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Performance Enhancement of Low Voltage Distribution Network by Optimal Inverter
Control of Solar PV System

by

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A THESIS

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The undersigned certify that they have read, and recommended to the Department of Electrical Engineering for acceptance, a thesis entitled “Performance Enhancement of Low Voltage Distribution Network by Optimal Inverter Control of Solar PV System” submitted by Surendra Chaudhary in partial fulfillment of the requirements for the degree of **M. Sc. in Power System Engineering**.

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ABSTRACT

The thesis highlights the increasing contribution and impact of grid-connected photovoltaic (GCPV) systems, a type of renewable energy source, in electrical distribution systems. GCPV systems offer several advantages to customers and distribution network utilities. They enable consumers to fulfill their own electricity demand, reduce electricity bills, and even feed surplus power back into the grid. Additionally, GCPV systems can act as backup systems when there is insufficient or no PV generation. The increasing number of network-connected PV inverters also allows for their usage as Volt Ampere Reactive Compensators, which can regulate distribution network voltage and eliminate the need for expensive compensation devices like capacitor banks. However, introducing a large number of small-scale rooftop grid-connected PV systems with varying ratings into the distribution network can lead to technical challenges. One major problem is the voltage rise along the distribution network, causing reverse power flow, especially during low power demand and high PV generation conditions. This voltage rise limits the network's ability to accommodate more PV connections. Another issue is the possibility of voltage drop along the network during periods of no PV generation, particularly when there is high power demand and no PV generation.

To address these technical problems, the thesis proposes a new PV operational optimization strategy to enhance the performance of Low Voltage Distribution Systems (LVDS) with rooftop PVs. The strategy involves optimizing the reactive power control of PV inverters and implementing real power cut-off if necessary. The study focuses on the Butwal Distribution Centre, Kalika Feeder, Shiva Mandir Chowk Distribution Network, using bus data of load and solar PV generation patterns obtained from the allocated area. Three scenarios of PV penetration levels are considered: low PV generation with respect to consumer load (LPVCL), high PV generation with respect to consumer load (HPVCL), and medium PV generation with respect to consumer load (MPVCL). The programming for the proposed algorithms is implemented using MATLAB.

The results of the study indicate that in the LPVCL scenario, where solar PV generation is low compared to consumer load throughout the day, the reactive power capability limits of PV inverters are insufficient to maintain the desired voltage limit during peak loading hours. The minimum voltage recorded is 0.866 pu. In the HPVCL scenario, with high solar PV generation compared to consumer load from 9:00 to 17:00, the reactive power supply capability of PV inverters is unable to meet the desired voltage limit during 11:00 to 15:00 due to real power loss constraints. Therefore, real power cut-off becomes necessary, with specific kW values cut off from PV generation buses during different hours. In the MPVCL scenario, with PV generation lower than HPVCL but still high from 10:00 to 16:00, the reactive power capability of PV inverters is sufficient to maintain the desired voltage limit throughout the day with minimal real power cut-off. By optimizing reactive power control and implementing real power cut-off when necessary, the voltage profile of the distribution network improves in the third case (MPVCL scenario), with minimum and maximum voltages of 0.963 pu and 1.049 pu, respectively. This optimization strategy demonstrates the potential for power utilities to utilize PV systems installed in the distribution network to enhance overall network performance by controlling the active and reactive power of PV systems through inverters.

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LIST OF ACRONYMS, SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
GCPV	Grid Connected Photovoltaic
GoN	Government of Nepal
HPVCL	High PV Generation w.r.t. Consumer Load
IEEE	Institute of Electrical and Electronics Engineers
kV	kilo Volt
kVA	kilo Volt Ampere
kVAR	kilo Volt Ampere Reactive
kW	kilo Watt
LF	Load Flow
LPVCL	Low PV Generation w.r.t. Consumer Load
LV	Low Voltage
LVDS	Low Voltage Distribution System
MPVCL	Medium PV Generation w.r.t. Consumer Load
NEA	Nepal Electricity Authority
OLTC	On Load Tap Changer
OPF	Optimal Power Flow
PCC	Point of Common Coupling
PV	Photovoltaic
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition

CHAPTER ONE: INTRODUCTION

1.1 Background

The energy resources of Nepal comprise of petroleum products, biomass, hydroelectricity, solar energy, etc. Among all the energy resources petroleum products is the dominant resource of the country with respect to its overall utilization. Though Nepal has a huge potential of production of hydroelectricity, but it has remained untapped. The rapidly growing cost of fossil fuel and the increasing importance of environmental concerns, such as pollution and global warming, have motivated energy researchers to focus on developing renewable energy sources like wind and solar. This is done in order to meet the rising demand for electricity and reduce reliance on petroleum products. Traditionally, solar energy has been used for heating water and drying clothes, crops, wood, etc. The potential of solar energy in Nepal is estimated to be about 26 million MW. At present, solar energy technology used in Nepal are: Solar Photovoltaic (PV) System and Solar Thermal System. The installation and connection of solar PV systems to the grid offer several technical advantages. These include the flexibility and simplicity of installation, especially in areas with abundant solar irradiation. Additionally, solar PV systems are pollution-free, noise-free, and require minimal repair and maintenance. As a result, many governments are encouraging their citizens to install solar PV systems, enabling them to generate their own power and reduce their electricity bills. This initiative also contributes to the reduction of environmental pollution by increasing the utilization of solar energy.

Consequently, there has been a significant increase in the installation of solar PV systems in the distribution network, as consumers seek to limit their electricity bills. However, the expansion of rooftop PV system connections to the network has introduced certain detrimental impacts on the performance and operation of the distribution network. These issues primarily revolve around network voltage deviation from its reference level and voltage unbalance. These challenges need to be addressed in order to ensure the optimal functioning of the distribution network.

During periods of high PV energy generation, there is a possibility of reverse power flow into the grid, leading to voltage rise in the network. Conversely, voltage drop may occur during nighttime or cloudy days when there is no PV generation. The increasing installation of rooftop PV systems with varying ratings further exacerbates the already poor network profile. Current technologies used to address network voltage regulations include VAR compensators, on-load tap changers, auto-transformers, and voltage regulators. However, these methods have limitations such as infrequent tap position operation, additional failure points, and extra investment requirements. Among various methods to mitigate voltage deviation in low voltage distribution systems, the most recent and effective approach is high penetration of PV generation with PV inverter reactive power control. This approach offers superior transient performance and does not require additional investment. Grid-connected PV inverters can act as reactive power compensators when PV generation is unavailable, ensuring voltage regulation in the distribution network. As the number of grid-connected PV inverters increases, collective VAR compensation will further stabilize and regulate the network voltage

1.2 Problem Statement

At present, the installation of Solar Panels (Photovoltaic system) in household has increased significantly. So, the grid connected PV system could provide advantage to the distribution network system and the consumers. Grid connected PV system will overcome the consumer's electric power necessity, minimize the electricity unit consumption, while supplying the extra power generated into the distribution grid and also utilize the grid supply as a backup at low or no PV generation hours. However, introducing a high PV generation and penetration of randomly located small scale PVs with different ratings into the low voltage distribution network will create some technical problems, which are mentioned below:

1. In case of PVs generation is much less compared to consumer load or at no PV generation period, network voltage may drop drastically.
2. When PVs generation is higher compared to consumer load, reverse power may flow towards the grid causing voltage rise of the network.
3. Further, with huge number of single-phase rooftop PV system at haphazard locations with different ratings of PVs will further degrade the voltage profile of low voltage distribution network.

1.3 Objective and Scope

Considering the problems stated above, the objective of this thesis is to

investigate the impact of PV generation in low voltage distribution system. The main objective of this thesis is to minimize the voltage deviation to all nodes of the network. The scope of this thesis is to determine the impact of different PV generation levels in low voltage distribution network and provide the optimal control to minimize the voltage deviation.

Three levels of PV generations considered are:

- 1. Low PV Generation w.r.t Consumer Load (LPVCL),**
- 2. High PV Generation w.r.t. Consumer Load (HPVCL),**
- 3. Medium PV Generation w.r.t. Consumer Load (MPVCL).**

Applying these three circumstances, it is used to investigate the impacts in the network and give the optimal control for each PV generation level. If real time load data & PV generation data are available, the proposed algorithm can also be implemented for real time.

1.4 Organization of the Report

The report consists of the following five chapters:

Chapter 1 is an introductory chapter, which includes background of the study, Solar PV Rooftop Net Metering System, Problem Statement, Objective and Scope to executive the study topic.

Chapter 2 is literature review and theoretical background to the topic is explained. It further explains some concepts in understanding the problem and some expected outcome of the integration of solar PV power.

Chapter 3 describes the methodology of distribution system load flow with PV generation. And describe the reactive power control and real power cut off approach of PV inverter.

Chapter 4 presents the results with optimal real power control and reactive power control of the PV inverter in the network. The impacts of three PV generation levels on the network are presented.

Chapter 5 is a conclusive chapter, which presents the major inferences from the research. This chapter presents conclusions and suggestions for future work that can be carried out on the topic presented in the study.

CHAPTER TWO: LITERATURE REVIEW

2.1 Today's Electric Power System

The electric power system in current perspective is centralized, one-way power flow system. It can be categorized into generation, transmission and distribution system. In present scenario, electric power generation and distribution in the entire world is mostly done by centralized energy units. The energy units (power plants) are mostly of thermal, nuclear hydropower plants. These centralized plants module require distribution from the center to outlying network. Substations location can be at any distance from 10s to 100s of km away from the actual consumers of the electric power generated. This requires long distance transmission lines. In addition to long distance transmission lines issues, these systems contribute to environmental concerns like carbondioxide gas production (greenhouse gas emission), pollution, inefficiencies and power loss over the long transmission lines, environmental disturbance where the power lines are constructed, and security related issues. Depletion of fossil fuel due to ever increasing rate of fuel consumption (Lack of sustainability).

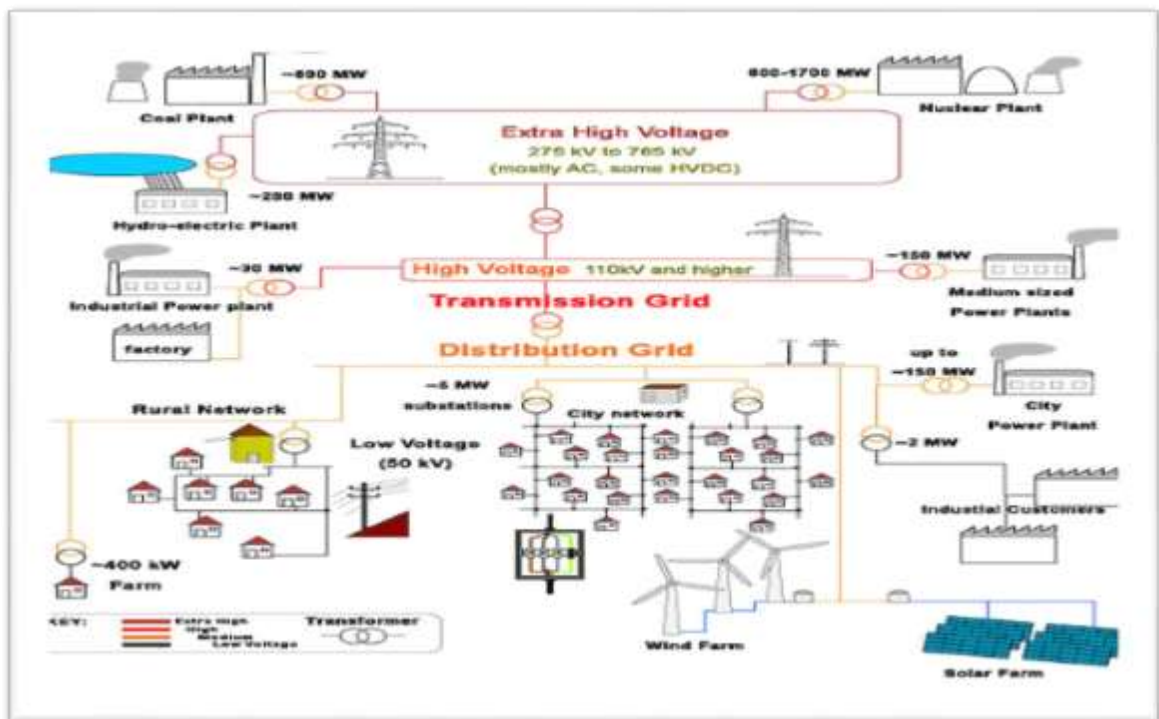


Figure 2. 1 Schematic model of electric power system

2.2 Renewable and distributed generation

Distributed generation in context of Nepal are solar (photovoltaic & thermal), wind turbine, hydroelectric (small scale micro-hydropower), etc. The main advantage of these energy plants is that it is placed near to the consumers. Capacity of the energy plants are likely to be ranging from few KW to MW. Here, combustion plants benefit from the economies of scale, whereas distributed generation plants with low investment benefit from economies of mass production. Environmental health and power supply reliability is increased. Many distributed generation units tied to the grid permits peak-shaving and supplying surplus energy to the grid which energy is not needed to be consumed by consumers. In addition, consumers benefit from the electricity supply in remote areas where national grid has not reached. It is cost effective to install distributed generation unit rather than to construct the transmission grid.

2.3 Distribution Network Model

There are three fundamentally different ways of networking: Radial, Loops & Network. The distribution network considered in the study is radial system. The biggest advantage of the radial system configuration, in addition to its lower cost, is the simplicity of analysis. Variety of option but two major classification possible. Major drawback of the radial feeder network is it is less reliable than network or loop network system being only single path to follow between the substation and consumer. Thus if any faults occurs along the path, results in the power loss of whole network. But a clever planning and design of radial distribution network can improve a fair degree of reliability even with minimum of additional cost.

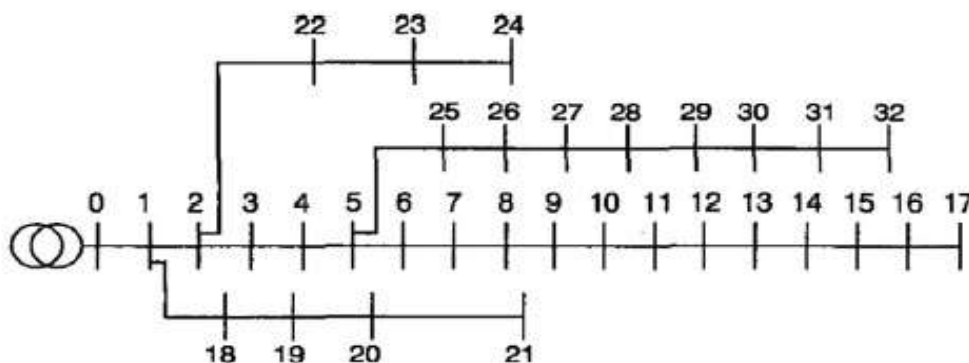


Figure 2. 2 Schematic model of radial distribution network

2.4 Solar Photovoltaic (PV) Cell

A solar cell, or photovoltaic cell converts the light energy directly into electrical energy by the photovoltaic effect, which is a physical and chemical phenomenon. It is a form of photoelectric cell, defined as a device whose electrical characteristics, such as voltage, current or resistance, vary when exposed to light. Individual solar cell devices are often the electrical building blocks of photovoltaic modules, known colloquially as solar panels. The single junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 volts to 0.6 volts.

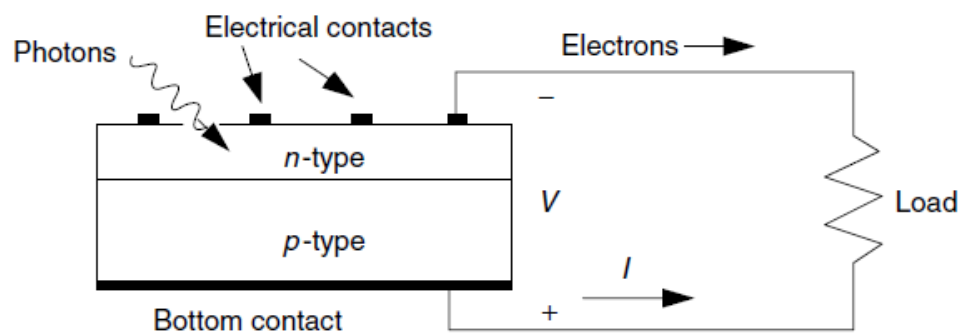


Figure 2. 3 Simple equivalent circuit of a photovoltaic cell

Solar cells are described as being photovoltaic, irrespective of whether the source of light is sunlight or any other source of light. In addition to producing energy, they can be used as a photodetector (infrared detectors), detecting light or other electromagnetic radiation near the visible range, or measuring light intensity.

The operation of a photovoltaic (PV) cell requires three basic attributes:

- The absorption of light, generating excitons (bound electron-hole pairs), unbound electron-hole pairs (via excitons).
- The separation of charge carriers of opposite types.
- The separate extraction of those carriers to an external circuit.

2.5 Solar Photovoltaic Panel or Module

Solar photovoltaic module or panel consists of multiple solar cells in an integrated group, all oriented in one plane. Photovoltaic modules often have a sheet of glass on the sun-facing side, allowing light to pass while protecting the semiconductor wafers. Series connection of solar cells create additive voltage. Parallel connection of cell yields a higher current.

However, problems in paralleled cells such as shadow effects can shut down the weaker i.e. less illuminated parallel string i.e. a number of series connected cells causing considerable power loss and possible damage because of the reverse bias applied to the shadowed cells by their illuminated partners.

Although solar modules are interconnected to form an array with the desired peak DC voltage and loading current capacity, which can be done with or without using independent maximum power point trackers or, specific to each module, with or without module level power electronic units such as micro inverters or DC-DC optimizers. To reduce the shadowing power loss shunt diodes can be used in arrays with series/parallel connected cells.

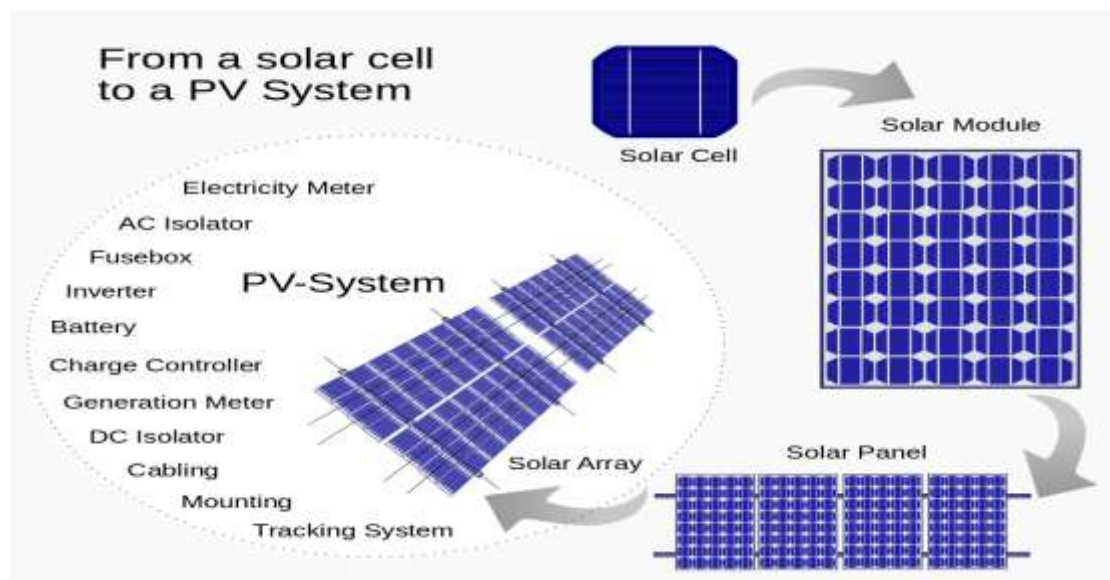


Figure 2. 4 Solar cell to a PV system

2.6 Solar PV Smart Inverter

A solar PV inverter converts the variable direct current (DC) output of a photovoltaic solar into a grid frequency alternating current (AC) that is fed to commercial distribution network or used by off-grid or local network.

It is a critical balance of system (BOS)–component in a photovoltaic system, allowing the use of ordinary AC-powered equipment. Solar PV inverters have special feature which includes maximum power point tracking and anti-islanding protection. Recently, there has been a shift in the approach of distribution companies and power providers towards the utilization of PV inverters. While solar PV inverters were originally designed to input active power at unity power factor based on available solar energy, they are now being utilized to provide and absorb reactive power to and from the grid. This shift in focus allows PV inverters to play a role in voltage regulation and power factor correction within the distribution network. Mostly the solar PV inverter is operating at 95.00% of its rated output current while converting DC solar power to AC active power. The remaining 5.00% of the inverter capacity can be used to produce the reactive power. The output of a smart PV inverter has both reactive and active AC currents that add geometrically to the apparent power, which will be limited by the current rating of the inverter. The active power flow and reactive power flow in the grid are independent of each other and require different control strategy. Active power control is achieved by controlling grid frequency, whereas reactive power control is obtained with controlling the grid voltage.

2.7 Reactive Power & Voltage Control

Voltage control of transmission and distribution system is obtained by injecting or absorbing reactive power (VAR) at various points throughout the network, although reactive power can be controlled at power generating plants. Abnormal voltage level can damage the network equipment and loads. Reactive power control strategy enhances grid stability and reduces transmission line losses. Transmission lines depending on nature of load and line length, either absorb or provide reactive power. Interestingly, at very high voltage levels the resistive power loss component is often insignificant in comparison to the reactive power component.

The PV inverter reactive power capacity can be utilized as a fast-acting static VAR compensator, controlled either through a SCADA system (supervisory control and data acquisition system) or as a stand-alone voltage regulator and acting as either a shunted capacitor or inductor increasing or decreasing the AC voltage along the line. The major benefit of this is that it comes at very little additional cost (component cost). In the USA, the first implementation of large PV systems went online alongside transmission lines in 2010, connected through dedicated collector substations and providing static voltage support according to a voltage schedule provided by the distribution company.

The smart PV inverter's ability to feed reactive power to the line can also be used to help the grid recover from a distant fault that causes the grid voltage to sag momentarily. While riding through a low voltage transient, the smart PV inverter goes into a reactive power overdrive mode to support the grid voltage up until the fault is cleared. Low voltage ride through is a standard feature in wind turbine plants today and were adopted for large PV sites in the US in 2011. On the distribution side, smart PV inverters are used to correct the power factor by providing VARs close to where they are being used, rather than importing them from far away. Transformers and most electrical loads are inductive in nature and therefore consume reactive power. Traditionally, power factor correction is done by connecting large, paralleled capacitor banks to many of the voltage levels of the distribution system. These shunt switched capacitors are strategically placed to adjust voltage along the feeder, as the tap-changing voltage regulators only control voltage at the beginning of the branch. Not only can both power factor correction and AC voltage regulation be performed much more economically by distributed smart PV inverters along the feeder, but they will also do it in a continuous and smooth fashion, without any step changes or noticeable switching events. Lastly, development for the large-scale deployment of smart meters, smart PV inverters distributed throughout the grid, combined with a smart grid inverter data monitoring system, provide a plethora of new features to progressive customer-oriented utilities today. Real-time data monitoring allows the reporting of voltage quality problems to the utility before equipment is damaged, whereas voltage quality visibility to the utility is usually limited to substations and major distribution feeders.

2.8 Reactive Power (VAR) Compensation Operating Mode of PV Inverter:

Although the number of PV installations is rapidly growing, the effective utilization of PV inverters remains low. On average, most of today's grid-tie PV inverters operate an average of 6-8 hours per day. In order to increase the utilization of grid-tie PV inverters, they can be operated in reactive power compensation mode when PV power is unavailable. As the number of grid-tied inverters increases, their usage as VAR compensators will help in grid voltage regulation and reduce the need of expensive capacitor banks. While injecting reactive power into the grid can be easily realized by applying the appropriate phase shift between current reference and grid voltage, the task gets more complex when PV power is not available since the inverter needs to draw power from the grid, regulate the DC bus, and inject the desired level of reactive power.

Operating the inverter in VAR mode involves two steps shown in Figure 2.4:

1. Pre charging the DC bus capacitance.
2. Regulating the DC bus voltage within limits while regulating the injected reactive power.

