PV INTEGRATION INTO DISTRIBUTION NETWORKS IN SAUDI ARABIA

Thesis submitted for the degree of

Doctor of Philosophy

At the University of Leicester

By

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February 2012

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Abstract

One of the most important operational requirements for any electrical power network for both distribution and transmission level is voltage control. Many studies have been carried out to improve or develop new voltage control techniques to facilitate safe connection of distributed generation. In Saudi Arabia, due to environmental, economic and development perspectives a wide integration of photovoltaic (PV) generation is expected in the near future. This development in the networks may cause voltage regulation problems due to the interface with the existing conventional control system. Therefore, this work determines the impact of linking PV directly with the grid to find the level of penetration that can be achieved without any technical changes in the distribution network. Then, the effect of Grid-Connected Photovoltaic (GCPV) systems on the voltage regulation in residential networks has been investigated. This thesis introduces a new voltage control scheme for residential area networks in Saudi Arabia based on Fuzzy Logic concept (FL). The structure of two implementations of FL control to regulate the voltage by setting the on-load tap changing transformer in the primary substation is proposed. Finally, another approach for solving the feeder voltage regulation problem at a local level is presented with the goal of fulfilling the plug-and-play feature desired by manufacturers and regulatory bodies. Also, this technique use the FL concept to set up the operating power factor for the inverter used to connect the PV generator. In order to confirm the validity of the proposed methods, simulations using PVSYST, ETAP and MATLAB/Simulink softwares have been carried out for a realistic distribution network with real data for load and solar radiation. Results showing the performance of each scheme are presented in detail, and demonstrate that each scheme is capable of keeping the voltage levels within statutory limits, both in steady-state and under dynamic condition.

Acknowledgements

I would like to express my sincere appreciation and thanks to my supervisor, Dr. Hans Bleijs, for his guidance and mentorship during my graduate studies. His impressive knowledge and creative thinking have been source of inspiration throughout this work.

My deepest gratitude goes to my parents, brothers and sister, to whom I am most indebted. I thank them for constant love, prayers, patience and support while I was studying abroad. I know I can never come close to returning their favour upon me.

A special thanks to my beloved wife Fareeda for her sacrifices, never-ending support and encouragement during my study. I would like to thank her for being a constant source of inspiration and motivation for me.

I will always be thankful to my friends and colleagues for their unlimited support. I extend my thanks to all the Saudi community that gave me a second family away from home.

Lastly but not the least, I would like to thank my mother and father in law for their prayers and support.

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List of abbreviation

AC	Alternative Current
AVC	Automatic Voltage Controller
AVR	Automatic Voltage Regulators
BIPV	Building Integrated Photovoltaic
CHP	Combined Heat And Power
CPV	Concentrated Photovoltaic
DC	Direct Current
DG	Distributed Generation
FL	Fuzzy Logic
FLC	Fuzzy Logic Controller
GCPV	Grid-Connected Photovoltaic
HV	High Votlage
KACST	King Abdulaziz City Of Science And Technology
LDC	Line Drop Compensator
LT	Load Tap Changing
LV	Low Voltage
MAS	Multi Agent System
MV	Medium Voltage
OLTC	On-Load Tap Changing
P	Active Power
PCC	Point Of Common Coupling
PF	Power Factor
PV	Photovoltaic
Q	Reactive Power
SEC	Saudi Electricity Company
SG	Synchronous Generator
TC	Tap Changer
VR	Voltage Regulation

Chapter 1

1 General Introduction

1.1 Introduction

Electrical energy is one of the most important daily human needs. Therefore life without this kind of energy cannot be imagined. Nowadays Saudi Arabia, like the rest of Arabian Gulf countries, depends on oil and gas for the production of electric power. Since both of these sources will deplete one day, it becomes necessary to look for alternative resources for electric energy such as wind and solar energy. One of the great blessings that the Kingdom of Saudi Arabia has is the tremendous amount of solar energy incident on its territory. Therefore, the importance of exploiting this energy and converting it to electrical energy through photovoltaic systems becomes obvious.

Photovoltaic systems have a wide range of application, from very small units for pocket calculators (low power) to large PV power plants in the MW range. Despite this wide range the most important application fields of PV systems have historically been for electricity generation onboard craft and for standalone systems in areas with poor or no electricity supply from the public grid. In the last few years a significant growth of grid-connected PV systems has been observed, especially in industrialized countries. Several reasons lie behind this fact apart from the traditional advantages of PV systems:

1. Utility grid –interactive PV systems are becoming more economically viable as the cost of PV components has been significantly decreasing in recent years, in

particular the average cost of PV modules and inverters. Also, this system usually does not need storage batteries when the peak load coincides with the maximum incident solar radiation. This will reduce the cost of the system compared with the stand-alone one [1].

2. Technical issues associated with inverters and interconnection of PV systems to the grid have been addressed by manufacturers and today's generation of inverters have enhanced reliability and reduced size[2].
3. There are utility benefits. The fact that solar electricity is produced in middle of the day can add value to the electricity. Usually in hot countries, the peak demand of electricity happens in mid day due to air conditioning loads. This power peak demand can be partially supplied by distributed grid-connected PV systems that are able to generate power at the same place where this power is used, reducing load supported by transmission systems and achieving benefits in distribution and line support[3].
4. International programmes are promoting the implementation of grid-connected PV systems. Most industrialized countries have started programmes offering different incentives to small-scale renewable energy producers. The World Bank has committed itself to increase its financial support for renewable energies and energy efficiency by at least 20 per cent every year[4].

Even with the abovementioned benefits and the significant cost reductions achieved, these systems still cannot compete with other energy resources on a pure financial analysis without reasonable funding and promotion from public bodies. The lack of standardization of integration requirements in different countries, for PV system components, especially inverters, is also an important barrier to the market growth of grid connected PV systems. Despite these obstacles, this market is becoming one of the most important PV applications. PV power generation systems are likely to become important sources of distributed generation interconnection with the grid.

In a grid-connected power system the grid acts like a battery with an unlimited storage capacity. Therefore the total efficiency of a grid-connected PV system will be better than the efficiency of a stand-alone system; as there is virtually no limit to the storage capacity, the generated electricity can always be used, whereas in stand-alone applications the batteries of the PV system will be sometimes fully charged, and therefore the potential generation needs to be "thrown away".

1.2 Thesis Objectives

The main objectives of this work are:

- To determine the ability of GCPV systems to reduce total and peak load demand in residential and industrial distribution networks in Saudi Arabia. Firstly, the impact of linking commercial PV panels directly with the grid has been assessed to find the level of penetration that can be achieved without any technical changes in the utility network.
- To investigate the effect of GCPV systems on the voltage regulation of a residential electricity network in Saudi Arabia using concentrated PV (CPV) cells.
- To develop a new voltage control scheme for GCPV systems in residential area networks in Saudi Arabia. The controller must be capable of managing the voltage level within the permissible limits in all possible load and solar radiation conditions. Also this controller has to facilitate a safe integration of PV generator units.

1.3 Thesis Outline

The thesis contains seven chapters. The first Chapter highlights the importance of PV technology in producing electrical energy as an alternative source in Saudi Arabia. It also presents the main objectives of the thesis. Chapter 2 starts with a brief history of distributed generation (DG) and a summary of different types of distributed generators. Then, the chapter states the problems associated with integrating distributed generation into the national grid. In chapter 3 the general information on Saudi Arabia include the weather and solar radiation data is presented. A brief description of the power system and the current applications of PV systems in Saudi Arabia is mentioned. Following that, the impact of grid-connected PV systems in a residential area in Saudi Arabia is studied using commercial PV panels. Chapter 4 shows the influence of using concentrated photovoltaic CPV on voltage regulation of residential area networks. In this chapter four different solutions to mitigate the voltage rise problem caused by implementing CPV in residential area networks are presented. Chapter 5 includes a literature survey proposed by other authors to solve the voltage rise problems related to DG integration into distribution networks. In this a novel technique is proposed to overcome the voltage rise problem associated with the high penetration level of PV power based on fuzzy logic control. The technique has been demonstrated to be effective in normal and fault conditions. The main advantage of proposed technique is that there is no need to sense the voltage level at each node in the system to regulate the supplied voltage. This will eliminate the need for a communication network between the nodes which has cost and reliability issues. Chapter 6 introduces another novel technique to regulate the voltage along the feeder based on local power factor control of each PV generator unit. Finally, Chapter 7 concludes and summarises the main contributions and achievements from this research with potential future developments.

Chapter 2

2 Literature review and Background of study

2.1 Electricity

Electrical energy is so fundamental to daily living in the world that it is impossible to imagine having a similar quality of life without it. Lighting that allows us to see through darkness, refrigeration that preserves the food we eat, heating and air-conditioning that increase our comfort level indoors; today these processes are made exceptionally convenient through the availability of electrical energy. Consider further the broad applications in digital media: televisions, computers, cellular phones, MP3 players, kitchen appliances, digital components in auto mobiles, and even the vehicles themselves. According to the Energy Information Administration, electrical energy is projected to remain the fastest-growing end-form of energy used worldwide through 2030 [5]. With society in the present and foreseeable future relying so heavily on electrical energy, the methods and resources chosen to generate it have vast consequences for environmental preservation.

The electrical nature of matter is well understood. This knowledge enables diverse applications of electrical energy. Integration of green electrical generation into the existing infrastructure is happening slowly, but governments must offer financial incentives to make renewable resources economically competitive with fossil fuels. New technologies for electrical generation aim to reduce greenhouse gas emissions and limit reliance on fossil fuels. Conserving electrical energy is a practical and simple method for consumers to contribute to these goals at home.

2.2 The Electric power grid

Today's power system is a complex interconnected network (Fig. 2.1) that can be subdivided into four major parts: generation, transmission, distribution, and loads. In the generation phase, electric power is currently generated at 11-30 kV via large central generators located in remote areas.

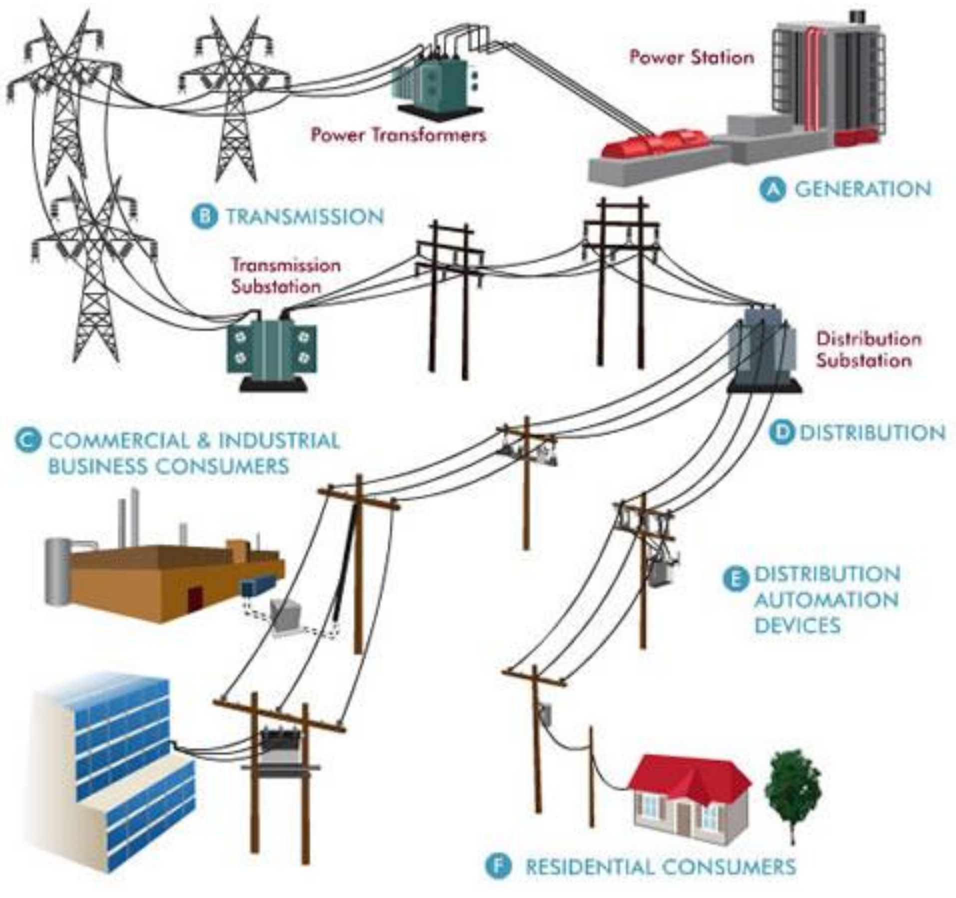


Figure 2.1 The Electric power grid [6]

The purpose of the overhead transmission network is to transfer electric energy from generating units at various locations to the distribution network. The distribution network is a medium to low voltage network that is connected to a high voltage transmission network through "step down" transformers. Each transformer feeds power to a number of feeders to which customers are connected either directly or through a distribution transformer which further steps down the voltage to the utilization level.

The most important goal in power system operation and planning is to continually provide reliable electric energy to customers. Meanwhile, the system must optimize the available resources to minimize the total system production cost subject to all kinds of constraints.

2.3 Distributed generation

Distributed generation (DG) refers to the notion of generating power using a set of small sized generators that produce power at low voltage levels and usually use alternative fuel. The generators are mainly designed to be connected directly to the distribution network near load centres. A typical arrangement of a power system with distributed generation which is expected in the future is shown in Fig. 2.2[6].

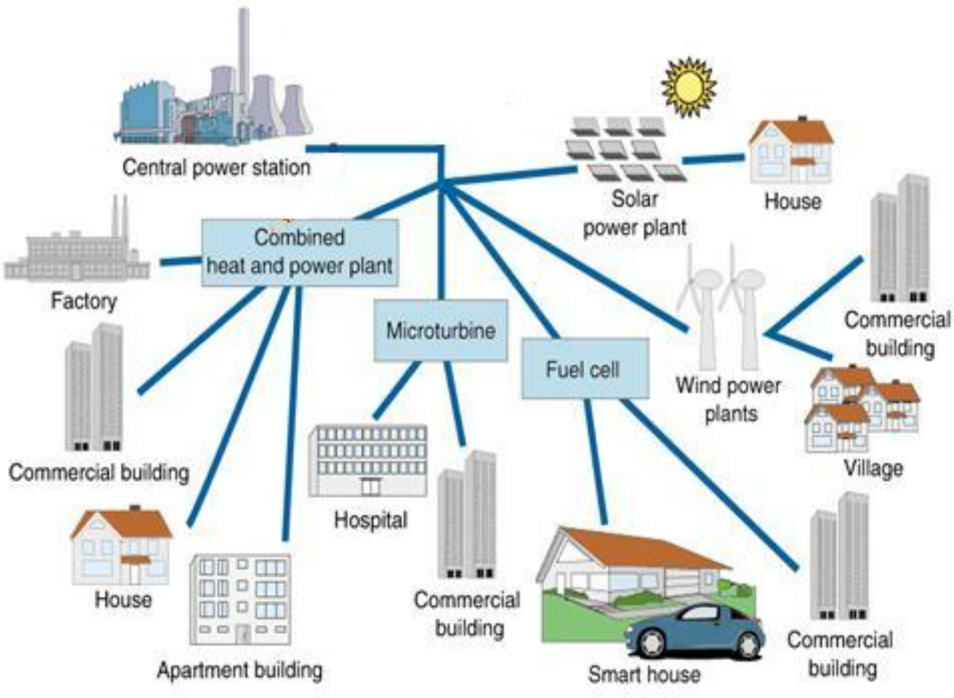


Figure 2.2 A Power System with Distributed Generation[6]

DG has generally been considered and studied as emergency back-up power or limited to a small portion of grid-connected electricity supply. In many countries, the economies of scale of centralised generation, the low price of oil and coal as fuel for electricity generation, and regulatory barriers have reduced the widespread adoption of DG. These institutional barriers have included a lack of interconnection protocols, low electricity buy-back tariffs, and little consideration of the system's benefits of distributed resources. However, changes in the relative economics of centralised versus distributed energy, the increasing use of natural gas, restrictions on new electricity transmission lines, recognition of the environmental benefits of DG, and improved DG control technologies have resulted in the reconsideration of the widespread use of DG.

2.3.1 Historical Development of Distribured Generation

The shift toward DG can in many ways be viewed as power generation coming full circle. In the 1880s[8], Thomas Edison's Pearl Street electricity system serving Wall Street and the surrounding city blocks was a distributed generation system. This paradigm was continued over the next 20 years with schemes in the United States and across the world serving limited urban areas with small-scale direct current (DC) systems. Also popular were installations serving individual factories and supplying electricity and heat in combined heat and power (CHP) applications. One large drawback of using DC was the large losses from this low-voltage system when transmitting power over longer distances. An alternative system based on alternating current (AC) was promoted by a number of competitors, including George Westinghouse. AC systems had the advantage when serving larger and more spread-out service areas, as the voltage could be stepped up using a transformer to minimize losses. In the late of 1880s, Nikola Tesla invented the three-phase AC arrangement, which simplified the number and size of wires, and in 1893 [9] the universal system was introduced wich had a series of technical standards that allowed the interconnection of AC and DC systems and users.

With technology facilitating AC systems, a significant financial impetus for larger, more centralised systems was the requirement for consistently high-load factors on the electricity network. Large amounts of electricity cannot be stored, thus requiring that demand meets supply at all times. Economical use of the transmission and generation capacity thus requires that a diverse customer base maintains electricity demand through the days and seasons. A combination of residential, commercial, and industrial applications enables the demand profile to be smoothed out as much as possible and this generally requires a large service area.

Another stimulus of larger electricity networks was the availability of energy inputs. Hydroelectric power and coal mines for electricity generation are usually located some distance from population and industrial centres. Either the fuel was to be transported to distributed power plants (an impossibility in the case of hydroelectricity sites) or electricity was to be transmitted at high voltages.

An additional driving force for the centralised electricity network was the rise of natural monopolies. Although the institutional structure of emerging systems was very different, ranging from private companies to state-owned enterprises, competition in electricity generation was viewed as infeasible due to the prohibitive costs of laying competing wires and the institutional difficulties (at that time) of being able to verify and charge for use of an electricity network by different firms and organizations. By the 1930s, industrialized countries had set up large electricity utilities, coalescing around the dominant generation design of the steam turbine. Smaller systems were either absorbed or shut down.

This centralised model led to the developments of larger and larger generating plants as economies of scale were pursued to raise total electricity system efficiencies and reduce costs. The size of the largest generating units jumped from 80MW in 1920, to 600 MW in 1960, to 1400 MW in 1980. In order to finance these enormous capital investments in generation and related transmission, utility monopolies relied on guaranteed revenue streams from predetermined electricity prices to their “locked-in” customer base. Other advantages of this system included reliability due to the integrated nature of the electricity network and reductions of local air pollution near population centers as generation took place in remote areas. In addition, large-scale nuclear power stations were well suited to this paradigm as they required the enormous initial investment and guaranteed investment recovery promised by the centralised electricity network model.

The turning point of the return to DG came with the oil shocks of the 1970s and the drive toward higher efficiencies. Despite economies of scale, overall electricity system efficiencies were restricted to 30-33% of input energy [2]. A major reason for this was the inability to capture the large amounts of waste heat during the electricity production process and hence renewed efforts were made toward technological and regulatory arrangements to allow distributed combined heat and power (CHP) facilities with overall efficiencies of greater than 80% [3]. The most impressive technological development was in high-efficiency combined-cycle turbines (CCGT) using natural gas. This technology became the mode of generation of choice, capturing most incremental capacity growth in most markets [10]. Progress on smaller DG technologies included significant cost, reliability, and emissions improvements of engines, microturbines, fuel cells, and photovoltaics (PV). In parallel, and especially in the past 10 years, there have been developments in control, management and monitoring technologies [11-13]. The telecommunications revolution has enabled cheap, real-time operation and integration of small-scale power technologies.

Institutional progress has centered around the drive to restructure electricity markets, from monopolies (often publicly owned) to a competitive generation market in which market participants are free to choose technology type and their customer base. The motivations for this shift were to lower power costs and improve customer choice and also to raise revenues in the case of state-owned enterprises. A major consequence of this market restructuring was the increase in volatility and the resultant uncertainty in recovering investment costs. Firms were less and less willing to commit huge sums in centralised plants with repayment occurring over decades. Additional incentives have stemmed from changing public pressures. It has become increasingly difficult to build additions to electricity networks, especially near population centers. In addition, the demand for very reliable and higher quality power has emerged, spurred by the rapid penetration of electronic appliances and industrial processes that are extremely sensitive to supply disruption. Finally, other energy delivery infrastructures, especially the natural gas system, have emerged to compete with electricity transmission. Energy must be moved from source to demand, but where the conversion to electricity is carried out, and at what scale, will be part of the emerging model to come. This is particularly relevant to developing countries where it may or may not be optimal to construct a capital-intensive centralised electricity network.

2.3.2 DG market status

It is difficult, or even impossible, to provide values for the total installed capacity of DG technologies and resources [14]. This is due to the range of technologies, their varying levels of use in different countries, and ambiguity over what constitutes a DG application as unit sizes become larger and units are sited further from demand centers. In addition, some of the most promising technologies, including fuel cells, photovoltaics, and microturbines are just entering commercialization. The relative rate of technological progress and the regulatory structure of energy markets will determine to what degree and how quickly DG will penetrate the market [15].

2.3.3 Different types of DG technologies

There are several types of distributed generators in the market. Some are conventional such as the diesel generators and some are new technologies such as the micro-turbines. The following section briefly describes major DG technologies.

2.3.3.1 Engines

Reciprocating IC engines are an established and well-known technology. Engines for stationary power are derived from automobile engines. These engines are fired by either natural gas or diesel and use spark ignition or compression ignition depending on the compression ratio used. A typical energy balance is: electricity, 26-39% (this range is due to type, size, and operation of engine limited by Carnot cycle); useful heat, 46-60%; losses (radiation from engine and exhaust, lubrication, gearbox, generator), 10-20%.

Power production engines are typically less than 1 MW and have become the most common DG technology for both standby and peaking applications and are increasing in use as base-load CHP units [16]. Engines have low capital costs and high reliability, although they require a regular maintenance and overhaul schedule. Regular maintenance is essential for good performance and ranges from weekly oil changes to major overhauls after 25,000-40,000h of operation. Heat recovery is from the engine jacket and cylinder head cooling water and from the hot engine exhaust, resulting in hot water at 80-120°C. A combination of combustion modifications and the use of catalytic converters has greatly reduced local air pollutant emissions, although in this regard engines are still inferior to other DG technologies.

2.3.3.2 Gas Turbines

Derived from aero-applications, power generation with gas turbines is commonplace, with an extensive installed capacity and sizes ranging from 500 kW to over 50 MW. Low maintenance costs and high-grade heat recovery have made gas turbines a favorite in industrial DG applications[17].

The unit has a turbine and compressor on the same shaft and compressed combustion products at high temperature drive the turbine. Compressor losses and materials restrictions limit the upper temperature of the cycle and thus constrain efficiency. Hot exhaust gases are used to preheat incoming air (regeneration). The remaining thermal energy of these exhaust gases can be reclaimed as waste to heat a boiler. Turbines are classified as temperature-limited cycles and increases in efficiency continue to occur through materials developments and cooling technologies to allow the turbine to run at higher maximum temperatures.

2.3.3.3 Microturbines

Microturbines follow the same cycle as conventional gas turbines, although they are at a less developed stage of commercial development. Their development has come from the design of small, very high speed turbines (with compressors on the same shaft) rotating up to 100,000 rpm. Additional scaling down of components, particularly nozzles and burners, has been achieved. The marketed size range is 30-250 kW [18].

Microturbines use regeneration, with resultant lowered exhaust gas temperatures (~300°C). The unit is air-cooled. Maintenance requirements are reduced due to the elimination of an oil-based lubricating system in favor of air bearings and because the microturbines have no gearbox. Efficiencies are a few percentage points less than those of conventional gas turbines, primarily due to lower operating temperatures.

2.3.3.4 Fuel Cells

Fuel cells (FC) convert chemical energy directly into electrochemical work without going through an intermediate thermal conversion. Thus, the second law of thermodynamics does not apply, they are not limited by Carnot's theorem, and, therefore, they offer the potential of very high electrical efficiencies. In a fuel cell, the fuel (H_2) and the oxidiser (O_2) are supplied continuously and the FC can therefore deliver power over long period of time (unlike in a battery). A dynamic equilibrium is maintained, with the hydrogen being oxidised to water with electrons going around an external circuit to provide useful electrical work. A major limitation of fuel cells is that direct efficient oxidation of natural gas (CH_4) is not yet possible. Therefore, a reformer is used to convert CH_4 to H_2, with resulting losses in overall efficiency and creation of CO_2 as a by-product.

Fuel cells have many admirable qualities for power production including a high potential efficiency, no loss in performance when operating at partial load, ultralow emissions, and quiet operation. Their high capital costs are a major barrier to deployment [19].

2.3.3.5 Stirling Engines

A Stirling engine is an external combustion engine, where the fuel source is burned outside the engine cylinder. This energy source drives a sealed inert working fluid, usually either helium or hydrogen, which moves between a hot chamber and a cold chamber. Stirling engines can be very small in scale (as little as 1 kW), which in combination with very low maintenance, low noise, and low emissions makes them ideal for residential CHP applications. Another advantage of Stirling engines is that they can utilize almost any fuel, including direct solar energy. However, significant challenges remain in reducing the high capital costs and overcoming remaining technical barriers, primarily related to durability.

2.3.3.6 Wind Turbines

Wind-based power generation may or may not be a DG technology, depending on whether it is located near the demand source or at a remote wind farm. Generally, wind turbines are located in areas with good winds and have annual capacity factors ranging from 20 to over 40%. The typical life span of a wind turbine is 20 years. Maintenance is required at 6-month intervals.

A wind turbine with blades is placed at the top of a tall tower. The tower is tall in order to harness the wind at a greater velocity and to be free of turbulence caused by interference from obstacles such as trees, hills, and buildings. As the turbine rotates in the wind, a generator produces electrical power. A single wind turbine can range in size from a few kilowatts for residential applications to greater than 5 MW[20].

Drawbacks of wind power include high capital costs and reliance on the kinetic energy in the wind which is an intermittent resource.

2.3.3.7 Photovoltaics (PV)

PV cells, or solar cells, convert sunlight directly into electricity using the photo-voltaic effect [21]. PV cells are assembled into flat plate systems that can be mounted on rooftops or other sunny areas. They generate electricity with no moving parts, operate quietly with no emissions, and require little maintenance. An individual photovoltaic cell will typically produce between 1 and 2 W. To increase the power output, several cells are connected in series to form a module. Photovoltaic systems are available in the form of small rooftop residential systems (less than 10kW), medium-sized systems in the range of 10 to 100kW, and larger systems greater than 100 kW connected to utility distribution feeders.

Two semiconductor layers in the solar cell create a number of free electrons and holes by capturing photons in sun light. Materials such as silicon are suitable for making these semiconducting layers and each of these materials has benefits and drawbacks for different applications. In addition to the semiconducting materials, solar cells consist of two metallic grids or electrical contacts. One is placed above the semiconducting material and the other is placed below it. The top grid or contact collects electrons from the semiconductor and transfers them to the external load. The back contact layer is connected to complete the electrical circuit.

Commercially available PV modules convert sunlight into energy with approximately 5 to 20% efficiency. Efforts are under way to improve photovoltaic cell efficiencies as well as reduce capital costs. One of the best examples of these efforts is the concentrated PV (CPV) systems. CPV systems concentrate sunlight on multijunction (MJ) solar cells, greatly increasing the efficiency of the cells. The Author in [22] concluded that 50% efficiency of CPV can be achived. The PV cells in a CPV system are built into concentrating collectors that use a lens or mirrors to focus the sunlight onto the cells. CPV systems must track the sun to keep the light focused on the PV cells. The primary advantage of CPV systems is high efficiency, however, the systems generally require highly sophisticated tracking devices which is an important technical challenge for this emerging technological approach. This type of PV technology will be assumed in Chapter 4. Considerable attention is also being given to fully building-integrated PV panels, where the PV panels are an alternative to other construction materials. A principal drawback of PV cells is their reliance on solar radiation which is an intermittent power source.

2.3.3.8 Hybrid Systems

A combination of various DG technologies or inclusion of energy storage options (including batteries and flywheels) has been proposed to overcome specific limitations (e.g. intermittency) and to boost primary performance characteristics (e.g., electrical efficiency). Examples of hybrid systems include the following [23-25]:

- Solid oxide fuel cell (SOFC) combined with a gas turbine or microturbine.

- Stirling engine combined with a solar dish.
- Wind turbines with battery storage and diesel backup generators.

The SOFC/gas turbine hybrid system can provide electrical conversion efficiencies of 60 to 70%, through a combined cycle where the waste heat from the fuel cell reaction drives a secondary microturbine. Stirling engine/solar dish hybrid systems can also run on other fuel sources during periods without sunlight. Wind turbines can be used in combination with energy storage and some type of backup generation (e.g., an IC engine) to provide a steady power supply to remote locations not connected to the grid. Energy storage devices such as flywheels are being combined with IC engines and microturbines to provide a reliable backup power supply. The energy storage device provides ride-through capability to enable the backup power supply to get started. In this way, electricity users can have an interruption-free backup power supply.

In this study, we will be focusing only on distributed generation using photovoltaic cells.

2.4 Statement of problems

The distribution network was originally designed to transfer power from the transmission network and distribute it to the loads. It was not designed to have generators directly connected to it. The distribution network topology, control, and protection are all designed assuming that power is flowing in one direction, from transmission to loads. The connection of DGs to the feeders of the distribution network can cause the power flow to be bi-directional instead of unidirectional affecting the network performance and stability in a number of ways [26]. An extensive literature[27-36] review of the impact of connecting PV systems to electric networks has shown that the most serious impacts that could not be resolved using conventional techniques were found to be the impact of PV systems on the voltage regulation.

A short overview of the most important problems associated with the connection of DGs to the utility grid is described below:

- Voltage Regulation
- Power quality
- Harmonics
- Fault level
- Protection challenges

2.4.1 Voltage Regulation

Generally, distribution utilities deliver electric energy to their customers within an appropriate voltage range to meet customer requirements. For a radial configuration the bus voltage, voltage drop, power flow, and power loss can be calculated by using a simplified model such as the two-bus system [26] as shown in Fig. 2.3.

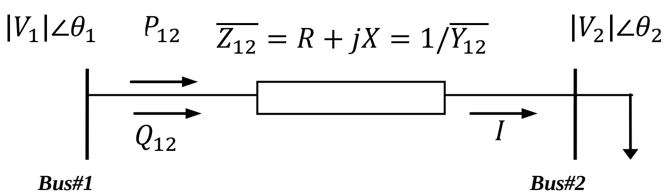


Figure 2.3 Model of a two-bus power system.

Where: $\overline{Z_{12}}$ is the complex impedance and $\overline{Y_{12}}$ is the complex admittance of the line.

The model consists of a short distance line represented by a series connection of resistance (R) and inductive reactance (X). In this case, real and reactive power transfer between bus #1 and bus #2 is given by eq. (2.1) and eq. (2.2).

$$P_{12} = Y_{12}V_1^2\cos(-\delta_{12}) - Y_{12}V_1V_2\cos(\theta_1 - \theta_2 - \delta_{12}) \qquad \textbf{(2.1)}$$

$$Q_{12} = Y_{12}V_1^2\sin(-\delta_{12}) - Y_{12}V_1V_2\sin(\theta_1 - \theta_2 - \delta_{12}) \qquad \textbf{(2.2)}$$

Where: θ_1 is the voltage angle at bus #1

θ_2 is the voltage angle at bus #2

δ_{12} is the admittance angle

Power loss between bus #1 and bus #2 can be calculated by eq.(2.3).

$$P_{loss} = |I|^2R = \left|\frac{P_{12} - jQ_{12}}{V_1^*}\right|^2 R = \left(\frac{P_{12}^2 + Q_{12}^2}{V_1^2}\right)R \qquad \textbf{(2.3)}$$

Where: V^* is a complex conjugate voltage

In addition, the voltage at bus #2 and the voltage drop between the buses can be calculated in term of the voltage at bus #1 by using eq. (2.4) and eq. (2.5), respectively.

$$V_2 = V_1 - (R + jX)\frac{(P_{12} - jQ_{12})}{V_1^*} \qquad \textbf{(2.4)}$$

$$\Delta V = V_1 - V_2 \approx \frac{RP_{12} + XQ_{12}}{V_1} \qquad \textbf{(2.5)}$$

In a typical distribution system there are many modes to be considered, and to calculate the power flow and voltage distribution in a large system, power system simulation software is required.

Any injection of power from DGs into a distribution system will cause a voltage rise in the point of connection and in the surrounding network. It is possible to estimate that rise by using the standard voltage drop equation (2.5) with reverse power flow.

When a PV system is connected to a grid, it will affect the voltage regulation of the network depending on the location, size, and operating scheme of the PV generator. It seems that there is no great impact for small PV private installations due to the limited level of power produced. But in the case of high penetration of PV systems, the situation may be more critical as has been shown in Oota City, Japan [37]; under certain circumstances such as the high level of solar radiation and the low level of consumption, for instance during the weekend, the voltage at end of line far from the distribution transformer increases above the security threshold level and leads to disconnection and energy loss of conventional PV systems. The penetration level can be defined here as: the percentage of customers who install PV generator in their properties and connect it to the grid.

There have been several studies conducted to examine the possible impacts of levels of utility penetration of this type of PV system on voltage disturbances. A recent study [38] reached some striking conclusions. This study examined the impact of PV penetration in the UK. It examined the probability distributions of voltages in a simulated 11 kV distribution system with varying levels of PV penetration, using an unbalanced load flow model. PV output was simulated using measured data with one-minute resolution. As expected, the probability density functions shown indicate that PV causes the distribution to shift toward higher voltages, but only by a small amount. The mean point of common coupling voltages increased by less than 2 volts (on a 230-V nominal base). The study’s conclusions include the following:

- PV penetration is limited to approximately 33% by voltage rise issues if the strictest standard in the UK (BS EN50160) is used. However, at 50% penetration, the voltage rise above the allowed limits was small, and so the authors suggest that the 33% limit is somewhat arbitrary.
- "Voltage dips" due to cloud transients *might* be an issue at 50% penetration, and the authors suggest further study of this.

Although the voltage disturbances are considered as one of the most serious problems, there are several options to resolve it from the generator side such as:

- Size: ensure that the size of the PV generator is below the level necessary to cause a problem.
- Location: select a suitable location for the generation on the distribution network.
- Operation time: shift the operating time of the energy coming from PV generator to coincide with the peak load. This needs storage batteries to do that in this case which adds some cost to the system [39].
- Operation mode: operating the generator at lagging power factor in order to consume some reactive power can also be used to keep the voltage within its limits.

On the other hand, many standard techniques for electrical networks have been used to control the voltage level such as:

1- On-Load Tap Changing (OLTC) Transformers:

One of the most common voltage control techniques on the distribution network is to use an OLTC transformer which can maintain a stable secondary voltage by selecting the appropriate tap position. This technique is usually controlled by an automatic voltage controller (AVC) relay with line drop compensator (LDC). The AVC continuously monitors the output voltage from the transformer, when the voltage is above the pre-set limits, a tap change command will be initiated. The LDC is used to compensate for the additional voltage drop on the line between the transformer and load location. However, the integration of DG into distribution systems has resulted in voltage regulation problems [39]. It has been found that the voltage measured by a conventional AVC relay is shifted up or down compared with that obtained without DG depending on the power factor of the current through the OLTC transformer. It also depends on the power factor of the DG and the system load [40]. As a result, proper voltage control of a distribution network cannot be achieved. In order to solve this problem, coordination between DG output and OLTC tap control is necessary as been shown in [41].

2- Reactive Power Control Approach

In Power Factor Control (PFC), the ratio P/Q is maintained constant. According to eq.2.5, any fluctuation in P due to integration with DG brings about a proportional variation of voltage. If the voltage variation generated by P can be compensated by adjusting Q in the opposite direction, then the voltage variation can be maintained within pre-set limits.

3- Power curtailment

One of the straight ways to solve the voltage rise problem is to disconnect any DG from the network that causes the problem. This operation largely wastes the potential of renewable energy and reduces the profit of DG [42]. Alternatively, reducing DG power production will solve voltage variation problem with a more efficient technique.

4- Network reconfiguration

Network reconfiguration means changing the operation of the network from radial to ring form and vice versa by closing/opening the normal open point (NOP) between the feeders. This solution can be realised by using one of the new artificial intelligence control techniques, control such as, fuzzy logic and genetic algorithm (GA) which are still considered as complex ways to cooperate with exiting network strategy.

2.4.2 Power quality

The definition of power quality given in the IEEE dictionary originates in IEEE Std 1100 [43]: “Power quality is the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment”. Despite this definition the term power quality is clearly used in a more generic way.

In general, the back-up generation and the on-site power supply provided by DG improve the system power quality. However, some issues might arise when distributed generators, with their different types and technologies, are interconnected to the utility distribution system. Among these issues are sustained interruptions, voltage regulation, voltage flicker, voltage sag and harmonics.

2.4.3 Harmonics

A harmonic is a signal whose frequency is an integral multiple of the frequency of a reference signal. Harmonics are a particularly common type of distortion that repeats every cycle. Distortions in voltage and current wave shapes can upset end-use equipment and cause other problems.

Recently, power system harmonics have become an important issue because of the presence of nonlinear devices in most electrical apparatus. Traditionally, the main sources of harmonics in power systems are power electronic devices such as rectifiers, inverters, etc. Since these harmonic sources are connected to the system, they may create problems to local equipment depending on their harmonic orders and amplitudes, and system characteristics. For example, harmonics will increase the losses of transformers and motors,

In order to limit the effect from harmonics, the IEEE provides a recommended practice for harmonics, IEEE 519 -1992 [44], which set limits for utilities and for end users. Utilities are expected to maintain reasonably distortion-free voltages to customers. For suppliers at 69 kV and below, IEEE voltage limits are 3% on each individual harmonic and 5% on the total harmonic distortion. Each utility has harmonic standards, which provide guidelines for maximum voltage distortion at the point of common coupling (PCC). Limiting the voltage distortion at the PCC is the concern of the utility. It can be expected that the voltage distortion at the PCC will be within the specified limits if every customer follows the rules.

The total harmonic distortion of current and voltage, THDI and THDV, are defined by eq.(2.6) and eq.(2.7) respectively.

$$\mathrm{THD_I} = \sqrt{\left(\sum_{n=2}^{\infty} |I_n|^2 / |I_1|^2\right)} \times 100\% \tag{2.6}$$

$$\mathrm{THD_V} = \sqrt{\left(\sum_{m=2}^{\infty} |V_m|^2 / |V_1|^2\right)} \times 100\% \tag{2.7}$$

Before connecting DGs to the utility distribution system, DGs must comply with that utility's standards for harmonic injection. PWM-based inverters and rotating generators can meet these limits, so harmonic problems should be rare. However, line commutated inverters normally require filtering to meet harmonic limits [39].

2.4.4 Fault level

Every component in the network has a permissible limit of the amount of current it can handle or see through without damage. It is often called “maximum withstand current”. When a fault takes place anywhere in the system, the equivalent Thevenin impedance seen by the voltage would be smaller with DGs than the case without DGs. This means connecting DGs also means increasing fault feeding sources in the system. Depending on the type and location of the fault, there can be a significant amount of fault current fed by the DGs. If the total fault current supplied by the utility source plus that supplied by the DGs is more than the maximum withstand current the components will be exposed to levels of mechanical and thermal stresses that they are not designed to withstand. This calls for an upgrade of the existing system components, such as reclosers, fuses; even the cable or overhead conductors may have to be upgraded to withstand the extra fault current fed by DGs. This obviously is impractical and unfeasible as doing so would undermine the very purpose of introducing DGs i.e. the economical advantage of generating electricity at customer’s property. It is quite possible that the cost of upgrade might exceed the savings associated with the generation of electricity close to the point of consumption.

The fault level contribution from DG is determined by a number of factors, including:

- The type of DG, as different types of DG contribute different fault currents.
- The distance of the DG from the fault, as the increased cable impedance over longer distances will reduce the fault current.

- Whether or not a transformer is present between the fault location and the contributing DG (which is often the case for voltage regulation purposes), as the transformer short circuit impedance may assist in limiting the fault current.
- The configuration of the network between the DG and the fault, as different paths for the flow of the fault current will alter the magnitude of the fault current (due to cable impedances and other installed equipment).
- The method of coupling the DG to the network. Directly connected DG will contribute significantly higher fault current than DG connected via power electronics interfaces such as PV generators.

2.4.5 Protection challenges

The straight protection scheme of each feeder in the network is designed, assuming the feeder is radial. But the presence of DGs on a feeder will cause bi-directional power flow, which means that part of the feeder will no longer be radial [45]. This will create a number of problems to the current protection schemes used, as shown in several papers including [46] and [47].

Ackermann in [48] shows that the presence of DGs will result in an increase in fault current levels, and that the detailed assessment of the impact DGs might have on fault currents is very challenging as the impact depends on a large number of factors. Among these are “the technology of the DG, its operation mode, interface with the DG, system voltage prior to fault, etc…” In [49], Gomez claims that there is no concern with the DG when its power is less than 10 percent of the minimum load demand by the feeder. The most immediate consequence is the need for verification of the protective device breaking capacity, which might not be enough due to the increase of the available short-circuit power. As mentioned in [47], the fault contribution from a single small DG unit is not large, however, the collective contributions of many small units, or a few large units, can alter the short-circuit levels enough to cause protective devices to fail.

The main protection problems caused by DG integration into distribution networks are:

- Blinding of protection
- False tripping
- Loss-of-mains (islanding).
- Protection coordination

<u>Blinding of protection:</u> When a large distributed generation production unit or several small ones are connected to a medium voltage network, the fault current seen by the feeder protection relay may be reduced, which can lead to the prevention of the operation of over current relays. This is also called protection under-reach [50]. It is explained in Fig. 2.4.

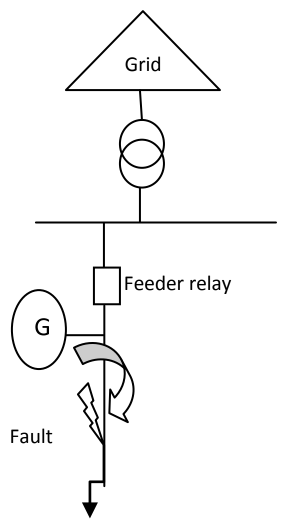


Figure 2.4 Blinding of protection

The current contribution from the distributed generator reduces the current seen by the feeder relay. So, the impact of the DG increases with the size of the generator and with the length of the line section between the production unit and the fault.

False tripping: The basic principle of false tripping is shown in Fig. 2.5. The short-circuit fault occurs on feeder 1, but also feeder 2 is tripped because of over-current fed by the DG unit. False tripping can be solved by directional over-current relays.

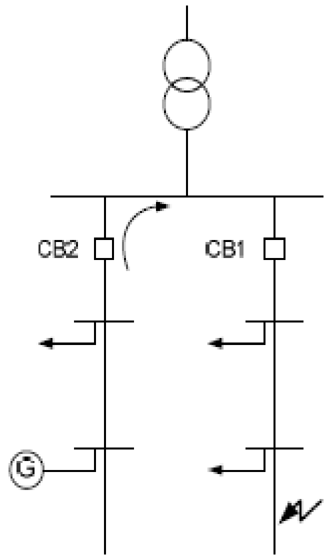


Figure 2.5 False tripping

Loss-of-mains (islanding): In the case of a sudden loss of grid connection, a part of the network may keep operating as an island as shown in Fig. 2.6.

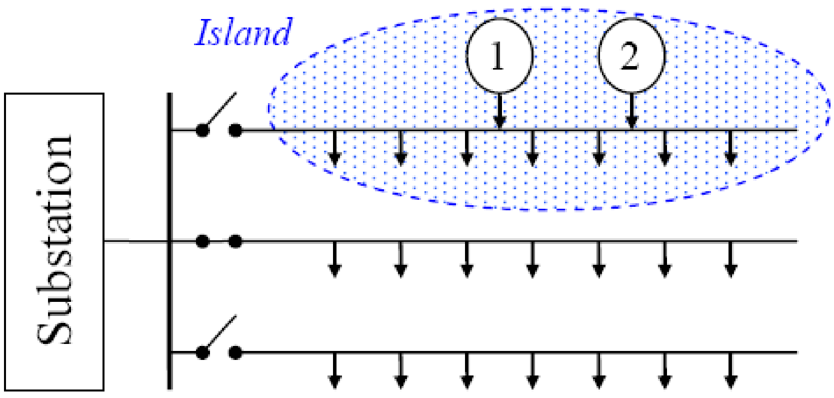


Figure 2.6 Islanding

In most cases this is not desirable for the following reasons:

- Reconnection of the islanded part becomes complicated, especially when automatic reclosing is used. This can lead to damage of equipment and can decrease the reliability of the network.
- The network operator is unable to guarantee the power quality in the island. There could be abnormal voltage levels or frequency fluctuations, and the fault level may be too low resulting in the over current protection not working the way it is designed.
- Safety problems to maintenance personnel arise when de-energized circuits are back-fed.

Another problem associated with unintentional islanding is voltage and frequency control, especially when generation does not match the load.

Protection coordination is used in distribution networks so that only the faulted part of the network is isolated. When PV is connected, currents flowing through different protection devices are no longer the same, and therefore coordination becomes difficult to achieve, and in certain cases impossible.

It is recognized that network design strongly influences the protection practice in a given system, but when it comes to considering PV or any other DG impact on protection settings, this will mainly depend on two parameters:

1. The location of the DG unit in the grid
2. The size of the DG unit.

2.5 Conclusion

A brief history of distributed generation has been presented in this chapter. Also a summary of different types of distributed generators has been discussed. Finaly this chapter has concluded with a statement of the problems associated with integrating distributed generation into the national grid.

Chapter 3

3 Load and solar radition data in Saudi Arabia and Simulation of Typical Power Networks

3.1 Introduction

Data has been gathered from the Saudi Electricity Company (SEC) in the Western region on the layout and operation of the network and the control system used by the company. Also, actual load data has been collected for residential and industrial areas in order to build a realistic model. Furthermore, solar radiation data for this research has been obtained from King Abdul-Aziz City for Science and Technology (KACST) which has 40 stations around the country recording the solar radiation every 5 minutes. This data has been used as input data for the software package PVSYST to find the total power that can be extracted from different sizes of PV systems. The size of the PV system selected is based on average spaces available on the roofs of houses connected to the residential networks in Saudi Arabia.

3.2 General information on Saudi Arabia

3.2.1 Geographical data

Figure 3.1 Map of Suadi Arabia (Source:google map)

The Kingdom of Saudi Arabia lies between latitudes 31ºN and 17.5ºN and longitudes 50ºE and 36.6ºE. The land elevation varies between 0 and 3,133 m above the mean sea level. Complex terrain is found in the southwest region of the Kingdom. The East and the West coasts of the Kingdom are located on the Arabian Gulf and the Red Sea respectively, as shown in Fig. 3.1. Mainly two seasons, winter and summer, are observed during the year. The vast open land experiences high intensities of solar radiation and long hours of sunshine.

3.2.2 Weather and solar radiation data

Saudi Arabia is a country that receives a large amount of solar radiation on its territory and has a large number of sunshine hours per day, especially in the summer. Solar radiation data has obtained for this research from KACST which has 40 stations around the country recording the solar radiation every 5 minutes.

In this study, only data for Jeddah city has been used. Fig. 3.2 shows the maximum, minimum and monthly average solar radiation in January and June 2002 recorded at Jeddah station.

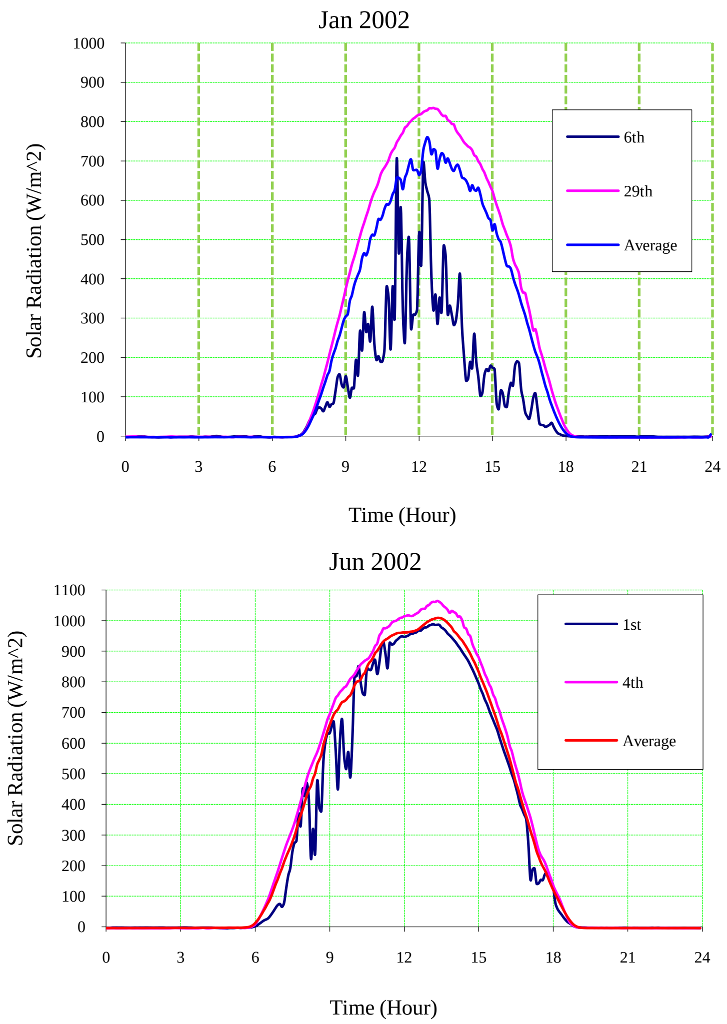


Figure 3.2: Peak, minimum and average solar radiation (Jeddah, Jan & Jun 2002)

The peak radiation occurs in the middle of the day which coincides with the maximum temperature recorded. Also, the average minimum temperature in winter is 18° C as presented in Fig. 3.3. So, the climate in Jeddah is hot throughout the year and air conditioning (AC) systems are required even at winter time.

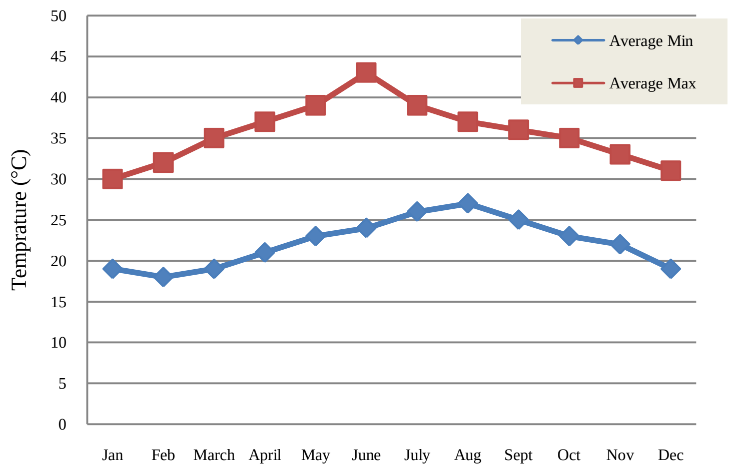


Figure 3.3: Minimum and maximum monthly average temperature, Jeddah

3.2.3 PV generators and its aplication in Saudi Arabia

Even though Saudi Arabia is a leading oil producer, it is keenly interested in taking an active part in the development of new technologies for exploiting and utilizing renewable sources of energy because of the following considerations:

(i) Saudi Arabia has an area of more than 2 million km^2 where many remote villages and settlements can benefit from renewable energy applications.

(ii) Saudi Arabia has enormous potential for exploiting solar energy. Therefore, if a major breakthrough is achieved in the field of solar-energy conversion, Saudi Arabia can be a leading producer and exporter of solar energy in the form of electricity.

(iii) Renewable energy sources are essentially considered as providing support to depletable sources of energy (hydrocarbon resources), which in the past were generously consumed and dissipated. It is the Kingdom’s view that such exhaustible resources ought to be used more wisely, for the development of other products more beneficial and useful to humankind, such as petro-chemicals.

Applications of solar energy in Saudi Arabia have been growing since the early 1960s, when the first photovoltaic (PV) beacon was established by the French at the small airport of Madinah Al-Munnawara. Research activities commenced with small-scale university projects during 1969, while a major systematic research and development (R&D) programme for the development of solar energy technologies were initiated by the King Abdulaziz City for Science and Technology (KACST) in 1977 [52]. For the last three decades the Energy Research Institute (ERI) at KACST has conducted major RD&D work in this field. The ERI has conducted a number of international joint programs in the field of solar energy.

In October, 1977, Saudi Arabia and the United States signed a project agreement for cooperation in the field of solar energy under the Solar Energy Research American Saudi: Saudi Arabian-United States Program for cooperation in the Field of Solar Energy Program (SOLERAS). The Solar Energy Research Institute (SERI) has been designated as the Operating Agent for the SOLERAS program. SOLARAS has addressed solar energy in terms of both technological and economic issues. One of the several projects being conducted under SOLERAS supplied two traditional Saudi Arabian villages, not connected to the central electric grid, with solar energy. These first villages of Al-Jubaila and Al-Uyaina were realized in the early 1980s as an innovation for the region. Saudi Arabia was the first country in the Gulf Cooperation Council (GCC) countries as well as in the entire Middle East to research how to make villages independent from the central system of power production.

After the pilot schemes to develop solar energy in the 1980s, Saudi Arabia has taken a much more active approach to solar power development. A Long-term German-Saudi Arabian Cooperative Programme for Research, Development and Demonstration of Solar Hydrogen Production as well as Utilization of Hydrogen as an Energy Carrier (HYSOLAR) was started in 1986 with the Federal Republic of Germany. The first phase of HYSOLAR ended in 1991, focused mainly on investigation, test and improvement of hydrogen production technologies, while in the second phase, more emphasis was laid on hydrogen utilization technologies. The SOLARES program was a unique bilateral, international, cooperative research effort. The US Department of Energy and the Saudi Arab National Center for Science and Technology (SANCST) had each committed US$50 million to this program, while the Solar Energy Research Institute (SERI) in Golden, Colorado, was responsible for it. These joint programs were directed towards projects that were of mutual interest to the committed countries involved and concentrated on large demonstration projects such as electricity generation, water desalination, agricultural applications, and cooling systems. In view of the importance of the need for exact measurements of solar radiation, the Saudi Atlas Project was initiated in 1994, as a joint R&D project between the ERI and the National Research Energy Laboratory (NREL) in the U.S. Twelve locations in the following cities throughout the country were carefully selected for solar data collection: Riyadh, Gassim, Al-Ahsa, Al-Jouf, Tabuk, Madinah, Jeddah, Wadi Al Dawasir, Abha, and Gizan. All of these stations are connected to a central unit for data collection and all the instruments are calibrated on a regular basis (at 6-month periods) in order to derive reliable and accurate data. In this regard, NREL and KACST realized the value of accurate surface solar radiation flux measurements for validation of satellite derived surface and atmospheric solar radiation flux measurements. They ara making this data available to support validation of satellite data products related to the NASA Mission to Planet Earth component of the Earth Science Enterprise Earth Observing System (EOS) projec. The aim here is to evaluate long term climate trends based on measurements from EOS Terra Platforms. Until April 18, 2000, the data available for the Saudi Network stations was quality assessed and flagged, based on the use of a single composite calibration factor for the pyranometer deployed at each station.

