

PHOTOVOLTAIC (PV) TYPE SOLAR GENERATORS AND THEIR EFFECT ON
DISTRIBUTION SYSTEMS

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MASTER OF SCIENCE

by
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University of Missouri–Kansas City, 2013

ABSTRACT

Distribution systems are designed to operate in radial mode (the simplest system topology) without any generation on the system, unidirectional power flow from the distribution substation to the customers via main feeder(s) and its(their) laterals within a specified range of operating points. The rapid growth of PV module installations on the distribution systems could not only offset the load but also cause a significant impact on the flow of power (active and reactive), voltage level, and fault currents, therefore; concerns about their potential impacts on the stability and operation of the power system have become one of the important issues and may create barriers to their future expansion. The most likely potential impact of the high PV penetration level is losing the voltage regulation, because it is directly related to the amount of reverse power flow. The main goal of this thesis is to approximate the maximum level of PV penetration which the system can accommodate without any impact on the voltage profile, stability, and operation.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering, have examined a thesis titled “Photovoltaic (PV) Type Solar Generators and their effect on distribution systems,” presented by Abdulsalam Elsaidi, candidate for the Master of Science degree, and hereby certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

Photovoltaic (PV) solar generation has grown steadily in United States in the last few years. As per Solar Energy Industry Association, the installed capacity has increased from 848 MW installed capacity in 2010 to 3328 MW in 2012 and is projected to increase to 9186 MW in 2016 which is over 10 times increase in 6 years. Fig. 1, indicated the cumulative growth per sector as published by the Solar Energy Industry Association [2].

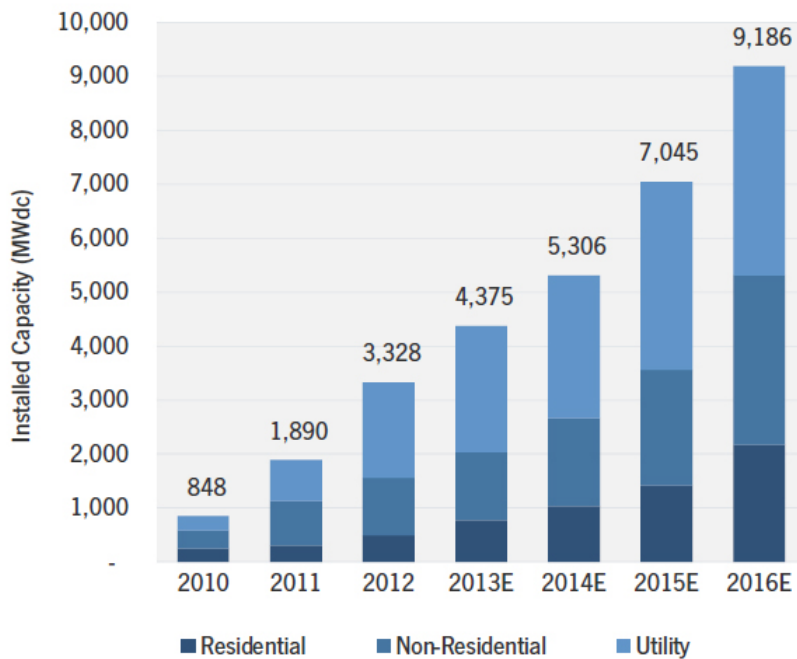


Figure 1: U.S. PV Installation Forecast, 2010-2016E

The character “E” in Fig. 1, denotes to an abbreviation to the word expected. Also,

you will find list of the used abbreviations in chapter 2 under “List of Acronyms” section.

Utility scale PV generators are typically interconnected to the grid at EHV (69 KV and above) level, whereas the residential and non-residential (commercial) type PV generators are connected to the distribution feeders (12 KV and below). Integration of utility scale PV generation is regulated by the Utilities Generation Interconnection Procedures, whereas no such procedures are available for the PV generators connected to distributed systems.

A number of studies have been conducted in the past to assess the impact of PV type solar generators on the distributed systems, but a notable study was the one conducted by U.S Department of Energy in 2007. In spring 2007, the U.S. Department of Energy (DOE) has launched the Renewable Systems Interconnection (RSI) study [3]. This study consists of many reports that are related to distribution system developments; advanced distribution systems integration, system-level tests and demonstrations, technical and market analysis, resource assessment and codes, standards, and regulatory implementation. The key point of RSI study is to address the technical and analytical issues in order to enable high penetration levels of distributed renewable energy technologies.

The number of distributed solar photovoltaic (PV) installations, in particular, are growing rapidly, which can be seen either as a change of load profiles when production replaces a part of the load or as an addition of production units to the distribution system. Therefore, concerns about their potential impacts on the stability and operation of the electrical power system, especially the voltage regulation, may create barriers to their future expansion. A commonly used rule of thumb in the U.S. allows distributed PV

systems with peak powers up to 15% of the peak load on a feeder (or section) to be permitted without a detailed impact study [4]. However, as total distributed PV units increase on many feeders, a more rigorous study of the impacts of various PV penetration levels on feeder voltages is justified.

1.1 Problem Statement

The voltage regulation of radial distribution system is accomplished by using on-load tap changer at HV/MV substation and reactive power compensation upon the estimated voltage raise/drop based on load profiles and load-flow calculations. The penetration of PV units (residential and commercial) at the load side reduces the load demand which leads to reduce losses and improved voltage profile. Obviously, this is true as long as the power flows in its conventional direction (from the substation into the end-user). If a great amount of distributed PV generators is connected into the distribution system, the flow of power may be reversed, from the load (distributed PV) towards the substation. Consequently, there is a possible voltage rise along distribution feeders as a result of reverse power flow, especially at low demand and high generation conditions, and hence the effectiveness of voltage regulation may be lost.

1.2 Purpose of Thesis

The reverse power flow of both active and reactive power components injected by PV systems may lead to losing the voltage regulation, which is the most likely impact caused by the high PV penetrations, for the distribution power system.

The purpose of this thesis is to investigate the voltage regulation of the system during various levels of PV penetration and different inverter topologies every 30 minutes of steady state operations and to estimate the maximum level of penetration, which will not affect the stability and operation of the power system. Also, to review the capability of existing inverter topologies to support the future growth of PV generators.

1.3 Rationale of Study

Two main rules, which have major influences in any study, were considered in this thesis as study bases and these are:

- The load is variable: The load demands of different consumers vary upon their activities and therefore the load in each bus is never constant. The consequences of these changes have a direct impact on the voltage regulation of the bus, i.e. voltage drop usually happens during peak load while the voltage rises during the light load period.
- PV Generation is uncertain: The most common impact on the generated power from PV units is the weather and the solar irradiation which leads to temporarily reduce the PV capability of power generation. For example, clouds covering the sun can cut Photovoltaic (PV) array and reduce the energy absorption by the solar panel depending on how much daylight they diffuse. Also, twilight sun has an impact on the generated power and has to be considered.

CHAPTER 2

BACKGROUND AND REVIEW

2.1 Definition of Terms

2.1.1 AC Power Classification

Real power (P): Power dissipated by a load is referred to as active power. Active power is symbolized by the letter P and is measured in the unit of Watts (W);

$$P = VI\cos\varphi \quad \text{"W"} \quad (1)$$

Reactive power (Q): Power merely absorbed and returned in load due to its reactive properties is referred to as reactive power. Reactive power is symbolized by the letter Q and is measured in the unit of Volt Amps reactive (VA_r);

$$Q = VI\sin\varphi \quad \text{"VA}_r\text{"} \quad (2)$$

Phase angle (φ): the angle of difference (in degrees) between voltage and current. This angle is the monitor of load behavior (resistive, inductive, or capacitive). If the phase difference is zero ($\varphi = 0$) then the load is purely resistive. If the current leads the voltage (quadrant IV operating region) then the load is inductive behavior. If the current lags the voltage (quadrant I operating region) then the load is capacitive behavior.

Complex power (S): The complex power is the vector sum of real and reactive power;

$$S = P + jQ \quad \text{"VA"} \quad (3)$$

Apparent Power ($|S|$): The apparent power is the magnitude of the complex power;

$$|S| = \sqrt{P^2 + Q^2} \quad \text{"VA"} \quad (4)$$

Both apparent and complex power quantities are symbolized by the letter S and are measured in the unit of Volt-Amps VA. Fig. 2, illustrates the relation among real, reactive, apparent, and complex power.

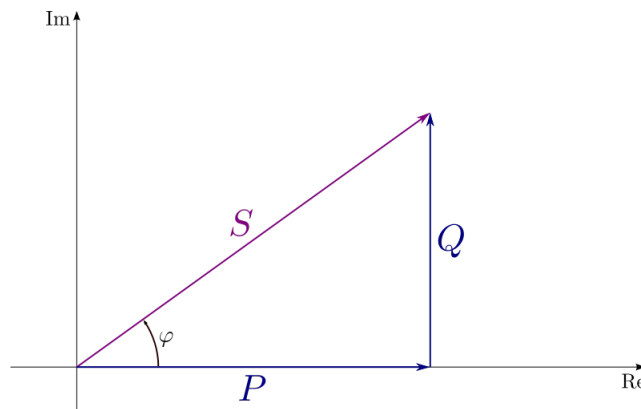


Figure 2: AC Power Relationships

2.1.2 Basic Load Definitions

Load Demand: Is the load at the receiving terminals averaged over a specified interval of time.

Demand Interval: It is the time period over which the load is averaged.

Maximum Demand: Is the greatest of all demands which occurred during a specified period of time.

Connected Load: Is the sum of the continuous ratings of the connected apparatus to the system.

Demand Factor: It is the ratio of the maximum demand of a system to the total connected load to that system.

Load Factor: It is the ratio of the average load to the peak load over a specified period of time.

Load Diversity: It is the difference between the sum of two or more individual peak loads and the peak of the combined load.

Diversity Factor: It is the ratio of the sum of individual maximum demands of various subdivisions to the maximum demand of the entire system.

Utilization Factor: It is the ratio of the maximum demand of a system to the rated capacity of the system.

Loss Factor: It is the ratio of the average power loss to the peak load power loss during a specified period of time.

2.1.3 System Buses

Swing bus (or Slack bus): It is a reference bus for which $V \angle \varphi$ typically $1.0 \angle 0^\circ$ is input data while P and Q are unknown values.

Load (PQ) bus: P and Q are input data whereas V and φ are unknown. Most buses in a typical system are load buses.

Voltage controlled (PV) bus: are buses to which generators, switched shunt capacitors, or static var systems are connected. P and V are input data while Q and φ are unknown to be computed.

Primary bus: The connection point between the TL's and the DS.

Secondary bus: Where the distributed power starts to flow towards the load.

Service entrance: The load side of the point of common coupling (PCC).

Utilization bus: The point of use where the outlet equipment is plugged in.

2.2 Voltage Instability Consequences

The following voltage stability definition is according to Definition and Classification of Power System Stability by IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, 2004: According to Prabha Kundur [5], “Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition”. Voltage instability implies an uncontrolled drop/rise in voltage triggered by a disturbance, leading to voltage regulation collapse and is primarily caused by dynamics connected with the load. There are two categories of voltage instability; voltage drop and/or rise situations. The fluctuation of the load is the main reason in the fluctuation of voltage profile in the utility grid. Voltage drop is when voltage at sending end of a distribution line is higher than the voltage at receiving end of the same line. Voltage drop usually occurs at maximum load case and in starting operation of large motors. Excessive voltage drop, significantly, impairs the starting and the operation of an electrical equipment (i.e. motors). Voltage drops could be manipulated through appropriate location of power factor correction capacitors at some buses of the distribution system. Voltage rise is opposite to voltage drop, the voltage at sending end of a distribution line is lower than the voltage at receiving end of the same line. The voltage rise is more severe when there is no demand (minimum load durations)

because all the local generation is exported back to the primary distribution substation. For PV systems, when a grid-connected inverter produces ac current, the impedance from the grid and inverter output circuit conductors causes an increase in voltage at the inverter relative to the utility voltage. This phenomenon is commonly referred to as voltage rise.

2.3 PV Type Generator System

A solar cell is a very large p-n junction (or diode). PV cells convert sunlight into electricity by an energy conversion process; photons of sunlight hit the cells, exciting electrons in the atoms of a semi-conducting material. The freed electrons go into the n-type layer while the holes go down into the p-type layer. The flow of these electrons produce a DC current. An inverter is used for AC requirements. Silicon is the most commonly used semi-conductor, due to its properties of acting like an insulator at room temperature and a conductor after providing the supply. The following are definitions to PV jargon:

- PV Module: A group of PV cells connected in series and/or parallel (as needed to reach the specific voltage and current requirements) and encapsulated in an environmentally protective laminate.
- PV Panel: A group of modules that is the basic building block of a PV array.
- PV Array: A group of panels that comprises the complete PV generating unit.
- PV Inverter: Converts DC power from the solar array into AC form.

Because of their modularity, PV systems can be designed to meet any electrical requirement. Typically, PV systems are made of the following elements:

- PV modules, cables, and mounting or fixing hardware.
- An inverter and controller.
- Batteries, back-up generators, and other components in off-grid situations.
- Special electricity meters, in the case of grid-connected systems.

Fig. 3, illustrates how solar works to convert sunlight to electricity with solar power cells. Typically, the generated power from a PV module passes through a charge controller before DC uses or AC conversion through an inverter.

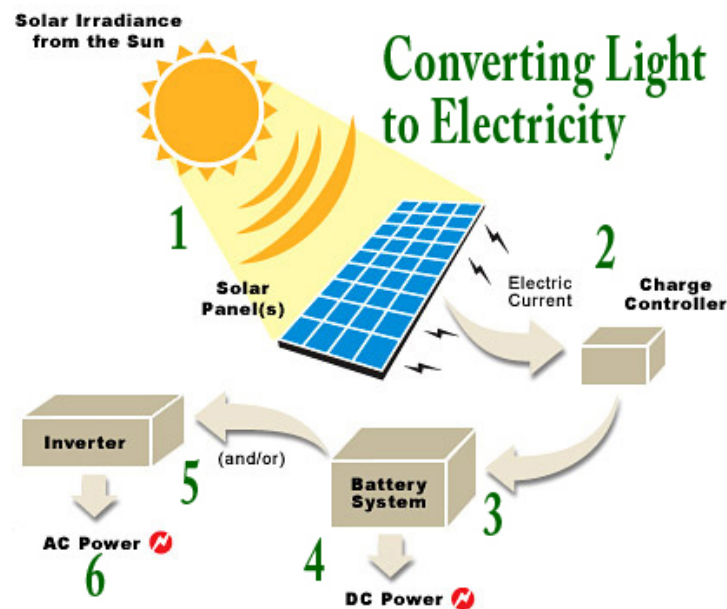


Figure 3: The process of the PV system (Courtesy of “www.TheSolarPlanner.com”)

PV panels and arrays are used in stand-alone power systems, grid-connected generation systems, and other small applications (i.e. weather stations, road signs, and parking meters). Stand-alone power system is an off-the-grid electricity system and completely independent from any electric utility grid. It is used in remote areas where distribution system is not available or more costly and complicated compared with an alternative energy system. Grid-connected generation system is connected directly to the utility grid. Unlike Stand-alone photovoltaic power systems, these systems seldom have batteries and they supply the excess power, beyond consumption by the connected load, to the utility grid. Fig. 4, illustrates an example of a grid-connected PV system, the output of a PV module has to be connected to an inverter unless a DC load is presented as seen the figure.

