Department of Electrical Engineering

Optimal Volt Var control in Smart Distribution Networks

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Shamraiz Shamraiz

15/05/2021

Abstract

Both the generation and transmission power networks are facing new threats and opportunities as the number of distributed energy resources (DERs) grows. Because of the high solar PV penetration, voltage rise and voltage volatility are becoming major problems in the distribution network. Voltage regulating devices (VRDs), such as on load tap changers (OLTCs), phase voltage regulators (SVRs), and switched capacitor banks, have traditionally been used to regulate voltage throughout the distribution power system (DPS) (SCBs). IEEE 1547-2018, published in March 2018, mandates that inverter-fed distributed energy resources (DERs) contribute reactive power to maintain grid voltage.

Our research uses the reactive power capabilities of PV smart inverters to resolve the voltage problems that the distribution grid faces as a result of solar PV penetration. The slope sensitive local droop has been design and validate using co-simulation of OPENDSS and MATLAB.

Table of Contents

Table of Figures

List of Tables

Abbreviations

PV – Photovoltaic

DC – Direct Current

AC – Alternating Current

PWM – Pulse Width Modulation

MPPT – Maximum Power Point Tracking

PCC – Point of Common Coupling

OC – Open Circuit

VAR – Volt Ampere Reactive

VA – Volt Ampere

NOMENCLATURE

I Current [A]

V Voltage [V]

P Power [W]

t Time [s]

Rsh Shunt resistance

Rse Series resistance

va, vb, vc PCC voltage [V]

vd, vq d and q axis voltages [V]

id, iq d and q axis currents [A]

Ipv=output current(A)

I0=Leakage current of the diode (A)

vpv=Voltage at MPP(V)

1 Chapter 1: Introduction

With high penetration of distributed energy resources, the new power grid is undergoing rapid changes on the distribution side (DERs). By 2020, DER is expected to account for 42 percent of overall capacity expansion [1]. It's worth noting that, from 2012 to 2020, the average expected growth rate for centralized power is 2.8 percent, while it's 4.4 percent for distributed power. In 2019, photovoltaics (PV) accounted for nearly all of Germany's solar power production, accounting for 8.2 percent of the country's total electricity generation. The German Federal Government's annual target of increasing PV capacity by 2.5 GW was met in 2020, but the energy transformation's targets are still a long way off.

A major expansion of installed PV capacity, as well as a range of other steps, are needed to meet all of our energy needs from renewable energies (RE). With a PV expansion corridor of 130-650 GWp nominal size, more recent model-based scenarios measure a reduction in energy-related greenhouse gas emissions of at least 90% compared to 1990. [2], [3], [4] The German Renewable Energy Sources Act [5] sets the target of making Germany's electricity generation and consumption greenhouse gas neutral by 2050. A 65 percent share of renewable energies (RE) in gross electricity consumption is set as an intermediate target for 2030. Depending on the evolution of electricity demand and the growth of wind power, this would necessitate an annual PV addition of at least 5-10 GWp. [6], [7] The German Renewable Energy Sources Act [5], on the other hand, sets a goal of 100 GWp for PV growth, which translates to an annual addition of just under 5 GWp per year. Power plants with a nominal capacity of just 1.9 GWp/a were built on average in Germany between 2013 and 2018 [8].

PV is expected to cover 9.3% of Germany's gross electricity consumption in 2020, with 50 TWh of electricity generation [9], with all renewables (RE) accounting for 46% (Figure 1: Percentage renewable energy in net electricity consumption for Germany, data from. [8] Grid, storage, and self-consumption losses are all included in gross electricity consumption. PV electricity will cover more than two-thirds of our existing electricity usage on sunny days. PV modules with a nominal capacity of 54 GWp were deployed in Germany by the end of 2020 [10], spanning 2 million systems [11].

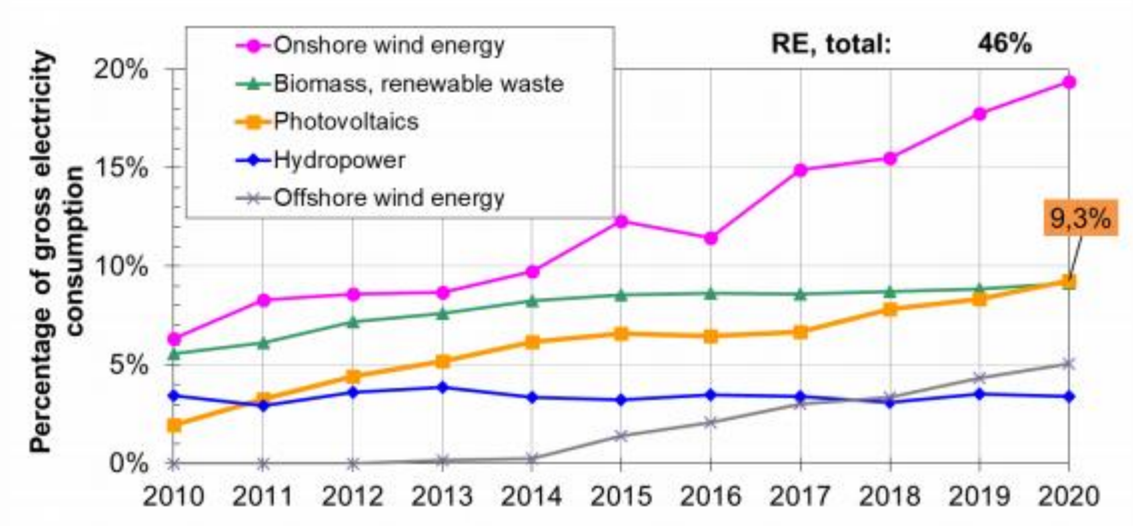

Figure 1 Percentage renewable energy in net electricity consumption for Germany[10]