As of April 18, 2000, the global horizontal data posted for all of 1998 to date has been corrected for the cosine response of the individual pyranometer deployed at each station. In March 2008, Saudi Arabia's oil minister, Ali Al-Naimi, stated that Saudi Arabia's strategic plan is to sharpen its solar energy expertise, essentially similar to that Saudi Arabia already enjoys in the oil industry. Al- Naimi advised the French newsletter Petrostrategies : "One of the research efforts that we are going to undertake is to see how we make Saudi Arabia a center for solar energy research, and hopefully over the next 30–50 years, we will be a major megawatt exporter" [53].

The Kingdom of Saudi Arabia has begun building the first solar powered water desalination plant in 2010, the first step in a three-part program to give significant boost to the development of solar energy sector in the country. Under the terms of an agreement signed June 2010, Saudi Aramco are to develop a pilot solar power plant that will have a capacity of 10 MW and is due to come on stream in 2011. Another 20 MW solar power plant is due to be built at King Abdullah University of Science and Technology, along with a center devoted to PV technology (Arab states may become solar energy exporters).

Since the solar data is very necessary for any research in renewable energy, the Saudi government established a network of 40 stations where global solar radiation and sunshine duration is being recorded since 1970 and a large number (more than 40) of full meteorological data collection stations where all meteorological parameters are being recorded. The solar radiation data for the year of 2002 of seven of these stations around the country have obtained from KACST for use in this research (see summary in Appendix A).

Although a lot of activity and research has been done on renewable energy and its application, still there are many topics not investigated, especially at the side of the technical issues and their details. The impact of grid-connected PV Systems in residential and industrial area in Saudi Arabia using commercial PV panels is the subject of study in the remainder of this chapter.

3.3 The Saudi Arabia power system

The Saudi Electricity Company (SEC) network is the power supply utility responsible for generation, transmission and distribution. It is divided into four main regions: West, Central, East and South. The central and western networks were interconnected 10 years ago. However, the company connected the entire region in 2010. In this research we will concentrate on the western region (WR) network. All information for this research has been collected from SEC-WR main office in Jeddah through an arranged visit in February 2008. Fig. 3.4 shows the SEC-WR 380 kV Network.

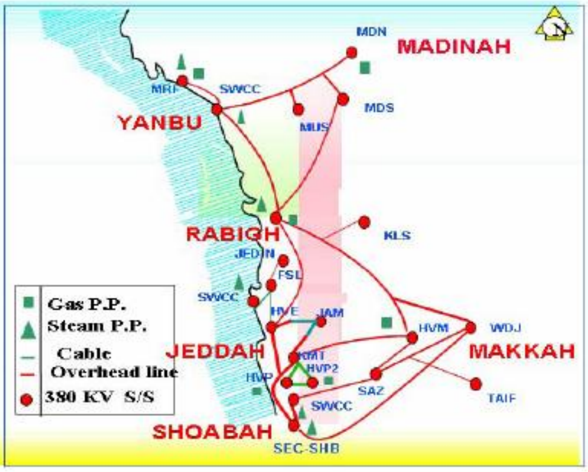


Figure 3.4: SEC-WR 380 kV Network (Source: SEC)

3.3.1 Generation sources

The SEC-WR actual 2005 generation capacity at Peak load is 8727 MW including 1028 MW import from the Saline Water Conversion Corporation (SWCC) Power Plants. The peak output recorded until now (2005) is 8559 MW. This load includes network losses and auxiliary power plants load. The actual capacity of the SEC-WR Generation System is shown in Table 3.1.

Power Plant	S.T	C.C	G.T	2005 output (MW)	Actual Capacity (MW)
Rabigh	6	3	12	2584	2584
SEC-SHB	5	-	-	1998	1998
PP3/Jeddah	-	-	33	1541	1650
PP2/Jeddah	-	-	3	58	58
Makkah	-	-	18	758	760
Madinah	-	-	9	283	285
Taif	-	-	6	75	75
Yanbu	-	-	1	45	45
Royal Com.	3	-	7	189	244
SWCC-Jeddah	6	-	-	400	400
SWCC-Yanbu	5	-	-	180	180
SWCCShoaiba	9	-	-	448	448
TOTAL	34	3	89	8559	8727

S.T : Steam Units C.C : Combined cycle G.T : Gas Turbine

Table 3.1: 2005 SEC-WR GENERATION SYSTEM ACTUAL CAPACITY

The existing SEC-WR 380 kV Network is connected with Makkah, Jeddah including SWCC Jeddah, Rabigh Plant and Al-Madinah including SWCC Yanbu and Yanbu Area (Fig. 3.4). The 110 kV sub-transmission network in Jeddah City is divided into eight electrical islands fed radially from the 380 kV primary transmission network.

In Makkah the 110 kV Network is divided into three islands including Taif network. The 110KV network in the other cities in the area is operated as one island.

The SEC-WR power network comprises five main power plants; three main SWCC power plants, seventeen 380 / 110 kV substations; about 160, 110/33 and 110/13.8(11) kV substations, more than 5000 km of 380 kV and 110 kV over-head transmission lines and underground cables, and a distribution network exceeding 56000 km of mainly under ground 33 kV and 13.8 (11) kV cables.

The Royal Commission (RC) power system in Yanbu Industrial City (MARAFEQ) is interconnected with SEC-WR System.

3.3.2 Load profiles

Actual load data have been collected for residential and industrial areas in order to build a realistic model. Many types of load profiles are obtained from SEC-WR with different time intervals including the following (full data is represented in Appendix B):

- Daily load profile in summer with one hour intervals for the main cities in the western region of Saudi Arabia (Fig. 3.5).

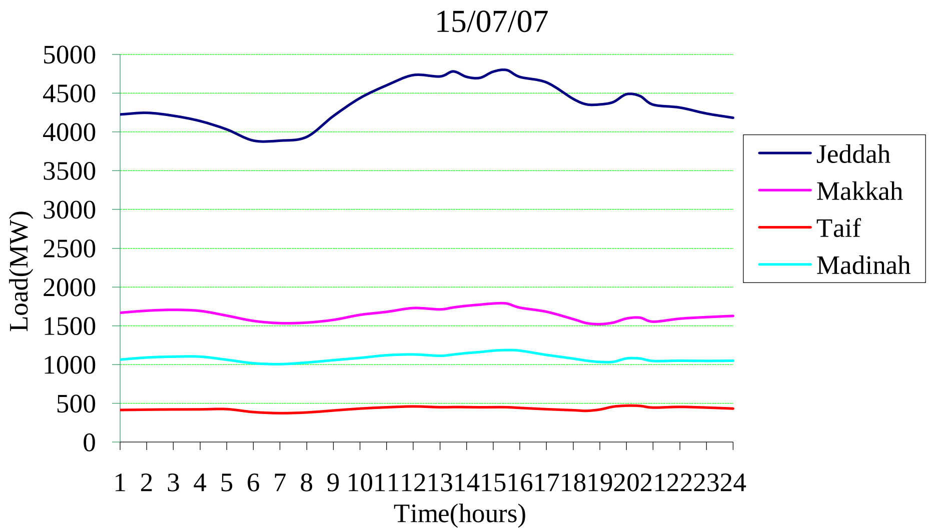


Figure 3.5 Cities load profile on 15/07/07

- Daily load profile for the middle of each month at 30 minute intervals for a residential area. (Fig. 3.6)

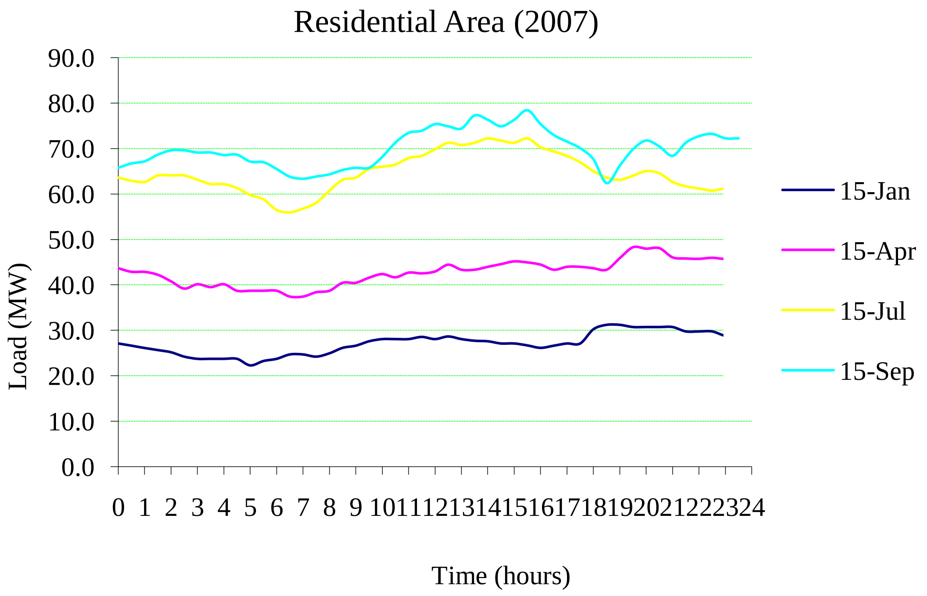


Figure 3.6 Residential area load profile of about 5000 houses

- Daily load profile for the middle of each month at 30 minute intervals for an industrial area. (Fig. 3.7)

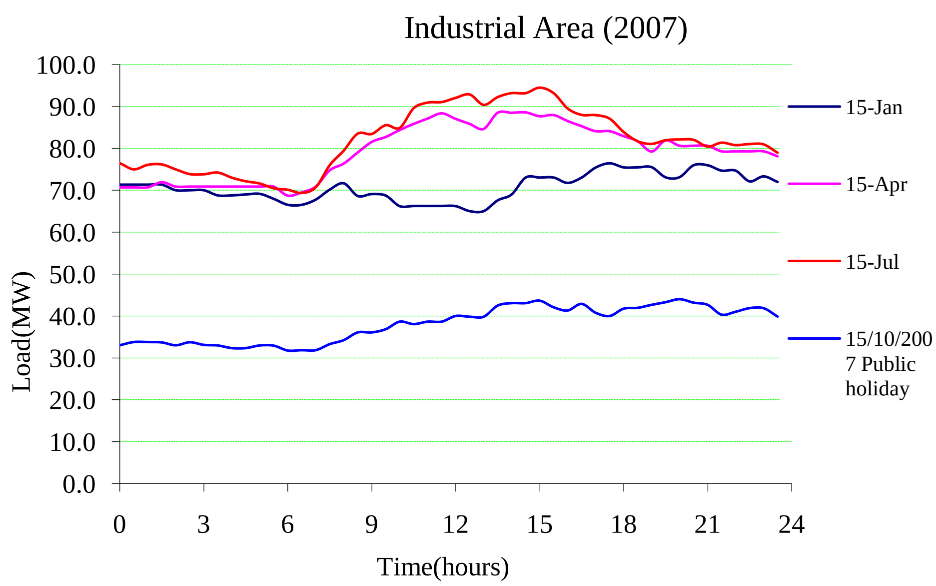


Figure 3.7: Industrial area load profile

A sample of load data obtained from SEC for residential and industrial areas is shown in Appendix B.

In both residential and industrial areas, the air-conditioner load represents a high portion of the power demand. So, the peak load occurs in the middle of the day which coincides with the maximum temperature recorded. The effect of the air-conditioner load remains relatively constant throughout the day and night for residential areas.

3.3.3 Distribution system in residential and industrial areas

The power distribution system of the Saudi SEC-WR is operated in a radial configuration where there is one source and the feeders extend radially from the source. As shown in Fig. 3.8, a power grid supplies the distribution network through a 380kV/110kV step down transformer. The distribution network consists of a number of main (primary) substations (ISK11, RSF04, ISK10) each are equipped with a HV/MV transformer to step down the voltage level and feed a number of medium voltage (MV) feeders. The feeder starts from the main substation bus and low voltage feeders are tapped off at every secondary substation.

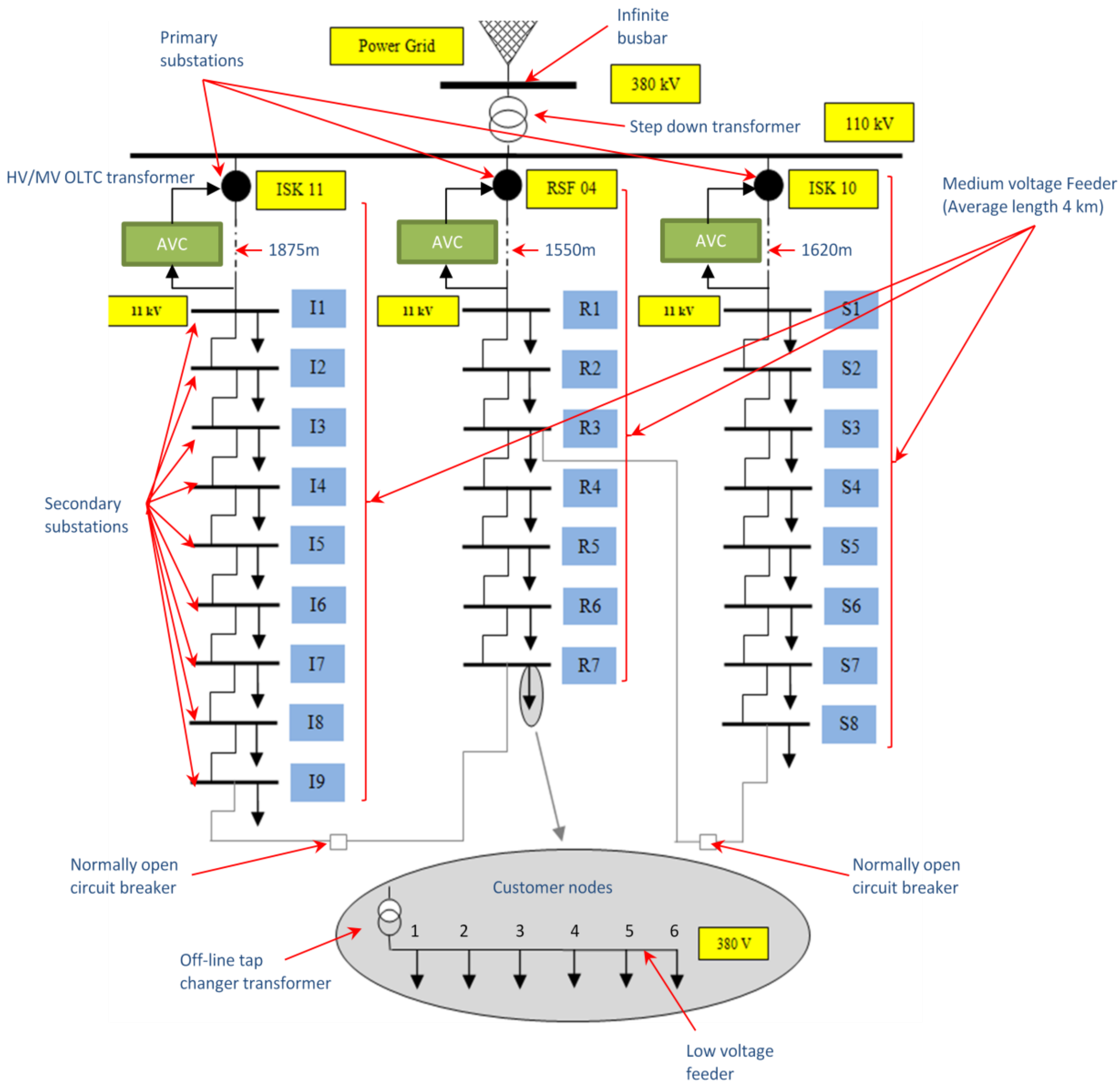


Figure 3.8 Typical distribution network

The voltage drop along the MV feeder depends on the feeder loading, where the maximum voltage drop occurs during peak load. The voltage along the feeder should be within ± 5 percent of the nominal voltage. In order to keep the voltage within this limit, the SEC-WR uses on-line tap changers (OLTC) at primary substations and reactive power compensation. For the MV/LV secondary substations (I1-I9, R1-R7, S1-S8 in

Fig. 3.8), the company does not use any on-line regulation technique such as an (OLTC) transformer, an automatic voltage controller (AVC), a reactive power compensator or a line drop compensator (LDC) to control the voltage along the feeder. However, in order to regulate the voltage along the low voltage feeder, a very restricted design for the feeder with very high safety factor for the secondary substation transformer rating, cable specifications and maximum length of the feeder has been used. Through the experience of the company this method is mostly adequate except for very rare cases when the voltage becomes very low for the farthest customer from the substation. In this case, the company needs to change the tap of the substation transformer manually (so called off-line tap changing). Because of this method that is used in preparation of any new feeder, it has been found that most feeders in residential areas are typical of this design. They have almost the same number of customer connected to them; have the same length and the same impedances.

For industrial areas, the SEC uses another technique to connect each customer. Therefore, instead of connecting all the customers along a feeder; a direct cable from the substation is used for each customer. It uses this type of connection to increase the protection level of the system

The layout and operation of the network used by the company have been provided by the company for this study.

In order to gauge the impact of PV generation on power system performance it was first necessary to model the PV system as synchronous generators operating at unity power factor coupled to a typical power system distribution network. Data required for the synchronous generators were obtained using commercial software, PVSYST, and solar radiation data. Another commercial software package ETAP was used to model a power system coupled to the grid, having medium volt feeder and customer feeders. Customer loadings were taken for typical data obtained from SEC. each customer was assumed to have a PV generator system connected directly to the feeder at the customer property.

3.4 Impact of DGs on distribution networks

Traditionally, the distribution network of a power system is a passive network with a radial configuration. Electric power flows one way from a substation to a large grid distribution network. During normal operation or planning period, a steady-state analysis of voltage regulation, system losses, protection coordination, power quality, and system reliability must be performed to ensure proper operation within appropriate operating range. Each utility has its own operation and planning criteria depending on distribution system characteristics and philosophy of design criteria. This chapter will investigate the influence of using GCPV on voltage regulation of residential area networks.

Traditionally, distribution networks are designed to transfer power from the transmission network and distribute it to the loads. It is not normally designed to have generators directly connected to it. The distribution network topology and its control and protection are all designed assuming that power is flowing in one direction, from transmission system to loads. The connection of DGs to the feeders of the distribution network can cause the power flow to be bi-directional instead of unidirectional affecting the network performance and stability in a number of ways. An extensive literature review on the impact of connecting DGs systems to electric networks [26, 54] has shown that the most serious impacts that could not be resolved using conventional techniques were found to be the impact of the DGs on voltage regulation. In the following subsection, this implication will be discussed in more detail.

3.5 Impact of DG on voltage regulation

Considering a DG connected on Bus#2 of Fig. 3.9, and the associated active and reactive power output, P_g and Q_g respectively, eq. 3.1 can take the following form:

$$\Delta V \approx \frac{R(P_L - P_G) + X(Q_L - Q_G)}{V_1} \qquad (3.1)$$

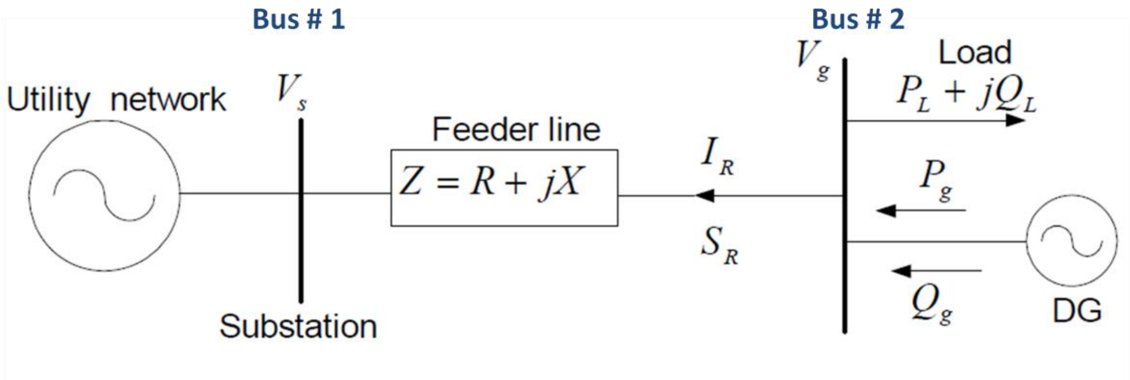


Figure 3.9 Utility network with DG.

Theoretically, eq. 3.1 describes how the voltage level is changed at the point of connection of the DG. In the following section, the conventional voltage control method will be discussed, followed by the impact of the DG's presence on such voltage control technique.

3.5.1 Conventional voltage control

A distribution network consists of a number of main substations which steps down the voltage level and feed a number of branches. Fig. 3.8 shows a typical distribution network in Saudi Arabia. The branch starts from the main substation bus and number of feeders is tapped off through secondary substations.

Each MV feeder is equipped with a HV/MV on-line tap changing transformer (OLTC) that has the ability of changing the voltage level of the branch at the main substation bus. The voltage drop along the branch depends on the feeders loading, where the maximum voltage drop occurs during peak load with an inductive character (see eq. 3.1). The LTC and its associated automatic voltage controller (AVC) regulate the voltage at the substation end to compensate for the voltage drop due to the change in loading. The aim is to always keep the voltage along all feeders within ± 5 percent of the nominal voltage. Normal practice is to sense the load current (local to the transformer) and use this to estimate the voltage drop on the feeder at the remote load centre according to the following equation:

$$V_s^{desired} = V_{LR}^{set} + I_L.(R_{set} + j\,X_{set}) \tag{3.2}$$

where I_L= load current, V_s = substation bus voltage, and V_{LR}^{set} = voltage required at the remote load centre. R_{set} and X_{set} inside the AVR are adjusted to correspond directly to the branch's impedance. Thus the substation bus voltage is adjusted to ensure that the remote load voltage is within acceptable limits.

3.5.2 Impact of DG on Conventional voltage control

As previously indicated, in a conventional feeder the voltage level is regulated by the AVR, which estimates the voltage drop over the branch by measuring the branch current at the main substation end. However, this depends mainly on the simple fact that the power is unidirectional from the main substation bus (where the AVR is located) flowing into the end of the branch. The presence of DGs on feeders makes the power bi-directional, and if the DGs connected to feeders are carrying most or all of the branch load, then the voltage profile along the feeders depends mainly on the DGs' location, power generated, and the DG power factor. This creates an unpredictable and uncontrolled situation where the voltage level of all nodes might or might not be within acceptable limits. If a number of DGs are connected to feeders along one of the branches in Fig. 3.8 and carry most of the branch load, the current flowing from the on-load-transformer will be very low. The AVR will assume that this case is the same with the branch's load at the minimum level; therefore it will adjust its voltage level to 1.00 p.u. This will cause a voltage rise at the point of connection and in the surrounding network.

So, the conventional voltage control technique cannot properly adjust the voltage level of feeders with various DGs connected to them, since it depends mainly on measuring the branch's current at the main substation end, which is no longer a good indication of the feeder status. Therefore, a new technique must be developed to facilitate the coordination between DGs and the LTC for safe integration of a larger PV and better voltage control.

3.6 Impact of high penetration level of Grid-Connected PV systems on voltage regulation of a residential area network in Saudi Arabia

It is difficult to regulate voltage in rural areas, which have long distance distribution lines, on account of a large voltage drop caused by customer loads. Therefore, electric distribution utilities may install capacitor bank and/or Automatic Voltage Control (AVC) distributed in the system to provide a voltage boost, which cancels part of the voltage drop. In addition, capacitor banks not only reduce losses by cancelling the reactive power from the customer load, but also improve the power factor of the system. Load variation, location, type and size of capacitor bank affect the voltage regulation (VR) of the distribution networks. These parameters have to be analyzed for better system performance with optimum investment. For long distribution lines where the voltage at the end of feeders is outside the acceptable range, distribution utilities normally install AVCs in those feeders with line drop compensators (LDC).

AVC is an autotransformer with automatically adjustable taps. If the voltage is out of bounds, the controller makes tap changes until the voltage is brought within bounds.

In practice, the voltage level along with the distribution feeder decreases due to the voltage drop caused by system loads. If AVC is installed in the system, the voltage level will be raised at the secondary side of AVC. The LDC is used to compensate the additional voltage drop on the line between the transformer and load location, particularly at the far end of the feeder. If distributed generators such as PV are installed in the distribution network, voltage profile and system losses may be changed.

3.6.1 Modelling of a residential network

In order to study the effect of GCPV systems on voltage regulation of a distribution network, the typical residential network shown in Fig. 3.8 was used as the base case in this study.

The distribution network starts from the Station bus at 110 kV, through a step-down 110/11 kV power transformer at each primary substation (ISK11, RSF04, and ISK10) connecting to 3 branches. Each branch includes a number of secondary substations (labeled as I1, I2,I9, R1,....R7,S1....and S9), connecting to a customer feeder through another step-down 11/0.38 kV transformer (see detail in Fig. 3.8)

There are 6 load nodes tapped off from each MV feeder. Each MV feeder is equipped with on-load tap changing transformer (LTC) that has the ability of changing the voltage level of the branch at the main substation bus in small steps (0.5% of nominal voltages), adjusted by the automatic voltage controller (AVC). The main branches can be interconnected through normally-open circuit breakers in the case of outage of one of the 110/11 kV transformers.

Since this study is concentrating on the effect of GCPV on the voltage regulation in the network under normal operation (no faults), the longest branch which is ISK11 will be the most sensitive because it will have the largest variations for the different load and irradiation scenarios. The line parameters of this branch are shown in Table 3.2.

From Bus	To Bus	Length (m)	Impedance (Ω/km)
ISK11	I1	1875	0.128+j0.1344
I1	I2	15	0.128+j0.1344
I2	I3	327	0.128+j0.1344
I3	I4	153	0.128+j0.1344
I4	I5	513	0.128+j0.1344
I5	I6	396	0.128+j0.1344
I6	I7	132	0.128+j0.1344
I7	I8	648	0.128+j0.1344
I8	I9	255	0.128+j0.1344

Table 3.2 MV line parameters of ISK11

3.6.2 Load conditions

Real load data for the selected residential area has been collected from the Saudi Electricity Company in the Western Region (SEC-WR) who has also provided details of the transformers and lines of the network. Based on this information a detailed model of the distribution network has been created in ETAP. Fig. 3.10 shows the average daily load profile for this area during each month. This area includes 5000 residential properties.

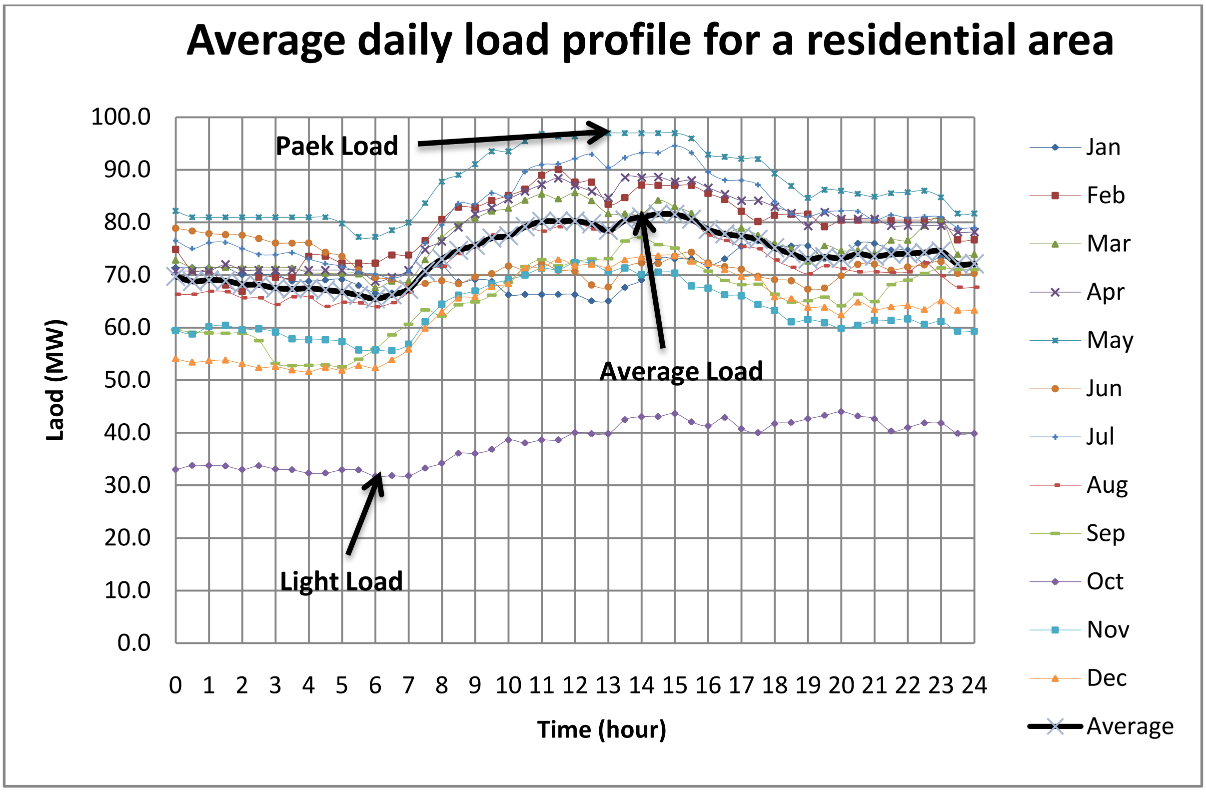


Figure 3.10 Average daily load profile for a residential Area

A considerable part of the load is due to air conditioning (A/C) systems and in general the load reaches its maximum between noon and 16:00 h in summer. This type of load can reach 65 per cent of the total load during summer and since the A/C systems are motor-driven, this reduces the power factor (PF) of the total load to approximately 0.85. The minimum load is equal to about 30% of summer peak load. Therefore, the following situations with and without PV generation are studied:

1. Voltage profile at peak load condition and 0.85 PF(inductive).
2. Voltage profile at 40% of peak load.

3.7 Modelling and Simulation of distribution systems

3.7.1 Modelling softwares

In this work, two software packages have been used:

1- PVSYST (version 4.21): was used for sizing, simulation and data analysis of complete PV systems including solar panels and inverters. It is suitable for grid-connected and stand-alone systems. It also offers an option to use any meteorological data. Furthermore, it has a large PV-components database which gives the ability to model most of the commercially available solar panels type connected to suitable inverters. The main purpose of using this software in this study is to find the total power output for different size of PV system based on the solar radiation data for that area. The solar radiation data has been collected from King Abdul-Aziz City for Science and Technology (KACST) for selected areas.

2- ETAP (version 4.0.0): is a comprehensive analysis platform for the design, simulation, operation, control, optimization, and automation of generation, transmission, distribution, and industrial power systems. Its modular functionality can be tailored to fit the needs of any network, from small to large power systems. The main purpose of using this software in the study is to model the electricity networks in residential and industrial areas based on real load for each area. Also, the software will be used to find the problem caused by the grid connected PV systems and apply the proposed solution techniques.

3.7.2 Modelling of PV generators

PV generators are connected to the grid through power-electronic inverters. The current generations of PV inverters operate at unity power factor. So, their behavior during steady state is almost the same as that of a Synchronous Generator (SG). Therefore, a SG with unity power factor is used in ETAP to represent each PV generator.

The solar radiation data for this study has been obtained from King Abdul-Aziz City for Science and Technology (KACST) which has 40 stations around the country recording the solar radiation every 5 minutes. The monthly average solar radiation that was recorded at Jeddah meteorology station for year 2002 is shown in Fig. 3.11.

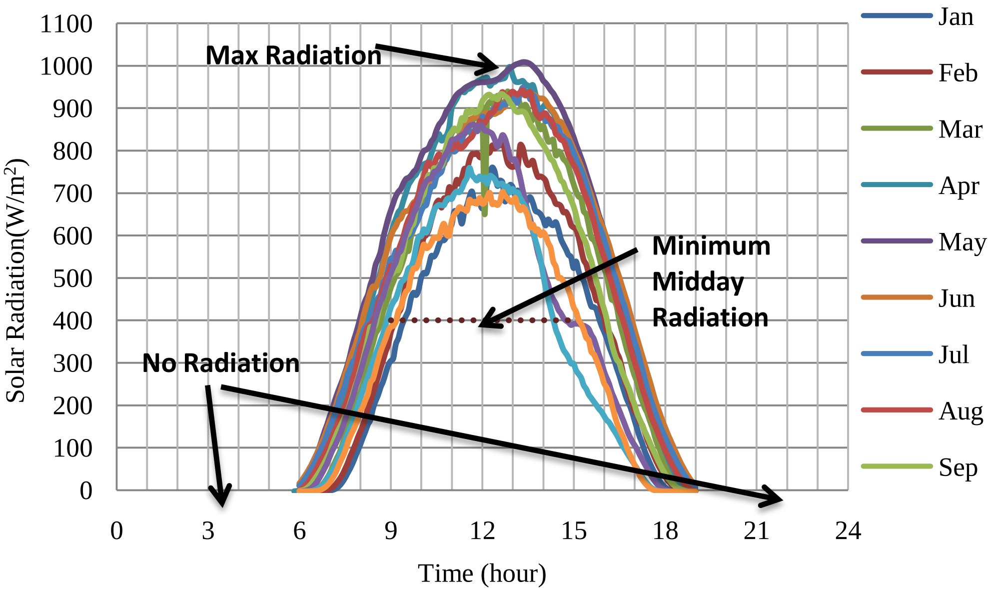


Figure 3.11 Monthly average solar radiation, Jeddah 2002.

Fig. 3.11 shows clearly that large amount of solar radiation occurs between 9:00 to 15:00 throughout the year with minimum value of 400 W/ m^2 and maximum value of about 1000 W/ m^2.

3.7.3 Residential Networks

Only one actual LV feeder described in Fig. 3.8 has been considered first. The branch I1 to I9 is not simulated at this stage. Furthermore it is assumed that no PV generators are connected to the feeder. The system has been modelled and simulated using the ETAP software package as shown in Fig. 3.12. The loads are modelled as constant impedance loads at every test, set to a given value corresponding to the real load demand at that time. The test has been repeated for every half hour at day time to get the full day load and voltage profile.

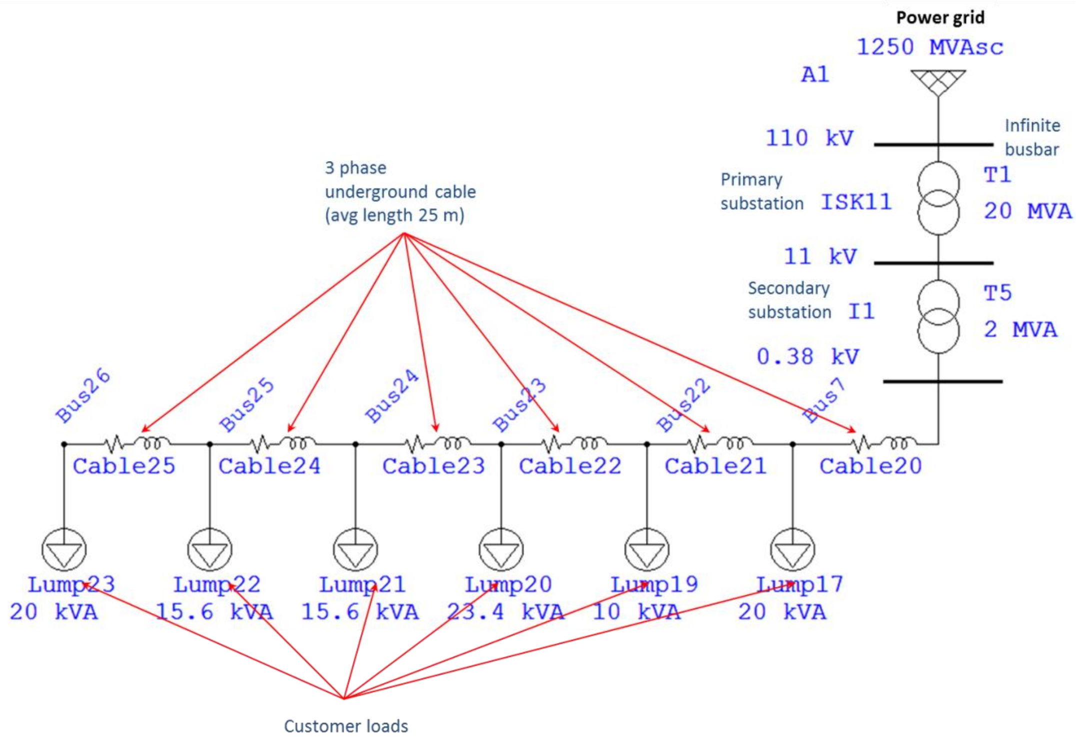


Figure 3.12: The network model simulated by ETAP

The main characteristics of the feeder are shown in Table 3.3.

Feeder nominal line voltage	380 V
Network nominal frequency	60 Hz
Substation transformer capacity	2 MVA
Cable Type	Aluminum conductors
Cable size	185 mm^2
Cable length	According to exact situation, ranging from 20m to 30m
Cable Impedance(Ω/km)	0.19385+j0.10524
Load data	Real data obtained from SEC, ranging from 0 kW to 20 kW

Table 3.3 Characteristics of the studied feeder

The PV output was calculated by PVSYST based on real irradiance data obtained from KACST. In this study, the use of PV module of 90 W_{peak} , comprised of mono-Si Solar cells from BP Solar has been selected as one of the commercial panels in the market. Also, it has a model in PVSYST software package. The specifications of the module are summarized in Table 3.4.

Item Description	Item specification
Peak power @ standard test conditions (STC) (W)	90
Voltage @ peak power (V)	18.5
Current @ peak power (A)	4.86
Voltage [open circuit] (V)	22.3
Current [short circuit] (A)	5.2
Frame size (m^2)	0.63
Thickness (mm)	43.5
Width (mm)	530
Length (mm)	1188
Weight (kg)	7.5
Certification	Canadian Standards Association (CSA) , California Energy Commission (CEC)

Table 3.4 PV module specification

The output power of any PV system depends on the size of the system. Since in this research Building Integrated photovoltaic (BIPV) systems will be used to address the effect of such system on voltage regulation, the available roof area of the selected buildings must be known. The average available roof area for PV installation on houses in a residential area is about $100m^2$. This figure comes out from about 29 different designs of residential houses in Saudi Arabia. Fig 3.13 shows the satellite view of the selected area that used in this study . It shows also the total land area for each customer which is about 500m^2 but the house is constructed on about 300m^2. Also, 100m^2 in the middle of the roof space are used for the water tank and its connection and another part usually used as storage or utility area which needs another area as a pathway. These make it possible to integrate 100m^2 of PV or more in this particular design.

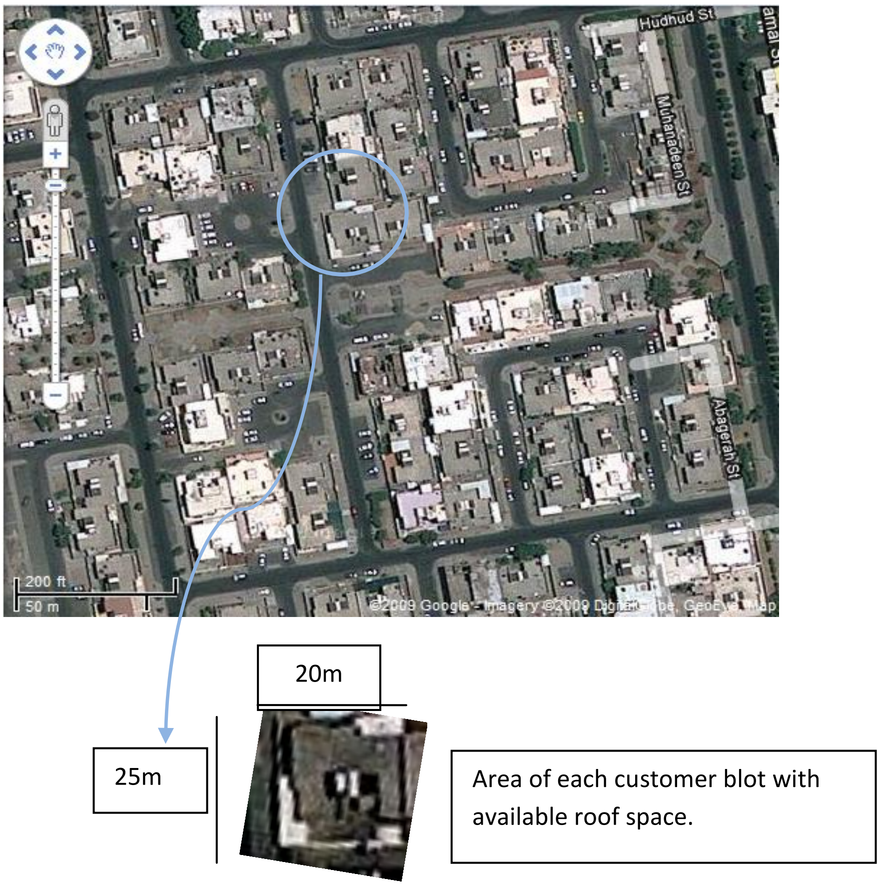


Figure 3.13 Satellite view of the area use in this study (Source:google map).

Different sizes of PV system are modelled by PVSYS software package using the solar radiation data collected from KACST in order to simulate the PV output. Fig. 3.14 shows the output power of different size of PV system in summer.

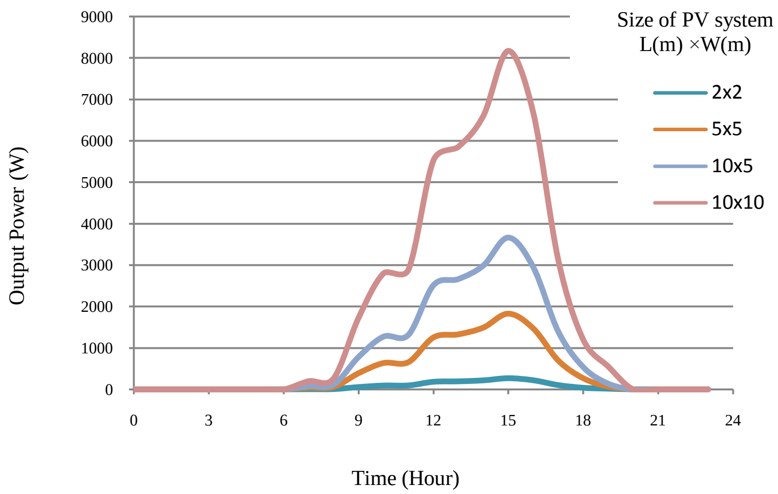


Figure 3.14 The output power of different size of PV system in summer.

As can be seen from Fig. 3.6 and Fig. 3.14, the electricity demand pattern in Jeddah matches closely the maximum output of the PV system on day time. Hence this favours the usage of PV electricity generation to meet the peak load requirements during day light hours throughout the year.

Standard PV panels have been considered in this study, which limit the amount of the PV panels that can be placed on each house.

The present work deals with the case in LV distribution networks with small PV systems, which are typically integrated in the form of roof top PV systems.

3.8 Conclusion

In this chapter general information on Saudi Arabia include the weather and solar radiation data is presented. A brief description of the power system and the current applications of PV systems in Saudi Arabia are also mentioned. Following that, a design of a residential network presented using ETAP software package. Furthermore, the PVSYST used to determine the total power generated by different size of standard PV cells. The next chapter will investigate the impact of integration standard and concentrated PV cells into distribution networks in Saudi Arabia.

Chapter 4

4 Simulation of conventional PV in residential and industrial networks

4.1 Introduction

The main objective of this chapter is to study the impact of linking commercial and concentrated PV directly with the grid in distribution networks in Saudi Arabia. The effect of this type of integration will be assessed to find the level of penetration that can be tolerated without any technical changes in the existing network operation. Also, the ability of GCPV systems to reduce the total and peak load demand in the selected networks is studied. To achieve that, data from the previous chapter is used to design a model which represents an actual network with real data for both loads and irradiance by using the power systems simulation package ETAP.

4.2 Simulation procedures

As shown in Fig. 4.1, various steps were carried out on order to run the simulation and achieve the required results. Solar radiation data was imported into PVSYST software package using commercial panels to determine the total output PV power that can be generated. Simultaneously, the load data was plotted and the maximum pattern was chosen. Both output PV power data and the maximum load pattern were plotted in Microsoft Excel in order to understand the affect of commercial PV on the load pattern.

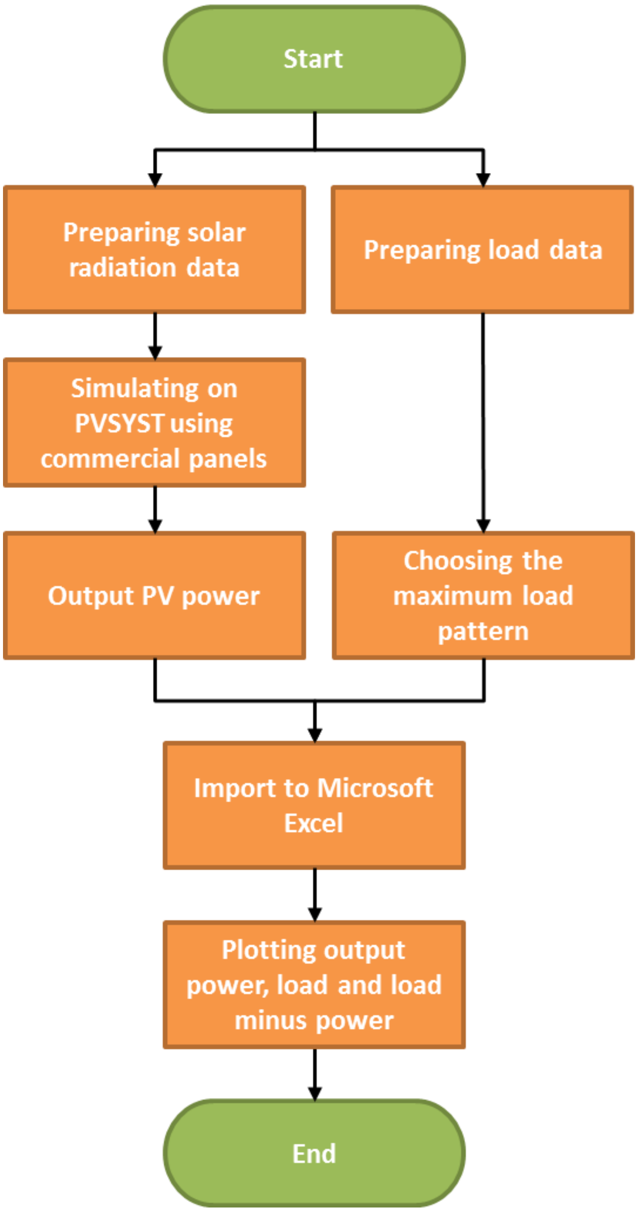


Figure 4.1 Simulation flow chart for calculating the impact of using conventional PV

4.3 Model parameters used

Data presented in chapter 3 are used in the simulation presented in this chapter. This includes solar radiation data, load data and network parameters. These can be obtained from Fig. 3.8, Fig. 3.10, Fig. 3.11, Table 3.2 and Table 3.3.

4.4 Simulation output for conventional PV generation in residential networks

In order to focus on an actual case, a real residential feeder managed by SEC-WR is taken into consideration assuming that is connected to 110 kV infinite bus-bar. This, however, does not diminish the generality of the conclusions drawn, especially since it has been shown that the most residential feeders are typical in design.

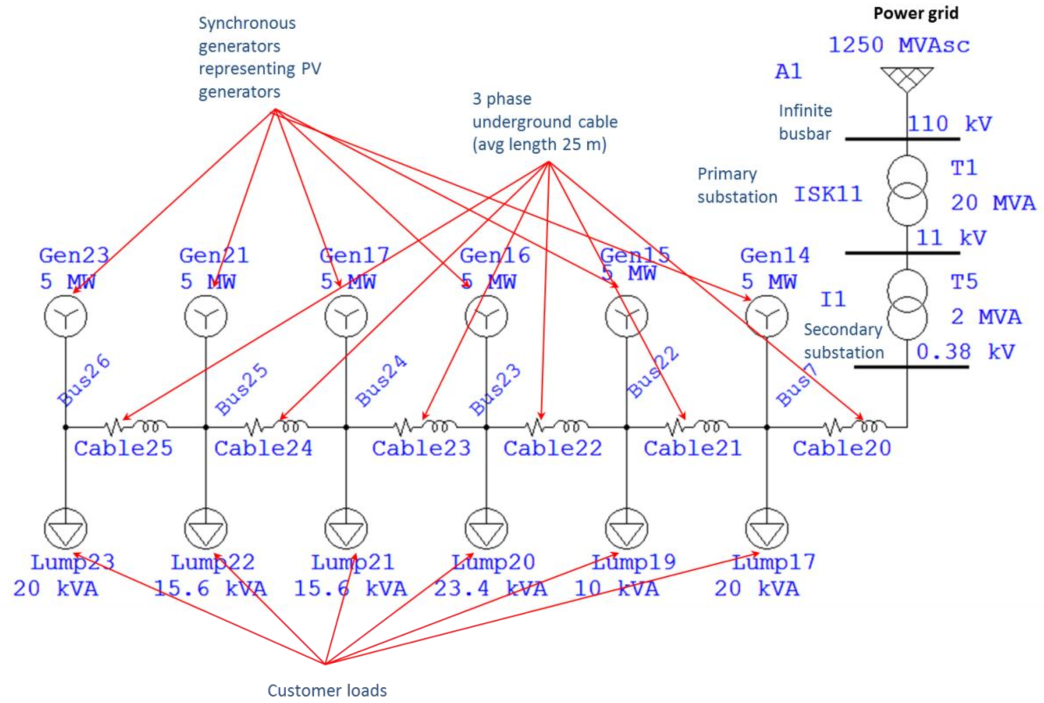


Figure 4.2 The network model simulated by ETAP with the PV systems integration modelled as synchronous generators at each customer location.

At each node a PV system is connected and represented by a synchronous generator with a unity power factor and its output power set according to the results obtained from the PVSYST at that time. Fig. 4.2 shows the simulated model.

In order to show the impact of the grid-connected PV system, Firstly, a model was been designed to represent the realistic feeder with its load without any integration of PV generation. Fig. 4.3 shows the voltage profile for each consumer along a feeder. In this case a maximum load pattern for each costumer has been considered. Even in this case, which represents the extreme case, the voltage level of the last customer does not reach the minimum limit of the voltage and this shows that the method used by the company to maintain the voltage within its limit is adequate.

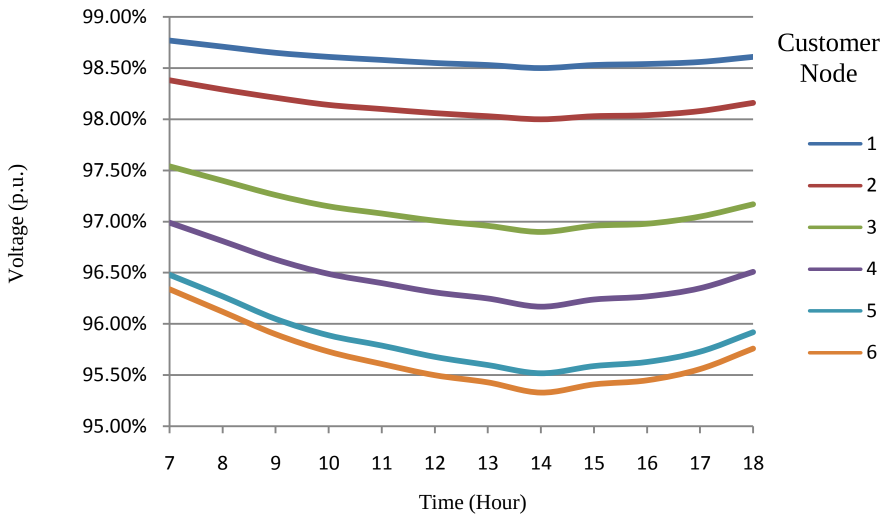


Figure 4.3 The voltage profile of each customer at peak load pattern (no PV generator).

Secondly, integration of standard PV system at each node was considered. Since, standard solar panels were considered in this study and the instant match between the peak load and the PV output throughout the year, the PV output never exceeds the customer load throughout the year. This means that the PV system will not feed excess power into the utility grid.

Fig. 4.4 shows the voltage profile of each customer along a feeder with 100% PV penetration which means all customers have a commercial (5m*10m) PV panel.

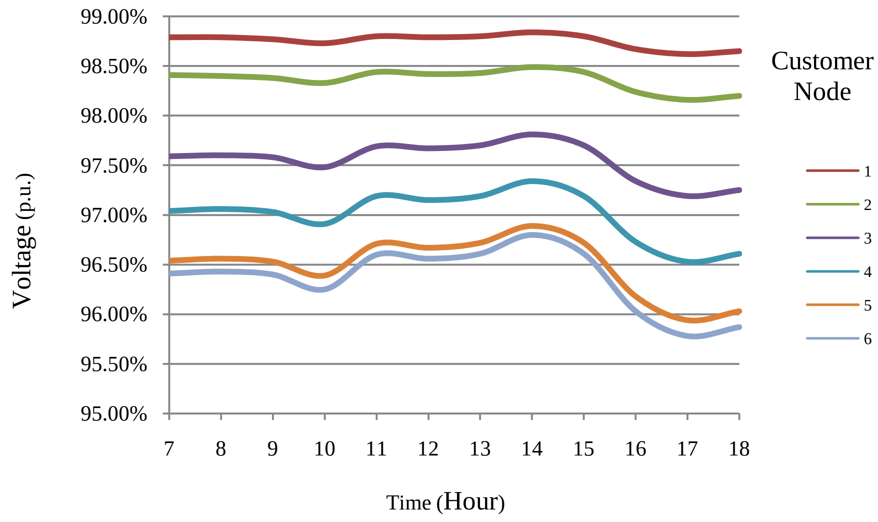


Figure 4.4: The voltage profile of each customer with 100% PV penetration.

The simulations show that the voltage rise over the line voltage limit will not happen. At the same time, it will improve the voltage profile along the feeder as shown in Fig 4.4. Furthermore, it will reduce the peak load delivered from the utility grid to each customer by about 42% (6.3kW) and reduce the daily average power from 13kW to 11.1 kW as shown in Fig 4.5. These figures represent the minimum reduction in the system because the maximum recorded pattern of the customer load has been used.