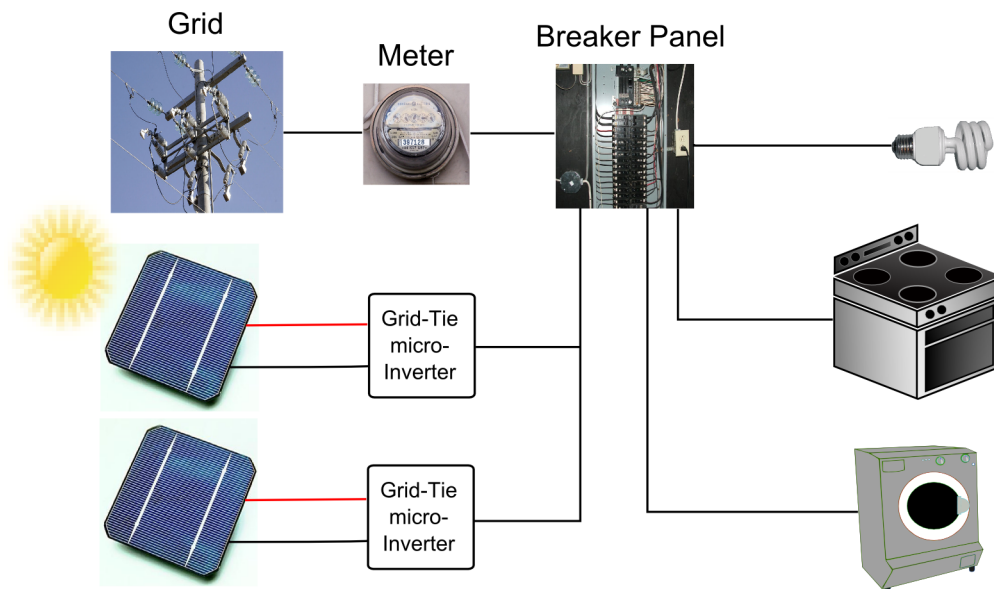


Figure 4: A residential grid-connected PV system (Courtesy of “en.Wikipedia.org”)

2.4 PV Inverter Principle

An inverter is a DC-to-AC converter which converts the variable direct current (DC) output generated from a photovoltaic (PV) solar panel into a utility frequency alternating current (AC) that can be used for AC applications or directly connected into an electrical grid network. A solar or PV inverter is a critical component in a photovoltaic system because it is designed to operate over a variable DC input voltage range in order to perform a maximum power generation process under the continuously varying solar irradiation and ambient temperature.

Standards such as IEEE 1547 and UL1741 state that the PV inverter shall not actively regulate the voltage at the PCC [3]. This means that PV inverters are designed to operate at unity power factor (net active power produced) at anytime of generation process. In reality, many inverters have the ability to regulate the voltage profile by providing/absorbing reactive power ,in addition to the generated active power by their PV modules, to/from the electrical power system because their capabilities are measured by their apparent power that combines both active and reactive power components, therefore; providing/absorbing reactive power to/from the electrical grid depends on the inverter's apparent power rating (S) and the active power (P) supplied by the PV array. Fig. 5, illustrates the reactive power limitations with respect to the total apparent power. 'Re' denotes to the real part of complex power which in turn means the active power component while 'Im' is the imaginary part or the reactive power component. The drawn semicircle in Fig. 5, with a radius S denotes to the boundary of the inverter's feasible operating range in PQ space.

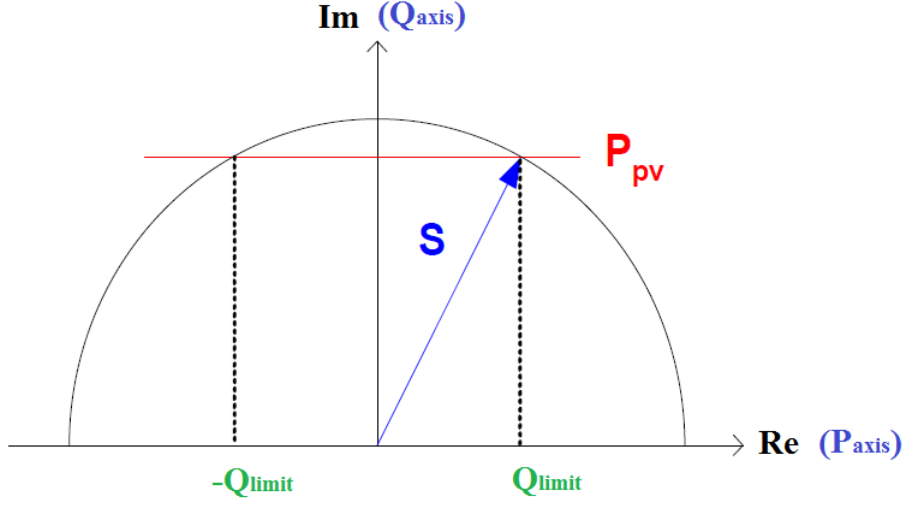


Figure 5: An inverter's reactive power limits

As shown in Fig. 5, an inverter has the ability to provide and/or absorb a specified reactive power upon its apparent power capability (S) and the power produced by a PV array (P_{PV}). To clarify this ability of providing/absorbing reactive power, let us assume for instance that an inverter's apparent power capability has been chosen for a PV system to be equal to the maximum active power that a PV system can generate from the solar irradiance, $S = P_{PVmax}$ or a unity power factor at peak time of generation. As previously mentioned in the first chapter, the energy absorption by the solar panel depends on the weather and the solar radiation that a PV system can diffuse, therefore; the power produced by a PV array (P_{PV}) varies upon the solar irradiation, i.e. the feasible operating space reduces to the red line denoted by P_{PV} in Fig. 5, but the apparent power (S) is constant. Obviously, from AC power equations;

$$Q = \sqrt{S^2 - P^2} \quad \text{"Var"} \quad (5)$$

From Fig. 5, reactive power (Q) limits are found by the intersection points of the red line segment with the semicircle, by projecting the end points of the segment down to the Q_{axis} , these points are labeled as $-Q_{limit}$ and Q_{limit} . This means that an inverter can behave as an inductor or a capacitor upon the required voltage profile (provide or absorb a reactive power). Also, an inverter can use its entire rating (S) to provide or absorb reactive power (Q) if P_{PV} equals zero (there is no sun), on the other hand, it has no Q capability if P_{PV} equals S (at P_{max} generated by a PV array).

To provide reactive power injection while supplying maximum active power from PV modules, it is necessary to increase the inverter size in order to increase the capability of its rated power. By increasing the inverter size by 5%, making $S = 1.05 P_{PVmax}$, the reactive power capability can be increased from zero to nearly 32% in the maximum PV power generation condition. This will give the power factor range of unity to 0.95 leading/lagging. The Q capacity during no sun condition is then 105%. Fig. 6, illustrates the active and reactive power capability of the inverter versus the its size.

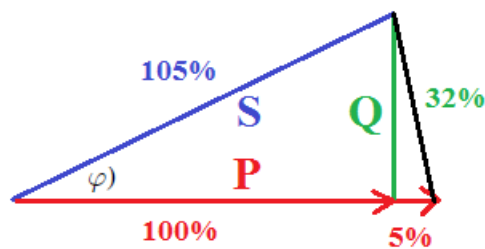


Figure 6: Relationship between inverter size and its reactive power capability

2.5 List of Acronyms

AC	Alternating Current
CIGRE (in French)	Conseil International des Grands Reseaux Electriques
CIGRE (in English)	International Council on Large Electric Systems
Δ	Delta
DC	Direct Current
DG	Distributed Generation
DS	Distribution Substation
DOE	Department of Energy
E	Expected
EHV	Extra High Voltage
GSO	Glover, Sarma, and Overbye edition
GTM	Greentech Media
GY	Grounded Star (or Grounded Wye)
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
IJRER	International Journal of Renewable Energy Research
Im	Imaginary
KV	Kilo Volt
MV	Medium Voltage
MVA	Mega Volt Ampere
MVA _r	Mega Volt Ampere reactive

MW	Mega Watt
NREL	National Renewable Energy Laboratory
PCC	Point of Common Coupling
PF	Power Factor
PU	Per Unit
PV	Photovoltaic
Re	Real
RSI	Renewable Systems Interconnection
SCB	Shunt Capacitor Bank
SEIA	Solar Energy Industries Association
TL	Transmission Line
UL	Underwriters Laboratories
WRT	With Respect To

CHAPTER 3

METHODOLOGY

3.1 Approach

This thesis develops and tests a theoretical distribution power system and examines the factors that influence the adoption and acceptance of the selected network. The following approach has been adopted in thesis:

- Selecting a representative distribution power system network from NREL study [6].
- Expanding the network to include a low-voltage service transformer and a secondary circuit.
- Loading the power system to nearly its capability with a mix of residential and commercial load in the secondary circuit.
- Modeling the network with various typical voltage support equipment such as capacitors and voltage regulators.
- Simulating the model using a simulation program with various scenarios of PV penetration levels and load profiles every 30 minutes.
- Investigating the voltage profile for each bus every 30 minutes with different PV penetration and PV inverter topology scenarios.

In this thesis, PV penetration is defined as the ratio of total peak apparent power of PV to peak load apparent power on the feeder:

$$PV\ Penetration = (Peak\ PV\ Apparent\ Power) / (Peak\ Load\ Apparent\ Power)$$

3.2 Data Gathering Method

Data gathering is an important aspect for any type of study. The choice of method is influenced by the data collection strategy, the type of variable, and the accuracy required. Regardless of the field of study or preference for defining data, accurate data collection is essential to maintaining the integrity of any study. Both the selection of appropriate data collection instruments (existing, modified, or newly developed) and clearly instructions for their correct use reduce the likelihood of errors occurring. Inaccurate data collection can impact the results of a study and ultimately leads to invalid results. In this thesis, we have used standards, previous researches, and the rule of thumb in gathering the data.

The load profiles represent a mix of residential and commercial load and were scaled with a load diversity factor of about 1.3 for each load class according to NREL study [4]. The load diversity factor is defined as the ratio of the sum of the individual maximum loads of various laterals of the system to the maximum demand of the entire distribution system. The considered load behavior in thesis was normalized to reach its maximum point at 100%. Fig. 7, shows final scaled and randomized total load profiles (residential and commercial) for a typical feeder over two consecutive days (weekday and weekend). As can be seen from Fig. 7, the load behavior is almost the same for both

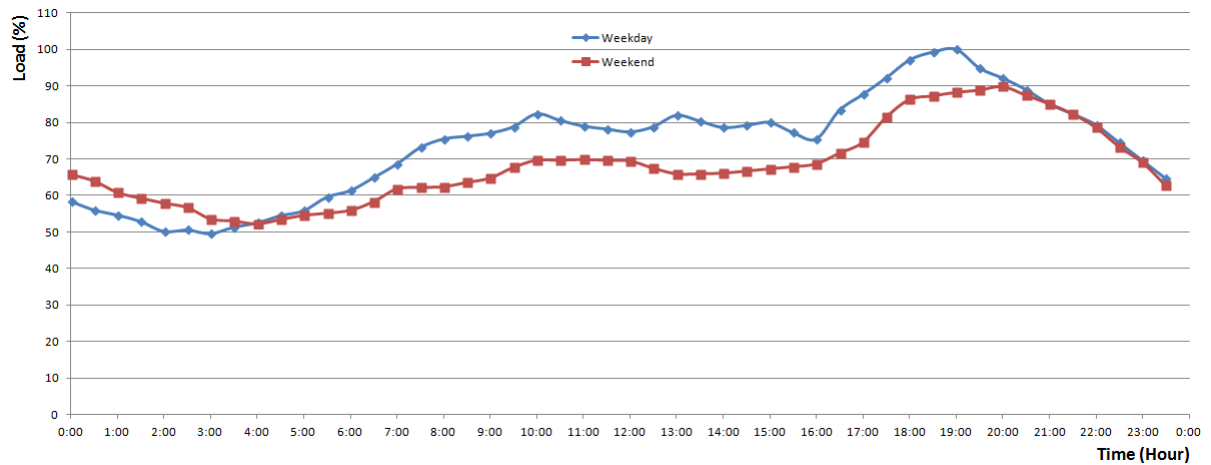


Figure 7: Weekend and weekday loads

the days (weekday and weekend). The load demands for a weekday is a little bit more with the same behavior compared to a weekend case. The load drops to its minimum demand at 3:00 AM and starts to increase till 10:00 AM then it fluctuates around almost the same demand until 4:00 PM. The load demand usually in its peak value at 7:00 PM during weekday situation, therefore; it is justifiable to study just the load behavior during weekday situation.

The amount of generated power from a PV system depends upon the intensity of the sunlight to which it's exposed. Even though the weather situation fluctuates, PV panels still produces electricity on cloudy days but less than sunny days (direct sunlight). Obviously PV panels generate no electricity at night, and less in the morning and evening compared with the middle of the day. Referred by many references and researches, PV production is generally at its optimum at approximately 7:30 AM to about 6:00 PM. As mentioned in the first chapter, a PV system is affected by the weather which leads to

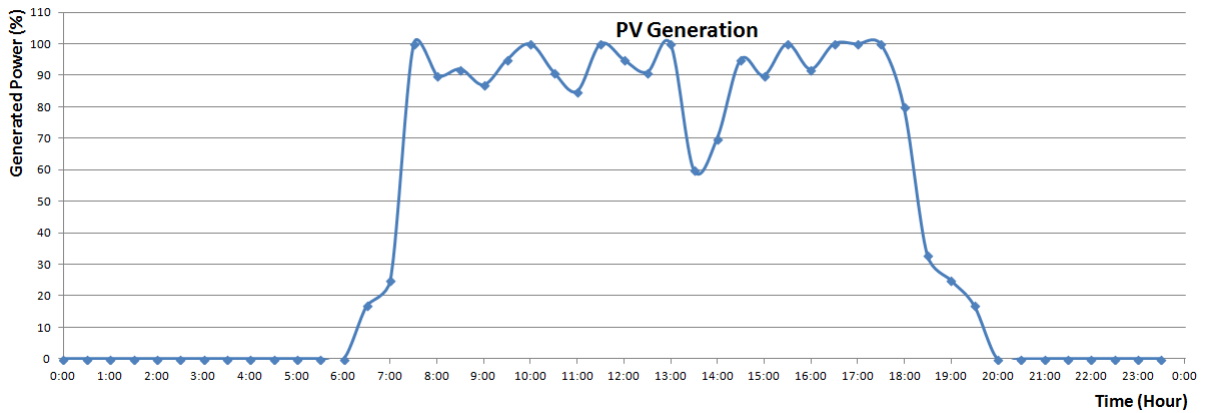


Figure 8: Anticipated PV power generation

temporarily reduce the PV capability of power generation, therefore; twilight sun and clouds were considered as the most common impacts on the generated power from PV arrays in this thesis. Fig. 8, shows anticipated PV power generation from the sun after taking minor and major cloud covers into account. The effect of clouds in the daytime depends upon cloud type and their height. Thin clouds (or minor cloud covers) obscured less sunlight so their net effect may be a slight reduction in solar radiation absorption (5 - 15% reduction of the anticipated produced power) while thick clouds (or major cloud covers) may obscured a notable amount of sun irradiation (up to 40% reduction) as seen in Fig. 8, at 1:30 PM. As shown in Fig. 8, thin clouds have been considered during different periods of time in this thesis while thick clouds is considered during one interval of time. The goal of these considerations is to take in account every possible situation that could happen during the solar generation process.