1.1 The Importance of Power Quality in PV-Integrated LV Networks

Power quality issues such as local voltage increase, voltage unbalance, reverse power flow (RPF), and neutral to ground voltage (NGV) are introduced by the uneven distribution of PV generation. Usually, distribution networks are designed for a particular load profile based on demand patterns. As rooftop PVs are installed at any arbitrary phase, the pattern of power consumption changes, resulting in a local voltage rise issue.[12] PV generation's fluctuating nature can result in constant voltage fluctuations and voltage unbalance in the distribution system. The effect of PV generation on the voltage profile of the distribution network has been studied in the literature [13–18]. Voltage fluctuation depends on the size of the PV plant, distance from the distribution transformer, and length of mutual secondary between consumers for a consumer connected to the same distribution transformer. It has also been found that voltage variation caused by a single PV generator with no reverse power flow through the transformer can be worse than voltage variation caused by a group of PVs with reverse power flow [13]. The introduction of broad PV power can trigger a voltage rise of 1–2 percent and a voltage unbalance of 1–2 percent, according to measurements and analyses carried out in different countries with high PV penetration [15].

Grid-connected appliances and safety equipment are harmed by voltage imbalance. Extra power failure, safety deficiencies, relay malfunction (due to zero and negative sequence current), incorrect calculation, and transformer/motor life cycle decrement may all be caused by voltage unbalance [14]. Motor torque pulsation and excessive noise are caused by an unbalanced voltage supply. A voltage imbalance causes a current imbalance, which causes the motor to overheat. The voltage imbalance in an induction motor does not exceed 5%, according to the National Electrical Manufacturers Association (NEMA). With an unbalanced voltage supply, line current through the switching portion increased significantly in the rectifier. Due to the increased current, switching devices and rectifier capacitors are placed under a lot of strain. Furthermore, a higher supply current peak reduces the supply distortion power factor (DPF) [16].

Unbalanced voltage, which can be triggered by unbalanced PV allocation or varying consumer generation/consumption, has the potential to exacerbate the classic neutral current and neutral potential problem [17]. If the neutral current exceeds the rated phase current, the neutral conductors, which are normally the same size as the phase conductors, may be overloaded. The distribution transformer may be overloaded if there is an excessive amount of neural current. When the neutral impedance is not negligible, neutral current will cause common mode noise. Regardless of frequency, computer vendor requirements usually call for less than 0.5–3 V RMS, neutral to ground (NGV) [18].

1.2 Problem Description

Voltage rise due to PV power injection in distribution network is serious concern for the consumer. Voltage rise beyond the permissible limit can damage the consumer's appliances. Apart from this voltage rise in distribution network is the prime limiting factor of the PV integration on the distribution network. If the voltage rise issue in distribution network strongly address it will allow us to integrate more amount of PV generation in the distribution network.

In the following parts, the impact of a PV system on local voltage rise in an LV distribution network has been investigated and clarified.

1.3 Objective

Following objective have been addressed in this thesis:

- Study and analysis of effect of PV generation in distribution network

- Mitigation of voltage rise using volt/var control

1.4 Distribution Systems with Volt/Var Control (VVC)

All electric distribution systems need volt/var control (VVC) as a basic operating requirement. VVC's main goal is to maintain an optimal voltage profile at all points along the distribution feeder, regardless of load. Different regulatory agencies in different places determine the appropriate voltage range. On load tap changer (OLTC), phase voltage regulator (SVR), substation capacitor, and feeder capacitor are the four types of devices traditionally used to regulate voltage and reactive power flow in distribution systems, as shown in 2.

However, due to their slow and discrete power, these devices are insufficient to alleviate voltage challenges associated with solar PV. They are unable to cope with the rapid fluctuations in solar generation, i.e., cloud shadow. [19],[20],[21] Fortunately, most inverter-based DERs, such as wind, solar PV, electric vehicles, and synchronous generator-based generation, have inherent volt/var control capacity that can be used to improve the network's voltage profile. In the following part, we'll go through them in depth.

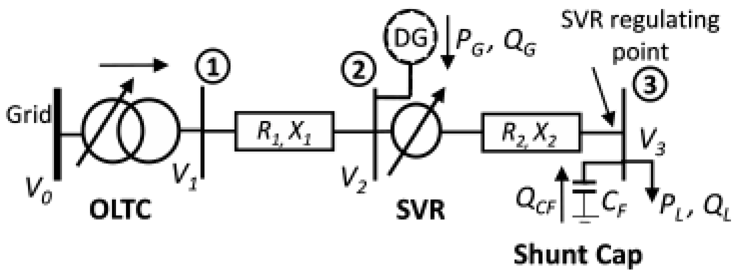

Figure 2 One line diagram of a typical distribution feeder with solar PV

1.5 Volt/Var Control Capability of Solar PV Smart Inverters

An inverter is used in grid-connected solar PV generation systems to convert input DC power to output grid-compatible AC power. Surprisingly, by injecting and absorbing reactive electricity, the same inverter can also be used to control the voltage at the point of common coupling (var). This mode is known as voltage control mode, and these multi-functional PV inverters with volt/var functionality are often widely referred to as "smart inverters" (VCM). Constant power factor (CPF) mode is another typical DER operation mode, in which DERs are run at unity or another constant power factor (usually lagging PF to compensate for voltage rise). The rated capacity of the inverters limits their ability to inject or absorb var. The following relationship must be met by the inverter.

$$P^2 + Q^2 = S^2 \dots\dots\dots\dots\dots (1)$$

Where,

P = Active Power Capacity

Q = Reactive Power Capacity

S = Rated Apparent Power of Inverter

As a result, the overall var magnitude that the inverter can inject or absorb at any given time can be calculated as

$$Q_{max} = \sqrt{S^2 - P^2} \dots\dots\dots\dots\dots (2)$$

PV inverters have emerged as effective volt/var controllers to handle rapid variations in the modern distribution system by providing faster and continuous VVC capability in comparison to slower and discrete response of conventional VVC devices due to their quick switching control behavior at seconds time-scale and dynamic nature of control.