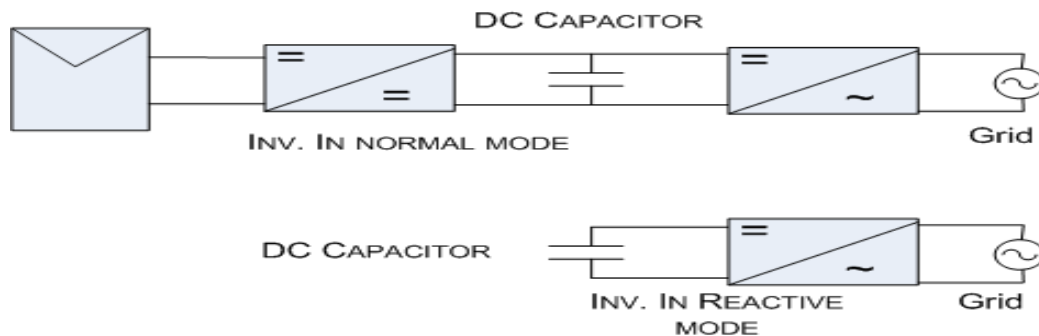


Figure 2. 5 Inverter Operating Mode

2.9 Solar PV Roof Top Net Metering System

Net metering system provides the solar energy producers credits for the electric power that they input to the distribution network. When solar PV panels produce extra power, that power is transmitted to the grid. And this power can be reversed back when the solar PV panels are not functioning – example, during the cloudy condition or at night. When

a unit of solar PV energy that has been 'net metered', the bi-directional electricity meter will run backwards. Customers are charged only for the 'net' energy use.

The solar power systems are connected to the utility grid via the customers' main service panel and meter and, when generating more power than is needed at the site, return excess electricity to the grid through the power meter, reversing the meter from its usual direction. Thus, a bi-directional meter is needed to avail net metering. Since the meter works in both directions (i.e. bi-directional meter)– one way to measure power purchased (when on-site demand is greater than on-site power production), and the other way to measure power returned to the grid – the customer pays the "net" of both transactions.

Many countries have passed net metering laws. In Nepal, Nepal Government, Ministry of Energy, Water Resources and Irrigation (MoEWRI) and Nepal Electricity Authority (NEA) had formulated rules and regulations for any institution or individual who generate electricity from solar panels and connect to the national grid. The electricity generated should be 500 watts in minimum and 5 kW in maximum. There are separate rules and regulations for larger than that size. For example, if a residential customer has a PV system on the home's rooftop, it may generate more electricity than the home uses during daylight hours. If the home is net metered, as shown in Figure 1.1 the electricity meter will run backwards to provide a credit against what electricity is consumed at night or other periods where the home's electricity use exceeds the system's output. Customers are only billed for their "net" energy used. Net metering is a billing mechanism that credits solar energy system owners for the electricity they add to the grid.

Single Line Diagram of Rooftop Facility for Net Metering Interconnection

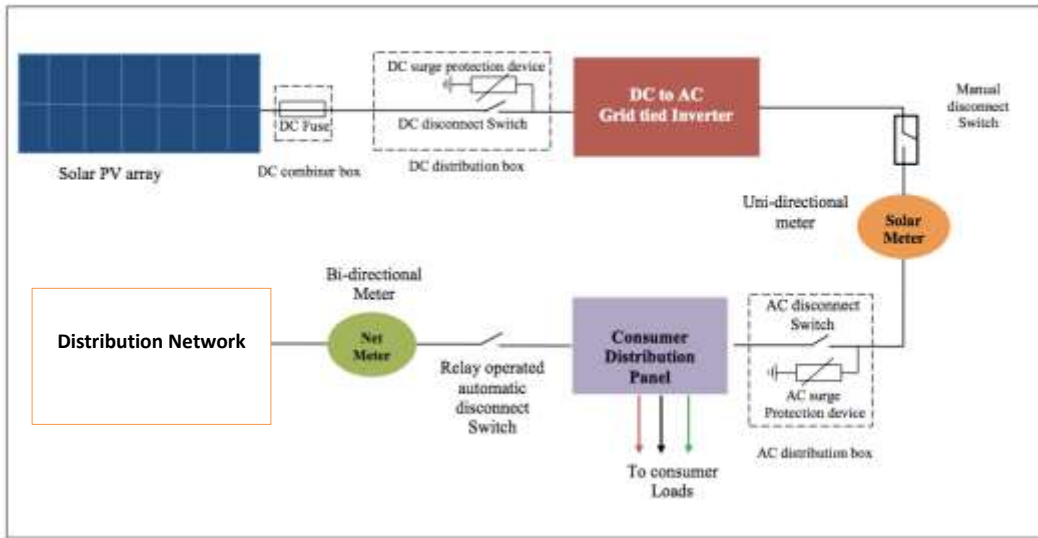


Figure 2. 6 Single line diagram of rooftop facility for net metering interconnection

The model of test system is considered as the bi-direction signal control between each house and controller as shown in Figure 1.2. In the figure distribution transformer of 11/0.23 kV is considered as a grid after that there is controller which receives the data of each house and the optimal control for each house is sent through the bi-direction signal control mechanism.

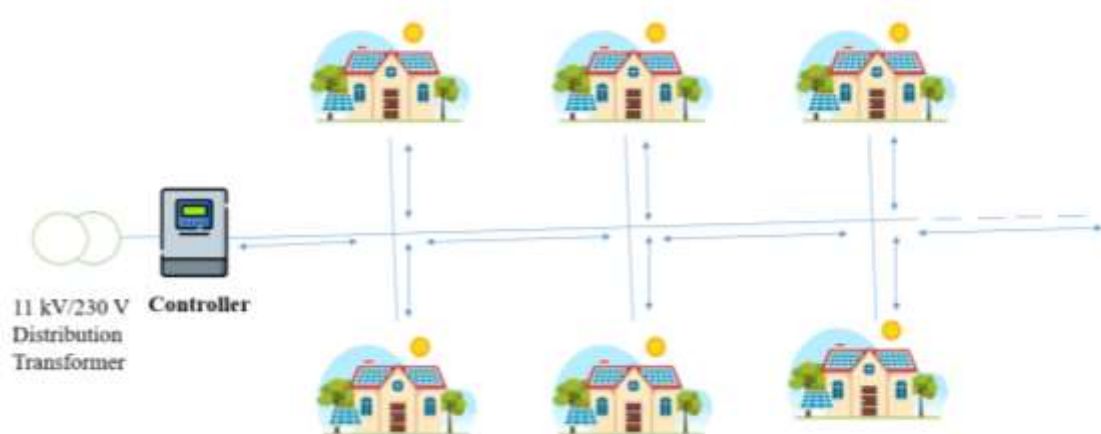


Figure 2. 7 Model of bi-directional signal flow between controller & household

CHAPTER THREE: METHODOLOGY

3.1 Overview

The study is carried out of the distribution network in Butwal Distribution Centre. The details of the distribution network studied are as below:

1. Distribution Centre: Butwal
2. Substation: Rajmargha Chauraha Substation
3. Power Transformer: 2 sets of 6/8 MVA Power Transformer
4. Feeder: Kalika Feeder
5. Distribution Transformer: 200 kVA, Shiv Mandir Chowk Area
6. Consumers Connected: most of them are residential and some consumers with small inductive loading in nature.
7. Assumptions: Solar roof top PVs connected to the households are assumed to be connected as per the conditions of PVs required for the study.

The study focuses on the single-phase (R Phase) loading condition for both Solar PV and consumer load. It explores the implementation of optimal reactive power control and, in rare cases, real power cut-off to enhance the capability of the distribution network. The distribution systems under consideration have line/cable configurations with high R/X ratios, making the decoupling assumptions invalid. To achieve optimal control of the distribution system network, the program operates continuously, evaluating different proposed control options.

3.2 Load Flow Solution of Radial Distribution Networks

Necessity of The separate load flow for Distribution system:

Most of the time conventional load flow methods cannot be applied to distribution systems due to following reasons:

- The limitation of the Gauss-Seidel (G-S) method in load flow analysis is widely recognized. In the case of distribution systems, which typically consist of a large number of buses, the G-S method becomes impractical due to its extensive computation time requirements. As a result, alternative load flow methods more suitable for distribution network analysis are typically employed. Distribution

systems have lines/cables with high R/X ratio. Thus decoupling assumptions are not valid.

- Most of the systems are radial in nature having single in-feed. Systems having multiple in-feed or ultimately operated as radial systems.
- Distribution Systems are unbalanced and in certain sections and carry only single or two phases. Three phase representation is required.

3.3 Forward-Backward Load Flow for Distribution System

- Generally, radial distribution network works in backward-forward fashion.
- Assume the voltage of each node, except the source node.
- In a backward propagation, the current in the upstream branch can be calculated by summing up the load currents and downstream branch currents.
- In the forward propagation, the network bus voltages are updated from the source node using the network branch currents obtained in the backward propagation.
- The backward-forward propagation process continues until the voltages of the network buses converge within a pre-specified acceptance limit.

3.4 Distribution System load flow

Load flow analysis of distribution system has not received much attention unlike load flow analysis of transmission system. However, some work has been carried out on load flow analysis of distribution network but the choice of a solution method for a practical system is often difficult. Generally, distribution networks are balanced radial and the R/X ratio is very high.

Because of this, distribution networks are ill-conditioned and conventional NR and fast decoupled load flow methods are inefficient at solving such networks. So, the following method is used to solve the load flow of the balanced radial distribution networks.

- ▶ A simple and powerful method for load flow solution of radial distribution network.
- ▶ The method is based on computation of
 - *Bus-Injection to Branch-Current Matrix*
 - *Branch-Current to Bus-Voltage Matrix*
- ▶ The **BIBC** matrix is responsible for the variation between the bus current injection and branch current,
- ▶ And the **BCBV** matrix is responsible for the variation between the branch current and bus voltage.

Let's consider an example:

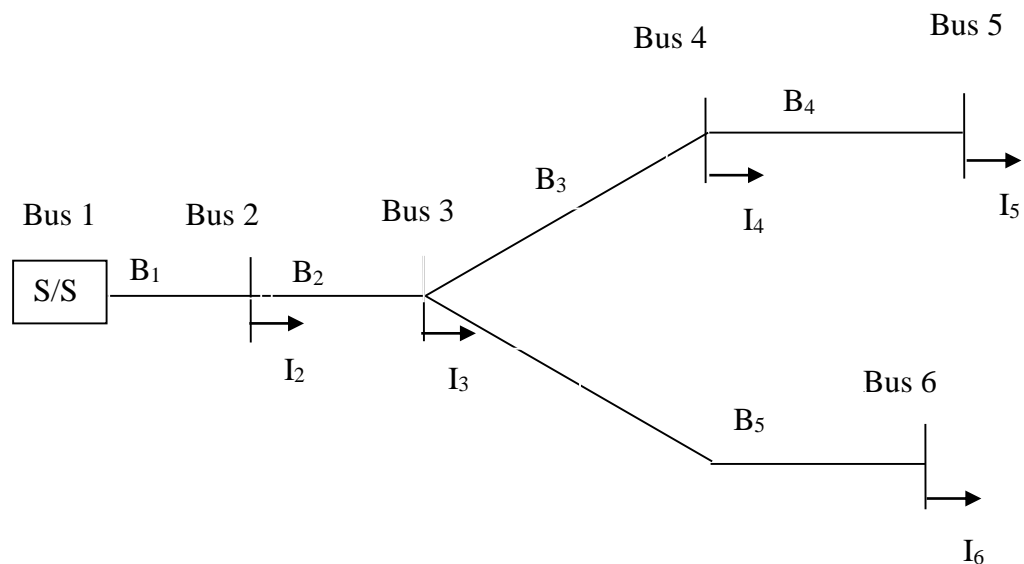


Figure 3. 1 A Simple Distribution System

- ▶ From the network an algorithm is developed to compute the nodes fed by a particular branch:
- ▶ For example, network

$$B_5 = I_6$$

$$B_4 = I_5$$

$$B_3 = I_4 + I_5$$

$$B_2 = I_3 + I_4 + I_5 + I_6$$

$$B_1 = I_2 + I_3 + I_4 + I_5 + I_6$$

Furthermore, the Bus Injection to Branch-Current (**BIBC**) matrix can be obtained as,

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} .$$

► **Branch-Current to Bus-Voltage Matrix**

► The relations between the branch currents and bus voltages is then obtained

► For example, feeder it can be seen that

$$V_2 = V_1 - B_1 Z_{12}$$

$$V_3 = V_2 - B_2 Z_{23}$$

$$V_4 = V_3 - B_3 Z_{34}$$

Where V_i is the bus voltage of Bus i , and Z_{ij} is the line impedance between Bus i and Bus j .

From the above the voltage at each buses can be obtained as a function of bus 1 (substation voltage)

For example

$$V_4 = V_1 - B_1 Z_{12} - B_2 Z_{23} - B_3 Z_{34}$$

► Thus the bus voltages can be updated as

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \quad (10a)$$

► The above expression is written as

$$\begin{aligned} [\Delta V] &= [BCBV] * [BIBC] * [I] \\ &= [DLF] * [I] \end{aligned}$$

Algorithm

Step 1: Read the system configuration, physical parameters and loads

Step 2: Compute [BCBV] and [BIBC] Matrices

Step 3: Assume the voltage at each bus as $1+j0$

Step 4: Compute the node currents as:

$$I_i(k) = [(P_i(k) + j Q_i(k)) / V_i(k)]^* \quad \{k \text{ is the iteration no.}\}$$

Step 5: Compute $[\Delta V] = [BCBV] [BIBC][I]$ and update voltages

Step 6: Compute the branch real and Reactive loss as:

$$PL_j(k) = B_j^2 R_j \text{ and } QL_j(k) = B_j^2 X_j \quad \{j \text{ is the branch no.}\}$$

Step 7: Add these losses to the demand of sending end node of the respective branch (j):

$$P_i(k) = P_i + PL_j(k) \text{ and } Q_i(k) = Q_i + QL_j(k)$$

Where: P_i & Q_i are the initial (specified) load at i th Bus

Step 8: Check $\Delta V(k) - \Delta V(k-1)$ less than convergence criterion if not go back to step 4 and repeat the whole procedure

Step 9: Compute total system losses and print node voltages

3.5 Radial Distribution System with PV Generation

Distributed Generation are modeled as Negative PQ Load:

- 1 In a radial distribution feeder, the flow of current and thus the power occurs from the buses to the loads.
- 2 The distributed generations connected to the distribution system are usually small fractions of the total generations or the power flowing from the source end.
- 3 In contrary, generation provides current and power to the system. So, the flow of direction of current and power is reversed.
- 4 i.e. The buses, to which the distributed generations are connected, are indicated as load buses but the negative sign will carry the information that they are actually acting as generators.
- 5 When the distributed generators are modeled as negative PQ load, they will have no capability of regulating their reactive power output
- 6 Hence, they cannot help in keeping the voltages to the specified values at the buses where they are connected.

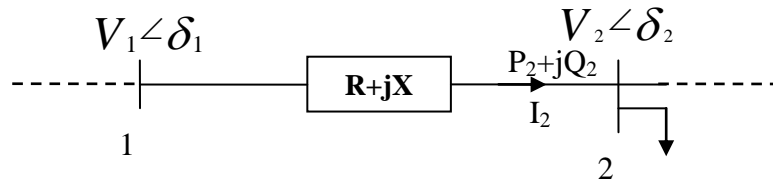
Distributed Generation Modeled as PV Model

In this scenario, the Distributed Generation (DG) possesses the capability to regulate the reactive power within predefined limits.

As a result, the network voltage at the bus point of coupling can be effectively regulated.

Derivation of Reactive Power to be Generated to Keep Voltage at the Specified Value

Let's reconsider a distribution branch



$$I_2 = \frac{P_2 - jQ_2}{V_2^*} \qquad I_2 = \frac{|V_1| \angle \delta_1 - |V_2| \angle \delta_2}{R + jX}$$

From above two equations

$$P_2 - jQ_2 = \frac{(|V_2| \angle -\delta_2)(|V_1| \angle \delta_1 - |V_2| \angle \delta_2)}{R + jX}$$

$$P_2 - jQ_2 = \frac{(|V_2||V_1| \angle (\delta_1 - \delta_2) - |V_2||V_2| \angle (\delta_2 - \delta_2))}{|Z| \angle \theta}$$

That is;

$$Q_2 = \frac{(|V_2||V_1|(\sin(\theta - \delta_1 + \delta_2))}{|Z|} - \frac{(|V_2||V_2| \sin(\theta))}{|Z|}$$

If the total reactive power connected to bus '2' equals the value given by above equation the voltage at bus '2' will be 'V2'.

'V2' can be the specified voltage at bus '2'.

Hence, if there is any load ($Q_{totbranch}$) connected to bus '2' already, the reactive power (Q_{gen}) that has to be generated by the generator to keep the voltage at bus '2' equal to 'V2' is given by

$$Q_{gen} = Q_{req} - Q_{totbranch}$$

Where

Q_{gen} : reactive power to be generated

Q_{req} : total reactive power that has to be connected to the bus

$Q_{totbranch}$: total reactive load that is already connected to the bus

Rest of the L.F. procedure is same

3.6 Power Control Strategy of PV Inverter

The capacity of the PV inverter and real power can be visually represented in Figure 3.2 using vectors with magnitudes S and P . The operating range of the PV inverter, limited by the PQ circle, is depicted by the radius of the semicircle. The available reactive power (Q) from the PV inverter is restricted by the equation.

$$-\sqrt{S^2 - P^2} \leq Q \leq \sqrt{S^2 - P^2}$$

The amount of reactive power supply by inverter is represented by vector Q_{ub}

The amount of reactive power absorbed by inverter is represented by vector Q_{lb} .

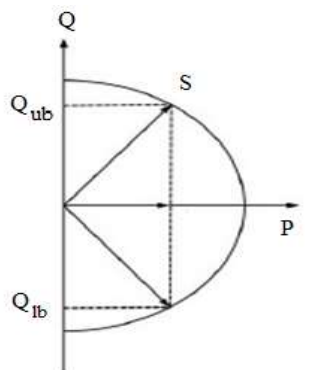


Figure 3. 2 The Reactive power capability curve of Solar PV inverter

3.7 Proposed Power Control Strategy of PV Inverter

Based on the reactive power capability and real power cut off of the PV inverters, one of the following proposed three control options is selected for the desired network performance.

Option 1 (Optimal Q-control with Rated Inverter Power Factor Capacity):

This option is chosen for normal operating conditions. Since the inverter's real power generation is typically lower than its rating, the inverter has the ability to supply or absorb reactive power. However, this capability comes at the cost of PV inverter power losses.

Option 2 (Optimal Q-control with Rated Inverter Capacity):

If the network criteria are not within the permissible limit even with option 1, option 2 is chosen. In this case, comprehensive control can be implemented to regulate reactive power using the rated capacity of the solar PV inverter.

Option 3 (Optimal Q control with Real Power Cut Off of Inverter):

If the network criteria are still not within the permissible limit with option 2, option 3 is selected. Real power cut-off is then employed for each inverter, allowing both real power and reactive power controls. This cut-off comes at a higher cost in terms of optimization, but partial cut-off can be utilized to distribute the network PV generation among all consumers.

The reactive power control for the above explain options is shown in Figure 3.3

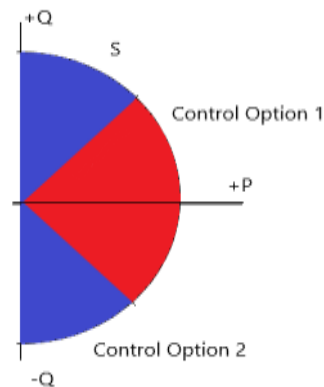


Figure 3. 3 Solar PV inverter control scheme

3.8 Objective Function

Real power control, reactive power control, and real power cut-off from solar PV inverters are valuable tools for enhancing the capability of distribution networks with solar PV generation. The control scheme focuses on selecting optimal active and reactive power control strategies that minimize voltage changes across network buses, reduce power loss, minimize real power cut-off from PV systems, and meet operational constraints. In the formulation of the voltage deviation equation, a lower limit of 0.99 pu is considered instead of 0.95 pu to leverage the reactive power capability of the solar PV inverter, despite the acceptable lower limit voltage being 0.95 pu.

3.8.1 Minimization of distribution network voltage deviation

$$V_{dev}(i) \quad \forall i, i \in \text{All network bus} \quad (3.6)$$

Where,

$$V_{dev} = |V_a - V_b|$$

V_b is node voltage

if $V_b \geq 1.05 pu$

fif $V_b \leq 0.99 pu$

; *otherwise*

3.8.2 Minimization of power losses

$$P_{loss} = \sum_{i=1}^{N_{br}} I_i^2 R_i \quad (3.7)$$

Where,

i is any feeder branch.

N_{br} is the total number of branches.

R_i is the resistance of branch i .

I_i is the magnitude of current flows through branch i .

3.8.3 Minimization of total real power cut-off of PVs

$$PV_{P(cut-off)} = \sum_{i=1}^n (\text{Real power cut-off of PV})_i \quad (3.8)$$

Where,

i is any number of solar PV

n is total number of solar PV

So, mathematically these multi-objective optimization problems can be represented as,

$$\text{Min} F = [V_{dev}(x), P_{loss}(x), PV_{P(curtailment)}(x)]$$

Where, x is the optimal real power cut-off and reactive power control of the solar PV inverter.

3.9 Constraints

3.9.1 Capacity limit of the PV inverter

$$P_{PV}^2 + Q_{PV}^2 \leq S_{PV}^2 \quad (3.9)$$

Where,

P_{PV} is real power of solar PV

Q_{PV} is reactive power of solar PV

S_{PV} is apparent power of solar PV

3.9.2 Power loss before and after control

$$\left(P_{loss} = \sum_{i=1}^{N_{br}} I_i^2 R_i \right) \text{after control} \leq \left(P_{loss} = \sum_{i=1}^{N_{br}} I_i^2 R_i \right) \text{before control} \quad (3.10)$$

Where,

i is any feeder branch.

N_{br} is the total no. of branches.

R_i is the resistance of branch i .

I_i is the magnitude of current flows through branch i .

3.10 Algorithm for Optimal Real Power Cut-off & Reactive Power Control of solar PV Inverter

Step1: Read all network topology data such as line data, bus data (Load and PV generation data)

Step2: Solve the load flow for the distribution system as explained in 3.3, 3.4 and 3.5

Step3: Check the voltage (V) to all nodes of the network.

Step4: If V are within the limit $\{0.99 \leq V \leq 1.05 pu\}$, then stop and print the result otherwise go to step 5

Step5: Solve the repeated load flow solution for the distribution system considering the constraints for option 1 as explained in 3.7 and 3.8

Step6: Check the voltage deviation (V) to all nodes of the network.

Step7: If V are within the limit $\{0.99 \leq V \leq 1.05 pu\}$, then stop and print the result otherwise go to step 8

Step8: Solve the repeated load flow solution for the distribution system considering the constraints for option 2 as explained in 3.7 and 3.8

Step9: Check the voltage deviation (V) to all nodes of the network.

Step10: If V are within the limit $\{0.99 \leq V \leq 1.05 pu\}$, then stop and print the result otherwise go to step 11

Step11: Solve the repeated load flow solution for the distribution system considering the constraints for option 3 as explain in 3.7 and 3.8, then stop and print the result.

The outcomes of the algorithm are the real power cut-off and the optimal reactive power control settings for the solar PV inverter, achieved based on the defined objective function. For the above algorithm, the computational flow chart is shown in the Figure 3.4.