3.3 Selected Network of Study

A typical distribution system arrangement was selected from a previous NREL study [6]. The selected network includes voltage control equipment such as on-load tap-changing transformer and switched capacitors. The model was further modified and expanded to represent service transformers and secondary circuits (end-user and most likely the point of the PV inverter connection). The major assumptions were considered are:

- The considered distribution system operates in steady-state behavior and in its intended manner for voltage regulation according to utility's guidelines.
- The considered distribution system is radial and supplied by a medium-voltage transformer equipped with a tap changer.
- The distribution system consists of 39 buses; slack, primary and secondary, 18 service, and 18 utilization buses.
- The distribution system includes two main feeders with laterals and distributed loads; feeder I supplies 11 service buses while feeder II seven buses.
- The load in each bus is a mix of residential and commercial loads.
- Distribution substation protections allow active and reactive power back feed.
- The PV units are clustered at the lateral buses of feeder I as one after the other with equal magnitude upon the penetration level.
- Energy Storage devices are not considered.

- The model is suitable for examination of equipment interaction and the impact on the feeder voltage profile at different PV penetration levels.
- The selected distribution system was modeled using PowerWorld Simulator 15 GSO; the system base is 100 MVA, bus 99999 is the infinite bus and it denotes to the system swing or slack bus, bus 5 and 10 represent primary and secondary distribution substation respectively, and all the load buses are modeled as PQ buses.

Fig. 9, illustrate the voltage limits for the primary circuit, the service entrance, and utilization based on Willis standard [1]. Although some standards state that $\pm 10\%$ of voltage variations is acceptable ($\pm 5\%$ during normal operations or steady state conditions and $\pm 10\%$ during maximum and minimum load requirements), this standard has been used in thesis as the reference operating points for the voltage profile.

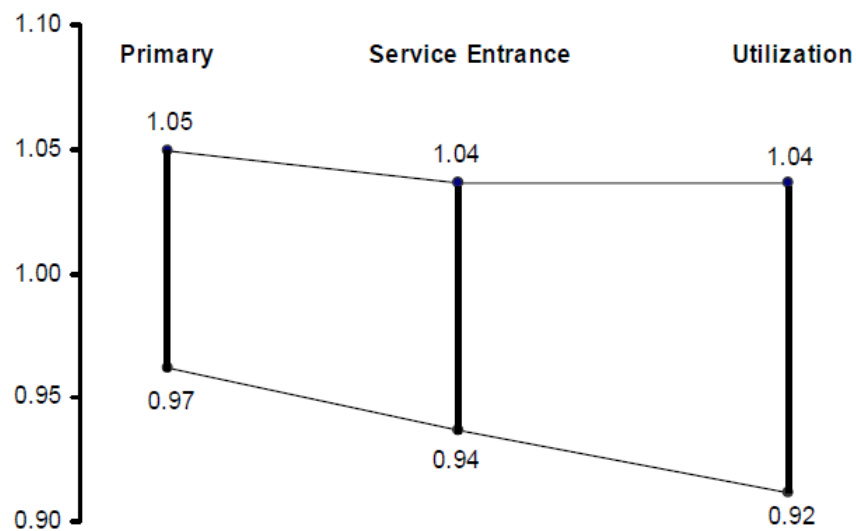


Figure 9: Voltage range limits used in this thesis according to Willis [1]

3.4 Major Component Data and Assumption

Because the resistive part (R) of a transformer impedance is very small compared with the inductive part (X), it has been neglected. Also, the susceptance (B) which denotes to the imaginary part of admittance of a transmission line is neglected. The models of the major components in this thesis were assumed to be of typical values and described as follow:

3.4.1 Transformers

The main transformer (substation transformer) was modeled as tap-changing transformer. The tap range is $\pm 10\%$ of rated and the step voltage is 0.00625. The impedance of the main transformer (69 Δ / 12.47 GY) KV is assumed as 5% on its rating with an X/R ratio of 2.5. The impedance of each service transformers (12.47 GY / 0.48 GY) KV is assumed as 2.5% [7] on its rating with an X/R ratio of 1.5. To insert the impedance for each transformer in the program, the following formulas were used to determine each impedance in PU upon the specified bases.

$$Z_0(\%) = Z_{PU(100MVAbase)} \times (MVA_{Transformerbase} \div MVA_{100MVAbase}) \times 100 \quad (6)$$

$$Z_0 = Z_{PU(100MVAbase)} \times MVA_{Transformerbase} \quad \% \quad (7)$$

$$Z_{PU(100MVAbase)} = Z_0 \div MVA_{Transformerbase} \quad PU \quad (8)$$

Table 1 shows the transformer ratings used in this distribution system.

Table 1: Transformer Ratings

From (Substation No)	To (Substation No)	Rating (MVA)
5	10	35.00
101	1001	1.50
102	1002	5.00
1021	10021	0.50
1022	10022	0.50
103	1003	1.25
104	1004	1.50
105	1005	2.50
106	1006	3.00
107	1007	0.75
108	1008	0.75
109	1009	0.50
201	2001	1.25
202	2002	1.50
203	2003	5.00
204	2004	3.00
205	2005	2.50
206	2006	2.50
207	2007	0.75

3.4.2 Transmission Lines

Table 2 shows the assumed length of each transmission line (in miles) and Table 3 illustrates the impedance for each used conductor in the transmission lines.

$$Z = |Z| \angle \tan^{-1}(X/R) \quad \text{Ohm/mile} \quad (9)$$

$$Z = |Z| \cos(\tan^{-1}(X/R)) + j |Z| \sin(\tan^{-1}(X/R)) \quad \text{Ohm/mile} \quad (10)$$

Since;

$$Z = R + jX \quad \text{Ohm/mile} \quad (11)$$

Table 2: Transmission Lines Length

From	To	Length (mile)	Conductor Type
Swing Bus	Primary Subs.	20.00	Z1
Secondary Subs.	101	1.20	Z2
101	102	0.85	Z2
102	1021	0.50	Z3
1021	1022	0.30	Z3
102	103	1.38	Z2
103	104	0.67	Z2
104	105	0.72	Z2
105	106	0.90	Z2
106	107	1.25	Z3
107	108	0.46	Z3
108	109	0.78	Z3
Secondary Subs.	201	1.30	Z2
201	202	0.65	Z2
202	203	0.65	Z2
203	204	0.97	Z2
204	205	1.10	Z3
205	206	1.10	Z3
206	207	0.48	Z3

Therefore;

$$R = |Z| \cos(\tan^{-1}(X/R)) \quad \text{Ohm/mile} \quad (12)$$

$$X = |Z| \sin(\tan^{-1}(X/R)) \quad \text{Ohm/mile} \quad (13)$$

By using the previous formulas and the given characteristics for each conductor type, the impedance components (real and imaginary parts) per mile and the total impedance for each transmission line with the given length can be found. Real and imaginary parts represent the resistance and inductance of a transmission line.

Table 3: Conductor Characteristic

	[Z] (ohm/mile)	X/R Ratio
Z1	0.366	1.73
Z2	0.648	2.00
Z3	0.768	2.00

3.4.3 Load

The load refers to the power consumed by a connected electrical equipment. The load profiles were rescaled to reach the peak (maximum value) at 100%. This was done by dividing the load in each interval of time by the peak point that the load can reach. All loads were modeled in PowerWorld program as a constant power (active and reactive) load. All loads have a power factor of 0.92, which is representative of the mixture of residential and commercial loads. Table 4 shows the maximum load for each bus.

3.4.4 Capacitor Banks

A capacitor bank is a grouping of several identical capacitors interconnected in parallel or in series with one another. Shunt capacitor banks (fixed or discrete) are mainly installed to provide capacitive reactive compensation/power factor correction. The use of SCBs has significantly increased because they are relatively inexpensive and can be easily installed anywhere on the network. Its installation has other beneficial effects on the system such as: improvement of the voltage drop at the load side, better voltage regulation (if they were adequately designed), reduction of losses and reduction or postponement of investments in transmission. Table 5 shows the provided shunt capacitors (Fixed and Discrete) and their location in the distribution system.

Table 4: The Maximum Load for each Bus

Bus Number	P(MW)	Q(MVAr)	S(MVA)
1001	1.150	0.490	1.250
1002	3.833	1.633	4.166
10021	0.400	0.170	0.435
10022	0.383	0.163	0.416
1003	1.000	0.426	1.087
1004	1.150	0.490	1.250
1005	2.000	0.852	2.174
1006	2.400	1.022	2.609
1007	0.575	0.245	0.625
1008	0.585	0.249	0.636
1009	0.377	0.161	0.410
2001	0.958	0.408	1.041
2002	1.221	0.520	1.327
2003	4.000	1.704	4.348
2004	2.400	1.022	2.609
2005	1.917	0.816	2.083
2006	2.000	0.852	2.174
2007	0.600	0.255	0.652

Table 5: Modeled Shunt Capacitors

Bus Number	Capacitor Type	Max Rating (MVAr)
102	Discrete (2 equally steps)	12.0
106	Fixed	4.5
203	Discrete (2 equally steps)	10.0
206	Fixed	3.0

3.4.5 Photovoltaic Systems

The word “photovoltaic” combines two terms; “photo” means light and “voltaic” means voltage. Basically, a PV system is an arrangement of components designed to supply usable electric power for a variety of purposes (DC and AC applications) using the sun irradiation as the power source. Grid-connected photovoltaic power systems comprise of Photovoltaic panels, solar inverters and their associated devices, protection units, and grid connection equipment. The grid-connected PV system may supply excess power, i.e. more than the connected load, to the utility grid. The PV system was modeled in PowerWorld simulator as a generator model due to unavailability of the PV system in this software. A generator can be used as a PV system in this software because of the available options of control (active and reactive power flows).

3.5 Existing Network Behavior

PowerWorld is a power system visualization, simulation, and analysis tool designed to simulate high voltage power system operation on a time frame ranging from several minutes to several days. A one-line diagram for the selected network in PowerWorld Simulator 15 GSO is shown in Fig. 10. The one-line diagram also shows the PV unit locations in the system as assumed.

Fig. 11, through Fig. 13, illustrate the voltage behavior for each utilization, service, and main substation (primary and secondary) bus in the system. Each figure demonstrates the steady state voltage profile for a specified number of buses upon the system bus type. Fig. 14, illustrates the supported reactive power via the provided shunt capacitors.

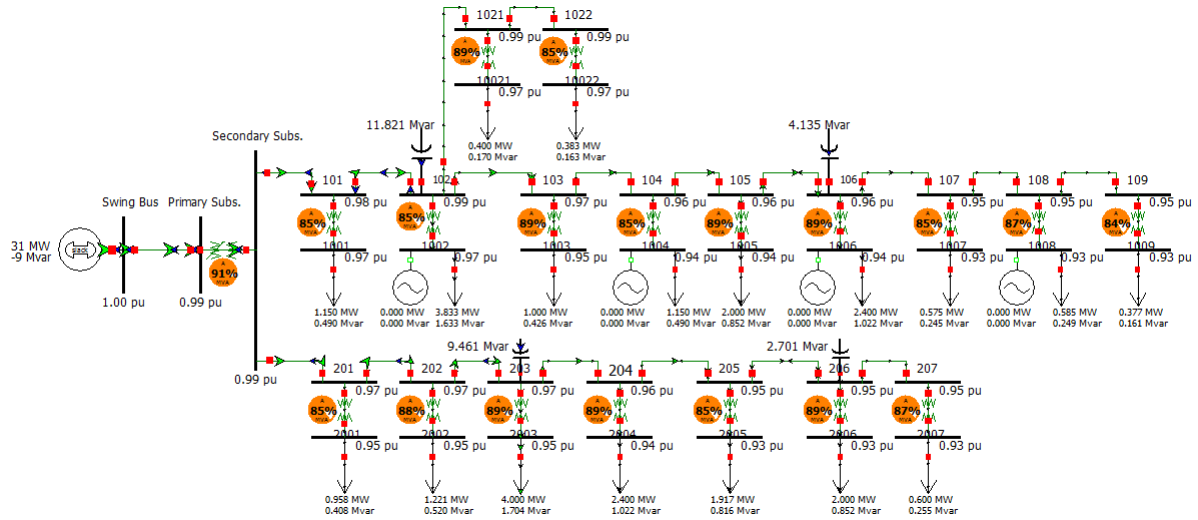


Figure 10: A One-Line Diagram of the Selected Distribution System

Obviously, the voltage profiles for all buses are directly proportional with each other, that is; any increase or decrease in the voltage profile behavior at utilization bus (where a PV system is installed) will be noted in service and main distribution (primary and secondary) buses, also vice versa is applicable.

Starting at midnight, the voltage profile increases and the load demand decreases while the provided reactive power from the shunt capacitors remains constant (4.5, 5.0, and 3.0 MVAR at 106, 203, and 206 buses respectively). This increase of voltage profile lasts till the load demand starts to increase slightly then the voltage profile decreases as soon as the load increases (voltage profile is inversely proportional with the load demand). At the time when the load demand starts to increase, the voltage profile decreases till the shunt capacitors compensate this drop and raises from 12.5 into 18.5 MVAR (6.0 MVAR at bus No. 102 is added) at 5:30 AM. The provided shunt capacitors remain constant

and the voltage profile fluctuates within the specified operating range till 8:00 AM then the provided reactive power is increased to 23.5 MVAR (10.0 instead of 5.0 MVAR at bus No 203). The voltage profile then fluctuates in a good operating range till 4:30 PM, where a change in its profile is notable, the provided reactive power via shunt capacitors is increased at 5:00 PM to 29.5 MVAR (extra 6.0 MVAR is supported at bus No 102). At 7:00 PM, the load reaches its maximum demand and as consequent the voltage profile drops but still lies within the specified operating range. At 8:30 PM the supported reactive power component starts to decrease into 23.5 MVAR at 9:00 PM. At this time, the voltage profile decreases to its minimum point of operating range (at the edge with compared with the used standard) whereas the provided reactive power through the shunt capacitors remain the same. After this peak time of demand, the load starts to decrease gradually and the voltage profile begins to improve, also, the provided reactive power is decreased slightly (in the conventional steps) till it reduced to 18.5 MVAR (6.0, 4.5, 5.0, and 3.0 MVA at 102, 106, 203, and 206 buses) at 11:30 PM.

The voltage profile for the main substation lies from 0.985 to 1.005 PU. The voltage profiles for the service buses range from 0.94 to 1.04 PU. The voltage profiles for the utilization buses vary from 0.935 to approximately 1.03 PU. From Wills standard [1], the operating ranges of the voltage profile are; 0.97 to 1.05 PU for the main substation (primary and secondary buses), 0.94 to 1.04 PU for the service buses, and 0.92 to 1.04 PU for the utilization buses. By comparing these values with the used reference standard, we found that the system works within the limited range.