1.6 Methodology

To understand the impact of PV integration on distribution network, several articles have been studies and summarized in chapter 2. IEEE 906 bus European LV network has been considered for the validation of this study. Chapter 3 include the simulation study. Simulation study has been divided in three part. In 3.1 IEEE 906 bus European LV network has been studied without PV integration, in 3.2 impact of PV Integration on IEEE 906 bus European LV network has been studied. In 3.3 PV system with Volt/VAR control has been considered.

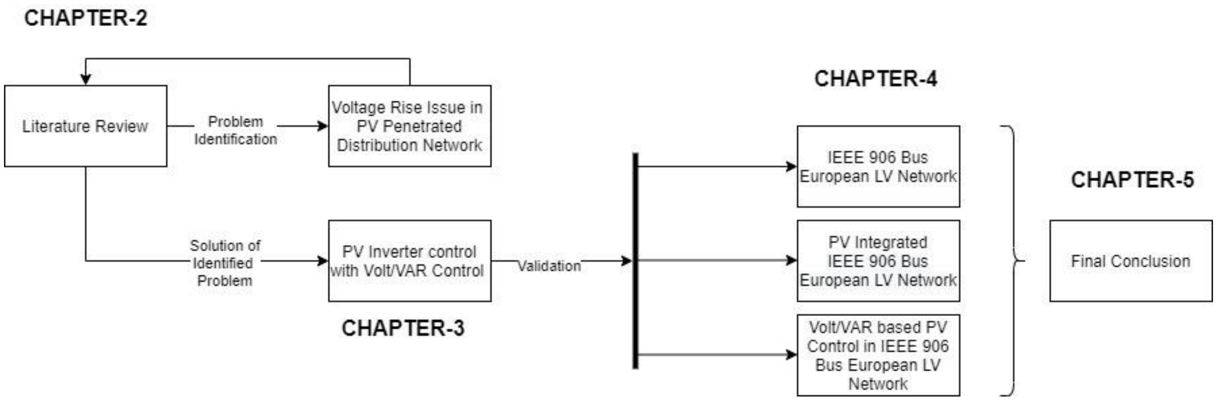

Figure 3 Methodology

2 Chapter 2: Literature Review

Over the years there has been extensive research on the field of reactive DER unit power management, including (i) constant power factor mode, (ii) voltage-reactive power mode, (iii) active power/reactive power mode and (iv) constant reactivation power mode. [22], [23]. DER units are defined in detail in [24] the various autonomous violation control systems for the DER inverters. It shows that the volt/VAr power is best regulated and that DER generations control the voltage. However, the reactive power support from the inverter is not specified in the response time. In the [25] report, non-linear regulation of reactive power in DER units were proposed to increase DER units penetration into DPS. DER's active power generation and impedance of the system have measured the reactive power needed. In addition to standard voltage support, the authors of [26] tested the grid voltage support through an automated default active and reagent power support from a bacterial power storage device. It shows that grid stability with power balance in high-penetration PV/wind is achieved by the proposed strategy. The study proposed the autonomous reactive power regulation, which is based on the voltage drop, which provides the grid with reactive power on the basis of changes in grid voltage.

X. Zhao et al. analysed the different functions used in today's smart inverter units and addressed reactive power management solutions for the safe functioning of high DER-infiltrated power systems [27]. Despite the fact that many studies have been conducted on autonomous reactive power control in DER units, further research is required, including

1. response time for DER-reactive power support to the grid, which is critical in practical applications due to grid stability and protection devices used in the system,
2. maximising reactive power support to the grid.

OLTC, SVR, SCB, static VAR compensator (SVC), static synchronous compensator (STATCOM), dynamic VAR compensator (DVC), and DER units have all been studied in relation to grid voltage support in conjunction with VRDs. [28] Furthermore, utilities used these machines in their delivery systems to increase voltage control. VRDs can be used independently or in a synchronised manner. According to article [29], DER units will effectively accommodate grid voltage within their power limits. The relationship of synchronous system fed distribution generator systems and voltage regulators in a practical medium voltage feeder was explored in [30].

The authors of [31] looked at how OLTC, SCB, and DER units affected voltage management in distribution systems. The simultaneous running of an autonomous OLTC control and autonomous solar PV reactive power control for regulating grid voltage in the PV-rich DPS in Germany was detailed in the study [32]. It looked at how various reactive power control techniques in PV affected the number of unintended OLTC switching operations, and found that voltage-reactive power mode had the least effect on the number of unintended OLTC switching operations. According to a study [33], the synchronised application of remote monitoring-based OLTC control and autonomous PV reactive power control in the Taiwan power grid mitigates the voltage quality impacts caused by the system's high PV penetration.

The online voltage regulation technique for an Australian grid with voltage controlling equipment and DER units was studied in reference [34]. [35] discusses the combined autonomous (local) and centralised voltage control of DER units via reactive power control. It was discovered that DER unit local control meets IEEE 1547-2018 rules, and if reactive power is already usable (estimated based on obvious power limit), the centralised control system instructs the DER unit to provide the available reactive power support. It has been discovered that autonomous and remote control of DER units is needed to sustain the grid for at least 3–90 seconds after voltage fluctuations, as dictated by IEEE guidelines due to grid oscillatory behaviour and safety equipment. In conclusion, current literatures primarily concentrate on controlling VRDs and DER units via online/remote contact control for improved grid service. In addition, some studies have proposed that additional voltage regulators such as SVC, STATCOM, and DVC units be used to control grid voltage in DER-rich delivery networks. In addition, in their DER units, utilities have adopted the IEEE 1547-2018 legislation. Despite this, utilities are requiring:

I. autonomous or minimal contact and time-graded operation of VRDs and DER systems,
II. maintaining grid voltage output without installing additional voltage regulators such as SVC, STATCOM, DVC, and so on, due to expense and location of voltage regulating equipment.

3 Chapter 3: PV System integrated Distribution Network

3.1 PV System

3.1.1 PV Module

PV module is a nonlinear energy source made up of a group of series connected solar cells. Its optimum power generation potential is strongly influenced by irradiance and temperature, while its instantaneous power generation is specifically influenced by its output impedance [9]. As seen below [10], a PV Module can be represented by a single diode equivalent circuit.