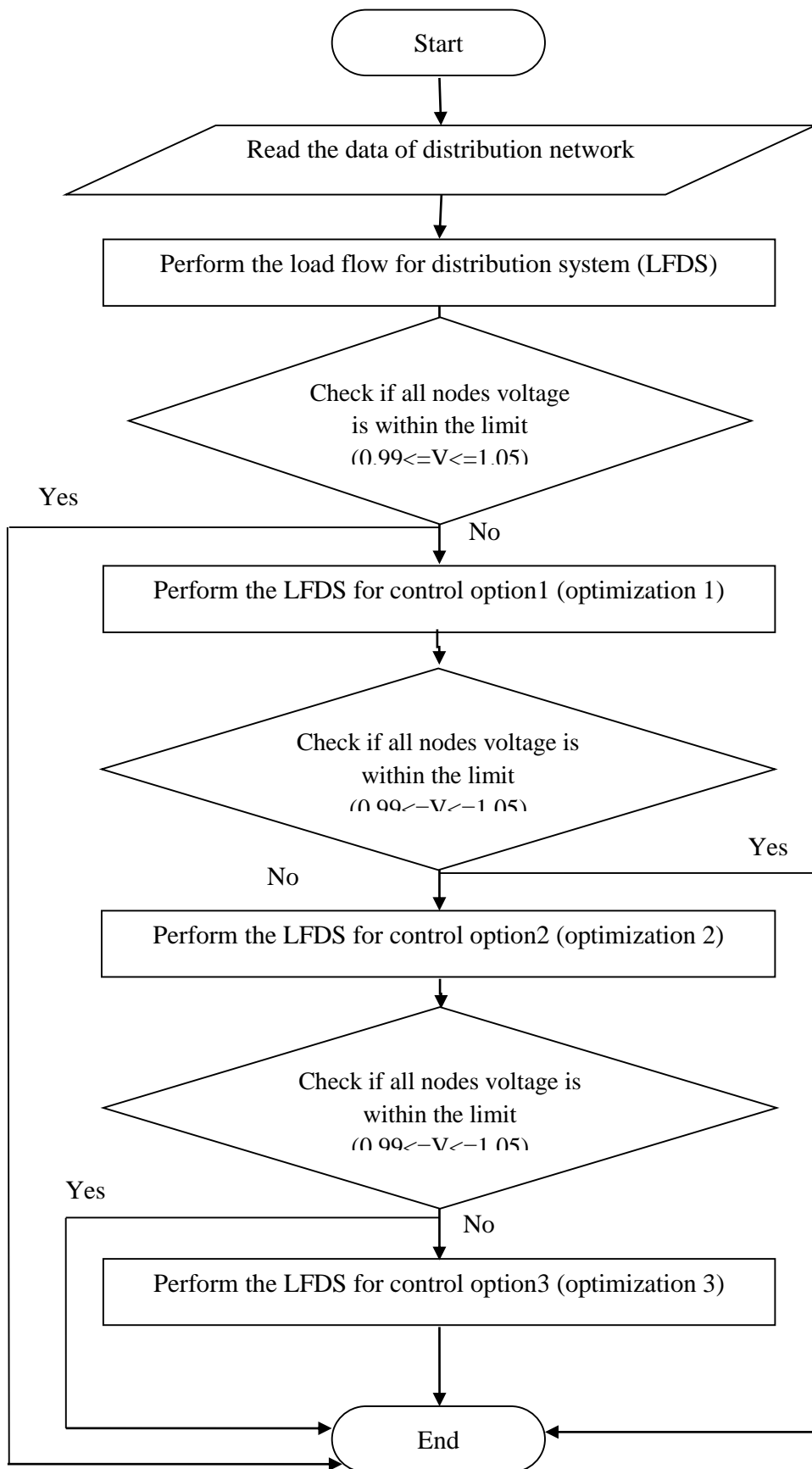


Figure 3. 4 Flowchart of proposed algorithm

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Overview

The study is carried out on the Kalika Feeder, Shiv Mandir Chowk Area distribution network of Butwal Distribution Centre. The detail of the distribution network studied is as below:

1. Distribution Centre: Butwal
2. Substation: Rajmargha Chauraha Substation
3. Power Transformer: 2 sets of 6/8 MVA Power Transformer
4. Feeder: Kalika Feeder
5. Distribution Transformer: 200 kVA, Shiv Mandir Chowk Area
6. Consumers Connected: most of them are residential and some consumers with small inductive loading in nature. Total of 33 load centres (buses).
7. Assumptions: Solar roof top PVs connected to the households are assumed to be connected as per the conditions of PVs required for the study.

First of all, normal distribution load flow is carried out without any control. Secondly reactive power control is taken into account to improve the voltage profile. After that where necessary, real power cut off and reactive power control is taken into account to further improve the voltage profile of the network. MATLAB code is developed for all control options.

The distribution network in question is supplied by a 200 kVA, 11/0.4 kV distribution transformer located at the Substation grid. The hourly bus data, considering three cases (MPVCL, HPVCL, and LPVCL), includes load and solar PV generation profiles for the Kalikanagar area connected to the 200 kVA transformer. Each node in the network is assumed to have a span of 35 meters, and the conductor used is a 100 mm² ACSR (Dog) Conductor. The distribution network is modeled as a low voltage three-phase four-wire system. The base values for load and solar PV generation are taken as 5 kVA and 0.23 kW, respectively. The thesis results focus on the single-phase R component of the network.

The study is carried out during each hour of the day in three scenarios:

1. MPVCL (Medium PV Generation w.r.t. Consumer Load)

2. HPVCL (High PV Generation w.r.t. Consumer Load)
3. LPVCL (Low PV Generation w.r.t. Consumer Load)

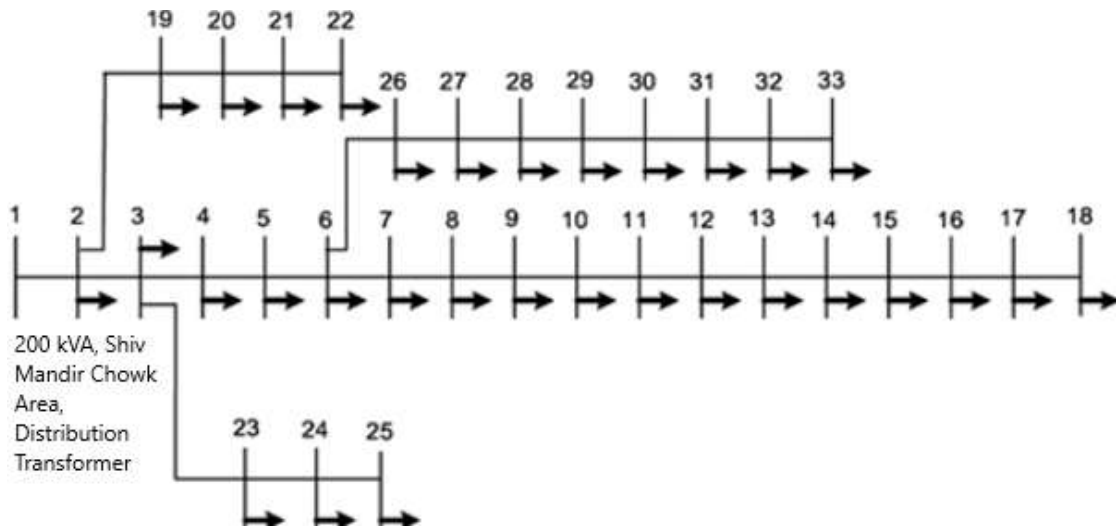


Figure 4. 1 Shiv Mandir Chowk Area Distribution Network

4.2 Case 1: Test Results for Medium PV Generation w.r.t. Consumer Load (MPVCL) Case

Following the algorithm mentioned earlier and using all the mathematical expressions, complete coding of the work is done in MATLAB. The program is run for MPVCL Case and the results observed are explained below:

The initial voltage profile of the Shiva Mandir Chowk Area Distribution Network, Butwal is shown in table B 4 and graphically expressed in Figure 4.34. All the results are of R phase of the network. From the data, it is observed that during high PV generation period i.e. 11:00 to 15:00 hour voltage of network lies between 1 to 1.051 p.u. and during no PV generation & high load period i.e. 18:00 to 21:00 hour network voltage lies below 0.95 p.u. The maximum voltage noted is 1.051 pu at bus 18 at 12:00 hour and minimum voltage noted is 0.837 at bus 18 at 19:00 hour. The summarized initial result of Network Voltage before optimization is shown in table A.1.

Table A. 1 Initial Voltage Profile & Loss of Network

Voltage	Value	Bus No.	Time (hr)	Real Power Loss (kW)
Min. Voltage	0.837	18	19	6.840
Max. Voltage	1.051	18	12	1.489

Table 1

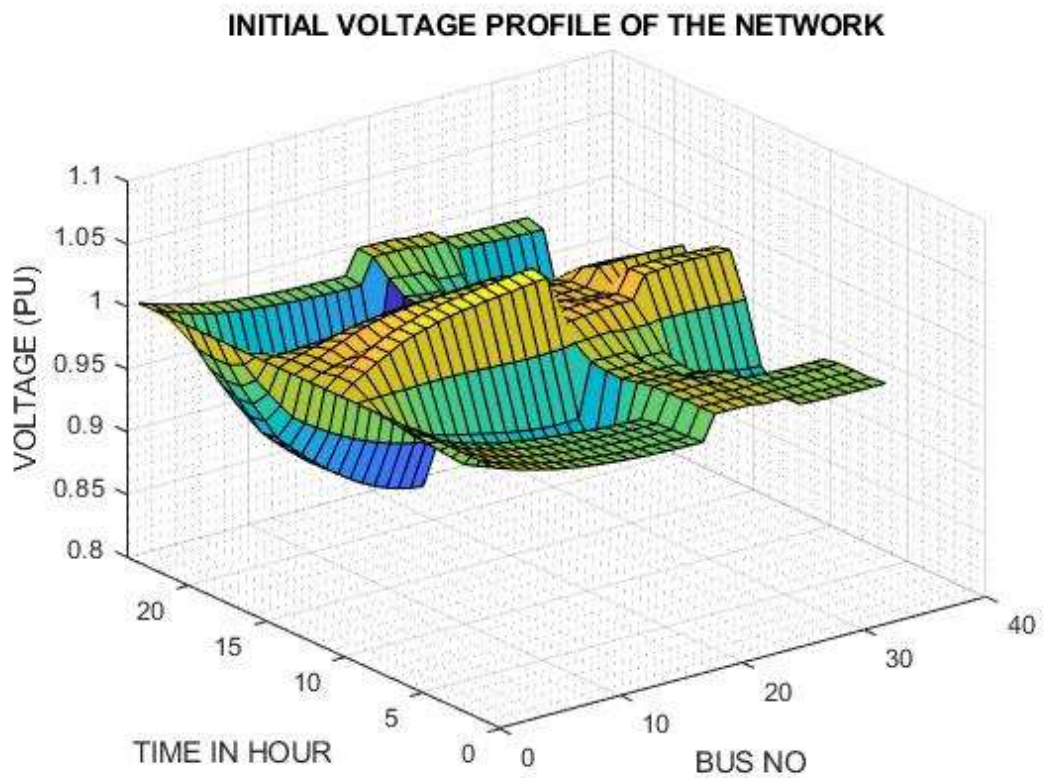


Figure 4. 2 Initial network voltage profile for MPVCL

The program is run for the optimal condition result and the optimal voltage profile condition is obtained at option 3. The optimal voltage of the network is presented in

table B 6 and graphically expressed in Figure 4.35. At optimal condition maximum voltage is 1.04 p.u. of bus 18 at 12:00 hour and minimum voltage obtained is 0.96 pu of bus 18 at 19:00 hours which is within the $\pm 5\%$ limit range. Here real power cut off during optimization process is 0.49 kW which is comparatively very low. The summarized result of Network Voltage after optimization is shown in table A.2.

Table A. 2 Optimal Voltage Profile & Loss of Network

Voltage	Value	Bus No.	Time (hr)	Real Power Loss (kW)
Min. Voltage	0.963	18	19	4.608
Max. Voltage	1.049	18	12	1.444

Table 2

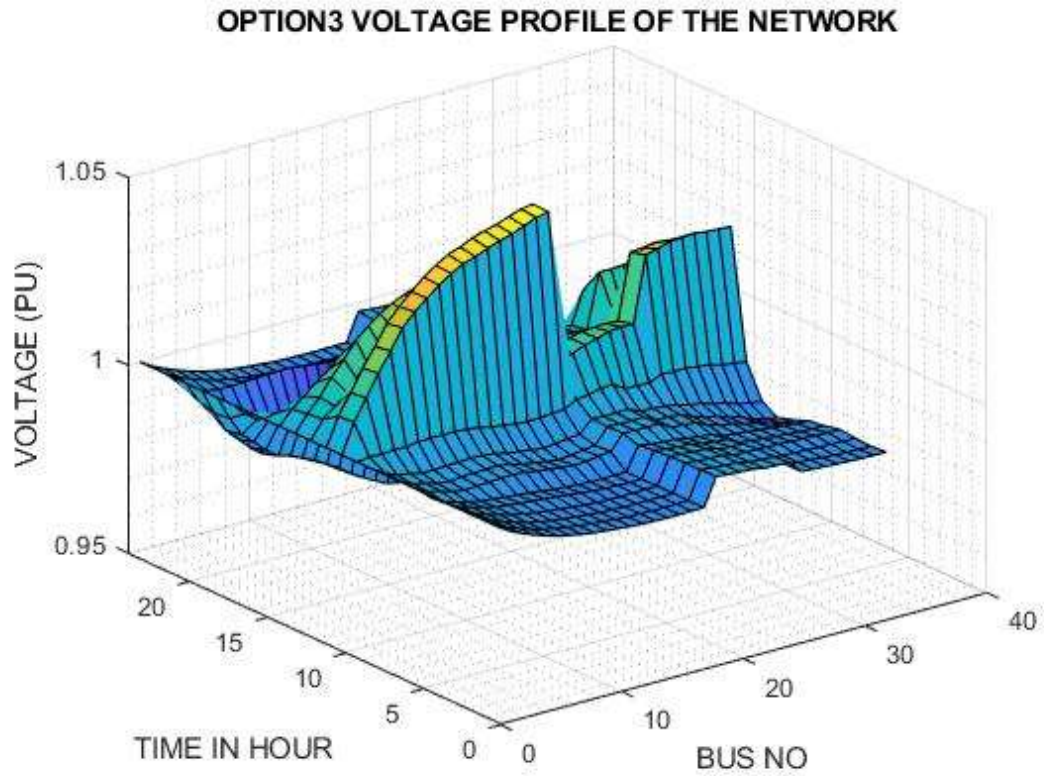


Figure 4. 3 Optimal condition network voltage profile for MPVCL

The data obtained for the real power flow within the Shiva Mandir Chowk Distribution Network is presented in table B 3 and B 5 and graphically represented in Figure 4.4. Here, the results show that at 10:00 to 16:00 hour time PV generation is greater than the load of network so net real power is supplied towards the grid at 10:00 to 16:00 hours and for the other hours power is supplied from the grid. At optimal condition, some real power cut off of PV occurs i.e. 0.49 kW at 12:00 hour. Thus, optimal condition during MPVCL is obtained with minimal real power cut off of PV generation.

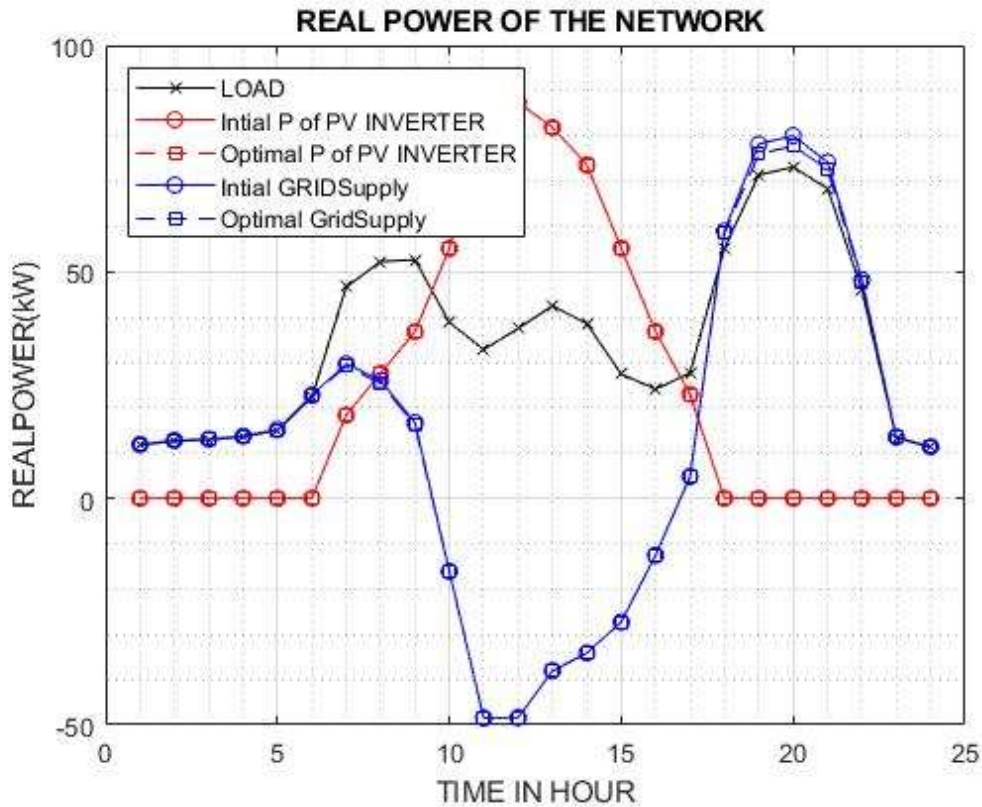


Figure 4. 4 Real power of Load, PV inverter and grid for MPVCL

The data obtained for the reactive power flow within the Shiva Mandir Chowk Distribution Network is presented in table B 3 and B 5 and graphically represented in Figure 4.5. Initially, reactive power of load and PV generation have different combination for each hour of the day and net reactive power to & from the grid varied accordingly. At optimal condition, the reactive power supplied by the PV inverters varied from its rated power factor to its rated capability limit to maintain the voltage limit and the net reactive power supplied towards the grid or from the grid varied according to the supply of reactive power from the PV inverters.

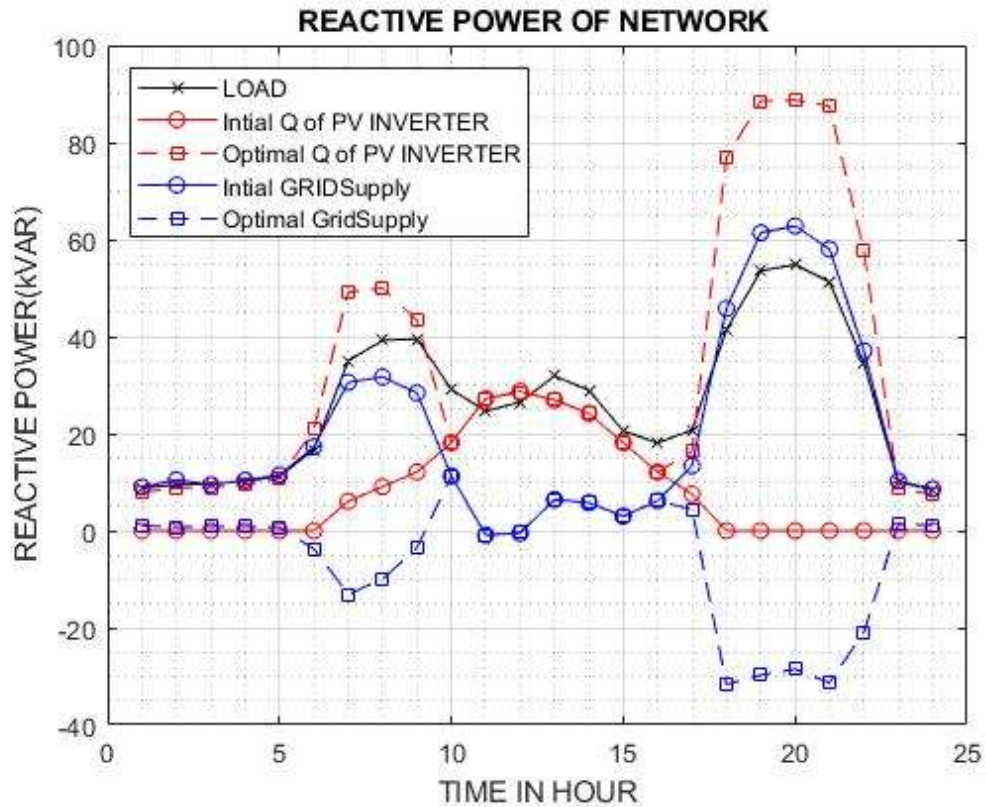


Figure 4. 5 Reactive power of load, PV inverter and grid for MPVCL

The data obtained after the running the program for optimal condition with real power cut off of PV generation is presented in Table B 5 and graphically represented by Figure 4.6. Here, the real power cut off is applied on the PVs whose voltage has exceeded 1.05 pu limit. It is observed that the real power cut off is maximum of 0.17 & 0.32 kW for bus 17 &18 inverter at 12:00 hour.

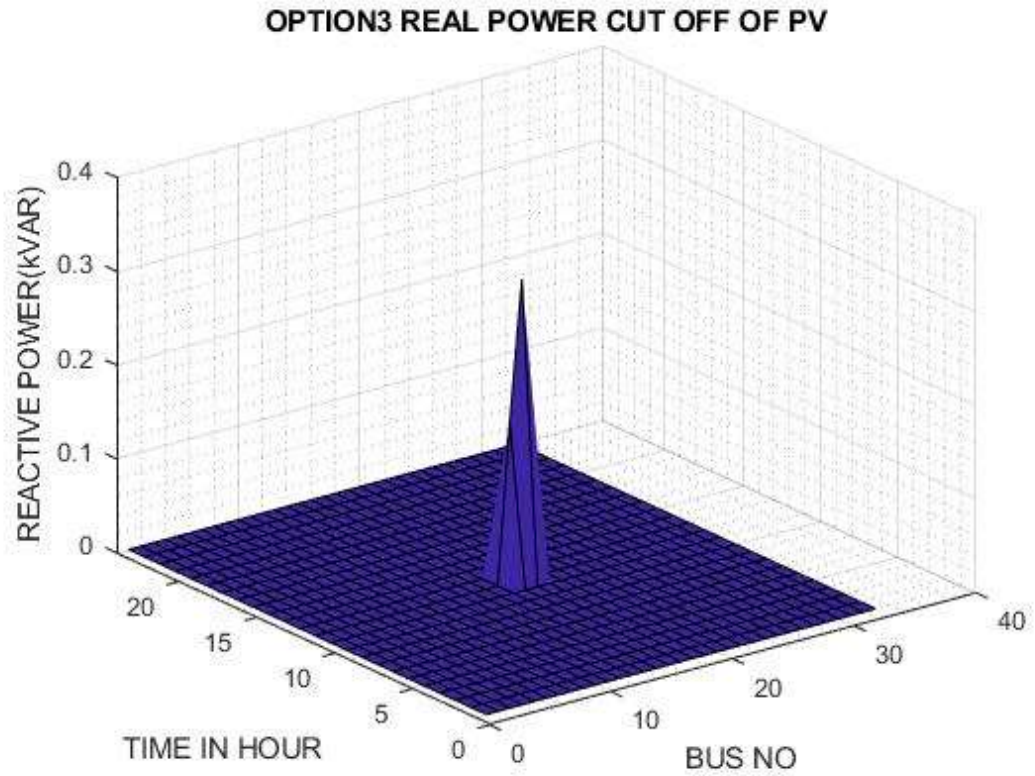


Figure 4. 6 Real power cut off of PV for MPVCL

The data obtained at optimal condition with net reactive generation by PV inverter during each hour of the day for each bus is presented in table B 5 and graphically shown in figure 4.7. It is observed from the figure that the reactive power of the PV inverters varied from its rated power factor to its rated capability limit according to the PV generation and load condition to maintain the voltage limit.

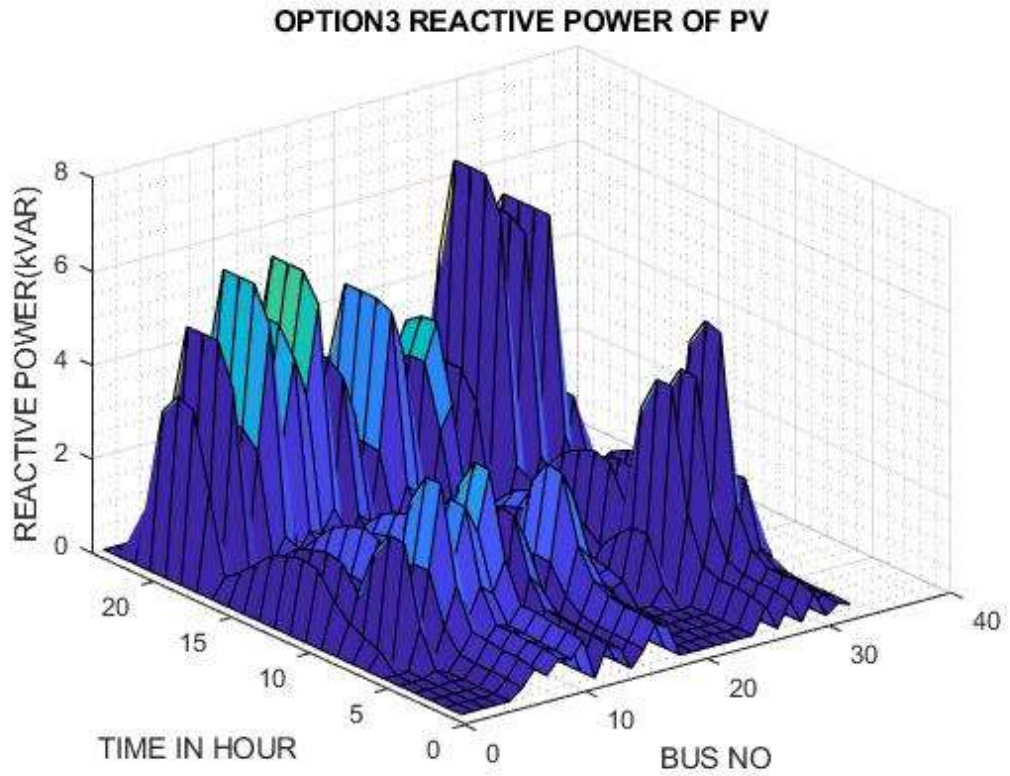


Figure 4. 7 Optimal condition reactive power of PV inverter for MPVCL

The data obtained at optimal condition with real power loss in the distribution network during each hour of the day for each bus is presented in table B 5 and graphically shown in figure 4.8. The optimal condition LF result for the power loss of the network showed that the real power loss during entire hour of the day is always less than the power loss at initial condition (without optimization).



