactive power flow between node 632 and node 671 are 1.4 MW and 0.7 Mvar respectively. The total real and reactive power loss between node 632 and 671 are 0.02 MW and 0.07 Mvar respectively. Similarly the real and reactive power loss between other nodes can be obtained from this figure. To obtain the values of real power loss coefficients between nodes, the real power losses values between nodes are used in section 4.4 of this chapter.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Substation	14	650	1	Closed	Transformer	YES	2.5	1.6	2.9	0.0	0.0	0.00	0.01
2	632	3	633	1	Closed	Line	NO	0.4	0.3	0.5	0.0	0.0	0.00	0.00
2	632	5	645	1	Closed	Line	NO	0.4	0.2	0.4	0.0	0.0	0.00	0.00
2	632	7	671	1	Closed	Line	NO	1.4	0.7	1.6	0.0	0.0	0.02	0.07
14	650	2	632	1	Closed	Line	NO	2.5	1.6	2.9	0.0	0.0	0.06	0.19
3	633	4	634	1	Closed	Transformer	YES	0.4	0.3	0.5	0.0	0.0	0.00	0.00
5	645	6	646	1	Closed	Line	NO	0.2	0.1	0.2	0.0	0.0	0.00	0.00
7	671	8	684	1	Closed	Line	NO	0.3	0.1	0.3	0.0	0.0	0.00	0.00
7	671	11	692	1	Open	Line	NO	0.0	0.0	0.0	0.0	0.0	0.00	0.00
7	671	13	680	1	Closed	Line	NO	0.0	0.0	0.0	0.0	0.0	0.00	0.00
8	684	9	611	1	Closed	Line	NO	0.2	-0.0	0.2	0.0	0.0	0.00	0.00
8	684	10	652	1	Closed	Line	NO	0.1	0.1	0.1	0.0	0.0	0.00	-0.00
11	692	12	675	1	Closed	Line	NO	0.0	0.0	0.0	0.0	0.0	0.00	0.00

Figure 4.42 Branch State Output of Simulation Case 1

In fig 4.43 the load flow information of all nodes are obtained. For an example for the nodes 632,633, 634,645,646, 671,684,611,652,680 and 650 voltage drops of 0.227, 0.242, 0.029, 0.247, 0.253, 0.345, 0.351, 0.354, 0.359, 0.345, and 0.006 respectively in kV are observed.

Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar
Substation	1	115.00	1.00000	115.000	0.00			2.49	0.00	
632	1	4.20	0.94596	3.973	-2.74	0.20	0.12			
633	1	4.20	0.94229	3.958	-2.83					
634	1	0.50	0.94218	0.471	-2.83	0.40	0.29			
645	1	4.20	0.94126	3.953	-2.81	0.17	0.12			
646	1	4.20	0.93980	3.947	-2.83	0.20	0.12			
671	1	4.20	0.91787	3.855	-4.50	1.15	0.66			
684	1	4.20	0.91635	3.849	-4.56					
611	1	4.20	0.91566	3.846	-4.61	0.16	0.07			0.08
652	1	4.20	0.91462	3.841	-4.54	0.11	0.07			
692	1	4.16	0.00000	0.000	0.00	0.00	0.00			
675	1	4.20	0.00000	0.000	0.00	0.00	0.00			0.00
680	1	4.20	0.91787	3.855	-4.50					
650	3	4.20	0.99849	4.194	-0.11					

Figure 4.43 Load Flow of Simulation Case

Case 2: Simulation while turning on the switch between node 671 and 692

In case 2 the switch between node 671 and 692 is turned on which creates an overloading situation and dramatic voltage drop occur in that case. In fig 4.44 and 4.45 the branch and load inputs are given which are not same as case 1.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	R	X	B	Lim A MVA	Lim B MVA	Lim C MVA
1	Substation	14	650	1	Closed	Transformer	YES	0.01000	0.08000	0.00000	0.0	0.0	0.0
2	632	3	633	1	Closed	Line	NO	0.40402	0.63421	0.00000	0.0	0.0	0.0
2	632	5	645	1	Closed	Line	NO	0.71216	0.72580	0.00000	0.0	0.0	0.0
2	632	7	671	1	Closed	Line	NO	0.74405	2.21926	0.00000	0.0	0.0	0.0
14	650	2	632	1	Closed	Line	NO	0.74405	2.21926	0.00000	0.0	0.0	0.0
3	633	4	634	1	Closed	Transformer	YES	0.01100	0.02000	0.00000	0.0	0.0	0.0
5	645	6	646	1	Closed	Line	NO	0.42729	0.43548	0.00000	0.0	0.0	0.0
7	671	8	684	1	Closed	Line	NO	0.42729	0.43548	0.00000	0.0	0.0	0.0
7	671	11	692	1	Closed	Line	NO	0.00000	0.00001	0.00000	0.0	0.0	0.0
7	671	13	680	1	Closed	Line	NO	0.37125	1.10732	0.00000	0.0	0.0	0.0
8	684	9	611	1	Closed	Line	NO	0.43641	0.44241	0.00000	0.0	0.0	0.0
8	684	10	652	1	Closed	Line	NO	1.17539	0.44862	0.00000	0.0	0.0	0.0
11	692	12	675	1	Closed	Line	NO	0.43514	0.23650	0.00000	0.0	0.0	0.0

Figure 4.44 Branch Input Simulation Case 2

Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar
2	632	1	1	1	Closed	0.20	0.12	0.23	0.20	0.12
4	634	1	1	1	Closed	0.40	0.29	0.49	0.40	0.29
5	645	1	1	1	Closed	0.17	0.12	0.21	0.17	0.12
6	646	1	1	1	Closed	0.20	0.11	0.23	0.00	0.00
7	671	1	1	1	Closed	1.15	0.66	1.33	1.15	0.66
9	611	1	1	1	Closed	0.15	0.07	0.17	0.00	0.00
10	652	1	1	1	Closed	0.10	0.07	0.12	0.00	0.00
11	692	1	1	1	Closed	0.15	0.14	0.20	0.00	0.00
12	675	1	1	1	Closed	0.84	0.46	0.96	0.84	0.46

Figure 4.45 Load Input of Simulation Case 2

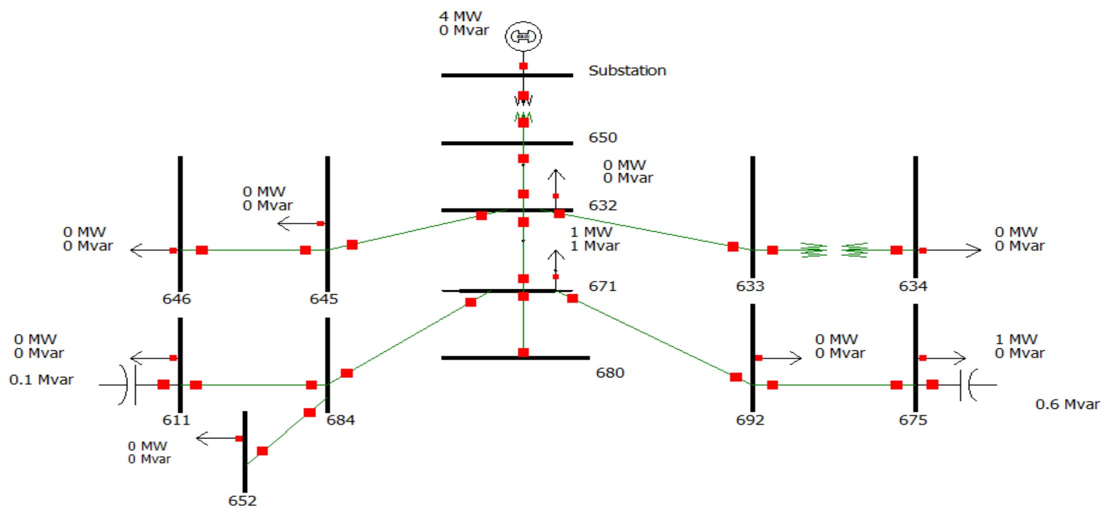

Figure 4.46 Simulation of IEEE 13 Node Test Distribution Feeder (Case 2)

In above fig 4.46 the simulation is shown for case 2 using power world simulator. It is clearly shown in that fig that the switch between node 671 and 692 is turned. In the following fig 4.47 the generator output of 3.56 MW attached with slack bus is observed to feed the loads in the network.

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	Substation	1	Closed	3.56	0.00	1.00000	NO	YES	0.00	1000.00	0.00	0.00	None	10.00

Figure 4.47 Generator Output of Simulation Case 2

In fig 4.48 the shunt capacitor is attached at node 611 and 675. Figure 4.49 shows the transformer control for the simulation of case 2.

Number of Bus	Name of Bus	ID	Reg Bus Num	Status	Control Mode	Regulates	Actual Mvar	Volt High	Volt Low	Reg Volt	Deviation	Nominal Mvar	Max Mvar	Min Mvar
9	611	1	9	Closed	Fixed	Volt	0.08	1.0000	0.9900	0.8939	-0.0961	0.10	0.10	0.00
12	675	1	12	Closed	Fixed	Volt	0.60	1.0000	0.9900	0.8922	-0.0978	0.75	0.60	0.00

Figure 4.48 Switched Shunts of Simulation Case 2

From Name	To Number	To Name	Circuit	Type	Status	Tap Ratio	Phase (Deg)	XF Auto	Reg Bus	Reg Value	Reg Error	Reg Min	Reg Max	Tap Min	Tap Max
Substation	14	650	1	Fixed	Closed	1.00000	0.00000	No	0	0.00000	-0.51000	0.51000	1.50000	0.51000	1.50000
633	4	634	1	Fixed	Closed	1.00000	0.00000	No	0	0.00000	-0.51000	0.51000	1.50000	0.51000	1.50000

Figure 4.49 Transformer Control of Simulation Case 2

Fig 4.50 shows the branch state of the simulation in case 2. The real and reactive power flow between node 650 and 632 is 3.6 MW and 1.8 Mvar respectively. The real and reactive power losses between those nodes are 0.12 MW and 0.36 Mvar respectively which is one of the highest compare to other nodes. The real and reactive power flow between the nodes 632 and 671 is 2.5 MW and 0.8 Mvar whereas the real and reactive power losses are 0.06 MW and 0.17 Mvar respectively.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Substation	14	650	1	Closed	Transformer	YES	3.6	1.8	4.0	0.0	0.0	0.00	0.01
2	632	3	633	1	Closed	Line	NO	0.4	0.3	0.5	0.0	0.0	0.00	0.00
2	632	5	645	1	Closed	Line	NO	0.4	0.2	0.4	0.0	0.0	0.00	0.00
2	632	7	671	1	Closed	Line	NO	2.5	0.8	2.6	0.0	0.0	0.06	0.17
14	650	2	632	1	Closed	Line	NO	3.6	1.8	4.0	0.0	0.0	0.12	0.36
3	633	4	634	1	Closed	Transformer	YES	0.4	0.3	0.5	0.0	0.0	0.00	0.00
5	645	6	646	1	Closed	Line	NO	0.2	0.1	0.2	0.0	0.0	0.00	0.00
7	671	8	684	1	Closed	Line	NO	0.3	0.1	0.3	0.0	0.0	0.00	0.00
7	671	11	692	1	Closed	Line	NO	1.0	-0.0	1.0	0.0	0.0	0.00	0.00
7	671	13	680	1	Closed	Line	NO	-0.0	0.0	0.0	0.0	0.0	0.00	0.00
8	684	9	611	1	Closed	Line	NO	0.2	-0.0	0.2	0.0	0.0	0.00	0.00
8	684	10	652	1	Closed	Line	NO	0.1	0.1	0.1	0.0	0.0	0.00	-0.00
11	692	12	675	1	Closed	Line	NO	0.9	-0.1	0.9	0.0	0.0	0.00	0.00

Figure 4.50 Branch State Output of Simulation Case 2

Fig 4.51 shows the load flow of the simulation in case 2 where the p.u voltage at nodes 671, 684, 611, 652,692,675,680 and 650 are below the minimum acceptable limit for the voltage which is 0.90 p.u.

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar
1	Substation	1	115.00	1.00000	115.000	0.00			3.56	0.00	
2	632	1	4.20	0.93359	3.921	-4.18	0.20	0.12			
3	633	1	4.20	0.92988	3.905	-4.27					
4	634	1	0.50	0.92977	0.465	-4.27	0.40	0.29			
5	645	1	4.20	0.92890	3.901	-4.24	0.17	0.12			
6	646	1	4.20	0.92746	3.895	-4.27	0.20	0.11			
7	671	1	4.20	0.89614	3.764	-7.52	1.15	0.66			
8	684	1	4.20	0.89463	3.757	-7.58					
9	611	1	4.20	0.89392	3.754	-7.63	0.15	0.07			0.08
10	652	1	4.20	0.89294	3.750	-7.55	0.10	0.07			
11	692	1	4.16	0.89614	3.728	-7.52	0.15	0.14			
12	675	1	4.20	0.89220	3.747	-7.72	0.84	0.46			0.60
13	680	1	4.20	0.89614	3.764	-7.52					
14	650	3	4.20	0.99818	4.192	-0.15					

Figure 4.51 Load Flow of Simulation Case 2

Case 3: Simulation with DG addition at node 684 for same loads and branch input as case 2

To observe the effect of adding distributed generation with IEEE 13 node test distribution feeder, a DG output of 1 MW is added to the node 684 at power factor 0.80 using with same branch and load inputs as case 2 in fig 4.52.

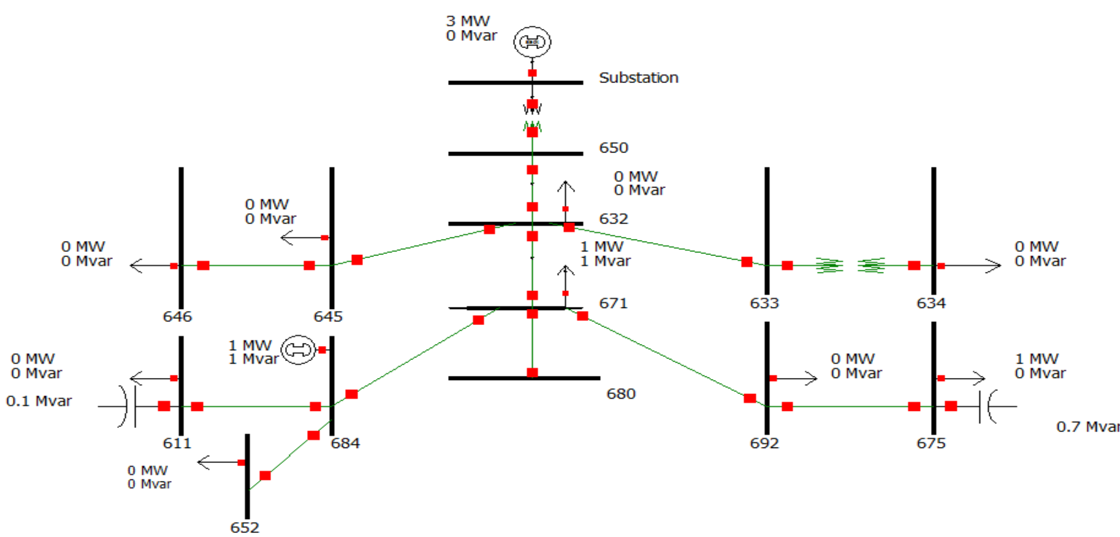

Figure 4.52 Simulation of IEEE 13 Node Test Distribution Feeder (Case 3)

The fig 4.53 shows that the slack generator produces 2.54 MW, while the DG outputs 1 MW real power approximately. Hence it is observed that real power is generating locally to reduce the slack bus generation.