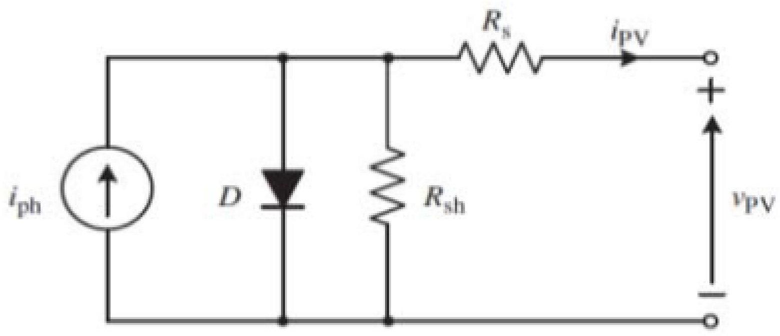

Figure 4 Single diode PV Cell circuit

The equations below are used to model PV cells, PV modules, and PV arrays.[6]

The output current I_{pv} of a PV module can be determined by,

$$I_{pv} = I_{ph} - I_0\left[\exp\left(\frac{v_{pv} + I_{pv}R_s}{a}\right) - 1\right] - \frac{v_{pv} + I_{pv}R_s}{R_{sh}} \ldots\ldots..(3)$$

Where,

$I_{pv} = output\ current(A)$

$I_0 = Leakage\ current\ of\ the\ diode\ (A)$

$v_{pv} = Voltage\ at\ MPP(V)$

$R_{sh} = Shunt\ Resistance$

$R_{se} = Series\ Resistance$

3.1.2 GRID CONNECTED PV SYSTEM

PV source, DC/DC converter, and DC/AC converter are all part of a grid-connected PV system. To ensure optimum power generation from the PV source, the MPPT algorithm is used to operate the DC/DC converter. With the aid of an inverter, the generated power is shifted to the AC side. Grid synchronisation, DC connection voltage balance, and Active/Reactive power control are all examples of inverter control. Inverter current is usually regulated for both active and reactive power management. Voltage Oriented Control (VOC) is commonly used in inverter-based distributed generation systems for current control. VOC necessitates the use of a reference frame of grid voltage. The dq reference frame orientation also allows for DC transformation of AC quantities, which can be managed easily with a PI controller. Grid current is decomposed into two components in the dq reference frame: active current Id and reactive current Iq (grid voltage is oriented with the d axis).

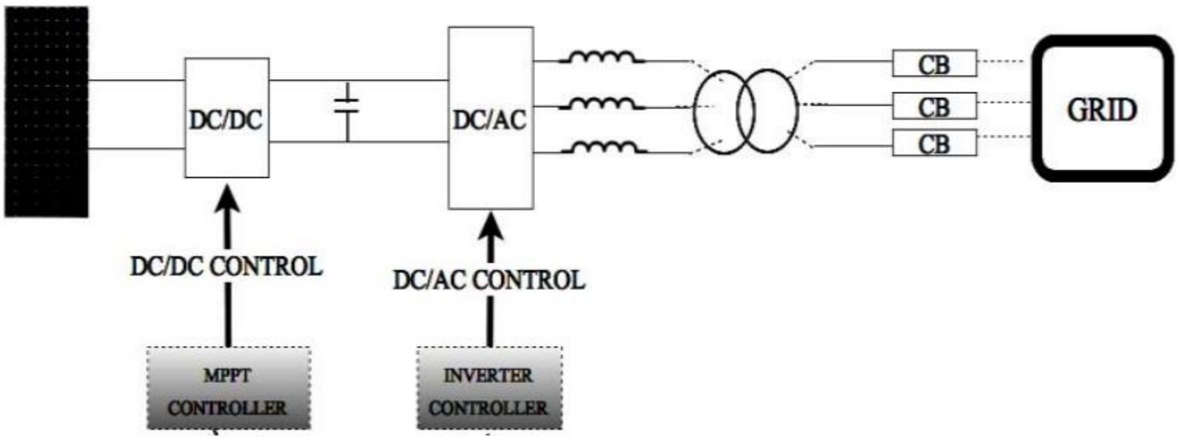

Figure 5 Grid Connected PV System

The Active power Id control loop is cascaded with the DC Link voltage controller, and all Idq are operated by the PI controller, which generates sine pulse width modulation (SPWM) switching references.

The grid-side voltage equation is as follows:

$$v_s = i_s R_s + L_s \frac{di_s}{dt} + jw_s L_s I_s + v_c$$

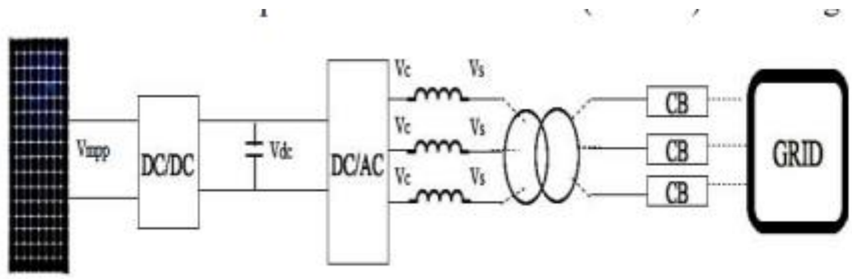

Figure 6 Grid Connected Inverter

The following is the product of decomposing above into its d and q components:

$$v_{sd} = i_{sd}R_s + L_s\frac{di_{sd}}{dt} - jw_sL_sI_{sq} + v_{cd}$$

$$v_{sq} = i_{sq}R_s + L_s\frac{di_{sq}}{dt} + jw_sL_sI_{sd} + v_{cq}$$

The currents Id and Iq are seen to be coupled in this equation.

This coupling term's feed forward decouples active current Id and reactive current Iq, allowing active and reactive power to be regulated independently.