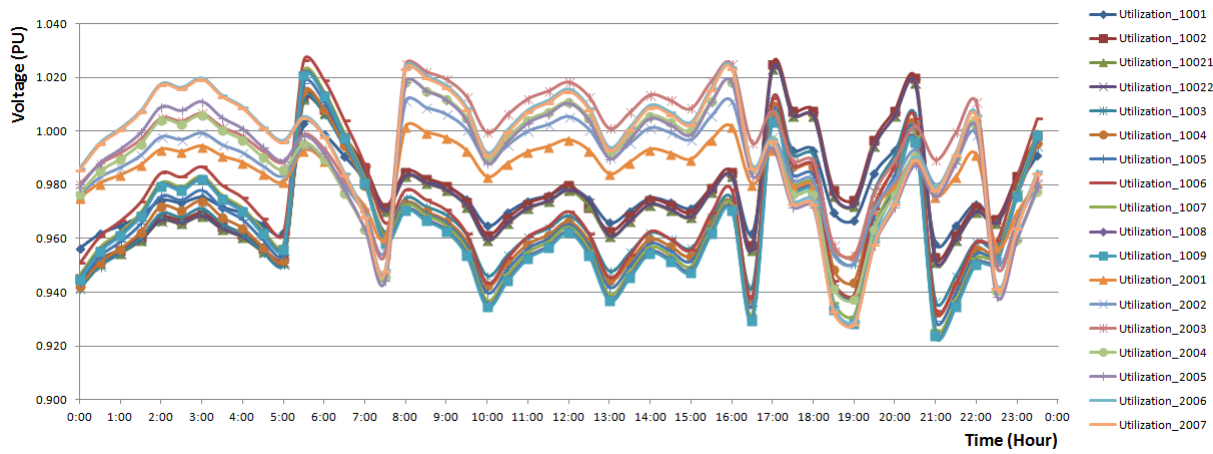


Figure 11: The Steady-State Voltage Profile - Utilization Buses (No PV Penetration)

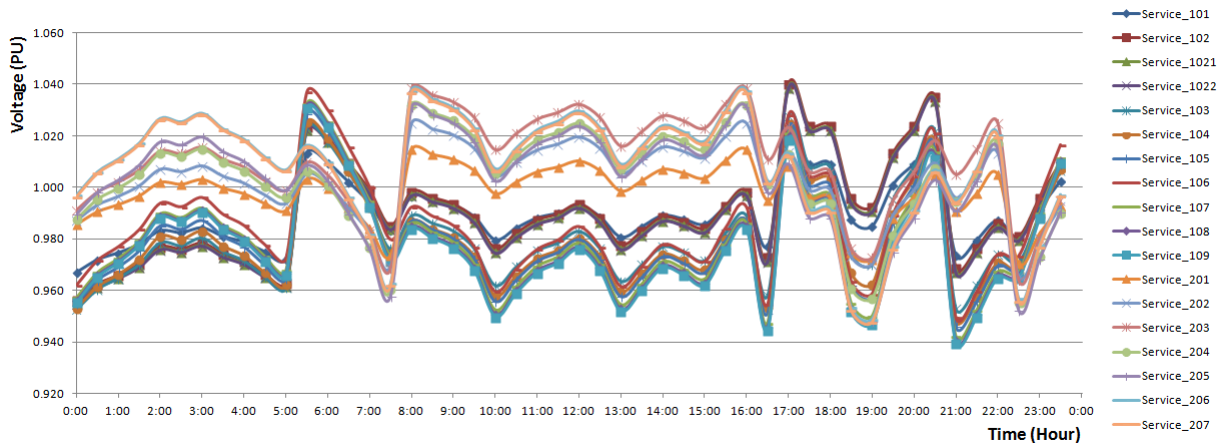


Figure 12: The Steady-State Voltage Profile - Service Buses (No PV Penetration)



Figure 13: The Steady-State Voltage Profile - Main Substation (No PV Penetration)

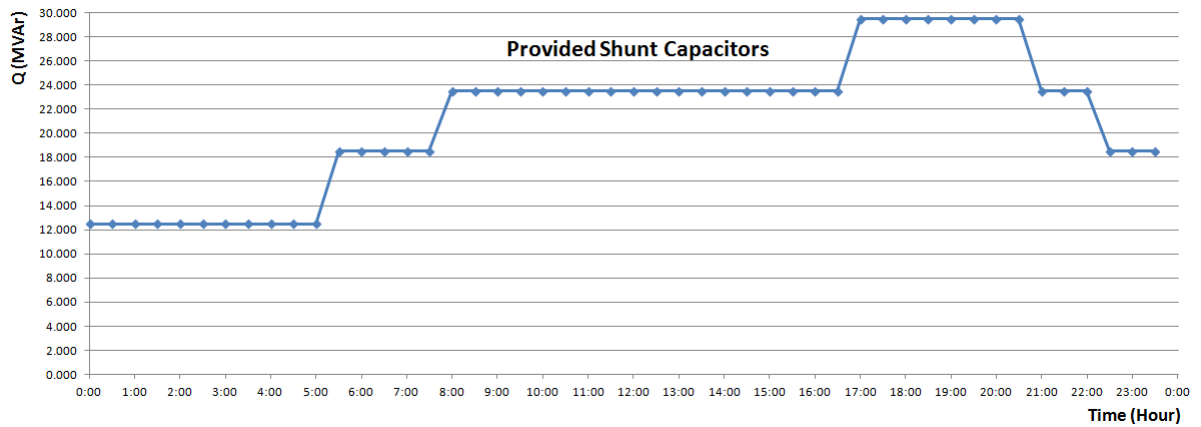


Figure 14: Provided shunt capacitors during Steady-State Conditions (No PV Penetration)

CHAPTER 4

PRESENTATION OF FINDINGS

In normal operating conditions, the feeder voltage profile decreases as the load demand on that feeder increases whereas this situation is reflected once the load demand starts to decrease and it may become higher than the voltage specified by the utility's guidelines. A baseline can be defined as a benchmark that is used as a foundation for measuring or comparing current and past values. In this thesis, a Wills standard [1] has been used as the voltage limits for the primary circuit, the service entrance, and utilization bus. We have considered four baselines in our study upon different PV inverter typologies. Each baseline has included different PV penetration levels. The PV units are connected to feeder I and therefore the penetration of PV units is limited to the total connected load of that feeder. The results were obtained in steady state conditions.

4.1 Baseline 1: $S_{PV} = P_{PV}$

In the first baseline configuration, an inverter that is compliant with IEEE 1547 and UL1741 “an inverter shall not actively regulate the voltage at the PCC” or an inverter operates at a unity power factor at anytime of generation process, has been used. This topology of operation for the inverter is considered as the worst case inverter's topology scenario because it does not provide a reactive power component. A reactive power component is an important role in controlling the active power flow through the distribution

system (it acts like a traffic light in controlling the active power flow) and it has a tremendous effect for the voltage profile of the distribution system(it raises the voltage drop in the conventional direction of power flow and minimizes the voltage rise in reverse direction of power flow). The conventional flow of power is from the distribution substation towards the load. In this baseline, three different PV penetration levels (10%, 20%, and 40%) have been discussed.

4.1.1 10% PV Penetration

The PV penetration is defined as the contribution amount of power in percentage from a PV module with respect to a specified distribution feeder's load.

$$PV_{Penetration} = (PeakPV_{ApparentPower}) / (PeakLoad_{ApparentPower})$$

A major factor in determining the impacts of PV generation is an understanding of the amount of system peak load demand that can be expected to be reduced, resulting from an ongoing uptake of PV's. In this thesis, the penetration level was taken with respect to the load on feeder I. For example, the penetration level of PV module at maximum load on feeder I is 1.5058 MVA (10% x 15.058 MVA).

Fig. 15, through Fig. 17, illustrate the voltage regulation behavior or the voltage profile for each bus in the distribution system (utilization, service, and main substation respectively) during different intervals of time. Each figure demonstrates the steady state voltage profile behavior for a specified number of buses upon the distribution system bus type. Fig. 18, illustrate the shunt capacitors provided by the system during different intervals of time (whole day).

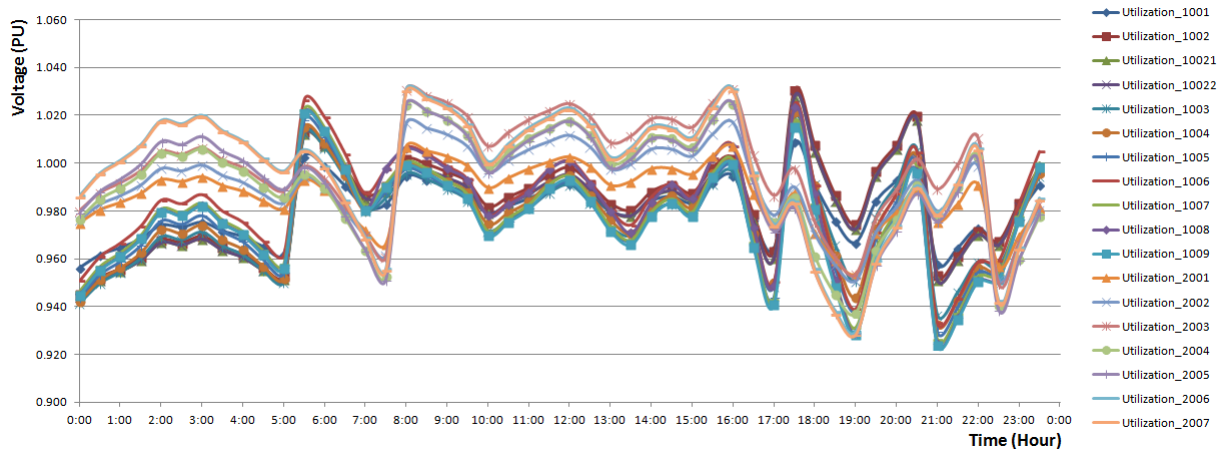


Figure 15: Baseline 1-10% PV Penetration-Utilization voltage

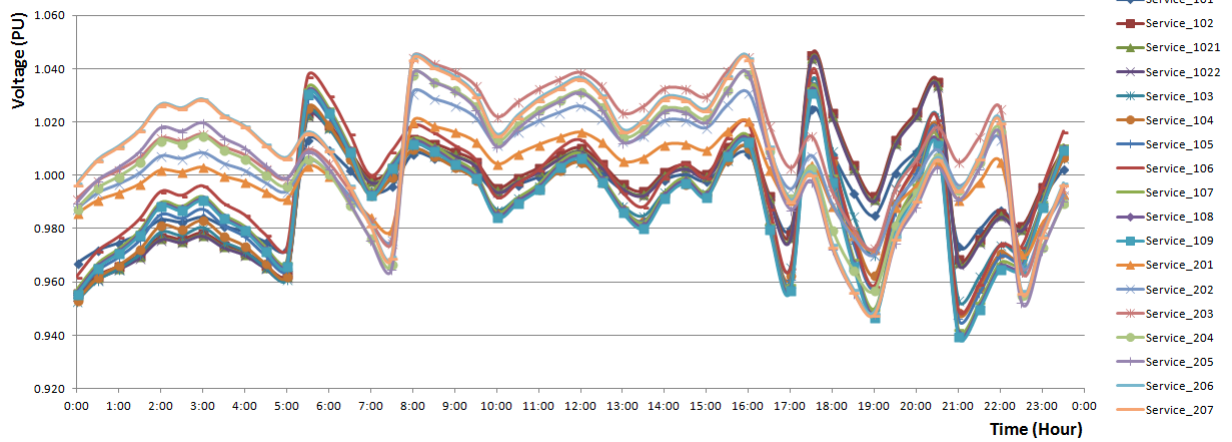


Figure 16: Baseline 1-10% PV Penetration-Service voltage

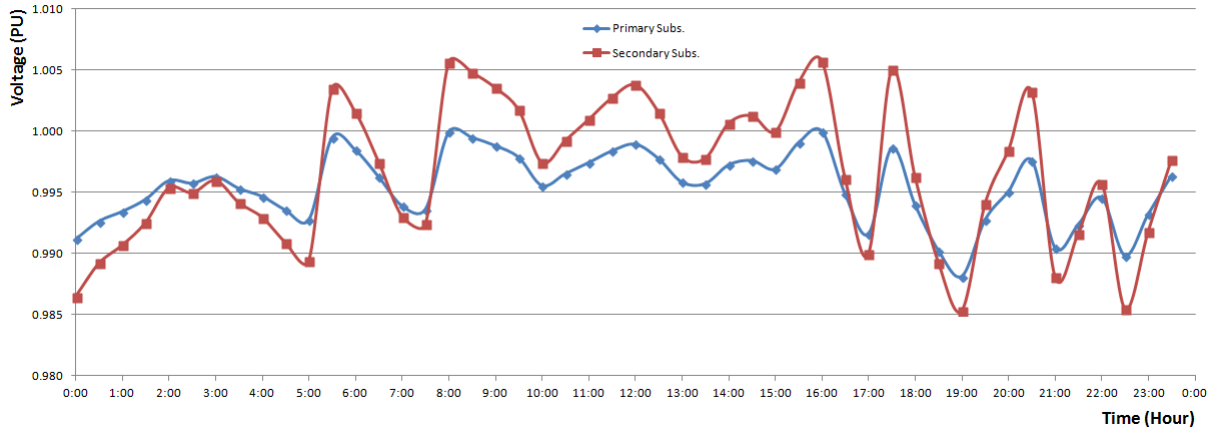


Figure 17: Baseline 1-10% PV Penetration-Main substation voltage

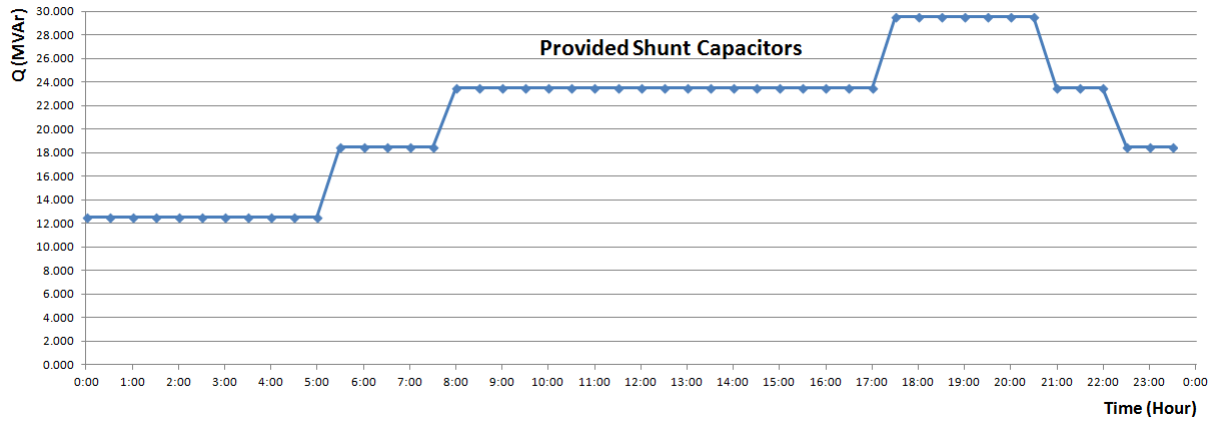


Figure 18: Baseline 1-10% PV Penetration-Provided shunt capacitors

As shown from Fig. 15, through Fig. 17, the voltage behavior for utilization buses (where PV systems are installed) are directly proportional with service and main substation buses; any increase or decrease in the voltage profile at utilization bus will result in an increase or decrease in the corresponding service bus and will have the same impact in the main substation buses (primary and secondary).