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	Substation	1	Closed	2.54	0.00	1.00000	NO	YES	0.00	1000.00	0.00	0.00	None	10.00
8	684	1	Closed	1.00	0.75	1.00000	NO	YES	0.00	1000.00	0.75	0.75	None	10.00

Figure 4.53 Generator Output of Simulation Case 3

In fig 4.54 the shunt capacitor is attached at node 611 and 675. Fig 4.55 shows the transformer control for the simulation of case 3.

Number of Bus	Name of Bus	ID	Reg Bus Num	Status	Control Mode	Regulates	Actual Mvar	Volt High	Volt Low	Reg Volt	Deviation	Nominal Mvar	Max Mvar	Min Mvar
9	611	1	9	Closed	Fixed	Volt	0.09	1.0000	0.9900	0.9564	-0.0336	0.10	0.10	0.00
12	675	1	12	Closed	Fixed	Volt	0.67	1.0000	0.9900	0.9473	-0.0427	0.75	0.60	0.00

Figure 4.54 Switched Shunts of Simulation Case 3

To Number	To Name	Circuit	Type	Status	Tap Ratio	Phase (Deg)	XF Auto	Reg Bus	Reg Value	Reg Error	Reg Min	Reg Max	Tap Min	Tap Max	Step Size
14	650	1	Fixed	Closed	1.00000	0.00000	No	0	0.00000	-0.51000	0.51000	1.50000	0.51000	1.50000	0.00625
4	634	1	Fixed	Closed	1.00000	0.00000	No	0	0.00000	-0.51000	0.51000	1.50000	0.51000	1.50000	0.00625

Figure 4.55 Transformer Control of Simulation Case 3

Fig 4.56 shows the branch state of the simulation in case 3. The real and reactive power flow between node 650 and 632 is 2.5 MW and 0.9 Mvar respectively. The real and reactive power losses between those nodes are 0.05 MW and 0.16 Mvar respectively which is one of the highest compare to other nodes. The real and reactive power flow between the nodes 632 and 671 is 1.5 MW and 0 Mvar whereas the real and reactive power losses are 0.02 MW and 0.05 Mvar respectively.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Substation	14	650	1	Closed	Transformer	YES	2.5	0.9	2.7	0.0	0.0	0.00	0.01
2	632	3	633	1	Closed	Line	NO	0.4	0.3	0.5	0.0	0.0	0.00	0.00
2	632	5	645	1	Closed	Line	NO	0.4	0.2	0.5	0.0	0.0	0.00	0.00
2	632	7	671	1	Closed	Line	NO	1.5	0.0	1.5	0.0	0.0	0.02	0.05
14	650	2	632	1	Closed	Line	NO	2.5	0.9	2.7	0.0	0.0	0.05	0.16
3	633	4	634	1	Closed	Transformer	YES	0.4	0.3	0.5	0.0	0.0	0.00	0.00
5	645	6	646	1	Closed	Line	NO	0.2	0.1	0.2	0.0	0.0	0.00	0.00
7	671	8	684	1	Closed	Line	NO	-0.7	-0.7	1.0	0.0	0.0	0.00	0.00
7	671	11	692	1	Closed	Line	NO	1.0	0.0	1.0	0.0	0.0	0.00	0.00
7	671	13	680	1	Closed	Line	NO	-0.0	0.0	0.0	0.0	0.0	0.00	0.00
8	684	9	611	1	Closed	Line	NO	0.2	-0.0	0.2	0.0	0.0	0.00	0.00
8	684	10	652	1	Closed	Line	NO	0.1	0.1	0.1	0.0	0.0	0.00	-0.00
11	692	12	675	1	Closed	Line	NO	0.8	-0.2	0.9	0.0	0.0	0.00	0.00

Figure 4.56 Branch State of Simulation Case 3

Fig 4.57 shows the load flow of the simulation in case 3 where the p.u voltages at all the nodes are within acceptable limit which is between 1.1 and 0.90 p.u.

Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar
2	632	1	1	1	Closed	0.20	0.12	0.23	0.20	0.12
4	634	1	1	1	Closed	0.40	0.29	0.49	0.40	0.29
5	645	1	1	1	Closed	0.17	0.12	0.21	0.17	0.12
6	646	1	1	1	Closed	0.21	0.12	0.24	0.00	0.00
7	671	1	1	1	Closed	1.15	0.66	1.33	1.15	0.66
9	611	1	1	1	Closed	0.16	0.08	0.18	0.00	0.00
10	652	1	1	1	Closed	0.12	0.08	0.14	0.00	0.00
11	692	1	1	1	Closed	0.16	0.14	0.22	0.00	0.00
12	675	1	1	1	Closed	0.84	0.46	0.96	0.84	0.46

Figure 4.57 Load Flow Simulation of Case 3

<u>Case 4: Simulation of under loading situation with additional DG generation for same branches input in case 2</u>

In fig 4.58 the load input for the case 4 has been shown. In this case the network has been under loaded to observe the changes in simulation while keeping the same branch input data as case 2.

Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar
2	632	1	1	1	Closed	0.20	0.12	0.23	0.20	0.12
4	634	1	1	1	Open	0.00	0.00	0.00	0.40	0.29
5	645	1	1	1	Open	0.00	0.00	0.00	0.17	0.12
6	646	1	1	1	Closed	0.25	0.14	0.28	0.00	0.00
7	671	1	1	1	Open	0.00	0.00	0.00	1.15	0.66
9	611	1	1	1	Open	0.00	0.00	0.00	0.00	0.00
10	652	1	1	1	Open	0.00	0.00	0.00	0.00	0.00
11	692	1	1	1	Closed	0.19	0.16	0.25	0.00	0.00
12	675	1	1	1	Open	0.00	0.00	0.00	0.84	0.46

Figure 4.58 Loads of Simulation Case 4

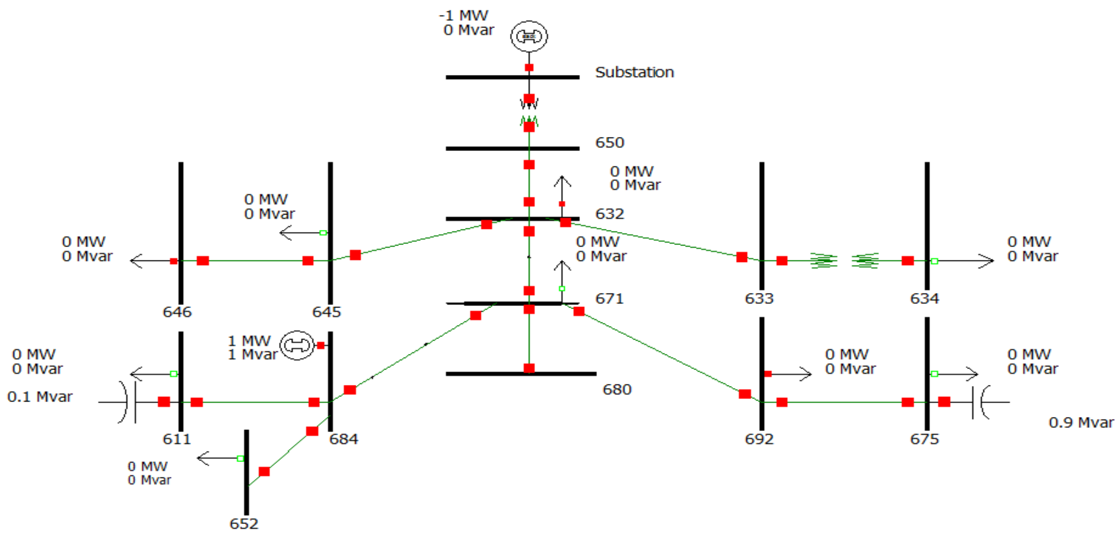

Figure 4.59 Simulation of IEEE 13 Node Test Distribution Feeder (Case 4)

In above fig 4.59 shows the DG outputs the same as case 3 but the only difference is under loading the network to show the affect on IEEE 13 node test distribution feeder. In fig 4.60 the slack generator produces reverse real power flow of 0.78 MW. The DG generates real and reactive power of 1.50 MW and 1.12 Mvar respectively.

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	Substation	1	Closed	-0.78	0.00	1.00000	NO	YES	0.00	1000.00	0.00	0.00	None	10.00
8	684	1	Closed	1.50	1.12	1.00000	NO	YES	0.00	1000.00	1.12	1.12	None	10.00

Figure 4.60 Generator Output of Simulation Case 4

The fig 4.61 shows that actual Mvar output of the nodes 611 and 675 are 0.12 and 0.89 respectively. Fig 4.62 shows the transformer control data for the case 4 simulation.

Number of Bus	Name of Bus	ID	Reg Bus Num	Status	Control Mode	Regulates	Actual Mvar	Volt High	Volt Low	Reg Volt	Deviation	Nominal Mvar	Max Mvar	Min Mvar
9	611	1	9	Closed	Fixed	Volt	0.12	1.0000	0.9900	1.1005	0.1005	0.10	0.10	0.00
12	675	1	12	Closed	Fixed	Volt	0.89	1.0000	0.9900	1.0913	0.0913	0.75	0.60	0.00

Figure 4.61 Switched Shunts of Simulation Case 4

From Name	To Number	To Name	Circuit	Type	Status	Tap Ratio	Phase (Deg)	XF Auto	Reg Bus	Reg Value	Reg Error	Reg Min	Reg Max	Tap Min	Tap Max
Substation	14	650	1	Fixed	Closed	1.00000	0.00000	No	0	0.00000	-0.51000	0.51000	1.50000	0.51000	1.50000
633	4	634	1	Fixed	Closed	1.00000	0.00000	No	0	0.00000	-0.51000	0.51000	1.50000	0.51000	1.50000

Figure 4.62 Transformer Control of Simulation Case 4

The fig 4.63 shows the real and reactive power flow between the nodes. For an example the reverse real and reactive power flow between the nodes 632 and 671 are 1.3 MW and 1.8 Mvar respectively. The real and reactive losses between those same nodes are 0.03 MW and 0.10 Mvar respectively and so on for the other nodes too.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	Substation	14	650	1	Closed	Transformer	YES	-0.8	-1.5	1.7	0.0	0.0	0.00	0.00
2	632	3	633	1	Closed	Line	NO	0.0	-0.0	0.0	0.0	0.0	0.00	0.00
2	632	5	645	1	Closed	Line	NO	0.2	0.1	0.3	0.0	0.0	0.00	0.00
2	632	7	671	1	Closed	Line	NO	-1.3	-1.8	2.2	0.0	0.0	0.03	0.10
14	650	2	632	1	Closed	Line	NO	-0.8	-1.5	1.7	0.0	0.0	0.02	0.07
3	633	4	634	1	Closed	Transformer	YES	-0.0	-0.0	0.0	0.0	0.0	0.00	0.00
5	645	6	646	1	Closed	Line	NO	0.2	0.1	0.3	0.0	0.0	0.00	0.00
7	671	8	684	1	Closed	Line	NO	-1.5	-1.2	1.9	0.0	0.0	0.01	0.01
7	671	11	692	1	Closed	Line	NO	0.2	-0.7	0.7	0.0	0.0	0.00	0.00
7	671	13	680	1	Closed	Line	NO	0.0	0.0	0.0	0.0	0.0	0.00	0.00
8	684	9	611	1	Closed	Line	NO	0.0	-0.1	0.1	0.0	0.0	0.00	0.00
8	684	10	652	1	Closed	Line	NO	0.0	0.0	0.0	0.0	0.0	0.00	-0.00
11	692	12	675	1	Closed	Line	NO	0.0	-0.9	0.9	0.0	0.0	0.00	0.00

Figure 4.63 Branch State Output of Simulation Case 4

The fig 4.64 shows that at node 684 and 611 the voltage in p.u exceeds the maximum acceptable voltage limit which is 1.1 p.u. The voltage at nodes 684 and 611 are increased by 0.420 and 0.422 p.u respectively.

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar
1	Substation	1	115.00	1.00000	115.000	0.00			-0.78	0.00	
2	632	1	4.20	1.04092	4.372	0.36	0.20	0.12			
3	633	1	4.20	1.04092	4.372	0.36					
4	634	1	0.50	1.04092	0.520	0.36	0.00	0.00			
5	645	1	4.20	1.03823	4.361	0.32	0.00	0.00			
6	646	1	4.20	1.03661	4.354	0.30	0.25	0.14			
7	671	1	4.20	1.08936	4.575	1.07	0.00	0.00			
8	684	1	4.20	1.10006	4.620	1.13			1.50	1.12	
9	611	1	4.20	1.10052	4.622	1.10	0.00	0.00			0.12
10	652	1	4.20	1.09997	4.620	1.13	0.00	0.00			
11	692	1	4.16	1.08936	4.532	1.07	0.19	0.16			
12	675	1	4.20	1.09129	4.583	0.89	0.00	0.00			0.89
13	680	1	4.20	1.08936	4.575	1.07					
14	650	3	4.20	1.00130	4.205	0.03					

Figure 4.64 Load Flow Output of Simulation Case 4

4.4 Simulation Result Discussion of IEEE 13 Node Distribution Test Feeder

In this section the summary of the above case studies (1-4) has been performed in order to simplify the findings of the study. The following observations have been performed on the basis of i) Voltage profile ii) Hosting capacity iii) Real and reactive power loss iv) Power line loss coefficients determination which is similar as section 4.2.