Figure 4. 8 Real power (kW) loss condition before & after optimization of the network for MPVCL

The data of the distribution network at initial condition and data obtained after optimization for each hour of the day is presented in Table B.1, B.2, B.3, B.4, B.5 & B.6.

In the case of the Shiva Mandir Chowk Distribution Network, a scenario is created where there is a medium level of PV generation in relation to consumer load. The load flow analysis with optimization is performed using MATLAB. The graphs obtained from the analysis reveal a significant improvement in network voltage after implementing option 3 control measures, which involve PV inverter reactive power control and real power cut-off if required. Additionally, substantial reduction in power loss of the distribution network is observed after the optimization process.

4.3 Case 2: Test Results for High PV Generation w.r.t. Consumer Load (HPVCL) Case

Following the algorithm mentioned earlier and using all the mathematical expressions, complete coding of the work is done in MATLAB. The program is run for HPVCL Case and the results observed are explained below:

The initial voltage profile of the Shiva Mandir Chowk Area Distribution Network, Butwal is shown in table B 9 and graphically expressed in Figure 4.9. All the results are of R phase of the network. From the data, it is observed that during high PV generation period i.e. 11:00 to 15:00 hour voltage of network is more than 1.05 p.u. and during no PV generation & high load period i.e. 18:00 to 21:00 hour network voltage lies below 0.95 p.u.. The maximum voltage noted is 1.051 pu at bus 18 at 12:00 hour and minimum voltage noted is 0.809 at bus 18 at 20:00 hour. The summarized initial result of Network Voltage before optimization is shown in table A.3.

Table A. 3 Initial Voltage Profile & Loss of Network

Voltage	Value (PU)	Bus No.	Time (hr)	Real Power Loss (kW)
Min. Voltage	0.809	18	20	8.187
Max. Voltage	1.123	18	12	5.914

INITIAL VOLTAGE PROFILE OF THE NETWORK

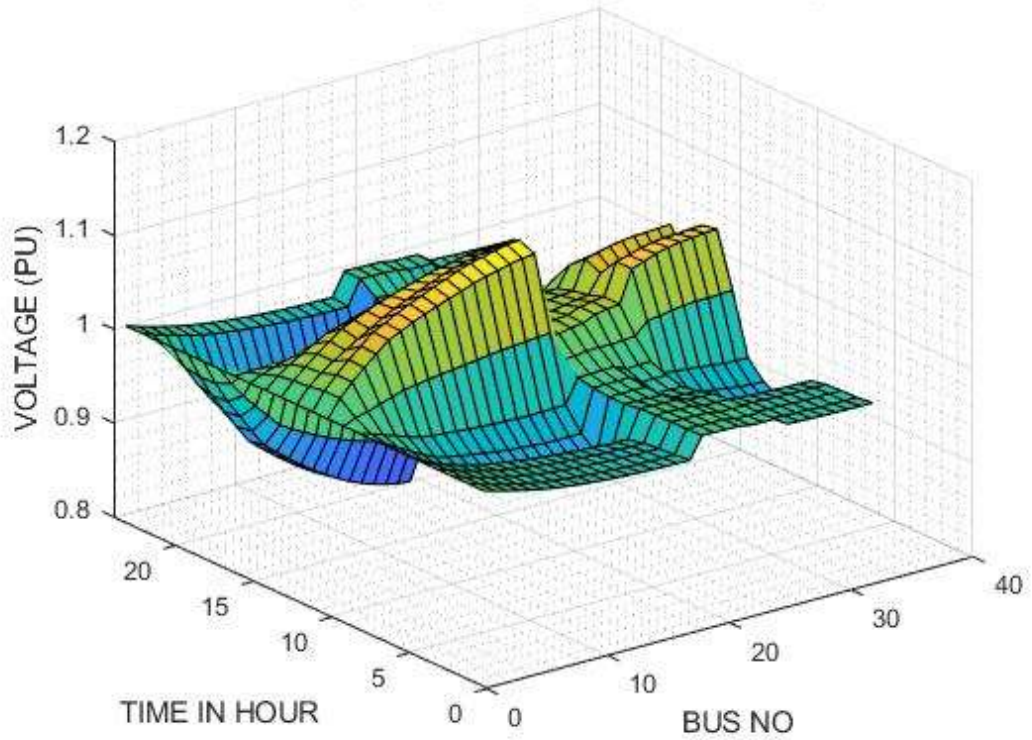


Figure 4. 9 Initial network voltage profile for HPVCL

The program is run for the optimal condition result and the optimal voltage profile condition is obtained at option 3. The optimal voltage of the network is presented in table B.11 and graphically expressed in Figure 4.10. At optimal condition maximum voltage is 1.04 p.u. of bus 18 at 11:00 hour and minimum voltage obtained is 0.989 pu of bus 31 at 18:00 hour which is within the $\pm 5\%$ limit range. Here real power cut off during optimization process is 30.74 kW 12:00 hour which is comparatively very high. The summarized result of Network Voltage after optimization is shown in table A.4.

Table A. 4 Optimal Voltage Profile & Loss of Network

Voltage	Value (PU)	Bus No.	Time (hr)	Real Power Loss (kW)
Min. Voltage	0.989	31	18	3.428
Max. Voltage	1.049	18	11	2.075

OPTION3 VOLTAGE PROFILE OF THE NETWORK

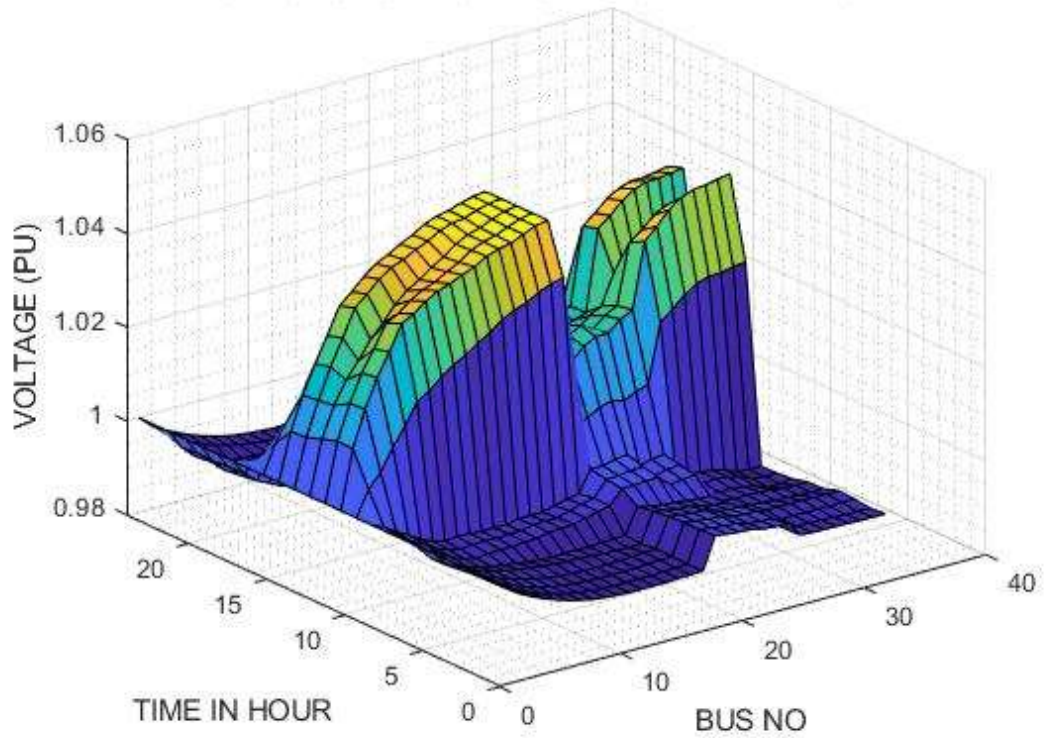


Figure 4. 10 Optimal condition network voltage profile for HPVCL

The data obtained for the real power flow within the Shiva Mandir Chowk Distribution Network is presented in table B.8 and B.10 and graphically represented in Figure 4.11. Here, the results show that at 9:00 to 17:00 hour time PV generation is greater than the load of network so net real power is supplied towards the grid at 9:00 to 17:00 hours and for the other hours power is supplied from the grid. At optimal condition, real power cut off of PV occurs i.e. 30.74 kW at 12:00 hour. Thus, optimal condition during HPVCL is obtained with real power cut off of PV generation.

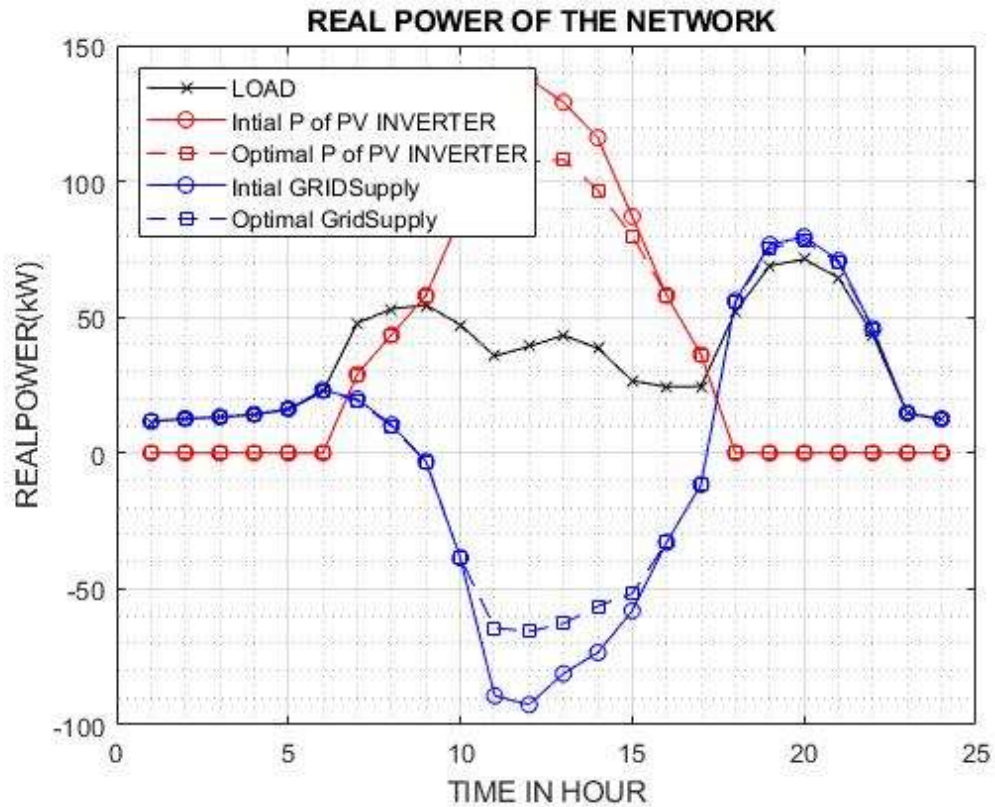


Figure 4. 11 Real power of Load, PV inverter and grid for HPVCL

The reactive power flow data within the Shiva Mandir Chowk Distribution Network is documented in tables B8 and B10. The graphical representation of this data can be found in Figure 4.12. Initially, there are different combinations of reactive power for load and solar PV generation on an hourly basis, resulting in varying net reactive power flow to and from the grid. In the optimal condition, the PV inverters supply reactive power within their rated power factor and capability limit to uphold the voltage limit. The net reactive power supplied to or from the grid adjusts accordingly based on the provision of reactive power from the PV inverters.

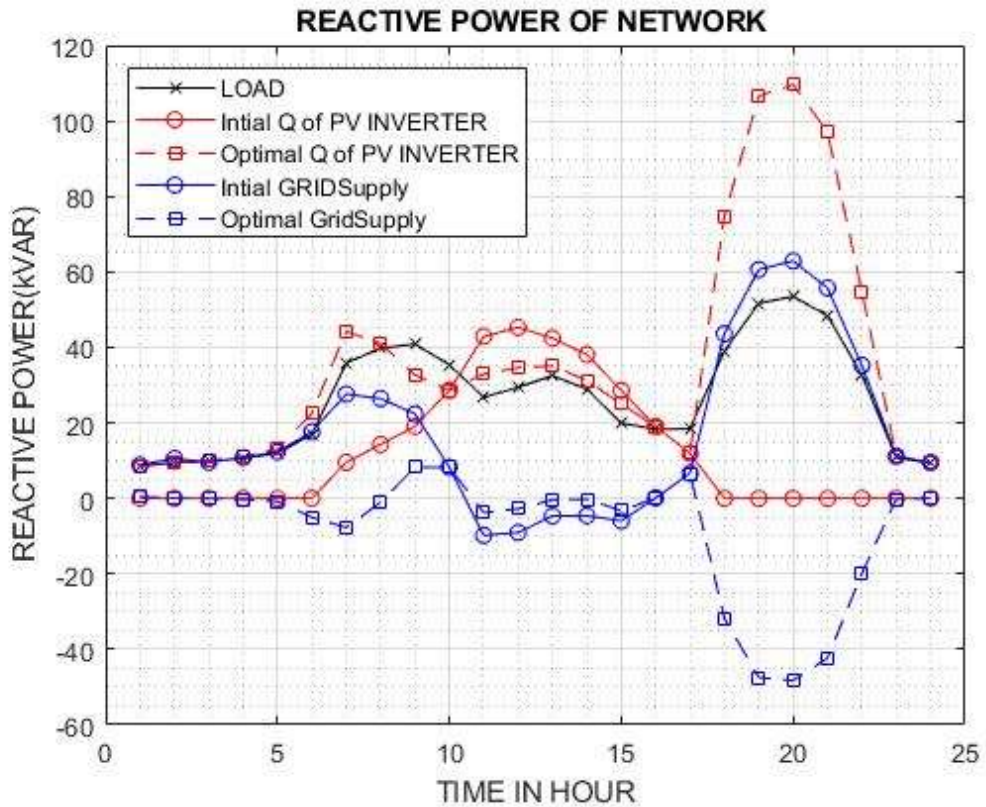


Figure 4. 12 Reactive power of load, PV inverter and grid for HPVCL

The data obtained after the running the program for optimal condition with real power cut off of PV generation is presented in Table B.10 and graphically represented by Figure 4.13. Here, the real power cut off is applied on the PVs whose voltage has exceeded 1.05 pu limit. It is observed that the real power cut off is maximum of 3.96 kW for bus 18 inverter at 12:00 hour.

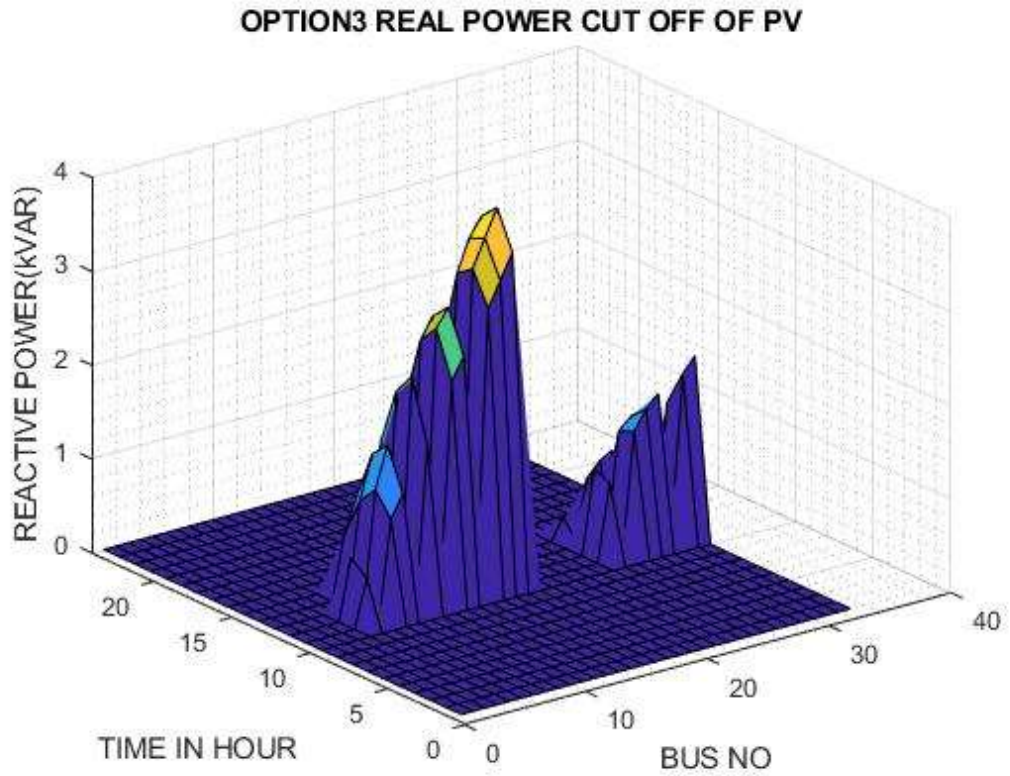


Figure 4. 13 Real power cut-off of PV for HPVCL

The data obtained at optimal condition with net reactive generation by PV inverter during each hour of the day for each bus is presented in table B.10 and graphically shown in figure 4.14. It is observed from the figure that the reactive power of the PV inverters varied from its rated power factor to its rated capability limit according to the PV generation and load condition to maintain the voltage limit.

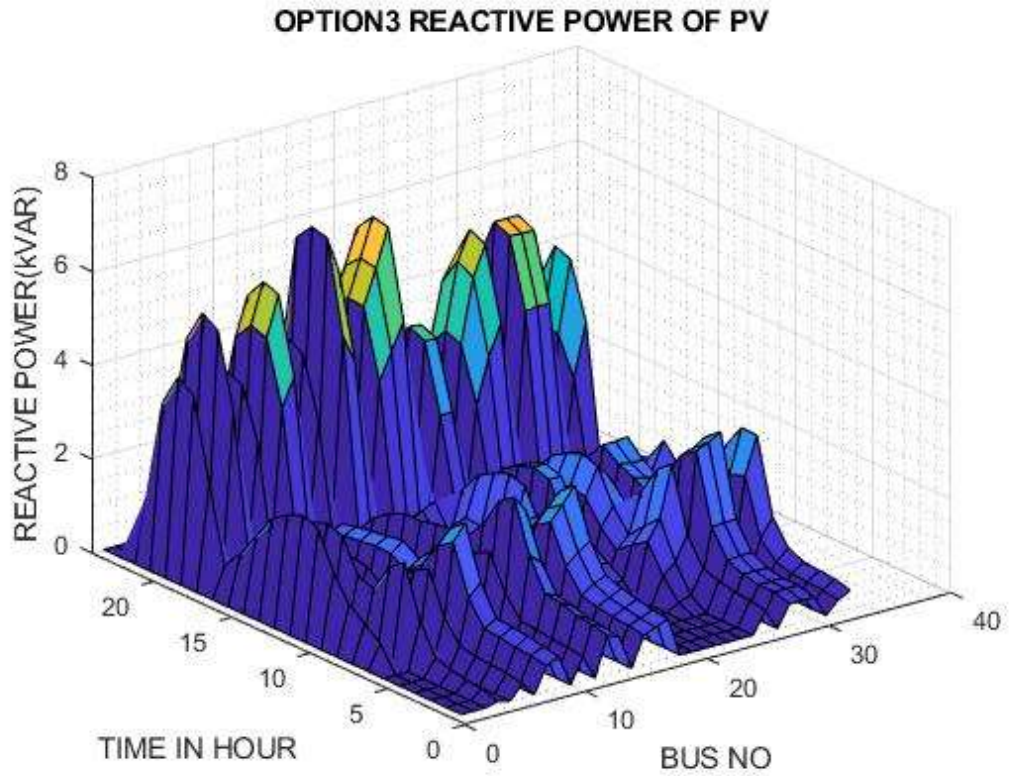


Figure 4. 14 Optimal condition reactive power of PV inverter for HPVCL

The data obtained at optimal condition with real power loss in the distribution network during each hour of the day for each bus is presented in table B.10 and graphically shown in figure 4.15. The optimal condition LF result for the power loss of the network showed that the real power loss during entire hour of the day is always less than the power loss at initial condition (without optimization).

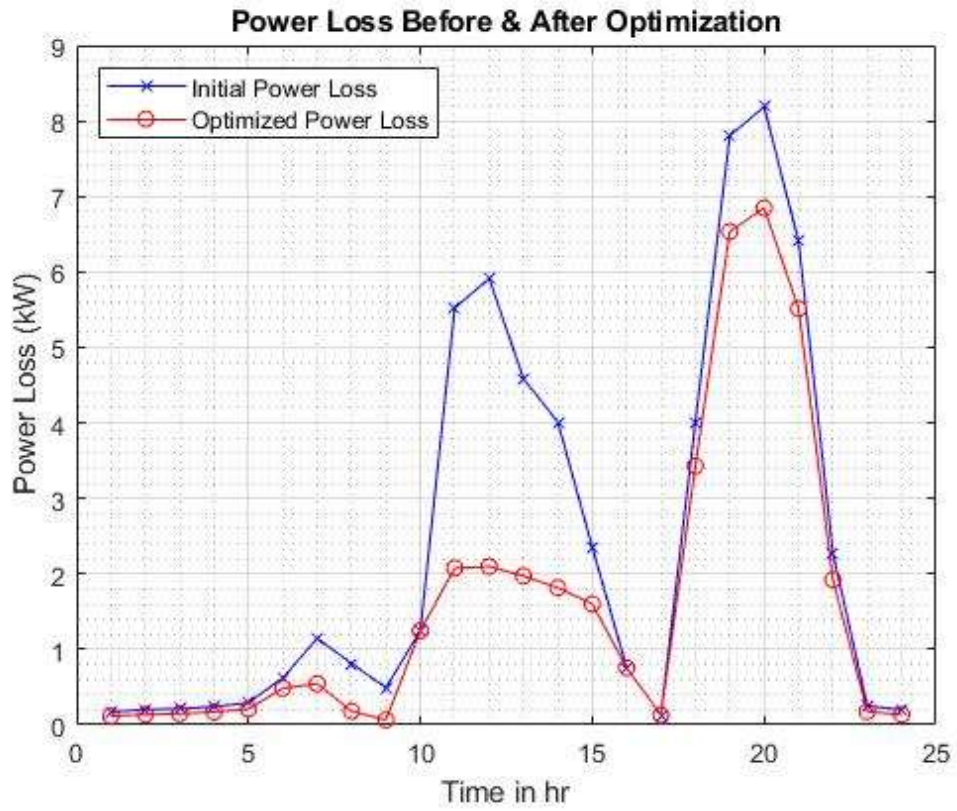


Figure 4. 15 Real Power (kW) Loss condition before & after optimization of the network for HPVCL

The data for the distribution network before and after optimization, corresponding to each hour of the day, can be found in Table B.7, B.8, B.9, B.10, and B.11.

In the case of the Shiva Mandir Chowk Distribution Network, a scenario with medium PV generation relative to consumer load is created. The load flow analysis with optimization is performed using MATLAB. The graphs presented demonstrate a significant improvement in network voltage after implementing option 3 control measures, which involve solar PV inverter reactive power control and real power cut-off if necessary. Initially, during the period between 11:00 and 15:00, when solar PV generation exceeds the load, the distribution network experiences poor performance with excessive voltage rise up to 1.123 pu. To mitigate this voltage rise and enhance the distribution network quality, the solar PV inverters are optimally controlled to inject inductive reactive power. However, the impact of reactive power control is limited due to the high R/X ratio of the distribution network, resulting in negligible improvement.

To address this limitation and further enhance network performance, real power cut-off of the solar PV generation is employed along with reactive power control as part of option 3. After implementing option 3, the real power is cut off during peak solar PV generation periods, leading to improved network performance. The voltage is improved from 1.123 pu to 1.049 pu, and the power loss is reduced from 5.91 kW to 2.07 kW.