Beginning with midnight, the voltage profile increases and the load demand decreases while the supported reactive power component from the provided shunt capacitors starts at 12.5 MVar (4.5, 5.0, and 3.0 MVar at 106, 203, and 206 buses respectively). This increase of voltage profile lasts till the load demand starts to increase slightly then the voltage profile decreases as soon as the load increases (voltage profile is inversely proportional with the load demand). At the time when the load demand starts to increase, the voltage profile decreases till the shunt capacitors compensate this decrease and raises from 12.5 into 18.5 MVar (additional reactive power injection by the switched capacitor at bus No. 102 is evident from the Q jump from 12.5 into 18.5 MVar) at 5:30 AM. The provided shunt capacitors remain constant and the voltage profile gradually drops but within the specified operating range till 8:00 AM then the provided reactive power is increased to 23.5 MVar (10.0 instead of 5.0 MVar at bus No 203) to compensate the resultant voltage drop. The voltage profile then fluctuates in a good operating range till 5:00 PM, where a drop in its profile is notable, the provided reactive power via shunt capacitors is increased at 5:30 PM to 29.5 MVar (additional 6.0 MVar is supported at bus No 102). At 7:00 PM, the load reaches its maximum demand and the voltage profile drops as consequent of this increase but still lies within the specified range of operation. After

this peak time of demand, the load starts to decrease gradually and the voltage profile begins to improve until 8:30 PM, where the provided reactive power component by the system starts to decrease into 23.5 MVAR at 9:00 PM. At this time, a change in voltage profile is notable (drops to its minimum operating point compared to the specified range of operation, almost right on the edge with compared with the used standard). Finally, the provided reactive power is decreased slightly (in the conventional steps) till it reduced to 18.5 MVAR (6.0, 4.5, 5.0, and 3.0 MVA at 102, 106, 203, and 206 buses) at 11:30 PM.

The voltage profile for the main substation lies from 0.985 to almost 1.005 PU. The voltage profiles for the service buses range from approximately 0.94 to 1.045 PU. The voltage profiles for the utilization buses ranges from 0.925 to around 1.03 PU. By comparing these values with the used reference standard, the maximum operating point for the service bus voltages is a little more than the one which is specified in the used standard (+0.005 PU) but its to small and it can be neglected, so, the system works within acceptable range.

4.1.2 20% PV Penetration

Herein, the PV penetration is doubled compared with the previous case (2 x 10%). At peak load in feeder I, 15.058 MVA, the PV penetration level reaches around 3.012 MVA. Fig. 19, through Fig. 21, illustrate the voltage regulation behavior for each bus in the distribution system (utilization, service, and main substation buses) during different intervals of time. Fig. 18, illustrate the shunt capacitors provided by the system during the time.

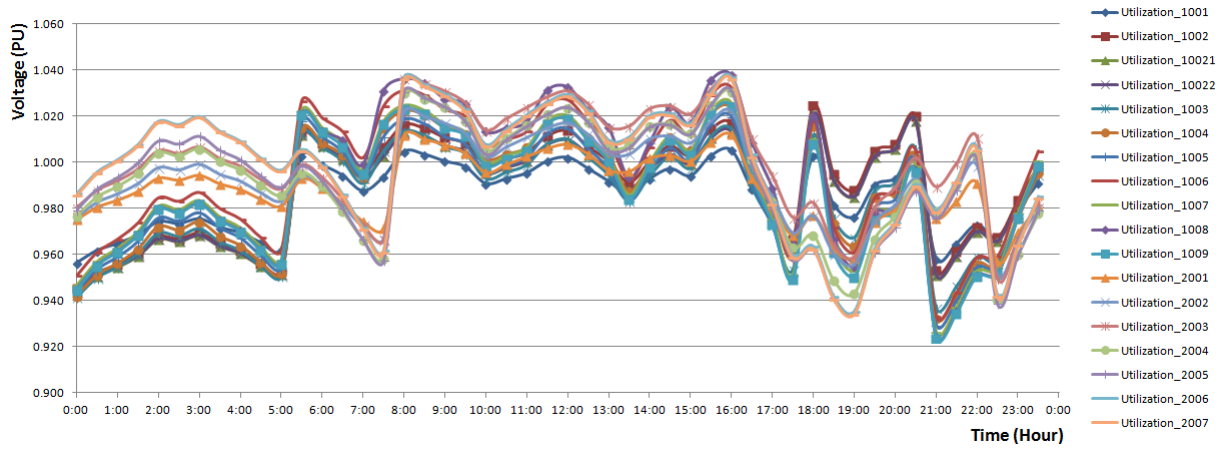


Figure 19: Baseline 1-20% PV Penetration-Utilization voltage

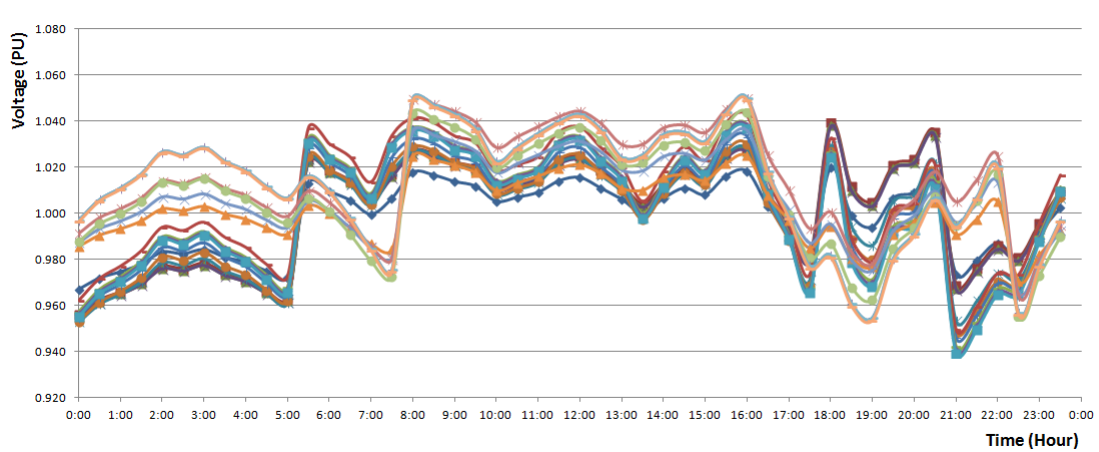


Figure 20: Baseline 1-20% PV Penetration-Service voltage

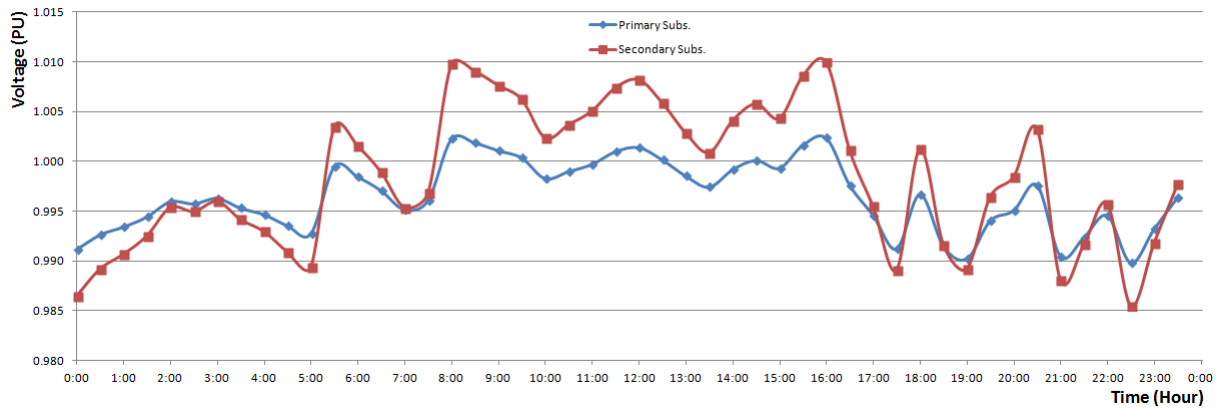


Figure 21: Baseline 1-20% PV Penetration-Main substation voltage

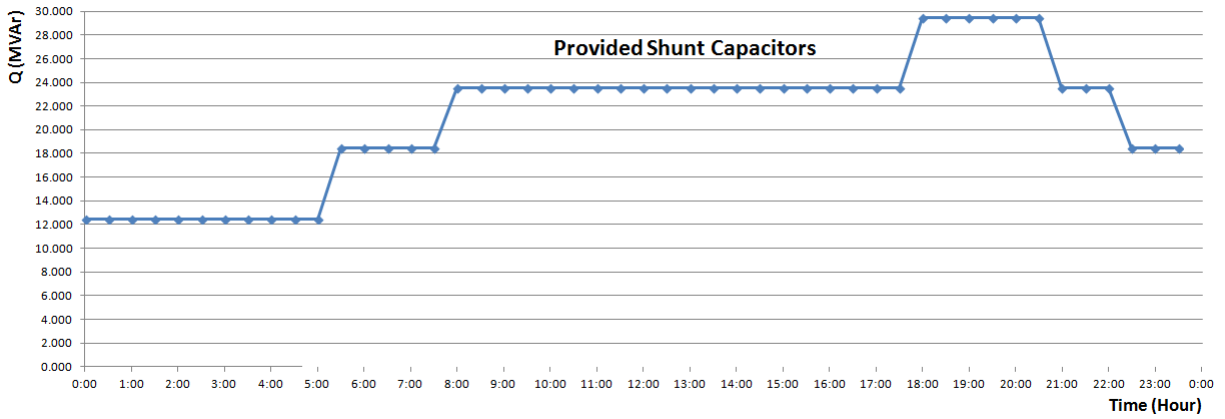


Figure 22: Baseline 1-20% PV Penetration-Provided shunt capacitors

At midnight, where the load is about 60% of peak demand, the supported reactive power component from the provided shunt capacitors is 12.5 MVAR (4.5, 5.0, and 3.0 MVAR at 106, 203, and 206 buses respectively) and the voltage profile for each bus in the distribution is within the specified operating range. The load demand decreases and the voltage profile increases gradually till around 1.02 PU (as a maximum reached point) for utilization and service buses at 2:00 AM. This behavior lasts about an hour then the voltage profile decreases while the load demand starts to increase notably. At 5:30 AM, additional reactive power is injected through bus No. 102 (6.0 MVAR) to compensate the resultant voltage drop due to the load demand rise (the load at this time reaches 60% of maximum demand). The provided shunt capacitors remain constant and the voltage profile gradually drops but within the specified operating range till 8:00 AM where a sudden jump in voltage profile is notable due to the additional injection of reactive power at bus No 203 (10.0 instead of 5.0 MVAR). This increase of the provided reactive power, a total of 23.5 MVAR, is a logically to compensate the resultant voltage drop. The voltage profile then fluctuates in a good operating range till 5:30 PM, where a drop in its profile is remarkable , the provided reactive power via shunt capacitors is increased at 6:00 PM to 29.5 MVAR (additional 6.0 MVAR is supported at bus No 102). At 7:00 PM, the load reaches its maximum demand and the voltage profile drops as consequent of this increase but still lies within the specified range of operation. After this peak time of demand, the load starts to decrease gradually and the voltage profile begins to improve until 8:30 PM, where the provided reactive power component by the system starts to decrease into 23.5 MVAR at 9:00 PM. At this time, a change in voltage profile is noteworthy (drops to its

minimum operating point compared to the specified range of operation, almost right on the edge for the utilization bus with compared to the used standard). Finally, the provided reactive power is decreased slightly (in the conventional steps) till it reduced to 18.5 MVAR (6.0, 4.5, 5.0, and 3.0 MVA at 102, 106, 203, and 206 buses) at 11:30 PM.

The voltage profile for the main substation lies from 0.985 to almost 1.01 PU. The voltage profiles for the service buses range from approximately 0.94 to 1.05 PU. The voltage profiles for the utilization buses ranges from 0.925 to around 1.04 PU. By comparing these values with the used reference standard, the maximum operating point for the service bus voltages is more than the one which is specified in the used standard (+0.01 PU). As a result, it can be accepted as a normal operation in case of considering a permitted error of $\pm 1\%$.

4.1.3 40% PV Penetration

In this case, the PV penetration at peak load is 6.023 MVA. This level of penetration is divided over four buses in equally magnitude (1002, 1004, 1006, and 1008 utilization buses). Fig. 23, through Fig. 25, illustrate the voltage regulation or the voltage profile behavior for each bus in the distribution system (utilization, service, and main substation respectively) during different intervals of time (every 30 minutes). Each figure demonstrates the steady state voltage profile behavior for the specified buses upon the distribution system bus type. Fig. 26, illustrates the provided shunt capacitors by 102, 106, 203, and 206 service buses in the distribution system during the specified intervals of time (every 30 minutes).