4.4-1 Voltage Profile of IEEE 13 Node Distribution Test Feeder:

The following table 4.5 shows how the connection of DG affects the voltage profile at substations in varying situations. Case 1 shows the voltage profile at nodes without any DG connected to the IEEE 13 node distribution test feeder and generator is only added to the slack bus. From the observation it can be told that the ideal IEEE 13 node distribution test feeder is highly overloaded since the switch between node 671 and 692 is turned off and once in case 2 while the switched is turned on that creates overloading situation in the feeder.

Table 4.5 Voltage Profile at Nodes Case 1-4

	Case 1	Case 2	Case 3	Case 4
Substation	1.0	1.0	1.0	1.0
632	0.946	0.934	0.962	1.041
633	0.942	0.930	0.959	1.041
634	0.942	0.930	0.958	1.041
645	0.941	0.929	0.958	1.038
646	0.940	0.928	0.956	1.037
671	0.918	**0.896**	0.951	1.089

684	0.916	**0.895**	0.957	**1.100**
611	0.916	**0.893**	0.956	**1.100**
652	0.915	**0.892**	0.955	**1.199**
692	0	**0.896**	0.951	1.089
675	0	**0.892**	0.947	1.091
680	0.918	**0.896**	0.951	1.089
650	0.999	0.998	0.999	1.001

In case 2 the distribution feeder is highly overloaded and exceeds the minimum acceptable voltage which is 0.90 p.u for this case at nodes 671, 684, 611, 652, 692, 675, and 680. Case 3 shows that adding DG of 1 MW at power factor 0.80 at nodes 684 improves the voltage profile significantly. In case 4 under loading situation has been created in which several loads connected to the feeder is turned off while the same DG output as case 3 is still connected to the distribution network. The voltages at node 684, 611 and 652 in case 4 exceed the maximum permitted voltage limit of 1.1 p.u . Figure 4.65 shows the voltage profile at nodes which is similar to that of table 4.5 but with clearer visual representation.

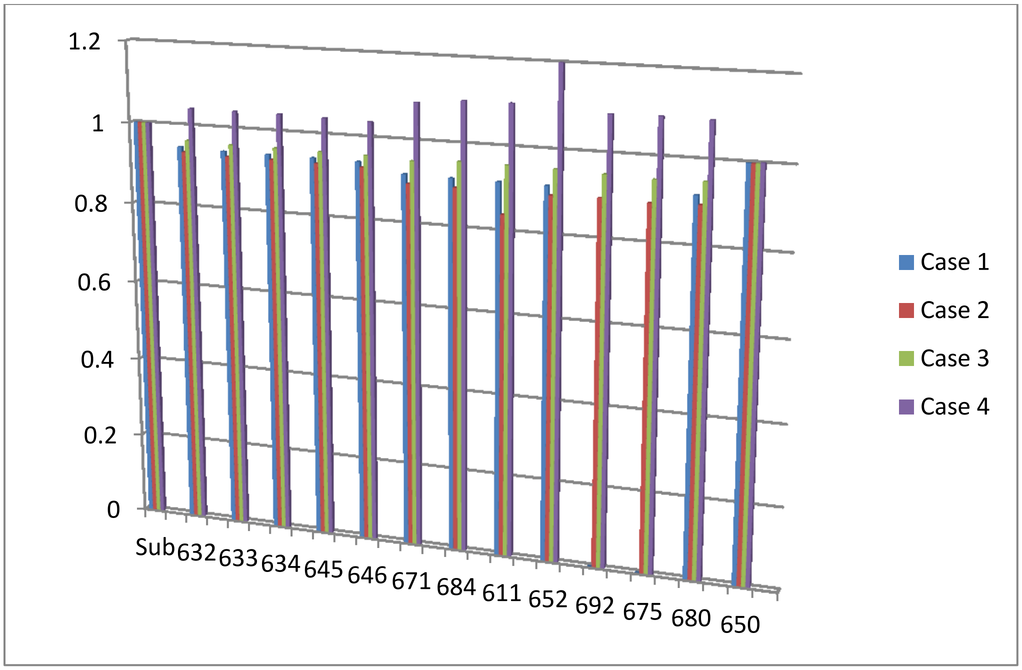

Figure 4.65 Voltage Profiles at Nodes Case 1-4

The fig 4.66 shows how the voltage profiles in each case are changing with the distance from the distribution transformer. For all the cases the voltage profile is unity at substation. The fig clearly shows that for case 1 voltage profile decreases gradually at nodes away from the distribution transformer. Voltage profile further decreases along with distance in case 2 compare to that of case 1. For case 3 the voltage profile at 1.31 km away from the distribution transformer increases as the DG of 1 MW is connected to the node 684 and at the following nodes 611 and 652 voltage profile again slightly decreases comparing to that of node 684. In case 4 voltage profiles further increases and exceeds the maximum voltage limit at distance between 1.31 and 1.55 km at nodes 684, 611 and 652.

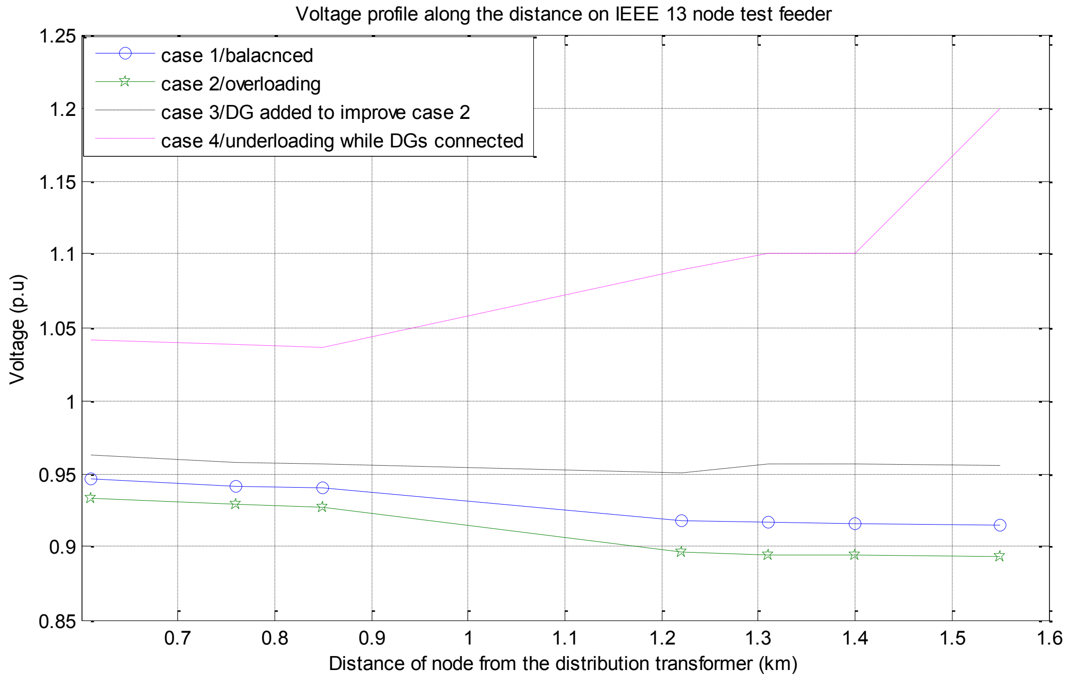

Figure 4.66 Voltage Profile vs. Distance

4.4-2 Hosting Capacity of IEEE 13 Node Distribution Test Feeder:

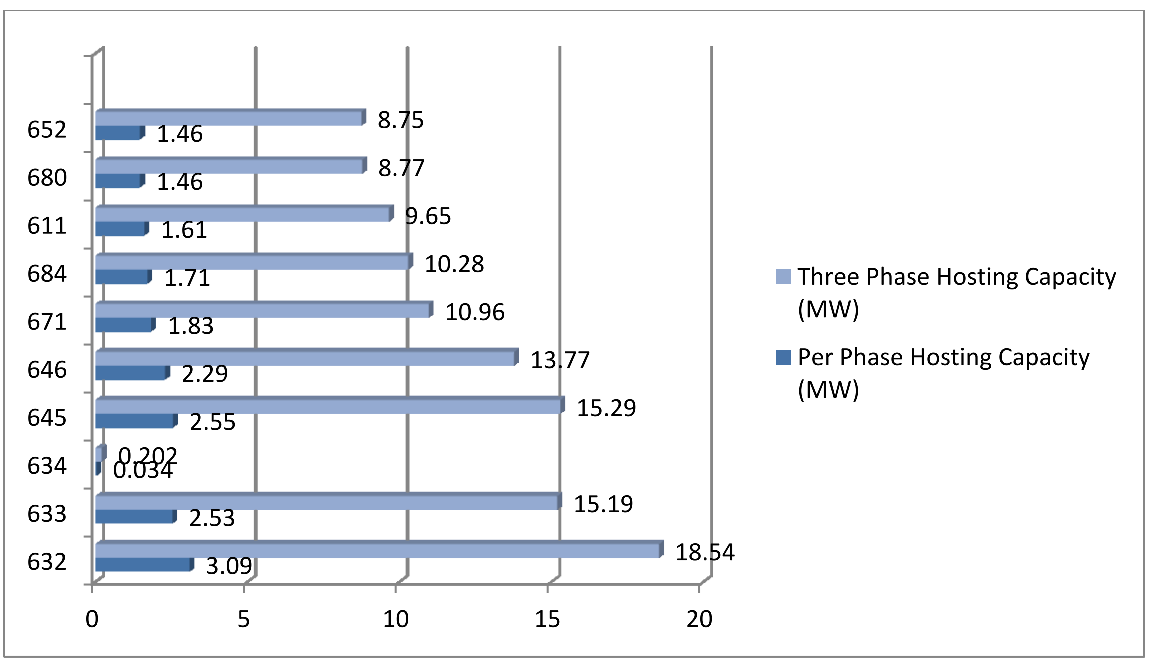

Figure 4.67 Hosting Capacity of Ideal IEEE 13 Node Test Distribution Feeder

Similar to that of section 4.2-2 the hosting capacity of the nodes has been determined for the ideal IEEE 13 node test distribution feeder and shown in fig 4.67. From the fig 4.67 it is visible that hosting capacity of the three phase network is approximately six times higher than that of per phase network. For an example, the hosting capacity of the node 632 is about 18.54 MW whereas for one phase network hosting capacity is about 3.09 MW.

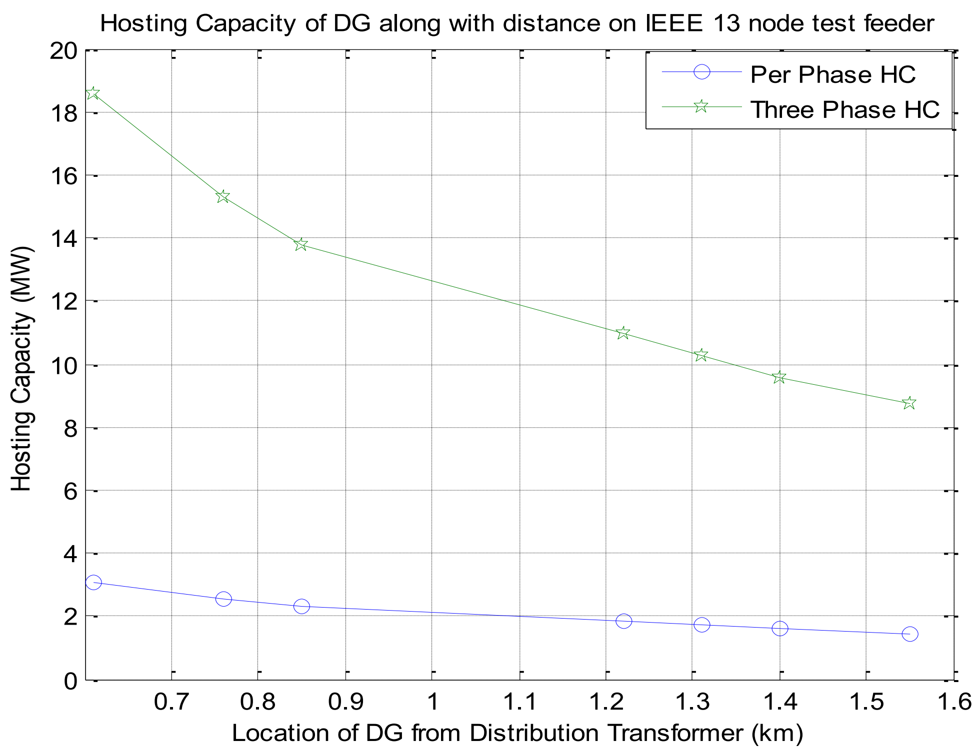

Figure 4.68 Hosting Capacity vs. Distance

While determining the hosting capacity of the nodes nominal voltage of the network is chosen 4.16 kV for three phases and 2.403 kV for per phase approximately. In above fig 4.68 again shows that the hosting capacity for both one and three phase of the network, which decreases with the increase of the distance. Or, in other words hosting capacity is the highest for the bus or substation nearer to the distribution transformer and decreases with the increase of the distance.

If the nominal voltage of the distribution feeder is decreases the hosting capacity also decreases. For an example the three phase hosting capacity at node 634 is about 0.202 MW in which the nominal voltage of that node is 0.48 kV.

4.4-3 Real and Reactive Power Loss of 10 kV Distribution Test Feeder:

The real and reactive power losses of the above cases are shown in table 4.6 and figure 4.69. From the following table it can be said that the case 2 has the highest both real and reactive power loss whereas case 4 has the lowest real and reactive power losses. In case 2 the switch between node 671 and 692 turned on which makes the feeder overloaded whereas in case 4 distributed generation of 1 MW is added at node 684 to feed the loads connected to the network.

Table 4.6 Real and Reactive Power Loss Case 1-4

	MW Loss	Mvar Loss
Case 1	0.08	0.27
Case 2	0.18	0.54
Case 3	0.07	0.22
Case 4	0.06	0.18

The following fig 4.69 also shows the same interpretation of the above table from which it can be said that case 4 is the best case whereas case 2 is the worst case in terms of both total real and reactive power losses in the test distribution network. Although by observing the total real and reactive power losses for the above cases, it is not possible to determine the best possible case which can be chosen in order to integrate DGs in distribution network.