4.4 Case 3: Test Results of Low PV Generation w.r.t. Consumer Load (LPVCL) Case

Following the flowchart mentioned earlier and using all the mathematical expressions, complete coding of the work is done in MATLAB. The program is run for LPVCL Case and the results observed are explained below:

The initial voltage profile of the Shiva Mandir Chowk Area Distribution Network, Butwal is shown in table B.14 and graphically expressed in Figure 4.16. All the results are of R phase of the network. From the data, it is observed that voltage is below than 1.0 pu during entire hours of the day and minimum voltage is 0.809 pu at node 18 (20:00 hour). This is due to no PV generation with respect to the load at that time. It is also observed that voltage varies according to load and PV generation. The summarized initial result of Network Voltage before optimization is shown in table A.5.

Table A. 5 Initial Voltage Profile & Loss of Network

Voltage	Value (PU)	Bus No.	Time (hr)	Real Power Loss (kW)
Min. Voltage	0.809	18	20	8.187
Max. Voltage	0.996	2	1	0.171

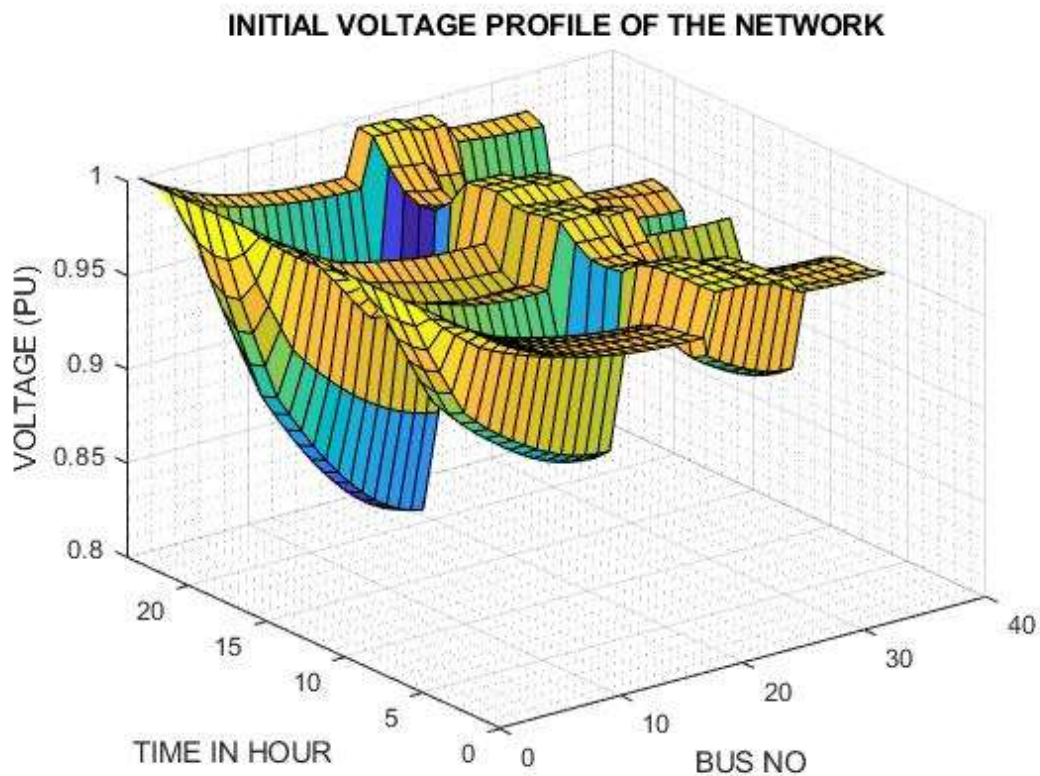


Figure 4. 16 Initial network voltage profile for LPVCL

The program is run for the optimal condition result and the optimal voltage profile condition is obtained at option 3. The optimal voltage of the network is presented in table B.16 and graphically expressed in Figure 4.17. From this figure it can be observed that voltage of the network is improved than initial condition due to the reactive power supplied from the PV inverters. During low or no PV generation period, the PV inverters act as VAR compensator to its capability limit. Between 7:00 to 9:00 hours, the PVs generation is low, so in this period voltage profile is improved to 0.95 pu.

Between 18:00 to 21:00 hours no PVs generation are there, so in this period voltage profile is improved to the values among them the minimum voltage is 0.866 pu at node 18 (20:00 hour). For the remaining hours of the day voltage is above 0.95 pu in the network. These voltages are obtained by varying the reactive power for PVs inverters from its rated power factor to its rated capability limit. The summarized result of Network Voltage after optimization is shown in table A.6.

Table A. 6 Optimal Voltage Profile & Loss of Network

Voltage	Value (PU)	Bus No.	Time (hr)	Real Power Loss (kW)
Min. Voltage	0.866521	18	20	5.20235266
Max. Voltage	0.99806	2	15	0.07429086

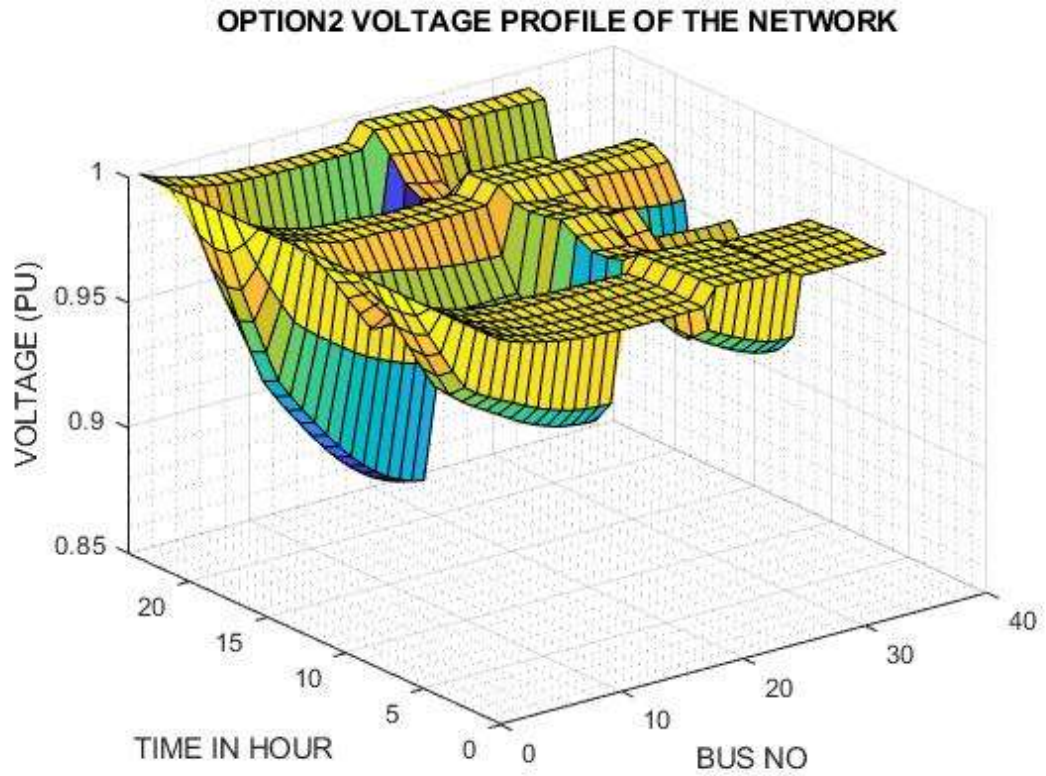


Figure 4. 17 Optimal condition network voltage profile for LPVCL

The data obtained for the real power flow within the Shiva Mandir Chowk Distribution Network is presented in table B.13 and B.15 and graphically represented in Figure 4.18. The results showed that real power of the load is greater than PV inverter for whole day duration. So, the net real power is supplied from the grid to meet the load for both the initial and optimal condition. In optimal condition the net real power supplied from the grid is less than initial condition. This is due to power loss in optimal condition is less than initial condition.

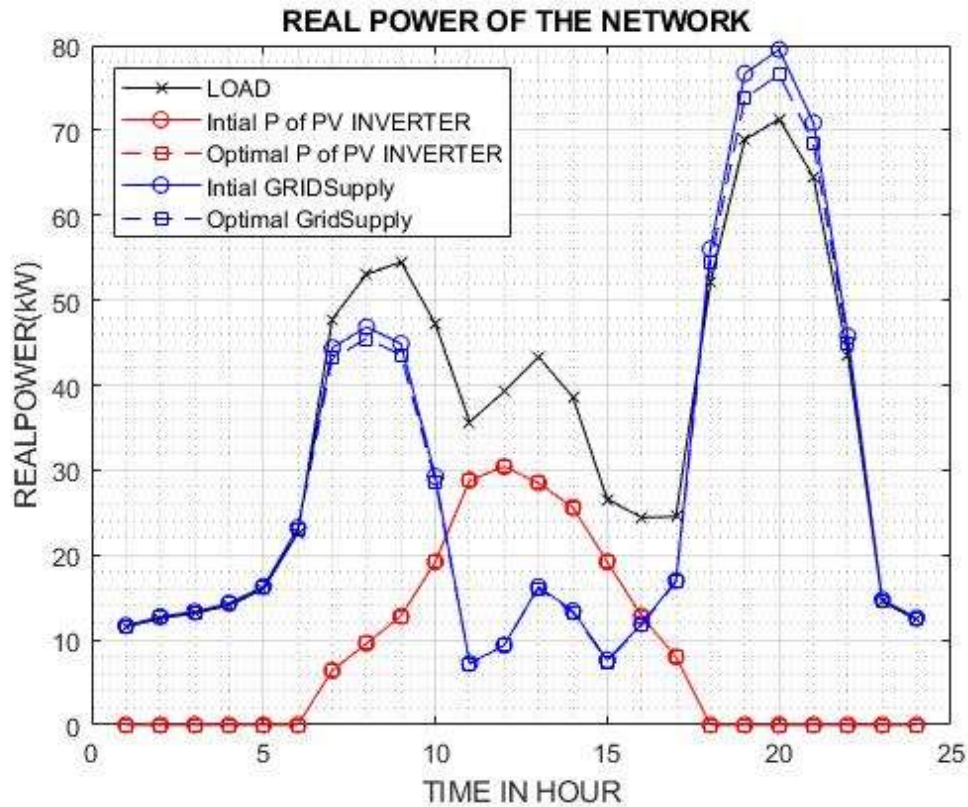


Figure 4. 18 Real power of Load, PV inverter and grid for LPVCL

The data obtained for the reactive power flow within the Shiva Mandir Chowk Distribution Network is presented in table B.13 and B.15 and graphically represented in Figure 4.19. Initially, reactive power of load and solar PV generation have different combination for entire hour of the day and net reactive power to & from the grid varied accordingly. At optimal condition, the reactive power supplied by the PV inverters varied from its rated power factor to its rated capability limit to maintain the voltage limit and the net reactive power supplied towards the grid or from the grid varied according to the supply of reactive power from the PV inverters. During low or no PV generation the inverter acts as VAR compensator to its capability limit.

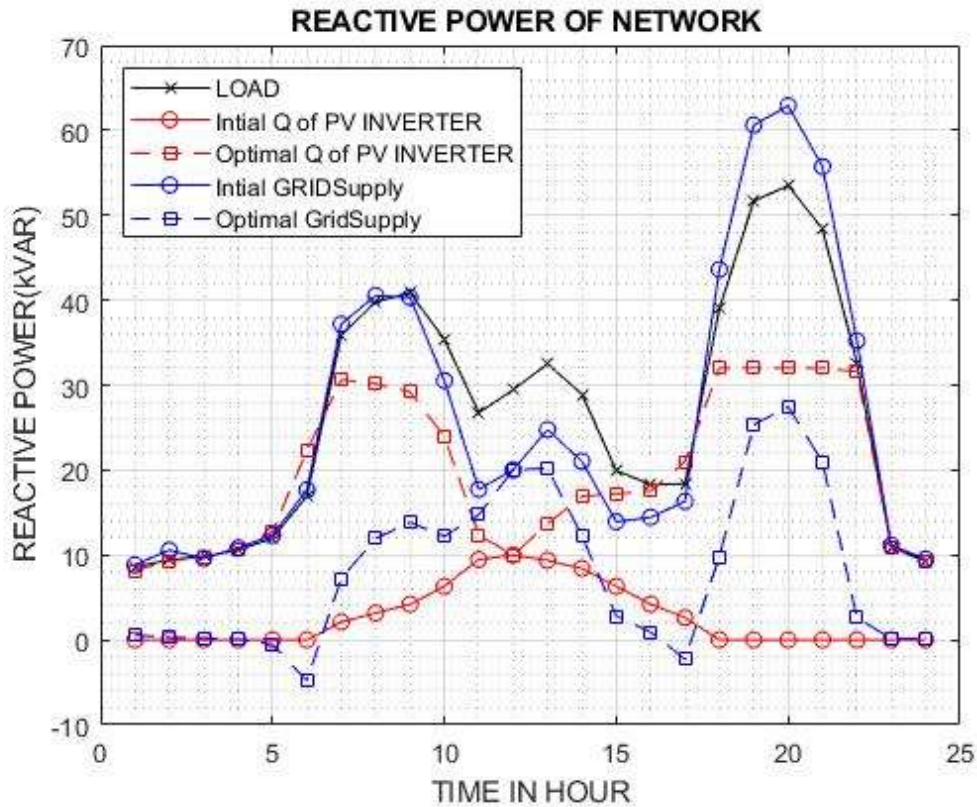


Figure 4. 19 Reactive power of Load, PV inverter and grid for LPVCL

The data obtained at optimal condition with net reactive generation by PV inverter during each hour of the day for each bus is presented in table B.15 and graphically shown in figure 4.20. It is observed from the figure that the reactive power of the PV inverters varied from its rated power factor to its rated capability limit according to the PV generation and load condition to maintain the voltage limit. It can be observed that the reactive power of the PV inverters is maximum according to its capability limit during no PV generation having high load period (18:00 to 21:00 hour).

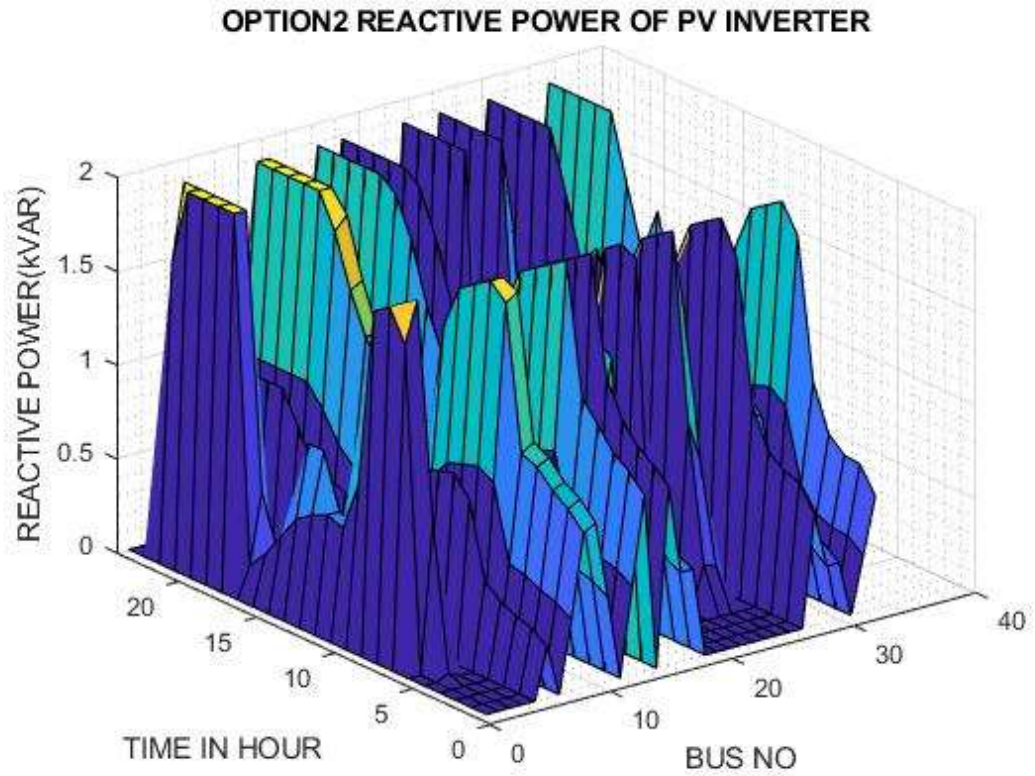


Figure 4. 20 Optimal condition reactive power of PV inverter for LPVCL

The data obtained at optimal condition with real power loss in the distribution network during each hour of the day for each bus is presented in table B.15 and graphically shown in figure 4.21. The optimal condition LF result for the power loss of the network showed that the real power loss during entire hour of the day is always less than the power loss at initial condition (without optimization).

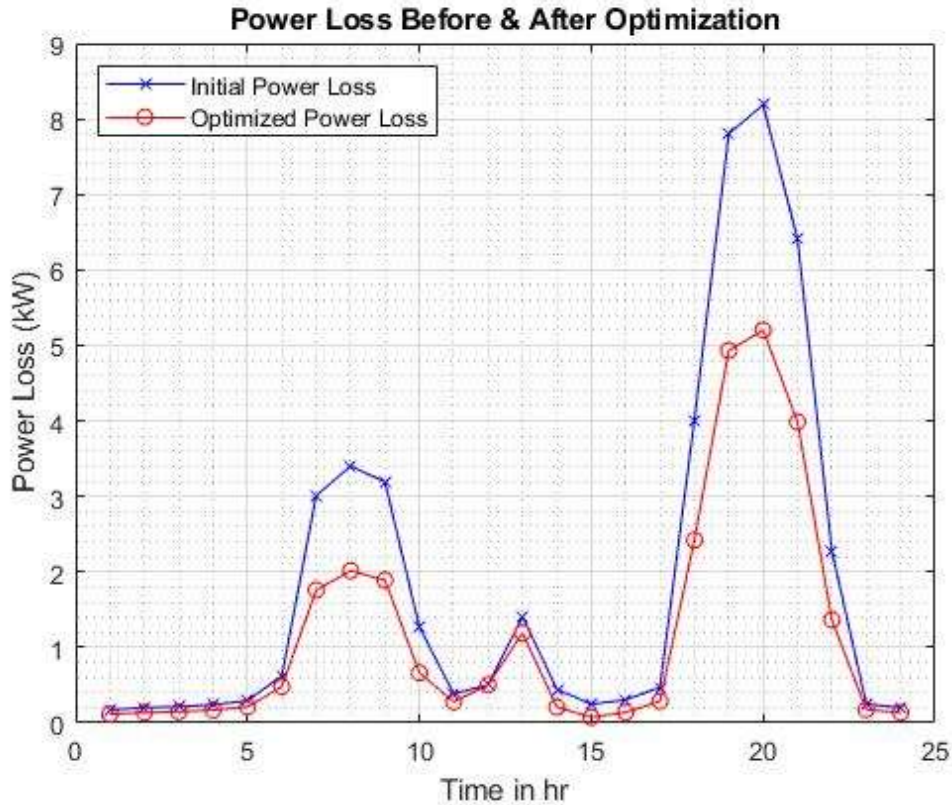


Figure 4. 21 Real Power (kW) Loss condition before & after optimization of the network for LPVCL

The data of the distribution network at initial condition and data obtained after optimization for each hour of the day is presented in Table B.12, B.13, B.14, B.15 & B.16.

Here, for the Shiva Mandir Chowk Distribution Network the case of Low PV generation w.r.t. consumer load is created and after the load flow with optimization is run in MATLAB. From the graphs presented above, it is found that the network voltage has improved drastically after applying option 2 control scheme, i.e. PV inverter reactive power control.

Figure 4.51 to 4.56 illustrate the initial condition of the distribution network, where the load demand significantly exceeds the solar PV generation, particularly between 18:00 to 21:00 hours. This results in a drastic voltage drop at bus 18; 20:00 hour, reaching as low as 0.809 pu. However, by implementing the proposed inverter control scheme, the voltage profile of the distribution network is improved. Specifically, at bus 18; 20:00 hour, the voltage improves from 0.809 to 0.866 pu, and the power loss is reduced from

8.187 kW to 5.202 kW. It is important to note that during the period of 18:00 to 21:00 hours, the network voltage profile cannot be further improved due to the low solar PV generation, as the generation and consumer peak load occur at different times of the day.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The study focuses on the distribution network of the Kalika Feeder in the Shiv Mandir Chowk Area, Butwal. The thesis proposes a solar PV inverter control strategy to effectively utilize the reactive power capability of the PV system. Three different cases of solar PV generation are considered:

1. Medium PV generation w.r.t. peak load (MPVCL): The PV generation is higher than the load between 10:00 to 16:00 hours. The results show that the reactive power capability of the PV inverters can maintain the desired voltage limit throughout the day with minimal real power cut-off during the peak energy generation period.
2. High PV generation w.r.t. consumer load (HPVCL): The PV generation is highest compared to the load between 9:00 to 17:00 hours. However, due to power loss constraints, the reactive power capability of the PV inverters is insufficient to maintain the required voltage limit between 11:00 to 15:00 hours. Therefore, real power cut-off is necessary for the PV system.
3. Low PV generation w.r.t. consumer load (LPVCL): The PV generation is low compared to the load throughout the day. The results indicate that the reactive power capability of the solar PV inverters can maintain the required voltage limit during peak load hours (18:00 to 21:00). Hence, solar PV generation and penetration in the network are beneficial for improving network performance.

So, the study provides a basis for electricity distribution system companies to use real and reactive power control strategy of rooftop PVs with inverter system to support low voltage system to improve the network voltage and also the operational performance of the network.

5.2 Recommendation

To successfully implement the solar PV power control scheme in a low voltage distribution network, the following factors need to be considered:

- **Reactive Power Feed-in Tariff:** Similar to the existing feed-in tariff for real power, a policy on the feed-in tariff for reactive power should be implemented. This will provide financial incentives to consumers who support the grid with their solar PV generation.
- **Advanced Metering System:** An advanced metering system, consisting of smart meters and smart PV inverters interfaced with the network, should be deployed. These systems have the capability to collect data, analyze it, and send control signals to optimize the PV inverters.

Despite the limitations of current advanced solar PV inverters in controlling reactive power and the absence of a reactive power feed-in policy, further research can be conducted to explore real-time control scenarios and overcome these challenges.