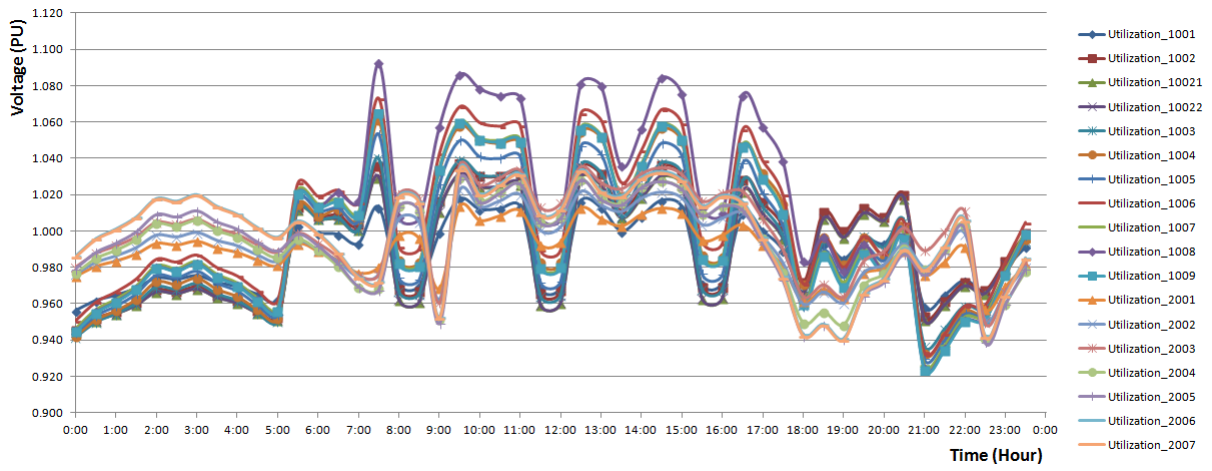


Figure 23: Baseline 1-40% PV Penetration-Utilization voltage

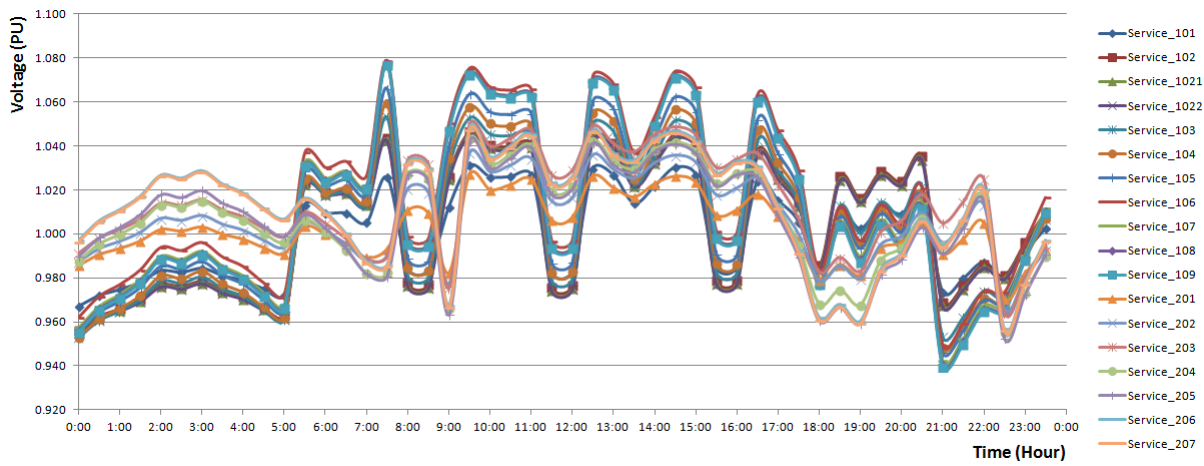


Figure 24: Baseline 1-40% PV Penetration-Service voltage

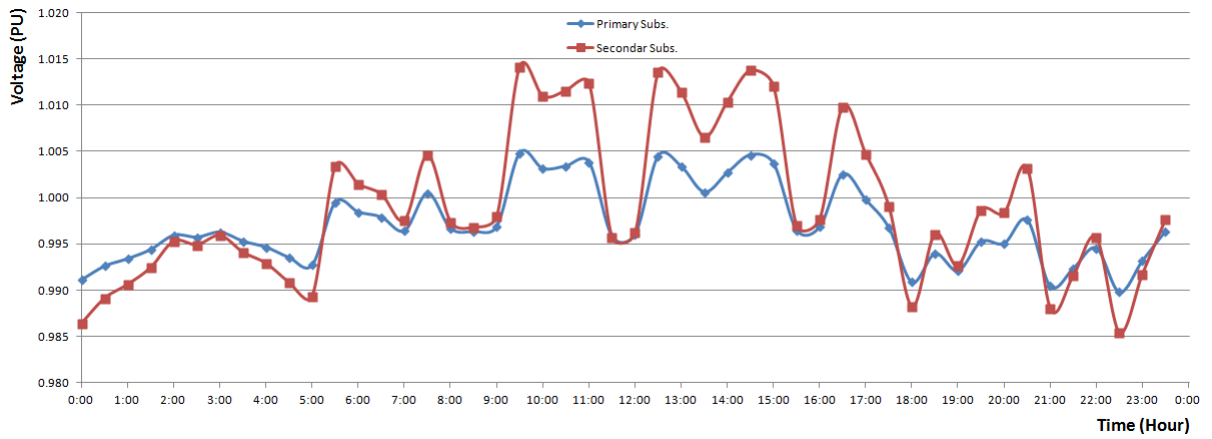


Figure 25: Baseline 1-40% PV Penetration-Main substation voltage

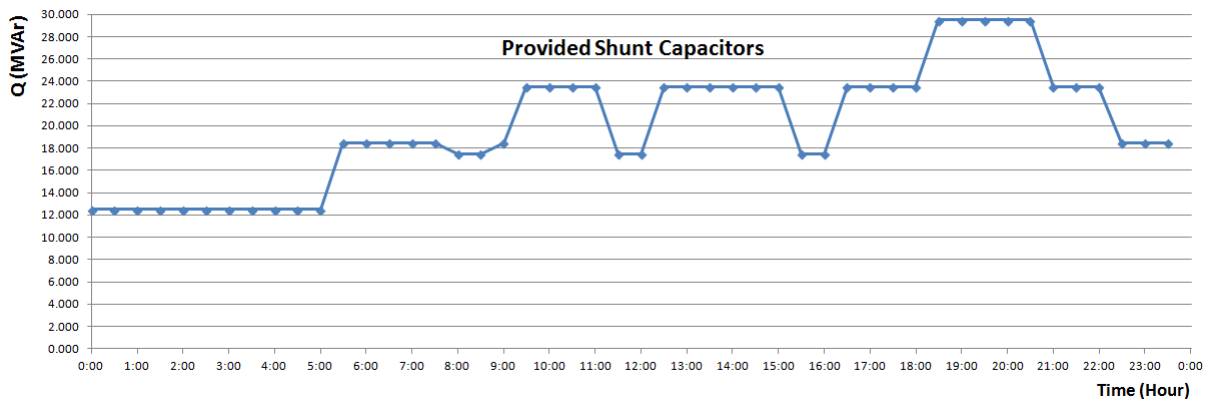


Figure 26: Baseline 1-40% PV Penetration-Provided shunt capacitors

Starting at 12:00 AM, where the load is about 60% of peak demand, the supported reactive power component from the shunt capacitors is 12.5 MVAR (4.5, 5.0, and 3.0 MVAR at 106, 203, and 206 service buses respectively) and the voltage profile for each bus in the distribution system is at the specified operating range. The load demand decreases and the voltage profile increases gradually till around 1.02 PU (as a maximum reached point) for the utilization bus and 1.025 PU for the service buses at 2:00 AM. This behavior remains almost the same for an hour then the voltage profile decreases as soon as the load demand starts to increase. At 5:30 AM, additional reactive power component is injected through bus No. 102 (6.0 MVAR) to compensate the resultant voltage drop because of the load demand rise (the load at this time reaches 60% of peak demand). The total provided shunt capacitors remain at 18.5 MVAR and the voltage profile fluctuates within the specified operating range till 7:30 AM where a sudden increase in voltage profile is notable (it reaches 1.09 PU) due to the maximum level of PV penetration in the system. After this sudden rise in voltage profile, it starts to decrease due to the minor cloud covers that reduce the PV generation but at 9:30 AM, where these covers disappear (PV level is at 95% of peak generation), additional injection of reactive power is provided through bus No. 203 (10.0 instead of 5.0 MVAR) and the voltage raises again to 1.085 PU. AT 11:30 AM, the provided reactive power is decreased to 17.5 MVAR (4.5, 10.0, and 3.0 MVAR at 106, 203, and 206 service buses respectively) and the voltage profile for each bus in the system is within the specified operating range. After an hour of this time, the supported reactive power component jumps to 23.5 MVAR (additional injection of 6.0 MVAR is injected via bus No. 102) to compensate the voltage drop occurred at 12:00 PM

but the voltage raises above the specified operating limit (it reaches 1.08 PU at 12:30 PM). The load demand is almost the same from 12:30 PM to 3:30 PM and the voltage profile fluctuates in the range of 0.96 to 1.085 PU. At 3:30 PM, the supported reactive power through the shunt capacitors drops to 17.5 MVAR and the load demand increases while the voltage profile's range diminishes (up to 1.075 PU). At 4:30 PM, the PV penetration is at its optimum (100%) and the load demand increases gradually while the reactive power component provided by the distribution system is 23.5 MVAR. After these sudden changes in network behavior, the voltage profile oscillates in a good operating range till 9:00 PM, where there is no PV penetration. At this time, a drop in voltage profile for the utilization buses (where PV systems are installed) is observable (\cong 0.92 PU, almost right on the edge) in synchronizing with the reactive power component decrease which becomes 17.5 MVAR. The voltage behavior for utilization buses is directly proportional to the voltage profile of service and main substation buses. Finally, the voltage profile is improved and the provided reactive power is decreased slightly (in the conventional steps) whereas the load demand starts to decrease. The provided shunt capacitors by the system reduced to 18.5 MVAR (6.0, 4.5, 5.0, and 3.0 MVA at 102, 106, 203, and 206 buses) at 11:30 PM.

The voltage profile for the main substation lies from 0.985 to almost 1.015 PU. The voltage profiles for the service buses range from approximately 0.94 to about 1.08 PU. The voltage profiles for the utilization buses ranges from 0.925 to a little more than 1.09 PU. By comparing these values with the used reference standard, the operating points for the utilization and service buses exceed the specified range of operation.

4.2 Baseline 2: Unity PF at P_{PVmax}

As mentioned in chapter 2, many inverters have the ability to regulate the voltage profile by providing/absorbing reactive power (in addition to the generated active power by their PV modules) to/from the electrical power system because their capabilities are measured by their apparent power that combines both active and reactive power components, the capability of the used inverter in this baseline is sized to be equal to the maximum active power generated from the PV module. This means that the inverter can supply a reactive power component to the grid in proportional to 1.0 PF at maximum P_{PV} , PF = 1.0 at P_{PVmax} . By using equation (5), the Q capacity of the PV inverter varies with time upon the absorbed energy by the PV module and can reach upto 100% in no sun conditions.

4.2.1 40% PV Penetration

Obviously, as concluded from the first baseline (the worst case for the inverter topology), a 40% of penetration level is the worst case scenario of PV systems, therefore; this penetration level has been discussed in the following baselines. The corresponding PV penetration level with respect to the peak load is 6.023 MVA (40% x 15.058 MVA) divided over the specified utilization buses (1002, 1004, 1006, and 1008 buses). Fig. 27, through Fig. 29, illustrate the voltage regulation behavior for each bus in the distribution system (utilization, service, and main substation buses) during different intervals of time (every 30 minutes). Fig. 30, illustrate the shunt capacitors provided by the distribution system (at 102, 106, 203, and 206 service buses) during the specified intervals of time.