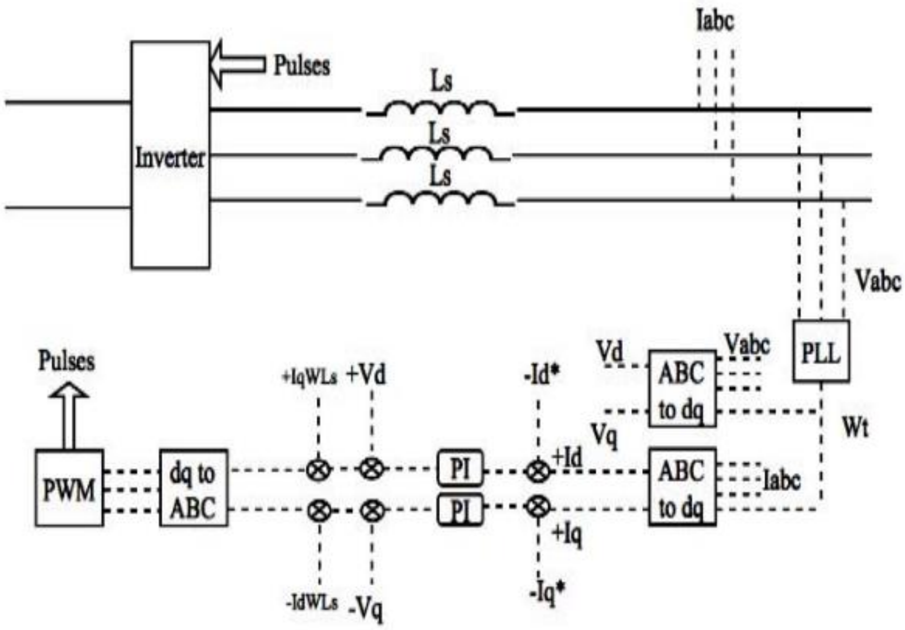

Figure 7 Decouple Current Control with Feed Forward

Figure 7 displays a grid-connected inverter with decoupled current power and a feed forward approach. As seen in Fig. 8, a DC connection voltage controller is cascaded with an active power loop to regulate capacitor power and thus voltage.

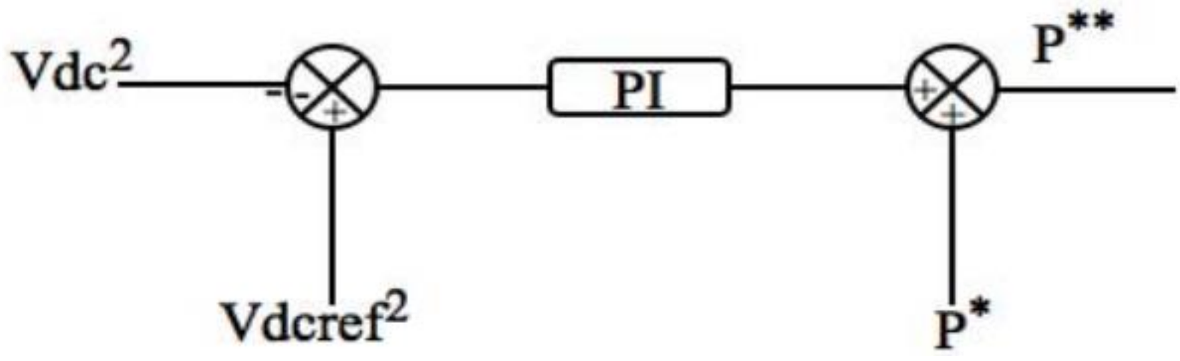

Figure 8 DC-Link voltage controller

The following equation can be used to quantify reference active and reactive power:

$$P = \frac{3}{2} v_{sd} i_{sd}$$

$$P = \frac{3}{2} v_{sq} i_{sq}$$

3.1.3 PV System with Volt/VAR Control

Fed by an smart inverter the PV System is a grid voltage regulator that controls the phase angle of the ac current relative to the ac voltage to provide both inductive and capacitive reactive power. The voltage and active power dependent reactive power management techniques of PV System are seen in Figures 9 and 10. The PV System may also use monitoring mechanisms such as constant power factor mode and constant reactive power mode. Based on these control techniques, the PV System will provide a maximum of 44 percent reactive power support to the grid between 1s and 90s to sustain grid voltage during the operating voltage area (0.88 p.u to 1.10 p.u).