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APPENDIX A

Table B. 1 Load data of the network in kW

Time/Bus No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.2	0.2	0.4	0.2	0.3	0.6	1.6	1.6	1.6	1.1	1	0.9	0.9	0.8	0.8	0.9	0.9	1.5	1.5	2.5	2.4	2	0.4	0.3
3	0.3	0.4	0.4	0.4	0.4	0.5	1.7	1.8	1.5	1.1	0.8	0.7	0.7	0.7	0.7	0.7	0.7	1.5	1.7	1.6	1.9	2	0.3	0.3
4	0.6	0.5	0.6	0.6	0.5	0.8	0.9	1.2	1.1	0.8	0.6	0.6	0.6	0.6	0.7	0.6	0.6	1.6	1.8	2.6	2.7	2	0.5	0.6
5	0.4	0.4	0.4	0.5	0.3	0.7	1.9	2	2	1.8	1.2	0.8	0.8	0.8	0.8	0.8	0.8	1.7	1.6	1.7	1.6	2	0.4	0.4
6	0.1	0.1	0.4	0.2	0.2	0.7	2.8	2.7	2.5	1.9	1.5	2	0.7	0.7	0.7	0.7	0.7	1.7	1.5	1.5	1.5	1	0.4	0.2
7	0.4	0.4	0.5	0.5	0.3	0.8	2.5	2.6	2.6	1.7	1.7	1.9	0.8	0.8	0.8	0.8	0.8	1.6	0.99	1.7	1.5	1	0.4	0.5
8	0.8	0.9	0.9	0.9	0.6	1	1.7	1.8	1.8	1.6	1.8	1.7	0.7	0.7	0.7	0.7	0.7	1.7	1.7	1.8	1.7	2	0.8	0.9
9	0.9	0.9	0.9	1	0.4	0.6	1.9	1.7	1.6	1.5	1.7	1.6	0.8	0.8	0.8	0.8	0.8	1.5	1.6	1.8	1.6	2	0.9	1
10	0.3	0.3	0.4	0.4	0.3	0.7	1	1	1.2	1.2	0.9	1.6	0.7	1.3	0.7	0.7	0.7	1.7	2.5	2.7	2.4	1	0.3	0.3
11	0.5	0.5	0.5	0.5	0.4	0.7	1.2	1.4	1.3	1.3	1.5	1	0.9	0.9	0.9	0.9	0.9	1.8	1.7	1.6	1.9	1	0.4	0.5
12	0.6	0.6	0.6	0.6	0.4	0.8	1.3	1.6	1.7	1.5	1.7	1.6	1.2	1.2	1.2	1.2	1.2	1.5	1.9	1.8	1.9	1	0.5	0.6
13	0.6	0.7	0.7	0.7	0.4	0.9	1.6	1.7	1.6	1.4	1.2	1.2	1.2	1.2	1.2	1.2	1.5	1.7	2.8	2.9	2.6	2	0.6	0.7
14	0.3	0.4	0.4	0.8	0.4	0.6	2	2.3	2.1	1.9	1.5	1.3	0.9	1.3	0.9	0.9	0.9	1.6	2.5	2.5	2.5	1	0.4	0.3
15	0.3	0.4	0.3	0.3	0.5	0.6	1.9	2.5	2.3	1.8	1.6	1.4	0.9	1.7	0.9	1	0.8	1.6	2.8	2.6	2.7	2	0.3	0.3
16	0.4	0.4	0.4	0.4	0.4	0.8	1.8	1.9	1.9	1.3	1.3	1.4	1.5	1.5	1.6	1.5	1.5	1.9	2.7	2.7	2.8	1	0.4	0.3
17	0.4	0.4	0.4	0.4	0.9	0.8	1.9	2	2	1.8	0.4	0.9	0.5	1.3	0.5	0.5	0.5	2.4	2.9	2.4	2.9	1	0.4	0.3
18	0.4	0.4	0.3	0.4	0.6	0.9	1	1.1	1.2	1.2	0.8	0.9	0.8	1.3	0.8	0.9	1.6	2.7	3.5	3.4	2.7	1	0.3	0.3
19	0.3	0.3	0.3	0.7	0.7	0.9	0.8	1.3	1.3	1.3	0.9	0.8	0.8	1.2	0.7	0.8	0.8	1.7	2.6	2.6	2.6	2	0.6	0.2
20	0.4	0.4	0.4	0.4	0.4	0.9	0.5	0.7	1.6	1.1	0.7	1.3	0.6	1.6	0.5	0.6	0.6	1.4	2.7	2.6	2.6	1	0.4	0.3
21	0.4	0.5	0.5	0.5	0.9	0.5	0.6	1	1.2	0.9	0.7	0.7	0.6	2	0.7	0.7	0.7	1.7	2.5	2.2	2.2	2	0.4	0.4
22	0.4	0.4	0.4	0.4	0.3	0.7	0.8	1.1	1.1	0.7	0.6	0.5	0.4	1.9	0.5	0.5	0.5	1.5	1.8	1.6	2	2	0.4	0.3
23	0.2	0.2	0.4	0.7	0.7	0.9	0.9	1.2	1.5	0.5	0.3	0.9	0.3	1.2	0.3	0.3	0.3	1.5	2.5	2.4	2.2	2	0.5	0.1
24	0.1	0.3	0.2	0.6	0.5	0.8	0.8	0.8	0.9	0.6	0.4	1.3	0.6	1.2	0.8	0.6	0.6	1.8	2.4	2.9	2.6	1	0.4	0.2
25	0.3	0.4	0.4	0.3	0.9	1	1	0.9	0.9	0.8	0.6	0.6	0.6	1.7	0.8	0.6	0.7	1.7	2.6	2.6	2.2	2	0.3	0.3
26	0.4	0.4	0.5	0.3	0.4	0.2	1.2	1.2	1.2	1	0.9	0.8	2	1.2	0.9	0.8	0.8	1.7	1.7	1.9	1.9	1	0.3	0.3
27	0.4	0.4	0.4	0.4	0.4	0.6	1.6	1.7	1.7	0.8	0.8	1.3	1.9	1.6	0.9	0.8	0.8	0.8	1.8	1.6	1.6	1	0.4	0.3
28	0.3	0.3	0.3	0.3	0.4	0.5	1.4	1.5	1.5	0.7	0.7	0.9	1.9	1.3	0.5	0.5	0.7	2.6	3.6	3.6	2.5	2	0.3	0.2
29	0.3	0.3	0.3	0.2	0.5	0.4	1.5	1.7	1.7	0.8	0.9	0.8	1.5	0.9	0.8	0.9	0.9	2.7	3.5	3.3	2.9	1	0.2	0.2
30	0.3	0.3	0.3	0.2	0.5	0.5	1.8	1.8	1.8	0.6	0.8	1.9	1.7	1.3	0.5	0.5	1.7	1.5	1.5	2	2	2	0.2	0.2
31	0.2	0.4	0.3	0.3	0.4	0.7	2.1	2.2	2.2	1.4	1.5	1.6	1.9	0.9	1.9	0.9	0.9	2.5	3.4	3.2	1.5	2	0.3	0.2
32	0.2	0.2	0.2	0.1	0.4	0.8	2.8	2.7	2.6	1.4	1	2	13	1.6	1.9	0.5	0.6	1.5	1.85	1.9	1.9	1	0.5	0.2
33	0.3	0.4	0.3	0.3	0.4	0.7	1.2	2.5	2.5	1.7	1.5	1.7	1.3	1.9	1.3	0.7	1.5	0.9	1.25	1.3	1.3	1	0.7	0.3

*Data are for the phase R of the network. Power factor of the load is 0.80

Table B. 2 PV Generation Data in kW for MPVCL

Time/Bus No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Installed PV (kVA)	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	1	1.5	2	3	4.5	4.75	4.45	4	3	2	1.25	0	0	0	0	0	0	0	0	5
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	1	1.5	2	3	4.5	4.75	4.45	4	3	2	1.25	0	0	0	0	0	0	0	0	5
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0.6	0.9	1.2	1.8	2.7	2.85	2.67	2.4	1.8	1.2	0.75	0	0	0	0	0	0	0	0	3
7	0	0	0	0	0	0	1.2	1.8	2.4	3.6	5.4	5.7	5.34	4.8	3.6	2.4	1.5	0	0	0	0	0	0	0	0	6
8	0	0	0	0	0	0	0.6	0.9	1.2	1.8	2.7	2.85	2.67	2.4	1.8	1.2	0.75	0	0	0	0	0	0	0	0	3
9	0	0	0	0	0	0	1	1.5	2	3	4.5	4.75	4.45	4	3	2	1.25	0	0	0	0	0	0	0	0	5
10	0	0	0	0	0	0	0.8	1.2	1.6	2.4	3.6	3.8	3.56	3.2	2.4	1.6	1	0	0	0	0	0	0	0	0	4
11	0	0	0	0	0	0	1.2	1.8	2.4	3.6	5.4	5.7	5.34	4.8	3.6	2.4	1.5	0	0	0	0	0	0	0	0	6
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0.8	1.2	1.6	2.4	3.6	3.8	3.56	3.2	2.4	1.6	1	0	0	0	0	0	0	0	0	4
14	0	0	0	0	0	0	0.6	0.9	1.2	1.8	2.7	2.85	2.67	2.4	1.8	1.2	0.75	0	0	0	0	0	0	0	0	3
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.78	1.6	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
17	0	0	0	0	0	0	1	1.5	2	3	4.5	4.75	4.45	4	3	2	1.25	0	0	0	0	0	0	0	0	5
18	0	0	0	0	0	0	0.8	1.2	1.6	2.4	3.6	3.8	3.56	3.2	2.4	1.6	1	0	0	0	0	0	0	0	0	4
19	0	0	0	0	0	0	0.6	0.9	1.2	1.8	2.7	2.85	2.67	2.4	1.8	1.2	0.75	0	0	0	0	0	0	0	0	3
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0.8	1.2	1.6	2.4	3.6	3.8	3.56	3.2	2.4	1.6	1	0	0	0	0	0	0	0	0	4
22	0	0	0	0	0	0	1	1.5	2	3	4.5	4.75	4.45	4	3	2	1.25	0	0	0	0	0	0	0	0	5
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0.6	0.9	1.2	1.8	2.7	2.85	2.67	2.4	1.8	1.2	0.75	0	0	0	0	0	0	0	0	3
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	0	7
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	1.2	1.8	2.4	3.6	5.4	5.7	5.34	4.8	3.6	2.4	1.5	0	0	0	0	0	0	0	0	6
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	1.2	1.8	2.4	3.6	5.4	5.7	5.34	4.8	3.6	2.4	1.5	0	0	0	0	0	0	0	0	6
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.78	1.6	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
33	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	0.95	0.89	0.8	0.6	0.4	0.25	0	0	0	0	0	0	0	0	1

*All data are for the phase R of the network. Initial operating power factor of PV inverter is 0.95

Table B. 3 Initial Results of the system for MPVCL

Time	Total Load (kW)	Total Load (kVAR)	Total Solar Generation (kW)	Total Solar Generation (kVAR)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVAR)	Total Real Power Supply by Grid (kW)	Total Reactive Power Supply by Grid (kVAR)
1	11.75	8.8125	0	0	0.154751557	0.177583754	11.90475156	8.990083754
2	12.62	9.465	0	0	0.176139505	0.202127301	12.79613951	10.47563651
3	12.9	9.675	0	0	0.178672192	0.205033663	13.07867219	9.469966337
4	13.57	10.1775	0	0	0.189771009	0.217770011	13.75977101	10.39527001
5	14.988	11.241	0	0	0.217950283	0.250106883	15.20595028	11.49110688
6	22.261	16.69575	0	0	0.514037546	0.589879152	22.77503755	17.28562915
7	46.66	34.995	18.4	6.047787535	1.432533141	1.64389049	29.69253314	30.59110295
8	52.284	39.213	27.6	9.071681303	1.332735946	1.529369118	26.01673595	31.67068782
9	52.68	39.51	36.8	12.09557507	0.834813616	0.957982839	16.71481362	28.37240777
10	38.83	29.1225	55.2	18.14336261	0.260813807	0.299294532	-16.10918619	11.27843193
11	32.84	24.63	82.8	27.21504391	1.45966577	1.675026294	-48.50033423	-0.910017615
12	37.5	26.51650429	87.4	28.72699079	1.489050422	1.708746386	-48.41094958	-0.501740113
13	42.53	31.8975	81.88	26.91265453	1.275271119	1.463425874	-38.07472888	6.448271342
14	38.56	28.92	73.6	24.19115014	0.89417642	1.026104088	-34.14582358	5.754953947
15	27.42	20.565	55.2	18.14336261	0.493479318	0.566287742	-27.28652068	2.987925136
16	24.14	18.105	36.8	12.09557507	0.129252243	0.148322246	-12.53074776	6.157747176
17	27.65	20.7375	23	7.559734419	0.17665503	0.202718887	4.82665503	13.38048447
18	55.2	41.4	0	0	3.822852139	4.386879504	59.02285214	45.7868795
19	71.39	53.5425	0	0	6.840544858	7.849805575	78.23054486	61.39230558
20	73.14	54.855	0	0	6.92495974	7.946675111	80.06495974	62.80167511
21	68.365	51.27375	0	0	5.867522951	6.733223059	74.23252295	58.00697306
22	46.04	34.53	0	0	2.205335254	2.530712586	48.24533525	37.06071259
23	13.37	10.0275	0	0	0.181333743	0.208087901	13.55133374	10.2355879
24	11.25	8.4375	0	0	0.144146449	0.165413957	11.39414645	8.602913957

Table B. 4 Initial voltage profile of the network in PU for MPVCL

Bus No./Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.000	0.997	0.994	0.991	0.988	0.986	0.984	0.983	0.981	0.980	0.979	0.978	0.978	0.977	0.977	0.976	0.976
2	1.000	0.996	0.993	0.990	0.988	0.985	0.983	0.981	0.980	0.979	0.978	0.977	0.976	0.976	0.975	0.975	0.975
3	1.000	0.996	0.993	0.990	0.987	0.985	0.983	0.981	0.980	0.979	0.978	0.977	0.976	0.975	0.975	0.975	0.975
4	1.000	0.996	0.993	0.990	0.987	0.984	0.983	0.981	0.979	0.978	0.977	0.976	0.975	0.974	0.974	0.974	0.974
5	1.000	0.996	0.992	0.989	0.986	0.984	0.982	0.980	0.979	0.978	0.976	0.975	0.974	0.973	0.973	0.972	0.972
6	1.000	0.993	0.988	0.983	0.979	0.974	0.972	0.969	0.967	0.965	0.963	0.961	0.960	0.959	0.958	0.957	0.957
7	1.000	0.990	0.980	0.972	0.963	0.956	0.952	0.948	0.945	0.942	0.939	0.937	0.934	0.932	0.931	0.930	0.930
8	1.000	0.990	0.981	0.973	0.965	0.958	0.954	0.951	0.948	0.945	0.942	0.939	0.937	0.935	0.933	0.932	0.932
9	1.000	0.992	0.985	0.979	0.973	0.967	0.965	0.962	0.960	0.958	0.956	0.954	0.952	0.950	0.949	0.949	0.948
10	1.000	1.001	1.000	1.001	1.001	1.001	1.001	1.001	1.001	1.001	1.000	1.000	0.999	0.999	0.998	0.999	0.999
11	1.000	1.008	1.013	1.019	1.024	1.029	1.033	1.036	1.038	1.040	1.042	1.043	1.045	1.046	1.047	1.048	1.049
12	1.000	1.008	1.013	1.019	1.024	1.029	1.033	1.036	1.039	1.042	1.044	1.045	1.047	1.048	1.049	1.050	1.051
13	1.000	1.005	1.007	1.010	1.012	1.014	1.019	1.023	1.026	1.029	1.031	1.032	1.034	1.035	1.036	1.038	1.039
14	1.000	1.004	1.008	1.012	1.016	1.020	1.023	1.026	1.028	1.029	1.030	1.031	1.031	1.032	1.032	1.033	1.033
15	1.000	1.004	1.006	1.009	1.012	1.014	1.016	1.018	1.020	1.021	1.022	1.022	1.022	1.023	1.023	1.024	1.025
16	1.000	1.001	1.001	1.002	1.003	1.003	1.004	1.004	1.004	1.004	1.004	1.003	1.003	1.003	1.003	1.003	1.003
17	1.000	0.997	0.994	0.991	0.989	0.986	0.985	0.984	0.983	0.981	0.980	0.979	0.978	0.977	0.976	0.976	0.975
18	1.000	0.983	0.968	0.955	0.942	0.930	0.923	0.916	0.910	0.905	0.900	0.895	0.892	0.888	0.885	0.883	0.881
19	1.000	0.977	0.957	0.940	0.924	0.908	0.898	0.889	0.881	0.873	0.866	0.859	0.853	0.848	0.844	0.841	0.839
20	1.000	0.976	0.956	0.939	0.922	0.906	0.897	0.888	0.880	0.872	0.865	0.859	0.853	0.849	0.845	0.842	0.840
21	1.000	0.978	0.960	0.944	0.929	0.914	0.905	0.897	0.889	0.881	0.874	0.868	0.863	0.858	0.855	0.852	0.850
22	1.000	0.986	0.974	0.964	0.955	0.946	0.941	0.937	0.933	0.929	0.926	0.923	0.920	0.918	0.916	0.915	0.914
23	1.000	0.996	0.993	0.990	0.987	0.985	0.983	0.981	0.980	0.979	0.978	0.977	0.977	0.976	0.976	0.975	0.975
24	1.000	0.997	0.994	0.991	0.989	0.986	0.985	0.983	0.982	0.981	0.980	0.979	0.978	0.978	0.977	0.977	0.977

Continued...

Bus No./Time	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	0.976	0.996	0.996	0.996	0.995	0.993	0.993	0.993	0.985	0.985	0.984	0.984	0.984	0.983	0.983	0.983
2	0.975	0.996	0.996	0.995	0.995	0.993	0.993	0.992	0.984	0.984	0.983	0.983	0.982	0.982	0.982	0.982
3	0.974	0.996	0.995	0.995	0.995	0.993	0.993	0.992	0.984	0.984	0.983	0.983	0.982	0.982	0.982	0.982
4	0.973	0.995	0.995	0.995	0.995	0.992	0.992	0.992	0.984	0.983	0.983	0.983	0.982	0.982	0.982	0.982
5	0.971	0.995	0.994	0.994	0.994	0.991	0.991	0.991	0.983	0.982	0.981	0.981	0.980	0.980	0.980	0.979
6	0.956	0.993	0.992	0.992	0.991	0.987	0.986	0.986	0.973	0.972	0.971	0.970	0.969	0.969	0.968	0.968
7	0.929	0.990	0.990	0.990	0.989	0.980	0.979	0.979	0.952	0.949	0.947	0.944	0.942	0.940	0.939	0.939
8	0.932	0.990	0.990	0.990	0.990	0.980	0.980	0.980	0.955	0.951	0.949	0.946	0.944	0.942	0.940	0.940
9	0.948	0.992	0.992	0.992	0.992	0.984	0.984	0.984	0.965	0.962	0.960	0.957	0.955	0.953	0.952	0.951
10	0.999	1.001	1.001	1.002	1.002	1.000	1.000	1.000	1.001	1.001	1.001	1.001	1.000	1.000	0.999	0.999
11	1.050	1.009	1.010	1.012	1.013	1.014	1.014	1.014	1.031	1.032	1.033	1.033	1.034	1.033	1.033	1.033
12	1.052	1.009	1.010	1.012	1.013	1.013	1.013	1.013	1.031	1.031	1.031	1.031	1.031	1.030	1.030	1.029
13	1.040	1.006	1.008	1.009	1.010	1.008	1.008	1.008	1.011	1.007	1.004	1.001	0.997	0.993	0.990	0.990
14	1.034	1.004	1.004	1.005	1.005	1.007	1.007	1.006	1.021	1.021	1.021	1.021	1.021	1.020	1.020	1.019
15	1.025	1.005	1.005	1.006	1.007	1.006	1.006	1.006	1.015	1.014	1.014	1.014	1.013	1.012	1.011	1.011
16	1.003	1.001	1.001	1.002	1.002	1.001	1.001	1.001	1.004	1.003	1.004	1.003	1.003	1.003	1.003	1.003
17	0.975	0.997	0.997	0.997	0.997	0.994	0.993	0.993	0.985	0.984	0.983	0.982	0.981	0.980	0.980	0.979
18	0.880	0.981	0.979	0.978	0.978	0.966	0.965	0.965	0.925	0.921	0.918	0.915	0.913	0.911	0.910	0.910
19	0.838	0.974	0.972	0.971	0.970	0.955	0.953	0.952	0.902	0.896	0.891	0.887	0.885	0.883	0.882	0.881
20	0.839	0.974	0.972	0.971	0.970	0.954	0.952	0.951	0.900	0.895	0.890	0.886	0.883	0.881	0.880	0.880
21	0.849	0.975	0.973	0.972	0.972	0.958	0.956	0.956	0.910	0.905	0.901	0.898	0.896	0.895	0.894	0.893
22	0.914	0.984	0.983	0.982	0.981	0.973	0.972	0.971	0.942	0.939	0.936	0.934	0.932	0.931	0.930	0.930
23	0.975	0.996	0.995	0.995	0.995	0.992	0.992	0.992	0.984	0.983	0.982	0.982	0.981	0.981	0.980	0.980
24	0.977	0.996	0.996	0.996	0.996	0.994	0.994	0.993	0.986	0.985	0.985	0.985	0.984	0.984	0.984	0.984

Table B. 5 Optimal condition results of the system for MPVCL

Time	Total Load (kW)	Total Load (kVAR)	Total Solar Generation (kW)	Total Solar Generation (kVAR)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVAR)	Total Real Power Supply by Grid (kW)	Total Reactive Power Supply by Grid (kVAR)	Total Solar PV Cut-Off (kW)
1	11.75	8.8125	0	7.901666538	0.101329998	0.116280325	11.85133	1.027113787	0
2	12.62	9.465	0	8.839341231	0.116322166	0.133484453	12.73632217	0.759143222	0
3	12.9	9.675	0	8.928465458	0.118177338	0.135613339	13.01817734	0.88214788	0
4	13.57	10.1775	0	9.466893067	0.127310535	0.146094057	13.69731054	0.85670099	0
5	14.988	11.241	0	10.67759241	0.149903659	0.172020592	15.13790366	0.735428185	0
6	22.261	16.69575	0	20.87902295	0.387845061	0.445068103	22.64884506	-3.738204843	0
7	46.66	34.995	18.4	49.14936256	0.93951731	1.078134619	29.19951731	-13.07622794	0
8	52.284	39.213	27.6	50.00523847	0.719746521	0.825938631	25.40374652	-9.966299836	0
9	52.68	39.51	36.8	43.31106022	0.289267388	0.331946183	16.16926739	-3.469114042	0
10	38.83	29.1225	55.2	18.14336261	0.260813807	0.299294532	-16.10918619	11.27843193	0
11	32.84	24.63	82.8	27.21504391	1.45966577	1.675026294	-48.50033423	-0.910017615	0
12	37.5	26.51650429	86.91	28.52135474	1.44445027	1.657565883	-47.96554973	-0.347284557	0.49
13	42.53	31.8975	81.88	27.05409526	1.269933247	1.457300447	-38.08006675	6.300705191	0
14	38.56	28.92	73.6	24.19115014	0.89417642	1.026104088	-34.14582358	5.754953947	0
15	27.42	20.565	55.2	18.14336261	0.493479318	0.566287742	-27.28652068	2.987925136	0
16	24.14	18.105	36.8	12.09557507	0.129252243	0.148322246	-12.53074776	6.157747176	0
17	27.65	20.7375	23	16.37949545	0.04005895	0.045969287	4.69005895	4.403973836	0
18	55.2	41.4	0	76.84121417	3.296077517	3.782384035	58.49607752	-31.65883014	0
19	71.39	53.5425	0	88.5541105	4.608862537	5.288858649	75.99886254	-29.72275185	0
20	73.14	54.855	0	88.71737574	4.654256327	5.340949883	77.79425633	-28.52142586	0
21	68.365	51.27375	0	87.51009989	4.283024083	4.914945669	72.64802408	-31.32140422	0
22	46.04	34.53	0	57.61330524	1.914624085	2.197109606	47.95462409	-20.88619563	0
23	13.37	10.0275	0	8.85679513	0.119590983	0.137235554	13.48959098	1.307940424	0
24	11.25	8.4375	0	7.360549832	0.093909011	0.107764439	11.34390901	1.184714607	0

Table B. 6 Optimal voltage profile of the network in PU for MPVCL

Bus No./Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990
2	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990
3	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990
4	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990
5	1.000	0.998	0.996	0.995	0.994	0.993	0.993	0.992	0.992	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990
6	1.000	0.997	0.995	0.994	0.994	0.993	0.993	0.992	0.992	0.992	0.991	0.991	0.990	0.990	0.990	0.990	0.990
7	1.000	0.998	0.996	0.995	0.994	0.994	0.994	0.994	0.994	0.995	0.994	0.994	0.993	0.993	0.993	0.993	0.993
8	1.000	0.998	0.996	0.996	0.995	0.994	0.995	0.995	0.995	0.995	0.995	0.994	0.993	0.993	0.992	0.992	0.993
9	1.000	0.998	0.997	0.996	0.996	0.995	0.996	0.996	0.996	0.996	0.995	0.995	0.994	0.994	0.993	0.994	0.994
10	1.000	1.001	1.000	1.001	1.001	1.001	1.001	1.001	1.001	1.001	1.000	1.000	0.999	0.999	0.998	0.999	0.999
11	1.000	1.008	1.013	1.019	1.024	1.029	1.033	1.036	1.038	1.040	1.042	1.043	1.045	1.046	1.047	1.048	1.049
12	1.000	1.008	1.013	1.019	1.024	1.029	1.032	1.035	1.038	1.041	1.043	1.044	1.045	1.046	1.047	1.048	1.050
13	1.000	1.005	1.007	1.010	1.012	1.014	1.019	1.023	1.026	1.029	1.031	1.033	1.034	1.036	1.037	1.038	1.039
14	1.000	1.004	1.008	1.012	1.016	1.020	1.023	1.026	1.028	1.029	1.030	1.031	1.031	1.032	1.032	1.033	1.033
15	1.000	1.004	1.006	1.009	1.012	1.014	1.016	1.018	1.020	1.021	1.022	1.022	1.022	1.023	1.023	1.024	1.025
16	1.000	1.001	1.001	1.002	1.003	1.003	1.004	1.004	1.004	1.004	1.004	1.003	1.003	1.003	1.003	1.003	1.003
17	1.000	0.998	0.997	0.996	0.995	0.994	0.994	0.994	0.993	0.993	0.992	0.992	0.991	0.991	0.990	0.990	0.991
18	1.000	0.997	0.994	0.994	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.992	0.991	0.991	0.990	0.990	0.990
19	1.000	0.994	0.988	0.986	0.982	0.980	0.979	0.978	0.976	0.974	0.972	0.970	0.968	0.966	0.965	0.964	0.964
20	1.000	0.993	0.987	0.984	0.981	0.979	0.978	0.976	0.975	0.973	0.972	0.970	0.968	0.967	0.965	0.965	0.965
21	1.000	0.994	0.990	0.988	0.987	0.985	0.985	0.984	0.982	0.981	0.979	0.977	0.976	0.974	0.973	0.972	0.972
22	1.000	0.996	0.994	0.994	0.993	0.993	0.993	0.993	0.993	0.994	0.994	0.993	0.993	0.992	0.992	0.992	0.993
23	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.991	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990
24	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990

Continued..