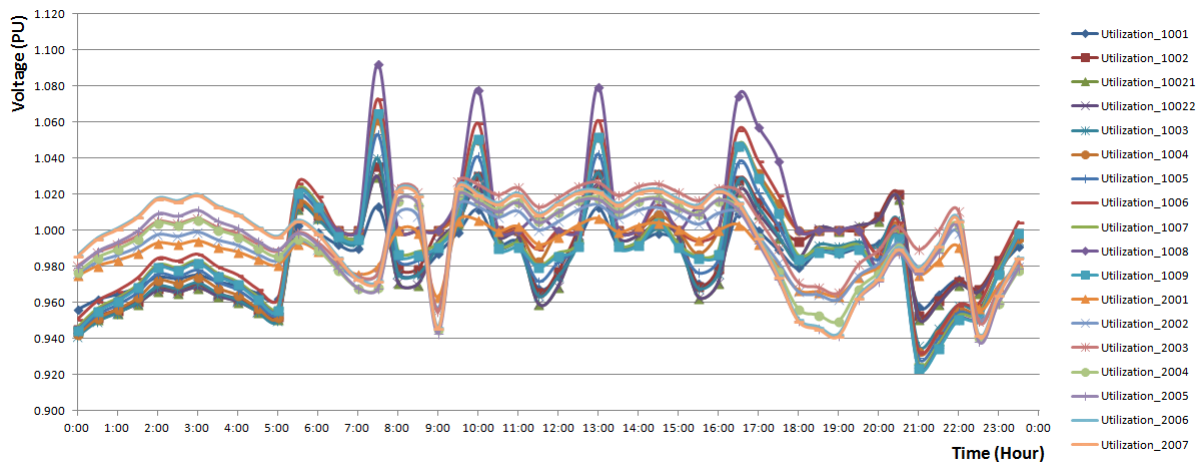


Figure 27: Baseline 2-40% PV Penetration-Utilization voltage

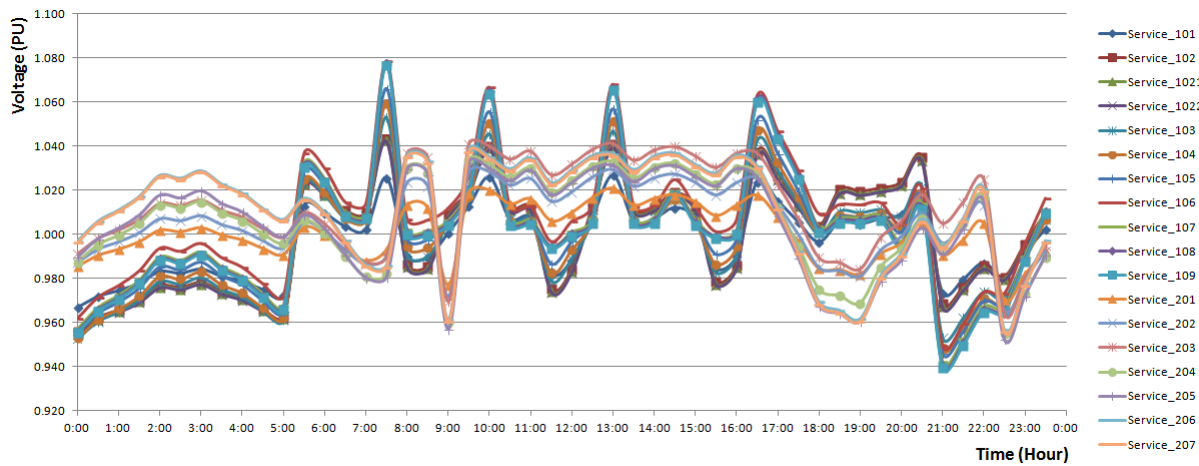


Figure 28: Baseline 2-40% PV Penetration-Service voltage

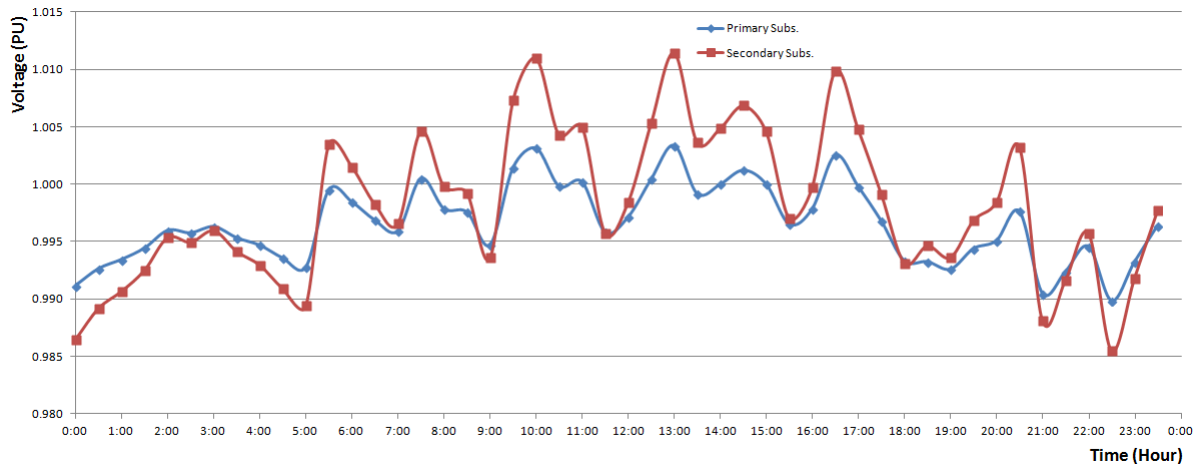


Figure 29: Baseline 2-40% PV Penetration-Main substation voltage

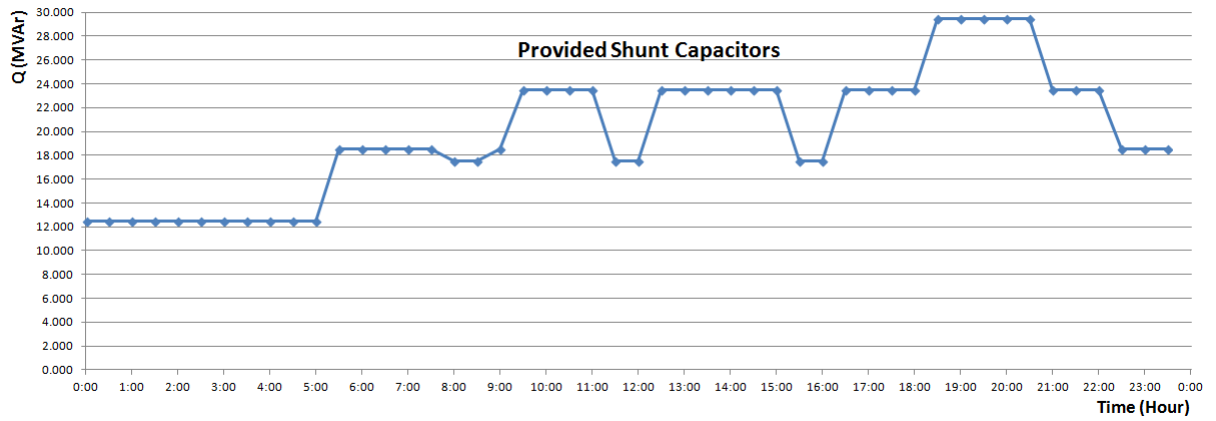


Figure 30: Baseline 2-40% PV Penetration-Provided shunt capacitors

The supported reactive power component via the distribution system is 12.5 MVAR (4.5, 5.0, and 3.0 MVAR at 106, 203, and 206 service buses respectively) at 12:00 AM, the first interval of time used in thesis, while the load demand is approximately 60% of maximum demand. Throughout this time to 5:00 AM, the voltage behavior for each bus in the distribution system ranges within the specified operating range; from about 0.94 (as a minimum operating point) to around 1.02 PU (as a maximum reached point) for the utilization buses, a little more than 0.95 to 1.03 PU for the service buses, and more than 0.98 to less than 1.00 PU for the main substation (primary and secondary buses), and the load demand fluctuates in the range of 55% to 60% of the peak demand (off-peak load). At 5:30 AM, the load demand starts to increase gradually and as a consequence of this rise, additional reactive power component is provided through 102 service bus (6.0 MVAR) to keep the voltage within the specified operating points. The total provided shunt capacitors by the distribution system becomes 18.5 MVAR. The voltage profile fluctuates within the specified operating range till 7:30 AM where a sudden increase in voltage profile is remarkable (it exceeds 1.09 PU) due to the peak penetration of the PV modules in the distribution system. The PV penetrations vary upon the weather situations (minor cloud covers effects which reduce the penetration level by 5 - 15% of the anticipated power generation) and therefore the voltage behavior follows these variations. At 9:30 AM, additional injection of reactive power is provided through bus No. 203 (10.0 instead of 5.0 MVAR) to compensate the resultant voltage drop and the PV level is at 95% of peak generation. The provided reactive power is decreased to 17.5 MVAR (4.5, 10.0, and 3.0 MVAR at 106, 203, and 206 service buses respectively) and the voltage profile for each

bus in the system is within the specified operating range at 11:30 AM. About an hour of time interval, upto 12:30 PM, the voltage regulation lies within the operating point and the supported reactive power components by the system remain the same. An additional reactive power of 6.0 MVAR is injected at 12:30 PM via bus No. 102, a total of 23.5 MVAR is provided by the shunt capacitors, to compensate the occurred voltage drop and to keep it within the specified operating points. The load demand is almost the same from 12:30 PM to 3:30 PM and the voltage profile fluctuates in the range of 0.96 to 1.08 PU. At 3:30 PM, the supported reactive power through the shunt capacitors drops to 17.5 MVAR to keep the voltage profile in the operating range and the load demand increases gradually. At 4:30 PM, the penetration level of PV systems is at maximum point (100%) and the load demand starts to increase gradually while the reactive power component provided by the distribution system is 23.5 MVAR. The voltage behavior fluctuates in a good operating range till 9:00 PM, where there is no PV penetration, then it drops to its minimum operating point (almost \cong 0.92 PU which is the edge point of limited range) as a response to the drop in the provided reactive power component which becomes 17.5 MVAR. Finally, the voltage profile is improved and the provided reactive power is decreased slightly whereas the load demand starts to decrease. The provided shunt capacitors by the system reduced to 18.5 MVAR at 11:30 PM.

The voltage profile for the main substation lies from 0.985 to almost 1.01 PU. The voltage profiles for the service buses range from approximately 0.94 to about 1.08 PU. The voltage profiles for the utilization buses ranges from 0.925 to a little more than 1.09 PU. As a result, the voltages for the utilization and service buses exceed the limit.

4.3 Baseline 3: 0.95 PF WRT P_{PV}

In this baseline, the capability of the used inverter is sized to be 105% of the maximum active power produced from the PV module, that is; the reactive power capability is increased from zero to nearly 32% at the maximum PV power generation condition compared with the previous baseline (baseline 2). This means that the inverter topology for providing a reactive power component to the grid is directly proportional to the active power generated from the PV module with a 0.95 leading/lagging power factor (the inverter can behave as both an inductor "absorb a reactive power component" and a capacitor "provide a reactive power component" upon the required voltage profile). The Q capacity during no sun condition for the inverter is then 0% (because Q is proportional to the generated P from the PV system).

4.3.1 40% PV Penetration

As mentioned before, a 40% of penetration level is corresponding to 6.023 MVA with respect to the peak load demand and divided over the specified utilization buses (1002, 1004, 1006, and 1008 buses) in equally magnitude. Fig. 31, through Fig. 33, illustrate the voltage regulation behavior for each bus in the distribution system (utilization, service, and main substation buses) during different intervals of time (every 30 minutes). Each figure demonstrates the steady state voltage profile behavior for the specified buses upon the distribution system bus type. Fig. 34, illustrate the provided shunt capacitors by the distribution system (at 102, 106, 203, and 206 service buses) during different intervals of time (whole day in a step of 30 minutes).

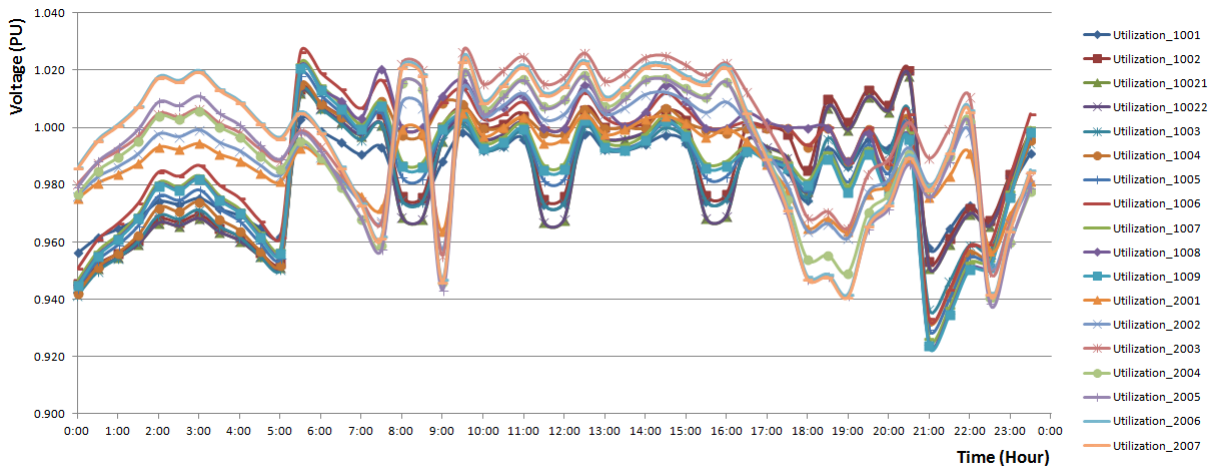


Figure 31: Baseline 3-40% PV Penetration-Utilization voltage

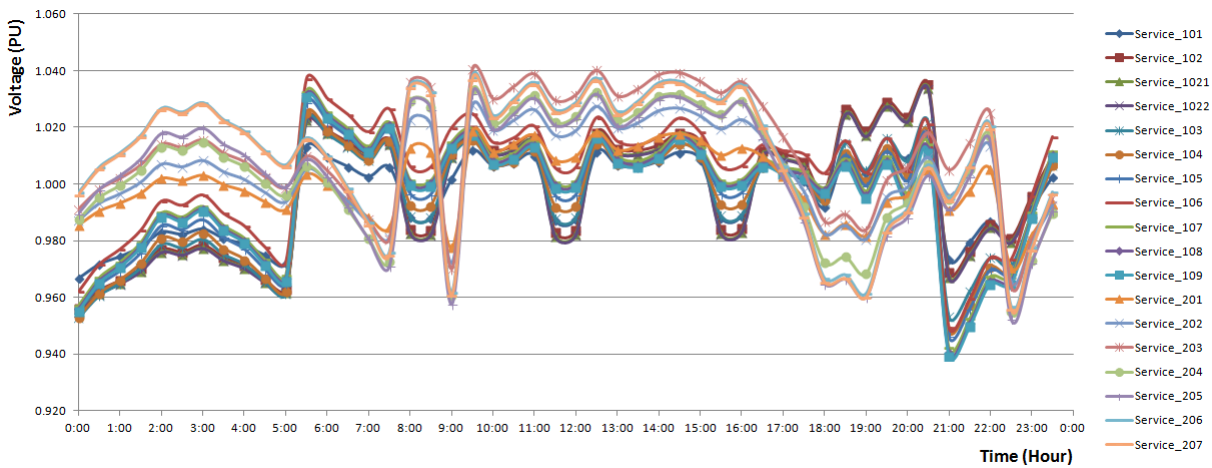


Figure 32: Baseline 3-40% PV Penetration-Service voltage

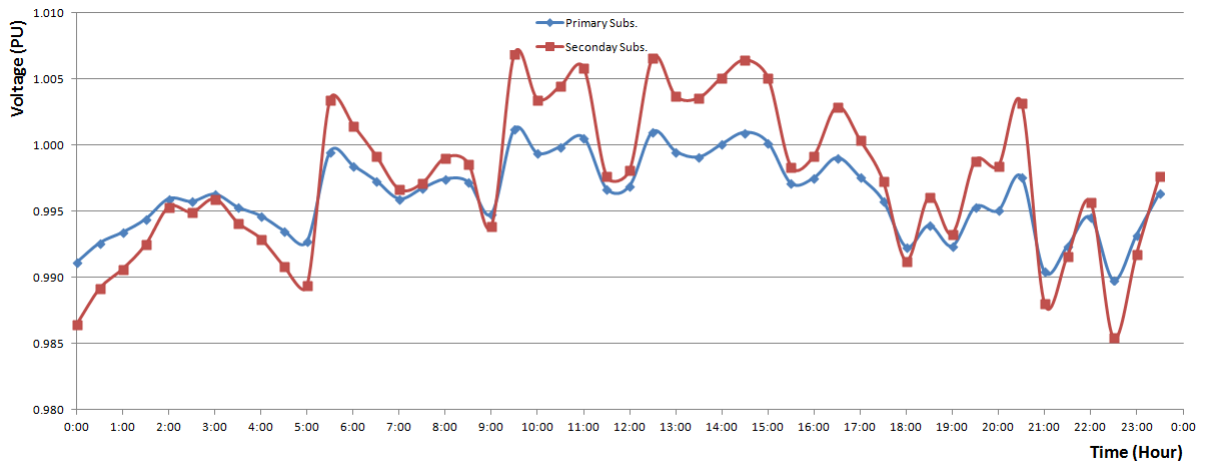


Figure 33: Baseline 3-40% PV Penetration-Main substation voltage

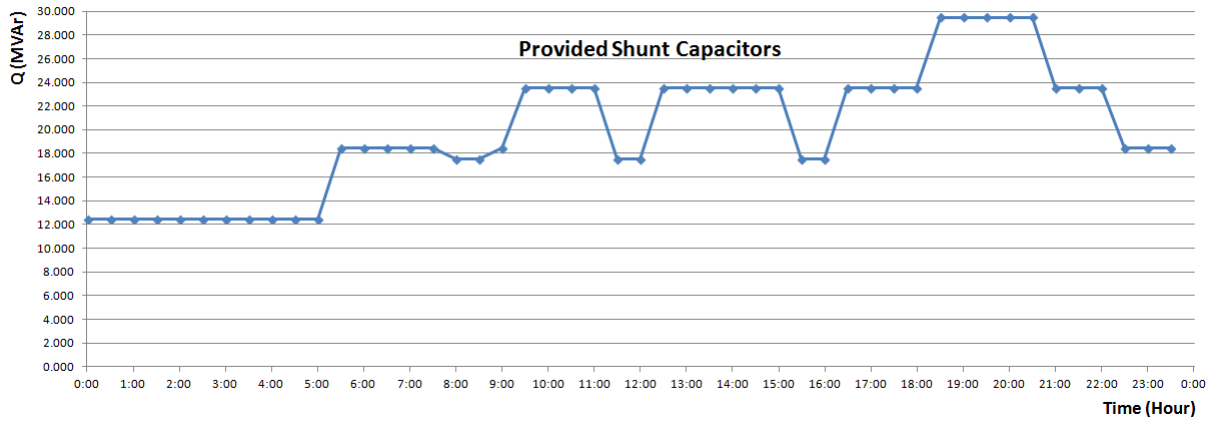


Figure 34: Baseline 3-40% PV Penetration-Provided shunt capacitors

The Q injection via the provided shunt capacitors, which are installed at 102, 106, 203, and 206 service buses, is exactly the same as the previous two baselines (baseline 1 and 2), starts with 12.5 MVAR and ends with 18.5 MVAR with identical steps as mentioned (2 fixed capacitors, 4.5 and 3.0 MVAR at 106 and 206 service buses respectively, and 2 discrete capacitors, 12.0 and 10.0 MVAR at 102 and 203 service buses in 2 equally steps each). The main purpose of the shunt capacitors is to compensate the drop in voltage profile and they are considered as the simplest and inexpensive way for the power factor correction.

In contrast with the provided reactive power through the shunt capacitors, the voltage profile for each bus in the system (utilization, service, and main substation buses) lies within the specified operating range compared with the previous baselines (1 and 2). For utilization and service buses, the minimum voltage magnitude occurred 9:00 PM while for the main substation (primary and secondary) is at 10:30 PM. The maximum reached point of operation to the voltage profile for the utilization, service, main substation buses occurred at 9:30 AM.

The voltage profile for the main substation lies from 0.985 to a little more than 1.00 PU. The voltage profiles for the service buses range from approximately 0.94 to 1.04 PU, right on the edge compared with the reference standard. The voltage profiles for the utilization buses ranges from 0.925 to almost 1.025 PU. As a result, the voltage profile for each bus in the system (utilization, service, and main substation "primary and secondary" buses) is within the specified limit of operation and therefore, the distribution system works well in the intended manner of voltage stability.