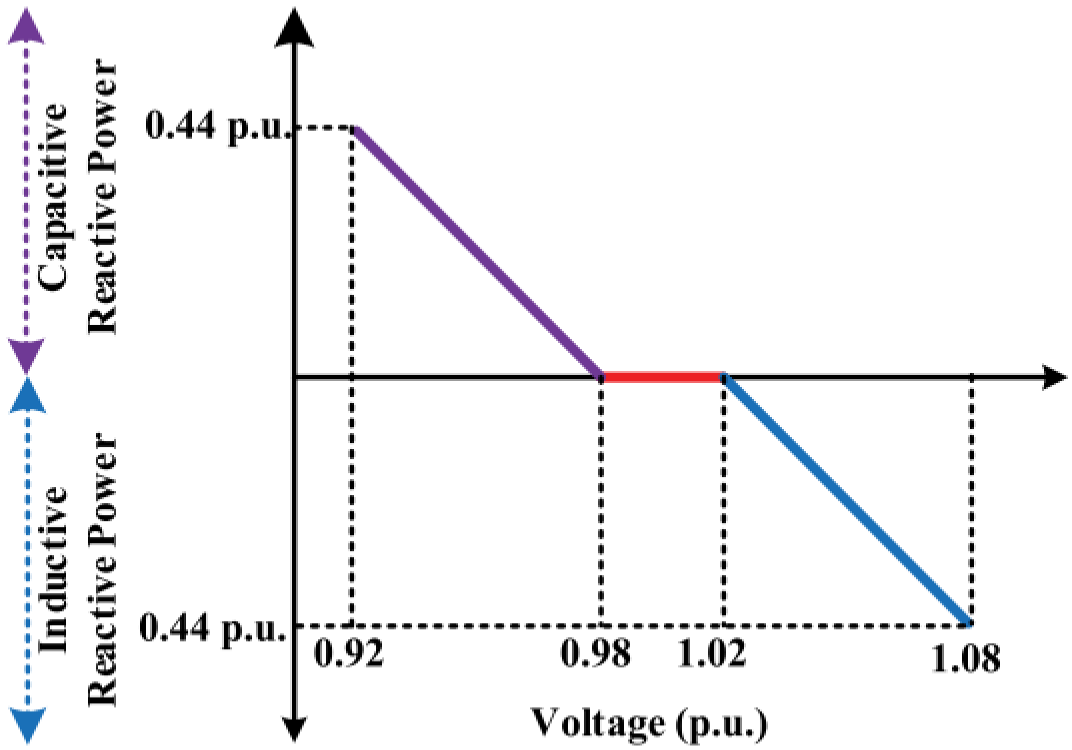

Figure 9 Voltage-reactive power mode

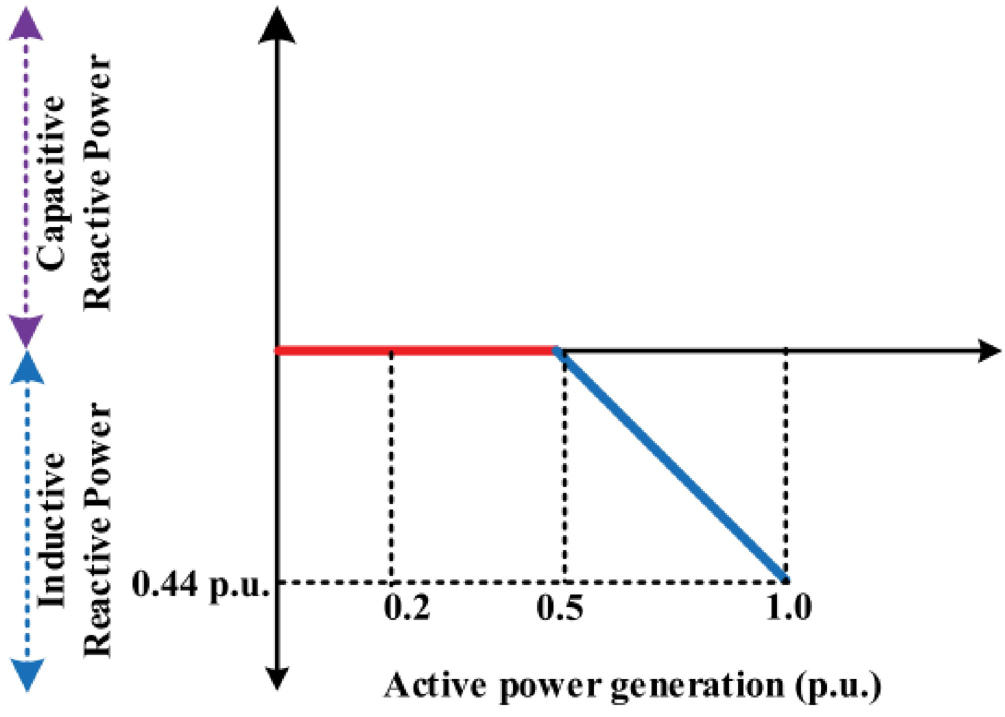

Figure 10 Active power - reactive power mode.

Voltage- Reactive power mode shown in Figure 9 controls the reactive power by observing the voltage at PCC. In a highly PV penetrated distribution network if any PV system violating the voltage profile by injecting an active power at PCC, it affects the neighboring consumers and entire distribution network. Regulating the PCC voltage ensure improved voltage profile for the entire distribution network.

Active power-reactive power mode shown in Figure.10 controls the reactive power as per the active power generation at PCC. This control strategy is most suitable for the DER having stable power generation. PV System having very fluctuating nature of active power generation is not suitable to be operated along with this control strategy.

For Voltage- Reactive power mode following configuration has been used.

- For PCC Voltage: $0.94 \leq V_{PCC} < 0.97$
    - PV system inject reactive power as per Figure.11
- For PCC Voltage: $1.03 < V_{PCC} \leq 1.06$
    - PV system absorb reactive power as per Figure.11