Bus No./Time	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	0.990	0.998	0.997	0.997	0.997	0.996	0.996	0.996	0.993	0.993	0.992	0.992	0.992	0.992	0.992	0.992
2	0.990	0.997	0.997	0.997	0.997	0.996	0.996	0.996	0.993	0.992	0.992	0.992	0.992	0.992	0.991	0.991
3	0.990	0.997	0.997	0.997	0.997	0.996	0.996	0.996	0.993	0.992	0.992	0.992	0.992	0.992	0.992	0.992
4	0.990	0.997	0.997	0.997	0.997	0.996	0.995	0.995	0.993	0.993	0.993	0.992	0.992	0.992	0.992	0.992
5	0.990	0.997	0.996	0.996	0.996	0.995	0.995	0.995	0.993	0.992	0.992	0.992	0.992	0.991	0.991	0.991
6	0.990	0.996	0.996	0.995	0.995	0.995	0.994	0.994	0.993	0.992	0.992	0.992	0.991	0.991	0.991	0.990
7	0.994	0.998	0.998	0.998	0.998	0.996	0.995	0.995	0.994	0.993	0.992	0.991	0.991	0.990	0.989	0.989
8	0.993	0.997	0.997	0.997	0.997	0.996	0.996	0.995	0.994	0.993	0.992	0.991	0.990	0.989	0.988	0.988
9	0.994	0.998	0.997	0.997	0.998	0.996	0.996	0.996	0.995	0.994	0.994	0.993	0.992	0.991	0.990	0.990
10	0.999	1.001	1.001	1.002	1.002	1.000	1.000	1.000	1.001	1.001	1.001	1.001	1.000	1.000	0.999	0.999
11	1.050	1.009	1.010	1.012	1.013	1.014	1.014	1.014	1.031	1.032	1.033	1.033	1.034	1.033	1.033	1.033
12	1.050	1.009	1.010	1.012	1.013	1.013	1.013	1.013	1.030	1.030	1.031	1.031	1.030	1.030	1.029	1.029
13	1.040	1.006	1.008	1.009	1.010	1.008	1.008	1.008	1.011	1.008	1.005	1.001	0.998	0.994	0.990	0.990
14	1.034	1.004	1.004	1.005	1.005	1.007	1.007	1.006	1.021	1.021	1.021	1.021	1.021	1.020	1.020	1.019
15	1.025	1.005	1.005	1.006	1.007	1.006	1.006	1.006	1.015	1.014	1.014	1.014	1.013	1.012	1.011	1.011
16	1.003	1.001	1.001	1.002	1.002	1.001	1.001	1.001	1.004	1.003	1.004	1.003	1.003	1.003	1.003	1.003
17	0.990	0.998	0.998	0.998	0.999	0.997	0.997	0.996	0.994	0.993	0.992	0.992	0.991	0.991	0.990	0.990
18	0.990	0.996	0.995	0.995	0.995	0.993	0.993	0.992	0.992	0.991	0.991	0.990	0.989	0.988	0.988	0.988
19	0.964	0.993	0.992	0.992	0.992	0.987	0.986	0.985	0.979	0.976	0.974	0.973	0.972	0.971	0.970	0.970
20	0.964	0.992	0.992	0.992	0.992	0.986	0.985	0.984	0.977	0.975	0.973	0.971	0.971	0.969	0.969	0.969
21	0.972	0.993	0.993	0.993	0.993	0.989	0.988	0.987	0.985	0.984	0.983	0.982	0.981	0.981	0.980	0.980
22	0.993	0.995	0.994	0.994	0.994	0.993	0.992	0.992	0.993	0.992	0.992	0.991	0.991	0.990	0.990	0.989
23	0.990	0.997	0.997	0.997	0.997	0.996	0.995	0.995	0.992	0.992	0.992	0.991	0.991	0.991	0.990	0.990
24	0.990	0.998	0.997	0.997	0.997	0.996	0.996	0.996	0.993	0.993	0.992	0.992	0.992	0.992	0.992	0.992

Table B. 7 PV generation data in kW for HPVCL

Time/Bus No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	1.6	2.4	3.2	4.8	7.2	7.6	7.12	6.4	4.8	3.2	2	0	0	0	0	0	0	0	8
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	1	1.5	2	3	4.5	4.75	4.45	4	3	2	1.25	0	0	0	0	0	0	0	5
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1.2	1.8	2.4	3.6	5.4	5.7	5.34	4.8	3.6	2.4	1.5	0	0	0	0	0	0	0	6
9	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	1	1.5	2	3	4.5	4.75	4.45	4	3	2	1.25	0	0	0	0	0	0	0	5
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	1.6	2.4	3.2	4.8	7.2	7.6	7.12	6.4	4.8	3.2	2	0	0	0	0	0	0	0	8
14	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	1.2	1.8	2.4	3.6	5.4	5.7	5.34	4.8	3.6	2.4	1.5	0	0	0	0	0	0	0	6
17	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
18	0	0	0	0	0	0	1.6	2.4	3.2	4.8	7.2	7.6	7.12	6.4	4.8	3.2	2	0	0	0	0	0	0	0	8
19	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
22	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	1	1.5	2	3	4.5	4.75	4.45	4	3	2	1.25	0	0	0	0	0	0	0	5
25	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
26	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
29	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
30	0	0	0	0	0	0	1.4	2.1	2.8	4.2	6.3	6.65	6.23	5.6	4.2	2.8	1.75	0	0	0	0	0	0	0	7
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0.8	1.2	1.6	2.4	3.6	3.8	3.56	3.2	2.4	1.6	1	0	0	0	0	0	0	0	4
33	0	0	0	0	0	0	1.2	1.8	2.4	3.6	5.4	5.7	5.34	4.8	3.6	2.4	1.5	0	0	0	0	0	0	0	6

Table B. 8 Initial results of the system for HPVCL

Time	Total Load (kW)	Total Load (kVAR)	Total Solar Generation (kW)	Total Solar Generation (kVAR)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVAR)	Total Real Power Supply by Grid (kW)	Total Reactive Power Supply by Grid (kVAR)
1	11.515	8.63625	0	0	0.171963921	0.197335647	11.68696392	8.833585647
2	12.54	9.405	0	0	0.201482843	0.23120982	12.74148284	10.5610491
3	13.11	9.8325	0	0	0.214304533	0.245923234	13.32430453	9.586576766
4	14.08	10.56	0	0	0.240290404	0.275743087	14.3202904	10.83574309
5	15.98	11.985	0	0	0.293105924	0.33635106	16.27310592	12.32135106
6	22.57	16.9275	0	0	0.623605985	0.715613425	23.19360598	17.64311343
7	47.79	35.8425	29	9.53183905	1.144773006	1.313673942	19.93477301	27.62433489
8	53.05	39.7875	43.5	14.29775858	0.813167811	0.933143389	10.36316781	26.42288481
9	54.49	40.8675	58	19.0636781	0.491257089	0.563737643	-3.018742911	22.36755954
10	47.18	35.385	87	28.59551715	1.248139673	1.432291428	-38.57186033	8.221774277
11	35.67	26.7525	130.5	42.89327573	5.5196405	6.334013688	-89.3103595	-9.806762038
12	39.26	29.445	137.75	45.27623549	5.914568073	6.787209264	-92.57543193	-9.044026225
13	43.34	32.505	129.05	42.41668377	4.582665959	5.258797003	-81.12733404	-4.652886771
14	38.59	28.9425	116	38.1273562	4.011263934	4.603089761	-73.39873607	-4.58176644
15	26.58	19.935	87	28.59551715	2.35353444	2.700777226	-58.06646556	-5.959739924
16	24.4	18.3	58	19.0636781	0.755642479	0.867130714	-32.84435752	0.103452614
17	24.53	18.3975	36.25	11.91479881	0.130438686	0.149683738	-11.58956131	6.632384925
18	52.03	39.0225	0	0	4.010814391	4.602573891	56.04081439	43.62507389
19	68.89	51.6675	0	0	7.80272769	8.953949809	76.69272769	60.62144981
20	71.33	53.4975	0	0	8.187181739	9.395126585	79.51718174	62.89262659
21	64.493	48.36975	0	0	6.403216456	7.34795331	70.89621646	55.71770331
22	43.49	32.6175	0	0	2.27417492	2.609708924	45.76417492	35.22720892
23	14.48	10.86	0	0	0.250847971	0.287858327	14.73084797	11.14785833
24	12.38	9.285	0	0	0.199815598	0.229296588	12.5798156	9.514296588

Table B. 9 Initial voltage profile of the network in PU for HPVCL

Bus No./Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.000	0.996	0.993	0.990	0.987	0.984	0.982	0.980	0.979	0.977	0.976	0.975	0.974	0.974	0.973	0.973	0.973
2	1.000	0.996	0.992	0.989	0.986	0.983	0.980	0.979	0.977	0.976	0.974	0.973	0.973	0.972	0.971	0.971	0.971
3	1.000	0.995	0.992	0.988	0.985	0.982	0.980	0.978	0.976	0.975	0.974	0.973	0.972	0.971	0.970	0.970	0.970
4	1.000	0.995	0.991	0.988	0.984	0.981	0.979	0.977	0.975	0.973	0.972	0.971	0.970	0.969	0.969	0.968	0.968
5	1.000	0.994	0.990	0.986	0.983	0.979	0.977	0.975	0.973	0.972	0.970	0.969	0.968	0.967	0.966	0.965	0.965
6	1.000	0.992	0.985	0.980	0.975	0.969	0.966	0.963	0.961	0.958	0.956	0.954	0.953	0.951	0.950	0.949	0.949
7	1.000	0.991	0.981	0.973	0.964	0.957	0.952	0.949	0.946	0.944	0.941	0.939	0.937	0.936	0.935	0.934	0.934
8	1.000	0.993	0.985	0.978	0.971	0.965	0.961	0.959	0.957	0.955	0.953	0.951	0.950	0.949	0.948	0.948	0.948
9	1.000	0.996	0.991	0.987	0.982	0.978	0.976	0.975	0.974	0.973	0.972	0.971	0.971	0.970	0.970	0.970	0.970
10	1.000	1.005	1.008	1.013	1.017	1.021	1.023	1.025	1.027	1.028	1.030	1.032	1.034	1.035	1.036	1.038	1.039
11	1.000	1.018	1.032	1.044	1.055	1.067	1.072	1.078	1.084	1.088	1.093	1.098	1.102	1.106	1.109	1.112	1.115
12	1.000	1.019	1.033	1.045	1.056	1.067	1.074	1.081	1.087	1.092	1.098	1.103	1.108	1.113	1.116	1.119	1.122
13	1.000	1.016	1.027	1.036	1.044	1.052	1.060	1.067	1.074	1.080	1.086	1.091	1.096	1.101	1.104	1.107	1.110
14	1.000	1.014	1.026	1.036	1.046	1.056	1.062	1.068	1.073	1.077	1.081	1.085	1.089	1.092	1.094	1.097	1.099
15	1.000	1.012	1.021	1.028	1.035	1.043	1.047	1.051	1.055	1.058	1.062	1.065	1.068	1.071	1.072	1.075	1.076
16	1.000	1.006	1.010	1.014	1.018	1.021	1.023	1.025	1.026	1.028	1.029	1.031	1.032	1.034	1.034	1.036	1.037
17	1.000	1.001	1.001	1.001	1.001	1.001	1.001	1.001	1.001	1.000	1.000	1.000	1.001	1.001	1.001	1.002	1.002
18	1.000	0.981	0.964	0.950	0.936	0.923	0.915	0.908	0.901	0.895	0.890	0.885	0.881	0.877	0.874	0.871	0.870
19	1.000	0.973	0.951	0.931	0.912	0.893	0.883	0.872	0.862	0.853	0.845	0.837	0.830	0.825	0.820	0.817	0.814
20	1.000	0.972	0.949	0.928	0.909	0.890	0.879	0.869	0.859	0.850	0.841	0.834	0.827	0.821	0.817	0.813	0.811
21	1.000	0.976	0.955	0.937	0.920	0.904	0.893	0.883	0.874	0.865	0.857	0.850	0.844	0.838	0.834	0.831	0.828
22	1.000	0.984	0.971	0.961	0.951	0.941	0.935	0.930	0.926	0.922	0.918	0.915	0.912	0.909	0.907	0.906	0.905
23	1.000	0.995	0.991	0.987	0.984	0.980	0.978	0.976	0.975	0.973	0.972	0.971	0.970	0.969	0.969	0.969	0.968
24	1.000	0.996	0.992	0.989	0.986	0.983	0.981	0.979	0.977	0.976	0.974	0.973	0.973	0.972	0.971	0.971	0.971

Continued..

Bus No./Time	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	0.973	0.996	0.995	0.995	0.995	0.992	0.992	0.992	0.983	0.983	0.982	0.982	0.981	0.981	0.981	0.981
2	0.971	0.995	0.995	0.994	0.994	0.992	0.991	0.991	0.982	0.981	0.980	0.980	0.980	0.979	0.979	0.979
3	0.970	0.995	0.995	0.994	0.994	0.991	0.991	0.991	0.981	0.980	0.980	0.980	0.979	0.979	0.979	0.979
4	0.968	0.995	0.994	0.994	0.994	0.990	0.990	0.990	0.980	0.980	0.979	0.979	0.978	0.978	0.978	0.978
5	0.964	0.994	0.993	0.993	0.993	0.989	0.989	0.988	0.978	0.977	0.976	0.975	0.975	0.974	0.974	0.974
6	0.948	0.991	0.990	0.990	0.990	0.985	0.984	0.984	0.968	0.966	0.965	0.964	0.963	0.962	0.962	0.961
7	0.934	0.991	0.991	0.991	0.991	0.981	0.981	0.981	0.953	0.950	0.948	0.946	0.943	0.942	0.941	0.941
8	0.948	0.993	0.993	0.993	0.993	0.985	0.985	0.985	0.962	0.960	0.958	0.956	0.954	0.952	0.951	0.950
9	0.971	0.996	0.996	0.997	0.997	0.991	0.992	0.992	0.977	0.975	0.974	0.972	0.971	0.969	0.968	0.968
10	1.039	1.007	1.008	1.009	1.010	1.009	1.011	1.012	1.024	1.026	1.029	1.030	1.031	1.031	1.032	1.032
11	1.116	1.022	1.024	1.027	1.028	1.034	1.036	1.038	1.072	1.076	1.081	1.084	1.087	1.088	1.089	1.090
12	1.123	1.023	1.025	1.028	1.029	1.034	1.037	1.038	1.072	1.076	1.080	1.082	1.084	1.084	1.085	1.086
13	1.111	1.020	1.022	1.025	1.026	1.029	1.031	1.032	1.052	1.052	1.052	1.051	1.049	1.046	1.043	1.044
14	1.100	1.016	1.017	1.019	1.020	1.027	1.028	1.029	1.060	1.063	1.066	1.069	1.070	1.071	1.071	1.072
15	1.077	1.014	1.016	1.017	1.018	1.022	1.023	1.024	1.046	1.048	1.050	1.052	1.053	1.053	1.053	1.054
16	1.037	1.007	1.008	1.009	1.010	1.011	1.012	1.012	1.023	1.025	1.026	1.028	1.029	1.029	1.029	1.030
17	1.003	1.001	1.001	1.002	1.002	1.001	1.001	1.002	1.001	1.002	1.002	1.003	1.003	1.003	1.003	1.003
18	0.869	0.978	0.977	0.976	0.975	0.962	0.961	0.961	0.917	0.913	0.908	0.905	0.902	0.901	0.900	0.899
19	0.813	0.970	0.968	0.967	0.966	0.948	0.947	0.946	0.886	0.880	0.874	0.870	0.867	0.864	0.863	0.863
20	0.809	0.969	0.967	0.966	0.965	0.947	0.945	0.944	0.883	0.877	0.871	0.866	0.863	0.860	0.859	0.859
21	0.827	0.973	0.971	0.969	0.969	0.952	0.951	0.950	0.899	0.895	0.891	0.888	0.885	0.884	0.882	0.882
22	0.904	0.982	0.980	0.979	0.979	0.970	0.969	0.968	0.937	0.934	0.931	0.929	0.927	0.926	0.925	0.925
23	0.968	0.994	0.994	0.994	0.994	0.990	0.990	0.990	0.979	0.978	0.978	0.977	0.976	0.976	0.975	0.975
24	0.971	0.995	0.995	0.995	0.994	0.992	0.992	0.991	0.982	0.981	0.981	0.980	0.980	0.980	0.979	0.979

Table B. 10 Optimal condition results of the system for HPVCL

Time	Total Load (kW)	Total Load (kVAR)	Total Solar Generation (kW)	Total Solar Generation (kVAR)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVAR)	Total Real Power Supply by Grid (kW)	Total Reactive Power Supply by Grid (kVAR)	Total Solar PV Cut-Off (kW)
1	11.515	8.63625	0	8.338445339	0.116314466	0.133475617	11.63131447	0.431280278	0
2	12.54	9.405	0	9.514232864	0.137922738	0.158271995	12.67792274	0.049039131	0
3	13.11	9.8325	0	10.03640056	0.148565572	0.170485083	13.25856557	-0.033415478	0
4	14.08	10.56	0	11.03560658	0.170038217	0.195125823	14.25003822	-0.280480755	0
5	15.98	11.985	0	12.9956201	0.210495391	0.241552088	16.19049539	-0.769068013	0
6	22.57	16.9275	0	22.53433282	0.486032571	0.557742294	23.05603257	-5.049090523	0
7	47.79	35.8425	29	44.20546664	0.544998619	0.625408251	19.33499862	-7.737558386	0
8	53.05	39.7875	43.5	41.04170401	0.1811551	0.207882901	9.7311551	-1.046321111	0
9	54.49	40.8675	58	32.69048737	0.06585538	0.075571748	-3.44414462	8.252584375	0
10	47.18	35.385	87	28.59551715	1.248139673	1.432291428	-38.57186033	8.221774277	0
11	35.67	26.7525	102.065	32.9319262	2.075957759	2.382246609	-64.31904224	-3.797179591	28.435
12	39.26	29.445	107.01	34.6039975	2.096836741	2.406206096	-65.65316326	-2.752791408	30.74
13	43.34	32.505	108.025	35.11943506	1.972705107	2.263759959	-62.71229489	-0.350675098	21.025
14	38.59	28.9425	96.71	31.22468236	1.816637581	2.084666077	-56.30336242	-0.197516279	19.29
15	26.58	19.935	79.865	25.02984085	1.601887848	1.838231957	-51.68311215	-3.256608892	7.135
16	24.4	18.3	58	19.0636781	0.755642479	0.867130714	-32.84435752	0.103452614	0
17	24.53	18.3975	36.25	11.91479881	0.130438686	0.149683738	-11.58956131	6.632384925	0
18	52.03	39.0225	0	74.71114632	3.428214742	3.934016917	55.45821474	-31.75462941	0
19	68.89	51.6675	0	106.6097923	6.533912892	7.497932827	75.42391289	-47.44435942	0
20	71.33	53.4975	0	109.6158013	6.846815976	7.85700194	78.17681598	-48.2612994	0
21	64.493	48.36975	0	96.99228382	5.51418081	6.32774847	70.00718081	-42.29478535	0
22	43.49	32.6175	0	54.72726464	1.922381823	2.206011928	45.41238182	-19.90375271	0
23	14.48	10.86	0	11.25116203	0.174843648	0.200640252	14.65484365	-0.190521781	0
24	12.38	9.285	0	9.45904346	0.136973462	0.157182661	12.51697346	-0.016860799	0

Table B. 11 Optimal voltage profile of the network in PU for MPVCL

Bus No./Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
2	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
3	1.000	0.998	0.996	0.995	0.993	0.993	0.992	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
4	1.000	0.997	0.996	0.995	0.994	0.993	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.991
5	1.000	0.997	0.995	0.994	0.993	0.993	0.992	0.992	0.991	0.991	0.991	0.991	0.991	0.990	0.990	0.990	0.990
6	1.000	0.997	0.995	0.994	0.993	0.992	0.992	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
7	1.000	0.998	0.996	0.995	0.993	0.992	0.992	0.992	0.992	0.992	0.992	0.993	0.993	0.993	0.993	0.994	0.995
8	1.000	0.998	0.997	0.995	0.994	0.993	0.992	0.992	0.993	0.992	0.993	0.993	0.993	0.993	0.993	0.994	0.995
9	1.000	0.999	0.997	0.996	0.994	0.993	0.992	0.993	0.993	0.992	0.992	0.992	0.993	0.993	0.993	0.994	0.994
10	1.000	1.005	1.008	1.013	1.017	1.021	1.023	1.025	1.027	1.028	1.030	1.032	1.034	1.035	1.036	1.038	1.039
11	1.000	1.013	1.020	1.026	1.031	1.036	1.038	1.040	1.041	1.042	1.043	1.044	1.046	1.047	1.047	1.048	1.049
12	1.000	1.013	1.020	1.026	1.030	1.035	1.036	1.038	1.040	1.041	1.042	1.044	1.046	1.047	1.047	1.048	1.049
13	1.000	1.012	1.018	1.023	1.026	1.030	1.033	1.036	1.038	1.040	1.042	1.043	1.045	1.047	1.047	1.049	1.050
14	1.000	1.010	1.018	1.024	1.029	1.035	1.037	1.040	1.042	1.043	1.044	1.045	1.047	1.048	1.048	1.049	1.050
15	1.000	1.010	1.017	1.023	1.028	1.034	1.036	1.039	1.041	1.042	1.044	1.045	1.047	1.048	1.048	1.049	1.050
16	1.000	1.006	1.010	1.014	1.018	1.021	1.023	1.025	1.026	1.028	1.029	1.031	1.032	1.034	1.034	1.036	1.037
17	1.000	1.001	1.001	1.001	1.001	1.001	1.001	1.001	1.001	1.000	1.000	1.000	1.001	1.001	1.001	1.002	1.002
18	1.000	0.997	0.994	0.993	0.992	0.991	0.991	0.991	0.991	0.990	0.990	0.990	0.991	0.991	0.991	0.991	0.991
19	1.000	0.996	0.994	0.993	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.991	0.991
20	1.000	0.996	0.993	0.992	0.991	0.991	0.991	0.991	0.991	0.990	0.990	0.990	0.991	0.991	0.990	0.991	0.991
21	1.000	0.996	0.994	0.993	0.992	0.993	0.992	0.992	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.991	0.991
22	1.000	0.996	0.993	0.992	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.991	0.991	0.991	0.991	0.992
23	1.000	0.997	0.996	0.994	0.993	0.992	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
24	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990

Continued..