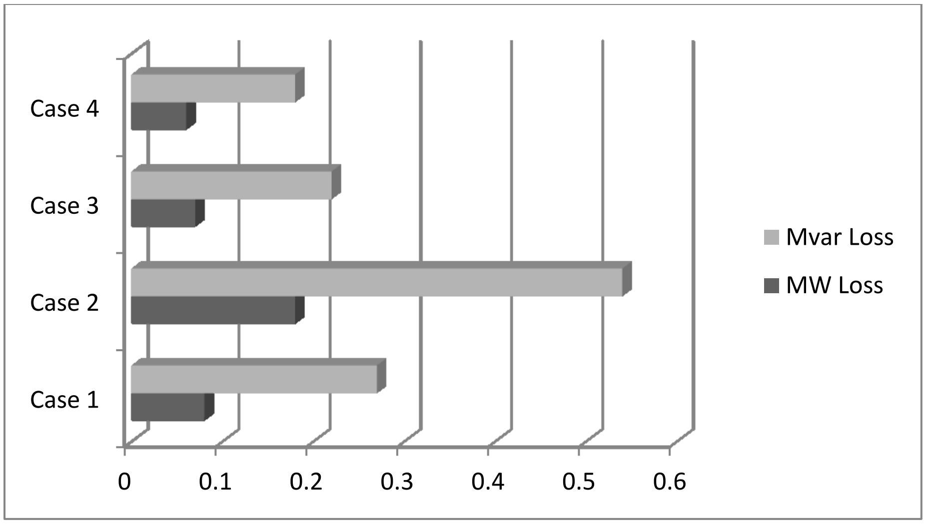

Figure 4.69 Real and Reactive Power Loss Cases 1-4

4.4-4 Power Line Loss Coefficient Determination of IEEE 13 Node Distribution Test Feeders:

Let us now consider the IEEE 13 node distribution test feeder. Similar to that of section 4.2-4 the power line loss is proportional to the square of the power flow through the lines. To evaluate the value of power line loss coefficients for all the case studies performed above, following equations have been determined. In order to obtain the approximate value of the power line loss coefficients a_{mk} , the value of the line loss $P_{L_{mk}}$ has been obtained from the branch state outputs of the performed simulations and the value of power demand P_D is given for each of the simulation.

$$\text{The power line } (650-632) \text{ loss}, P_{L_{650-632}} = a_{650-632}\,(P_{632_{in}}{}^2)$$

$$\text{The power line}(650-632) \text{ loss coefficient } \; a_{650-632} = \frac{P_{L_{650-632}}}{(P_{632_{in}}{}^2)} \qquad 4.6$$

$$\text{where } P_{632_{in}} = P_{D_{632}} + P_{L_{632-671}} + P_{L_{632-633}} + P_{L_{633-634}} + P_{D_{634}} + P_{L_{632-645}} + P_{D_{645}} + P_{L_{645-646}} + P_{D_{646}} + P_{L_{632-671}} + P_{D_{671}} + P_{L_{671-692}} + P_{D_{692}} + P_{L_{692-675}} + P_{D_{675}} + P_{L_{671-680}} + P_{L_{671-684}} + P_{L_{684-652}} + P_{D_{652}} + P_{L_{684-611}} + P_{D_{611}}$$

In which $a_{650-632}$ is the power line loss coefficients between nodes 650 and 632. $P_{632_{in}}$ is the injected power to the node 632. To obtain the value of $P_{632_{in}}$ the power demand of node 632, 634, 645, 646, 671, 692, 675, 652, and 611 are given in fig 4.37 for case 1. The power line loss value between nodes of case 1 can be obtained from fig 4.42. Similarly the line loss coefficients values for every case can be obtained using branch state and load data value obtained in above simulation.

$$\text{The power line } (632-633)\text{loss}, P_{L_{632-633}} = a_{632-633}\,({P_{633_{in}}}^2)$$

$$\text{The power line}(632-633)\text{loss coefficient}, a_{632-633} = \frac{P_{L_{632-633}}}{({P_{633_{in}}}^2)} \qquad 4.7$$

$$\text{where } P_{633_{in}} = P_{L_{633-634}} + P_{D_{634}}$$

$$\text{The power line loss}(633-634)\text{loss}, P_{L_{633-634}} = a_{633-634}\,({P_{634_{in}}}^2)$$

$$\text{The power line}(633-634)\text{loss coefficient}, a_{633-634} = \frac{P_{L_{633-634}}}{({P_{634_{in}}}^2)} \qquad 4.8$$

$$\text{where } P_{634_{in}} = P_{D_{634}}$$

$$\text{The power line}(632-645)\text{loss}, P_{L_{632-645}} = a_{632-645}\,({P_{645_{in}}}^2)$$

$$\text{The power line}(632-645)\text{ loss coefficient}, a_{632-645} = \frac{P_{L_{632-645}}}{({P_{645_{in}}}^2)} \qquad 4.9$$

$$\text{where } P_{645_{in}} = P_{D_{645}} + P_{L_{645-646}} + P_{D_{646}}$$

$$\text{The power line } (645-646)\text{loss}, P_{L_{645-646}} = a_{645-646}\,(P_{646_{in}}{}^2)$$

$$\text{The power line}(645-646)\text{loss coefficient}, a_{645-646} = \frac{P_{L_{645-646}}}{(P_{646_{in}}{}^2)} \qquad 4.10$$

$$\text{where } P_{646_{in}} = P_{D_{646}}$$

$$\text{The power line } (632-671)\text{loss}, P_{L_{632-671}} = a_{632-671}\,(P_{671_{in}}{}^2)$$

$$\text{The power line } (632-671)\text{loss coefficient}, a_{632-671} = \frac{P_{L_{632-671}}}{(P_{671_{in}}{}^2)} \qquad 4.11$$

$$\text{where } P_{671_{in}} = P_{L_{671-692}} + P_{D_{692}} + P_{L_{692-675}} + P_{D_{675}} + P_{D_{671}} + P_{L_{671-684}} + P_{L_{684-652}} + P_{D_{652}} + P_{L_{684-611}} + P_{D_{611}} + P_{L_{671-680}}$$

$$\text{The power line } (671-692)\text{loss}, P_{L_{671-692}} = a_{671-692}\,(P_{692_{in}}{}^2)$$

$$\text{The power line}(671-692) \text{ loss coefficient}, a_{671-692} = \frac{P_{L_{671-692}}}{(P_{692_{in}}{}^2)} \qquad 4.12$$

$$\text{where } P_{692_{in}} = P_{D_{692}} + P_{L_{692-675}} + P_{D_{675}}$$

$$\text{The power line}(692-675)\text{loss}, P_{L_{692-675}} = a_{692-675}\,(P_{675_{in}}{}^2)$$

$$\text{The power line } (692-675)\text{loss coefficient}, a_{692-675} = \frac{P_{L_{692-675}}}{(P_{675_{in}}{}^2)} \qquad 4.13$$

$$\text{where } P_{675_{in}} = P_{D_{675}}$$

$$\text{The power line } (671-684)\text{loss}, P_{L_{671-684}} = a_{671-684}\left(P_{684_{in}}{}^2\right)$$

$$\text{The power line } (671-684)\text{loss coefficient}, a_{671-684} = \frac{P_{L_{671-684}}}{(P_{684_{in}}{}^2)} \qquad 4.14$$

$$\text{where} \quad P_{684_{in}} = P_{L_{684-652}} + P_{D_{652}} + P_{L_{684-611}} + P_{D_{611}}$$

$$\text{The power line } (684 - 652) \text{ loss, } P_{L_{684-652}} = a_{684-652\,(P_{652_{in}}{}^{2})}$$

$$\text{The power line (684-652) loss coefficient, } a_{684-652} = \frac{P_{L_{684-652}}}{(P_{652_{in}}{}^{2})} \qquad 4.15$$

$$\text{where} \quad P_{652_{in}} = P_{D_{652}}$$

$$\text{The power line } (684 - 611)\text{loss, } P_{L_{684-611}} = a_{684-611\,(P_{611_{in}}{}^{2})}$$

$$\text{The power line}(684 - 611)\text{loss coefficient,}_{684-611} = \frac{P_{L_{684-611}}}{(P_{611_{in}}{}^{2})} \qquad 4.16$$

$$\text{where} \quad P_{611_{in}} = P_{D_{611}}$$

$$\text{The power line } (671 - 680) \text{ loss, } P_{L_{671-680}} = a_{671-680\,(P_{680_{in}}{}^{2})}$$

$$\text{The power line}(671 - 680) \text{ loss coeffient, } a_{671-680} = \frac{P_{L_{671-680}}}{(P_{680_{in}}{}^{2})} \qquad 4.17$$

$$\text{where} \quad P_{680_{in}} = P_{D_{680}}$$

Table 4.7 Power Line Loss Coefficients of Case (1-4)

Power Line Loss Coefficient a_{jk}	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Average of Line Loss Coefficients Case 1-4**
$a_{650-632}$	$9.835 * 10^{-9}$	$1.025 * 10^{-8}$	$4.249 * 10^{-9}$	$4.325 * 10^{-8}$	$1.689 * 10^{-8}$
$a_{632-633}$	0	0	0	0	0
$a_{633-634}$	0	0	0	0	0
$a_{632-645}$	0	0	0	0	0
$a_{645-646}$	0	0	0	0	0
$a_{632-671}$	$9.919 * 10^{-9}$	$1.050 * 10^{-8}$	$3.501 * 10^{-9}$	$75 * 10^{-8}$	$1.935 * 10^{-7}$
$a_{671-692}$	0	0	0	0	0
$a_{692-675}$	0	0	0	0	0
$a_{671-684}$	0	0	0	Undefined	Undefined
$a_{684-652}$	0	0	0	0	0
$a_{684-611}$	0	0	0	0	0
$a_{671-680}$	0	0	0	0	0

In table 4.7 the approximate values of power line loss coefficient for the cases (1-4) have been shown using equations 4.6 to 4.17. Above table shows that the case 3 has the lowest line loss coefficient among all the cases whereas case 4 has the highest line loss coefficient values. Line loss coefficient value of case 2 is much higher comparing to that of case 3 in which 1 MW DG is added to the network to feed loads locally. Hence it is proved from this value that line losses decrease while DGs are added in the medium voltage distribution network.

While performing more details it is observed that the line loss coefficient value increases eventually from case 1 to 2. In case 2 the line loss coefficient values increase compare to that of case 1 because the amount of loads increase in this case while turning on the switch between nodes 671 and 692. When the DG output of 1 MW is added to the network to feed the same amount of loads as of case 2 the line loss coefficient value notably decreases. Under loading the network in case 4 further increases the line loss coefficients and consequently the line loss coefficients reached to its peak in this case. It can be concluded by observing the line loss coefficient value that case 3 is one of the best cases and case 4 is one of the worst cases.

In above table 4.7 the average of the power line loss coefficients for all cases (1-4) has been determined. The average of power line loss coefficient is the lowest for the node between 650 and 632 and highest for the node between 632 and 671. The average of the power line loss coefficient is undefined for the node between 671 and 684.

Chapter 5 Integration of Fuzzy Logic Controller

It has been shown that the effects of adding distributed generation on the test feeder in terms of voltage profile, hosting capacity, real and reactive power loss and to determining the power line loss coefficients in chapter 4. Previously DGs were connected to the node randomly. Even the amount of DG output which supposed to be added in the network was chosen arbitrarily. Hence in this chapter it has been discussed the way of determining the amount of generation need to be added to the particular node according to the customer demand.

A fuzzy logic controller is proposed to determine the amount of generation need to be added in the network on the basis of power demand gap and the time of the day. Another fuzzy logic controller is proposed to select the bus where the generation will be installed. FL toolbox of Matlab is used for simulation. In fig 5.1 the inputs and output of the fuzzy controller 1 has been shown. A mamdani type fuzzy logic controller is chosen for this case. Two inputs are the time of the day and power demand gap of the network. The output is the amount of DG need to be connected in the distribution network.

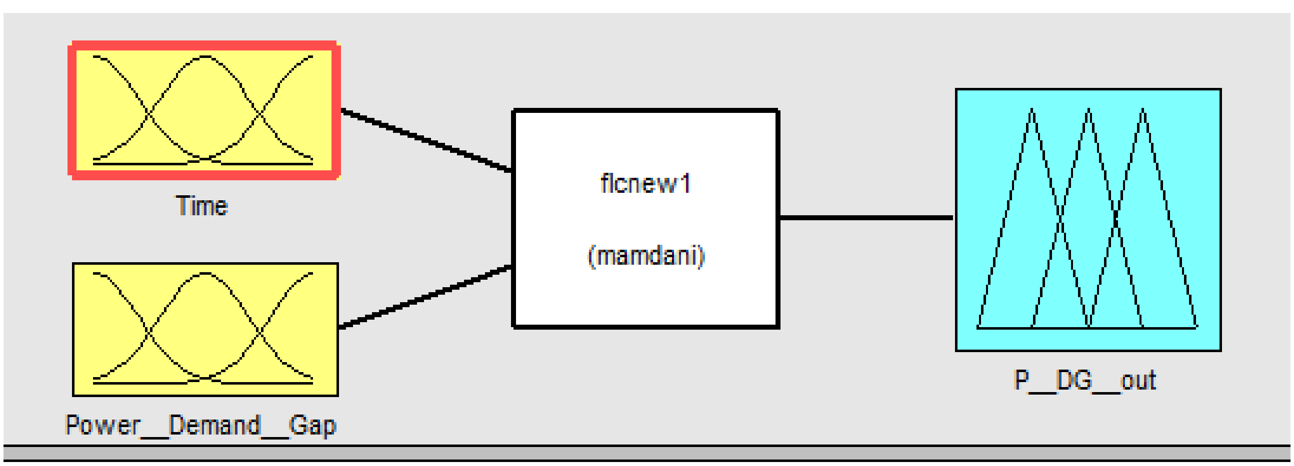

Figure 5.1 Fuzzy Logic Controller 1

Following fig 5.2 and 5.3 show the membership function of the fuzzy logic controller 1. The trapezoidal shape membership function of the fig 5.2 shows the time of the day. The trapezoidal curve is a function of vector x which depends on four scalar parameters a, b, c and d which is given below [24].

$$f(x; a, b, c, d) = \begin{cases} 0\,, & x \leq a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \frac{d-x}{d-c}, & c \leq x \leq d \\ 0, & d \leq x \end{cases} \qquad 5.1$$

Parameter a, d locate the feet and b, c locate the shoulder of the trapezoid [matlab help file trapmf]. There are five trapezoidal membership function curves intersecting each other in the input 1 in fig 5.2. For the off-peak (am) the membership function is assigned 1 between 0 and 5 hours in the day. For peak(am) hour 5.1 to 10, off-peak(am-pm) hour 10.1 to 17, peak (pm) hour 17.1 to 22, off-peak(pm) hour 22.1 to 24, the membership function is again assigned 1 for all the cases.