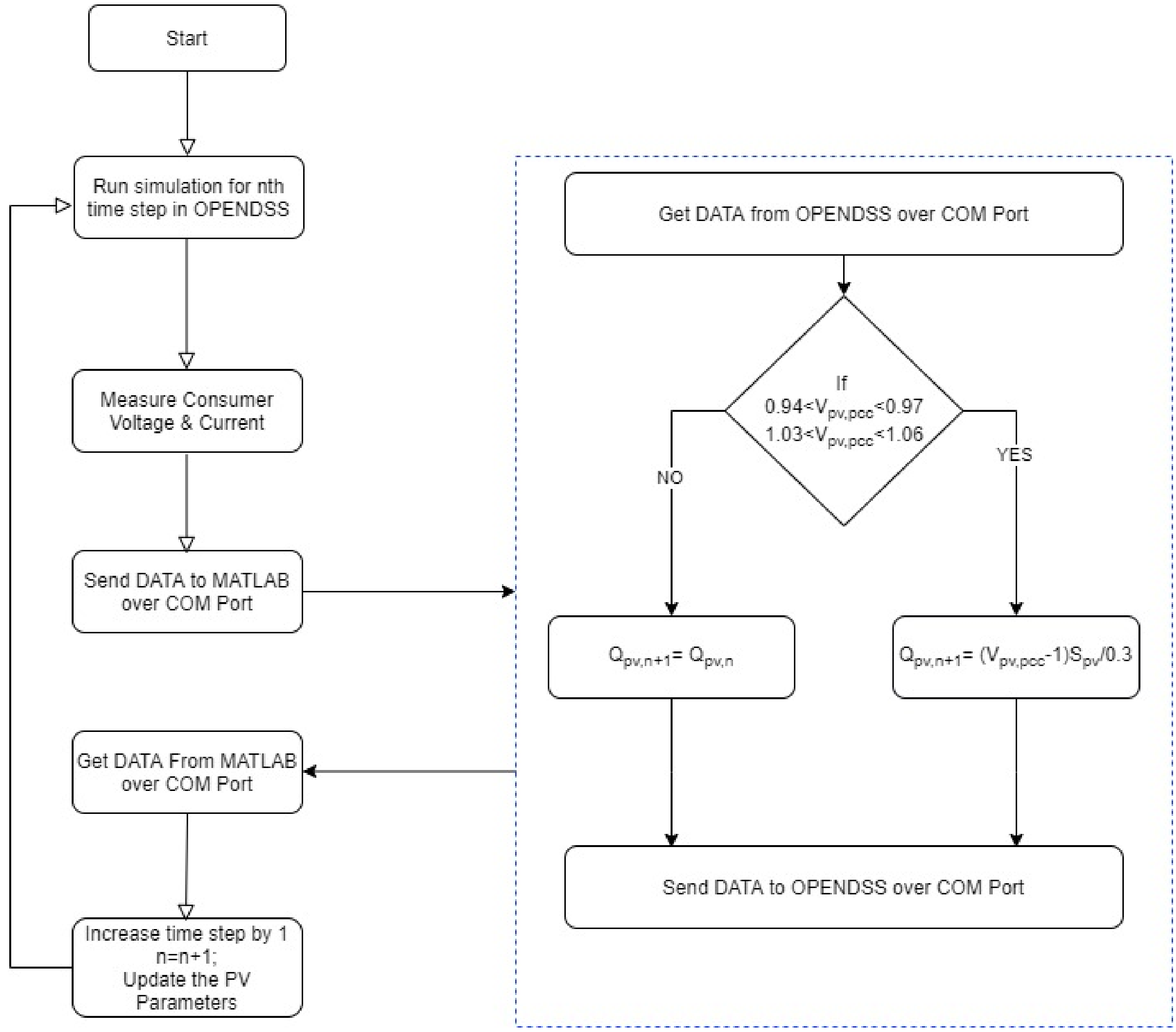

Figure 11 Reactive Power Control VL - Algorithm

In this case PV System continually regulate the PCC voltage by injecting or absorbing the reactive power with following constrain:

$$Q_{max,pv} = \sqrt{{S_{pv}}^2 - {P_{pv}}^2}$$

Where, $Q_{max,pv}$ is the maximum reactive power, S_{pv} is the rated apparent capacity of PV Inverter, and P_{pv} is the instantaneous active power generation from PV system

3.1.4 Co-simulation: OPENDSS & MATLAB

Co-simulation using OPENDSS and MATLAB was used to validate the proposed method for reducing voltage rise problem. OPENDSS is a script-based programming method that enables users to conduct quasi-time series analysis. Controlling PV System parameters in OPENDSS has become more flexible thanks to MATLAB. The technique for doing co-simulation with OPENDSS and MATLAB is shown in Figure.12. OPENDSS is used in the co-simulation to calculate the load flow of the IEEE 906 Bus European LV Test Feeder. In MATLAB, Volt-VAR algorithm has been developed as shown in Figure.12 was developed.