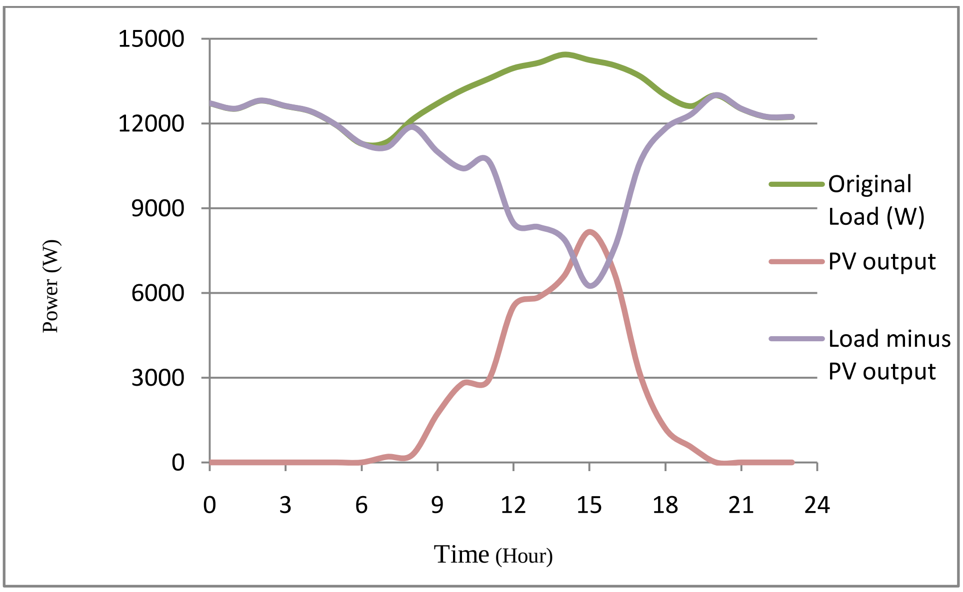


Figure 4.5 Impact of the PV system on the customer load profile.

4.5 Simulation output for conventional PV generation in industrial networks

Another case has been investigated for an industrial area in Jeddah. Fig. 4.6 shows the typical industrial network where each customer is connected directly by a cable from the substation with average distance of 100 m. The average roof size available in this industrial area which called IC3 in Jeddah is around 400m^2. The same model for the PV panel used in the previous simulation will be used in this case.

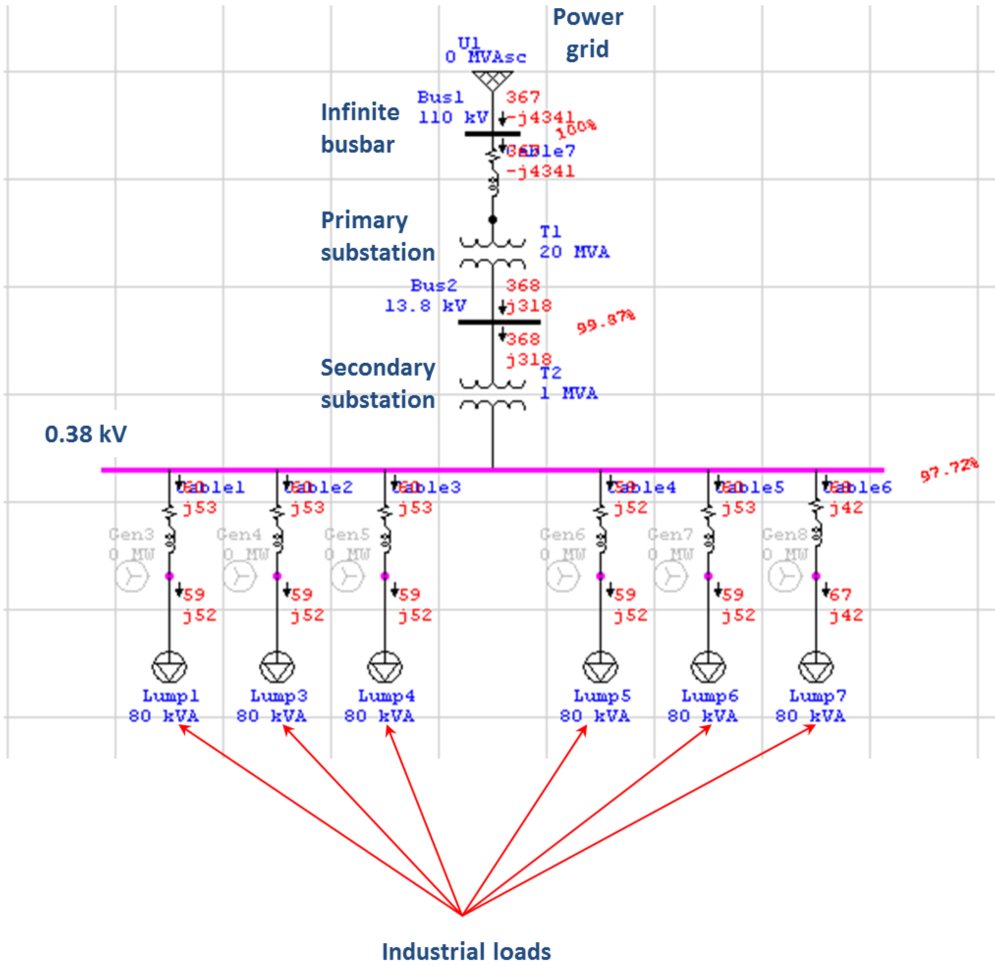


Figure 4.6 The network model simulated by ETAP for part of industrial area.

Fig. 4.7 shows the power generation from the PV system using the PVSYST software package. The maximum load data is used as shown in Fig. 3.7. In addition, maximum PV output in Fig. 3.14 is assumed. The results show clearly that the power generating from the commercial PV panels will hardly exceed the load demand throughout the selected year (2007) (Fig. 3.7).

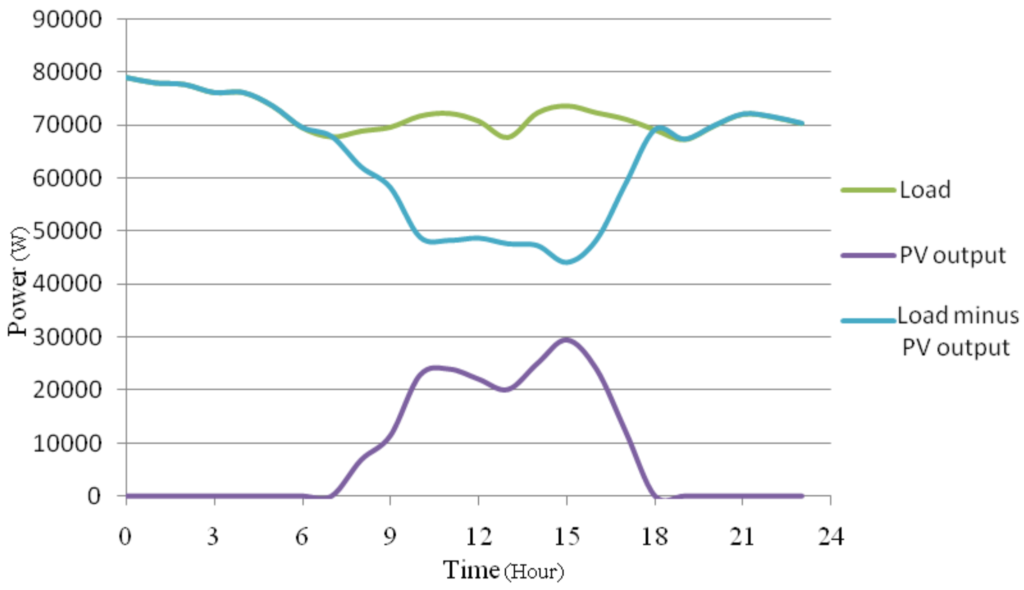


Figure 4.7 Impact of the PV system on the load profile for industrial customer.

Therefore, the case of injection power into network using standard PV will be very rare to happen in this case even at the time of public holidays when the industrial load is at minimum level. However, this case could change because some public holidays are based on the Arabic calendar which has also 12 months a year but around 354 to 355 days. This will make the Arabic calendar month not fixed with the seasons. So, for example, if the public holiday is in the summer this year it will be in winter after 15 years and the situation may change. In saying that, again it seems that there is no limit for integrating the commercial (standard) PV panel at industrial area networks.

4.6 Simulation output for concentrated PV generation in residential networks

Three scenarios for each situation have been considered:

1. Without PV generator.
2. With 14.4 kW PV generator installed at all customers.
3. With 36 kW PV generator installed at all customers.

Then for each case, the voltage levels at each substation along the branch ISK11 and the node voltage of each customer have been determined. Fig. 4.8 And Fig. 4.9 shows the results of these calculations in detail.

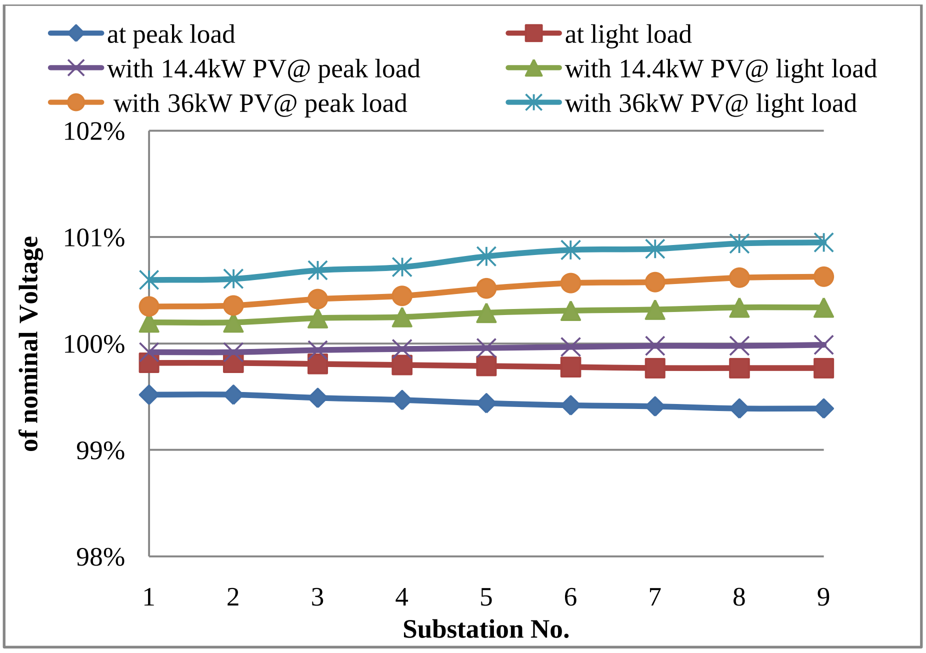


Figure 4.8 Voltage profile of ISK11 branch.

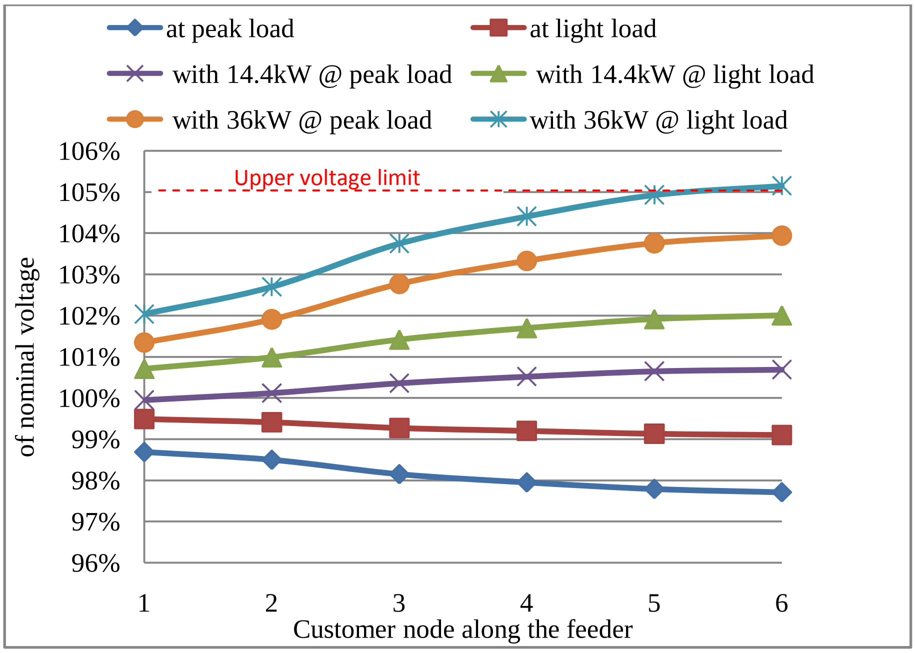


Figure 4.9 Voltage profile of I9 feeder.

The results show that the integration of PV generators increases the voltage at each substation along the branch and also increases the voltage of each customer. For most of the cases the voltage level remains within the permitted levels except for one rare case when the maximum solar power is delivered at light load. Even at this case, the voltage exceeds the limit for only the last two customers of the last feeder connected to main branch by a very small margin. However, this problem can be solved by one of the following methods which required only modest changes in the current network:

1. Disconnecting the PV generator at the affected node.
2. Using the off-line tap changer of the substation that controls the affected customers.
3. Operating the PV generator at 0.9 lagging power factor.
4. Using the on-line tap changer at the primary substation.

Fig. 4.10 and Fig. 4.11 show the effect of these measures and confirm that these proposed techniques can be used to mitigate the problem of voltage rise in the residential area.

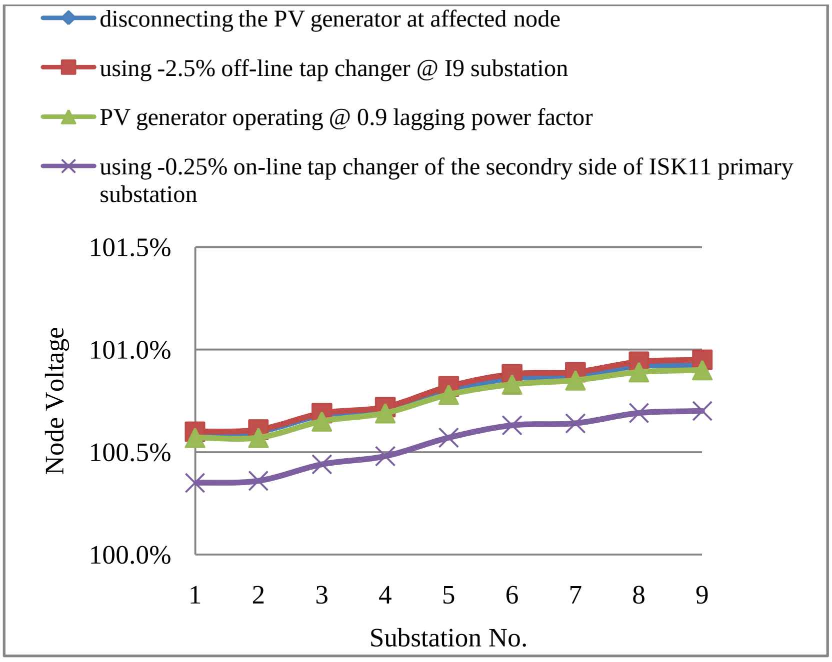


Figure 4.10 Voltage profile of ISK11 branch with 36kW PVs and light load.

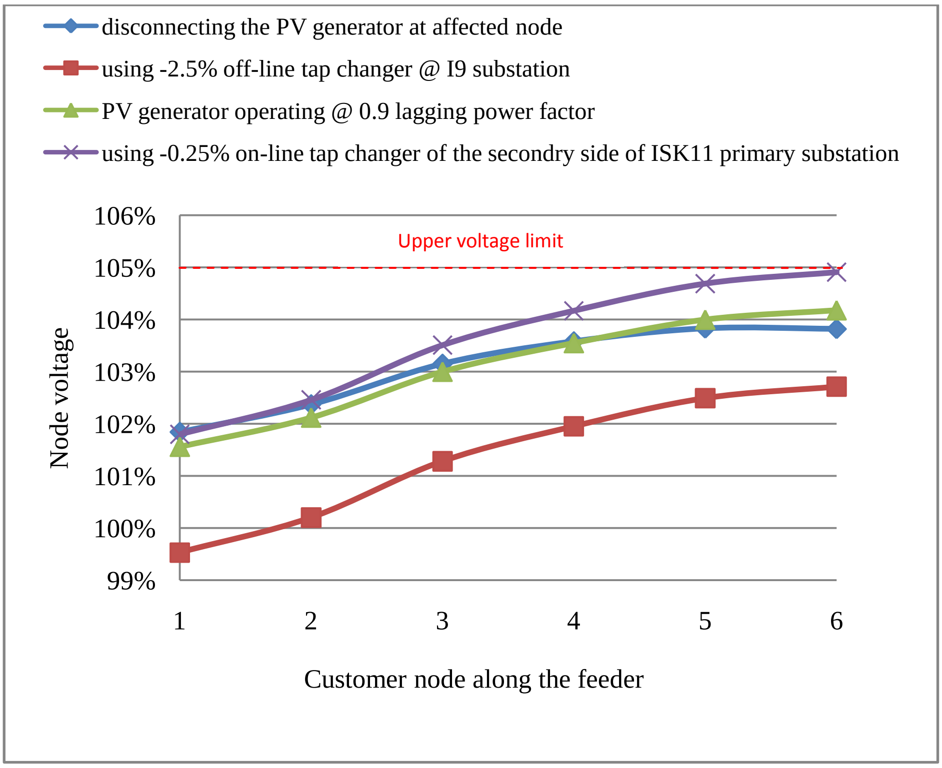


Figure 4.11 Voltage profile of I9 feeder with 36kW PVs and light load.

Disconnecting the generator at the affected node proposed as a straight forward method to solve voltage rise problem. However, this solution is not desirable from the customer side that is most likely the owner of the generator. Also, since it has been assumed that storage batteries are not used, the lost energy makes this method not recommended.

Changing the off-line tap changer of the substation transformer to -2.5% has the most effect on the voltage profile between itself and the last customer along the feeder. This method reduces the voltage at the end node to about 102.8% of nominal voltage. But it needs the DNO to dispatch an engineer to manually alter the substation transformers' tap changers each time the voltage exceeds or goes below the limits. These cases will occur frequently with using PV generators which changing its power during the day and switch off at night. All of these make it difficult to implement this method.

It seems that the most appropriate methods to deal with voltage rise problem caused by using GCPV system in residential area are using on-line tap changer at HV/MV prime substation or reactive power consumption at the PV generator. The next section represents the other methods that can deal with the voltage rise issue caused by DGs.

4.7 Conclusions

The results show a significant benefit of using grid connected photovolatics (GCPV) system in the Saudi utility network. It would reduce the energy supplied from the main generators and help to decrease the peak demand load. Also, this work shows that there is little impact of PV systems penetration in the distribution network if the commercial or low efficiency solar panels are used. Also, in this chapter the effect of a high penetration level of PV generation on the voltage regulation in a residential network has been studied. In general, the results show that SEC has a very strong network in residential areas. The voltage rise problem, which is considered as one of the important issue in the use of GCPV systems will occur infrequently to happen in that type of network. Only when using concentrated PV technology with high efficiency at high solar radiation and light load could the voltage limits be exceeded. However, if it occasionally occurs, methods such as operating the PV generator in lagging power factor or use of the OLTC which is usually exist in the primary station can be used to mitigate the problem. This research will be extended to cover a larger area of the distribution network connected to the 110 kV bus, taking into account higher penetration levels from other technologies such as CPV system.

In the next chapter a novel solution to mitigate the voltage rise caused by high penetration level of PV generation in distributed networks will be presented.

Chapter 5

5 Voltage Control Scheme Using Fuzzy Logic for Residential Area Networks with PV Generators in Saudi Arabia without utilizing the communication infrastructure

5.1 Introduction

This chapter starts with a brief review of previous proposed solutions to control the voltage profile in distribution networks with DG. Then, a novel approach to design and implement a control strategy for GCPV systems in residential areas in Saudi Arabia will be presented. The controller must be capable of managing the voltage level within the permissible limits in the distribution network. The controller must be able to operate well under varying load conditions and under different operating and environmental conditions. In order to confirm the validity of the proposed method, simulations are carried out for a real distribution network model with PV generation.

5.2 A review of previous proposed solution to control the voltage level in distribution networks with DG

Different voltage control strategies have been designed and implemented for distribution network with DG and successful results have been obtained [55-57]. These strategies can be divided into main three categories:

1- Control the voltage control devices in distribution system (Centerlized control system)

2- Control the DGs (Decentralized Control of DG).

3- Coordinate between the last two categories.

These control types have been addressed by many researchers. Authors in [58] have proposed an approach to limit the excess steady-state voltage rise using consumer load control, specifically for wind generation. Authors in [59] have assessed the operation and control of DG, as well as the dynamics of regulator-DG, DG-DG for single wire earth return (SWER) system. Authors in [60] have proposed a computational architecture for the voltage regulation of distribution networks with DG, using an adaptive local learning-based methodology. In [61], network voltage regulation is obtained by controlling the target voltage of automatic voltage control relays. In [62] a novel excitation control method for DG is described, which can provide voltage support to the network by altering reactive power generation. Authors in [63] have proposed a voltage regulation coordination method of DG in distribution system using on load-tap changing transformer (LTC) and line drop compensator (LDC). In [42], authors have developed a voltage control algorithm for grid-connected DGs based on active and reactive power control.

In [64] the authors instigated the use of fuzzy logic controller in calculating the voltage of automatic voltage control (AVC) relay. This study has considered a very simple model of power system network which cannot be applied to an arbitrary network. However, the result has shown that the proposed fuzzy logic controller based AVC has the ability to control the voltage level of distribution network as the load changes. It has also been shown that the ability to control the parallel transformer at substation for distribution network with DG.

Another technique that has become very popular to control power systems is Multi Agent System (MAS). MAS technology is a very promising solution for reactive power management and voltage control in power distribution system because of agent's good attributes such as autonomy, cooperation, intelligence, adaptation and social behaviour. In [65], the authors have proposed a decentralized agent mechanism for the secondary voltage control in power-system contingencies. The secondary voltage control mainly applied for the generator Automatic Voltage Regulators (AVRs) to improve the power system voltage stability. In this paper, different types of voltage controllers, such as an Automatic Voltage Regulator (AVR), a Static Var Compensator (SVC) or Static Synchronous Compensator (STATCOM), is treated as an agent. The agents that are electrically close are responsible for their own area voltage control. When an agent senses voltage violation it activates its reactive power reserve. If the voltage violation is not cleared by its own reactive power reserve then the agent starts asking for reactive power from its neighbour agents. The agents with sufficient reactive power will respond to the respective agent for voltage support. The agents share their common goal and achieve their goals by communication and coordination. The proposed scheme is applied on simple power system and the results are promising.

The authors in [66] have presented optimal coordination work for Multi-agent based secondary voltage control in power system. The agent architecture has a set of execution agents and a coordination agent. Individual voltage controllers, such as an AVR, a SVC and a STATCOM represent an execution agent. Under normal conditions, Multi-agent system based voltage co-ordination works as a conventional secondary voltage control and supports Var/Voltage control. When the system runs into contingencies, the Multi-agent system uses "contract net protocol" to realize coordination and cooperation among voltage control agents for eliminating voltage violation. During the contingency situations the execution agents (EA) will act independently and try to restore the voltage in their areas. If the execution agents fail in restoring the voltage within limits, they send a message to the coordination agent (CA). The coordination agent then will coordinate with its execution agents to restore the voltage profile. The authors have used New England 39-bus system as a test system to demonstrate the proposed agent architecture and the results were up to the mark.

A centralised voltage control system for distribution network has been addressed by many researchers. This method of control required a reliable communication infrastructure. If the communication system fails, the voltage regulation devices used by the system will detect a failure and the control methods have to change to keep the system stable. The authors in [67] have used the technique to control the static var compensator to keep the voltage of the distribution line within the permissible limits. Two type of reference mode have been used: reactive power and voltage. The “Tabu Search” Algorithm was used to find the optimal control parameter faster. This proposed technique shows an effective control method even if the output of photovoltaic (PV) generation changed rapidly and it has been more stable with V-reference mode. In another study [68] the centralized system is used to control the voltage of each node in distribution network by determining the tap location of substation transformer, on-off status of shunt capacitor (SC) and shunt reactor (ShR), and the capacity of static var compensator (SVC). The controller determines the amount of operation based on a genetic algorithm (GA). Three cases were used for both load and PV generation. The results confirmed that this method contributes to voltage regulation in the distribution network but it needs a very high speed communication network such an optical-fibre network to make the central coordination between the voltage regulation devices possible.

Even though these control strategies showed good stability and were able to control the voltage in the distribution networks, some of them contained advanced mathematics, their adaptability to changes in the operating points are debatable, had too many assumptions that may not be valid or don't take into consideration important factors that would affect the system.

This research aims to design and implement a control strategy for GCPV systems suitable for implementation in the distribution networks in Saudi Arabia. The controller must be capable of managing the voltage level within the permissible limits in the distribution network. The controller must be able to operate well under varying loads conditions and under different operating and environmental conditions. In order to confirm the validity of the proposed method, simulations must be carried out for actual distribution network model with PV generation.

5.3 Fuzzy logic

Fuzzy set theory was first introduced by Lotfi A. Zadeh of University of California, Berkeley in 1965, and handles the concept of partial truth. It deals with fuzziness in the real world and simulates a human's subjective thinking by incorporating the inherent imprecision of human thought processes. Based on linguistic variables and if-then rules, fuzzy systems are suitable for systems that are based on a mathematical model that is difficult to derive or systems dealing with nonlinear or incomplete information.

5.3.1 Fuzzy logic control

Fuzzy Logic Control (FLC) offers an alternative to conventional controllers when there is no available accurate model of the system to be controlled. By suitable selection of input-output linguistic variables and a rule base, a broad range of desirable control outcomes can be achieved. Possible features might include user-specified overall control 'tightness' analogous to a control range, closer adherence to set point conditions if desired, and the ability to explicitly set the trade-off between energy costs and interior environment.

Fuzzy logic controllers consist of a set of linguistic control rules based on fuzzy implications and the rules of inference. By providing an algorithm, they convert the linguistic control strategy based on expert knowledge into an automatic control strategy [69, 70]. Just as fuzzy logic can be described simply as "computing with words rather than numbers”, fuzzy control can be described simply as "control with sentences rather than equations". Therefore, in contrast to mathematical models or other expert systems, fuzzy logic controllers allow the representation of imprecise human knowledge in a logical way, with approximate terms and values, rather than forcing the use of precise statements and exact values, thus making them more robust, more compact, and simpler [71].

5.3.2 Fuzzy logic methodology

With fuzzy logic, the first step is to understand and characterize the system behaviour by using knowledge and that’s has been done in the last section. The second step is to directly design the control algorithm using fuzzy rules, which describe the principles of the controller's regulation in terms of the relationship between its inputs and outputs and that’s what will be done in the next section. The last step is to simulate and debug the design. If the performance is not satisfactory, modifications can be made to the fuzzy rules [72]. A summary of the Fuzzy Logic methodology is represented in Figure 5.1.

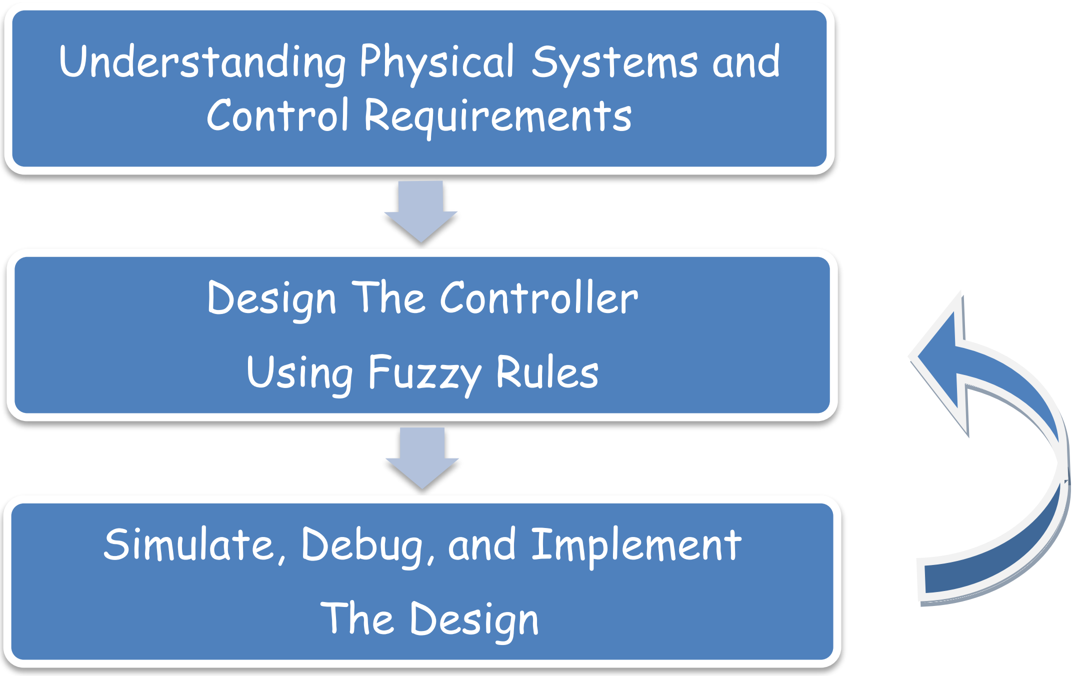


Figure 5.1 Fuzzy logic methodology summary

5.3.3 Advantages of fuzzy design

Fuzzy-based methodology substantially simplifies the design loop. This leads to the following significant advantages: simplified design complexity, reduced design development cycle, reduced hardware costs, simplified implementation, better alternative solution to non-linear control, and improved control performance [73].

In order to design the fuzzy logic controller for the tested network to change the tap to the desired location for all scenarios, all the following have to be defined:

1. The input memberships (minimise it as much as possible to reduce the number of sensors)
2. The output memberships (represents the action that has to be done in the system)
3. The rules

This will be developed by using the MATLAB fuzzy logic tool box.

5.4 System modelling

The same model for residential distribution network of Fig. 3.8 will be used in this chapter.

5.4.1 Load conditions

The following conditions of each consumer load in the network will be considered in this investigation:

1- Extreme load (Based on the maximum capacity of customer circuit breaker)

2- Peak load (Maximum Summer load)

3- Average load (Annual Average load)

4- Light load (30% of peak load)

5.4.2 PV generators

As shown in chapter 4 In this study, the range of power that can be generated by using a concentrating PV system between the times of 9:00 to 15:00 for each single house is between 14.4 kW to 36 kW. So, the following conditions for PV will be considered in this research:

1- Max PV = 36 kW;

2- Minimum midday PV = 14.4 kW;

3- No PV.

5.5 Scenarios and assumptions

In order to investigate if the adjustment of the OLTC only is sufficient to keep the voltage level along the branch within the permissible level, the system has been simulated for a number of possible scenarios of load conditions, PV status and combinations (see Fig. 3.10 and Fig. 3.11). It has been assumed that the PVs connected to each node in the system generate the same power. Also, the load is assumed to be the same for all houses. However, to make the scenarios more realistic a further 3 random conditions of the load feeders are also considered. A list of possible scenarios of PV power, load power and combinations is given in Table 5.1:

No.	Scenario	Load	PV
1	LLNPV	Light	No
2	LLAPV	Light	Min
3	LLMPV	Light	Max
4	ALNPV	Average	No
5	ALAPV	Average	Min
6	ALMPV	Average	Max
7	PLNPV	Peak	No
8	PLAPV	Peak	Min
9	PLMPV	Peak	Max
10	XLNPV	Extreme	No
11	XLAPV	Extreme	Min
12	XLMPV	Extreme	Max
13	R1LNPN	Random1	No
14	R1LAPV	Random1	Min
15	R1LMPV	Random1	Max
16	R2LNPV	Random2	No
17	R2LAPV	Random2	Min
18	R2LMPV	Random2	Max
19	R3LNPV	Random3	No
20	R3LAPV	Random3	Min
21	R3LMPV	Random3	Max

Table 5.1 List of possible load & PV generation scenarios

The standard deviation for all voltage nodes in the system from the nominal is used to determine the best possible position of LTC (-5.0% to +5.0% in 0.5% steps). However, in order to reduce the number of tap changing operations the best results are rounded to the nearest preferred position of (-5.0%,-2.5%,0%,+2.5%,+5%). This will increase the life time for the tap changer and reduce the disturbances in the system due to changing of the LTC setting. Figure 5.2 explains the steps followed in order to determine both best and preferred tap position for each scenario.

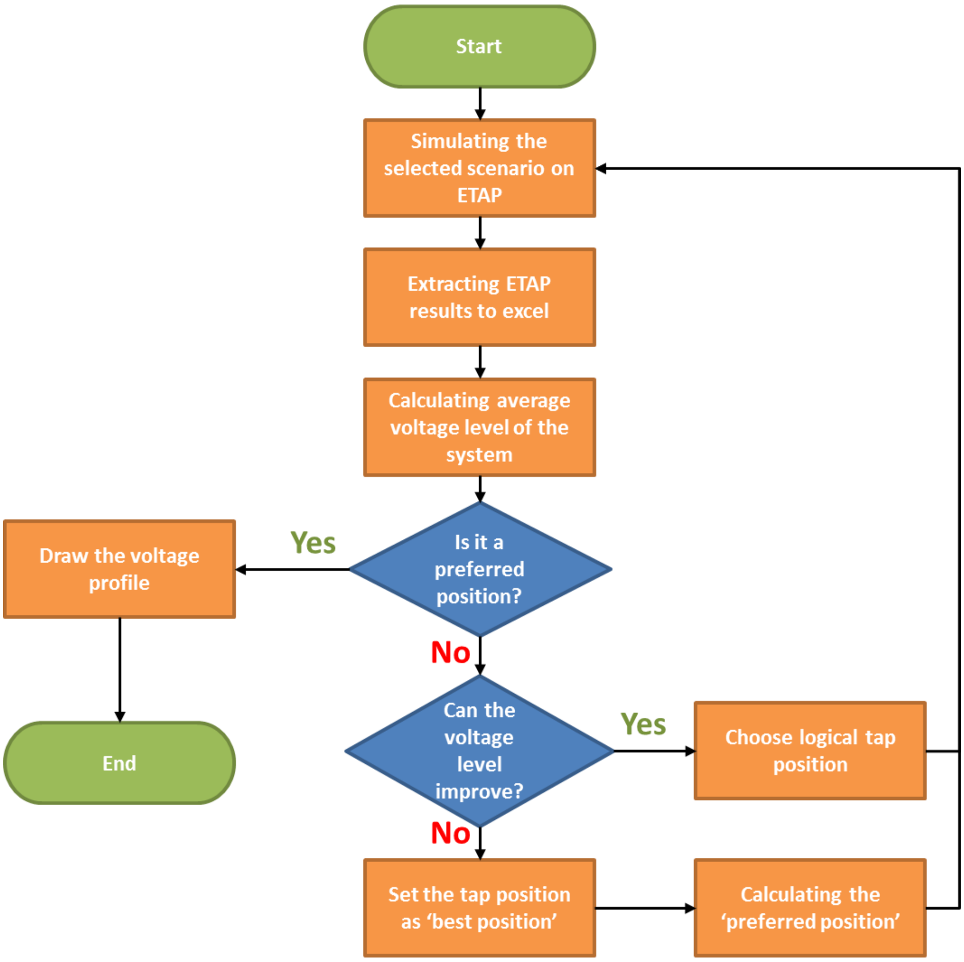


Figure 5.2 Best and preferred tap position calculation flow chart

Appendix C shows the voltage profiles for all scenarios. Table 5.2 shows the average voltage (in %) for the network when the LTCT is set at 0% for all scenarios. Also the best and preferred positions of tap changer at each scenario are presented.

Scenario	Load	PV	Average V(%)	Best	Preferred
LLNPV	Light	No	99.56	0.50%	0%
LLAPV	Light	Min	101.43	-1.50%	-2.50%
LLMPV	Light	Max	103.94	-4%	-5%
ALNPV	Average	No	98.19	2%	2.50%
ALAPV	Average	Min	100.12	0%	0%
ALMPV	Average	Max	102.71	-2.50%	-2.50%
PLNPV	Peak	No	96.32	3.50%	5%
PLAPV	Peak	Min	98.34	2%	2.50%
PLMPV	Peak	Max	101.04	-1%	0%
XLNPV	Extreme	No	94.39	5%	5%
XLAPV	Extreme	Min	96.51	3.50%	2.50%
XLMPV	Extreme	Max	99.33	0.50%	0%
R1LNPN	Random1	No	97.48	2.50%	2.50%
R1LAPV	Random1	Min	99.44	0.50%	0%
R1LMPV	Random1	Max	102.07	-2%	-2.50%
R2LNPV	Random2	No	96.92	3%	2.50%
R2LAPV	Random2	Min	98.91	1%	0%
R2LMPV	Random2	Max	101.58	-1.50%	-2.50%
R3LNPV	Random3	No	97.33	2.50%	2.50%
R3LAPV	Random3	Min	99.31	0.50%	0%
R3LMPV	Random3	Max	101.95	-2%	-2.50%

Table 5.2 Best & preferred position of tap changer for all tested scenarios

The worse cases are shown in Fig. 5.3, and Fig. 5.4, together with the preferred position of tap changer.

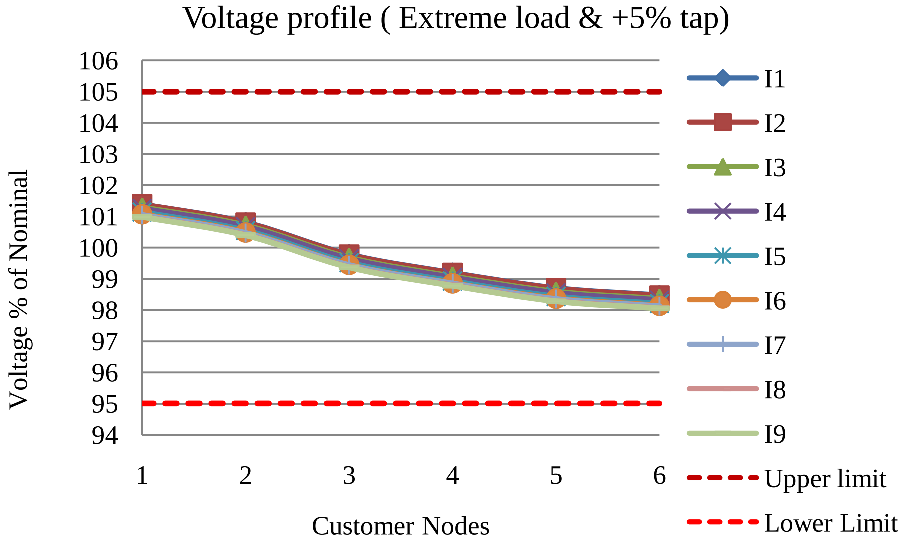


Figure 5.3 Voltage profile of XLNPV scenario with preferred position of tap changer

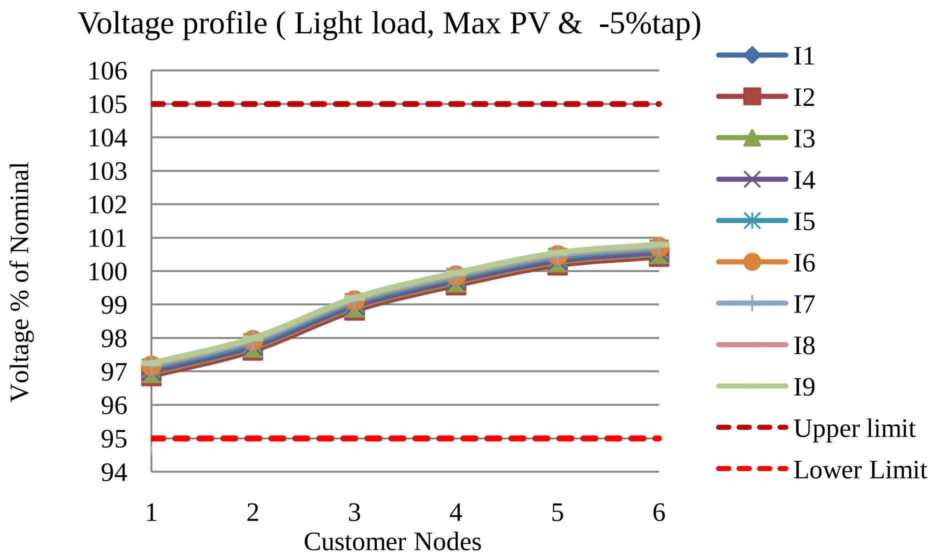


Figure 5.4 Voltage profile of LLMPV scenario with preferred position of tap changer

The simulations show that both the best and the preferred position for all scenarios improve the voltage level and keep it within the allowable limits for all customers on the branch. In the next section, a brief review of fuzzy logic concepts will be introduced for using this technique to control the LTCT in all scenarios.

5.6 A FLC based on average voltage of the network

Fig. 5.5 shows a straight forward application of a fuzzy logic controller based on the numerical solution for the preferred tap changer position at each scenario. This control system is simulated in MATLAB software. The controller consists of one input, the average customer voltage, and one output, the preferred tap changer setting.

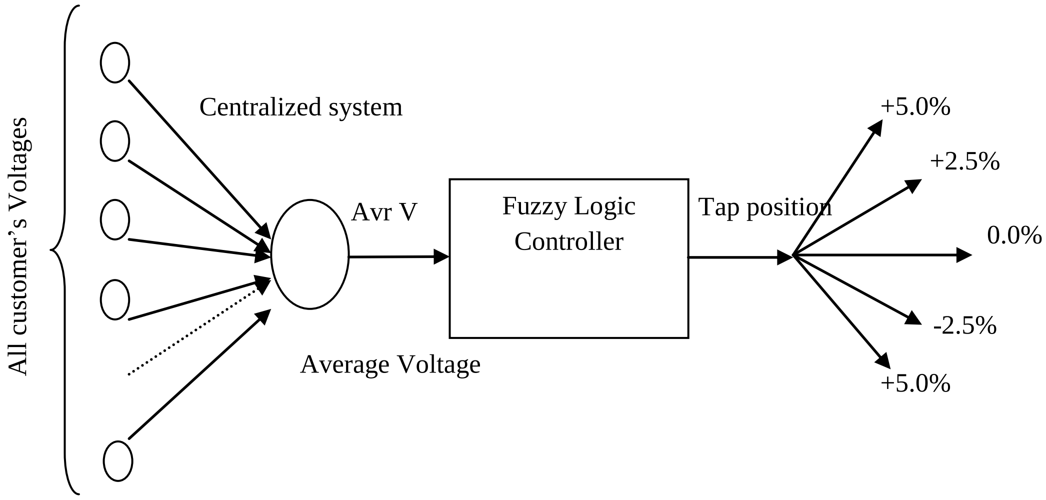


Figure 5.5 1st Implementation of FLC

5.6.1 Set up the input and the output memberships

Table (a) in Fig 5.6 is obtained by reordering of Table 5.2 base on the preferred position for LTC. It clearly shows a direct correlation between the average voltage and the preferred tap changer setting.

	Input	Output
Scenario	Avr V (%)	Preferred
XLNPV	94.3887	5.0%
PLNPV	96.32222	5.0%
XLAPV	96.51037	2.5%
R2LNPV	96.91574	2.5%
R3LNPV	97.33333	2.5%
R1LNPN	97.47667	2.5%
ALNPV	98.19407	2.5%
PLAPV	98.34241	2.5%
R2LAPV	98.91204	0.0%
R3LAPV	99.30667	0.0%
XLMPV	99.33259	0.0%
R1LAPV	99.44241	0.0%
LLNPV	99.56389	0.0%
ALAPV	100.1239	0.0%
PLMPV	101.0417	0.0%
LLAPV	101.4302	-2.5%
R2LMPV	101.5806	-2.5%
R3LMPV	101.9483	-2.5%
R1LMPV	102.0739	-2.5%
ALMPV	102.7117	-2.5%
LLMPV	103.9406	-5.0%
NLMPV	104.3461	-5.0%

Average V	Tap Changer
Input (Avr_V)	Output (TC)
Very Low (VL)	Very High (VH)
Low (L)	High (H)
Normal (N)	Normal (N)
High (H)	Low (L)
Very High (VH)	Very Low (VL)

(b)

(a)

Figure 5.6 Input and output classes for 1st implementation of FLC

Both the voltage level and the tap position can be simplified into a limited number of classes as shown in part (b) of Fig. 5.6. The average voltage (AvrV) of all customers in the branch will be used as an input for the FLC and its membership by a range of 0.92 p.u. to 1.06 p.u.

MF		Approximate range (p.u.)
VL	Very Low	0.92-0.964
L	Low	0.964-0.986
N	Normal	0.986-1.012
H	High	1.012-1.034
VH	Very High	1.034-1.06

Table 5.3 Membership function AvrV Range

The standard shape for each class of the input membership is used as shown in Fig.5.7.

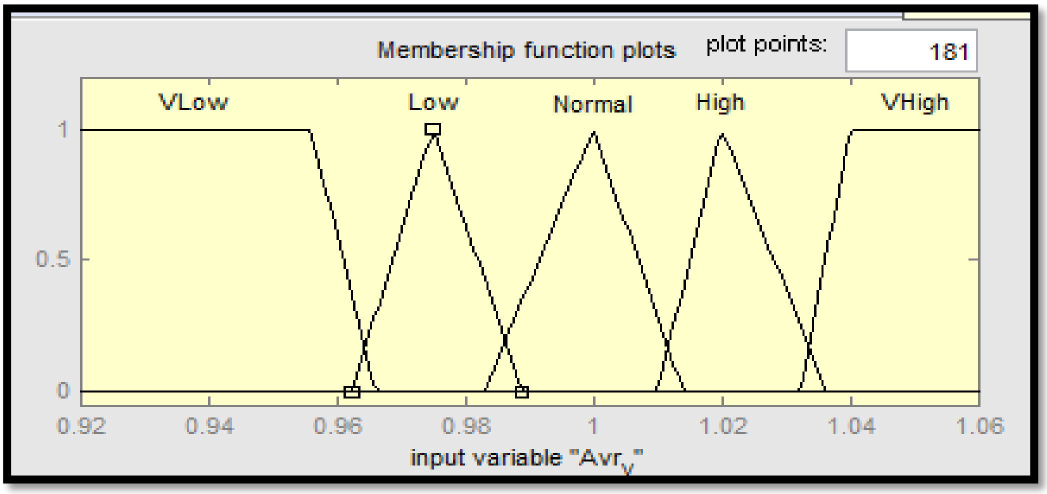


Figure 5.7 Input membership function for 1st implementation of FLC

In order to force the output of the controller to choose one of the preferred position for LTC (-5.0%,-2.5%,0%,+2.5%,+5%) a membership function with a single spike is used. In many cases it is much more efficient to use a single spike as the output membership function rather than a distributed fuzzy set. This is sometimes known as a singleton output membership function, and it can be thought as pre-defuzzified fuzzy set. It enhances the efficiency of defuzzification process because it greatly simplifies the computation required by the more general Mamdani method [74], which finds the centroid of a two-dimensional function rather than integrating across the two-dimensional function to find the centroid. The tap changer setting (TC) are Very High (VH), High (H), Normal (N), Low (L) and Very low (VL) as shown in Fig.5.8.

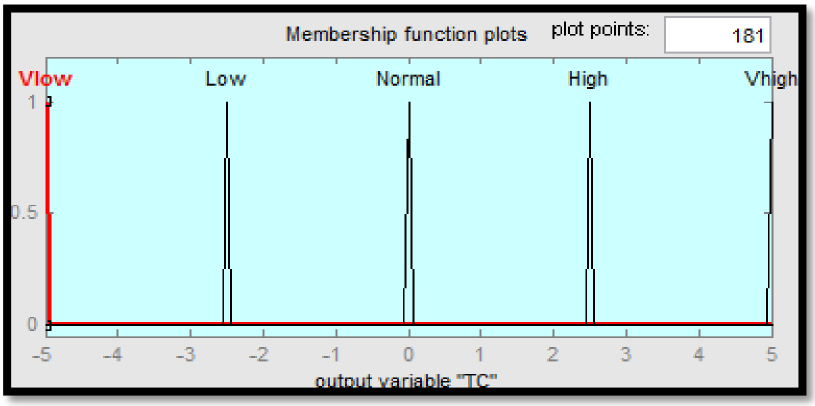


Figure 5.8 Output membership function for 1st implementation of FLC

5.6.2 The control rules

The most important advantage of the fuzzy basis functions is that a linguistic IF-THEN rule is directly related to a fuzzy basis function expansion providing a natural framework to combine both numerical and linguistic information in a uniform fashion. Because this implementation of FLC consists of a single input with 5 classes, the total number of rules are 5. The rules are described as follows:

1- If (AvrV) is (VH) then (TC) is (VL).
2- If (AvrV) is (H) then (TC) is (L).
3- If (AvrV) is (N) then (TC) is (N).
4- If (AvrV) is (L) then (TC) is (H).
5- If (AvrV) is (VL) then (TC) is (VH).

Input: AvrV	VH	H	N	L	VL
Output: TC	VL	L	N	H	VH

Table 5.4 Rule table for 1st implementation of FLC

5.6.3 Results of 1st implementation

Fig. 5.9 shows the difference between the numerically calculated and proposed FLC setting for the tap changer.

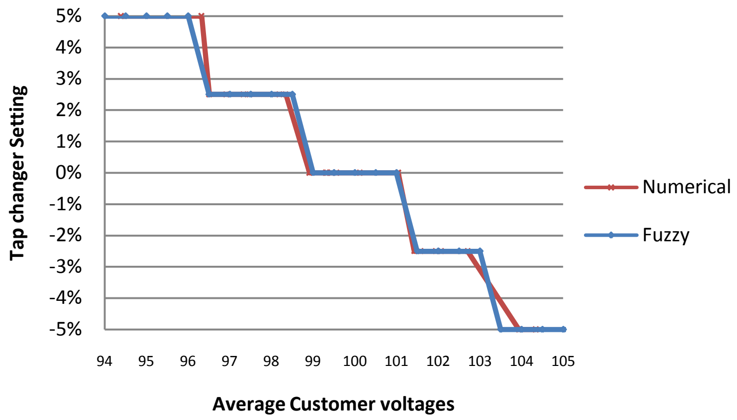


Figure 5.9 Numerical and Fuzzy Logic setting for LTC

The FLC gives almost the same results as the numerical solutions. The small differences in Fig. 5.9 are because the full range of variation in average voltage is not used in the numerical calculation (scenarios only). The main advantage of this way of control is that it is independent of branch and line parameters and can be applied to various types of networks. However, it needs the installation of a digital voltmeter at each customer to send the voltage values to a centralized system via a communication network. This makes this solution prohibitively expensive. Also, if all requirements for this method are available, there are many techniques other than FL can be used based on look-up tables for the average voltage and then set the preferred tap changer position which may does not give any advantages of using FLC.

5.7 A FLC based on the power flow at ISK11

In order to find a better solution than previously introduced for controlling the voltage in the branch without using a communication network and take the advantage of the FLC features, the correlation between the local measurements in the system and the preferred setting has to be established based on engineering sense. The basis of this method is that the network parameters are more or less set at the design stage and it may be possible to use network theory to find the desired correlations between power flows and voltage profile. Table 5.5 shows the measurements of active power (P) in kW and reactive power (Q) in kVar at ISK11.

Scenario	P@ISK11	Q@ISK11	Preferred
LLNPV	200	99	0.0%
LLAPV	-1502	130	-2.5%
LLMPV	-3946	315	-5.0%
ALNPV	805	479	+2.5%
ALAPV	-915	486	0.0%
ALMPV	-3382	638	-2.5%
PLAPV	-127	974	+2.5%
PLNPV	1619	1004	+5.0%
PLMPV	-2624	1082	0.0%
XLAPV	-670	1480	+2.5%
XLMPV	-1859	1540	0.0%
XLNPV	2444	1549	+5.0%
R1LNPV	1122	691	+2.5%
R1LAPV	-609	683	0.0%
R1LMPV	-3088	818	-2.5%
R2LNPV	1327	824	+2.5%
R2LAPV	-411	805	0.0%
R2LMPV	-2899	927	-2.5%
R3LAPV	-565	709	0.0%
R3LNPV	1168	720	+2.5%
R3LMPV	-3046	841	-2.5%

Table 5.5 Simulated with power flow @ ISK11 for all scenarios with preferred Tap position using ETAP

It is quite clear that there is a positive correlation between the load of the branch and the reactive power flow at ISK11. So, as the load increases the reactive power increases and vice versa. On the other hand there is a negative correlation between the PV generation and the active power flow at ISK11. Appendix C shows all the results for this case. The structure of a FLC based on above information is shown in Fig. 5.10.

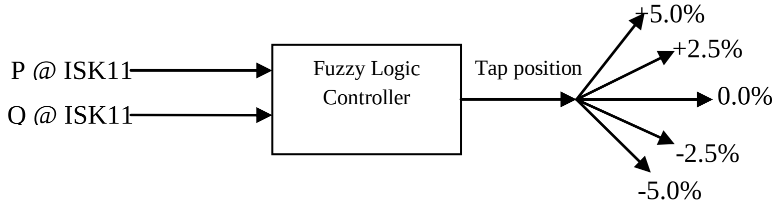


Figure 5.10 Fuzzy Logic controller based on the power flow at the primary substation

5.7.1 The membership of input and output signals:

- <u>1st input:</u> Sort the numerical solution based on active power flow and find the correlation between P and the status of PV as below. Fig. 5.11 shows how the 1st input membership can be established.