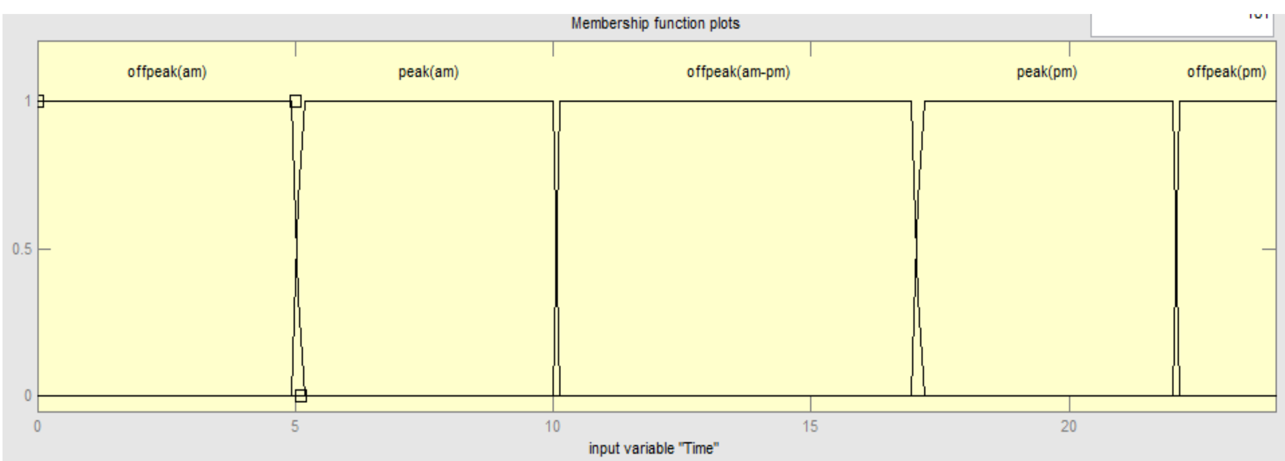

Figure 5.2 Membership Function of Time (Input 1 of FLC 1)

In fig 5.3 there are three different such as z, gauss and s shape membership curves which are intersecting each other. The z -shape membership function is the function of x which has two parameters a, b and located at the extreme of the sloped portion of the curve [25]. The function of z shape membership function is expressed as follows:

$$f(x; a, b) = \begin{cases} 1, & x \leq a \\ 1 - 2(\frac{x-a}{b-a})^2, & a \leq x \leq \frac{a+b}{2} \\ 2(\frac{x-b}{b-a})^2, & \frac{a+b}{2} \leq x \leq b \\ 0, & x \geq b \end{cases} \qquad 5.2$$

For the chosen z shape curve in fig 5.3 the parameters a and b are 0 and 0.5 respectively. The membership funtion is 1 when parameter a is zero and membership function is 0 when parameter b is 0.5 in the following figure.

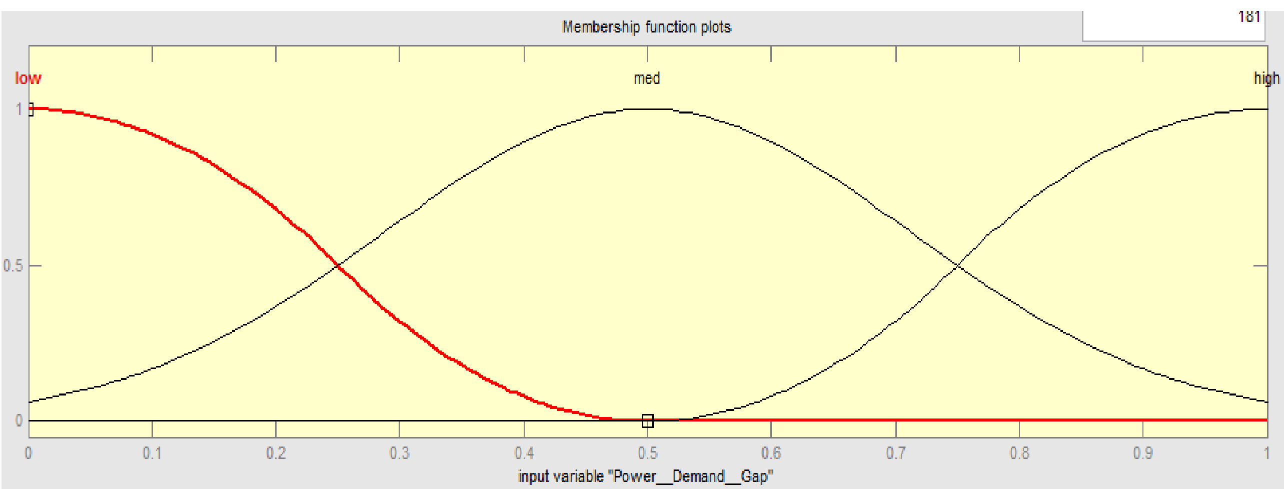

Figure 5.3 Membership Function of Power_Demand_Gap [Input 2 of FLC 1]

The symmetric Gaussian is a function of x which depends on the parameter σ, c and expressed as following [26]:

$$f(x; \sigma, c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \qquad 5.3$$

The parameter σ and c in the above fig are 0.2123 and 0.5 respectively in which the membership function is 1 at c. Similar to that of z shape curve, the s- shape curve also represents as of its name and the parameter a, b represent the extremes of the sloped portion of the curve [27]. The value of the parameter a and b are 0.5 and 1 respectively in which membership function is 1 at parameter b. The s- shape curve is function of x and expressed as follows:

$$f(x;a,b) = \begin{cases} 0, \; x \leq a \\ 2(\frac{x-a}{b-a})^2, \; a \leq x \leq \frac{a+b}{2} \\ 1-2(\frac{x-b}{b-a})^2, \; \frac{a+b}{2} \leq x \leq b \\ 1, \quad x \geq b \end{cases} \qquad 5.4$$

In fig 5.3 the power demand gap less than 0.5 MW is described by z-shape membership funtion or it can also be said as low power demand gap.The power demand gap about 0.5 MW is regarded as medium demand gap and represented by gauss membership function. The power demand gap greater than 0.5 MW is high and represented by s-shape membership curve.

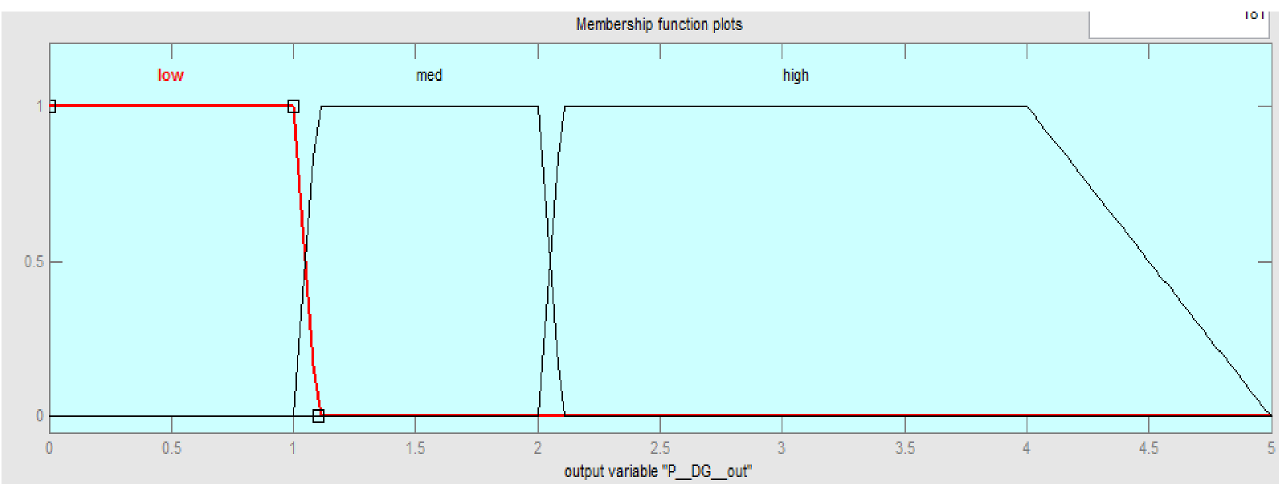

Figure 5.4 Membership Function of P_DG_out [Output 1 of FLC 1]

In above fig 5.4 the output of the fuzzy logic controller 1 is shown in which three trapezoidal membership functions represent the DG output of low, medium and high. The DG output is regarded as low for the output between 0 to 1 MW and membership function for that range is also 1. The DG output between 1.1 and 2 MW is considered as medium whereas the output between 2.1 and 4 is mentioned as high.

Table 5.1 Rules of FLC 1

P_DG_out

Power_Demand_Gap / Time	low	med	high
offpeak(am)	low	low	med
peak(am)	low	med	high
offpeak(am-pm)	low	low	med
peak(pm)	low	med	high
offpeak(pm)	low	low	med

Rules of fuzzy logic controller 1 are given in above table 5.1. In which two inputs power demand gap and time are given. For an example, if the power demand gap is medium and time is off-peak (am) then P_DG_out is low; if the power demand gap is medium and time is peak (am) then P_DG_out is medium; if the power demand gap is medium and time is off-peak (am-pm) then P_DG_out is low; if the power demand gap is medium and time is peak (pm) then P_DG_out is medium; if the power demand gap is medium and time is peak (pm) then P_DG_out is low.

Similarly the fig 5.5 shows the rules of FLC 1 in Matlab fuzzy logic toolbox interface. There are total fifteen rules in the following figure which in turns interpret the table 5.1.

1. If (Time is offpeak(am)) and (Power__Demand__Gap is low) then (P__DG__out is low) (1)
2. If (Time is offpeak(am)) and (Power__Demand__Gap is med) then (P__DG__out is low) (1)
3. If (Time is offpeak(am)) and (Power__Demand__Gap is high) then (P__DG__out is med) (1)
4. If (Time is peak(am)) and (Power__Demand__Gap is low) then (P__DG__out is low) (1)
5. If (Time is peak(am)) and (Power__Demand__Gap is med) then (P__DG__out is med) (1)
6. If (Time is peak(am)) and (Power__Demand__Gap is high) then (P__DG__out is high) (1)
7. If (Time is offpeak(am-pm)) and (Power__Demand__Gap is low) then (P__DG__out is low) (1)
8. If (Time is offpeak(am-pm)) and (Power__Demand__Gap is med) then (P__DG__out is low) (1)
9. If (Time is offpeak(am-pm)) and (Power__Demand__Gap is high) then (P__DG__out is med) (1)
10. If (Time is peak(pm)) and (Power__Demand__Gap is low) then (P__DG__out is low) (1)
11. If (Time is peak(pm)) and (Power__Demand__Gap is med) then (P__DG__out is med) (1)
12. If (Time is peak(pm)) and (Power__Demand__Gap is high) then (P__DG__out is high) (1)
13. If (Time is offpeak(pm)) and (Power__Demand__Gap is low) then (P__DG__out is low) (1)
14. If (Time is offpeak(pm)) and (Power__Demand__Gap is med) then (P__DG__out is low) (1)
15. If (Time is offpeak(pm)) and (Power__Demand__Gap is high) then (P__DG__out is med) (1)

Figure 5.5 Rules of FLC 1

In fig 5.6 shows the surface view of the FLC 1 in which x and y axis represents the time of the day and power demand gap respectively. On the other hand the z axis represents the output of distributed generation. Following the rules described in table 5.1 the output changes with the time of the day and power demand gap of customers. For an example during peak 0005 to 1000 hours of the day if the power demand gap is high such as greater than 0.5 MW then the DG output will be high such as between 2.1 and 4 MW. For the same time of the day if power demand gap is lower than 0.5 MW then the DG output will be between 0 and 1 MW; if power demand gap is medium or about 0.5 MW then the DG output will be between 1.1 and 2 MW.

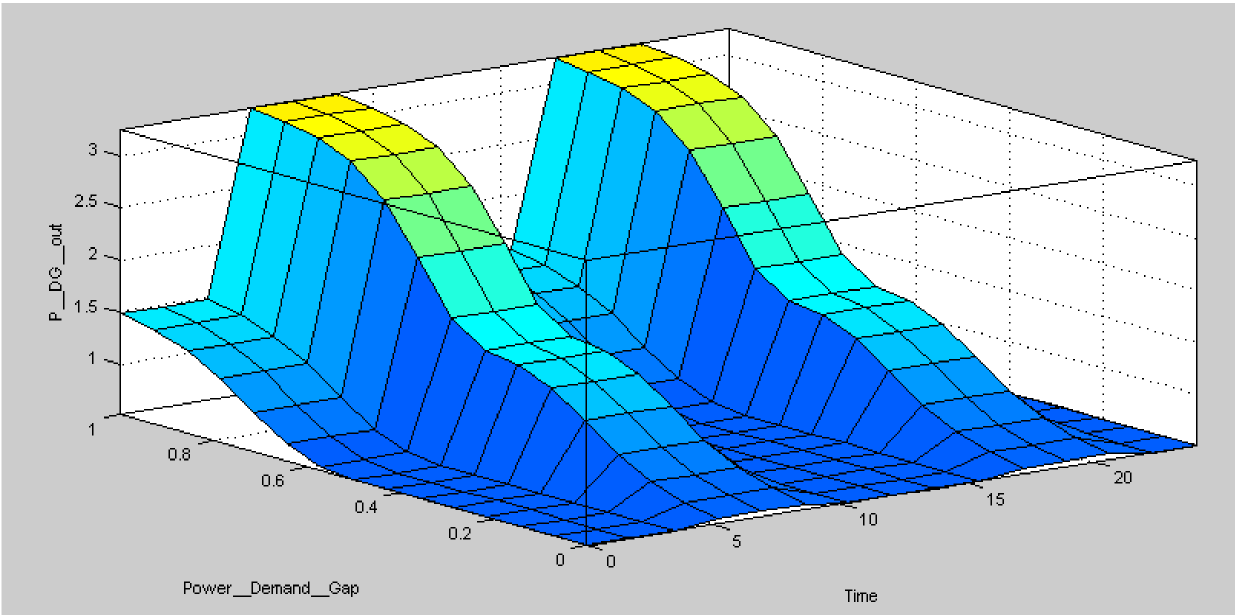

Figure 5.6 Surface View of Rule FLC 1

The fuzzy logic controller 2 has two inputs such as P_DG_out and distance of the DG from distribution transformer. Among which one of the inputs is the output of the FLC 1. The controller uses the sugeno fuzzy interference system. The output of the FLC 2 is DG_Node_Selection which determines the node in which the DG will be added to feed the loads locally specifically in peak hours of IEEE 13 node test distribution feeder.