Bus No./Time	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	0.990	0.997	0.997	0.997	0.997	0.996	0.996	0.996	0.993	0.992	0.992	0.992	0.992	0.992	0.992	0.992
2	0.990	0.997	0.997	0.996	0.996	0.996	0.995	0.995	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992
3	0.991	0.997	0.997	0.996	0.996	0.996	0.995	0.995	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992
4	0.991	0.997	0.996	0.996	0.996	0.995	0.995	0.995	0.993	0.993	0.993	0.993	0.993	0.992	0.992	0.992
5	0.990	0.996	0.996	0.995	0.995	0.995	0.994	0.994	0.992	0.992	0.992	0.992	0.992	0.991	0.991	0.991
6	0.990	0.996	0.995	0.995	0.995	0.994	0.994	0.994	0.992	0.992	0.992	0.992	0.992	0.991	0.991	0.991
7	0.995	0.998	0.998	0.998	0.998	0.996	0.997	0.997	0.992	0.992	0.992	0.992	0.991	0.990	0.990	0.990
8	0.995	0.999	0.999	0.999	0.999	0.997	0.997	0.998	0.993	0.992	0.992	0.992	0.991	0.990	0.990	0.990
9	0.995	0.999	0.999	1.000	1.000	0.997	0.998	0.998	0.993	0.992	0.992	0.992	0.991	0.990	0.990	0.990
10	1.039	1.007	1.008	1.009	1.010	1.009	1.011	1.012	1.024	1.026	1.029	1.030	1.031	1.031	1.032	1.032
11	1.050	1.016	1.018	1.021	1.022	1.022	1.025	1.026	1.040	1.042	1.045	1.047	1.048	1.048	1.049	1.049
12	1.050	1.016	1.019	1.022	1.023	1.022	1.024	1.025	1.038	1.040	1.042	1.044	1.044	1.044	1.045	1.045
13	1.050	1.015	1.018	1.020	1.022	1.020	1.022	1.024	1.030	1.029	1.029	1.028	1.026	1.023	1.021	1.022
14	1.050	1.012	1.013	1.015	1.016	1.018	1.020	1.021	1.038	1.040	1.043	1.044	1.045	1.045	1.046	1.046
15	1.050	1.012	1.014	1.016	1.016	1.018	1.020	1.021	1.037	1.039	1.041	1.043	1.044	1.044	1.044	1.045
16	1.037	1.007	1.008	1.009	1.010	1.011	1.012	1.012	1.023	1.025	1.026	1.028	1.029	1.029	1.029	1.030
17	1.003	1.001	1.001	1.002	1.002	1.001	1.001	1.002	1.001	1.002	1.002	1.003	1.003	1.003	1.003	1.003
18	0.991	0.996	0.995	0.995	0.995	0.994	0.994	0.994	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990
19	0.991	0.996	0.995	0.995	0.995	0.993	0.994	0.994	0.992	0.991	0.991	0.991	0.991	0.991	0.991	0.992
20	0.992	0.996	0.995	0.995	0.995	0.993	0.993	0.994	0.991	0.991	0.991	0.991	0.991	0.990	0.991	0.992
21	0.991	0.996	0.995	0.995	0.995	0.993	0.993	0.993	0.994	0.994	0.995	0.996	0.996	0.996	0.996	0.996
22	0.992	0.995	0.994	0.994	0.993	0.993	0.993	0.993	0.990	0.990	0.990	0.991	0.990	0.990	0.990	0.990
23	0.990	0.997	0.996	0.996	0.996	0.995	0.995	0.995	0.992	0.992	0.992	0.992	0.991	0.991	0.991	0.991
24	0.990	0.997	0.997	0.997	0.996	0.996	0.996	0.996	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992

Table B. 12 PV generation data in kW for LPVCL

Time/Bus No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Installed PV (kVA)	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
2	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	0	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
3	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	5.6	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	1	0.9	0	0.6	0.4	0.3	0	0	0	0	0	0	0	0	1
7	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	1	0.9	5.6	0.6	0.4	0.3	0	0	0	0	0	0	0	0	1
9	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	0	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
10	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	4	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
11	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	1	0.9	0	0.6	0.4	0.3	0	0	0	0	0	0	0	0	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	6.4	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	1	0.9	5.6	0.6	0.4	0.3	0	0	0	0	0	0	0	0	1
14	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	0	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
15	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	5.6	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
17	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	1	0.9	6.4	0.6	0.4	0.3	0	0	0	0	0	0	0	0	1
18	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	1	0.9	5.6	0.6	0.4	0.3	0	0	0	0	0	0	0	0	1
19	0	0	0	0	0	0	0.3	0.5	0.6	0.9	1.4	1.4	1.3	0	0.9	0.6	0.4	0	0	0	0	0	0	0	0	1.5
20	0	0	0	0	0	0	0	0	0	0	0	0	0	5.6	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	5.6	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	5.6	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
25	0	0	0	0	0	0	0.3	0.5	0.6	0.9	1.4	1.4	1.3	5.6	0.9	0.6	0.4	0	0	0	0	0	0	0	0	1.5
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	5.6	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	5.6	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2
29	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	1	0.9	5.6	0.6	0.4	0.3	0	0	0	0	0	0	0	0	1
30	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	1	0.9	0	0.6	0.4	0.3	0	0	0	0	0	0	0	0	1
31	0	0	0	0	0	0	0	0	0	0	0	0	0	3.2	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0.2	0.3	0.4	0.6	0.9	1	0.9	4.8	0.6	0.4	0.3	0	0	0	0	0	0	0	0	1
33	0	0	0	0	0	0	0.4	0.6	0.8	1.2	1.8	1.9	1.8	116	1.2	0.8	0.5	0	0	0	0	0	0	0	0	2

Table B. 13 Initial results of the system for LPVCL

Time	Total Load (kW)	Total Load (kVAR)	Total Solar Generation (kW)	Total Solar Generation (kVAR)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVA)	Total Real Power Supply by Grid (kW)	Total Reactive Power Supply by Grid (kVA)
1	11.515	8.63625	0	0	0.171963921	0.197335647	11.68696392	8.833585647
2	12.54	9.405	0	0	0.201482843	0.23120982	12.74148284	10.5610491
3	13.11	9.8325	0	0	0.214304533	0.245923234	13.32430453	9.586576766
4	14.08	10.56	0	0	0.240290404	0.275743087	14.3202904	10.83574309
5	15.98	11.985	0	0	0.293105924	0.33635106	16.27310592	12.32135106
6	22.57	16.9275	0	0	0.623605985	0.715613425	23.19360598	17.64311343
7	47.79	35.8425	6.4	2.103578273	3.010687495	3.454887289	44.40068749	37.19380902
8	53.05	39.7875	9.6	3.15536741	3.40065197	3.902387506	46.85065197	40.5345201
9	54.49	40.8675	12.8	4.207156546	3.191413187	3.662277427	44.88141319	40.32262088
10	47.18	35.385	19.2	6.310734819	1.269043694	1.456279649	29.24904369	30.53054483
11	35.67	26.7525	28.8	9.466102229	0.38580382	0.442725696	7.25580382	17.72912347
12	39.26	29.445	30.4	9.991996797	0.50366646	0.577977905	9.36366646	20.03098111
13	43.34	32.505	28.48	9.360923315	1.405139963	1.612455696	16.26513996	24.75653238
14	38.59	28.9425	25.6	8.414313093	0.444529217	0.510115495	13.43452922	21.0383024
15	26.58	19.935	19.2	6.310734819	0.24776131	0.284316258	7.62776131	13.90858144
16	24.4	18.3	12.8	4.207156546	0.305436862	0.350501316	11.90543686	14.44334477
17	24.53	18.3975	8	2.629472841	0.469890673	0.539218805	16.99989067	16.30724596
18	52.03	39.0225	0	0	4.010814391	4.602573891	56.04081439	43.62507389
19	68.89	51.6675	0	0	7.80272769	8.953949809	76.69272769	60.62144981
20	71.33	53.4975	0	0	8.187181739	9.395126585	79.51718174	62.89262659
21	64.493	48.36975	0	0	6.403216456	7.34795331	70.89621646	55.71770331
22	43.49	32.6175	0	0	2.27417492	2.609708924	45.76417492	35.22720892
23	14.48	10.86	0	0	0.250847971	0.287858327	14.73084797	11.14785833
24	12.38	9.285	0	0	0.199815598	0.229296588	12.5798156	9.514296588

Table B. 14 Initial voltage profile of the network in PU for LPVCL

Bus No./Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.000	0.996	0.993	0.990	0.987	0.984	0.982	0.980	0.979	0.977	0.976	0.975	0.974	0.974	0.973	0.973	0.973
2	1.000	0.996	0.992	0.989	0.986	0.983	0.980	0.979	0.977	0.976	0.974	0.973	0.973	0.972	0.971	0.971	0.971
3	1.000	0.995	0.992	0.988	0.985	0.982	0.980	0.978	0.976	0.975	0.974	0.973	0.972	0.971	0.970	0.970	0.970
4	1.000	0.995	0.991	0.988	0.984	0.981	0.979	0.977	0.975	0.973	0.972	0.971	0.970	0.969	0.969	0.968	0.968
5	1.000	0.994	0.990	0.986	0.983	0.979	0.977	0.975	0.973	0.972	0.970	0.969	0.968	0.967	0.966	0.965	0.965
6	1.000	0.992	0.985	0.980	0.975	0.969	0.966	0.963	0.961	0.958	0.956	0.954	0.953	0.951	0.950	0.949	0.949
7	1.000	0.984	0.970	0.956	0.943	0.931	0.924	0.919	0.914	0.909	0.905	0.901	0.898	0.895	0.892	0.891	0.890
8	1.000	0.983	0.968	0.953	0.940	0.927	0.920	0.914	0.908	0.903	0.899	0.894	0.891	0.888	0.885	0.883	0.882
9	1.000	0.983	0.969	0.955	0.942	0.929	0.922	0.917	0.911	0.906	0.902	0.898	0.894	0.891	0.888	0.887	0.886
10	1.000	0.988	0.978	0.970	0.962	0.955	0.950	0.946	0.943	0.939	0.936	0.933	0.931	0.928	0.927	0.926	0.925
11	1.000	0.995	0.990	0.985	0.980	0.976	0.973	0.970	0.968	0.967	0.964	0.963	0.962	0.961	0.960	0.960	0.960
12	1.000	0.994	0.988	0.982	0.977	0.971	0.969	0.967	0.965	0.964	0.962	0.961	0.960	0.960	0.959	0.959	0.959
13	1.000	0.992	0.984	0.975	0.967	0.959	0.958	0.957	0.957	0.956	0.955	0.955	0.954	0.954	0.954	0.954	0.954
14	1.000	0.993	0.988	0.983	0.978	0.974	0.972	0.970	0.968	0.967	0.965	0.963	0.962	0.961	0.960	0.960	0.959
15	1.000	0.996	0.992	0.988	0.984	0.980	0.979	0.977	0.976	0.974	0.973	0.972	0.971	0.971	0.970	0.970	0.970
16	1.000	0.995	0.990	0.986	0.982	0.978	0.976	0.973	0.971	0.970	0.968	0.966	0.965	0.964	0.963	0.963	0.963
17	1.000	0.994	0.988	0.983	0.978	0.973	0.970	0.967	0.965	0.962	0.960	0.959	0.957	0.956	0.955	0.955	0.954
18	1.000	0.981	0.964	0.950	0.936	0.923	0.915	0.908	0.901	0.895	0.890	0.885	0.881	0.877	0.874	0.871	0.870
19	1.000	0.973	0.951	0.931	0.912	0.893	0.883	0.872	0.862	0.853	0.845	0.837	0.830	0.825	0.820	0.817	0.814
20	1.000	0.972	0.949	0.928	0.909	0.890	0.879	0.869	0.859	0.850	0.841	0.834	0.827	0.821	0.817	0.813	0.811
21	1.000	0.976	0.955	0.937	0.920	0.904	0.893	0.883	0.874	0.865	0.857	0.850	0.844	0.838	0.834	0.831	0.828
22	1.000	0.984	0.971	0.961	0.951	0.941	0.935	0.930	0.926	0.922	0.918	0.915	0.912	0.909	0.907	0.906	0.905
23	1.000	0.995	0.991	0.987	0.984	0.980	0.978	0.976	0.975	0.973	0.972	0.971	0.970	0.969	0.969	0.969	0.968
24	1.000	0.996	0.992	0.989	0.986	0.983	0.981	0.979	0.977	0.976	0.974	0.973	0.973	0.972	0.971	0.971	0.971

Continued..

Bus No./Time	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	0.973	0.996	0.995	0.995	0.995	0.992	0.992	0.992	0.983	0.983	0.982	0.982	0.981	0.981	0.981	0.981
2	0.971	0.995	0.995	0.994	0.994	0.992	0.991	0.991	0.982	0.981	0.98	0.98	0.98	0.979	0.979	0.979
3	0.97	0.995	0.995	0.994	0.994	0.991	0.991	0.991	0.981	0.98	0.98	0.98	0.979	0.979	0.979	0.979
4	0.968	0.995	0.994	0.994	0.994	0.99	0.99	0.99	0.98	0.98	0.979	0.979	0.978	0.978	0.978	0.978
5	0.964	0.994	0.993	0.993	0.993	0.989	0.989	0.988	0.978	0.977	0.976	0.975	0.975	0.974	0.974	0.974
6	0.948	0.991	0.99	0.99	0.99	0.985	0.984	0.984	0.968	0.966	0.965	0.964	0.963	0.962	0.962	0.961
7	0.89	0.983	0.983	0.982	0.982	0.969	0.968	0.968	0.926	0.922	0.918	0.914	0.911	0.909	0.908	0.907
8	0.882	0.982	0.981	0.981	0.98	0.967	0.966	0.966	0.922	0.917	0.913	0.909	0.906	0.903	0.902	0.901
9	0.885	0.982	0.981	0.98	0.98	0.968	0.968	0.967	0.924	0.919	0.915	0.912	0.909	0.906	0.904	0.904
10	0.924	0.987	0.987	0.986	0.986	0.978	0.978	0.978	0.953	0.952	0.95	0.949	0.948	0.947	0.947	0.946
11	0.96	0.995	0.994	0.994	0.994	0.991	0.991	0.991	0.975	0.974	0.974	0.973	0.973	0.972	0.972	0.972
12	0.959	0.994	0.994	0.994	0.993	0.988	0.988	0.989	0.969	0.967	0.966	0.964	0.963	0.961	0.961	0.961
13	0.954	0.992	0.992	0.992	0.992	0.984	0.984	0.985	0.951	0.945	0.939	0.933	0.928	0.923	0.919	0.919
14	0.959	0.992	0.99	0.989	0.989	0.987	0.987	0.987	0.972	0.97	0.969	0.968	0.967	0.966	0.965	0.965
15	0.97	0.995	0.995	0.995	0.995	0.992	0.992	0.992	0.979	0.977	0.976	0.975	0.974	0.973	0.972	0.972
16	0.962	0.994	0.994	0.994	0.994	0.99	0.99	0.99	0.977	0.976	0.975	0.975	0.974	0.974	0.974	0.974
17	0.954	0.993	0.992	0.992	0.992	0.988	0.987	0.987	0.971	0.97	0.969	0.968	0.968	0.967	0.967	0.967
18	0.869	0.978	0.977	0.976	0.975	0.962	0.961	0.961	0.917	0.913	0.908	0.905	0.902	0.901	0.9	0.899
19	0.813	0.97	0.968	0.967	0.966	0.948	0.947	0.946	0.886	0.88	0.874	0.87	0.867	0.864	0.863	0.863
20	0.809	0.969	0.967	0.966	0.965	0.947	0.945	0.944	0.883	0.877	0.871	0.866	0.863	0.86	0.859	0.859
21	0.827	0.973	0.971	0.969	0.969	0.952	0.951	0.95	0.899	0.895	0.891	0.888	0.885	0.884	0.882	0.882
22	0.904	0.982	0.98	0.979	0.979	0.97	0.969	0.968	0.937	0.934	0.931	0.929	0.927	0.926	0.925	0.925
23	0.968	0.994	0.994	0.994	0.994	0.99	0.99	0.99	0.979	0.978	0.978	0.977	0.976	0.976	0.975	0.975
24	0.971	0.995	0.995	0.995	0.994	0.992	0.992	0.991	0.982	0.981	0.981	0.98	0.98	0.98	0.979	0.979

Table B. 15 Optimal condition results of the system for LPVCL

Time	Total Load (kW)	Total Load (kVAR)	Total Solar Generation (kW)	Total Solar Generation (kVAR)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVAR)	Total Real Power Supply by Grid (kW)	Total Reactive Power Supply by Grid (kVAR)	Total Solar PV Cut-Off (kW)
1	11.515	8.63625	0	8.185453068	0.115598784	0.132654342	11.63059878	0.583451274	0
2	12.54	9.405	0	9.287512552	0.137479046	0.157762839	12.67747905	0.275250287	0
3	13.11	9.8325	0	9.7647902	0.147827414	0.169638016	13.25782741	0.237347816	0
4	14.08	10.56	0	10.69125131	0.169096133	0.194044743	14.24909613	0.062793435	0
5	15.98	11.985	0	12.75612365	0.211898506	0.24316222	16.19189851	-0.527961433	0
6	22.57	16.9275	0	22.28000587	0.479363835	0.550089647	23.04936383	-4.802416224	0
7	47.79	35.8425	6.4	30.64016734	1.758751531	2.018239462	43.14875153	7.220572117	0
8	53.05	39.7875	9.6	30.15231772	2.015193365	2.312516976	45.46519336	11.94769925	0
9	54.49	40.8675	12.8	29.19149976	1.889960709	2.168807371	43.57996071	13.84480761	0
10	47.18	35.385	19.2	23.95107461	0.663290903	0.761153495	28.6432909	12.19507888	0
11	35.67	26.7525	28.8	12.3269134	0.278324523	0.319388797	7.148324523	14.74497539	0
12	39.26	29.445	30.4	9.991996797	0.50366646	0.577977905	9.36366646	20.03098111	0
13	43.34	32.505	28.48	13.66535301	1.189297328	1.364767426	16.04929733	20.20441441	0
14	38.59	28.9425	25.6	16.91750144	0.20831925	0.239054877	13.19831925	12.26405344	0
15	26.58	19.935	19.2	17.20207336	0.074290858	0.085251805	7.454290858	2.818178448	0
16	24.4	18.3	12.8	17.53517741	0.140520165	0.161252649	11.74052017	0.926075243	0
17	24.53	18.3975	8	21.00308597	0.284727309	0.326736256	16.81472731	-2.27884971	0
18	52.03	39.0225	0	31.99998985	2.419933425	2.776972782	54.44993342	9.799482928	0
19	68.89	51.6675	0	31.99998985	4.930930112	5.658444391	73.82093011	25.32595454	0
20	71.33	53.4975	0	31.99998985	5.202352663	5.969912892	76.53235266	27.46742304	0
21	64.493	48.36975	0	31.99998985	3.985420983	4.573433914	68.47842098	20.94319406	0
22	43.49	32.6175	0	31.57899797	1.364634822	1.565974386	44.85463482	2.604476419	0
23	14.48	10.86	0	10.90153471	0.174648652	0.200416486	14.65464865	0.158881774	0
24	12.38	9.285	0	9.27548785	0.136467496	0.156602044	12.5164675	0.166114194	0

Table B. 16 Optimal voltage profile of the network in PU for LPVCL

Bus No./Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990
2	1.000	0.998	0.996	0.995	0.993	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990
3	1.000	0.998	0.996	0.994	0.993	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990
4	1.000	0.997	0.996	0.994	0.993	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.990
5	1.000	0.997	0.995	0.994	0.993	0.993	0.992	0.992	0.992	0.992	0.991	0.991	0.991	0.991	0.990	0.990	0.990
6	1.000	0.997	0.995	0.994	0.992	0.992	0.991	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990	0.989
7	1.000	0.991	0.982	0.973	0.965	0.957	0.953	0.950	0.948	0.945	0.943	0.941	0.939	0.937	0.936	0.935	0.935
8	1.000	0.989	0.979	0.969	0.960	0.951	0.947	0.944	0.941	0.938	0.935	0.932	0.930	0.928	0.926	0.926	0.925
9	1.000	0.989	0.979	0.970	0.960	0.952	0.947	0.944	0.941	0.938	0.935	0.932	0.930	0.928	0.927	0.926	0.925
10	1.000	0.992	0.985	0.980	0.975	0.971	0.968	0.966	0.964	0.962	0.960	0.958	0.956	0.955	0.954	0.953	0.953
11	1.000	0.996	0.992	0.987	0.983	0.979	0.976	0.974	0.973	0.971	0.969	0.968	0.967	0.966	0.966	0.966	0.966
12	1.000	0.994	0.988	0.982	0.977	0.971	0.969	0.967	0.965	0.964	0.962	0.961	0.960	0.960	0.959	0.959	0.959
13	1.000	0.993	0.986	0.978	0.970	0.963	0.963	0.962	0.962	0.962	0.962	0.961	0.961	0.961	0.961	0.961	0.961
14	1.000	0.995	0.991	0.988	0.985	0.982	0.981	0.980	0.980	0.979	0.977	0.976	0.976	0.975	0.974	0.974	0.974
15	1.000	0.998	0.996	0.995	0.993	0.992	0.992	0.992	0.992	0.991	0.991	0.990	0.990	0.991	0.990	0.991	0.991
16	1.000	0.998	0.996	0.994	0.993	0.992	0.992	0.992	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990
17	1.000	0.997	0.996	0.994	0.993	0.992	0.991	0.991	0.991	0.991	0.990	0.990	0.989	0.990	0.989	0.990	0.990
18	1.000	0.988	0.978	0.969	0.960	0.952	0.947	0.943	0.940	0.936	0.933	0.930	0.927	0.925	0.923	0.922	0.921
19	1.000	0.981	0.965	0.951	0.938	0.925	0.918	0.911	0.904	0.898	0.892	0.887	0.882	0.878	0.875	0.872	0.871
20	1.000	0.980	0.964	0.949	0.935	0.922	0.915	0.908	0.901	0.895	0.889	0.884	0.879	0.875	0.872	0.869	0.868
21	1.000	0.983	0.969	0.957	0.945	0.935	0.928	0.921	0.915	0.909	0.903	0.898	0.894	0.890	0.887	0.885	0.883
22	1.000	0.991	0.984	0.979	0.973	0.968	0.966	0.964	0.962	0.960	0.959	0.957	0.956	0.955	0.954	0.953	0.953
23	1.000	0.997	0.995	0.994	0.993	0.992	0.991	0.991	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990
24	1.000	0.998	0.996	0.995	0.994	0.993	0.992	0.991	0.991	0.991	0.991	0.990	0.990	0.990	0.990	0.990	0.990

Continued..

Bus No./Time	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	0.990	0.997	0.997	0.997	0.997	0.996	0.996	0.996	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992
2	0.990	0.997	0.997	0.996	0.996	0.996	0.995	0.995	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992
3	0.990	0.997	0.997	0.996	0.996	0.995	0.995	0.995	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992
4	0.990	0.997	0.996	0.996	0.996	0.995	0.995	0.995	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992
5	0.990	0.996	0.996	0.995	0.995	0.995	0.994	0.994	0.992	0.992	0.992	0.992	0.991	0.991	0.991	0.991
6	0.989	0.996	0.995	0.995	0.995	0.994	0.994	0.994	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991
7	0.935	0.991	0.990	0.990	0.990	0.982	0.982	0.982	0.953	0.951	0.948	0.946	0.944	0.942	0.941	0.942
8	0.925	0.989	0.988	0.988	0.988	0.979	0.979	0.979	0.948	0.944	0.942	0.939	0.937	0.935	0.934	0.933
9	0.925	0.988	0.988	0.987	0.987	0.979	0.979	0.980	0.948	0.945	0.942	0.939	0.937	0.935	0.934	0.934
10	0.952	0.992	0.991	0.991	0.991	0.986	0.986	0.986	0.970	0.970	0.969	0.969	0.968	0.968	0.967	0.967
11	0.966	0.995	0.995	0.995	0.995	0.992	0.992	0.992	0.978	0.978	0.978	0.977	0.977	0.976	0.976	0.977
12	0.959	0.994	0.994	0.994	0.993	0.988	0.988	0.989	0.969	0.967	0.966	0.964	0.963	0.961	0.961	0.961
13	0.961	0.993	0.993	0.993	0.993	0.986	0.987	0.987	0.956	0.950	0.944	0.939	0.934	0.929	0.925	0.925
14	0.974	0.994	0.992	0.991	0.991	0.991	0.991	0.991	0.981	0.979	0.979	0.978	0.977	0.977	0.976	0.976
15	0.991	0.998	0.997	0.997	0.997	0.996	0.997	0.997	0.991	0.991	0.990	0.990	0.989	0.989	0.989	0.989
16	0.990	0.997	0.997	0.997	0.996	0.996	0.996	0.996	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992
17	0.990	0.997	0.996	0.996	0.996	0.996	0.996	0.995	0.992	0.991	0.992	0.992	0.992	0.991	0.992	0.992
18	0.920	0.987	0.985	0.985	0.984	0.977	0.976	0.976	0.948	0.945	0.942	0.940	0.939	0.938	0.937	0.938
19	0.870	0.979	0.977	0.976	0.975	0.964	0.963	0.962	0.920	0.915	0.912	0.908	0.906	0.905	0.904	0.904
20	0.867	0.978	0.976	0.975	0.975	0.962	0.961	0.961	0.917	0.912	0.908	0.905	0.903	0.901	0.901	0.901
21	0.882	0.981	0.980	0.979	0.978	0.967	0.967	0.966	0.932	0.929	0.927	0.925	0.924	0.923	0.922	0.922
22	0.952	0.990	0.989	0.988	0.987	0.984	0.983	0.983	0.966	0.965	0.964	0.963	0.962	0.961	0.961	0.961
23	0.990	0.997	0.996	0.996	0.996	0.995	0.995	0.995	0.992	0.991	0.991	0.991	0.991	0.991	0.991	0.991
24	0.990	0.997	0.997	0.996	0.996	0.996	0.996	0.995	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992

Performance Enhancement of Low Voltage Distribution Network by Optimal Inverter Control of Solar PV System

By Surendra Chaudhary

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