Scenario	PV	P
NLMPV	Max	-4134
LMPV	Max	-3946
ALMPV	Max	-3382
R1LMPV	Max	-3088
R3LMPV	Max	-3046
R2LMPV	Max	-2899
PLMPV	Max	-2624
XLMPV	Max	-1859
LLAPV	Min	-1502
ALAPV	Min	-915
XLAPV	Min	-670
R1LAPV	Min	-609
R3LAPV	Min	-565
R2LAPV	Min	-411
PLAPV	Min	-127
LLNPV	No	200
ALNPV	No	805
R1LNPN	No	1122
R3LNPV	No	1168
R2LNPV	No	1327
PLNPV	No	1619
XLNPV	No	2444

1st input based on P	
Active power	PV status
Light	Maximum (MaxPV)
Normal	Minimum (MinPV)
High	No (NoPV)

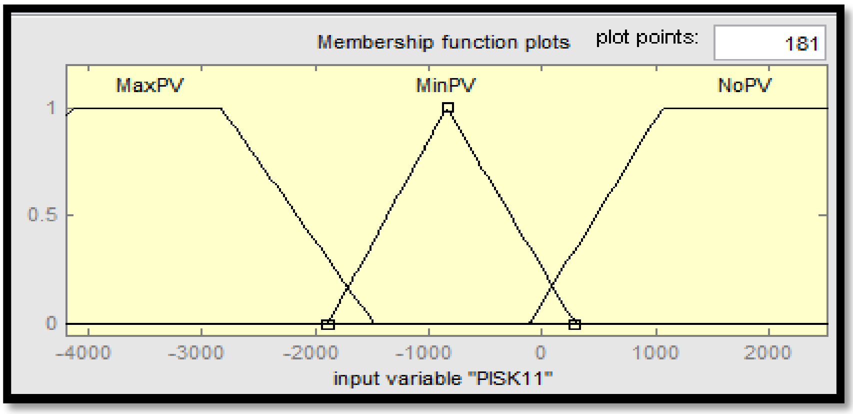


Figure 5.11 Establishing the input membership function 1 for 2nd implementation of FLC

- 2nd input: Sort the numerical solution based on reactive power flow and find the correlation between Q and the status of system load and set the membership function as shown in below:

Senario	Load	Q
LLNPV	Light	99
LLAPV	Light	130
NLMPV	No	208
LLMPV	Light	315
ALNPV	Average	479
ALAPV	Average	486
ALMPV	Average	638
R1LAPV	Random1	683
R1LNPN	Random1	691
R3LAPV	Random3	709
R3LNPV	Random3	720
R2LAPV	Random2	805
R1LMPV	Random1	818
R2LNPV	Random2	824
R3LMPV	Random3	841
R2LMPV	Random2	927
PLAPV	Peak	974
PLNPV	Peak	1004
PLMPV	Peak	1082
XLAPV	Extreme	1480
XLMPV	Extreme	1540
XLNPV	Extreme	1549

2^{nd} input based on Q	
Reactive power	Load status
Light	Light (LL)
Medium	Medium (ML)
High	High (HL)

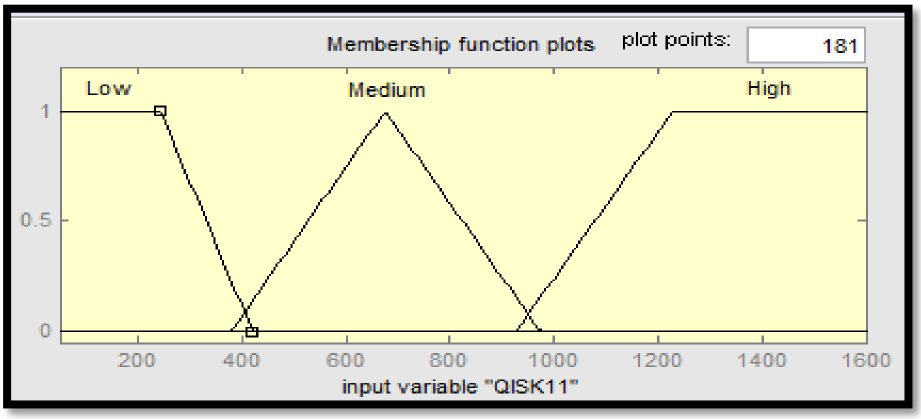


Figure 5.12 Establishing the input membership function 2 for 2^{nd} implementation of FLC

- Output: preferred tap changer position. Fig. 5.13 shows the step to establish the output membership function

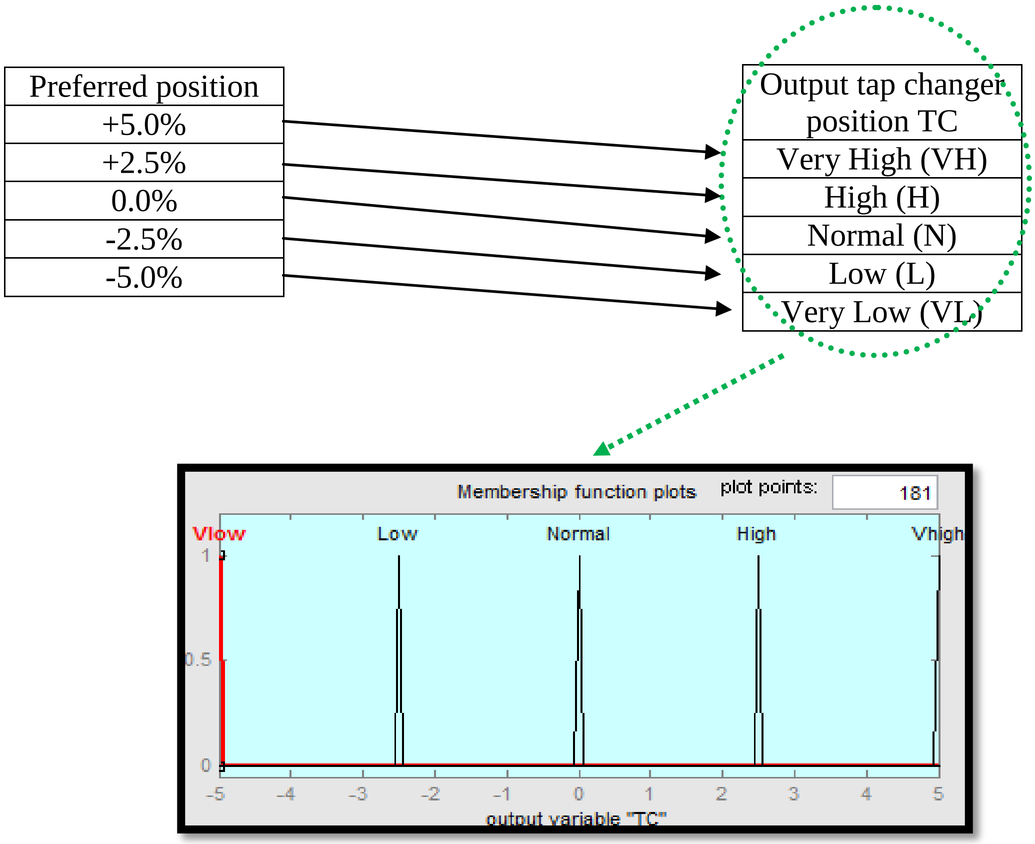


Figure 5.13 Establishing the output membership function for 2nd implementation of FLC

5.7.2 The control rules:

1- If (Q) is (HL) and (P) is(NoPV) then (TC) is (VH).
2- If (Q) is (HL) and (P) is(MinPV) then (TC) is (H).
3- If (Q) is (HL) and (P) is(MaxPV) then (TC) is (N).
4- If (Q) is (ML) and (P) is(NoPV) then (TC) is (H).
5- If (Q) is (ML) and (P) is(MinPV) then (TC) is (N).
6- If (Q) is (ML) and (P) is(MaxPV) then (TC) is (L).
7- If (Q) is (LL) and (P) is(NoPV) then (TC) is (N).
8- If (Q) is (LL) and (P) is(MinPV) then (TC) is (L).
9- If (Q) is (LL) and (P) is(MaxPV) then (TC) is (VL).

P→PV / Q→Load	No PV	Min PV	Max PV
HL	VH	H	N
ML	H	N	L
LL	N	L	VL

Table 5.6 Rule table for 2nd implementation of FLC

5.7.3 Results of 2nd implementation

Fig. 5.14 shows the tap changer settings for possible range of P and Q using the proposed FLC.

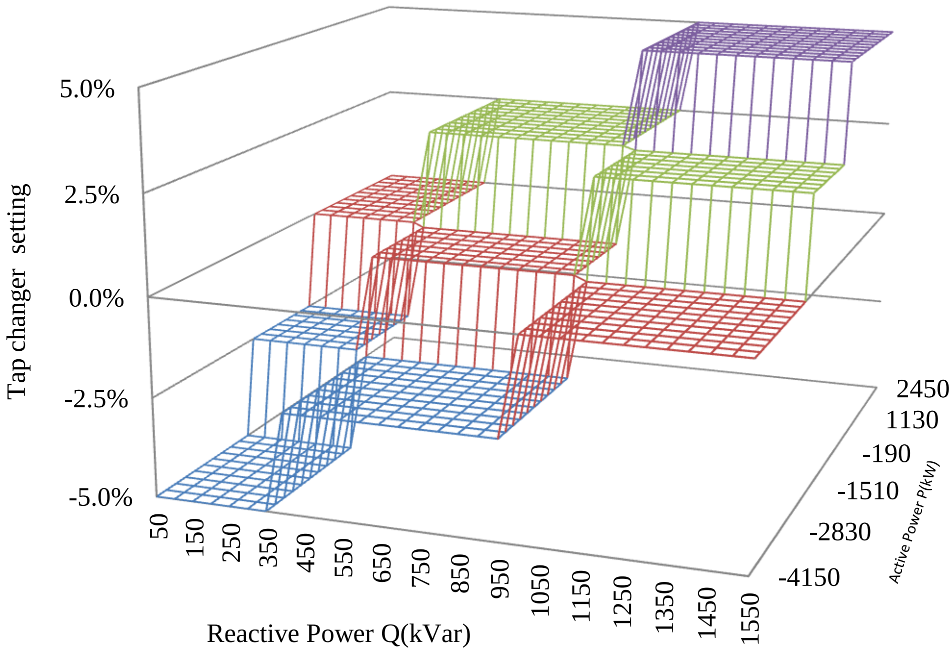


Figure 5.14 Fuzzy Logic set for LTC based on power flow @ ISK11

The controller gives the preferred tap changer position for all scenarios when the values of P and Q value of each scenario have been used as an input to the system. The key benefit of this implementation is that all measurements are taken locally and there is no need for remote communication. This makes this solution simple and cheap compared with other control techniques. In order to optimize this solution, the membership for the input has to be tuned by determining the preferred position numerically for the power flow values in the transition region.

5.8 Fault case

The previous work has proved that it sufficient to use only the tap changer for regulating the voltage in the distribution network in Fig. 3.8 in case of no fault at any transformer. Also, the control system has been developed for that case using a fuzzy logic technique. The worse operation scenario for this system is when the whole network is energised by only one primary substation and the other two are out of service (Fig. 5.15).

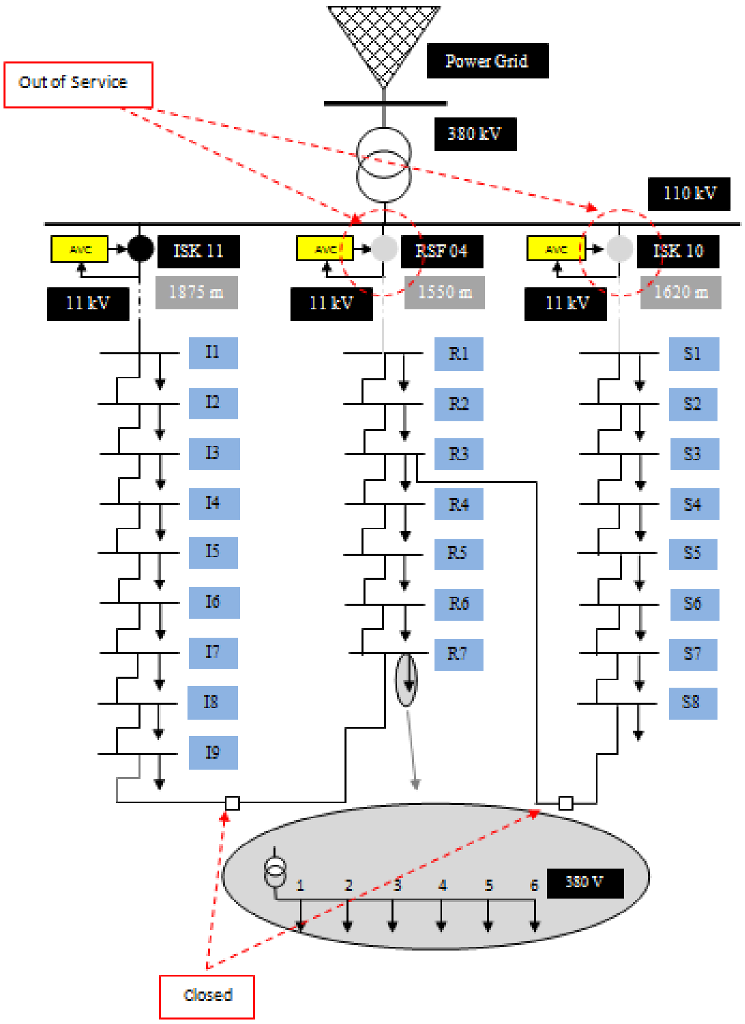


Figure 5.15 Worst case operation

The same steps used to design the FLC for the normal case are repeated for this case. All possible scenarios that can be driven from the combination of the load and the PV generators are tested to find the preferred tap changer positing at each of them. Appendix D shows all the results for this case.

Table 5.7 shows the power flow at ISK11 for all different scenarios.

Scenario	AvrV	P	Q	Preferred
XLNPV	89.90607	6641	4326	5%
PLNPV	93.4925	4352	2778	5%
ALNPV	96.84595	2153	1334	2.50%
LLNPV	99.23655	535	307	0%
XLMPV	98.25583	-4855	4273	2.50%
PLMPV	101.1077	-6826	3106	0%
ALMPV	103.8479	-8775	1991	-2.50%
LLMPV	105.8399	-10226	1186	-5%
NLMPV	106.4926	-10708	922	-5%
XLAPV	93.73863	1778	4010	5%
PLAPV	96.95619	-340	2649	2.50%
ALAPV	100.0092	-2419	1362	0%
LLAPV	102.2081	-3958	438	-2.50%
NLAPV	102.9255	-4468	138	-2.50%

Table 5.7 Power flow at ISK 11 for fault case

5.8.1 Set up the input and the output memberships

1st input: Sort the numerical solution based on active power flow and find the correlation between P and the status of PV.

Senario	AvrV	P	Q
NLMPV	106.4926	-10708	922
LLMPV	105.8399	-10226	1186
ALMPV	103.8479	-8775	1991
PLMPV	101.1077	-6826	3106
XLMPV	98.25583	-4855	4273
NLAPV	102.9255	-4468	138
LLAPV	102.2081	-3958	438
ALAPV	100.0092	-2419	1362
PLAPV	96.95619	-340	2649
LLNPV	99.23655	535	307
XLAPV	93.73863	1778	4010
ALNPV	96.84595	2153	1334
PLNPV	93.4925	4352	2778
XLNPV	89.90607	6641	4326

1st input based on P	
Active power	PV status
Light	Maximum (MaxPV)
Normal	Minimum (MinPV)
High	No (NoPV)

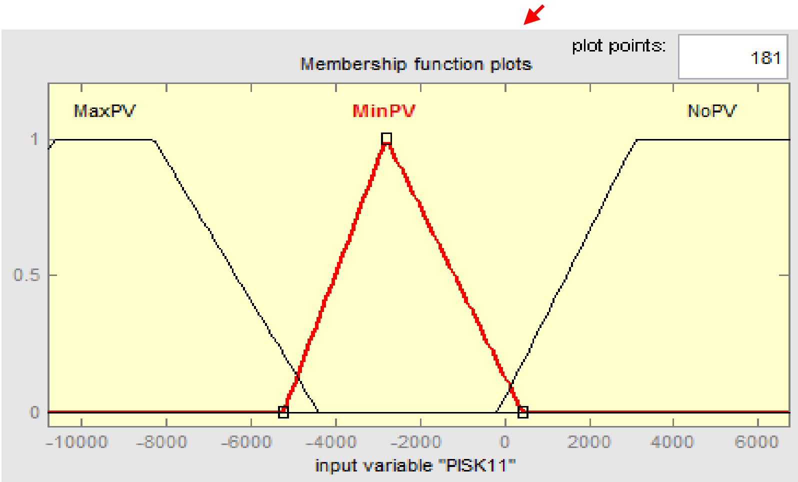


Figure 5.16 Establishing the input membership function 1 for FLC for fault case

<u>2nd input:</u> Sort the numerical solution based on reactive power flow and find the correlation between Q and the status of system load

Scenario	AvrV	P	Q
NLAPV	102.9255	-4468	138
LLNPV	99.23655	535	307
LLAPV	102.2081	-3958	438
NLMPV	106.4926	-10708	922
LLMPV	105.8399	-10226	1186
ALNPV	96.84595	2153	1334
ALAPV	100.0092	-2419	1362
ALMPV	103.8479	-8775	1991
PLAPV	96.95619	-340	2649
PLNPV	93.4925	4352	2778
PLMPV	101.1077	-6826	3106
XLAPV	93.73863	1778	4010
XLMPV	98.25583	-4855	4273
XLNPV	89.90607	6641	4326

2^{nd} input based on Q	
Reactive power	Load status
Light	Light (LL)
Medium	Medium (ML)
High	Low (HL)

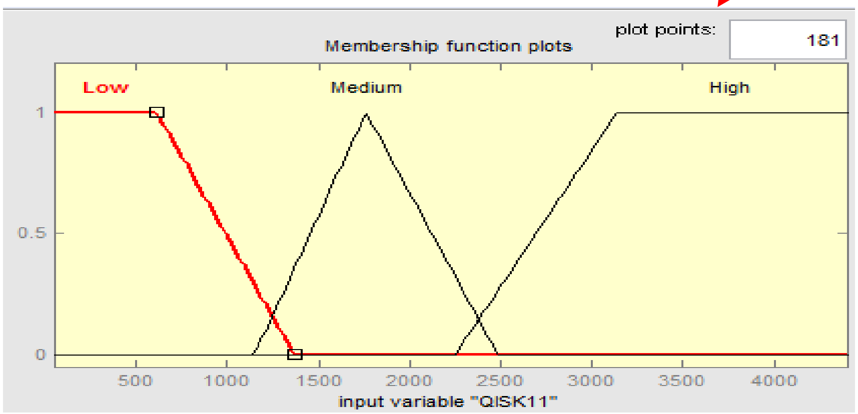


Figure 5.17 Establishing the input membership function 2 of FLC for fault case

<u>Output:</u> preferred tap changer position.

Preferred position	Output tap changer position TC
+5.0%	Very High (VH)
+2.5%	High (H)
0.0%	Normal (N)
-2.5%	Low (L)
-5.0%	Very Low (VL)

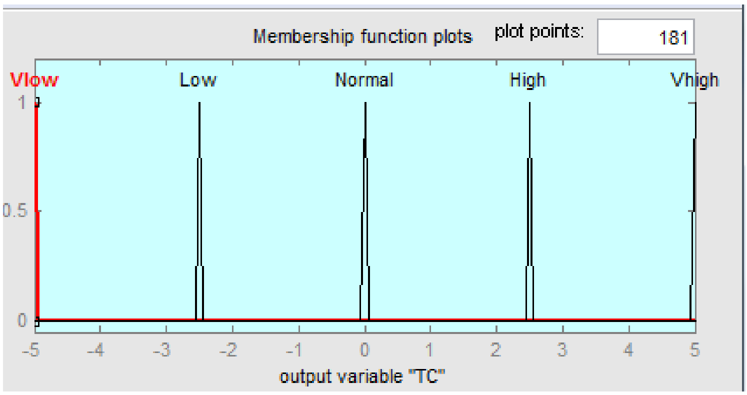


Figure 5.18 Establishing the output membership function of FLC for fault case

5.8.2 Set up the rules

1- If (Q) is (HL) and (P) is(NoPV) then (TC) is (VH).

2- If (Q) is (HL) and (P) is(MinPV) then (TC) is (H).

3- If (Q) is (HL) and (P) is(MaxPV) then (TC) is (N).

4- If (Q) is (ML) and (P) is(NoPV) then (TC) is (H).

5- If (Q) is (ML) and (P) is(MinPV) then (TC) is (N).

6- If (Q) is (ML) and (P) is(MaxPV) then (TC) is (L).

7- If (Q) is (LL) and (P) is(NoPV) then (TC) is (N).

8- If (Q) is (LL) and (P) is(MinPV) then (TC) is (L).

9- If (Q) is (LL) and (P) is(MaxPV) then (TC) is (VL).

P→PV / Q→Load	No PV	Min PV	Max PV
HL	VH	H	N
ML	H	N	L
LL	N	L	VL

Table 5.8 Rule table of FLC for fault case

5.8.3 Results

Fig. 5.19 shows the set up value for tap changer for possible range of P and Q using the proposed FLC.

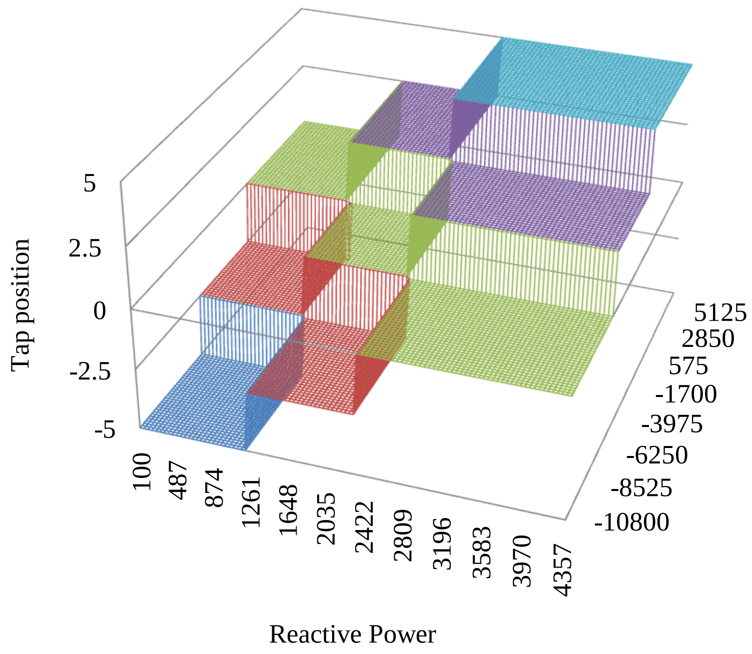


Figure 5.19 Fuzzy Logic set for LTC based on power flow @ ISK11 for fault case

Again the controller gives the preferred tap changer position for all scenarios when the values of P and Q for each scenario have been used as an input to the this system. Only the ranges of the input functions have to be changed, from its set for normal condition, to let the FLC adapt to the fault case. This required change can be correlated with the normal open circuit status in the network.

5.9 Stability assessment for the system

In order to check the stability of the proposed controller, the dynamic model of the system has to be tested. One of the best known software that can be used for dynamic solution is MATLAB/simulink with the power systems tool box where the whole network can be modelled. Fig. 5.20 shows the whole model in MATLAB/simulink where the distribution network subsystems block includes the rest of the network.

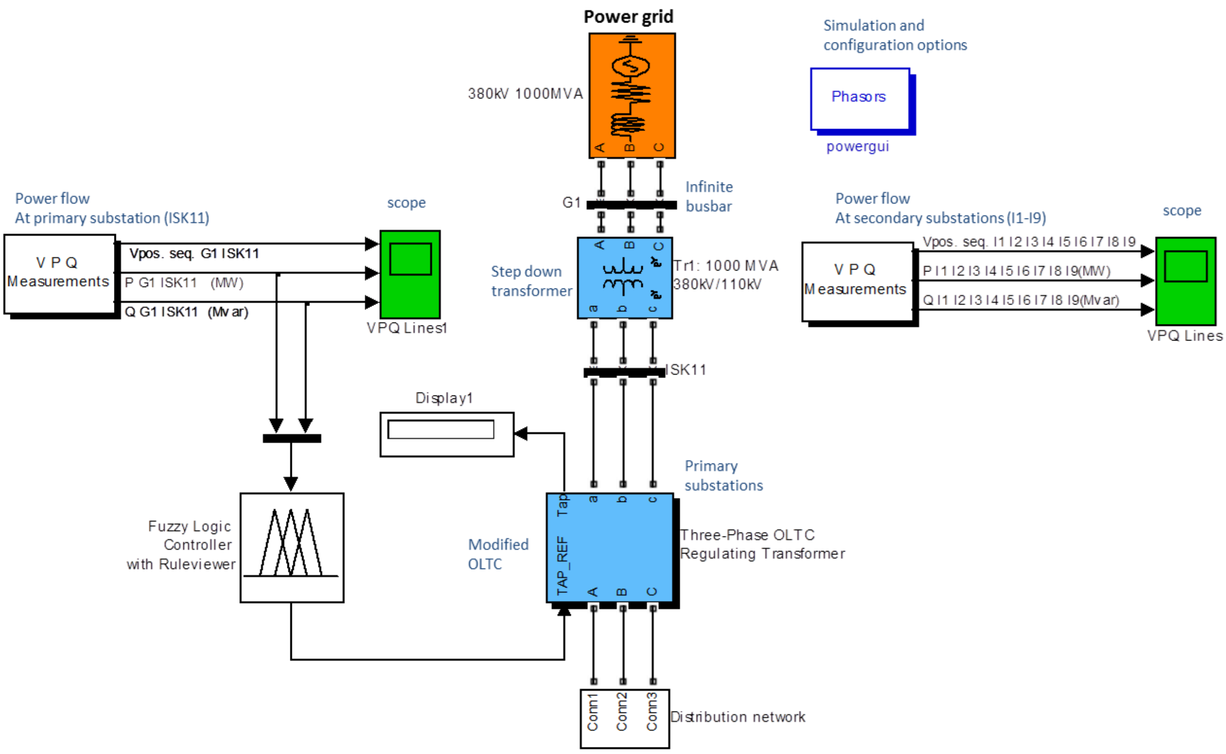
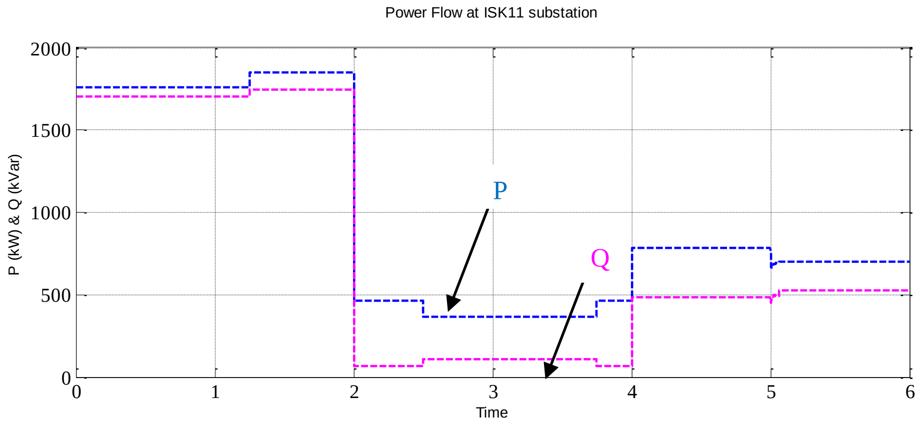
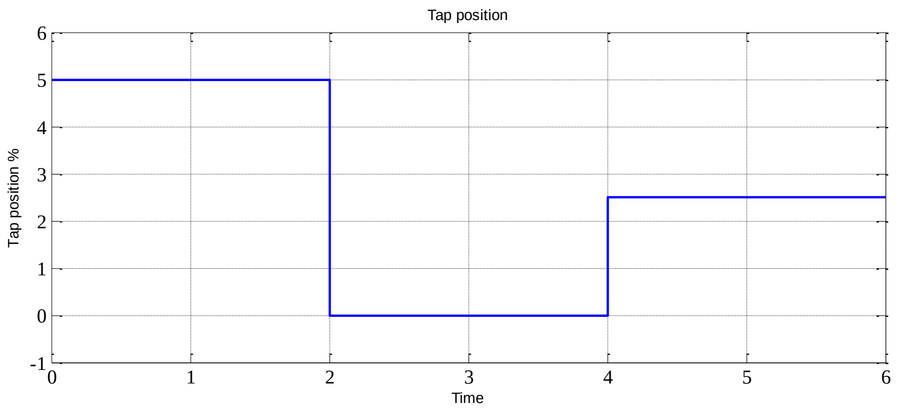


Figure 5.20 Model of the GCPV residential area network in Saudi Arabia using MATLAB/Simulink

A new transformer has been designed to fulfil the model requirement for the primary substation in the base case. The OLTC transformer model supplied with MATLAB/Simulink was modified as described below. It implements a fixed number of taps (8 taps per phase + tap 0 (nominal voltage ratio)). So firstly, the number of tap changer has been changed to 5 to presents the following tap position: (-5.0%, -2.5%, 0.0%, +2.5% and +5.0%). Then, the control for the tap changer in the transformer has been modified to follow the output signal of the fuzzy logic controller. The fuzzy logic controller block is used to call the designed fuzzy logic system and apply its output which needs to be run at the same time with the simulation. A sudden load change has been simulated to check the behaviour of the tap changer.



(a)



(b)

Figure 5.21 (a) Power flow and (b) tap position of the transformer at ISK11 substation

Fig. 5.21 shows that the tap position is changed according to the active and reactive power at primary substation. Also the results show that while there are small changes in P and Q before and after 2 and 4 second, but these doesn’t lead to any consequent changes in tap position which that exactly needed from the controller. When the power moved to the next level the tap position changes accordingly and stays at its position. That gives a good indication of the stability of the control technique.

5.10 Conclusions

Two methods of implementation of a fuzzy logic controller for setting the tap changer position in distribution networks were investigated in this chapter. It has been found that both proposed FLCs have the ability to improve the voltage profile of distribution network with high PV penetration and keep it within the permissible limits.

The first implementation is associated with significant costs due to the need for an extensive communication infrastructure but it can be applied to many networks since it is independent on the network parameters.

The second implementation shows a novel technique to control the LTCT based on the power flow information at the transformer itself. The main advantage of this implementation is that all measurements are taken locally and there is no need for remote communication with other information in the system. However, the main drawback of this method is that it depends on the network parameters and the load characteristics. So, for each network the FLC need to be set up based on analysis of the network load data. The stability dynamic of the proposed solution has also been assessed using a MATLAB/Simulink model with modified OLTC using Powersys toolbox and a stable response was found. In general, the results are encouraging and warrant further investigation using the fuzzy logic concept in such problems. The next chapter proposes another technique to keep the distribution voltage within the permissible level at the existing of GCPV system by controlling the power factor (PF) of the PV generators.

Chapter 6

6 Power Factor Control of Grid-Connected PV Generator

6.1 Introduction

This chapter presents an approach for solving the feeder voltage regulation problem in a local manner, with the goal of fulfilling the plug-and-play feature desired by manufacturers and regulatory bodies. The plug–and–play feature will enable customers to simply connect their PV systems to the distribution feeder, and through a FLC the power flow from the PV system through the inverters will be controlled to help maintain the feeder voltage level within limits at minimum cost. The chapter starts by the proposed controller objectives. The proposed controller design is based on FLC and the architecture is then presented. Test results of this system are shown to prove that the proposed controller can successfully regulate the voltage of a distribution feeder with PV systems connected to it. Finally the interaction between two controllers at the same feeder has been investigated and a simulation is carried out under MATLAB /Simulink environment to evaluate the stability of the control algorithm.

6.2 Control of the reactive power of PV generation using FLC

Consider a voltage source $V_S \angle \delta$ connected to a utility grid $V_G \angle 0°$ through a coupling impedance Z=R+jX, as shown in Figure 6.1.

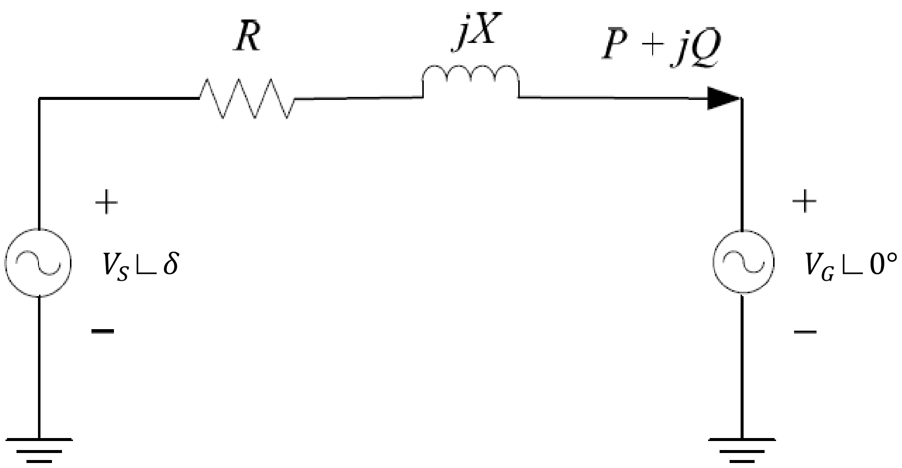


Figure 6.1 Power flow between a voltage source and utility grid.

The real and reactive power delivered to the utility grid is [75]:

$$\mathrm{P} = \frac{V_G V_S}{Z}\cos(\theta_Z - \delta) - \frac{V_G^2}{Z}\cos(\theta_Z) \quad (6.1)$$

$$\mathrm{Q} = \frac{V_G V_S}{Z}\sin(\theta_Z - \delta) - \frac{V_G^2}{Z}\sin(\theta_Z) \quad (6.2)$$

From eq. 6.1 and eq. 6.2, it is clear that the real and reactive power delivered to the utility grid are completely determined by the amplitude and angle of the sending voltage source, i.e. the output voltage of the inverter. On the other hand, the values of V_S and δ can be determined from eq. 6.3 and eq. 6.4 if the desired values of real and reactive power are given.

$$V_S = \left[\frac{\mathrm{Z}^2}{V_G^2}(\mathrm{P}^2 + \mathrm{Q}^2) + V_G^2 + 2\mathrm{PZ}\cos(\theta_Z) + 2\mathrm{QZ}\sin(\theta_Z)\right]^{1/2} \quad (6.3)$$

$$\delta = \theta_Z - cos^{-1}\left[\frac{ZP}{V_G V_S} + \frac{V_G}{V_S}\cos(\theta_Z)\right] \quad (6.4)$$

When the PV generator is connected to the radial feeder, its active power export reduces the power flow from the secondary substation. This causes reduction in the voltage drop along the feeder. If the generator's power export is larger than the feeder load, power flows from the generator to the primary substation and this causes a voltage rise along the feeder.

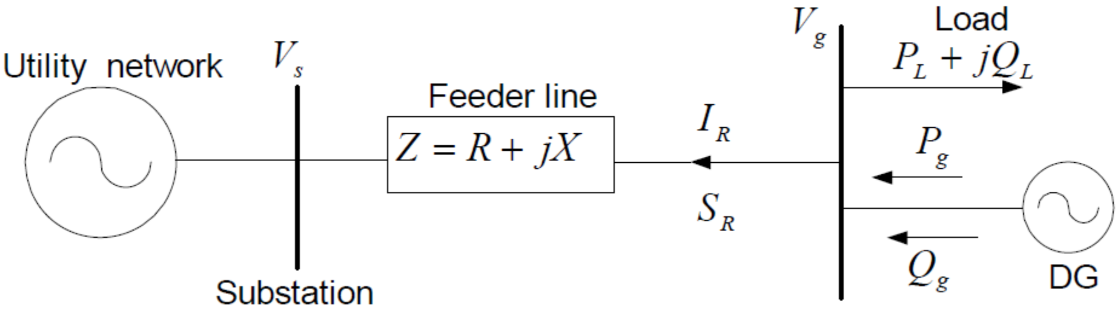


Figure 6.2 Utility network with DG.

Eq. 3.1 describes how the voltage level is changed at the point of connection of the DG. The active power produced by DG increase the voltage, whereas the reactive power can further increase or reduce it depending on the type of DG technology. The PV generator can generate or absorb reactive power depending on the operating power factor of the inverter. These outcomes, in combination with the system's R/ X ratio or distribution network characteristics and load profiles, determine the increase in voltage level at the connection point due to power production of the PV generator.

The inverter can only dispatch or consume the reactive power if its apparent power capability (S) exceed the instantaneous power generated by the connected PV panels. The range of allowable reactive power consumption or generation is given by eq. 6.5.

$$|Q| \leq \sqrt{S^2 - \mathrm{P_{PV}}^2} \qquad (6.5)$$

This relationship is also described by the phasor diagram in Fig. 6.3.

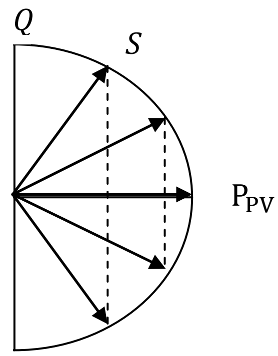


Figure 6.3 When S is larger than P_{PV}, the inverter can supply or consume reactive power (Q)

In this study the inverter is assumed to be operating up to 0.9 lagging power factor.

6.3 Design of FL power factor controller for inverter

According to eq. 3.1 the active power generated by the PV and the active power consumed by the load will be used as an input to the fuzzy logic controller. Also, the distance from the secondary substation will be used as third input. The operating power factor for the inverter will be the output of the controller. The customer feeder I9 in the typical model of the distribution network in chapter 4 will be considered for investigating the behaviour of the controller under different conditions of load and solar irradiation. Figure 5.2 shows the step by step design for the FL power factor controller for inverter.

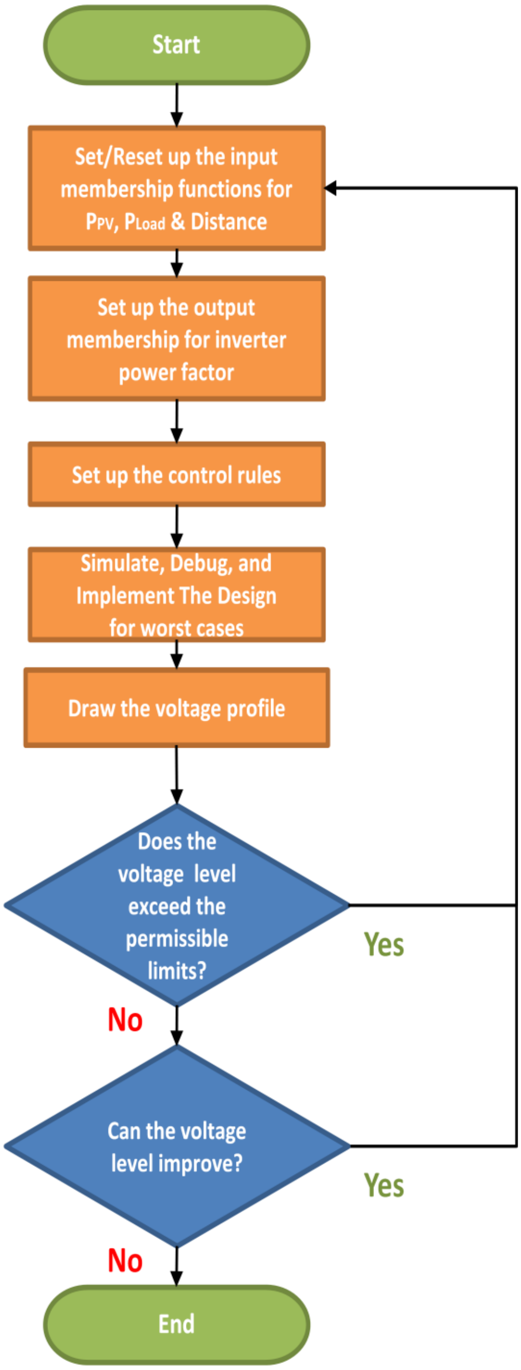


Figure 6.4 Step by step design for the FL power factor controller for inverter.

6.3.1 Input membership functions

6.3.1.1 Output power of PV (P_{PV})

The output power of PV generator membership is represented by a range of 0 kW to 40 kW.

MF		Approximate range (kW)
L	Low	0-9
M	Medium	9-24
H	High	24-40

Table 6.1 Membership function P_{PV} Range

The triangular membership function is used to take advantage of the simplicity of the system and reduce the running time of the program for the whole integrated fuzzy system.

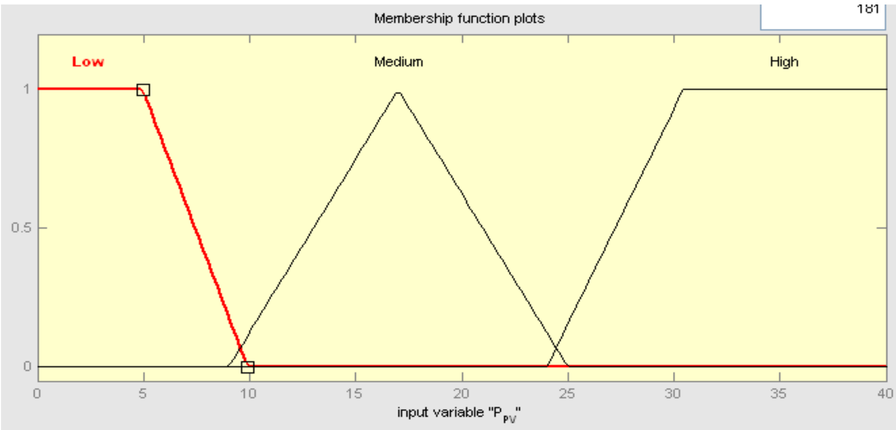


Figure 6.5 Input membership function P_{PV}

6.3.1.2 Load power P_L

The load power of each node membership is represented by a range of 0 kW to 20 kW.

MF		Approximate range (kW)
L	Low	0-7.5
M	Medium	7.5-16.5
H	High	16.2-22

Table 6.2 Membership function P_L Range

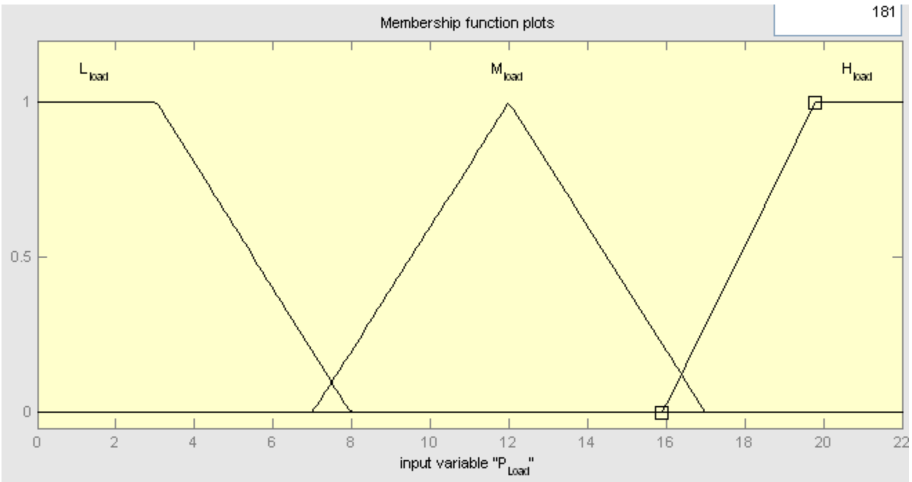


Figure 6.6 Input membership function P_L

6.3.1.3 Distance from secondary substation

The distance for each node from substation membership is presented by a range 0m to 200 m according to the base model.

MF		Approximate range (m)
N	Near	0-50
M	Medium	50-100
F	Far	100-200

Table 6.3 Membership function D range

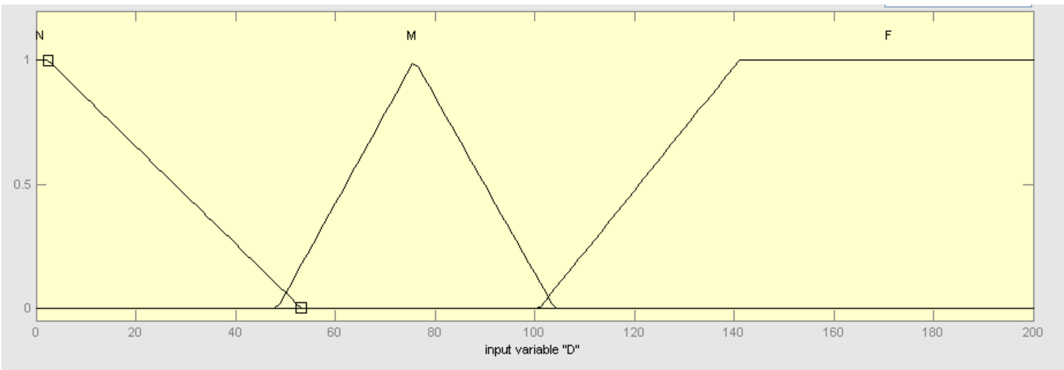


Figure 6.7 Input membership function D

6.3.2 Output membership function

As mentioned in chapter 4, overcoming the voltage rise issue at any node of the feeder with PVs (Fig. 3.8) can be done by operating the PV generators at 0.9 lagging power factor. This value will be used for the far nodes in the worst case scenario with maximum PV and no load. Fig. 6.8 shows the voltage profile along the I9 feeder with maximum PV at node 5 and 6 and no load at all nodes.

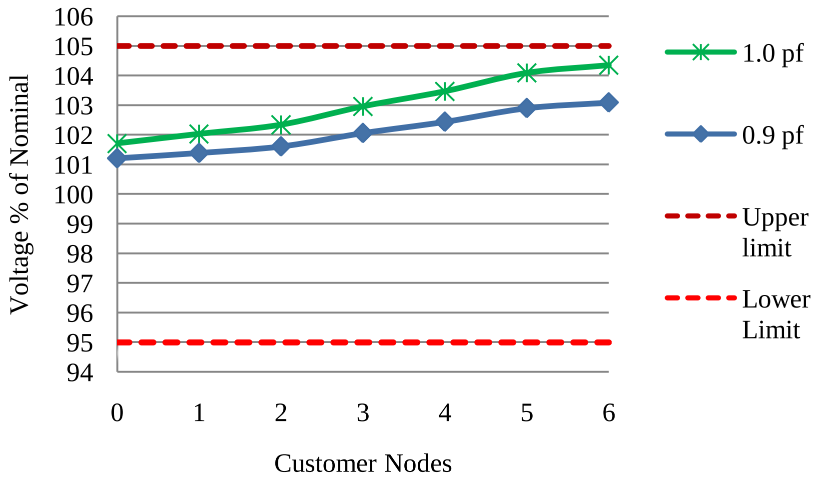


Figure 6.8 Voltage profile of I9 (No load & Max PV at node 5 & 6)

For the medium distance node from the secondary substation 0.95 lagging power factor will be used. Fig 6.9 shows the voltage profile along the I9 feeder with maximum PV at node 3 and 4 and no load at all nodes.

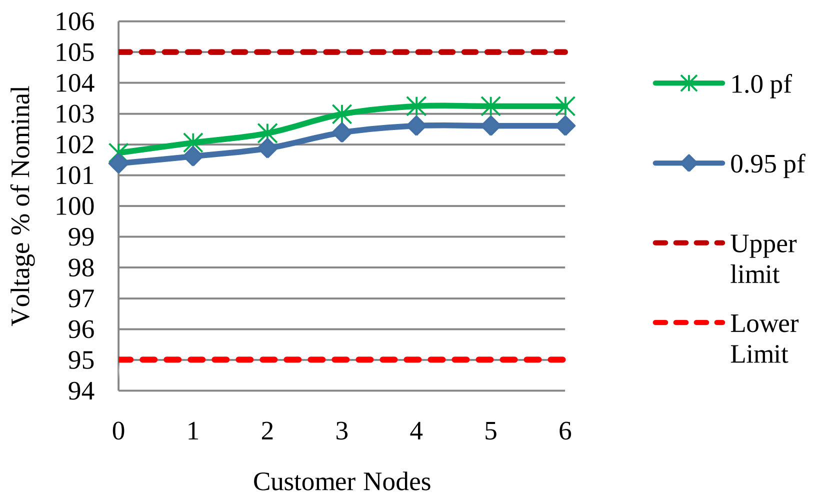


Figure 6.9 Voltage profile I9 (No load & Max PV at node 3 & 4)

Finally, for the near nodes from the substation the inverter will be kept uncontrolled which means that the inverter operates at unity power factor for all cases. This makes this proposed method cheaper. Fig 6.10 shows the voltage profile along the I9 feeder with maximum PV at node 1 and 2 and no load at all nodes.

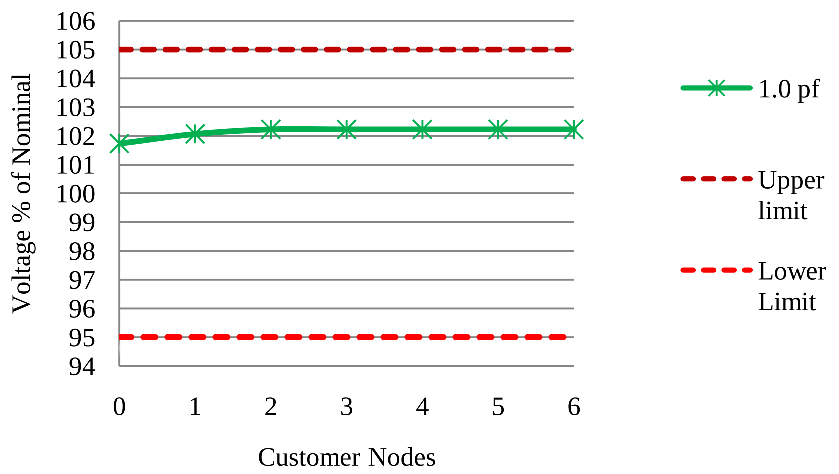


Figure 6.10 Voltage profile I9 (No load & Max PV at node 1 & 2)

In order to force the output of the controller to choose one of these lagging power factors (0.9 and 0.95) or keep it working at unity power factor a membership function with a single spike is used. Fig. 6.11 shows the output membership function for the power factor set.

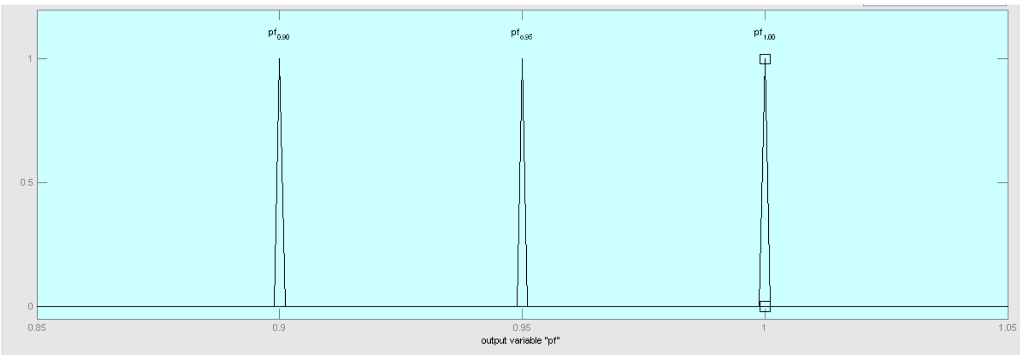


Figure 6.11 Output membership function lagging power factor set

6.3.3 The control rules

The possible combination between the 3 inputs situations will give a total number of 27 rules as there are 3 situations for each input. However, because the near nodes will be uncontrolled the total number of rules reduces to 18 rules. The desired power factor will be selected logically for each situation. The rules are described as follow:

1) If (P_{Load} is Low) and (P_{PV} is Low) and (D is M) then (pf is 1.00)
2) If (P_{Load} is Medium) and (P_{PV} is Low) and (D is M) then (pf is 1.00)
3) If (P_{Load} is High) and (P_{PV} is Low) and (D is M) then (pf is 1.00)
4) If (P_{Load} is Low) and (P_{PV} is Medium) and (D is M) then (pf is 1.00)
5) If (P_{Load} is Medium) and (P_{PV} is Medium) and (D is M) then (pf is 1.00)
6) If (P_{Load} is High) and (P_{PV} is Medium) and (D is M) then (pf is 1.00)
7) If (P_{Load} is Low) and (P_{PV} is High) and (D is M) then (pf is 0.95)
8) If (P_{Load} is Medium) and (P_{PV} is High) and (D is M) then (pf is 1.00)
9) If (P_{Load} is High) and (P_{PV} is High) and (D is M) then (pf is 1.00)

10) If (P_{Load} is Low) and (P_{PV} is Low) and (D is H) then (pf is 1.00)

11) If (P_{Load} is Medium) and (P_{PV} is Low) and (D is H) then (pf is 1.00)

12) If (P_{Load} is High) and (P_{PV} is Low) and (D is H) then (pf is 1.00)

13) If (P_{Load} is Low) and (P_{PV} is Medium) and (D is H) then (pf is 0.95)

14) If (P_{Load} is Medium) and (P_{PV} is Medium) and (D is H) then (pf is 1.00)

15) If (P_{Load} is High) and (P_{PV} is Medium) and (D is H) then (pf is 1.00)

16) If (P_{Load} is Low) and (P_{PV} is High) and (D is H) then (pf is 0.90)

17) If (P_{Load} is Medium) and (P_{PV} is High) and (D is H) then (pf is 0.95)

18) If (P_{Load} is High) and (P_{PV} is High) and (D is H) then (pf is 1.00)

Table 6.4 shows the fuzzy rules to set up the power factor of the inverter at customer in the middle range distance from substation (50-100m).

PV / Load	Low	Medium	High
Low	1.0	1.0	0.95
Medium	1.0	1.0	1.0
High	1.0	1.0	1.0

Table 6.4 fuzzy rule base for nodes in medium range distance

Table 6.5 shows the fuzzy rules to set up the power factor of the inverter at customer in the far distance from substation (100-200m).

PV / Load	Low	Medium	High
Low	1.0	0.95	0.90
Medium	1.0	1.0	0.95
High	1.0	1.0	1.0

Table 6.5 fuzzy rule base for nodes in far range distance

Fig. 6.12 shows the proposed FLC for each generator.

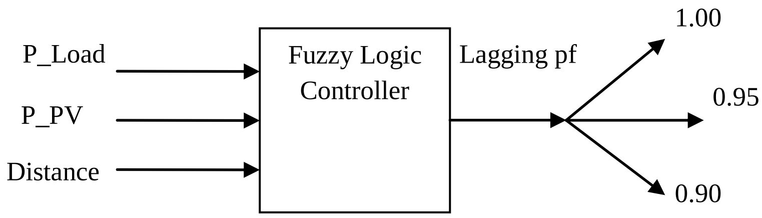


Figure 6.12 Proposed FLC for eacn generator

6.3.4 Simulations and results

The steady-state solution has been investigated to check the behaviour of the proposed controller at worst case scenarios. For each case the selected data for the load power, the power generated by PV and the distance from the secondary substation are used as inputs for the fuzzy system in MATLAB Simulink environment. The output of this system is used to set the operating pf for generators at each node in I9 feeder by using the ETAP software package. Then, the simulation is run to get the voltage level at each node with the fuzzy logic decision and rerun when the generators are kept uncontrolled. After that, the readings of voltages are taken to an excel spread sheet to draw the voltage profile of both cases:

1. Uncontrolled PV inverter (ie. 1.0 pf).
2. Controlled PV inverter by FLC.

Table 6.6 shows all possible worst case scenarios that can be happen at the feeder.