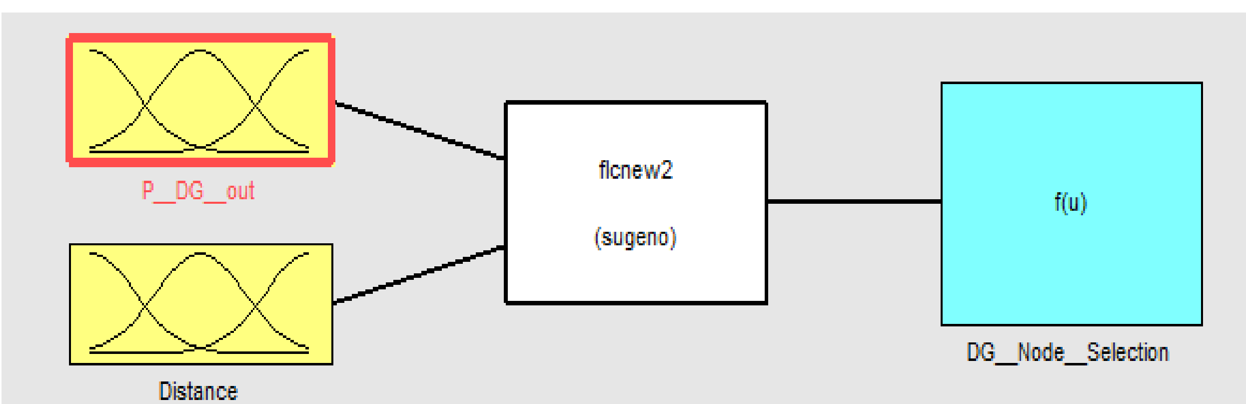

Figure 5.7 Fuzzy Logic Controller 2

The sugeno FIS is similar to that of mamdani FIS method especially in terms of fuzzifying the inputs, applying the fuzzy operators. The main difference between the mamdani and sugeno method is that sugeno output membership functions are either linear or constant. The following fig 5.8 similar to that of fig 5.4. The only difference is that the following figure represents one of the inputs of FLC 2.

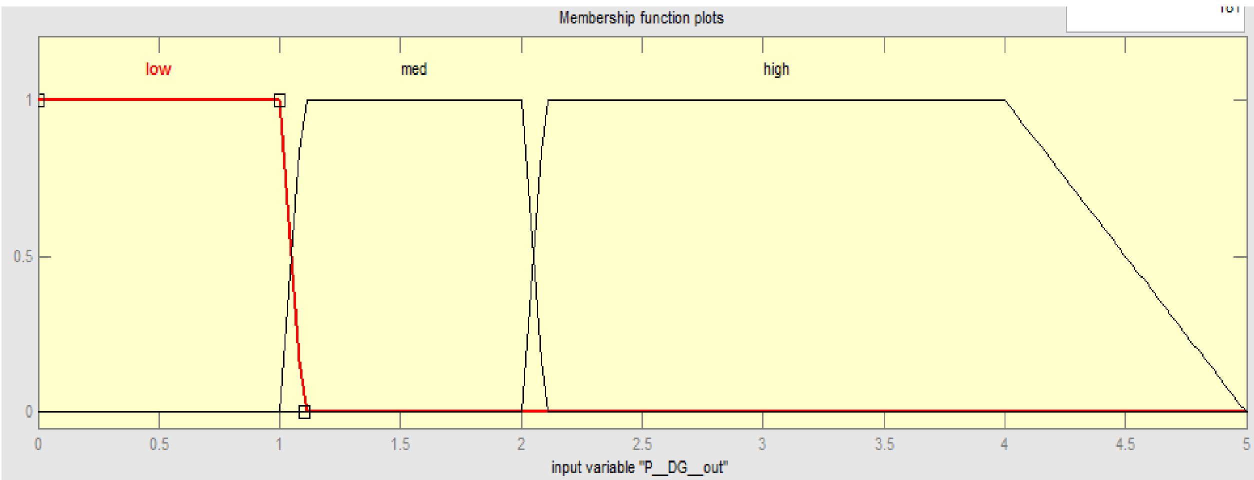

Figure 5.8 Membership Function of P_DG_out [Input 1 of FLC 2]

In the following fig 5.9 represents distance from distribution transformer where the distributed generation can be added according to the demand from the customer premises. There are three intersecting trapezoidal curve which represents the distance of low, medium and high.

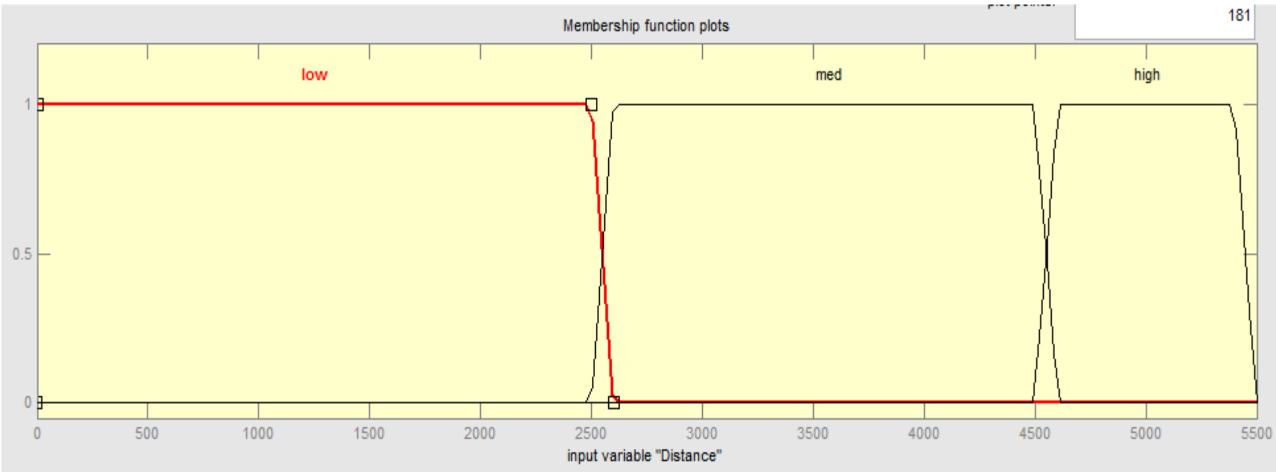

Figure 5.9 Membership Function of Distance [Input 2 of FLC 2]

The low distance corresponds to the distance between 0 to 2500 feet or about 0.76 km from the distribution transformer. Whereas the medium distance are between 2600 to 4500 feet; high distance between 4600 and 5400 feet. In fig 5.10 the membership function of FLC 2 output has been shown. In this case the membership functions are constant output which actually denotes the node number to be selected to add distributed generation.

Figure 5.10 Membership Function of DG_Node_Selection [Output of FLC 2]

Table 5.2 Rules of FLC 2

DG_Node_Selection

Distance / P_DG_out	**low**	**med**	**high**
low	634	675	652
med	633	684	680
high	632	646	611

The above table 5.2 shows the fuzzy rules for fuzzy logic controller 2. The table shows the determination of node selection on the basis of both inputs distance and P_DG_ out. For an example if the distance is low and P_DG_out is medium then the node 633 will be selected to add the distributed generation in that node; if the distance is high and P_DG_out is also high then node 611 will be selected and so on. For the same distance from the distribution transformer the bus which has higher hosting capacity is assigned for maximum DG. On the other hand, it means if two nodes are located in the same distance away from the distribution transformer then the node which has higher hosting capacity will be assigned for only higher amount DG requirement for the customers. The following fig 5.11 also represents the rules in fuzzy interference system. There are total nine rules in the following figure.

1. If (P__DG__out is low) and (Distance is low) then (DG__Node__Selection is 634) (1)
2. If (P__DG__out is low) and (Distance is med) then (DG__Node__Selection is 675) (1)
3. If (P__DG__out is low) and (Distance is high) then (DG__Node__Selection is 652) (1)
4. If (P__DG__out is med) and (Distance is low) then (DG__Node__Selection is 633) (1)
5. If (P__DG__out is med) and (Distance is med) then (DG__Node__Selection is 684) (1)
6. If (P__DG__out is med) and (Distance is high) then (DG__Node__Selection is 680) (1)
7. If (P__DG__out is high) and (Distance is low) then (DG__Node__Selection is 632) (1)
8. If (P__DG__out is high) and (Distance is med) then (DG__Node__Selection is 646) (1)
9. If (P__DG__out is high) and (Distance is high) then (DG__Node__Selection is 611) (1)

Figure 5.11 Rules of FLC 2

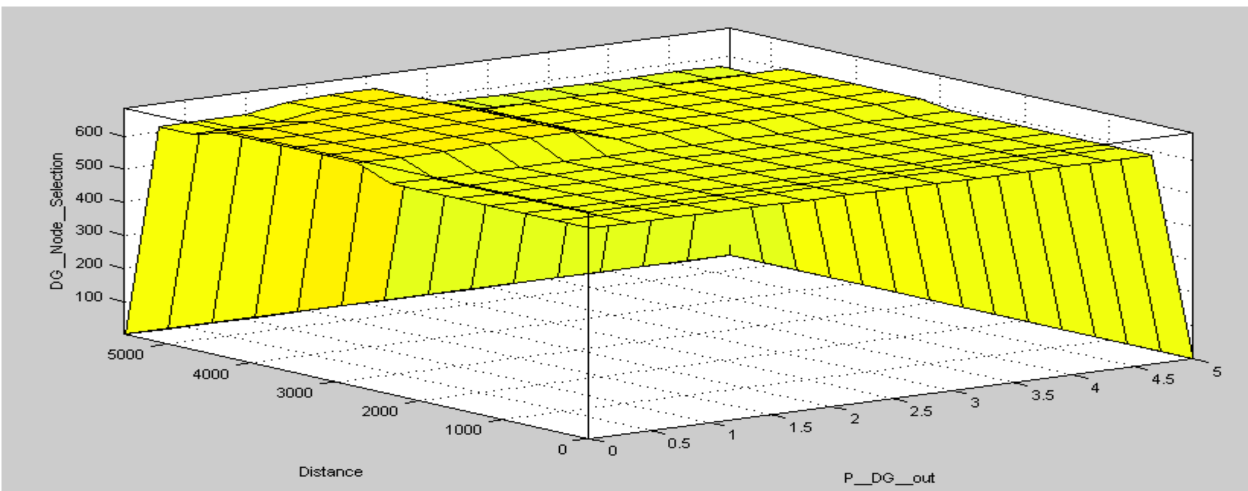

Figure 5.12 Surface view of Output FLC 2

Similar to that of fig 5.6, fig 5.12 also shows the surface view of the FLC 2 in which x and y axis represents P_DG_out and distance respectively. On the other hand the z axis represents the output of the node or bus selection. Following the rules described in table 5.2 the output changes with the change of any of the inputs.

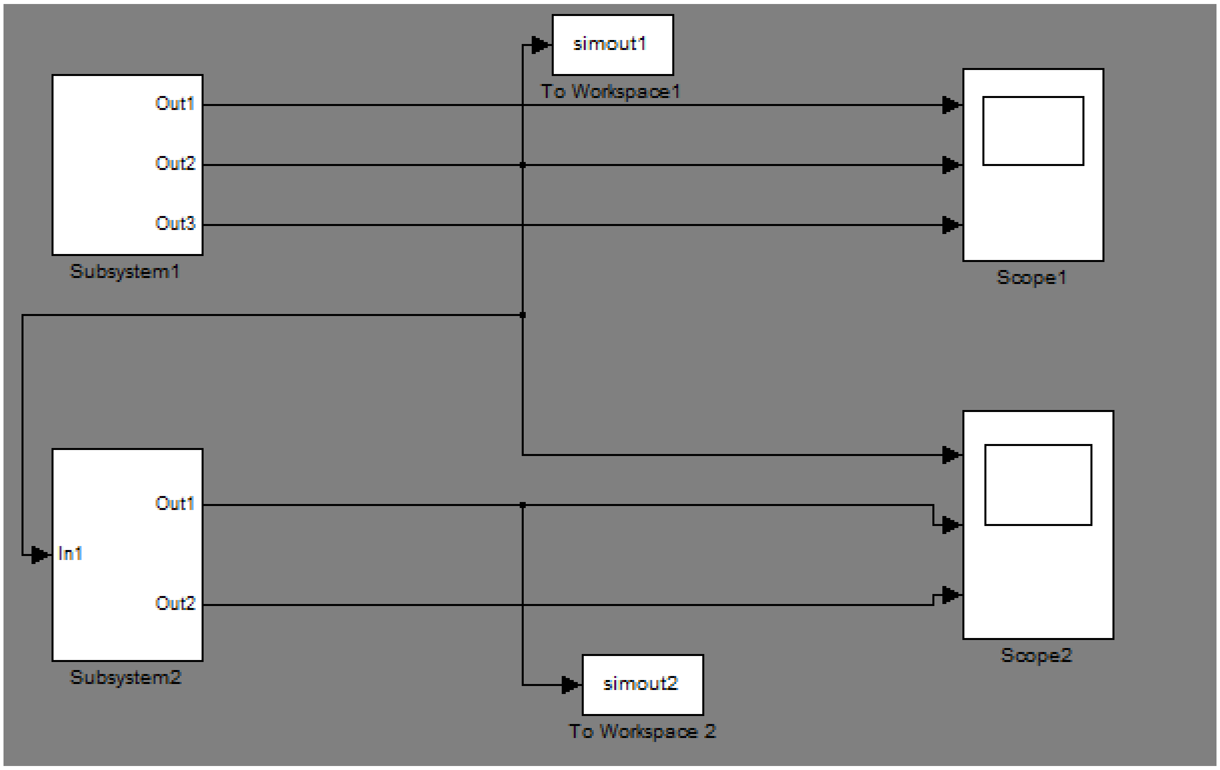

Figure 5.13 Simulation in Matlab Simulink

Using the matlab simulink the above simulation has been performed shown in fig 5.13. There are two subsytems used in the simulink model. The subsytem 1 and 2 are shown in the fig 5.14 and 5.15 respectively. The subsytem 1 includes the fuzzy logic controller 1 in which two inputs and one output are used to form the rules in order to control the different scenarios. Similarly in fig 5.15 the fuzzy logic controller 2 has been used to form the subsystem 2. More explanation of the controllers is described above for further understanding.