4.4 Baseline 4: 0.95 PF WRT S_{PV}

In this baseline, the capability of the used inverter is sized to be 105% of the maximum active power produced from the PV module, that is; the reactive power capability is increased from zero to nearly 32% at the maximum PV power generation condition as in baseline 3 except that the inverter topology for providing a reactive power component to the grid is directly proportional to the apparent power of the inverter. This means that the inverter has the ability provide/absorb the reactive power component with a power factor ranges from unity to 0.95 leading/lagging (the inverter can behave as both an inductor "absorb a reactive power component" and a capacitor "provide a reactive power component" upon the required voltage profile). The Q capacity during no sun condition for the inverter is then 105% (because Q is proportional to the inverter's apparent power).

4.4.1 40% PV Penetration

Herein, 40% of PV penetration with respect to the maximum load is 6.023 MVA (40% x 15.058 MVA). Fig. 35, through Fig. 37, illustrate the voltage regulation behavior for each bus in the distribution system (utilization, service, and main substation buses) during different intervals of time (every 30 minutes). Each figure demonstrates the steady state voltage profile behavior for the specified buses upon the distribution system bus type. Fig. 38, illustrate the shunt capacitors provided by the system during different intervals of time (every half an hour). The shunt capacitors are installed in four service buses (at 102, 106, 203, and 206 buses) whereas the PV systems are located on four utilization buses (1002, 1004, 1006, and 1008 buses) in equally magnitude.

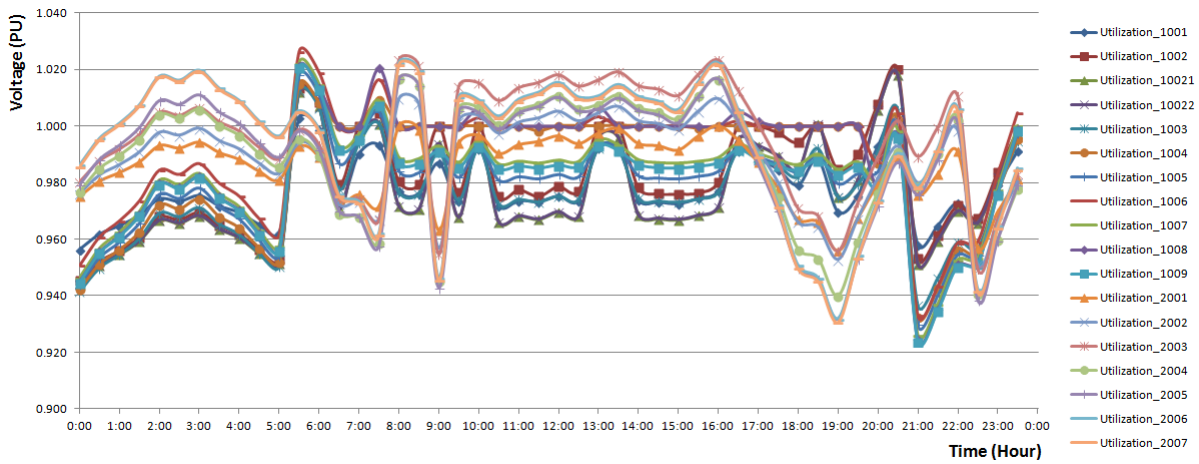


Figure 35: Baseline 4-40% PV Penetration-Utilization voltage

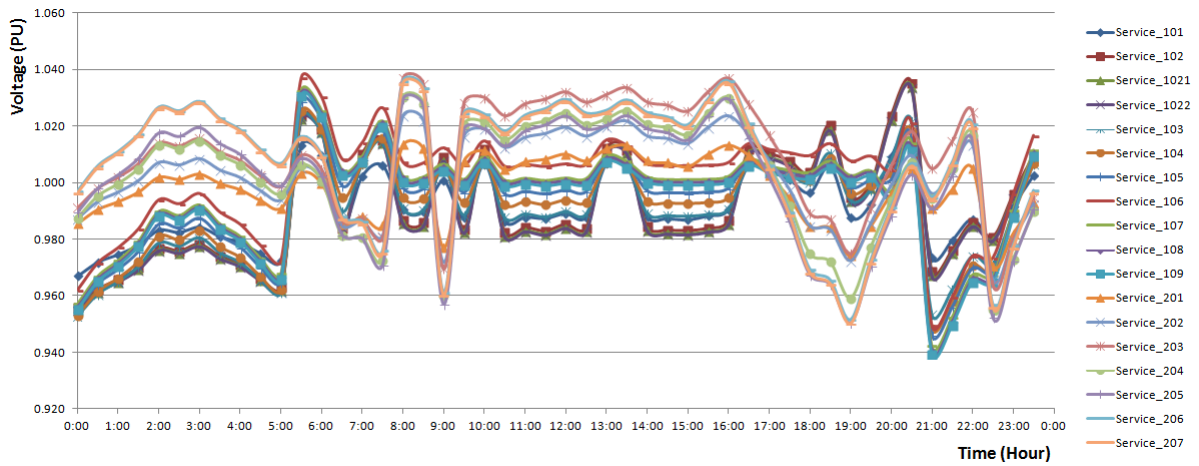


Figure 36: Baseline 4-40% PV Penetration-Service voltage

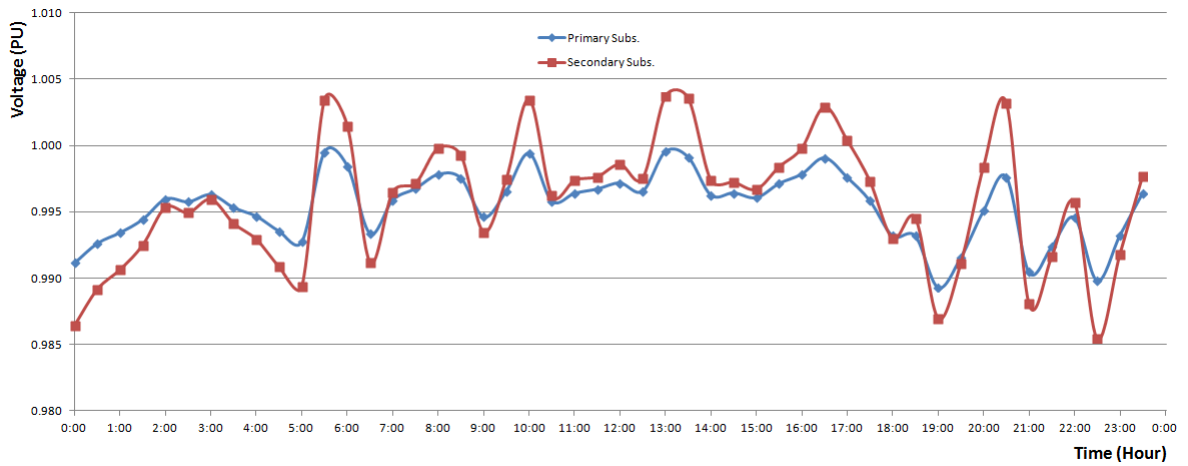


Figure 37: Baseline 4-40% PV Penetration-Main substation voltage

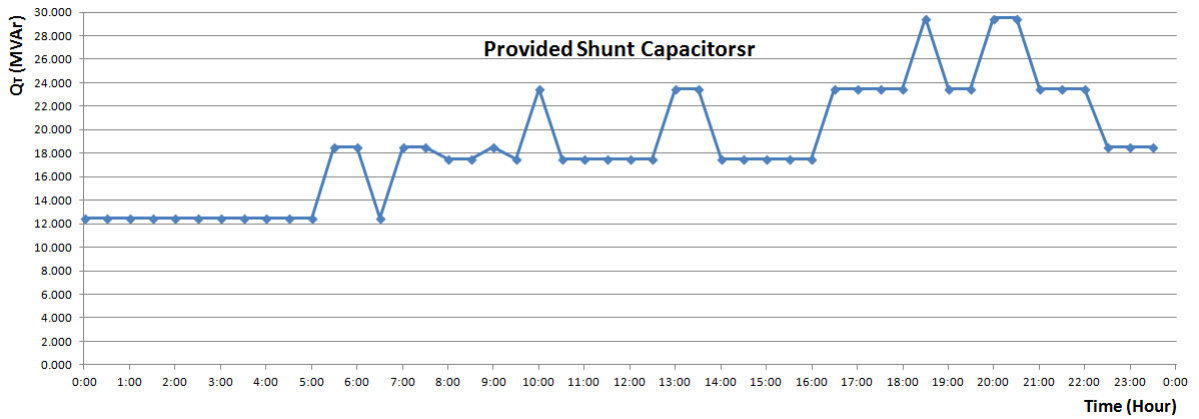


Figure 38: Baseline 4-40% PV Penetration-Provided shunt capacitors

4.5 Summary of Findings

Table 6 summarizes the provided reactive power components via the shunt capacitors throughout the actual load and the four baselines (in case of 40% penetration level of PV systems). The used shunt capacitors are classified into two categories: fixed capacitors at 106 and 206 service buses, and discrete capacitors with two equally steps at 102 and 203 service buses.

Table 6: Actual load and baselines comparison for the supported capacitors

Time (Hour)	Actual Load Q (MVar)	Baseline 1 Q (MVar)	Baseline 2 Q (MVar)	Baseline 3 Q (MVar)	Baseline 4 Q (MVar)
12:00 AM	12.5	12.5	12.5	12.5	12.5
5:30 AM	18.5	18.5	18.5	18.5	18.5
6:30 AM	18.5	18.5	18.5	18.5	12.5
7:00 AM	18.5	18.5	18.5	18.5	18.5
8:00 AM	23.5	17.5	17.5	17.5	17.5
9:00 AM	23.5	18.5	18.5	18.5	18.5
9:30 AM	23.5	23.5	23.5	23.5	17.5
10:00 AM	23.5	23.5	23.5	23.5	23.5
10:30 AM	23.5	23.5	23.5	23.5	17.5
11:30 AM	23.5	17.5	17.5	17.5	17.5
12:30 PM	23.5	23.5	23.5	23.5	17.5
1:00 PM	23.5	23.5	23.5	23.5	23.5
2:00 PM	23.5	23.5	23.5	23.5	17.5
3:30 PM	23.5	17.5	17.5	17.5	17.5
4:30 PM	23.5	23.5	23.5	23.5	23.5
5:00 PM	29.5	23.5	23.5	23.5	23.5
6:30 PM	29.5	29.5	29.5	29.5	29.5
7:00 PM	29.5	29.5	29.5	29.5	23.5
8:00 PM	29.5	29.5	29.5	29.5	29.5
9:00 PM	23.5	23.5	23.5	23.5	23.5
10:30 PM	18.5	18.5	18.5	18.5	18.5

Fig. 39, illustrates a comparison for the provided shunt capacitors among the actual load and the four baselines. Obviously, the provided reactive power throughout baselines 1, 2, and 3 are identical while in baseline 4 differs. This means that the power loss during the 4th baseline is reduced compared with the previous baselines. The voltage behaviors in baselines 3 and 4 are almost the same. The voltage profile for the utilization buses in baselines 3 and 4 lie in the range of 0.924 to 1.026 PU. The voltage profile for the service buses is in the range of 0.94 to 1.04 PU (in baseline 4, the maximum reached point is 1.037 PU). For the main substation, the minimum operating point of voltage profile is 0.985 PU while the maximum one fluctuates around 1.00 PU (a little more in baseline 3 compared with baseline 4). As a result, the inverter topologies used in both baselines 3 and 4 improve the voltage profiles because of their capabilities of providing/absorbing the reactive power component even though a different PF has been used in each scenario.

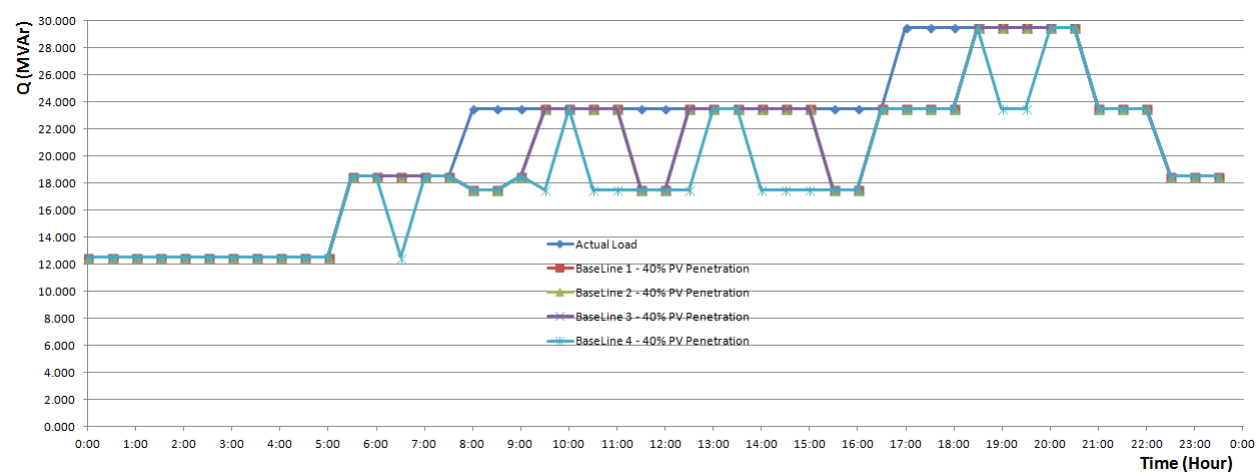


Figure 39: Comparison to the provided capacitors during actual and used baselines

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this thesis, a representative distribution system arrangement was selected from a NREL study [6]. The selected network includes voltage control equipment such as on-load tap-changing transformer and switched capacitors. The model was further modified and expanded to represent service transformers and secondary circuits (end-user and most likely the point of the PV inverter connection). The selected distribution system was modeled using PowerWorld Simulator 15 GSO after considering the major assumptions were described in chapter 3. The network was used for analyzing the impact of different penetrations of PV on the voltage profiles for each bus in the system. Four baselines were used upon different inverter topology and penetration scenarios of PV levels. The following summarizes the conclusions of this study:

- The study results show that the level of PV penetration depends on the feeder load profile, the inverter power factor capability, and the voltage operating points.
- The studies have shown that the level of penetration upto 20% is acceptable.
- The rule of thumb of maximum of 15% penetration is not valid assumption and the actual penetration level dependent in the individual feeder load profile, the inverter reactive power capability, and the voltage operating points.

5.2 Recommendations

With respect to reactive power supply to the system, PV inverters are disadvantaged because their capabilities of reactive power injections are limited by either apparent or generated active power from PV units. This can be resolved by coordinated control of utility equipment and inverters, also, the inverters reactive power capabilities might be needed during no sun conditions to improve the voltage profiles at some buses. This study illustrates several such cases, inverter topologies and PV penetration levels, but it is limited to one distribution feeder, a more comprehensive coverage of feeder profiles would be beneficial. Islanding refers to the condition of a DG generator that continues to feed the circuit with power, even after power from the electric utility grid has been cut off. Distributed generators must detect islanding and immediately stop feeding the utility lines with power, this is known as anti-islanding. The following summarizes the recommendations for future work in this field:

- Extend to include more feeder, load, and PV profiles, so that better rule of thumbs based on feeder loads and impedances can be formed without a detailed impact study can be formed.
- This study only considered the steady state performance of PV systems; the dynamic performance of PV system such as: frequency regulation, dynamic voltage regulation, short circuit current calculations, and anti-islanding also to be considered in the future work.

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