	P_{Load}			P_{PV}		
Node	1,2	3,4	5,6	1,2	3,4	5,6
Case 1	No	No	No	Max high	Max high	Max high
Case 2	No	No	Min medium	Max high	Max high	Max high
Case 3	No	Min medium	Min medium	Max high	Max high	Max high
Case 4	No	Min medium	Min high	Max high	Max high	Max high
Case 5	No	No	No	Max high	Max high	Max medium
Case 6	No	No	No	Max high	Max medium	Max medium
Case 7	No	No	No	Max high	Max high	Max low
Case 8	No	No	No	Max high	Max medium	Max low

Table 6.6 Worst case scenarios

Fig. 6.13 to Fig. 6.20 show the results for all worst case scenarios

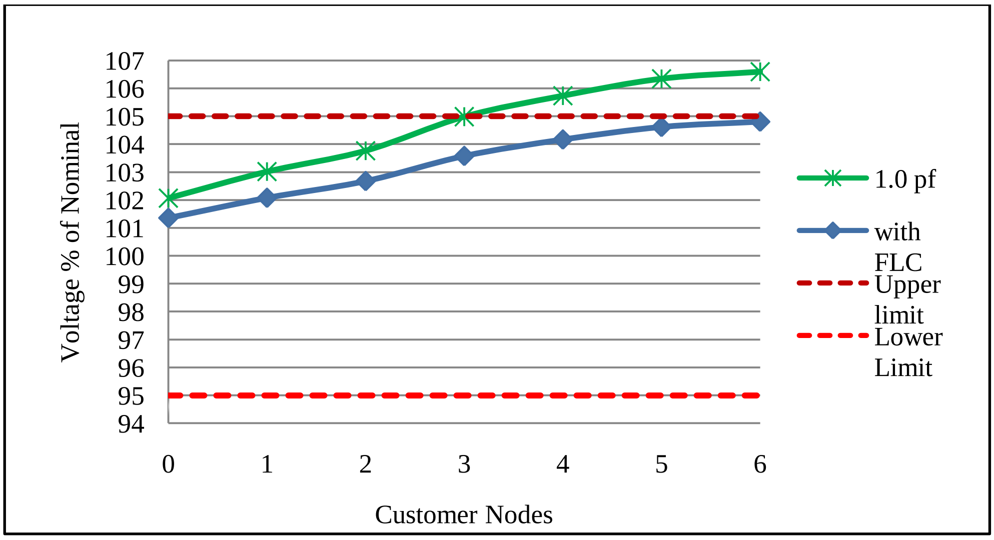


Figure 6.13 Case 1: Voltage profile I9 (No load & Max high PV at all node)

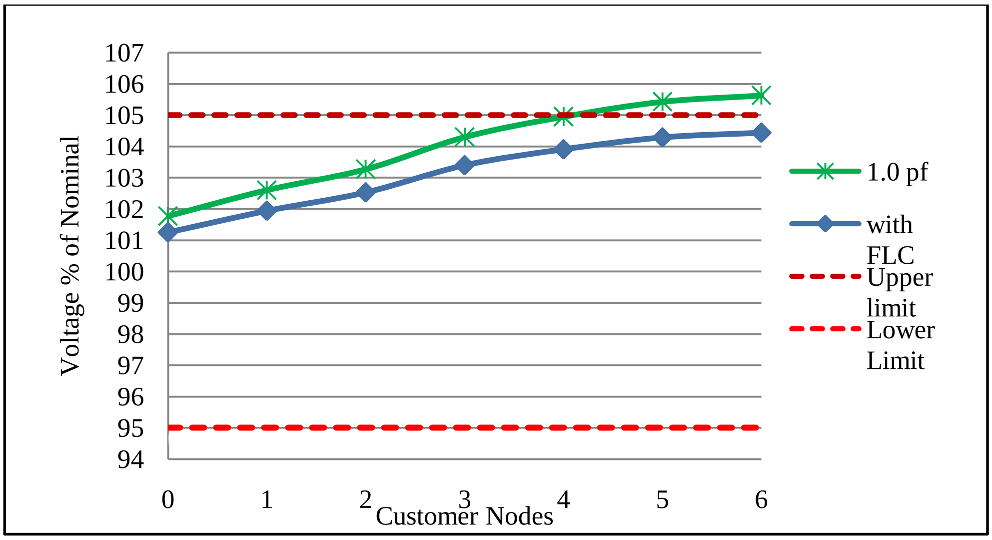


Figure 6.14 Case 2: Voltage profile I9 (Min medium load & Max high PV at node 5, 6 and No load & Max high PV at node 1, 2, 3, 4)

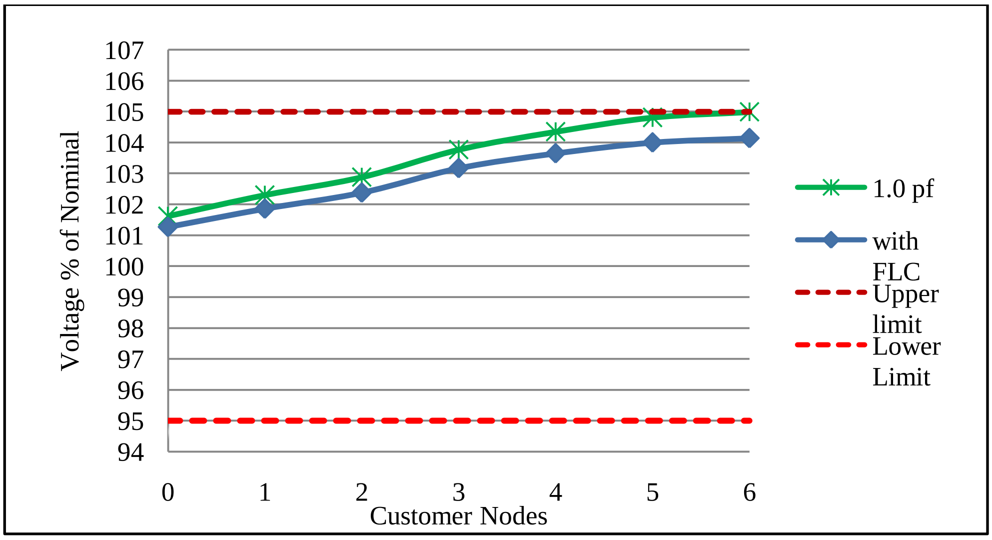


Figure 6.15 Case 3: Voltage profile I9 (Min medium load & Max high PV at node 3, 4, 5, 6 and No load & Max high PV at node 1, 2)

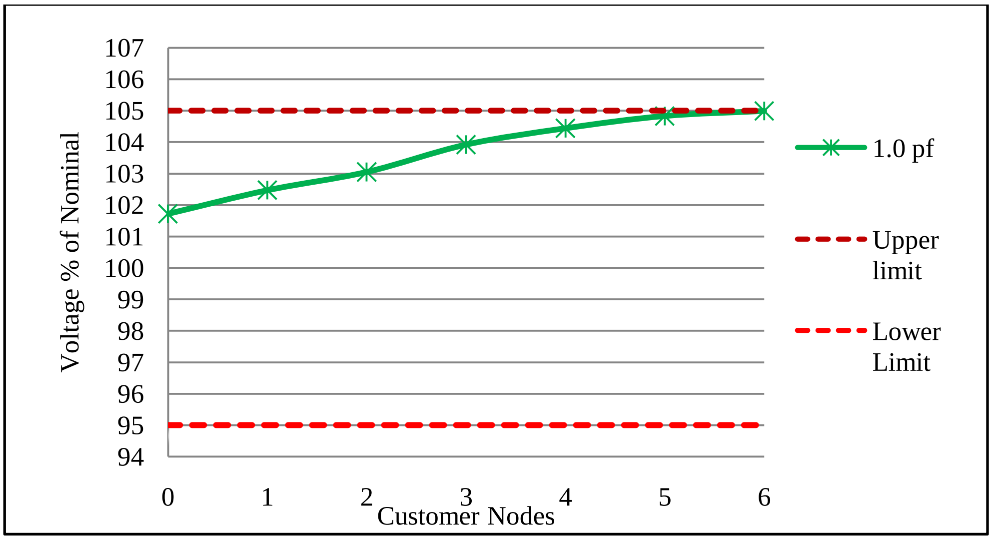


Figure 6.16 Case 4: Voltage profile I9 (Min high load & Max high PV at node 5, 6 and Min medium load & Max high PV at node 3, 4 and No load & Max high PV at node 1, 2)

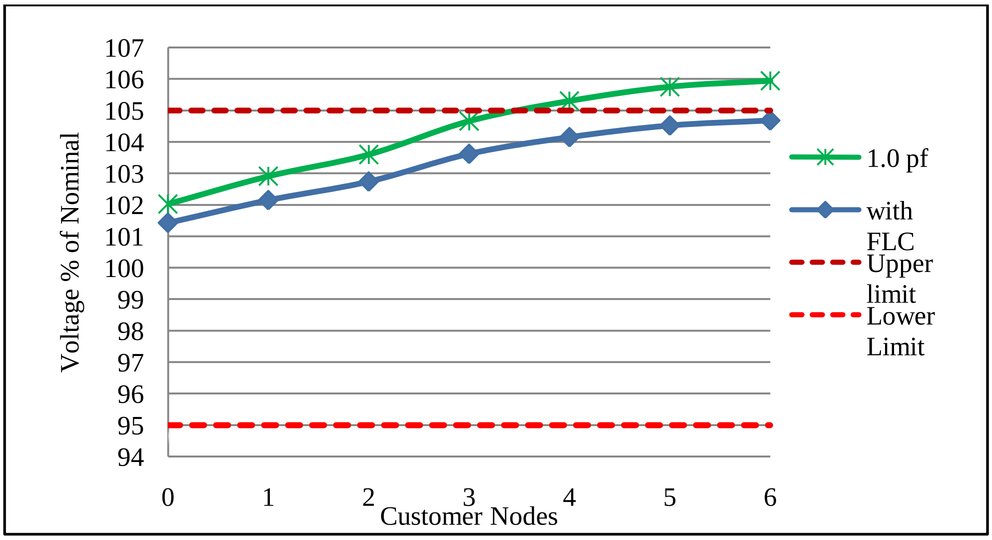


Figure 6.17 Case 5: Voltage profile I9 (No load & Max medium PV at node 5, 6 and No load & Max high PV at node 1, 2, 3, 4)

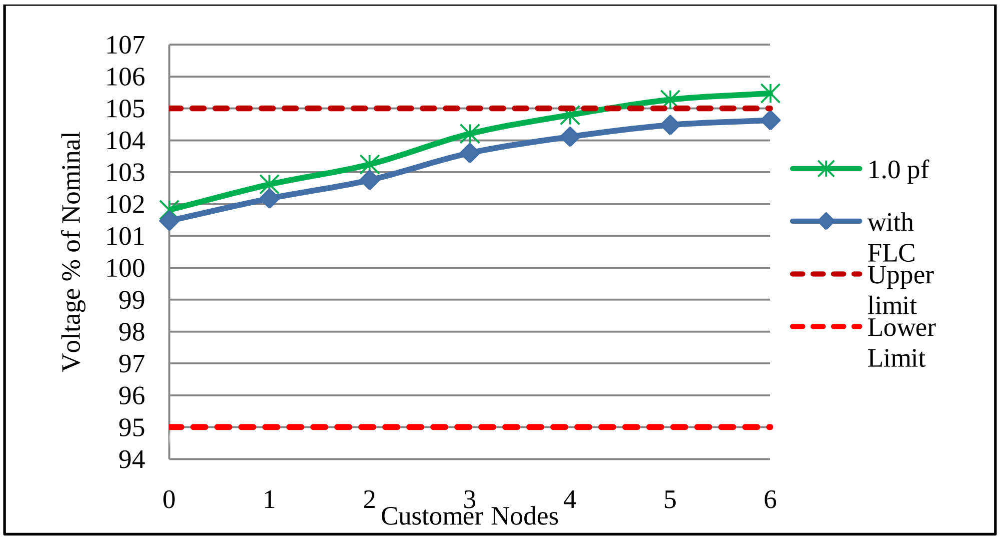


Figure 6.18 Case 6: Voltage profile I9 (No load & Max medium PV at node 3, 4, 5, 6 and No load & Max high PV at node 1, 2)

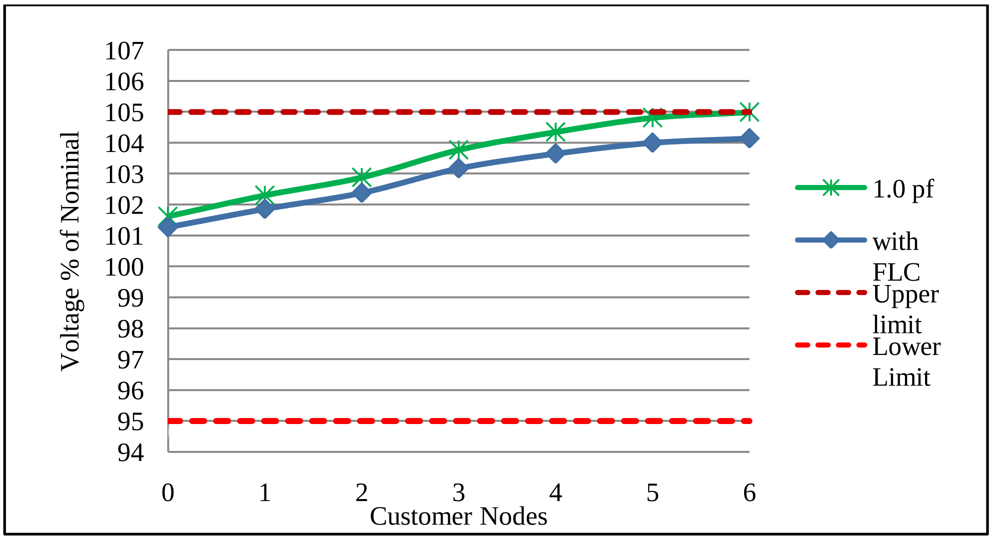


Figure 6.19 Case 7: Voltage profile I9 (No load & Max low PV at node 5, 6 and No load & Max high PV at node 1, 2, 3, 4)

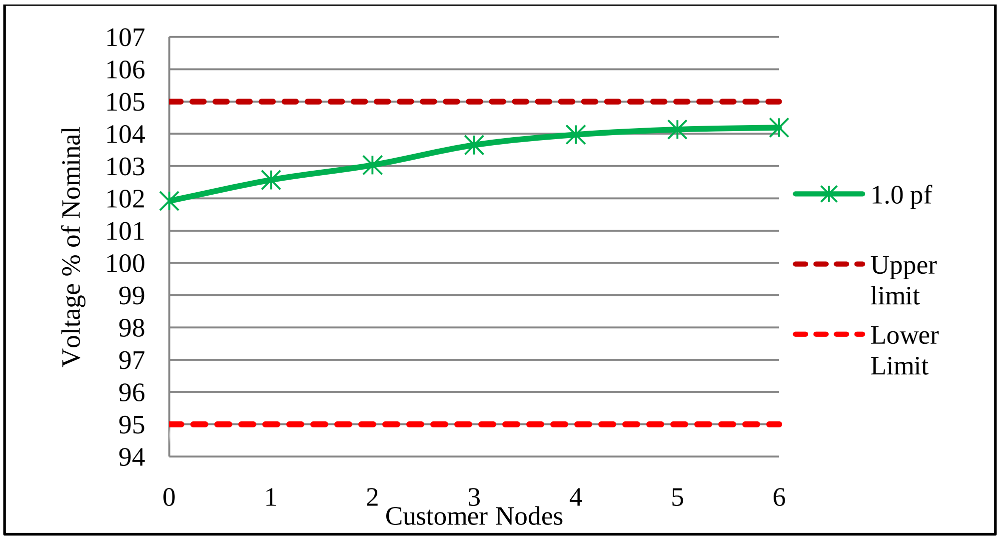


Figure 6.20 Case 8: Voltage profile I9 (No load & Max low PV at node 5, 6 and No load and Max medium PV at node 3, 4 and No load & Max high PV at node 1, 2)

The previous figures show clearly the ability of the proposed FLC to keep the voltage level for all nodes within the permissible level. Also, the voltage profile can be brought down for case 4 by resetting the range of the input memberships for medium load if this desired by the network operator. As the proposed FLC would manage to keep the voltage between the limits in all worst cases, it will be valid for all other possible scenarios, meaning that it offers a plug and play option for each customer.

6.4 Stability assessment for the proposed FLC

6.4.1 MATLAB/Simulink model

In order to check the stability of the previous proposed controller for each generator on a same feeder and check the interaction between them, a dynamic simulation is needed with at least two controller at the same feeder. In this section the MATLAB/Simulink with Powersys tool box will be used to investigate this issue. The same model designed in [76] to control the inverter for fuel cells by setting the required active and reactive power will be used. Fig. 6.21 shows the block diagram for the controller of the inverter.

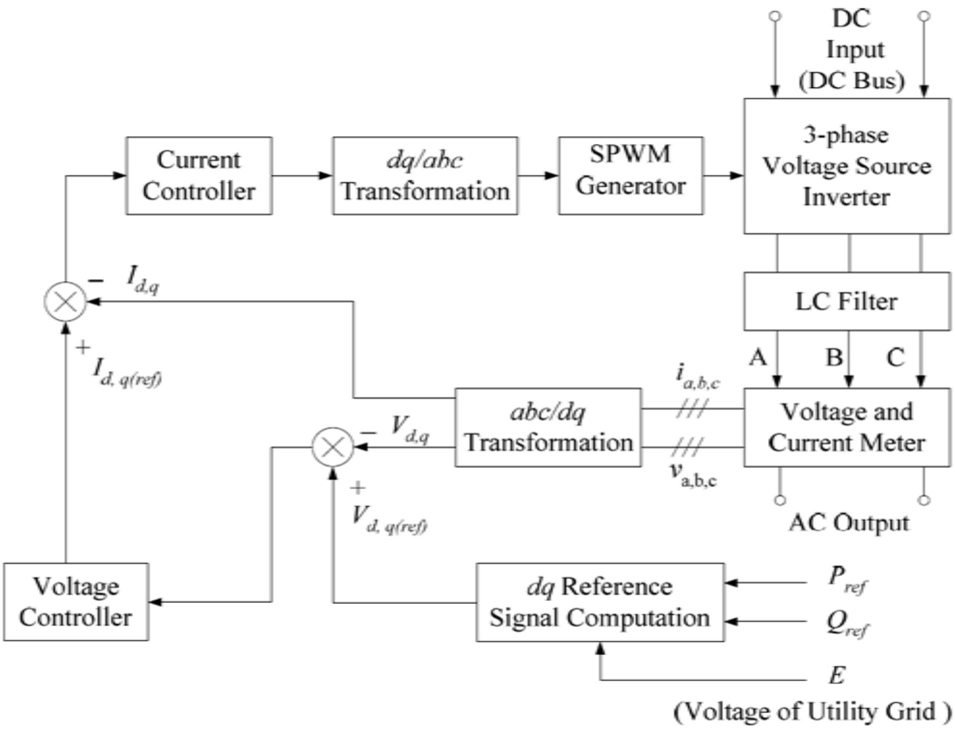


Figure 6.21 Block diagram of the controller for the inverter [76]

In Fig. 6.20, the “dq Reference Signal Computation” block, which is based on eq. (6.3) and (6.4), calculates the magnitude and angle of the filtered output voltages of the inverter and then converts them into dq voltage reference signals. The “abc/dq Transformation” block takes the current and voltage values (in abc coordinate) from the voltage and current meters and converts them into dq values. The outer voltage controller takes the error signals between the actual output voltage in dq frame ($V_{d,q}$) and the reference voltage ($V_{\mathrm{d,q(ref)}}$) and generates the current reference signals ($I_{\mathrm{d,q(ref)}}$) for the current control loop. The inner current controller produces the dq control signals, which are converted back into the control signals in abc coordinates through the “dq/abc Transformation” block. These control signals are used to modulate the sinusoidal pulse width modulation (SPWM) pulse generator to produce the proper pulses for the inverter switches, which control the inverter output voltage.

However, the desired active and reactive power is derived by the proposed FLC. The stability issue for such a system appears because the value of the voltage at the node of connection is taken into account for setting the reactive output power of the inverter. At the same time the voltage level at the node of connection is changed by the total power penetration from the inverter as has been shown before. So, the main objective of this section is to investigate the behaviour of two controllers at two nodes in the same feeder while changing the load and the power from the PV generator. Nodes 5 and 6 of I9 feeder have been taken into consideration with maximum power integration. The load at node 5 will be changed from low to high while the load at node 6 goes from high to low at the same time. All other nodes in the feeder are kept constant and without PV integration. Fig. 6.22 shows the simulation model for each inverter in MATLAB/Simulink.

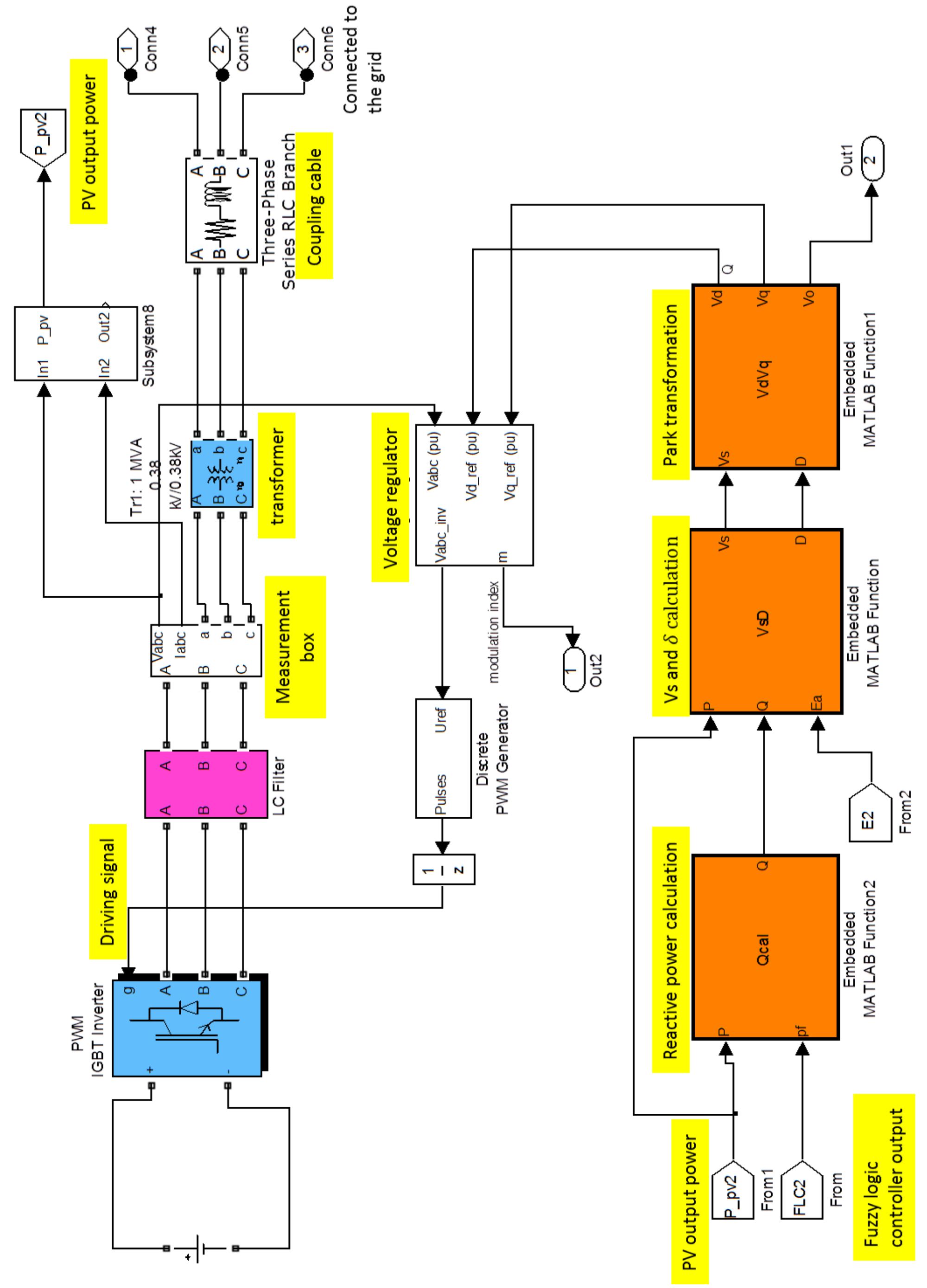


Figure 6.22 Controlled inverter

The output of the fuzzy logic controller (power factor) and the total power generated by PV will be used to calculate the required reactive power by using an embedded function, Qcal in MATLAB/Simulink. Another embedded function, VsD used to calculate V_S and δ based on eq. 6.3 and eq. 6.4. Then reference values for the voltage control loop ($V_{d,q(ref)}$) are calculated by Park's transformation. Also, the voltage regulator includes the current control loop to set up the pulses for the inverter to deliver the required active and reactive power to the system.

Fig.6.23 shows the simulation model for the feeder I9 with the FLC for node 5 and 6.

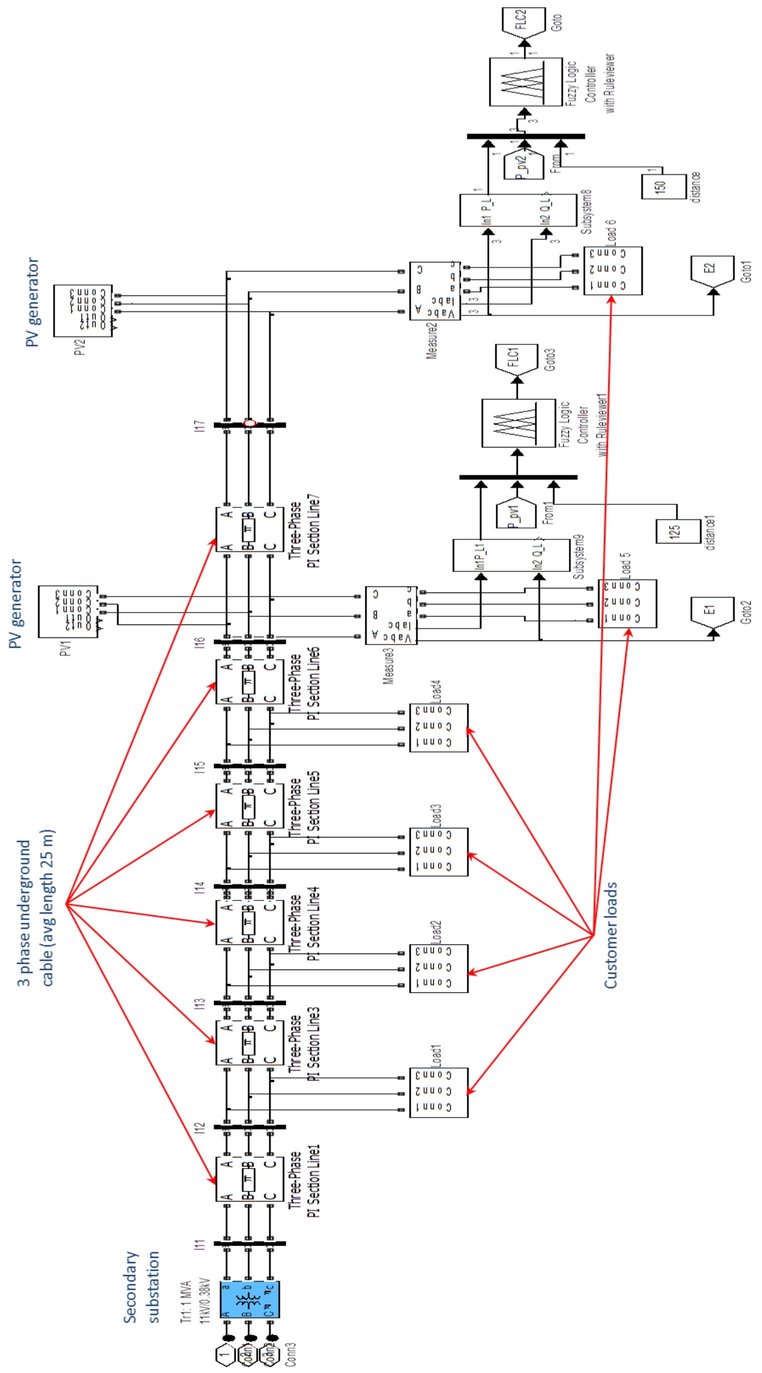
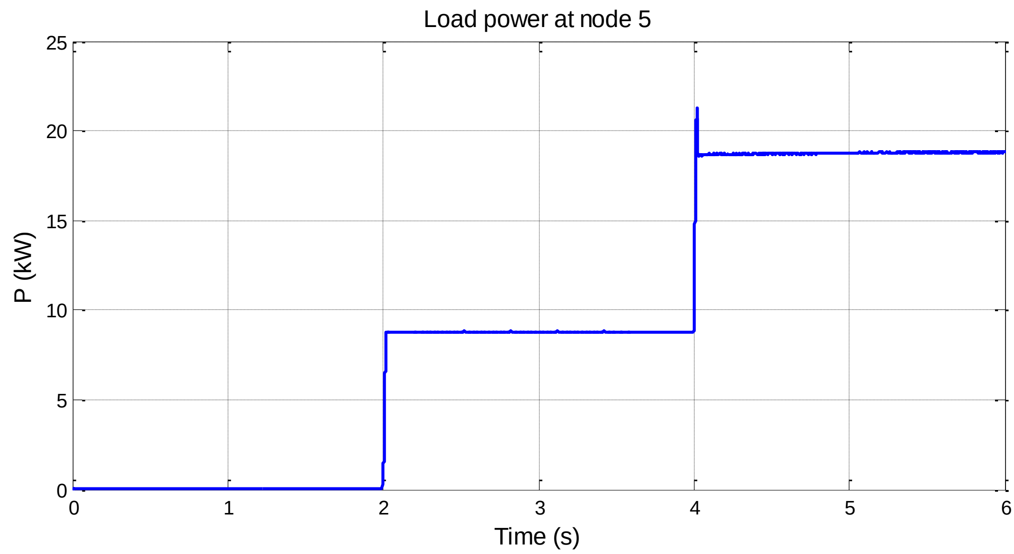


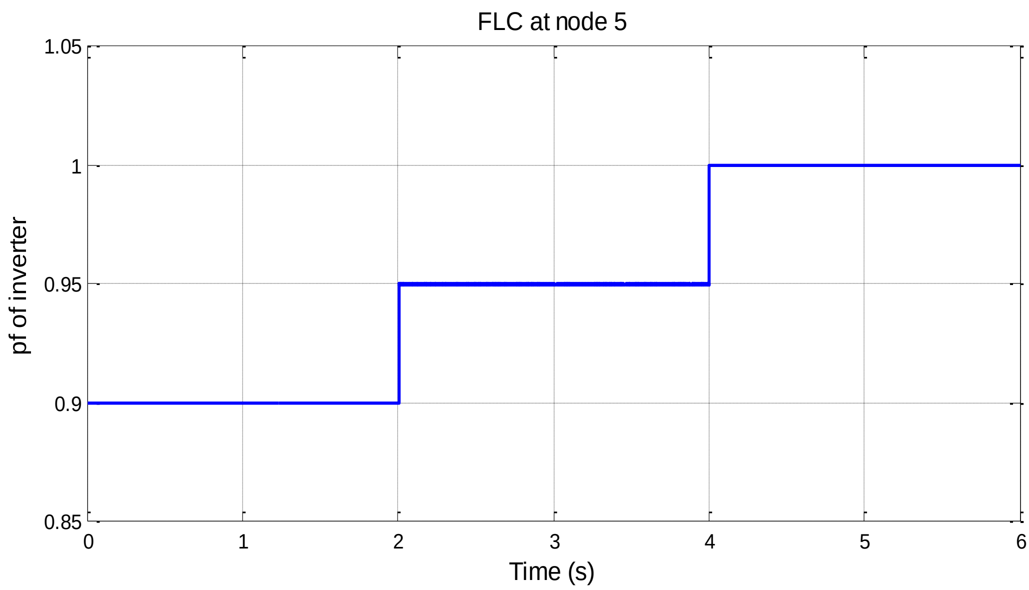
Figure 6.23 Simulation model for I9 feeder

6.4.2 Results of simulations

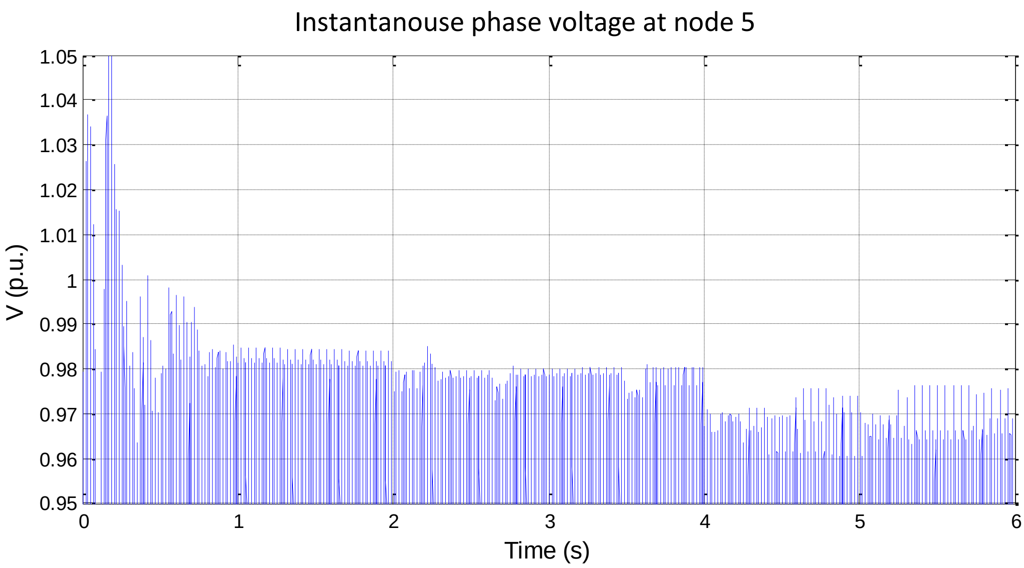
Fig 6.24 and Fig 6.25 shows the load and the FLC decision at node 5 and 6. The PV generators remain at maximum value during the simulation for both nodes.



(a)

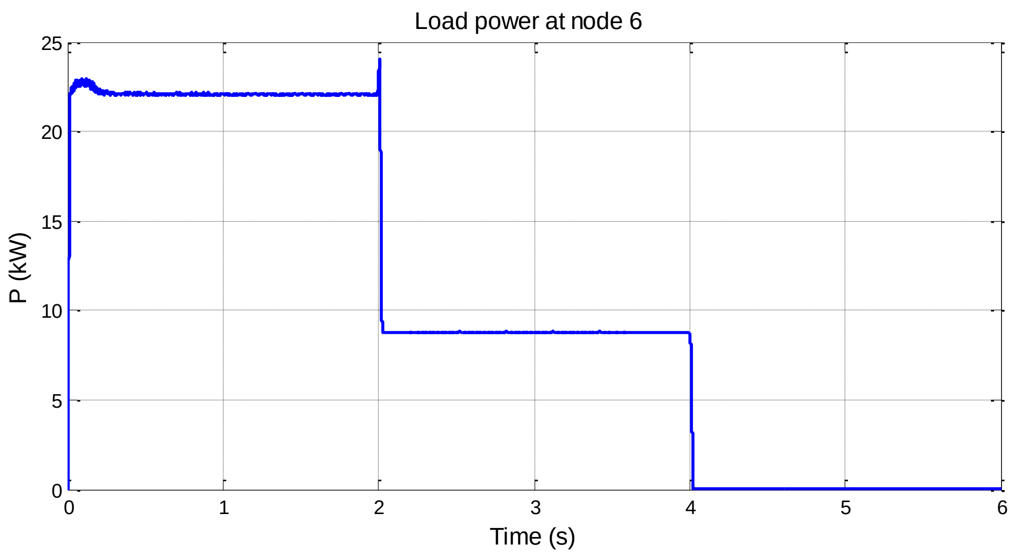


(b)

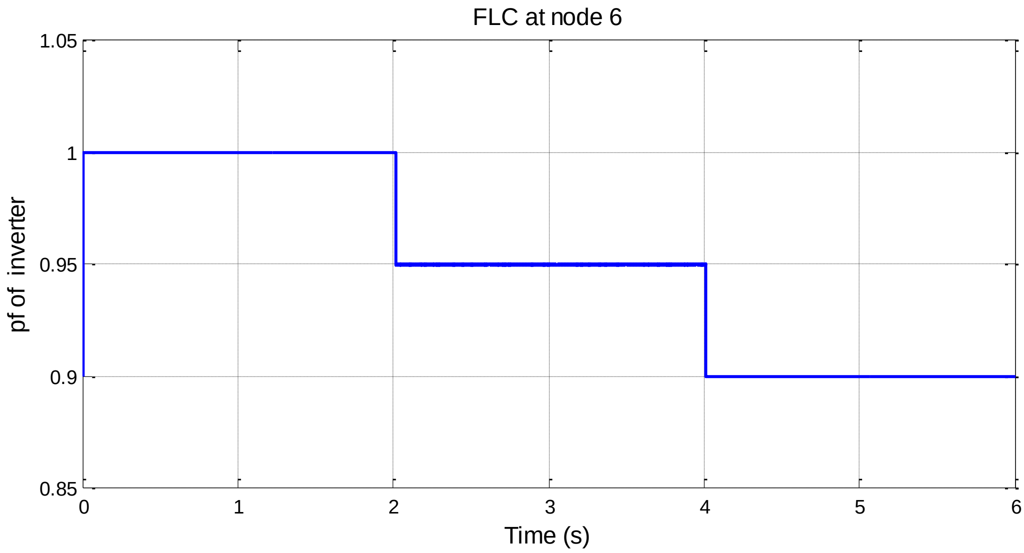


(c)

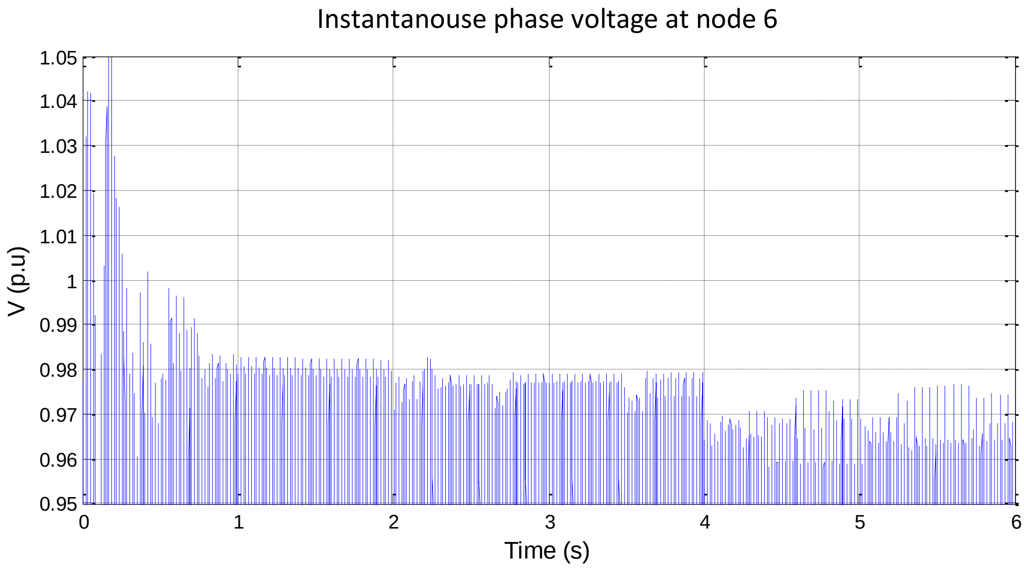
Figure 6.24 Node 5 (a) FLC decision (b) Load power (c) Line Voltage



(a)



(b)



(c)

Figure 6.25 Node 6 (a) FLC decision (b) Load power (c) Line Voltage

The results show that the decision of each FLC will not be affected by the situation of the other one and there is no interaction between them. This means that there is no need for any type of coordination between the local controllers. This gives a very good advantage for this technique comparing with other solutions that depends on coordination and communication network.

6.5 Conclusion

This chapter has presented another novel technique to regulate the voltage along a distribution feeder with PV integration. A local controller for each PV generator is designed using FL concepts to set the required consumption of reactive power for each inverter. The steady-state results have been presented which show the ability of the proposed control to handle the problem of voltage rise. Also, it offered a plug and play option for all customers on the feeder. Finally, the stability of the system has been assessed using MATLAB/Simulink with Powersys tool box. The simulation results show that the system with FLC of the power factor responds in a stable manner to dynamic changed in load and PV power.

Chapter 7

7 Conclusions

The integration of distributed generators into distribution networks greatly impacts the network's performance. This work focuses on PV generator impact on the voltage regulation of residential distribution networks in Saudi Arabia. In this chapter, the conclusions of the work are highlighted, followed by a list of possible avenues for future research that have been revealed.

7.1 Contribution to knowledge

The thesis has studied and proposed solution approaches for voltage rise problems related to the integration of PV generators to residential distribution networks in Saudi Arabia. The conclusion of this thesis could be summarized in the following points:

- The impact of GCPV systems in residential areas using standard PV panels has been investigated. The results show a significant benefit of using GCPV system in the Saudi utility network. It would reduce the energy supplied from the main generators and help to decrease the peak demand. Also, this work shows that conventional PV integration will have little impact on the power network, both for residential and industrial areas. However, new PV technologies such as CPV will have a significant impact on voltage control

Therefore development of voltage control systems is necessary in the case of CPV.

- The effect of a higher penetration level of PV generation on the voltage regulation in a residential network has been studied. In general, the results show that SEC has a very strong network in residential areas. The voltage rise problem, which is considered as one of the most important issue in the use of GCPV systems is very infrequent to happen in that type of networks. Only when using high efficiency concentrating PV technology at high solar radiation and light load could the voltage limits be exceeded. However, if it occasionally occurs, methods such as operating the PV generator at lagging power factor or use of the OLTC which usually exists in the primary station would mitigate the problem.
- This work formulates an optimised solution for regulating the distribution feeder's voltage at minimum costs, when CPV are connected to a distribution feeder. A supervisory central controller using fuzzy logic concepts to set up the OLTC for the primary substation in residential distribution networks has been developed. This includes a novel technique to control the OLTC based on the power flow information at the transformer itself. The main advantage of this approach is that all measurements are taken locally at the substation and there is no need for remote communication of other information in the system. The presented results shown how the controller effectively regulates the voltage level along the residential networks with CPV generators connected.
- The stability of the proposed controller has been assessed using MATLAB/Simulink software package with Powersyst toolbox. For this, an

OLTC model has been developed based on the existing model in the software, where the output signal of FLC is used for setting the tap position of OLTC. In general, the results are encouraging and warrant further investigation using the fuzzy logic concept in such problems.

- The fuzzy logic controller based on power flow in the primary substation proved to be working properly under fault conditions.
- Another novel technique to regulate the voltage along a distribution feeder with PV integration is presented at the end of this work. A local controller for each PV generator has been designed using FL concepts to set the required consumption of reactive power by the each inverter. The steady-state results have been presented which show the ability of the proposed control to handle the problem of voltage rise. Also, this technique offers a plug and play option for all customers on the distribution feeder.
- The stability of the system has been assessed using MATLAB/Simulink with Powersys tool box. The simulation results show that the system with FLC of the power factor responds in a stable manner to dynamic changs in load and PV power.

7.2 Limitations and future work

It is important to note that this research was conducted based on particular case i.e. Electric networks in Saudi Arabia. In order to be able to handle a wide range of different network variables (length of line, line impedance, more complex network topology, PV cells including conventional and concentrated), an automated solutions could have been suggested.

This work can be extended to several interesting topics that need to be studied. These include:

- The impact of GCPV systems in industrial and rural areas in Saudi Arabia.
- An investigation of the impact of GCPV systems on power quality and protection coordination in the networks.
- The impact of the integration of other types of distributed generation.
- Implementation of the proposed FLC on the real system. The hardware requirements for such systems need to be studied.
- The feasibility and required coordination of using both proposed control techniques simultaneously needs to be investigated.

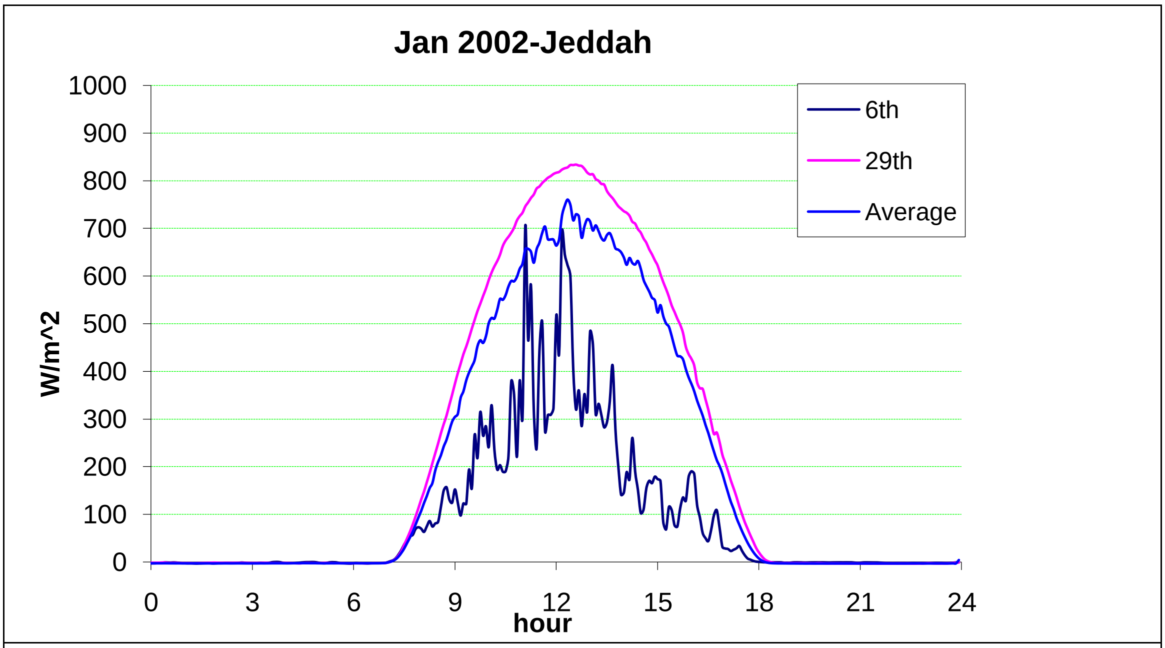
Appendix A: Solar Radiation data

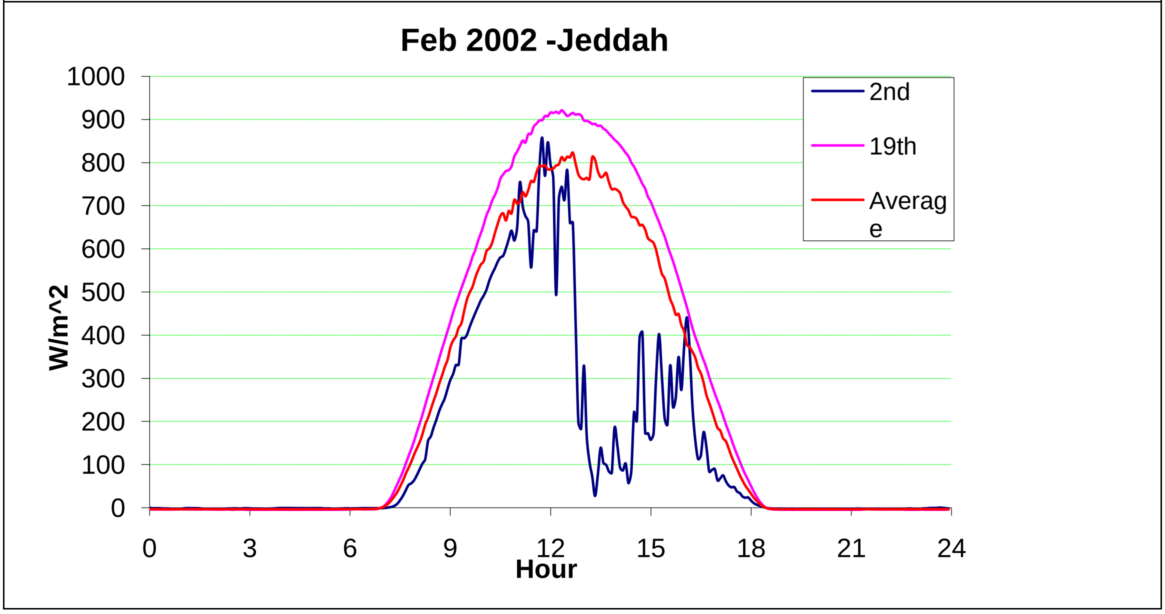
The solar radiation data for the year 2002 of the seven stations around the country have obtained from KACST for use it in this research. The locations of these stations are shown in the table below:

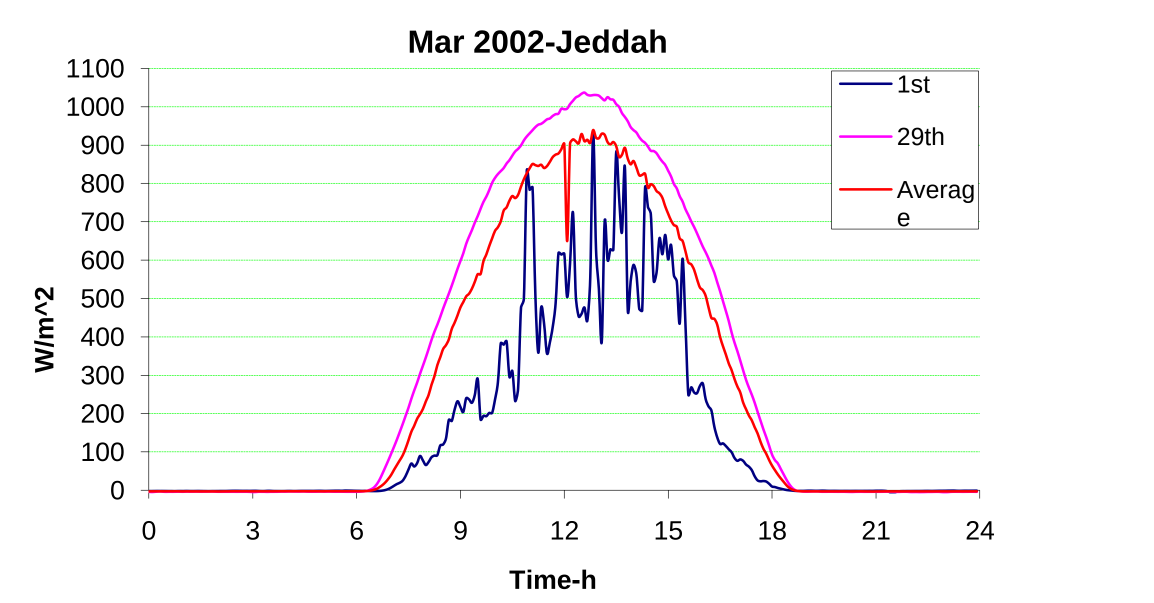
	Station	Latitude (°N)	Longitude (°E)	Elevation (meters)	On the map
1	Solar Village	24.91	46.41	650	
2	Abha	18.23	42.66	2039	
3	Al-Ahsa	25.30	49.48	178	
4	Jeddah	21.68	39.15	4	
5	Al-Madinah	24.55	39.70	626	
6	Al-Jouf	29.79	40.10	669	
7	WadiAl-Dawaser	20.44	44.68	701	

Table A.7 Station Sites

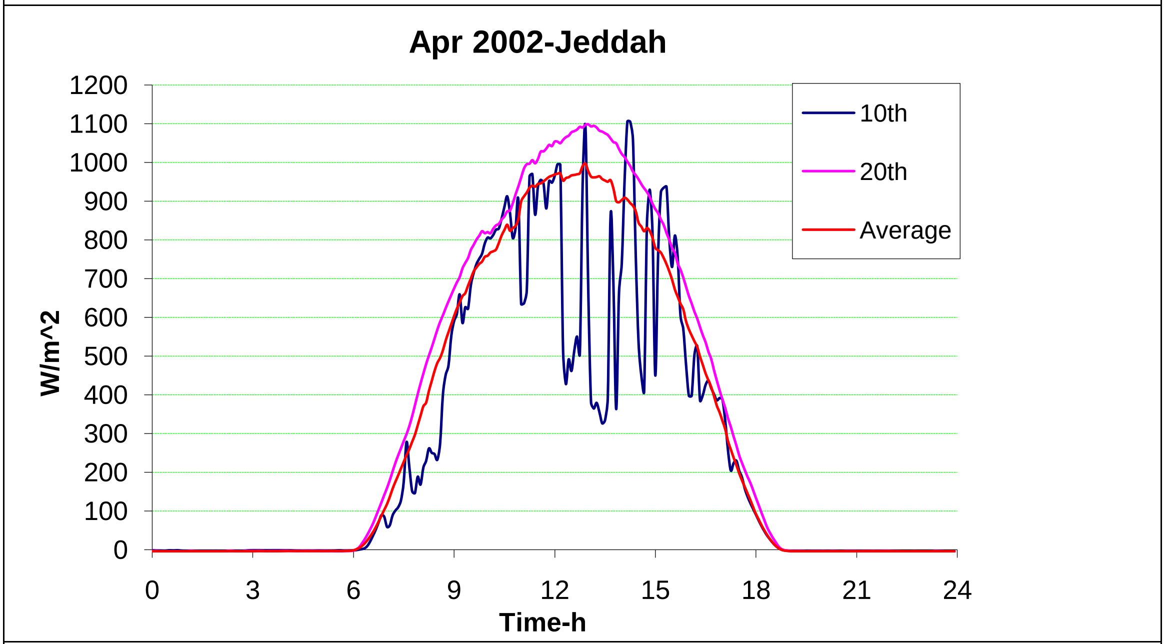
All data are stored in Microsoft Excel table format with different intervals. One minute intervals are used in the Solar Village and five minutes for the rest stations. The next figures show the peak, minimum and the average of solar radiation measured at Jeddah station. Each figure represents a specific month.