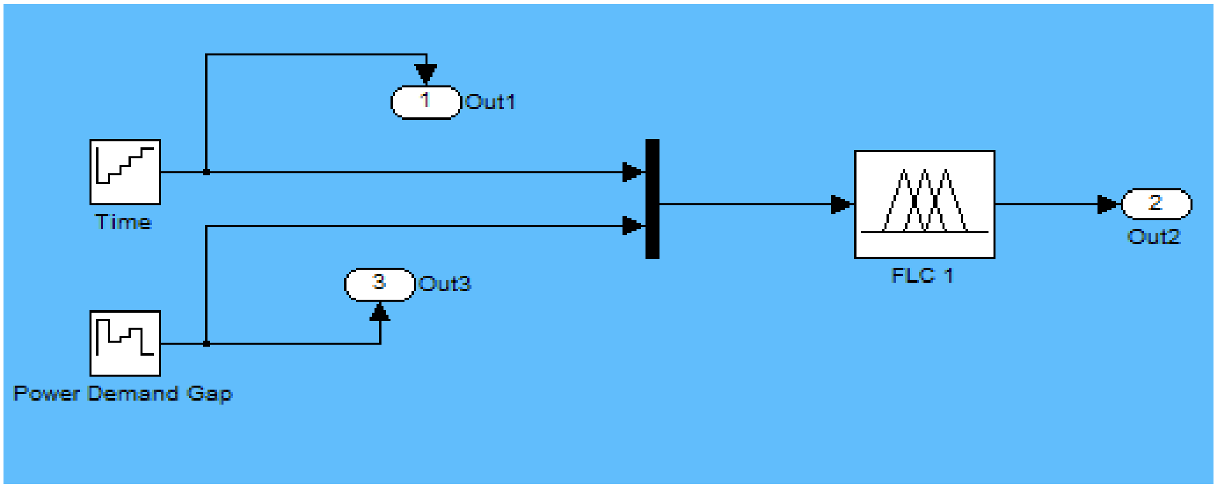

Figure 5.14 Subsystem1

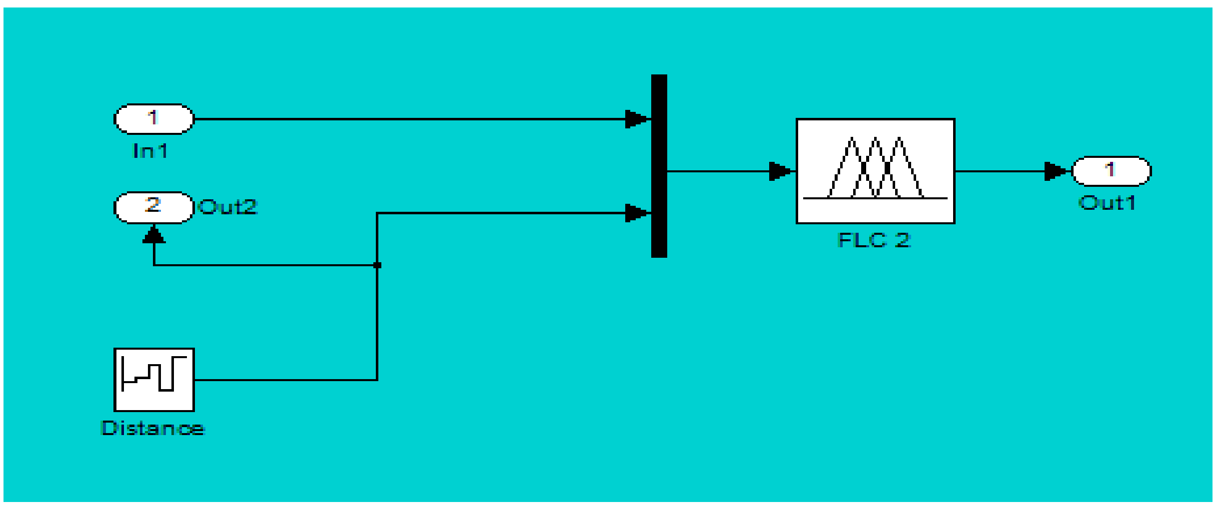

Figure 5.15 Subsystem 2

The first and third graphs in the following fig 5.16, 5.18 and 5.20 show the inputs of FLC 1 which are time of the day and power demand gap respectively. The second graph in the fig shows the DG output required on the basis of above mentioned two inputs. The output of the FLC 1 is one of the inputs of FLC 2. In fig 5.17, 5.19 and 5.21 the third graph shows the other input of the FLC 2, which represents the distance from the distribution transformer. The second graph of fig 5.16 (b) shows the output of the FLC 2 which indicates the node selection with respect to the change of both inputs of the FLC 2.

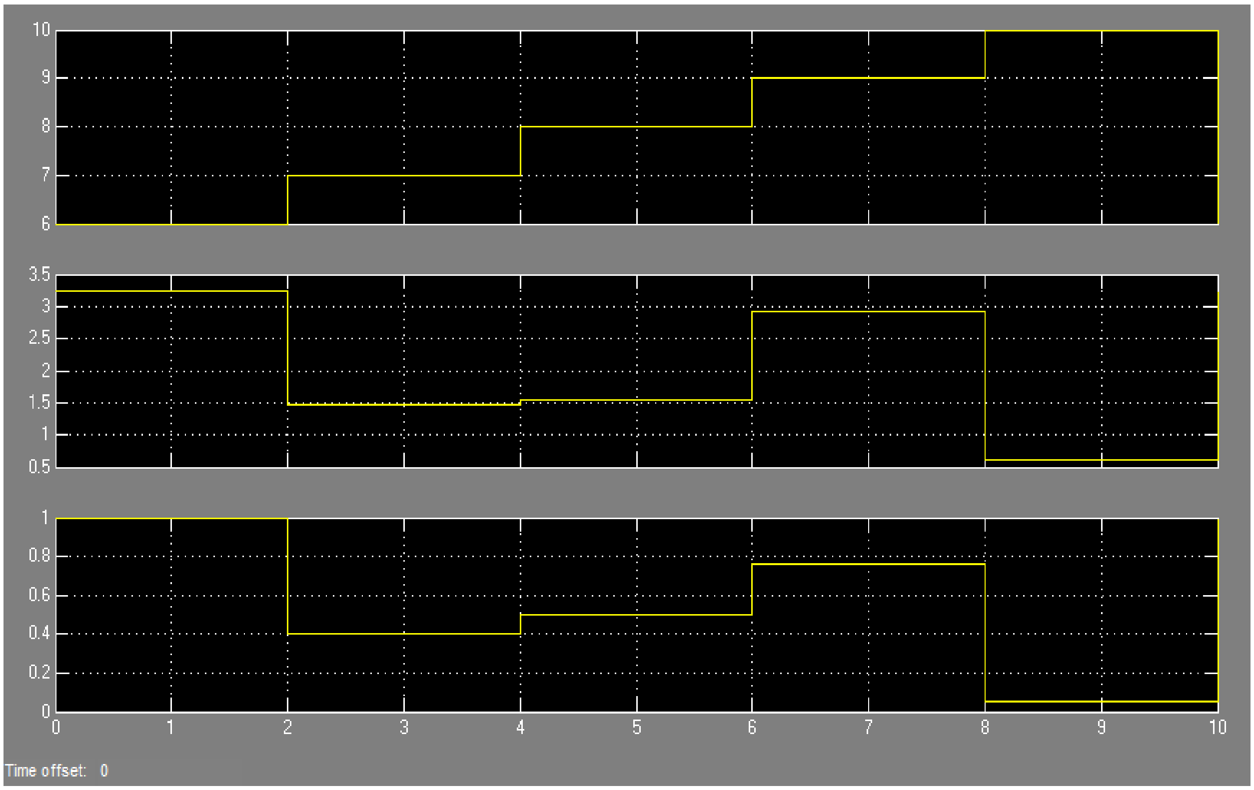

Figure 5.16 Simulink Output of FLC 1

The fig 5.16 shows two inputs of FLC 1 such as peak hour from 0600 to1000 and power demand gap of 1, 0.4, 0.5, 0.76, and 0.05 in MW which output the DG of 3.25, 1.46, 1.55, 2.93, and 0.61in MW respectively. This output is one of the inputs of FLC 2 in the following fig 5.17 and other input is distance of 2000, 2500, 4000, 1500 and 1000 in feet, which finally outputs the DG node selection of 632, 633, 684, 632, and 634 respectively.

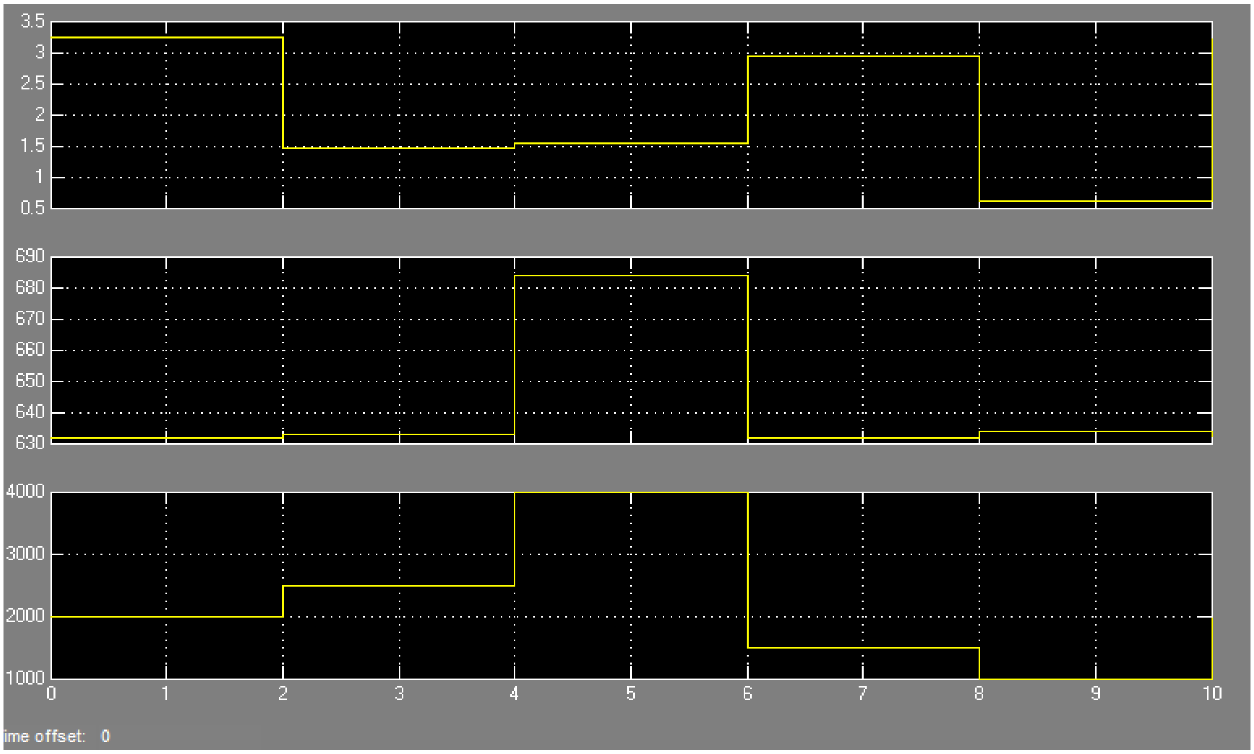

Figure 5.17 Simulink Output of FLC 2

The following fig 5.18 shows the two inputs of FLC 1 such as peak hour from 1800 to 2200 and power demand gap of 1, 0.4, 0.5, 0.76, and 0.05 in MW which output the DG of 3.25, 1.46, 1.55, 2.93, and 0.61 in MW respectively. This output is one of the inputs of FLC 2 in fig 5.19 and other input is distance of 5000, 4000, 3000, 2000 and 1000 in feet, which outputs the DG node selection of 611, 684, 684, 632, and 634 respectively. It is notable that both power demand gap for fig 5.16 and 5.18 are same but the distance of DG from the distribution transformer is different which results the different set of bus selection.