Jan 2002-Jeddah
W/m^2
1000
900
800
700
600
500
400
300
200
100
0
0
3
6
9
12
15
18
21
24
hour
6th
29th
Average

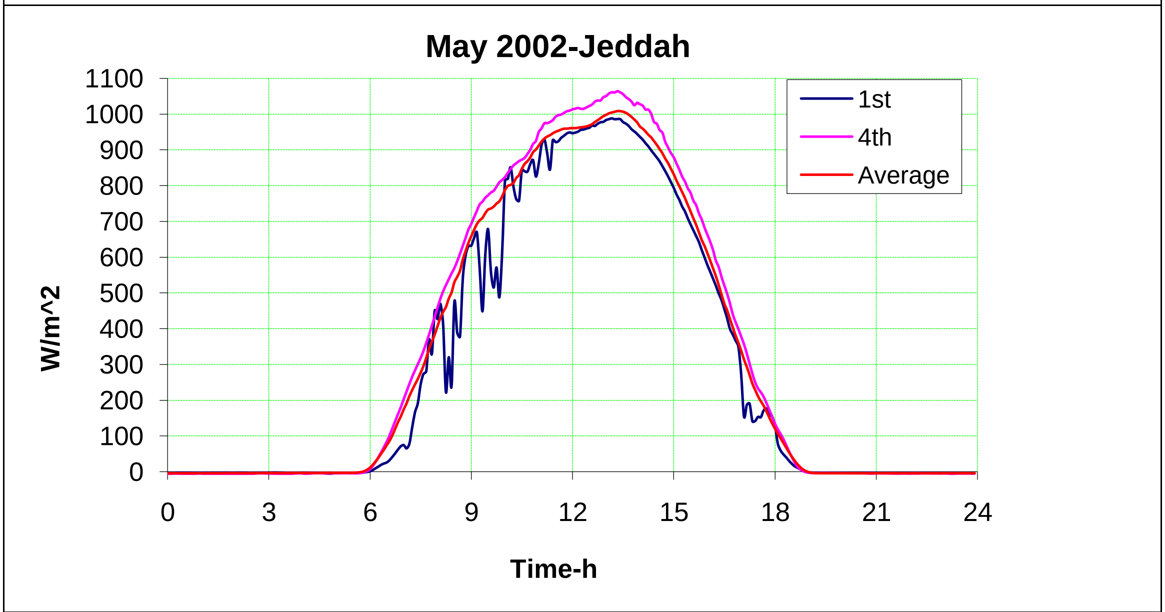

Feb 2002 -Jeddah
W/m^2
1000
900
800
700
600
500
400
300
200
100
0
0
3
6
9
12
15
18
21
24
Hour
2nd
19th
Average



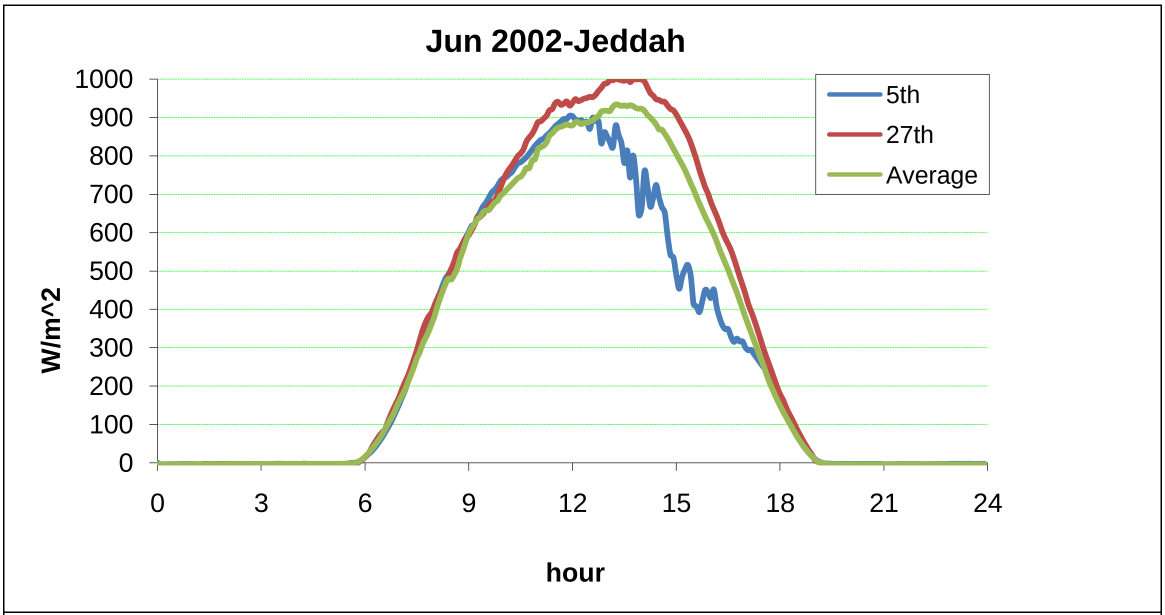
Mar 2002-Jeddah
W/m^2
1100
1000
900
800
700
600
500
400
300
200
100
0
0
3
6
9
12
15
18
21
24
Time-h
1st
29th
Average

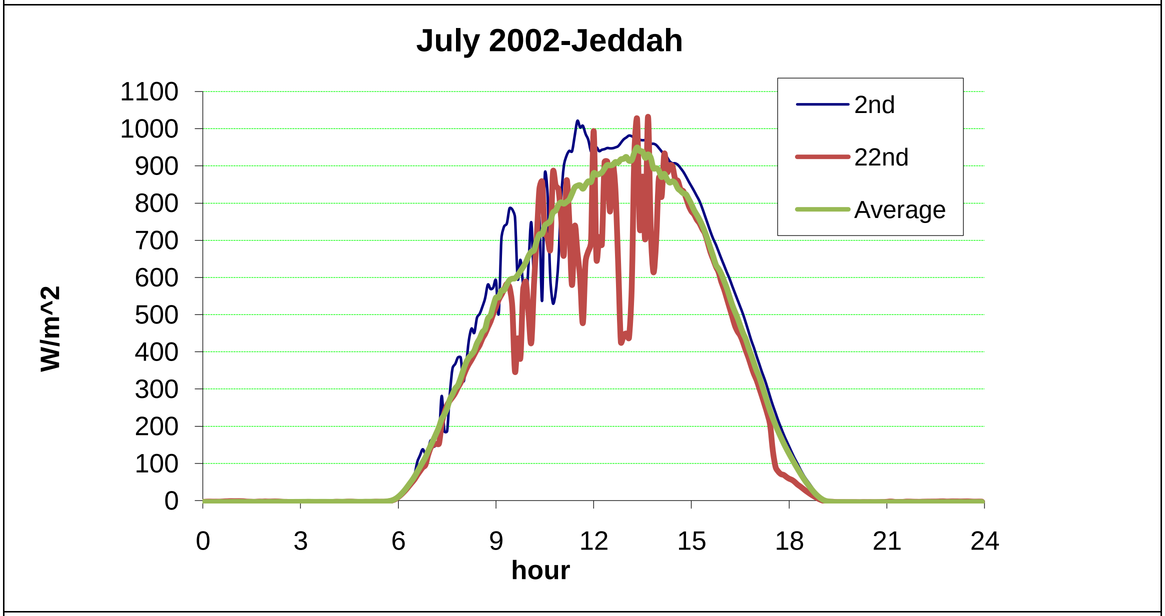


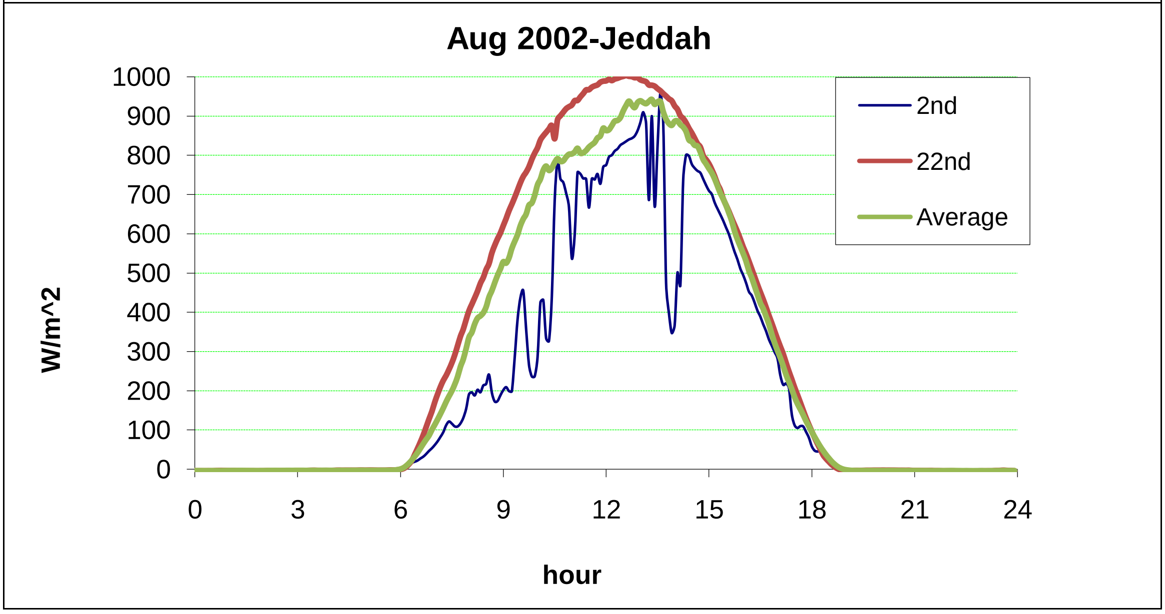
Apr 2002-Jeddah
W/m^2
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
3
6
9
12
15
18
21
24
Time-h
10th
20th
Average

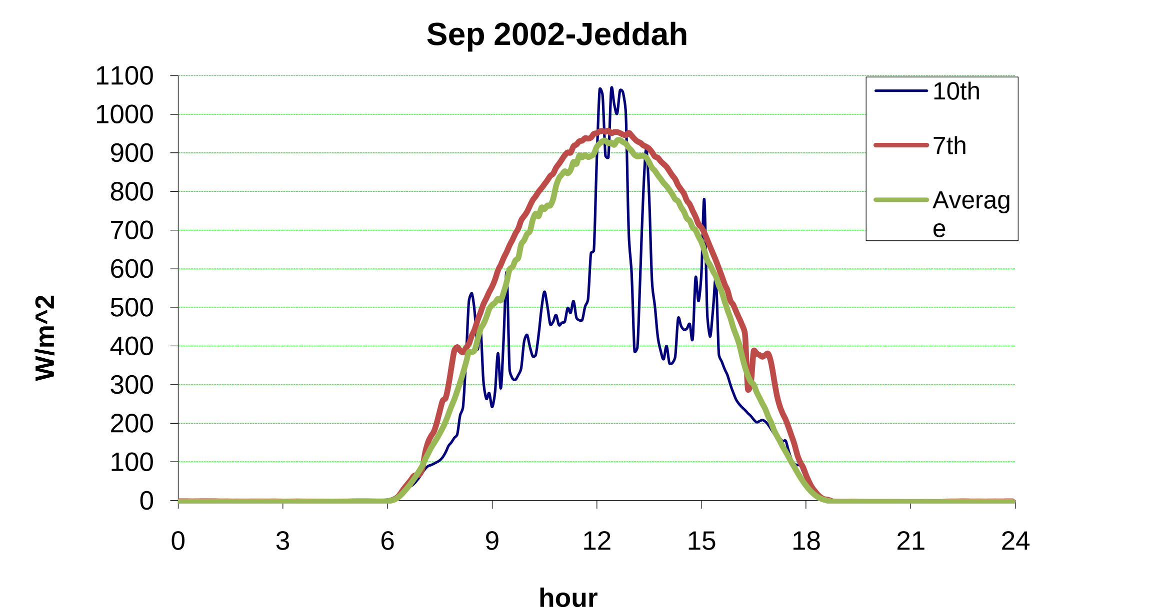


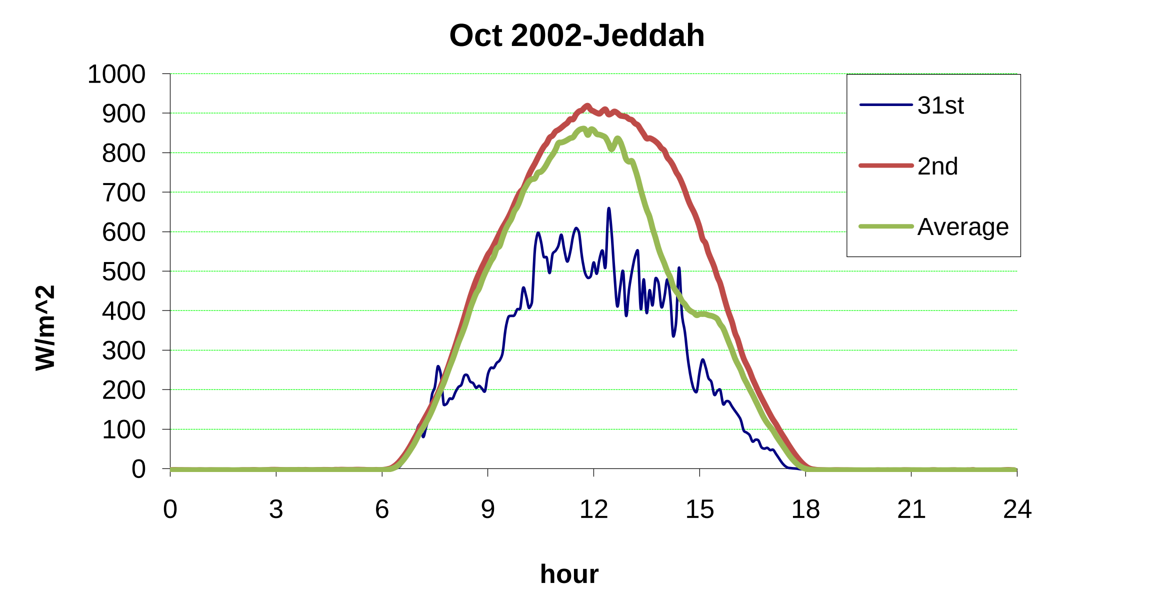
May 2002-Jeddah
W/m^2
1100
1000
900
800
700
600
500
400
300
200
100
0
0
3
6
9
12
15
18
21
24
Time-h
1st
4th
Average

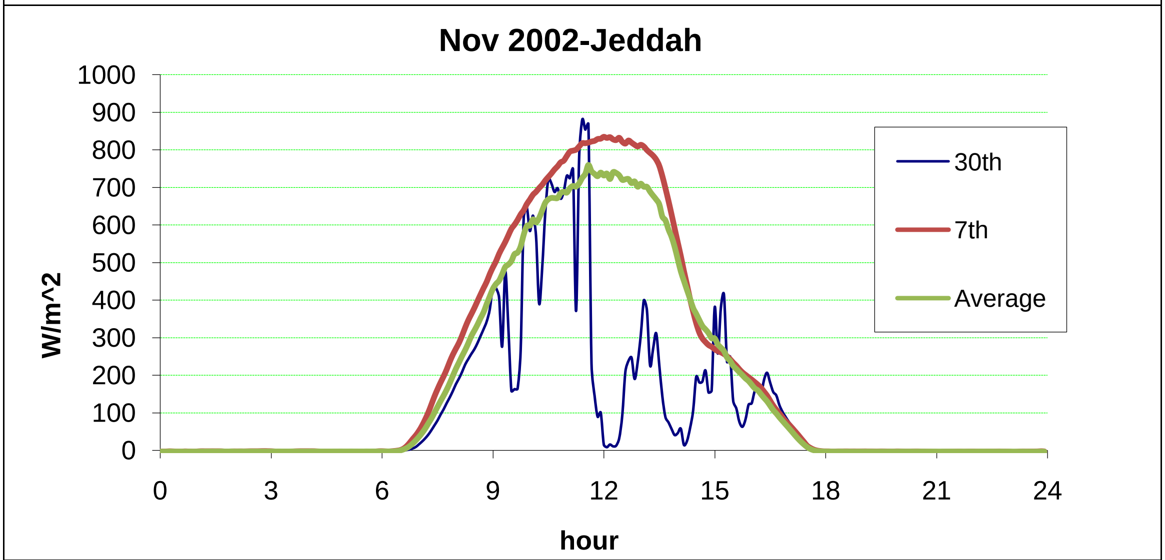

Jun 2002-Jeddah
W/m^2
hour
5th
27th
Average

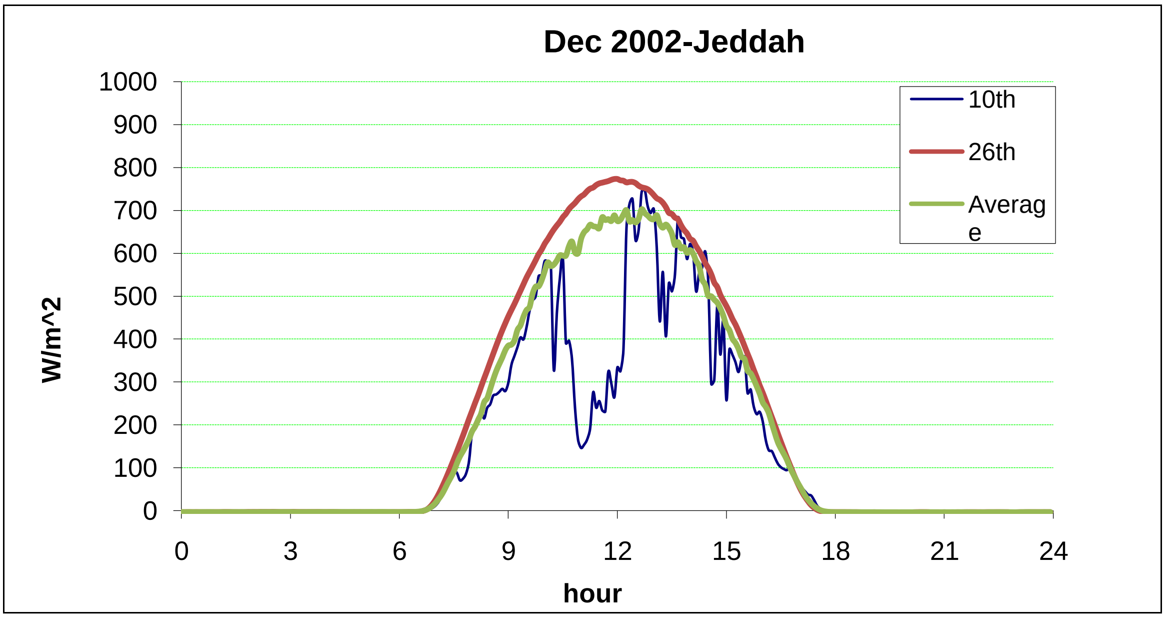

July 2002-Jeddah
W/m^2
hour
2nd
22nd
Average


Aug 2002-Jeddah
W/m^2
hour
2nd
22nd
Average


Sep 2002-Jeddah
W/m^2
1100
1000
900
800
700
600
500
400
300
200
100
0
0
3
6
9
12
15
18
21
24
hour
10th
7th
Averag
e


Oct 2002-Jeddah
W/m^2
1000
900
800
700
600
500
400
300
200
100
0
0
3
6
9
12
15
18
21
24
hour
31st
2nd
Average


Nov 2002-Jeddah
W/m^2
1000
900
800
700
600
500
400
300
200
100
0
0
3
6
9
12
15
18
21
24
hour
30th
7th
Average


Dec 2002-Jeddah
1000
900
800
700
600
500
400
300
200
100
0
W/m^2
0
3
6
9
12
15
18
21
24
hour
10th
26th
Average

Appendix B: Load data

Load data for residential area:

DATE & TIME	MW	DATE & TIME	MW
15/01/2007 00:00	27.1	15/02/2007 00:00	29.5
15/01/2007 00:30	26.6	15/02/2007 00:30	29.5
15/01/2007 01:00	26.1	15/02/2007 01:00	29.5
15/01/2007 01:30	25.7	15/02/2007 01:30	29.5
15/01/2007 02:00	25.2	15/02/2007 02:00	29.0
15/01/2007 02:30	24.2	15/02/2007 02:30	29.0
15/01/2007 03:00	23.8	15/02/2007 03:00	29.0
15/01/2007 03:30	23.8	15/02/2007 03:30	28.6
15/01/2007 04:00	23.8	15/02/2007 04:00	27.6
15/01/2007 04:30	23.8	15/02/2007 04:30	27.1
15/01/2007 05:00	22.3	15/02/2007 05:00	27.1
15/01/2007 05:30	23.3	15/02/2007 05:30	25.7
15/01/2007 06:00	23.8	15/02/2007 06:00	25.7
15/01/2007 06:30	24.7	15/02/2007 06:30	26.6
15/01/2007 07:00	24.7	15/02/2007 07:00	24.7
15/01/2007 07:30	24.2	15/02/2007 07:30	24.2
15/01/2007 08:00	25.0	15/02/2007 08:00	25.7
15/01/2007 08:30	26.2	15/02/2007 08:30	26.6
15/01/2007 09:00	26.6	15/02/2007 09:00	28.1
15/01/2007 09:30	27.6	15/02/2007 09:30	29.5
15/01/2007 10:00	28.1	15/02/2007 10:00	30.2
15/01/2007 10:30	28.1	15/02/2007 10:30	31.4
15/01/2007 11:00	28.1	15/02/2007 11:00	31.4
15/01/2007 11:30	28.6	15/02/2007 11:30	31.9
15/01/2007 12:00	28.1	15/02/2007 12:00	32.4
15/01/2007 12:30	28.7	15/02/2007 12:30	32.9
15/01/2007 13:00	28.1	15/02/2007 13:00	32.4
15/01/2007 13:30	27.7	15/02/2007 13:30	32.4
15/01/2007 14:00	27.6	15/02/2007 14:00	32.4
15/01/2007 14:30	27.1	15/02/2007 14:30	32.3
15/01/2007 15:00	27.1	15/02/2007 15:00	31.4
15/01/2007 15:30	26.7	15/02/2007 15:30	31.0
15/01/2007 16:00	26.2	15/02/2007 16:00	31.0
15/01/2007 16:30	26.6	15/02/2007 16:30	29.5
15/01/2007 17:00	27.1	15/02/2007 17:00	30.5
15/01/2007 17:30	27.1	15/02/2007 17:30	29.5
15/01/2007 18:00	30.2	15/02/2007 18:00	29.5
15/01/2007 18:30	31.2	15/02/2007 18:30	31.0
15/01/2007 19:00	31.2	15/02/2007 19:00	32.8
15/01/2007 19:30	30.7	15/02/2007 19:30	33.4
15/01/2007 20:00	30.7	15/02/2007 20:00	31.9
15/01/2007 20:30	30.7	15/02/2007 20:30	32.1
15/01/2007 21:00	30.7	15/02/2007 21:00	32.4
15/01/2007 21:30	29.8	15/02/2007 21:30	31.4
15/01/2007 22:00	29.8	15/02/2007 22:00	31.4
15/01/2007 22:30	29.8	15/02/2007 22:30	30.5
15/01/2007 23:00	28.8	15/02/2007 23:00	29.9
15/01/2007 23:30	28.8	15/02/2007 23:30	29.0

DATE & TIME	MW	DATE & TIME	MW
15/03/2007 00:00	40.8	15/04/2007 00:00	43.7
15/03/2007 00:30	41.3	15/04/2007 00:30	42.9
15/03/2007 01:00	41.3	15/04/2007 01:00	42.9
15/03/2007 01:30	41.3	15/04/2007 01:30	42.2
15/03/2007 02:00	41.8	15/04/2007 02:00	40.8
15/03/2007 02:30	41.3	15/04/2007 02:30	39.2
15/03/2007 03:00	41.3	15/04/2007 03:00	40.2
15/03/2007 03:30	40.8	15/04/2007 03:30	39.5
15/03/2007 04:00	39.8	15/04/2007 04:00	40.2
15/03/2007 04:30	39.8	15/04/2007 04:30	38.7
15/03/2007 05:00	37.9	15/04/2007 05:00	38.7
15/03/2007 05:30	37.9	15/04/2007 05:30	38.7
15/03/2007 06:00	37.0	15/04/2007 06:00	38.7
15/03/2007 06:30	35.0	15/04/2007 06:30	37.4
15/03/2007 07:00	32.6	15/04/2007 07:00	37.4
15/03/2007 07:30	31.4	15/04/2007 07:30	38.4
15/03/2007 08:00	33.4	15/04/2007 08:00	38.7
15/03/2007 08:30	33.6	15/04/2007 08:30	40.5
15/03/2007 09:00	36.5	15/04/2007 09:00	40.5
15/03/2007 09:30	36.5	15/04/2007 09:30	41.6
15/03/2007 10:00	37.0	15/04/2007 10:00	42.4
15/03/2007 10:30	37.0	15/04/2007 10:30	41.7
15/03/2007 11:00	37.4	15/04/2007 11:00	42.7
15/03/2007 11:30	37.3	15/04/2007 11:30	42.6
15/03/2007 12:00	37.6	15/04/2007 12:00	43.0
15/03/2007 12:30	37.3	15/04/2007 12:30	44.5
15/03/2007 13:00	36.5	15/04/2007 13:00	43.4
15/03/2007 13:30	37.0	15/04/2007 13:30	43.4
15/03/2007 14:00	36.5	15/04/2007 14:00	44.0
15/03/2007 14:30	36.5	15/04/2007 14:30	44.6
15/03/2007 15:00	36.5	15/04/2007 15:00	45.2
15/03/2007 15:30	36.0	15/04/2007 15:30	45.0
15/03/2007 16:00	35.2	15/04/2007 16:00	44.5
15/03/2007 16:30	33.1	15/04/2007 16:30	43.4
15/03/2007 17:00	32.2	15/04/2007 17:00	44.0
15/03/2007 17:30	31.7	15/04/2007 17:30	44.0
15/03/2007 18:00	31.2	15/04/2007 18:00	43.7
15/03/2007 18:30	31.7	15/04/2007 18:30	43.4
15/03/2007 19:00	34.6	15/04/2007 19:00	45.9
15/03/2007 19:30	34.6	15/04/2007 19:30	48.3
15/03/2007 20:00	34.1	15/04/2007 20:00	48.0
15/03/2007 20:30	33.6	15/04/2007 20:30	48.1
15/03/2007 21:00	33.1	15/04/2007 21:00	46.1
15/03/2007 21:30	32.6	15/04/2007 21:30	45.8
15/03/2007 22:00	32.2	15/04/2007 22:00	45.8
15/03/2007 22:30	32.2	15/04/2007 22:30	46.0
15/03/2007 23:00	31.2	15/04/2007 23:00	45.8
15/03/2007 23:30	30.2	15/04/2007 23:30	46.4
DATE & TIME	MW	DATE & TIME	MW

15/05/2007 00:00	59.5	15/06/2007 00:00	54.5
15/05/2007 00:30	59.5	15/06/2007 00:30	54.0
15/05/2007 01:00	60.0	15/06/2007 01:00	55.4
15/05/2007 01:30	59.0	15/06/2007 01:30	54.5
15/05/2007 02:00	57.1	15/06/2007 02:00	55.4
15/05/2007 02:30	56.2	15/06/2007 02:30	55.0
15/05/2007 03:00	54.7	15/06/2007 03:00	55.4
15/05/2007 03:30	54.2	15/06/2007 03:30	55.9
15/05/2007 04:00	53.3	15/06/2007 04:00	56.4
15/05/2007 04:30	53.3	15/06/2007 04:30	55.0
15/05/2007 05:00	51.4	15/06/2007 05:00	54.5
15/05/2007 05:30	50.4	15/06/2007 05:30	54.0
15/05/2007 06:00	47.9	15/06/2007 06:00	51.6
15/05/2007 06:30	45.6	15/06/2007 06:30	51.6
15/05/2007 07:00	46.9	15/06/2007 07:00	51.6
15/05/2007 07:30	48.5	15/06/2007 07:30	52.6
15/05/2007 08:00	51.0	15/06/2007 08:00	52.6
15/05/2007 08:30	53.8	15/06/2007 08:30	53.5
15/05/2007 09:00	54.2	15/06/2007 09:00	54.0
15/05/2007 09:30	55.7	15/06/2007 09:30	55.4
15/05/2007 10:00	56.2	15/06/2007 10:00	55.0
15/05/2007 10:30	56.6	15/06/2007 10:30	56.9
15/05/2007 11:00	57.6	15/06/2007 11:00	56.9
15/05/2007 11:30	56.6	15/06/2007 11:30	56.4
15/05/2007 12:00	58.6	15/06/2007 12:00	54.5
15/05/2007 12:30	60.0	15/06/2007 12:30	52.1
15/05/2007 13:00	61.0	15/06/2007 13:00	51.1
15/05/2007 13:30	61.4	15/06/2007 13:30	57.0
15/05/2007 14:00	61.9	15/06/2007 14:00	60.0
15/05/2007 14:30	62.4	15/06/2007 14:30	60.0
15/05/2007 15:00	63.8	15/06/2007 15:00	59.7
15/05/2007 15:30	63.4	15/06/2007 15:30	59.8
15/05/2007 16:00	61.0	15/06/2007 16:00	58.1
15/05/2007 16:30	59.5	15/06/2007 16:30	56.2
15/05/2007 17:00	58.8	15/06/2007 17:00	55.5
15/05/2007 17:30	56.2	15/06/2007 17:30	52.8
15/05/2007 18:00	53.8	15/06/2007 18:00	51.8
15/05/2007 18:30	52.8	15/06/2007 18:30	49.9
15/05/2007 19:00	52.3	15/06/2007 19:00	49.9
15/05/2007 19:30	55.2	15/06/2007 19:30	51.1
15/05/2007 20:00	55.2	15/06/2007 20:00	54.2
15/05/2007 20:30	54.2	15/06/2007 20:30	54.2
15/05/2007 21:00	54.2	15/06/2007 21:00	53.3
15/05/2007 21:30	54.2	15/06/2007 21:30	54.2
15/05/2007 22:00	54.7	15/06/2007 22:00	55.2
15/05/2007 22:30	55.7	15/06/2007 22:30	55.9
15/05/2007 23:00	55.7	15/06/2007 23:00	57.6
15/05/2007 23:30	57.1	15/06/2007 23:30	59.0

DATE & TIME	MW	DATE & TIME	MW
15/07/2007 00:00	63.6	15/08/2007 00:00	58.6
15/07/2007 00:30	62.9	15/08/2007 00:30	59.5
15/07/2007 01:00	62.6	15/08/2007 01:00	59.8
15/07/2007 01:30	64.1	15/08/2007 01:30	60.0
15/07/2007 02:00	64.1	15/08/2007 02:00	60.0
15/07/2007 02:30	64.1	15/08/2007 02:30	59.5
15/07/2007 03:00	63.1	15/08/2007 03:00	60.0
15/07/2007 03:30	62.2	15/08/2007 03:30	60.0
15/07/2007 04:00	62.2	15/08/2007 04:00	60.0
15/07/2007 04:30	61.3	15/08/2007 04:30	59.5
15/07/2007 05:00	59.8	15/08/2007 05:00	58.6
15/07/2007 05:30	58.8	15/08/2007 05:30	57.1
15/07/2007 06:00	56.5	15/08/2007 06:00	56.2
15/07/2007 06:30	55.9	15/08/2007 06:30	55.6
15/07/2007 07:00	56.8	15/08/2007 07:00	54.7
15/07/2007 07:30	58.0	15/08/2007 07:30	55.7
15/07/2007 08:00	60.7	15/08/2007 08:00	57.1
15/07/2007 08:30	63.1	15/08/2007 08:30	59.3
15/07/2007 09:00	63.6	15/08/2007 09:00	61.2
15/07/2007 09:30	65.5	15/08/2007 09:30	62.2
15/07/2007 10:00	66.0	15/08/2007 10:00	63.1
15/07/2007 10:30	66.5	15/08/2007 10:30	63.3
15/07/2007 11:00	67.9	15/08/2007 11:00	64.1
15/07/2007 11:30	68.4	15/08/2007 11:30	65.0
15/07/2007 12:00	69.8	15/08/2007 12:00	66.0
15/07/2007 12:30	71.3	15/08/2007 12:30	67.0
15/07/2007 13:00	70.8	15/08/2007 13:00	66.3
15/07/2007 13:30	71.3	15/08/2007 13:30	67.0
15/07/2007 14:00	72.2	15/08/2007 14:00	67.0
15/07/2007 14:30	71.8	15/08/2007 14:30	66.0
15/07/2007 15:00	71.3	15/08/2007 15:00	66.0
15/07/2007 15:30	72.2	15/08/2007 15:30	66.5
15/07/2007 16:00	70.3	15/08/2007 16:00	65.0
15/07/2007 16:30	69.4	15/08/2007 16:30	62.2
15/07/2007 17:00	68.4	15/08/2007 17:00	61.7
15/07/2007 17:30	67.0	15/08/2007 17:30	59.8
15/07/2007 18:00	65.0	15/08/2007 18:00	59.6
15/07/2007 18:30	63.6	15/08/2007 18:30	58.3
15/07/2007 19:00	63.1	15/08/2007 19:00	58.3
15/07/2007 19:30	64.0	15/08/2007 19:30	60.7
15/07/2007 20:00	65.0	15/08/2007 20:00	60.6
15/07/2007 20:30	64.6	15/08/2007 20:30	59.3
15/07/2007 21:00	62.6	15/08/2007 21:00	56.9
15/07/2007 21:30	61.7	15/08/2007 21:30	56.9
15/07/2007 22:00	61.2	15/08/2007 22:00	55.9
15/07/2007 22:30	60.7	15/08/2007 22:30	55.0
15/07/2007 23:00	61.2	15/08/2007 23:00	55.0
15/07/2007 23:30	60.7	15/08/2007 23:30	55.0

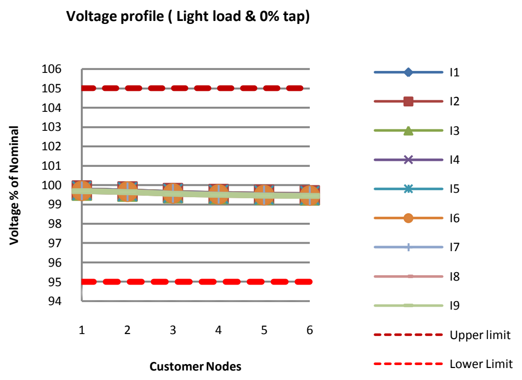
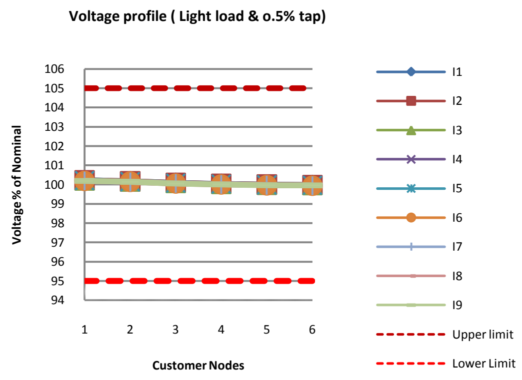
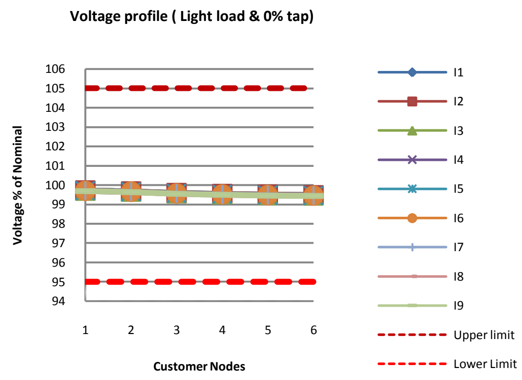
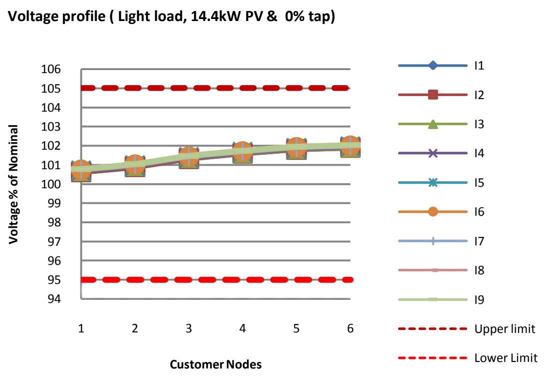
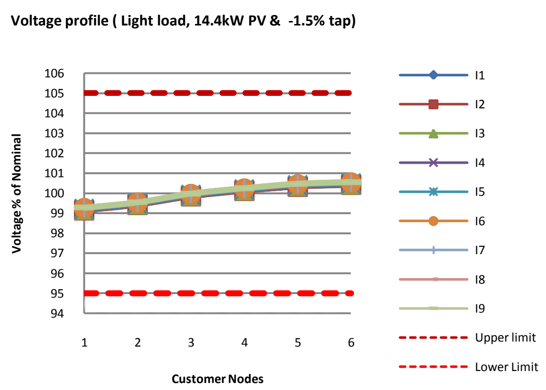
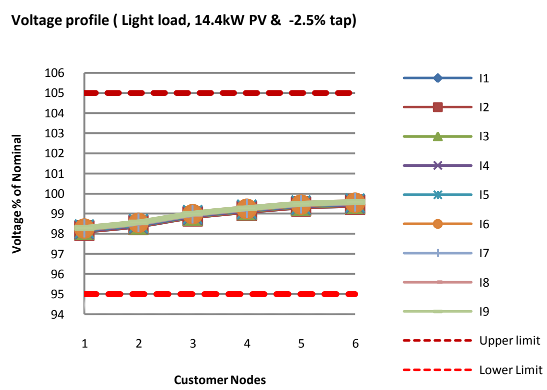
DATE & TIME	MW	DATE & TIME	MW
15/09/2007 00:00	65.8	15/10/2007 00:00	48.0
15/09/2007 00:30	66.7	15/10/2007 00:30	48.0
15/09/2007 01:00	67.2	15/10/2007 01:00	48.0
15/09/2007 01:30	68.6	15/10/2007 01:30	48.0
15/09/2007 02:00	69.6	15/10/2007 02:00	48.5
15/09/2007 02:30	69.6	15/10/2007 02:30	48.5
15/09/2007 03:00	69.1	15/10/2007 03:00	49.4
15/09/2007 03:30	69.1	15/10/2007 03:30	49.3
15/09/2007 04:00	68.6	15/10/2007 04:00	49.4
15/09/2007 04:30	68.6	15/10/2007 04:30	49.0
15/09/2007 05:00	67.1	15/10/2007 05:00	49.0
15/09/2007 05:30	67.0	15/10/2007 05:30	48.0
15/09/2007 06:00	65.5	15/10/2007 06:00	47.5
15/09/2007 06:30	63.8	15/10/2007 06:30	46.1
15/09/2007 07:00	63.4	15/10/2007 07:00	45.1
15/09/2007 07:30	63.8	15/10/2007 07:30	45.6
15/09/2007 08:00	64.3	15/10/2007 08:00	45.6
15/09/2007 08:30	65.3	15/10/2007 08:30	46.6
15/09/2007 09:00	65.8	15/10/2007 09:00	47.5
15/09/2007 09:30	65.8	15/10/2007 09:30	48.5
15/09/2007 10:00	68.2	15/10/2007 10:00	49.4
15/09/2007 10:30	71.3	15/10/2007 10:30	50.9
15/09/2007 11:00	73.4	15/10/2007 11:00	51.8
15/09/2007 11:30	73.9	15/10/2007 11:30	51.6
15/09/2007 12:00	75.4	15/10/2007 12:00	51.8
15/09/2007 12:30	74.9	15/10/2007 12:30	50.9
15/09/2007 13:00	74.4	15/10/2007 13:00	52.3
15/09/2007 13:30	77.3	15/10/2007 13:30	52.5
15/09/2007 14:00	76.3	15/10/2007 14:00	52.3
15/09/2007 14:30	74.9	15/10/2007 14:30	52.8
15/09/2007 15:00	76.3	15/10/2007 15:00	52.8
15/09/2007 15:30	78.4	15/10/2007 15:30	52.8
15/09/2007 16:00	75.4	15/10/2007 16:00	50.9
15/09/2007 16:30	73.0	15/10/2007 16:30	49.9
15/09/2007 17:00	71.5	15/10/2007 17:00	49.9
15/09/2007 17:30	70.1	15/10/2007 17:30	48.5
15/09/2007 18:00	67.6	15/10/2007 18:00	48.5
15/09/2007 18:30	62.4	15/10/2007 18:30	50.9
15/09/2007 19:00	66.2	15/10/2007 19:00	50.9
15/09/2007 19:30	69.8	15/10/2007 19:30	50.9
15/09/2007 20:00	71.8	15/10/2007 20:00	50.4
15/09/2007 20:30	70.4	15/10/2007 20:30	49.9
15/09/2007 21:00	68.4	15/10/2007 21:00	49.9
15/09/2007 21:30	71.3	15/10/2007 21:30	49.9
15/09/2007 22:00	72.7	15/10/2007 22:00	49.9
15/09/2007 22:30	73.2	15/10/2007 22:30	49.9
15/09/2007 23:00	72.2	15/10/2007 23:00	49.4
15/09/2007 23:30	72.2	15/10/2007 23:30	48.5

DATE & TIME	MW	DATE & TIME	MW
15/11/2007 00:00	48.5	15/12/2007 00:00	39.1
15/11/2007 00:30	48.5	15/12/2007 00:30	38.6
15/11/2007 01:00	49.7	15/12/2007 01:00	39.6
15/11/2007 01:30	50.6	15/12/2007 01:30	40.1
15/11/2007 02:00	50.6	15/12/2007 02:00	38.6
15/11/2007 02:30	50.6	15/12/2007 02:30	38.6
15/11/2007 03:00	50.2	15/12/2007 03:00	38.2
15/11/2007 03:30	49.2	15/12/2007 03:30	38.1
15/11/2007 04:00	49.2	15/12/2007 04:00	37.2
15/11/2007 04:30	47.3	15/12/2007 04:30	35.8
15/11/2007 05:00	45.9	15/12/2007 05:00	34.8
15/11/2007 05:30	44.9	15/12/2007 05:30	34.3
15/11/2007 06:00	43.9	15/12/2007 06:00	32.9
15/11/2007 06:30	42.5	15/12/2007 06:30	32.9
15/11/2007 07:00	41.5	15/12/2007 07:00	31.0
15/11/2007 07:30	41.5	15/12/2007 07:30	31.4
15/11/2007 08:00	42.8	15/12/2007 08:00	32.4
15/11/2007 08:30	44.4	15/12/2007 08:30	34.3
15/11/2007 09:00	45.8	15/12/2007 09:00	34.8
15/11/2007 09:30	46.8	15/12/2007 09:30	36.2
15/11/2007 10:00	47.3	15/12/2007 10:00	36.7
15/11/2007 10:30	47.8	15/12/2007 10:30	37.7
15/11/2007 11:00	48.4	15/12/2007 11:00	37.2
15/11/2007 11:30	48.7	15/12/2007 11:30	38.6
15/11/2007 12:00	49.2	15/12/2007 12:00	39.1
15/11/2007 12:30	49.7	15/12/2007 12:30	38.6
15/11/2007 13:00	50.6	15/12/2007 13:00	39.1
15/11/2007 13:30	50.6	15/10/2007 13:30	52.5
15/11/2007 14:00	51.1	15/10/2007 14:00	52.3
15/11/2007 14:30	50.6	15/10/2007 14:30	52.8
15/11/2007 15:00	50.2	15/10/2007 15:00	52.8
15/11/2007 15:30	48.7	15/10/2007 15:30	52.8
15/11/2007 16:00	46.1	15/10/2007 16:00	50.9
15/11/2007 16:30	44.9	15/10/2007 16:30	49.9
15/11/2007 17:00	43.7	15/10/2007 17:00	49.9
15/11/2007 17:30	43.4	15/10/2007 17:30	48.5
15/11/2007 18:00	44.4	15/10/2007 18:00	48.5
15/11/2007 18:30	46.8	15/10/2007 18:30	50.9
15/11/2007 19:00	46.3	15/10/2007 19:00	50.9
15/11/2007 19:30	45.4	15/10/2007 19:30	50.9
15/11/2007 20:00	46.3	15/10/2007 20:00	50.4
15/11/2007 20:30	45.4	15/10/2007 20:30	49.9
15/11/2007 21:00	45.4	15/10/2007 21:00	49.9
15/11/2007 21:30	44.9	15/10/2007 21:30	49.9
15/11/2007 22:00	46.3	15/10/2007 22:00	49.9
15/11/2007 22:30	45.0	15/10/2007 22:30	49.9
15/11/2007 23:00	45.4	15/10/2007 23:00	49.4
15/11/2007 23:30	46.3	15/10/2007 23:30	48.5

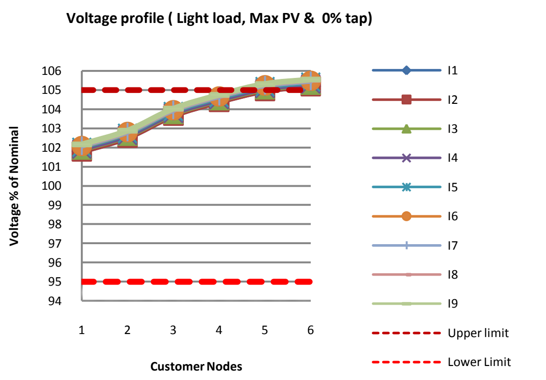
Load data for industrial area:

Time	15-Jan	15-Feb	15-Mar	15-Apr	15-May	15-Jun	15-Jul	15-Aug	15-Sep	15/10 Public holiday	15-Nov	15-Dec
0:00:00	71.4	74.9	72.8	70.7	82.1	78.9	76.5	66.4	59.6	33.0	59.4	54.1
0:30:00	71.4	70.8	71.4	70.7	81.0	78.4	75.0	66.4	59.1	33.8	58.8	53.4
1:00:00	71.4	70.8	71.4	70.7	81.0	77.9	76.1	66.9	59.0	33.8	60.2	53.7
1:30:00	71.4	68.1	71.4	72.0	81.0	77.6	76.2	66.8	58.9	33.7	60.4	53.8
2:00:00	70.1	66.9	71.4	70.9	81.0	77.6	75.0	65.7	58.9	33.0	59.6	53.1
2:30:00	70.1	69.6	71.4	70.9	81.0	76.9	73.9	65.6	57.5	33.7	59.8	52.4
3:00:00	70.1	69.6	71.4	70.9	81.0	76.1	73.8	64.4	53.2	33.1	59.2	52.6
3:30:00	68.8	69.6	71.4	70.9	81.0	76.1	74.3	65.9	52.8	33.0	57.9	51.9
4:00:00	68.8	73.6	70.5	70.9	81.0	76.1	73.0	65.8	52.8	32.3	57.7	51.6
4:30:00	69.0	73.6	70.3	70.9	81.0	74.3	72.2	64.0	52.9	32.3	57.7	52.4
5:00:00	69.2	72.3	70.3	70.9	79.8	73.5	71.6	64.8	52.5	33.0	57.3	51.9
5:30:00	68.0	72.3	70.2	70.9	77.2	71.0	70.5	64.7	54.0	32.9	55.7	52.8
6:00:00	66.6	72.3	67.6	68.8	77.2	69.5	70.1	64.0	55.9	31.7	55.7	52.3
6:30:00	66.6	73.8	68.8	69.6	78.5	69.2	69.4	64.7	58.6	31.8	55.6	53.9
7:00:00	67.8	73.8	68.8	70.9	79.9	67.8	70.7	66.8	60.6	31.8	56.9	55.9
7:30:00	70.2	76.6	72.9	74.8	83.7	68.4	76.0	70.8	63.4	33.3	61.1	59.9
8:00:00	71.7	80.5	77.1	76.4	87.7	68.9	79.5	71.6	62.2	34.2	64.5	63.0
8:30:00	68.7	82.9	79.6	79.1	89.0	68.3	83.6	74.1	64.4	36.1	66.2	65.6
9:00:00	69.1	82.9	80.8	81.6	91.1	69.6	83.5	75.4	64.9	36.1	67.0	65.9
9:30:00	68.8	84.2	82.1	82.8	93.5	70.2	85.6	77.6	66.1	36.8	68.3	67.8
10:00:00	66.3	85.1	82.7	84.4	93.5	71.7	84.9	77.5	68.6	38.7	69.1	68.4
10:30:00	66.3	86.4	84.2	85.9	95.5	70.9	89.6	79.1	71.5	38.1	70.0	71.4
11:00:00	66.3	89.0	85.4	87.2	96.8	72.2	91.0	78.4	72.9	38.7	71.3	71.4
11:30:00	66.3	90.1	84.5	88.4	96.4	70.9	91.1	79.2	71.8	38.7	71.0	72.9
12:00:00	66.3	87.7	85.6	87.1	-31.5	70.7	92.1	80.0	72.5	40.0	72.4	71.9
12:30:00	65.1	87.7	84.1	85.9	97.0	68.1	92.9	78.8	73.0	39.8	72.2	72.0
13:00:00	65.1	83.5	81.6	84.7	97.0	67.7	90.4	78.1	73.1	39.8	70.7	71.4
13:30:00	67.6	84.7	81.7	88.6	97.0	71.3	92.3	80.3	76.4	42.5	71.4	72.9
14:00:00	69.1	87.1	81.6	88.6	97.0	72.3	93.2	81.7	77.1	43.1	70.1	73.4
14:30:00	73.1	87.0	84.2	88.6	97.0	72.2	93.2	81.7	75.8	43.1	70.6	73.7
15:00:00	73.1	87.0	83.0	87.7	-33.5	73.6	94.5	81.5	75.1	43.7	70.4	73.7
15:30:00	73.1	87.0	81.7	88.0	96.0	74.3	93.2	80.2	72.4	42.1	67.9	72.6
16:00:00	71.8	85.5	78.4	86.6	92.9	72.3	89.6	77.6	70.7	41.3	67.5	72.2
16:30:00	73.1	84.3	77.9	85.4	92.5	71.6	88.0	76.6	68.9	42.9	66.3	71.0
17:00:00	75.5	82.1	78.9	84.2	92.1	71.1	88.0	75.4	68.2	40.8	66.1	69.7
17:30:00	76.5	80.2	77.6	84.2	92.0	69.7	87.1	75.0	68.2	40.0	64.4	69.6
18:00:00	75.5	81.4	76.0	83.0	89.3	69.1	83.9	72.9	66.4	41.8	63.3	65.9
18:30:00	75.5	81.6	75.0	81.8	86.9	68.9	81.7	71.5	64.8	42.0	61.1	65.5
19:00:00	75.6	81.6	72.6	79.3	84.6	67.3	81.1	70.2	65.1	42.7	61.5	63.9
19:30:00	73.1	79.2	75.6	82.0	86.2	67.5	82.0	71.8	65.8	43.3	60.9	63.9
20:00:00	73.2	80.5	74.6	80.7	86.0	69.8	82.2	71.2	64.2	44.0	59.8	62.4
20:30:00	76.0	80.5	74.7	80.7	85.4	72.0	82.1	70.6	66.4	43.2	60.4	64.9
21:00:00	76.0	80.5	74.1	80.7	84.9	72.0	80.5	70.6	64.9	42.7	61.4	63.5
21:30:00	74.7	80.5	76.6	79.4	85.6	70.9	81.4	70.5	68.2	40.3	61.3	64.0
22:00:00	74.7	80.5	76.6	79.4	85.7	71.5	80.8	70.6	69.0	41.0	61.7	64.2
22:30:00	72.2	80.5	79.4	79.4	86.0	71.9	81.1	72.3	70.3	41.9	60.6	63.5
23:00:00	73.4	80.5	80.6	79.4	84.7	72.5	81.0	69.9	71.3	41.9	61.2	65.1

Appendix C: Voltage level for all customers connected to feeder I9 in Fig. 5.1 for all tested scenarios.

Scenario			0%	Best Tap Position	Desired Tap Position
No	Load	PV			
1	Light	No			
2	Light	Min			

Appendix C: Voltage level for all customers connected to feeder I9 in Fig. 5.1 for all tested scenarios.

<table>
<tr><th colspan="3">Scenario</th><th rowspan="2">0%</th><th rowspan="2">Best Tap Position</th><th rowspan="2">Desired Tap Position</th></tr>
<tr><th>No</th><th>Load</th><th>PV</th></tr>
<tr><td>3</td><td>Light</td><td>Max</td>
<td>
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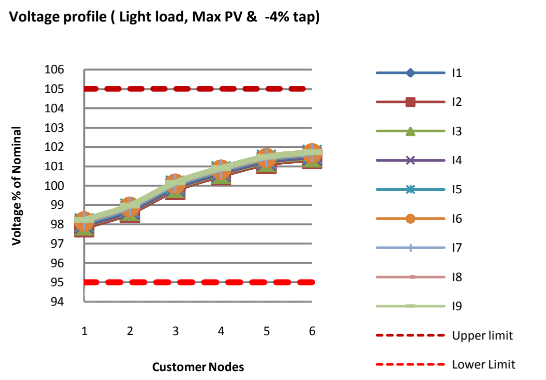
<td>
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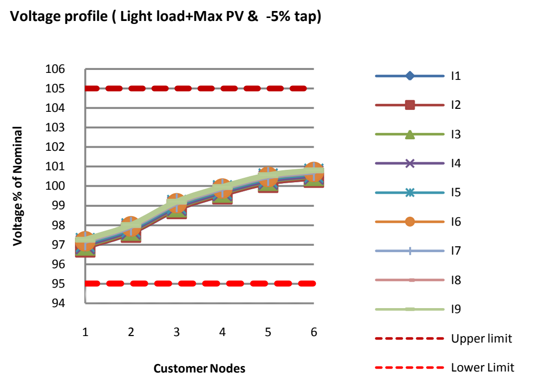
<td>
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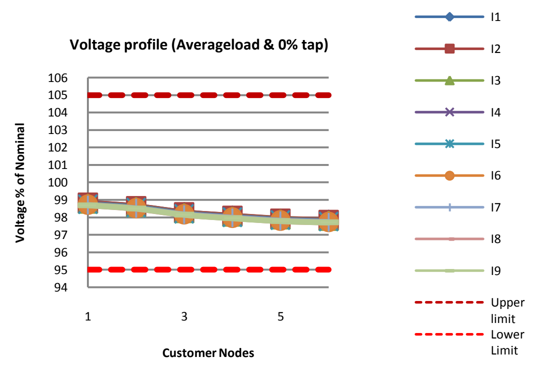
<tr><td>4</td><td>Average</td><td>No</td>
<td>
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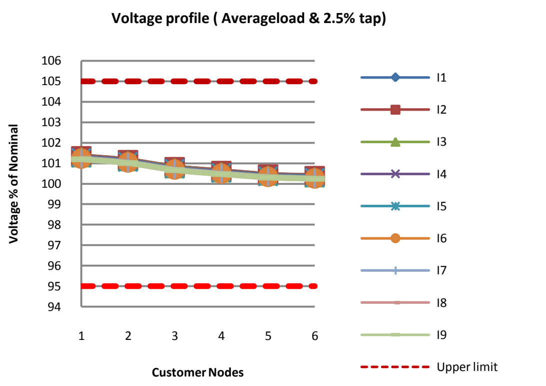
<td>
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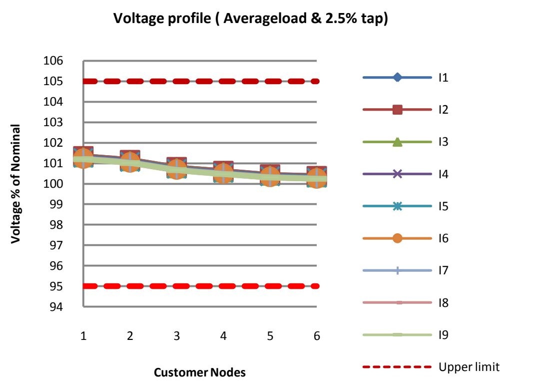
<td>
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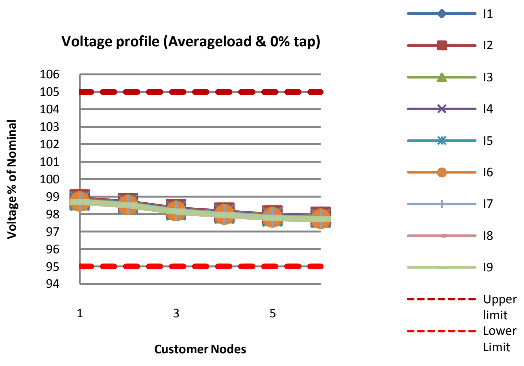
<tr><th colspan="3">Scenario</th><th rowspan="2">0%</th><th rowspan="2">Best Tap Position</th><th rowspan="2">Desired Tap Position</th></tr>
<tr><th>No</th><th>Load</th><th>PV</th></tr>
<tr><td>5</td><td>Average</td><td>Min</td>
<td>
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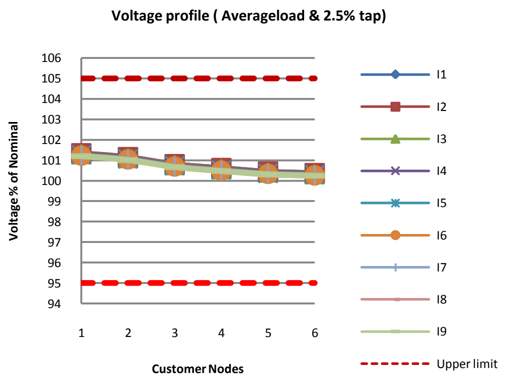
<td>
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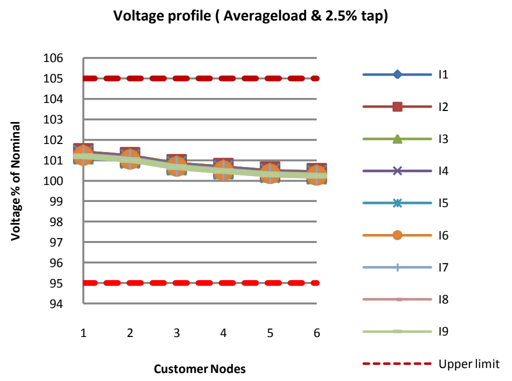
<td>
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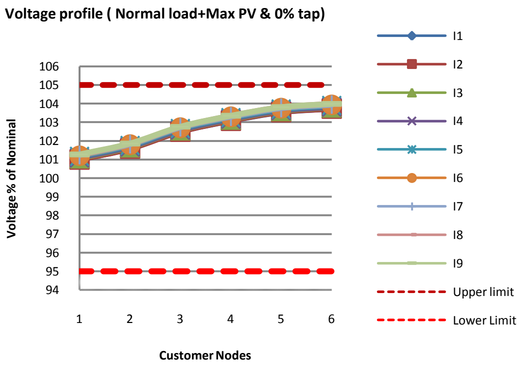
<tr><td>6</td><td>Average</td><td>Max</td>
<td>
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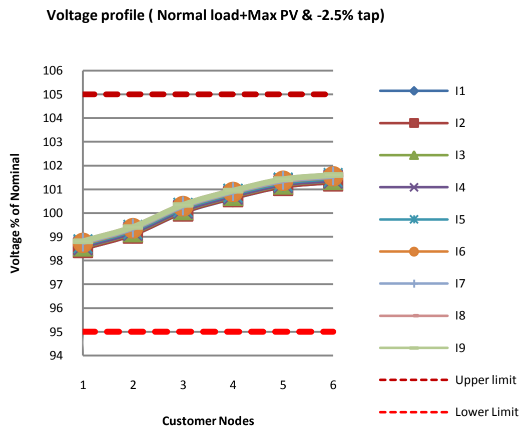
<td>
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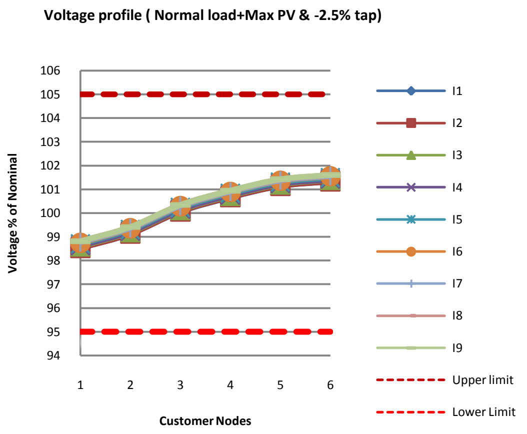
<td>
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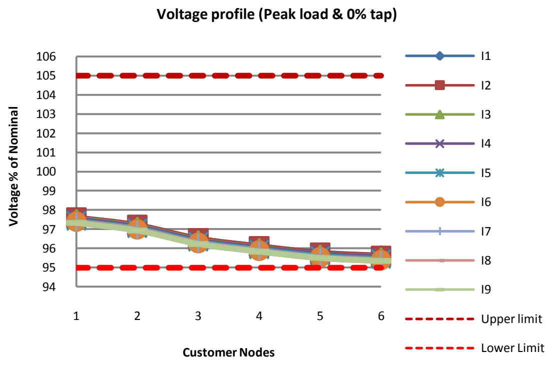
<tr><th colspan="3">Scenario</th><th rowspan="2">0%</th><th rowspan="2">Best Tap Position</th><th rowspan="2">Desired Tap Position</th></tr>
<tr><th>No</th><th>Load</th><th>PV</th></tr>
<tr><td>7</td><td>Peak</td><td>No</td>
<td>
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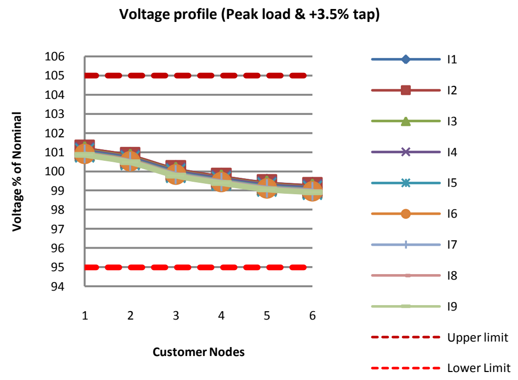
<td>
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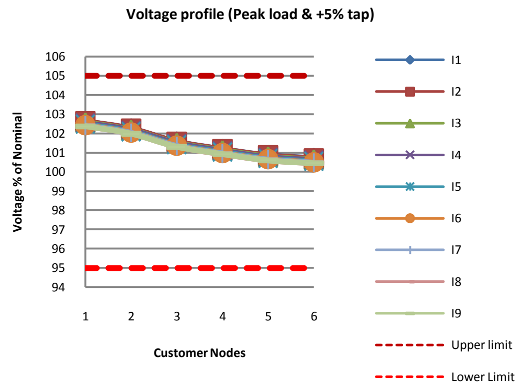
<td>
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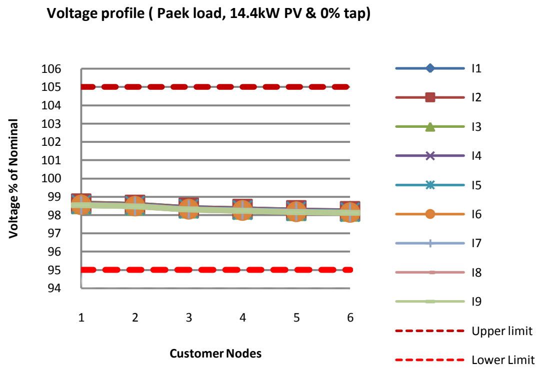
<tr><td>8</td><td>Peak</td><td>Min</td>
<td>
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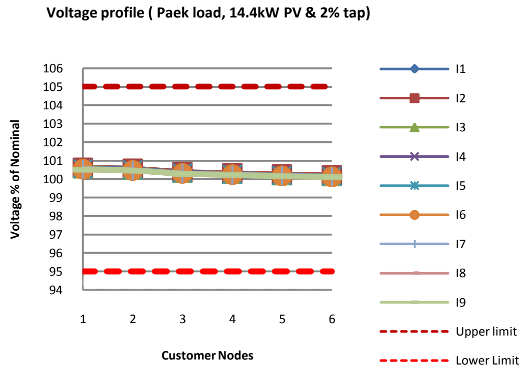
<td>
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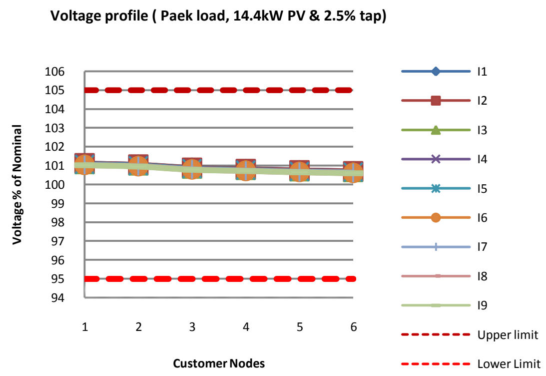
<td>
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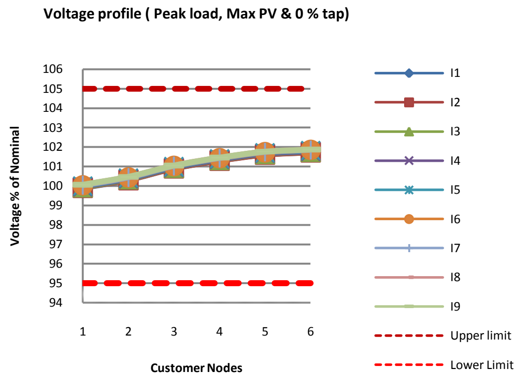
<tr><th colspan="3">Scenario</th><th rowspan="2">0%</th><th rowspan="2">Best Tap Position</th><th rowspan="2">Desired Tap Position</th></tr>
<tr><th>No</th><th>Load</th><th>PV</th></tr>
<tr><td>9</td><td>Peak</td><td>Max</td>
<td>
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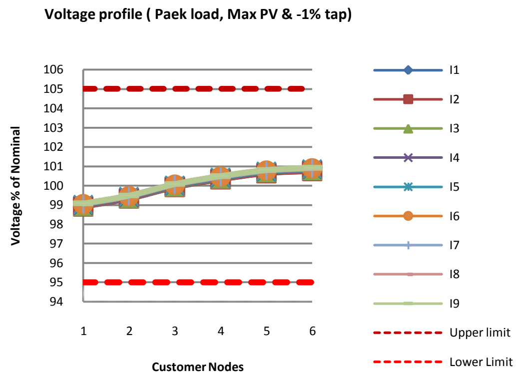
<td>
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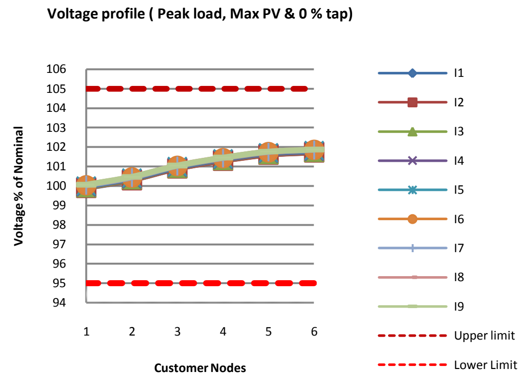
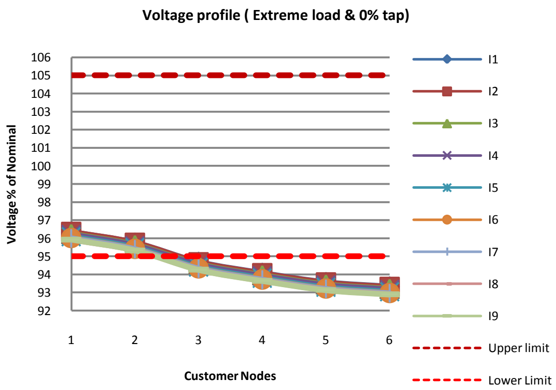
<td>
</td></tr>
<tr><td>10</td><td>Extreme</td><td>No</td>
<td>
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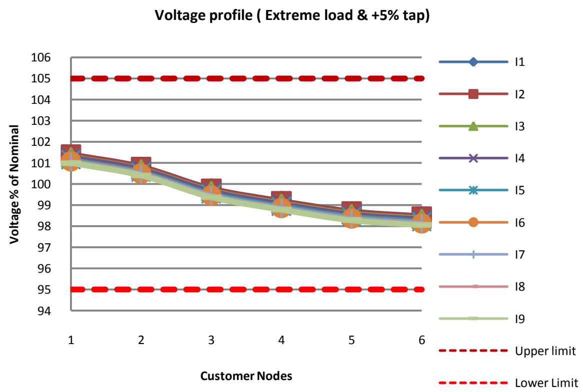
<td>
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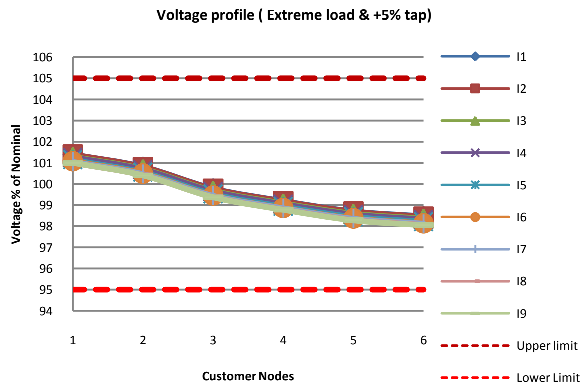
<td>
</td></tr>
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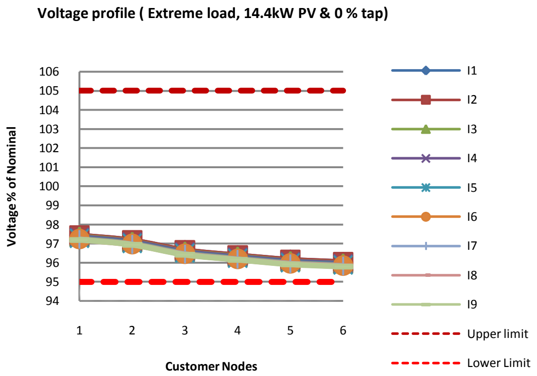
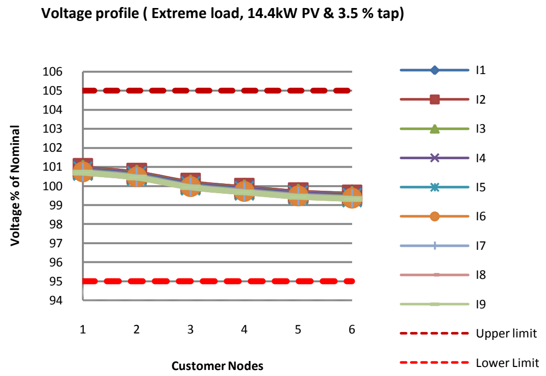
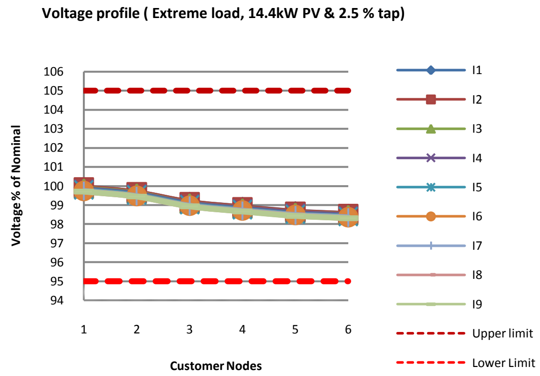
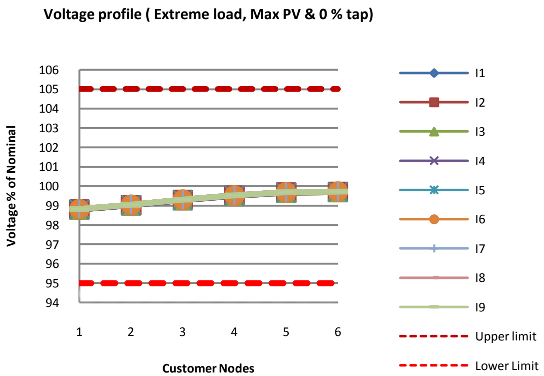
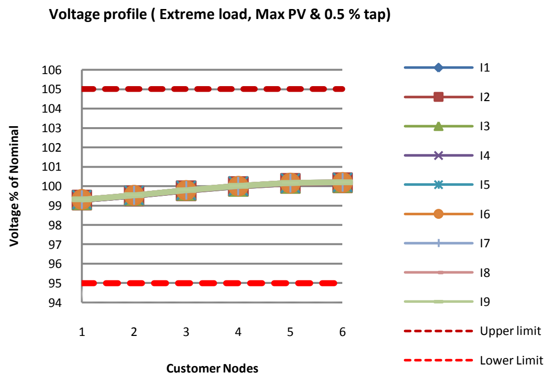
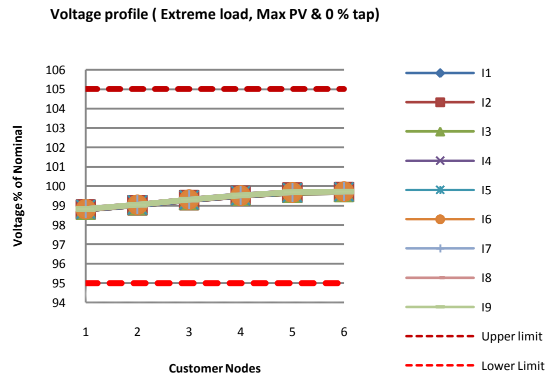
<tr><th colspan="3">Scenario</th><th rowspan="2">0%</th><th rowspan="2">Best Tap Position</th><th rowspan="2">Desired Tap Position</th></tr>
<tr><th>No</th><th>Load</th><th>PV</th></tr>
<tr><td>11</td><td>Extreme</td><td>Min</td>
<td></td>
<td></td>
<td></td></tr>
<tr><td>12</td><td>Extreme</td><td>Max</td>
<td></td>
<td></td>
<td></td></tr>
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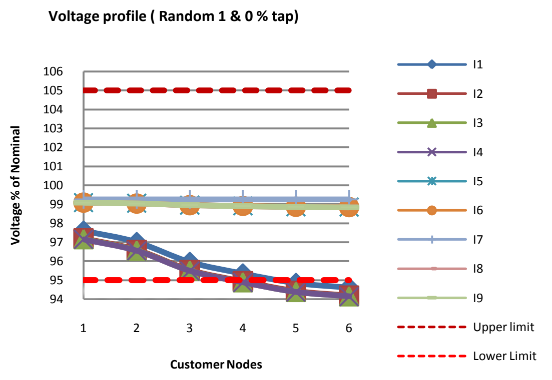
<tr><th colspan="3">Scenario</th><th rowspan="2">0%</th><th rowspan="2">Best Tap Position</th><th rowspan="2">Desired Tap Position</th></tr>
<tr><th>No</th><th>Load</th><th>PV</th></tr>
<tr><td>13</td><td>Random1</td><td>No</td>
<td>
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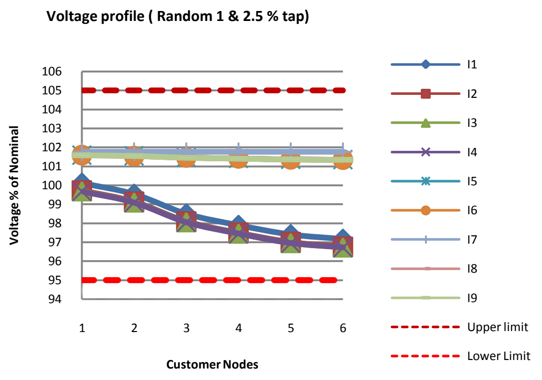
<td>
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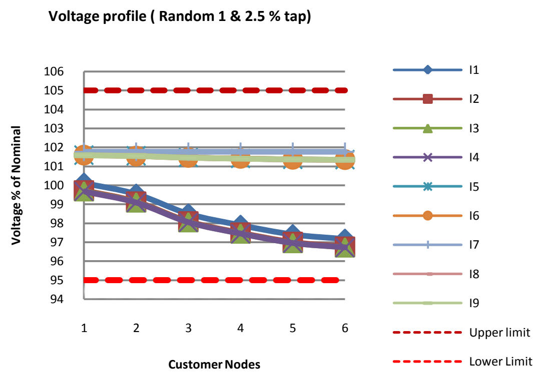
<td>
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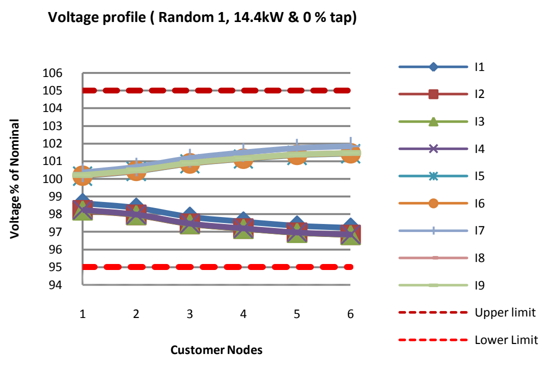
<td>
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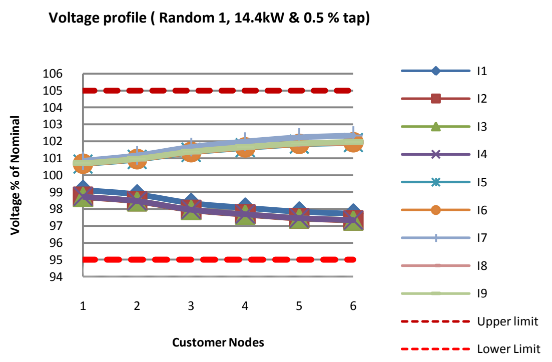
<td>
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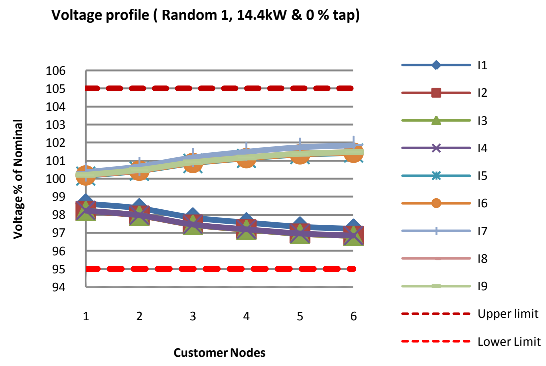
<td>
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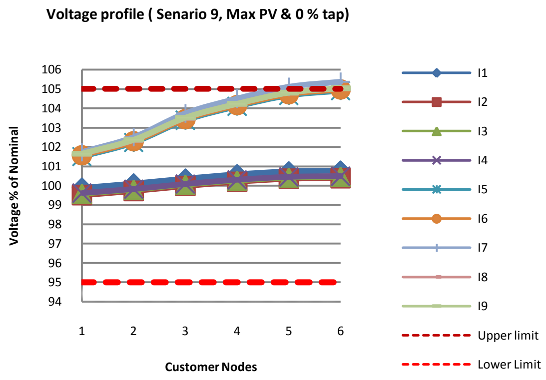
<tr><th colspan="3">Scenario</th><th rowspan="2">0%</th><th rowspan="2">Best Tap Position</th><th rowspan="2">Desired Tap Position</th></tr>
<tr><th>No</th><th>Load</th><th>PV</th></tr>
<tr><td>15</td><td>Random1</td><td>Max</td>
<td>
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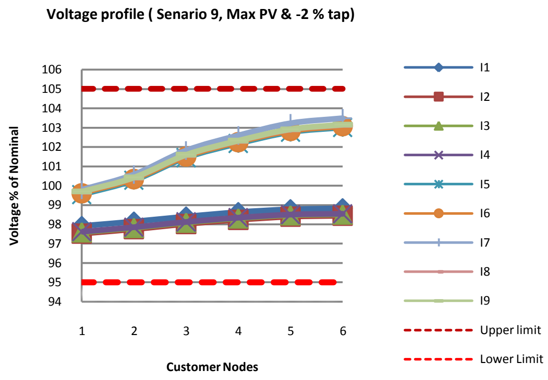
<td>
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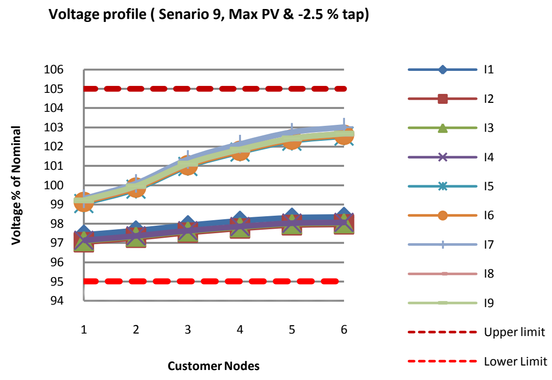
<td>
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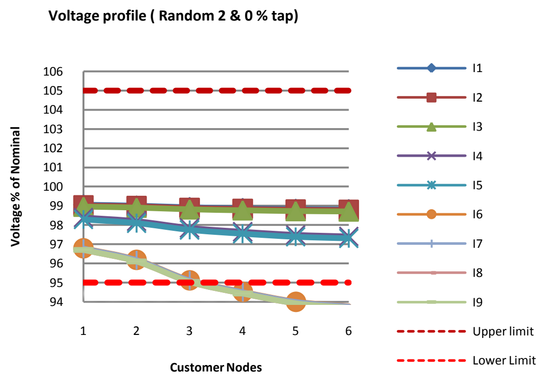
<tr><td>16</td><td>Random2</td><td>No</td>
<td>
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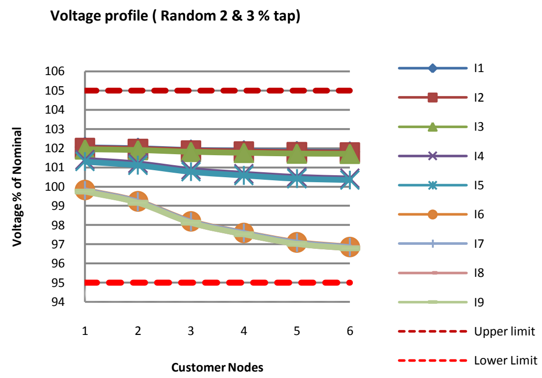
<td>
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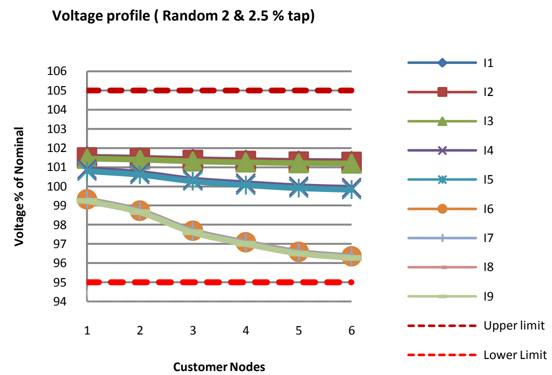
<td>
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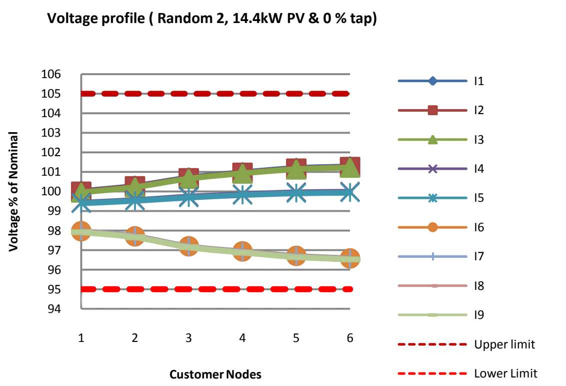
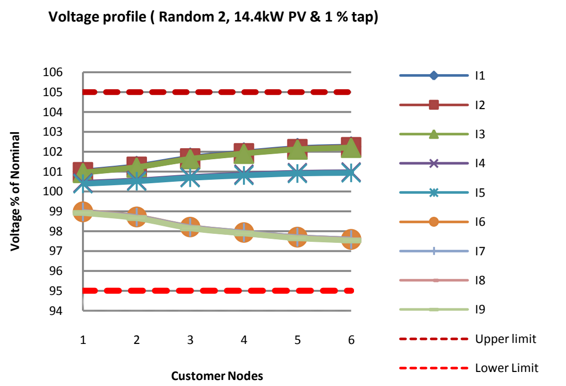
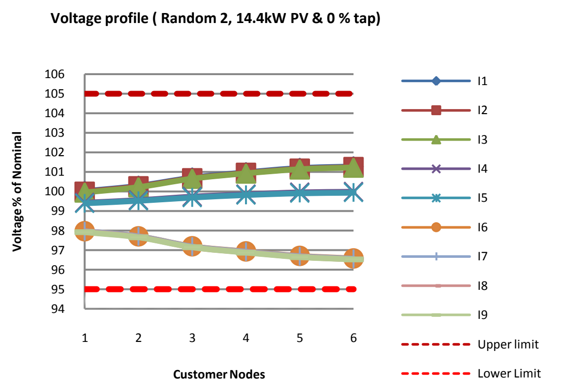
<tr><th>No</th><th>Load</th><th>PV</th></tr>
<tr><td>17</td><td>Random2</td><td>Min</td><td>
</td><td>
</td><td>
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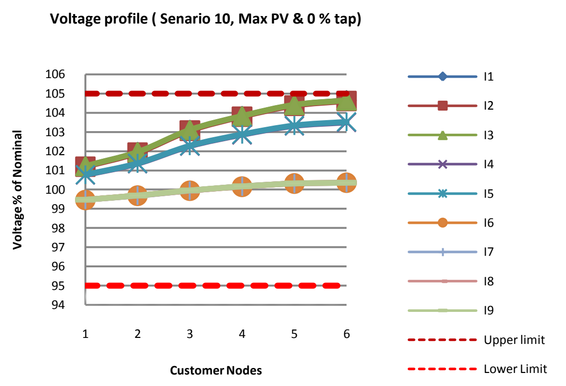
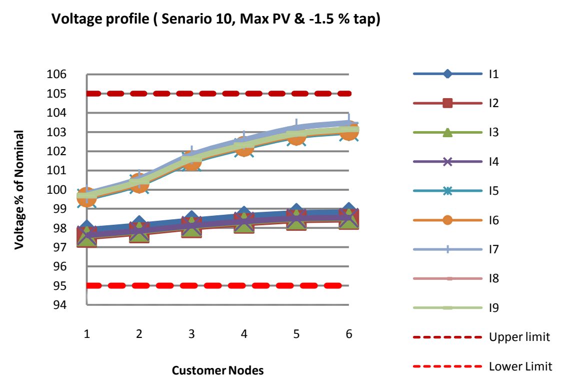
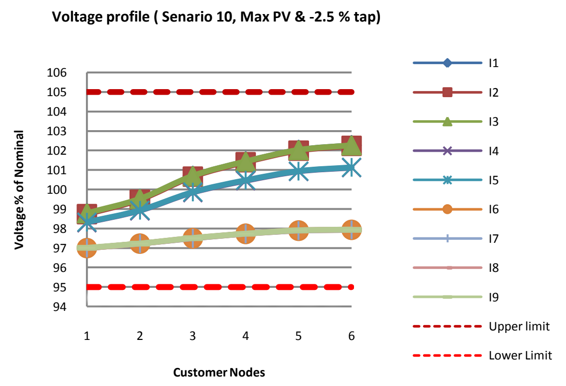
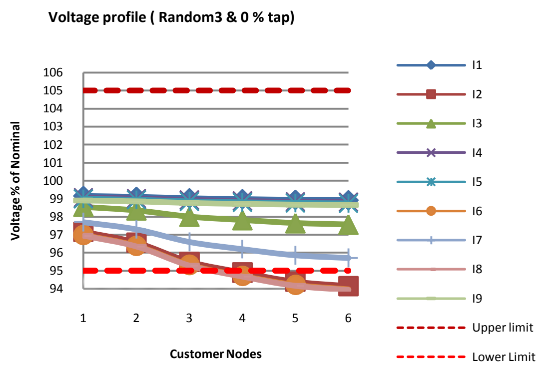
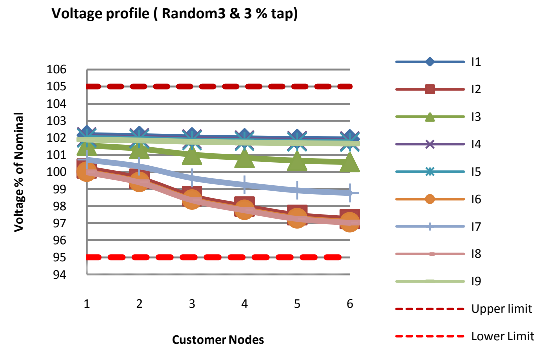
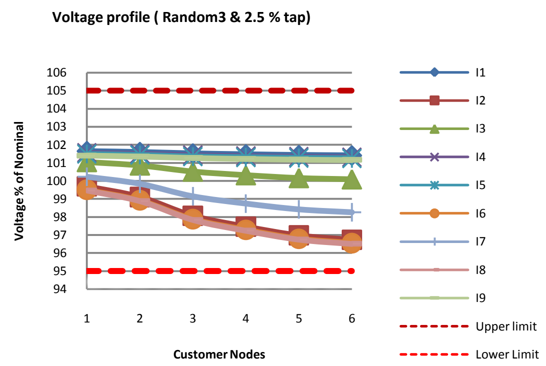
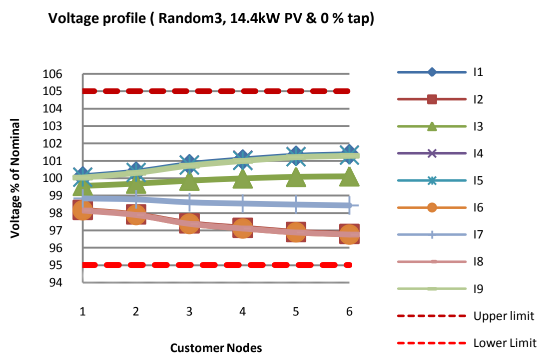
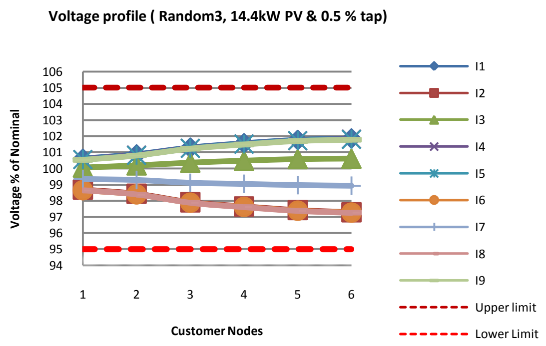
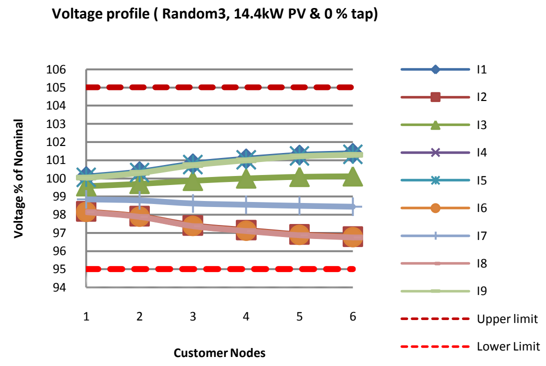
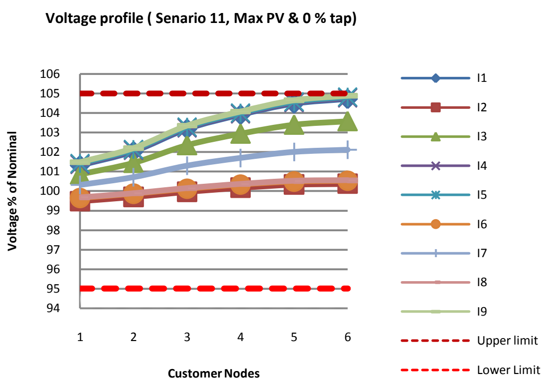
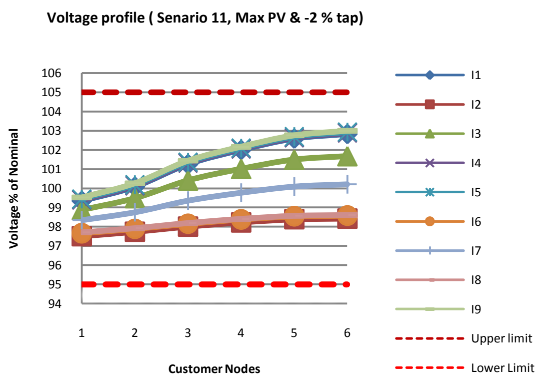
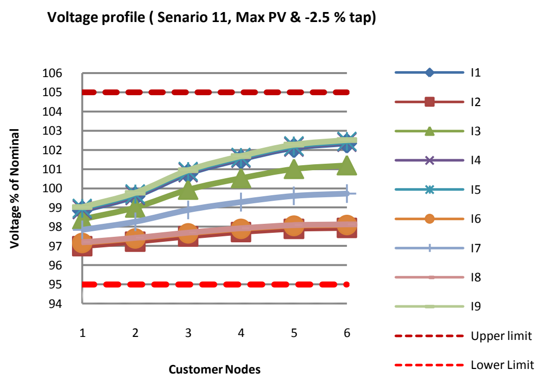
<tr><td>18</td><td>Random2</td><td>Max</td><td>
</td><td>
</td><td>
</td></tr>
</table>

Appendix C: Voltage level for all customers connected to feeder I9 in Fig. 5.1 for all tested scenarios.

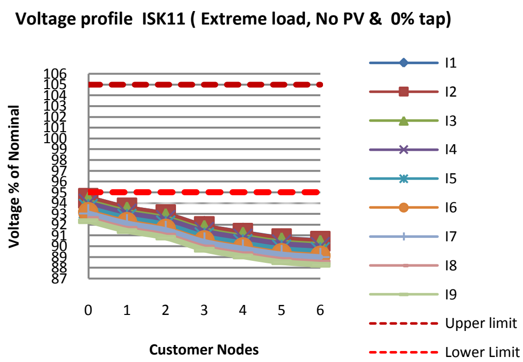
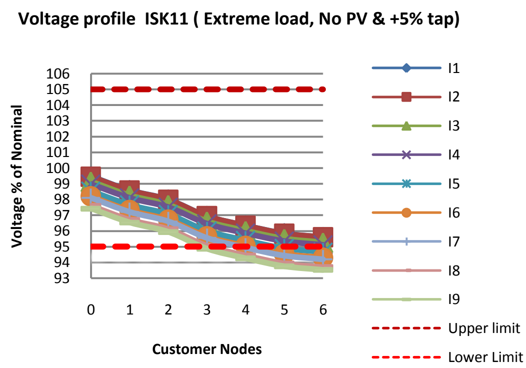
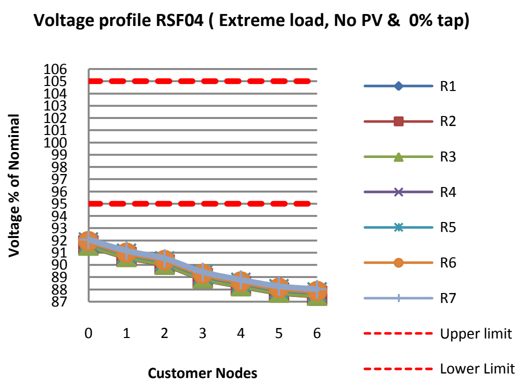
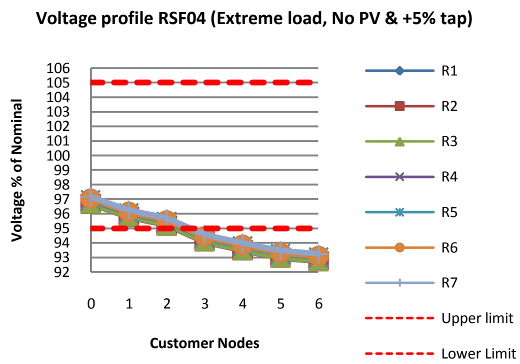
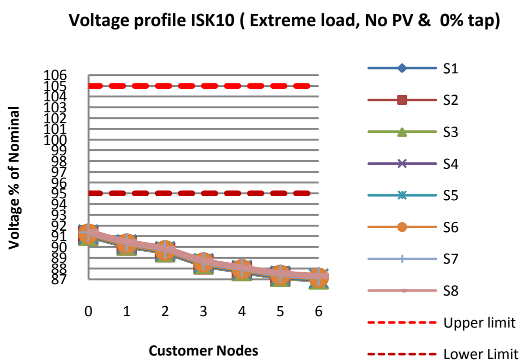
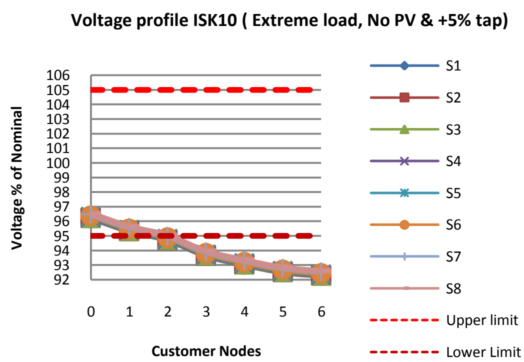
Scenario			0%	Best Tap Position	Desired Tap Position
No	Load	PV			
19	Random3	No			
20	Random3	Min			

Appendix C: Voltage level for all customers connected to feeder I9 in Fig. 5.1 for all tested scenarios.

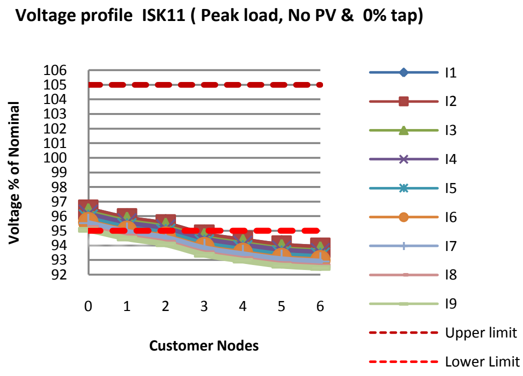
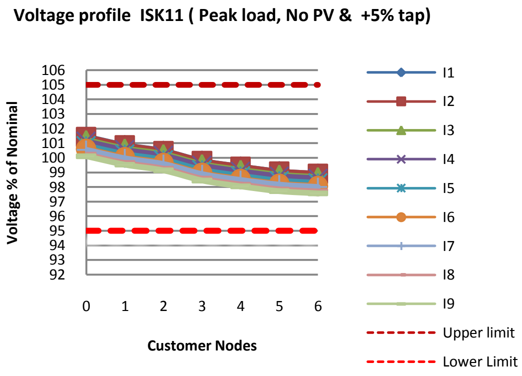
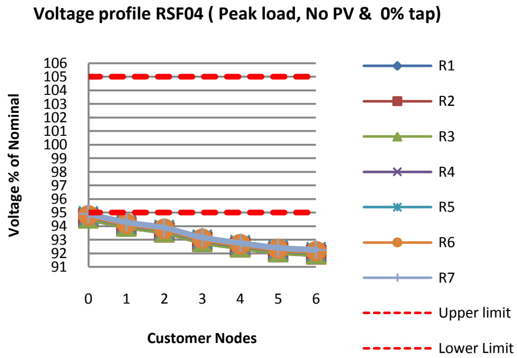
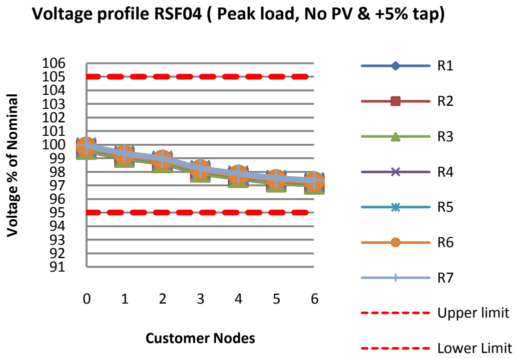
Scenario			0%	Best Tap Position	Desired Tap Position
No	Load	PV			
21	Random3	Max			

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

Appendix D

Scenario XLNP	0%	Preferred Tap Position
ISK11		
RSF04		
ISK10		

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><th>Scenario
PLNPV</th><th>0%</th><th>Preferred Tap Position</th></tr>
<tr><td>ISK11</td><td>
</td><td>
</td></tr>
<tr><td>RSF04</td><td>
</td><td>
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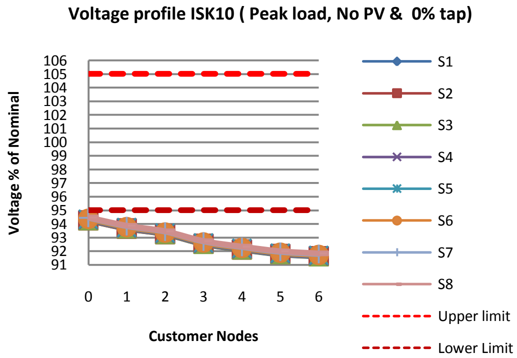
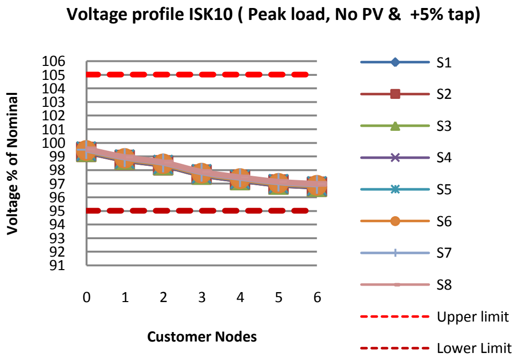
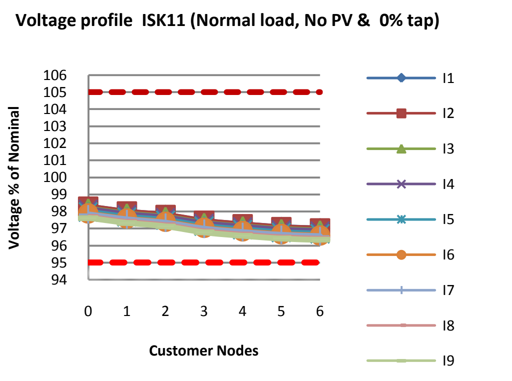
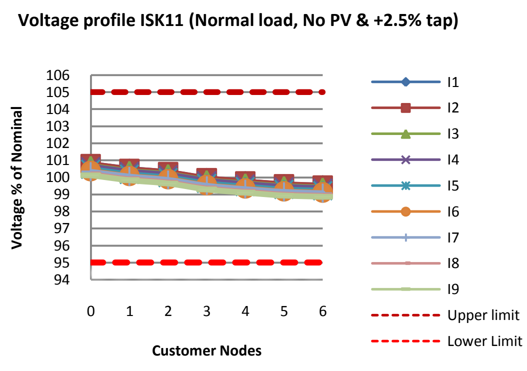
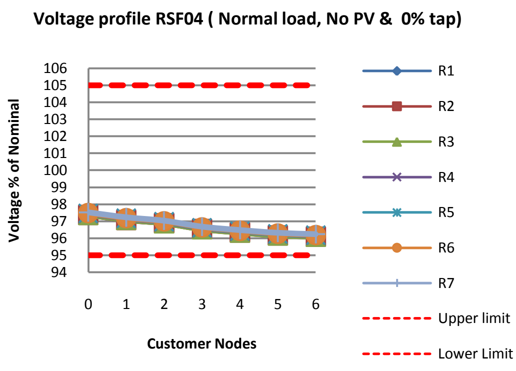
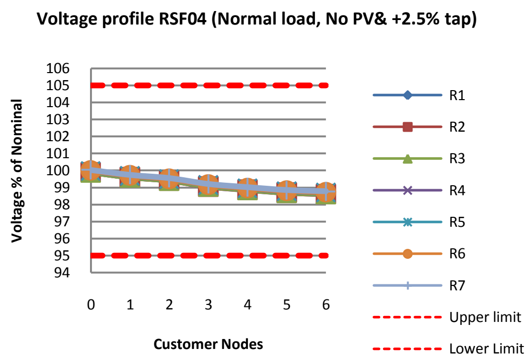
<tr><td>ISK10</td><td>
</td><td>
</td></tr>
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><td>Scenario</td><td>0%</td><td>Preferred Tap Position</td></tr>
<tr><td>ALNPV</td><td></td><td></td></tr>
<tr><td>ISK11</td><td>
</td><td>
</td></tr>
<tr><td>RSF04</td><td>
</td><td>
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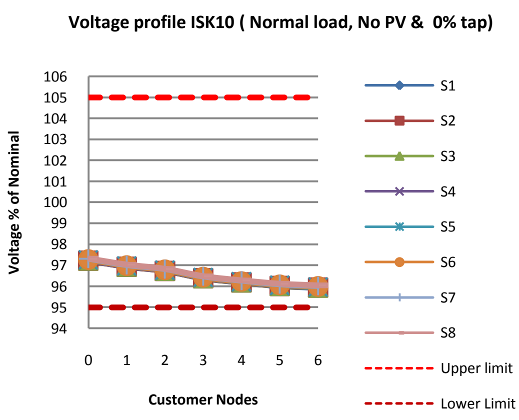
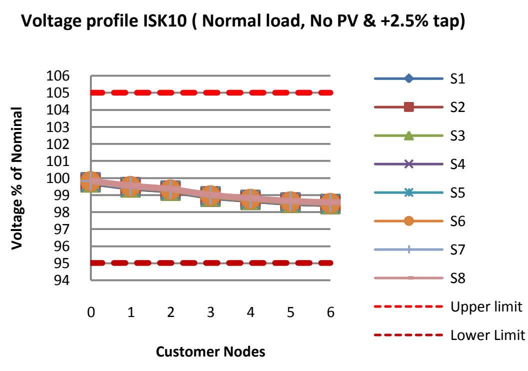
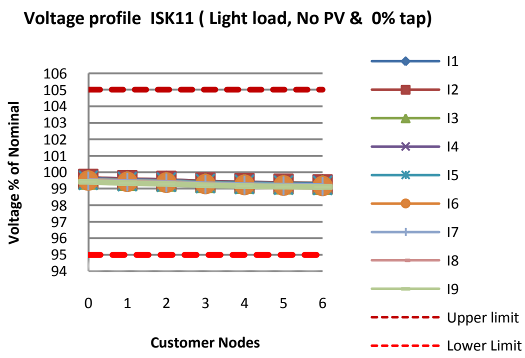
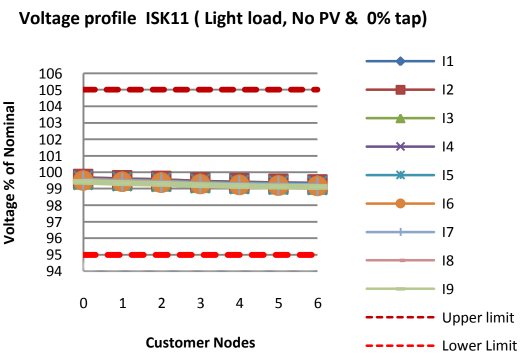
<tr><td>ISK10</td><td>
</td><td>
</td></tr>
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><td>Scenario
LLNPV</td><td>0%</td><td>Preferred Tap Position</td></tr>
<tr><td>ISK11</td><td>
</td><td>
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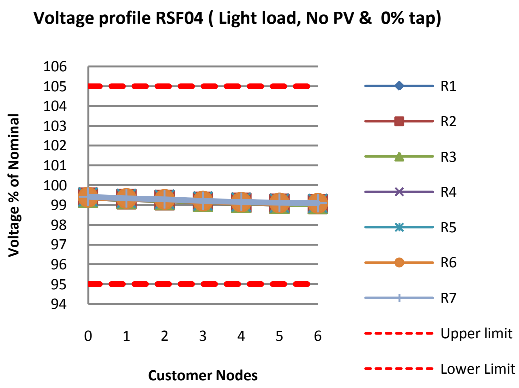
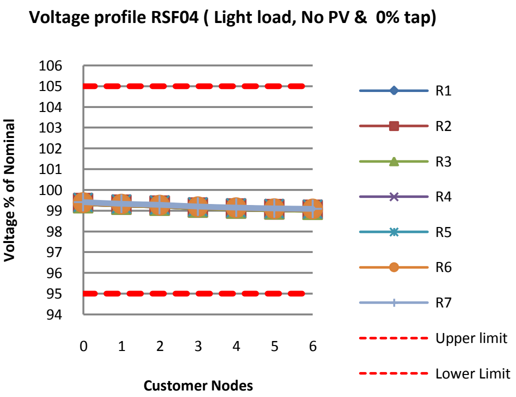
<tr><td>RSF04</td><td>
</td><td>
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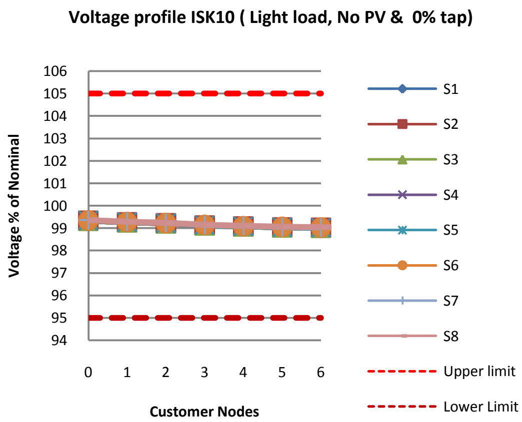
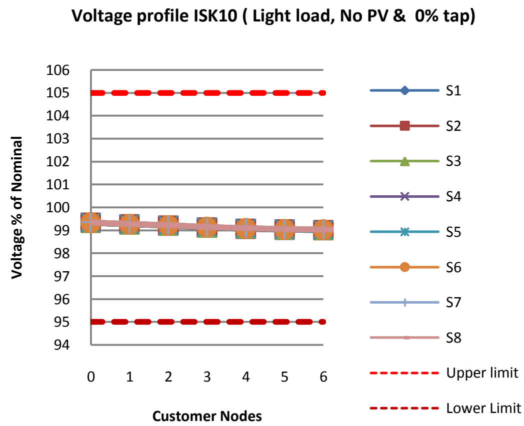
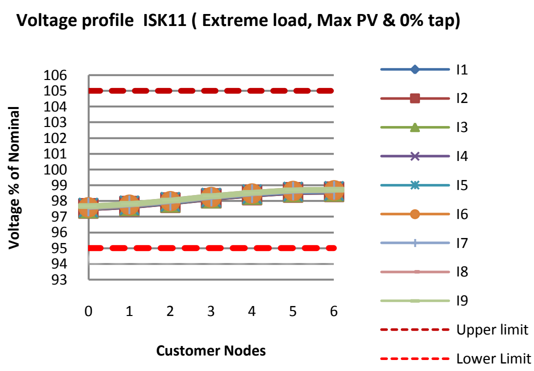
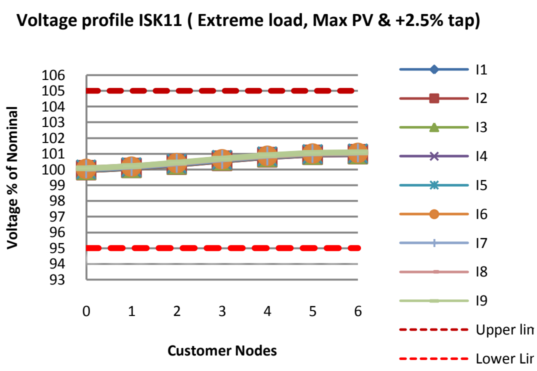
<tr><td>ISK10</td><td>
</td><td>
</td></tr>
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><th>Scenario
XLMPV</th><th>0%</th><th>Preferred Tap Position</th></tr>
<tr><td>ISK11</td><td>
</td><td>
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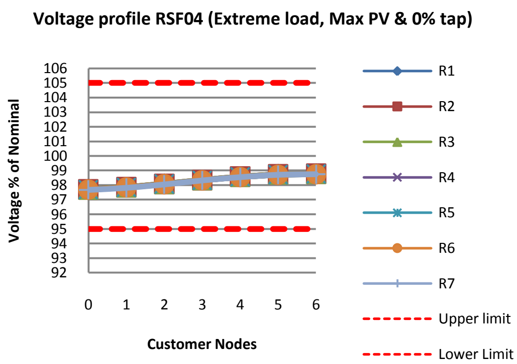
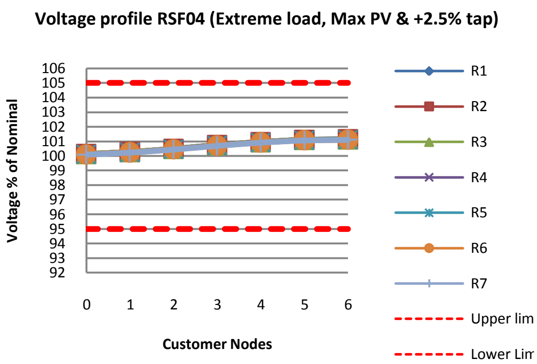
<tr><td>RSF04</td><td>
</td><td>
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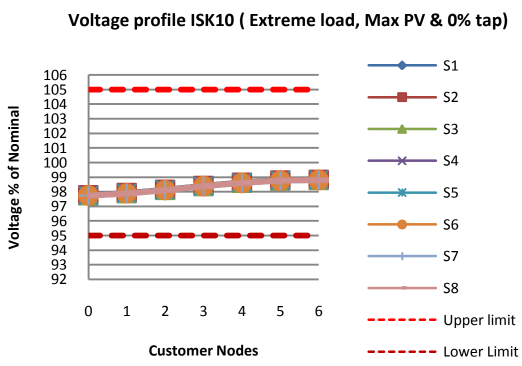
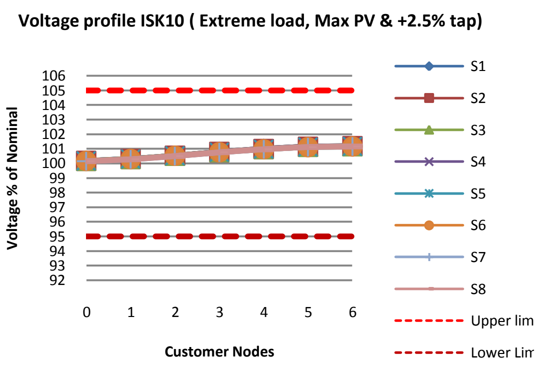
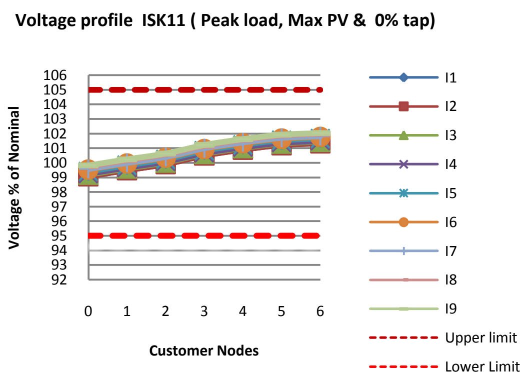
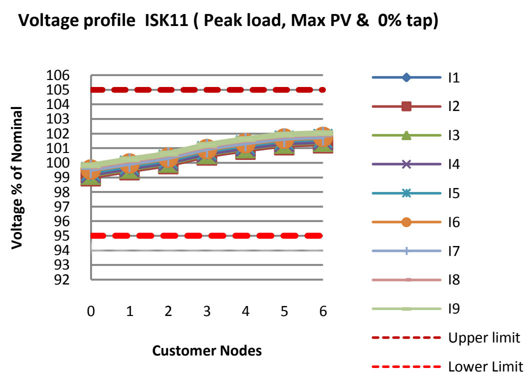
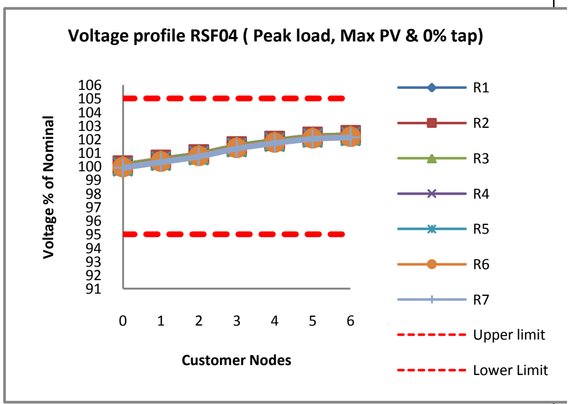
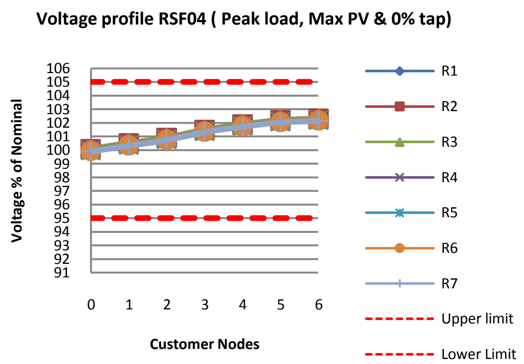
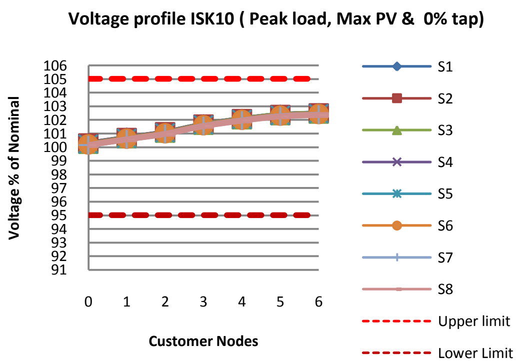
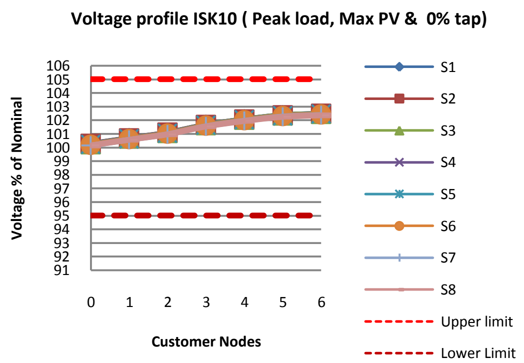
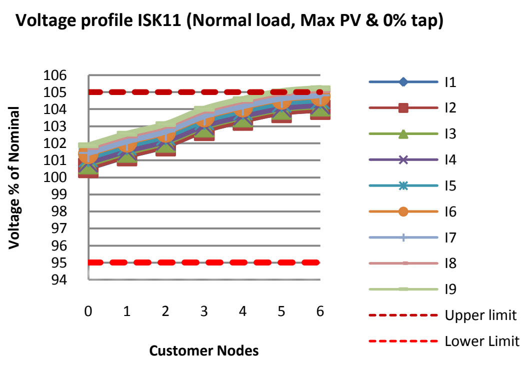
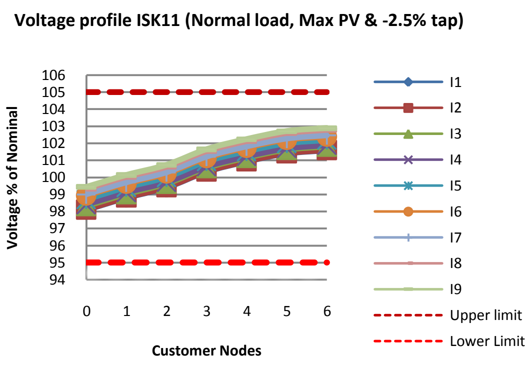
<tr><td>ISK10</td><td>
</td><td>
</td></tr>
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