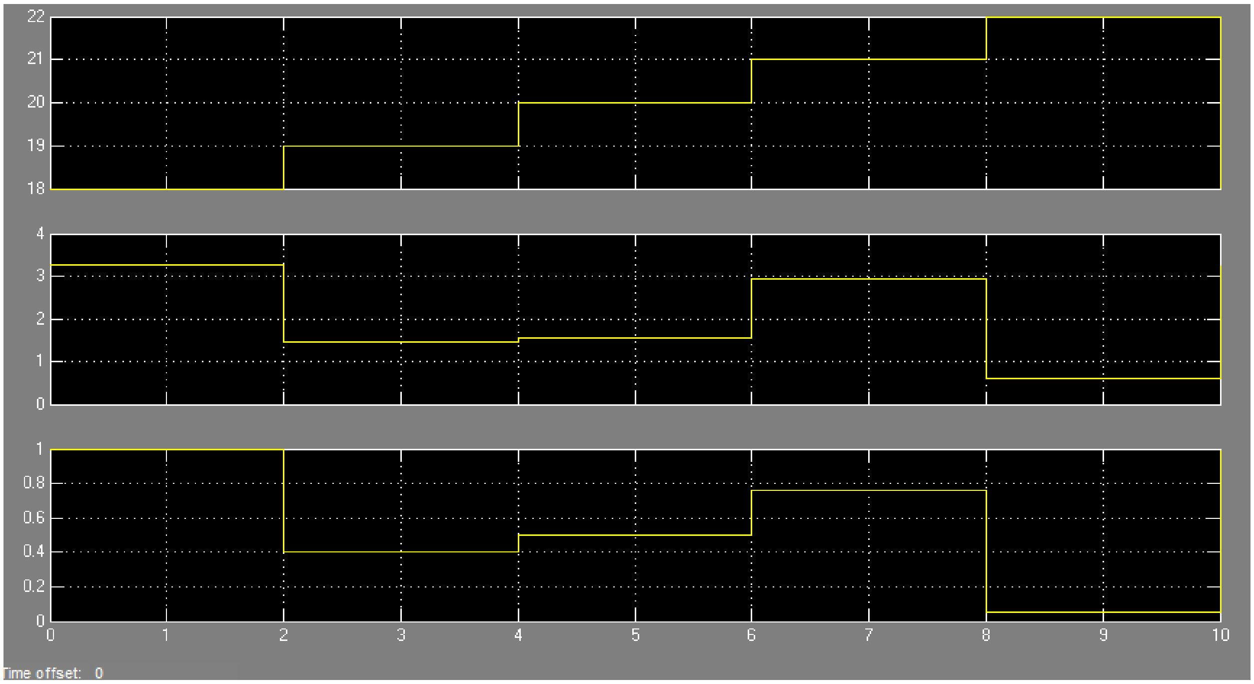

Figure 5.18 Simulink Output of FLC 1

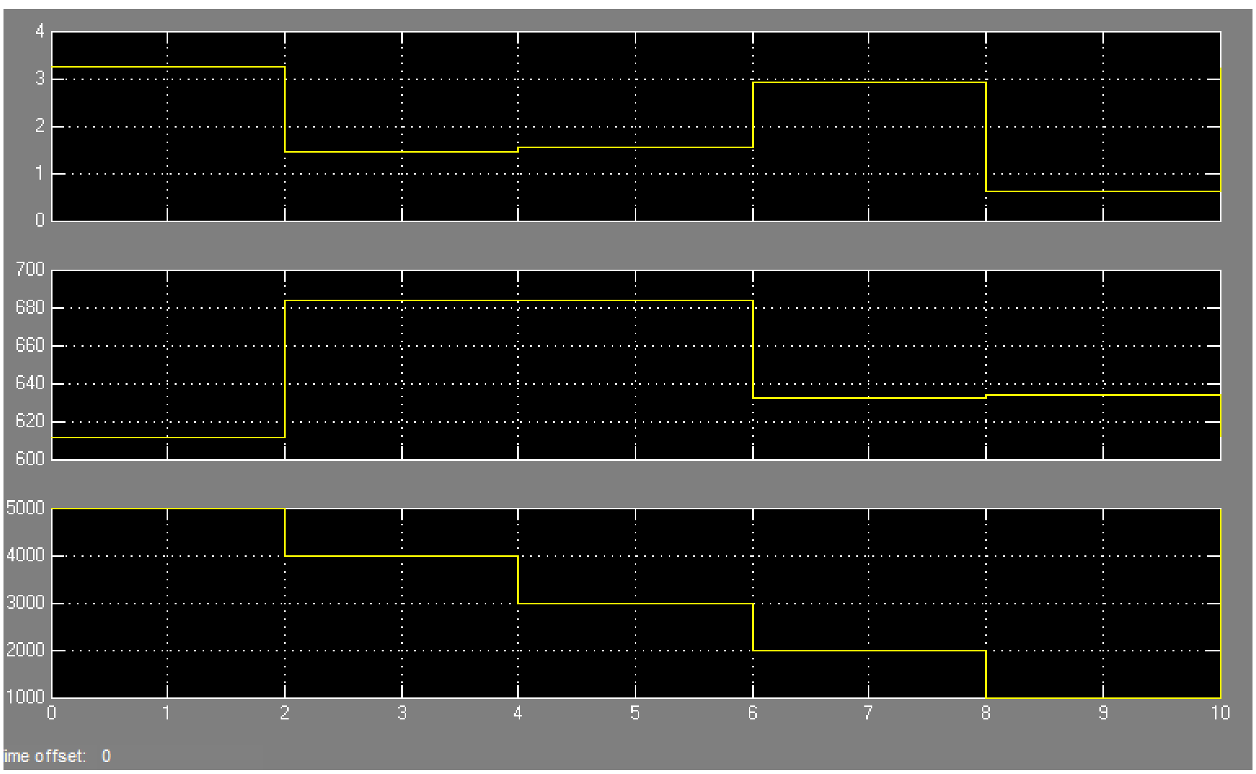

Figure 5.19 Simulink Output of FLC 2

Similar to previous examples the following fig 5.20 shows the two inputs of FLC 1 such as off-peak hour from 1100 to 1500 and power demand gap of 0.67, 0.23, 0.10, 0.34,and 0.18 in MW which output the DG of 0.76, 0.52,0.51,0.52, and 0.52 of in MW respectively. This output is one of the inputs of FLC 2 in fig. 5.21 and other input is distance of 5000, 4000, 3000, 2000 and 1000 in feet same as previous example, which outputs the DG node selection of 652, 675, 675, 634, and 634 respectively.

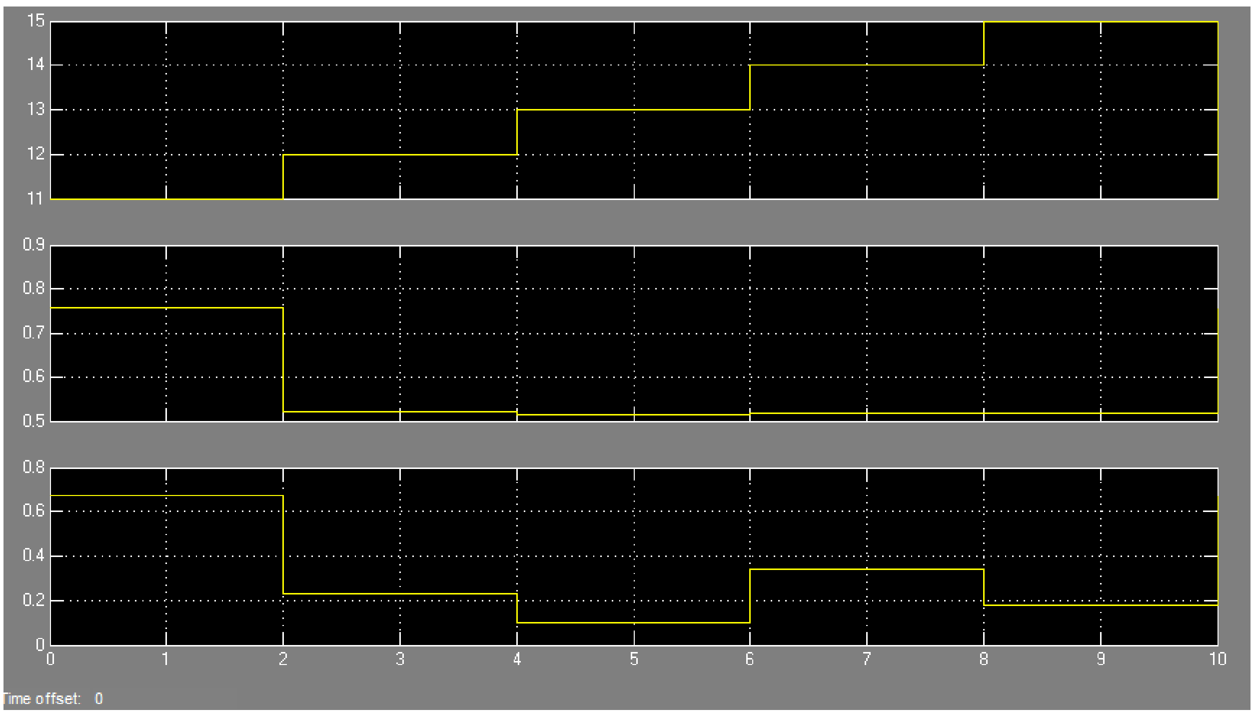

Figure 5.20 Simulink Output of FLC 1

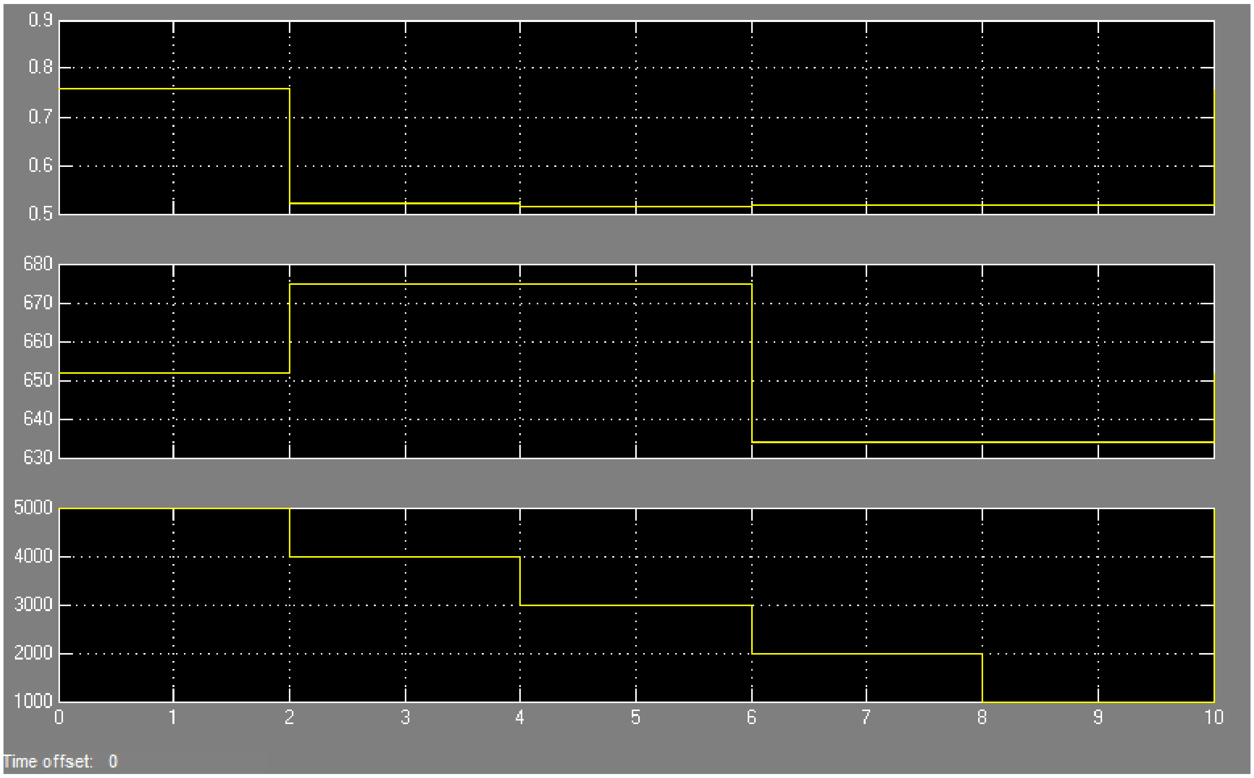

Figure 5.21 Simulink Output of FLC 2

Chapter 6 Conclusion

The motivation of the research work was to find out the technical difficulties analysis while adding distribution generations in the medium voltage distribution network. Most importantly in this research it has been shown that the voltage level fluctuates with respect to the load demand as well as addition of distribution generation on both 10 kV and IEEE 13 node test distribution feeder.

In chapter 4 case studies have been performed on both 10 kV and IEEE 13 node test distribution feeder which shows the best possible case to be considered on the basis of hosting capacity, power loss and real power loss coefficient for both distribution test feeders. Equations have been determined in order to find out the approximate values of real power line loss coefficients for both test feeders which is one of the major original contribution of this research work.

Chapter 5 shows the development of fuzzy logic controller by which it is possible to determine the amount of distributed generation needs to be connected to the distribution network to supply the power demand gap along with the time of the day. Another fuzzy logic controller determines the node in which distributed generation will be added in terms of required power demand and the distance of DG from the distribution transformer. The development of fuzzy logic controllers to integrate DGs in the medium voltage distribution network is another original contribution of this thesis work.

In chapter 4 DGs were added in the distribution network randomly, but in chapter 5 describes the way of choosing nodes in IEEE 13 node distribution test feeder in order to compensate the power supply demand gap mostly in the peak hour. In summary, this thesis develops an idea of adding distributed generation in medium voltage distribution network in order to compensate the demand side power management program which encourages the valued customers to change their energy consumption practice in order to avoid the power outage in peak hour. As we know nowadays renewable energy is used as alternate power sources at the client premises typically in low voltage distribution level. Instead of adding DGs in rooftop of the each buildings of any small neighborhood, if we add one large or few DGs in medium voltage distribution network which will be able to feed more loads efficiently. Since every customers who have rooftop DGs do not use the same amount of energy at the same time. Hence the idea of adding distributed generation in the medium voltage distribution network with fuzzy logic controller can benefit the total potential of using the energy competently.

Further research can be done to develop new fuzzy rules for the both controllers in order to find out more sophisticated and simple results. Moreover, in this research only fuzzy logic controlling technique has been used, hence other controlling technique such as neural network, genetic algorithm, PID controlling technique can also be performed to compare the results and to reduce the obstacles.

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Appendix A: IEEE 13 Node Distribution Test Feeder Data

Line Segment Data:

Node A	Node B	Length(ft.)	Config.	Node A	Node B	Length(ft.)	Config.
632	645	500	603	632	671	2000	601
632	633	500	602	671	684	300	604
633	634	0	XMF-1	671	680	1000	601
645	646	300	603	671	692	0	Switch
650	632	2000	601	684	611	300	605
684	652	800	607	692	675	505	606

Transformer Data:

	kVA	kV-high	kV-low	R - %	X - %
Substation:	5,000	115 - D	4.16 Gr. Y	1	8
XFM -1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

Capacitor Data:

Node	Ph-A	Ph-B	Ph-C
	kVAr	kVAr	kVAr
675	200	200	200
611			100
Total	200	200	300

Spot Load Data:

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
	Model	kW	kVAr	kW	kVAr	kW	kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

Distributed Load Data:

Node A	Node B	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
		Model	kW	kVAr	kW	kVAr	kW	kVAr
632	671	Y-PQ	17	10	66	38	117	68

Impedances Data:

Configuration 601:

Z (R +jX) in ohms per mile

0.3465 1.0179	0.1560 0.5017	0.1580 0.4236
	0.3375 1.0478	0.1535 0.3849
		0.3414 1.0348

B in micro Siemens per mile

6.2998	-1.9958	-1.2595
	5.9597	-0.7417
		5.6386

Configuration 602:

Z (R +jX) in ohms per mile

0.7526	1.1814	0.1580	0.4236	0.1560	0.5017
		0.7475	1.1983	0.1535	0.3849
				0.7436	1.2112

B in micro Siemens per mile

5.6990	-1.0817	-1.6905
	5.1795	-0.6588
		5.4246

Configuration 603:

Z (R +jX) in ohms per mile

0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1.3294	1.3471	0.2066	0.4591
				1.3238	1.3569

B in micro Siemens per mile

0.0000	0.0000	0.0000
	4.7097	-0.8999
		4.6658

Configuration 604:

Z (R +jX) in ohms per mile

1.3238	1.3569	0.0000	0.0000	0.2066	0.4591
		0.0000	0.0000	0.0000	0.0000
				1.3294	1.3471

B in micro Siemens per mile

4.6658	0.0000	-0.8999
	0.0000	0.0000
		4.7097

Configuration 605:

Z (R +jX) in ohms per mile

0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		0.0000	0.0000	0.0000	0.0000
				1.3292	1.3475

B in micro Siemens per mile

0.0000	0.0000	0.0000
	0.0000	0.0000
		4.5193

Configuration 606:

Z (R +jX) in ohms per mile

0.7982	0.4463	0.3192	0.0328	0.2849	-0.0143
		0.7891	0.4041	0.3192	0.0328
				0.7982	0.4463

B in micro Siemens per mile

96.8897	0.0000	0.0000
	96.8897	0.0000
		96.8897

Configuration 607:

Z (R +jX) in ohms per mile

1.3425	0.5124	0.0000	0.0000	0.0000	0.0000
		0.0000	0.0000	0.0000	0.0000
				0.0000	0.0000

B in micro Siemens per mile

88.9912	0.0000	0.0000
	0.0000	0.0000
		0.0000