Scenario PLMPV	0%	Preferred Tap Position
ISK11		
RSF04		
ISK10		

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><th>Scenario
ALMPV</th><th>0%</th><th>Preferred Tap Position</th></tr>
<tr><td>ISK11</td><td>
</td><td>
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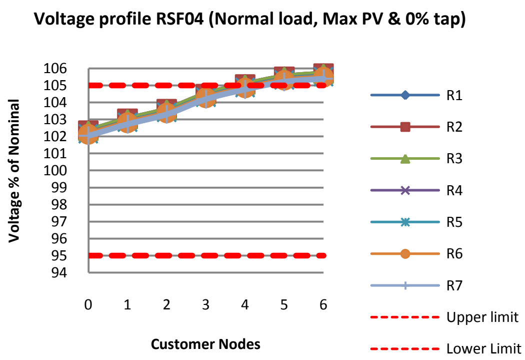
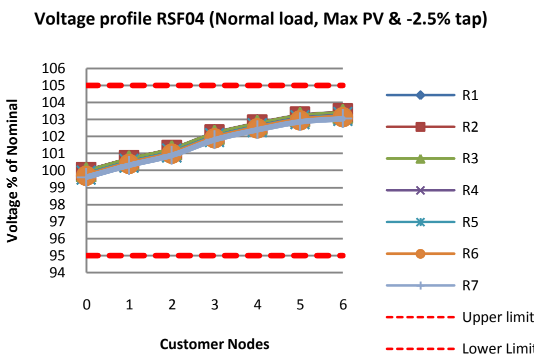
<tr><td>RSF04</td><td>
</td><td>
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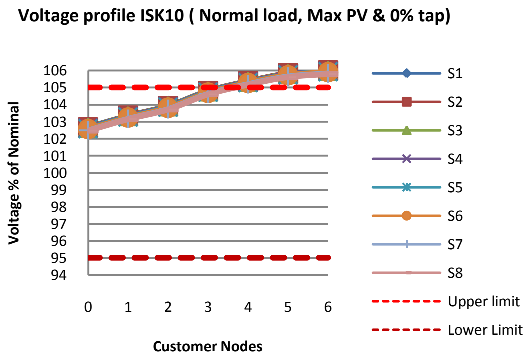
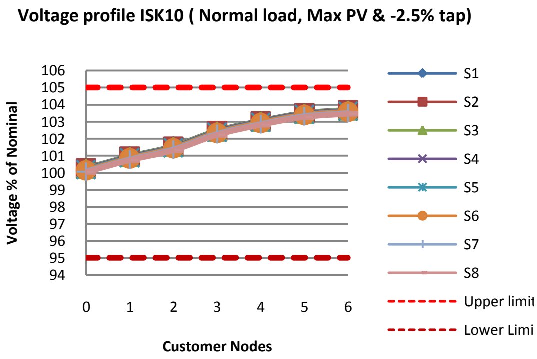
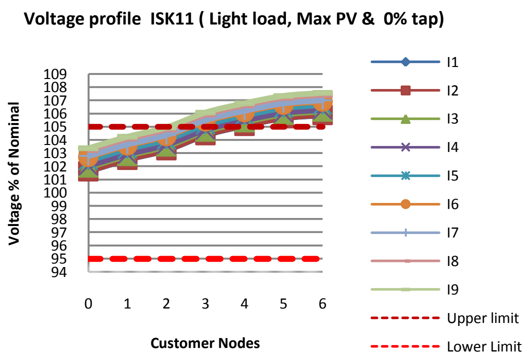
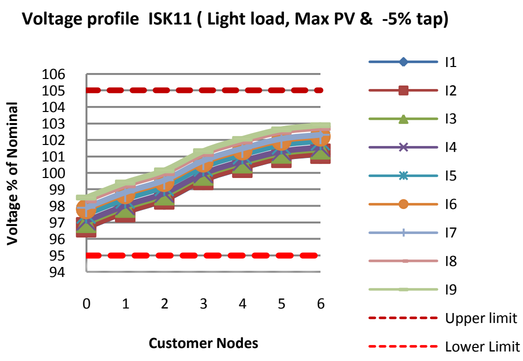
<tr><td>ISK10</td><td>
</td><td>
</td></tr>
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><th>Scenario
LLMPV</th><th>0%</th><th>Preferred Tap Position</th></tr>
<tr><td>ISK11</td><td>
</td><td>
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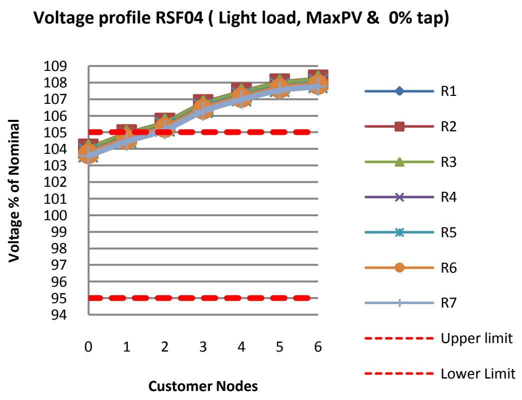
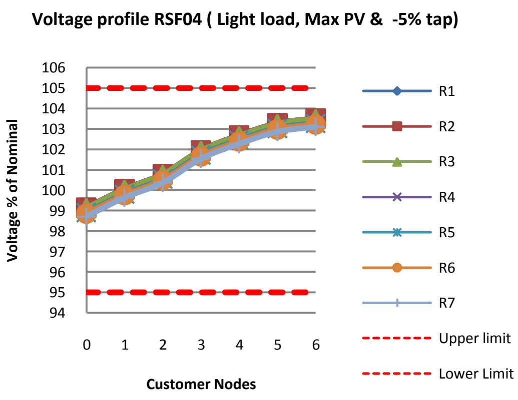
<tr><td>RSF04</td><td>
</td><td>
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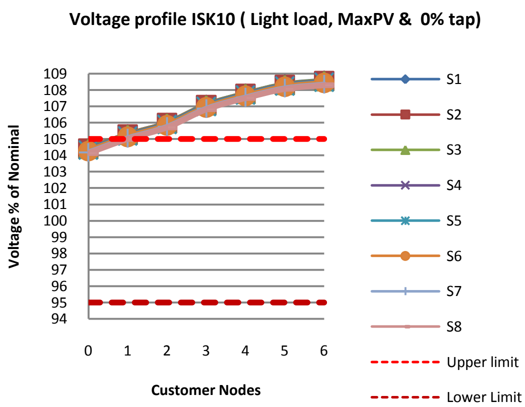
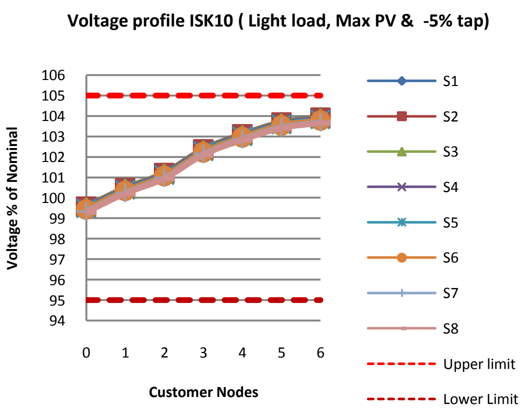
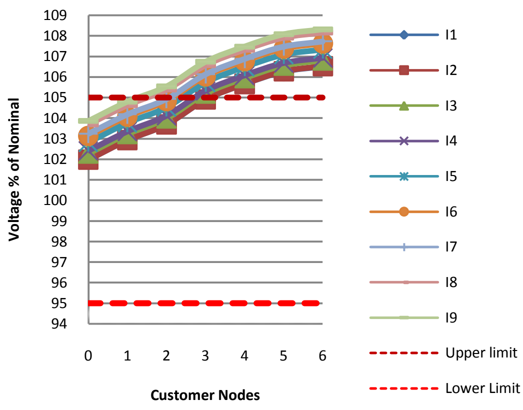
<tr><td>ISK10</td><td>
</td><td>
</td></tr>
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><td>Scenario
NLMPV</td><td>0%</td><td>Preferred Tap Position</td></tr>
<tr><td>ISK11</td><td>

Voltage profile ISK11 (No load, Max PV & 0% tap)



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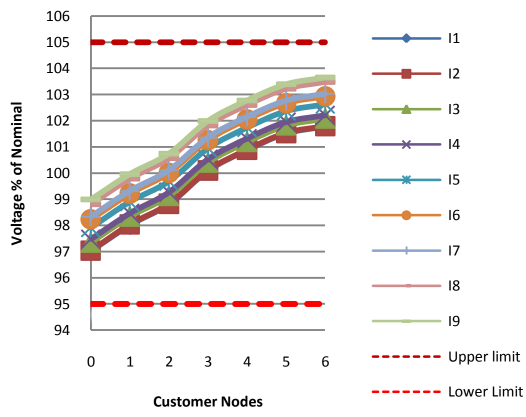
Voltage profile ISK11 (No load, Max PV & -5% tap)



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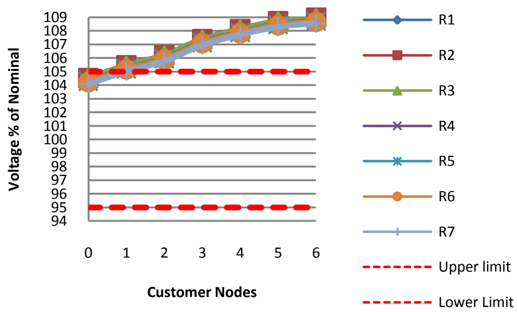
<tr><td>RSF04</td><td>

Voltage profile RSF04 (No load, Max PV & 0% tap)



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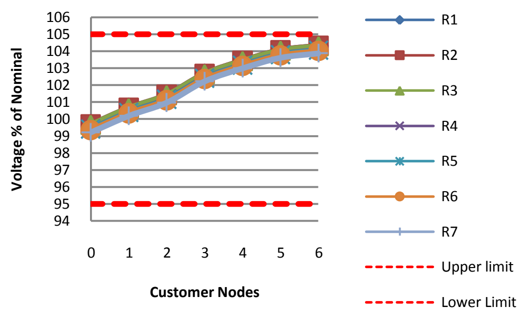
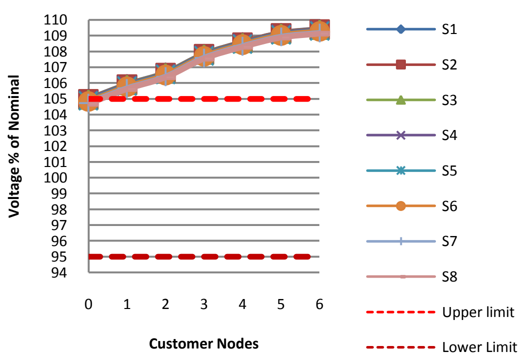
Voltage profile RSF04 (No load, Max PV & -5% tap)



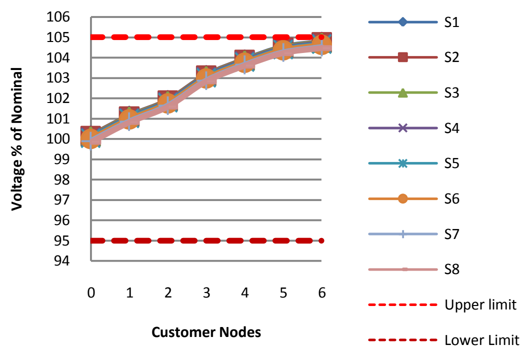
</td></tr>
<tr><td>ISK10</td><td>

Voltage profile ISK10 ((No load, Max PV & 0% tap)



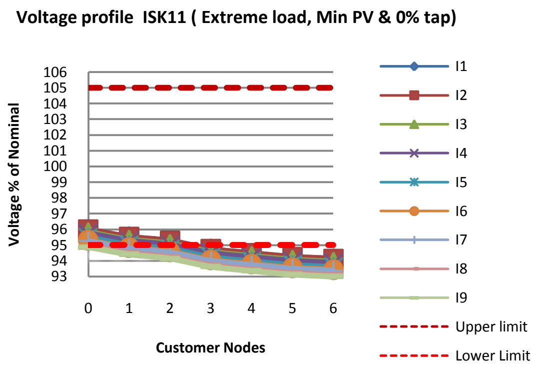
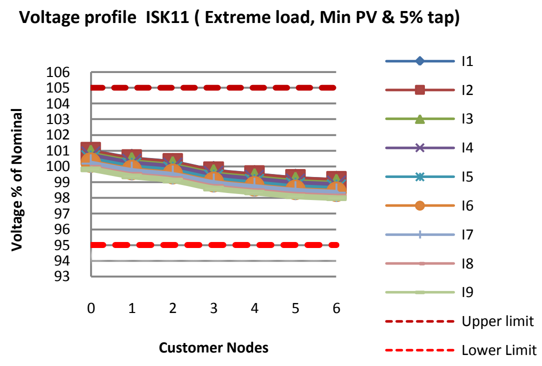
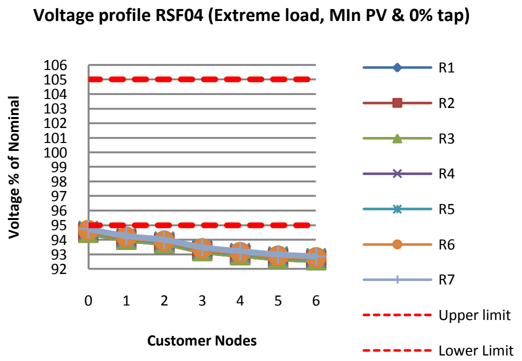
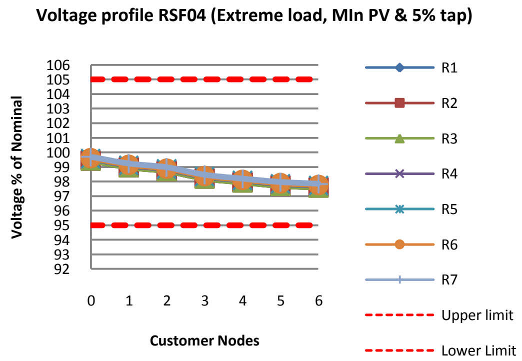
</td><td>

Voltage profile ISK10 ((No load, Max PV & -5% tap)



</td></tr>
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><th>Scenario
XLAPV</th><th>0%</th><th>Preferred Tap Position</th></tr>
<tr><td>ISK11</td><td>
</td><td>
</td></tr>
<tr><td>RSF04</td><td>
</td><td>
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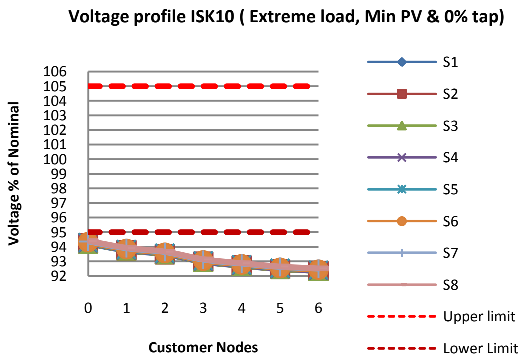
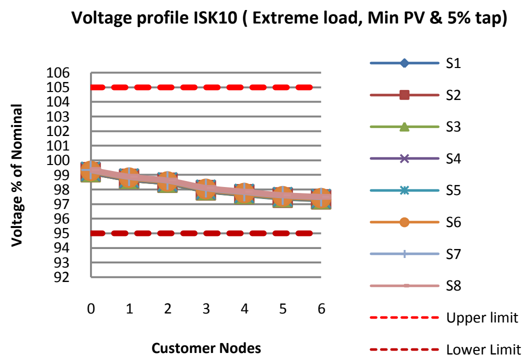
<tr><td>ISK10</td><td>
</td><td>
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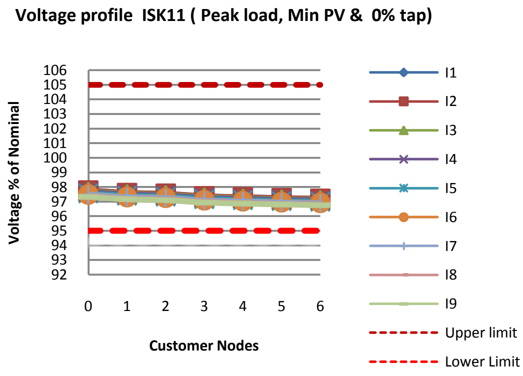
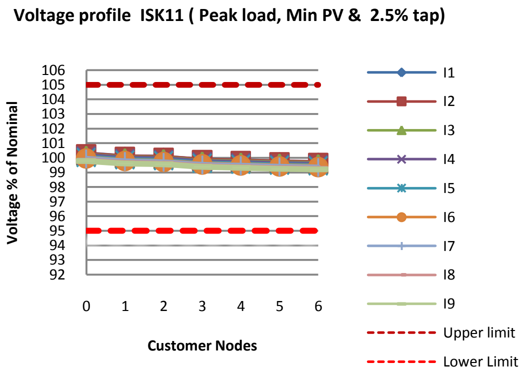
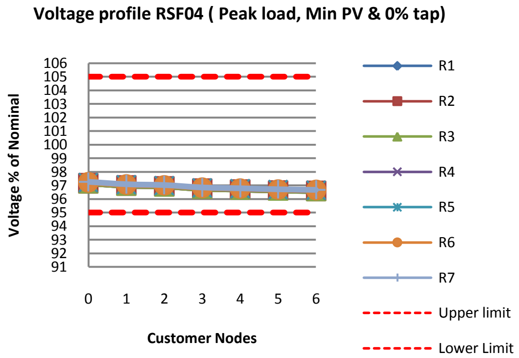
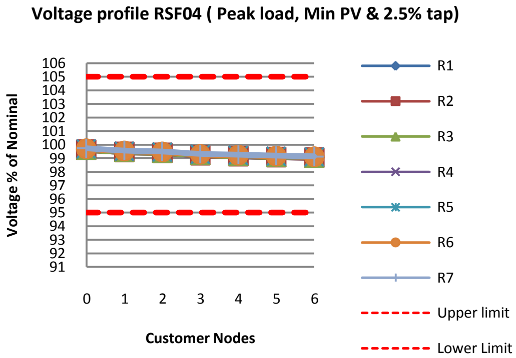
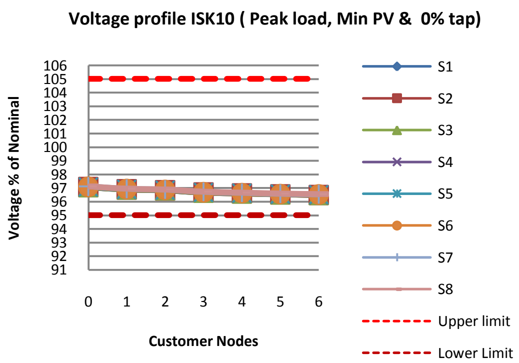
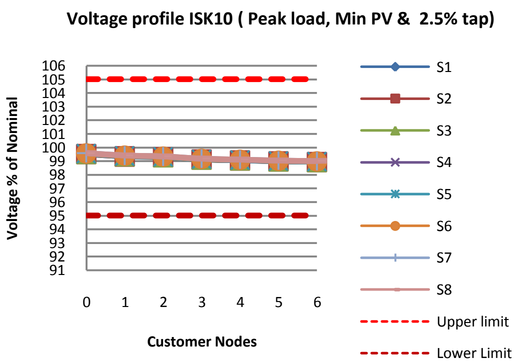
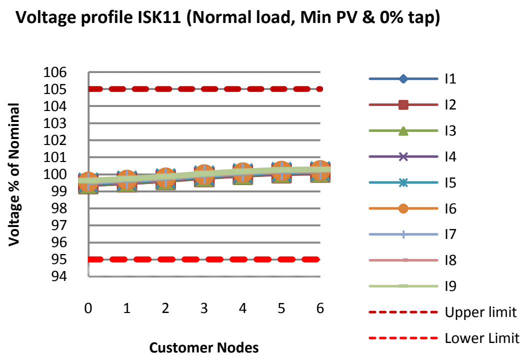
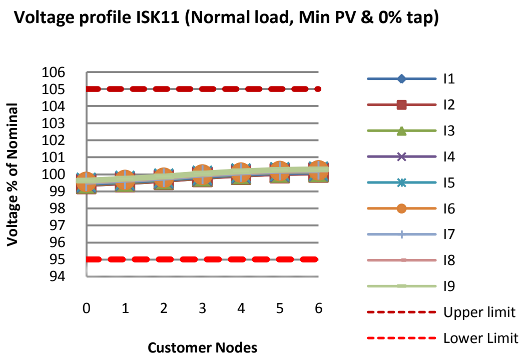
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

Scenario PLAPV	0%	Preferred Tap Position
ISK11		
RSF04		
ISK10		

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><th>Scenario
ALAPV</th><th>0%</th><th>Preferred Tap Position</th></tr>
<tr><td>ISK11</td><td>
</td><td>
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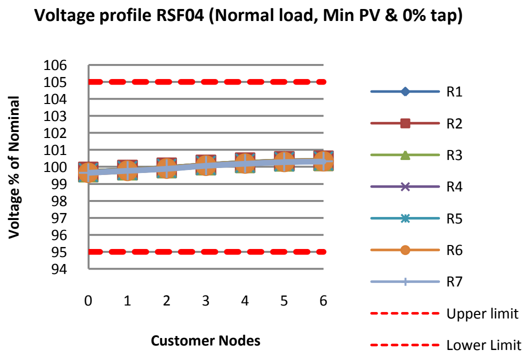
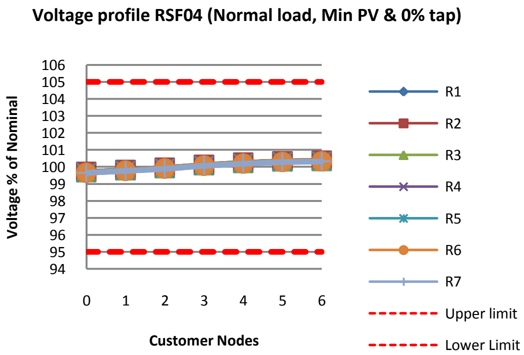
<tr><td>RSF04</td><td>
</td><td>
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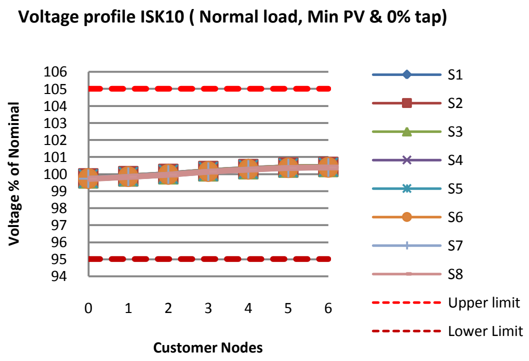
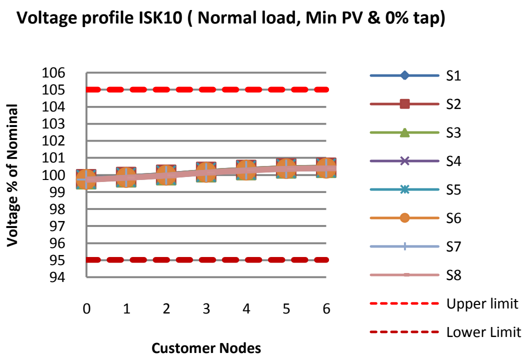
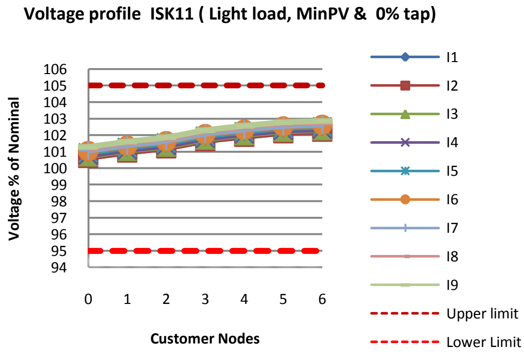
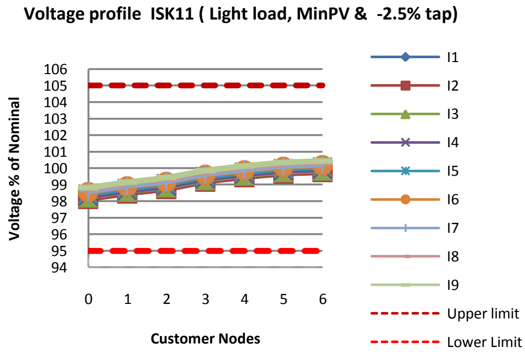
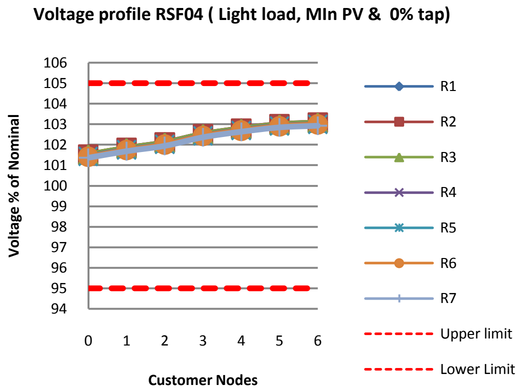
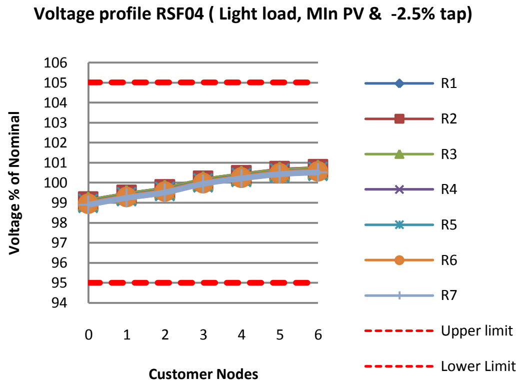
<tr><td>ISK10</td><td>
</td><td>
</td></tr>
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

<table>
<tr><th>Scenario
LLAPV</th><th>0%</th><th>Preferred Tap Position</th></tr>
<tr><td>ISK11</td><td>
</td><td>
</td></tr>
<tr><td>RSF04</td><td>
</td><td>
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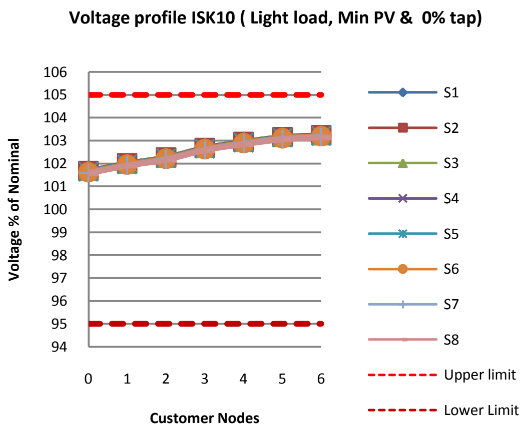
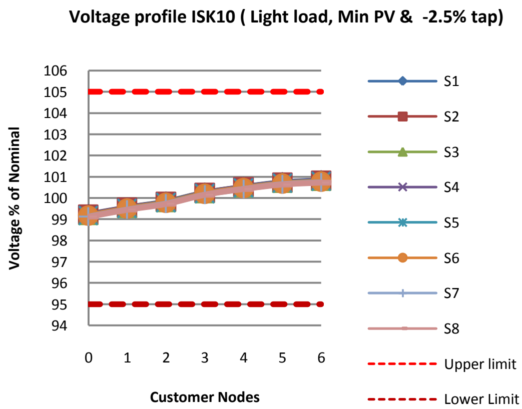
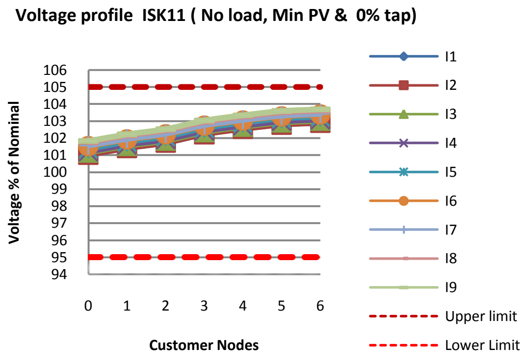
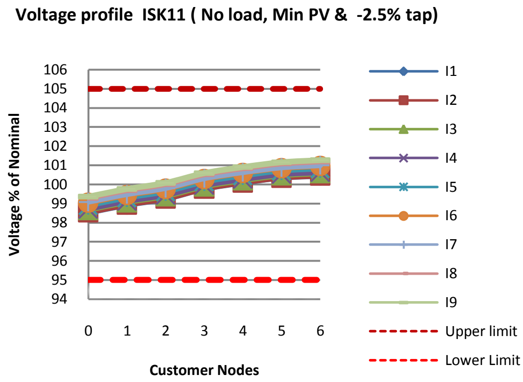
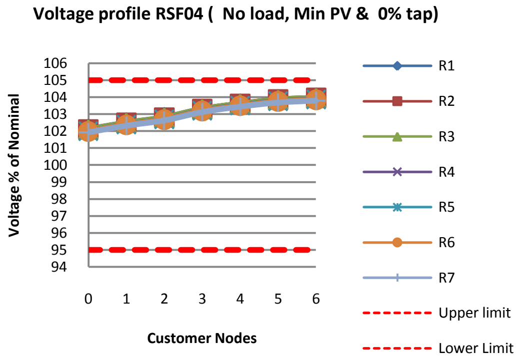
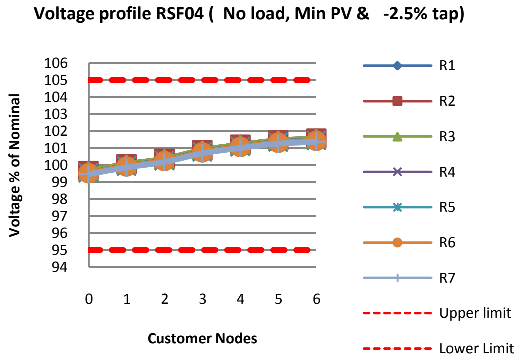
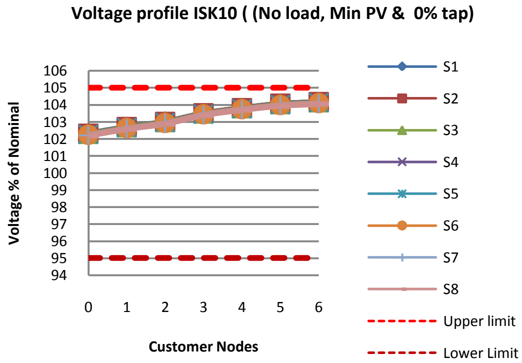
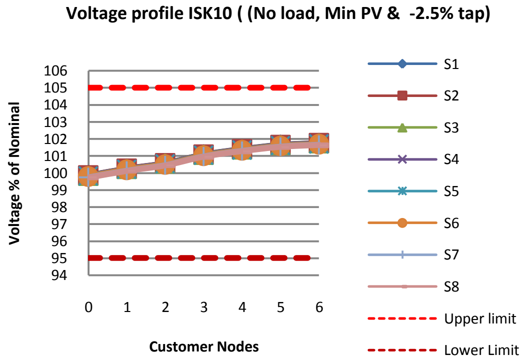
<tr><td>ISK10</td><td>
</td><td>
</td></tr>
</table>

Appendix D: Voltage level for all customers connected to feeder I9, R1 and S1 in Fig. 5.17 for all tested scenarios.

Scenario NLAPV	0%	Preferred Tap Position
ISK11		
RSF04		
ISK10		

Publications

[1] R. A. Shalwala and J. A. M. Bleijs, "Impact of Grid-Connected PV systems in residential areas in Saudi Arabia," in *Universities Power Engineering Conference (UPEC), 2009 Proceedings of the 44th International*, 2009, pp. 1-5.

[2] R. A. Shalwala and J. A. M. Bleijs, "Impact of Grid-Connected PV systems on voltage regulation of a residential area network in Saudi Arabia," in *Nuclear & Renewable Energy Conference (INREC), 2010 1st International*, 2010, pp. 1-5.

[3] R. A. Shalwala and J. A. M. Bleijs, "Voltage control scheme using fuzzy logic for residential area networks with PV generators in Saudi Arabia," in *Power Electronics, Drives and Energy Systems (PEDES) & 2010 Power India, 2010 Joint International Conference on*, 2010, pp. 1-6.

References

[1] S. A. Alajlan, "Photovoltaic grid-connection system as load-shaving tool in Riyadh, Saudi Arabia," *Applied Energy,* vol. 63, pp. 91-9, 1999.

[2] Y. Nishida, S. Nakamura, N. Aikawa, S. Sumiyoshi, H. Yamashita, and H. Omori, "A novel type of utility-interactive inverter for photovoltaic system," in *Industrial Electronics Society, 2003. IECON '03. The 29th Annual Conference of the IEEE*, 2003, pp. 2338-2343 Vol.3.

[3] A. Y. Al-Hasan, A. A. Ghoneim, and A. H. Abdullah, "Optimizing electrical load pattern in Kuwait using grid connected photovoltaic systems," *Energy Conversion and Management,* vol. 45, pp. 483-494, 2004.

[4] E. B. a. D. Waskow, "Renewable Energy Report7-2," 2005.

[5] J. P. Dorian, H. T. Franssen, and D. R. Simbeck, "Global challenges in energy," *Energy Policy,* vol. 34, pp. 1984-1991, 2006.

[6] É. p. f. d. L. EPFL. (2011, 12/12/2011). *Integration of distributed generation and storage technologies in distribution systems*. Available: http://pwrs.epfl.ch/page-47168-en.html

[7] (24/12/2011). *The "Grid" as it is today*. Available: earthtoys.com/emagazine.php?issue_number=09.0...

[8] T. P. Hughes, *Networks of power : electrification in Western society, 1880-1930*. Baltimore [u.a.]: Johns Hopkins Univ. Press, 1993.

[9] G. Knieps, *Privatisation of network industries in Germany : a disaggregated approach*. Munich: CES, 2004.

[10] M. A. Bolinger, "Surpassing Expectations: State of the U.S. Wind Power Market," ed, 2009.

[11] A. Hamlyn, H. Cheung, W. Lin, Y. Cungang, and R. Cheung, "Distributed monitoring and centralized forecasting network for DG-connected distribution systems," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-7.

[12] W. Lin, A. Hamlyn, H. Cheung, R. Yasin, C. Li, and R. Cheung, "Network-aided strategy and breaker impacts on voltage instability corrective actions for power systems with DGs," in *Power & Energy Society General Meeting, 2009. PES '09. IEEE*, 2009, pp. 1-7.

[13] W. Lin, Z. Libing, H. Cheung, A. Hamlyn, T. Mander, I. Lee, and R. Cheung, "Adaptive protection and control strategy for interfacing wind generators to distribution grids," in *Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on*, 2008, pp. 2478-2483.

[14] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'haeseleer, "Distributed generation: definition, benefits and issues," *Energy Policy,* vol. 33, pp. 787-798, 2005.

[15] C. C. Davidson and G. de Preville, "The future of high power electronics in Transmission and Distribution power systems," in *Power Electronics and Applications, 2009. EPE '09. 13th European Conference on*, 2009, pp. 1-14.

[16] J. M. Daley and R. L. Siciliano, "Application of emergency and standby generation for distributed generation. I. Concepts and hypotheses," *Industry Applications, IEEE Transactions on,* vol. 39, pp. 1214-1225, 2003.

[17] M. W. Davis, "Mini gas turbines and high speed generators a preferred choice for serving large commercial customers and microgrids. I. Generating system," in *Power Engineering Society Summer Meeting, 2002 IEEE*, 2002, pp. 669-676 vol.2.

[18] P. P.A, "Mini- and micro-gas turbines for combined heat and power," *Applied Thermal Engineering,* vol. 22, pp. 2003-2014, 2002.

[19] T. Thakur and S. Garg, "Economic viability of PEM fuel cells for harnessing solar energy," in *Industrial Electronics, 2008. ISIE 2008. IEEE International Symposium on*, 2008, pp. 2526-2531.
[20] D. A. Spera, *Wind Turbine Technology*, 1994.
[21] J. M. Ogden and R. H. Williams, *Solar hydrogen: Moving beyond fossil fuels*, 1989.
[22] A. Luque, "Will we exceed 50% efficiency in photovoltaics?," *Journal of Applied Physics,* vol. 110, pp. 031301-031301-19, 2011.
[23] P. Hoseinpoori, H. Najafi, and B. Najafi, "Optimal design of gas turbine-solid oxide fuel cell hybrid plant," in *Electrical Power and Energy Conference (EPEC), 2011 IEEE*, 2011, pp. 29-34.
[24] L. Xu, S. Islam, A. A. Chowdhury, and D. O. Koval, "Reliability evaluation of a wind-diesel-battery hybrid power system," in *Industrial and Commercial Power Systems Technical Conference, 2008. ICPS 2008. IEEE/IAS*, 2008, pp. 1-8.
[25] Z. Yixin and B. Osborn, "Solar Dish-Stirling Power Plants and Related Grid Interconnection Issues," in *Power Engineering Society General Meeting, 2007. IEEE*, 2007, pp. 1-5.
[26] R. A. N. Jenkins, P. Crossley, D. Kirschen, and G. Strbac, *Embedded generation*. London: The Institution of Electrical Engineers, 2000.
[27] Y. Ueda, K. Kurokawa, T. Tanabe, K. Kitamura, and H. Sugihara, "Analysis Results of Output Power Loss Due to the Grid Voltage Rise in Grid-Connected Photovoltaic Power Generation Systems," *Industrial Electronics, IEEE Transactions on,* vol. 55, pp. 2744-2751, 2008.
[28] X. Xiao-yan, H. Yue-hui, L. Chun, and W. Wei-sheng, "Impact of dispersed PV generation on voltage rise of distribution grid," in *Power System Technology (POWERCON), 2010 International Conference on*, 2010, pp. 1-6.
[29] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "A comprehensive assessment tool for solar PV impacts on low voltage three phase distribution networks," in *Developments in Renewable Energy Technology (ICDRET), 2012 2nd International Conference on the*, 2012, pp. 1-5.
[30] E. Demirok, D. Sera, R. Teodorescu, P. Rodriguez, and U. Borup, "Clustered PV inverters in LV networks: An overview of impacts and comparison of voltage control strategies," in *Electrical Power & Energy Conference (EPEC), 2009 IEEE*, 2009, pp. 1-6.
[31] Y. Liu, J. Bebic, B. Kroposki, J. de Bedout, and W. Ren, "Distribution System Voltage Performance Analysis for High-Penetration PV," in *Energy 2030 Conference, 2008. ENERGY 2008. IEEE*, 2008, pp. 1-8.
[32] R. Tonkoski, D. Turcotte, and T. H. M. El-Fouly, "Impact of High PV Penetration on Voltage Profiles in Residential Neighborhoods," *Sustainable Energy, IEEE Transactions on,* vol. PP, pp. 1-10, 2012.
[33] S. Conti, A. Greco, N. Messina, and S. Raiti, "Local voltage regulation in LV distribution networks with PV distributed generation," in *Power Electronics, Electrical Drives, Automation and Motion, 2006. SPEEDAM 2006. International Symposium on*, 2006, pp. 519-524.
[34] C. Debruyne, J. Vanalme, B. Verhelst, J. Desmet, J. Capelle, and L. Vandevelde, "Preventing overvoltages in PV grids by integration of small storage capacity," in *Innovative Smart Grid Technologies (ISGT Europe), 2011 2nd IEEE PES International Conference and Exhibition on*, 2011, pp. 1-7.
[35] S. Vlachopoulos and C. Demoulias, "Voltage regulation in low-voltage rural feeders with distributed PV systems," in *EUROCON - International Conference on Computer as a Tool (EUROCON), 2011 IEEE*, 2011, pp. 1-4.

[36] A. Keane, F. O. Luis, E. Vittal, C. J. Dent, and G. P. Harrison, "Enhanced utilization of voltage control resources with distributed generation," in *Power and Energy Society General Meeting, 2011 IEEE*, 2011, pp. 1-1.
[37] Y. Ueda, K. Kurokawa, T. Tanabe, K. Kitamura, K. Akanuma, M. Yokota, and H. Sugihara, "Study on the Over Voltage Poblem and Battery Operation for Grid-connected Residential PV systems," *22nd European Photovoltaic Solar Energy Conference, 3-7 September 2007, Milan, Italy,* 2007.
[38] M. Thomson and D. G. Infield, "Impact of widespread photovoltaics generation on distribution systems," *Renewable Power Generation, IET,* vol. 1, pp. 33-40, 2007.
[39] T. A. Short, *Electric Power Distribution Handbook*: CRC press LLC, 2003.
[40] S. K. Salman and I. M. Rida, "ANN-based AVC relay for voltage control of distribution network with and without embedded generation," in *Electric Utility Deregulation and Restructuring and Power Technologies, 2000. Proceedings. DRPT 2000. International Conference on*, 2000, pp. 263-267.
[41] C. Dai and Y. Baghzouz, "On the voltage profile of distribution feeders with distributed generation," in *Power Engineering Society General Meeting, 2003, IEEE*, 2003, p. 1140 Vol. 2.
[42] E. F. Mogos and X. Guillaud, "A voltage regulation system for distributed generation," in *Power Systems Conference and Exposition, 2004. IEEE PES*, 2004, pp. 787-794 vol.2.
[43] "IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment," *IEEE Std 1100-1992,* p. 0_1, 1992.
[44] "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," *IEEE Std 519-1992,* p. 0_1, 1993.
[45] A. Girgis and S. Brahma, "Effect of distributed generation on protective device coordination in distribution system," in *Power Engineering, 2001. LESCOPE '01. 2001 Large Engineering Systems Conference on*, 2001, pp. 115-119.
[46] S. K. Salman and I. M. Rida, "Investigating the impact of embedded generation on relay settings of utilities electrical feeders," *Power Delivery, IEEE Transactions on,* vol. 16, pp. 246-251, 2001.
[47] P. P. Barker and R. W. De Mello, "Determining the impact of distributed generation on power systems. I. Radial distribution systems," in *Power Engineering Society Summer Meeting, 2000. IEEE*, 2000, pp. 1645-1656 vol. 3.
[48] T. Ackermann and V. Knyazkin, "Interaction between distributed generation and the distribution network: operation aspects," in *Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES*, 2002, pp. 1357-1362 vol.2.
[49] J. C. Gomez and M. M. Morcos, "Coordinating Overcurrent Protection and Voltage Sag in Distributed Generation Systems," *Power Engineering Review, IEEE,* vol. 22, pp. 16-19, 2002.
[50] R. C. Dugan and T. E. McDermott, "Distributed generation," *Industry Applications Magazine, IEEE,* vol. 8, pp. 19-25, 2002.
[51] (Dec 2010). *Google map*. Available: http://maps.google.com/maps?hl=en&tab=wl
[52] A. Saleh H, "Evaluation of solar energy research and its applications in Saudi Arabia — 20 years of experience," *Renewable and Sustainable Energy Reviews,* vol. 5, pp. 59-77, 2001.
[53] N. S. Today, "Saudi Arabia Solar Announcement " in *Renewable energy world.com* vol. 2011, ed: Renewable Energy Network for News & Information, 2010.
[54] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, and G. Strbac, *Embedded generation*: The Institution of Electrical Engineers, London , UK, 1995.
[55] T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Smart Decentralized Control of DG for Voltage and Thermal Constraint Management," *Power Systems, IEEE Transactions on,* vol. PP, pp. 1-1, 2012.

[56] T. Sansawatt, J. O'Donnell, L. F. Ochoa, and G. P. Harrison, "Decentralised voltage control for active Distribution Networks," in *Universities Power Engineering Conference (UPEC), 2009 Proceedings of the 44th International*, 2009, pp. 1-5.

[57] A. Keane, L. F. Ochoa, E. Vittal, C. J. Dent, and G. P. Harrison, "Enhanced Utilization of Voltage Control Resources With Distributed Generation," *Power Systems, IEEE Transactions on,* vol. 26, pp. 252-260, 2011.

[58] N. C. Scott, D. J. Atkinson, and J. E. Morrell, "Use of load control to regulate voltage on distribution networks with embedded generation," *Power Systems, IEEE Transactions on,* vol. 17, pp. 510-515, 2002.

[59] M. A. Kashem and G. Ledwich, "Distributed generation as Voltage support for single wire Earth return systems," *Power Delivery, IEEE Transactions on,* vol. 19, pp. 1002-1011, 2004.

[60] D. Villacci, G. Bontempi, and A. Vaccaro, "An adaptive local learning-based methodology for voltage regulation in distribution networks with dispersed generation," *Power Systems, IEEE Transactions on,* vol. 21, pp. 1131-1140, 2006.

[61] C. M. Hird, H. Leite, N. Jenkins, and H. Li, "Network voltage controller for distributed generation," *Generation, Transmission and Distribution, IEE Proceedings-,* vol. 151, pp. 150-156, 2004.

[62] K. Pandiaraj and B. Fox, "Novel voltage control for embedded generators in rural distribution networks," in *Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on*, 2000, pp. 457-462 vol.1.

[63] T. E. Kim and J. E. Kim, "Voltage regulation coordination of distributed generation system in distribution system," in *Power Engineering Society Summer Meeting, 2001*, 2001, pp. 480-484 vol.1.

[64] S. K. Salman and Z. G. Wan, "Voltage control of distribution network with distributed/embedded generation using fuzzy logic-based AVC relay," in *Universities Power Engineering Conference, 2007. UPEC 2007. 42nd International*, 2007, pp. 576-579.

[65] H. F. Wang, "Multi-agent co-ordination for the secondary voltage control in power-system contingencies," *Generation, Transmission and Distribution, IEE Proceedings-,* vol. 148, pp. 61-66, 2001.

[66] G. Sheng, X. Jiang, and Y. Zeng, "Optimal Coordination For Multi-Agent Based Secondary Voltage Control In Power System," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, 2005, pp. 1-6.

[67] H. Hatta and H. Kobayashi, "Demonstration study on centralized voltage control system for distribution line with sudden voltage fluctuations," in *SmartGrids for Distribution, 2008. IET-CIRED. CIRED Seminar*, 2008, pp. 1-4.

[68] T. Senjyu, Y. Miyazato, A. Yona, N. Urasaki, and T. Funabashi, "Optimal Distribution Voltage Control and Coordination With Distributed Generation," *Power Delivery, IEEE Transactions on,* vol. 23, pp. 1236-1242, 2008.

[69] C. C. Lee, "Fuzzy logic in control systems: fuzzy logic controller. I," *Systems, Man and Cybernetics, IEEE Transactions on,* vol. 20, pp. 404-418, 1990.

[70] C. C. Lee, "Fuzzy logic in control systems: fuzzy logic controller. II," *Systems, Man and Cybernetics, IEEE Transactions on,* vol. 20, pp. 419-435, 1990.

[71] A. Jackson, "Fuzzy logic vs traditional approaches to the design of microcontroller-based systems," in *Aerospace Applications Conference, 1994. Proceedings., 1994 IEEE*, 1994, pp. 19-33.

[72] T. J. Ross, "Front Matter," in *Fuzzy Logic with Engineering Applications*, ed: John Wiley & Sons, Ltd, 2010, pp. i-xxi.

[73] H. J. Zimmerman, *Fuzzy set theory and its application* 2nd edition ed.: Kluwer Academic Publishers, 1990.

[74] J. H. Lilly, *Fuzzy control and identification*. Hoboken, N.J.: Wiley, 2010.
[75] J. D. Glover and M. S. Sarma, *Power system analysis and design*. Boston: PWS Pub., 1994.
[76] M. H. Nehrir and C. Wang. (2009). *Modeling and control of fuel cells distributed generation applications*. Available: http://ieeexplore.ieee.org/xpl/bkabstractplus.jsp?bkn=5443920