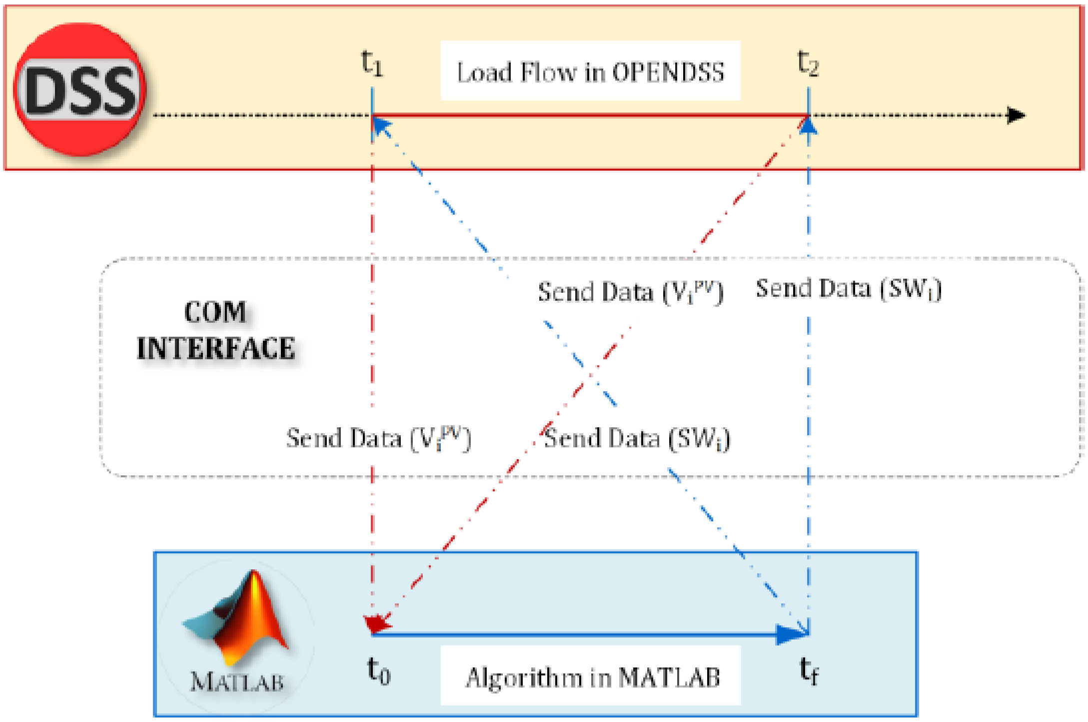

Figure 12 Co-simulation MATLAB -OpenDSS

4 CHAPTER 4: SIMULATION AND RESULTS

4.1 IEEE 906 bus European LV Network

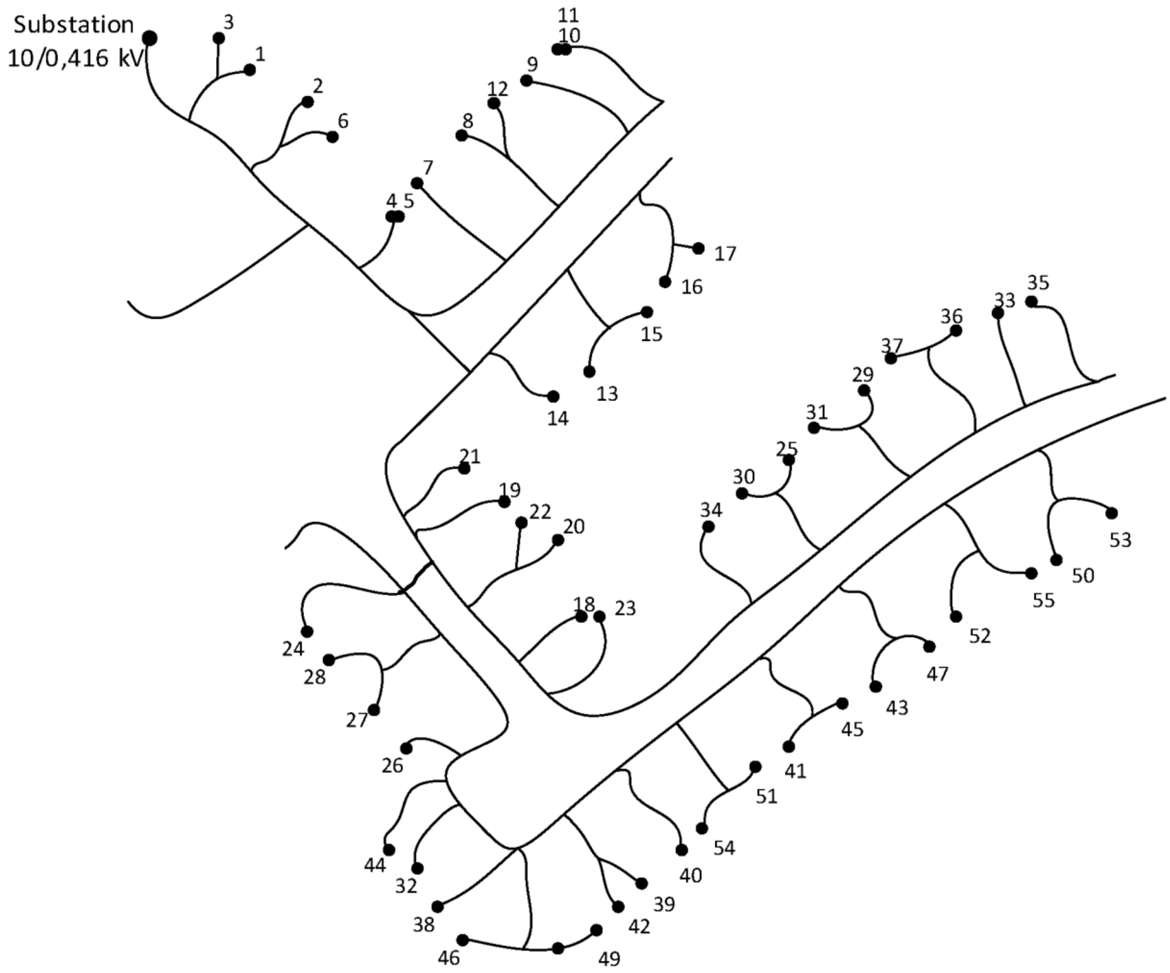

Figure 13 IEEE 906 bus European LV Network

Figure.13 shows IEEE 906 bus European LV Network. It is having 55 number of total consumers connected to different phases Phase-A, Phase-B or Phase-C. OPENDSS has been used to perform timeseries simulation of the distribution network. MATLAB has been used as a data collector to analyze the result in sophisticated manner.

Connection of all the consumers to different phases are shown in Table.1

Table 1 Consumer connection

Consumer Number		
Phase-A	Phase-B	Phase-C
1	2	8
3	6	12
4	7	16
5	10	17
9	11	18
14	13	**19**
20	15	24
21	23	27
22	26	28
25	35	32
29	36	33
30	37	39
31	38	42
34	40	43
46	41	47
48	**44**	
49	45	
51	50	
52	53	
54		
55		

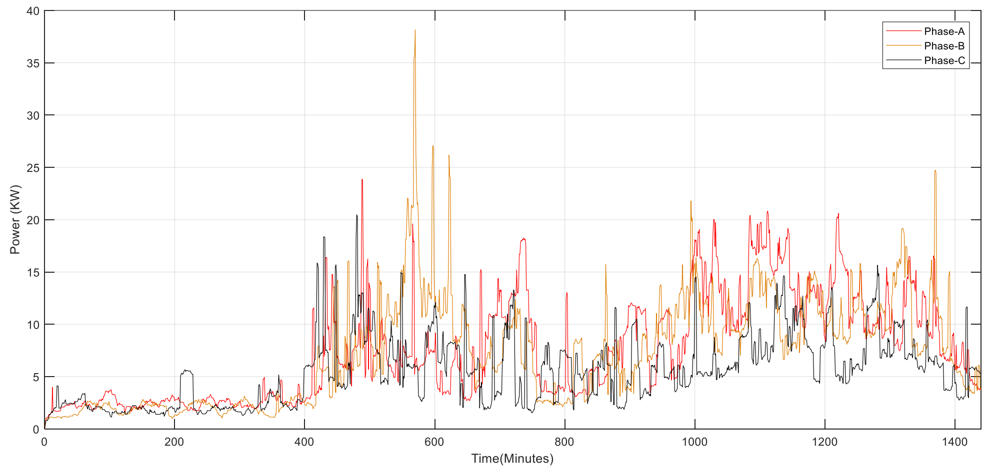

Figure 14 Active Power

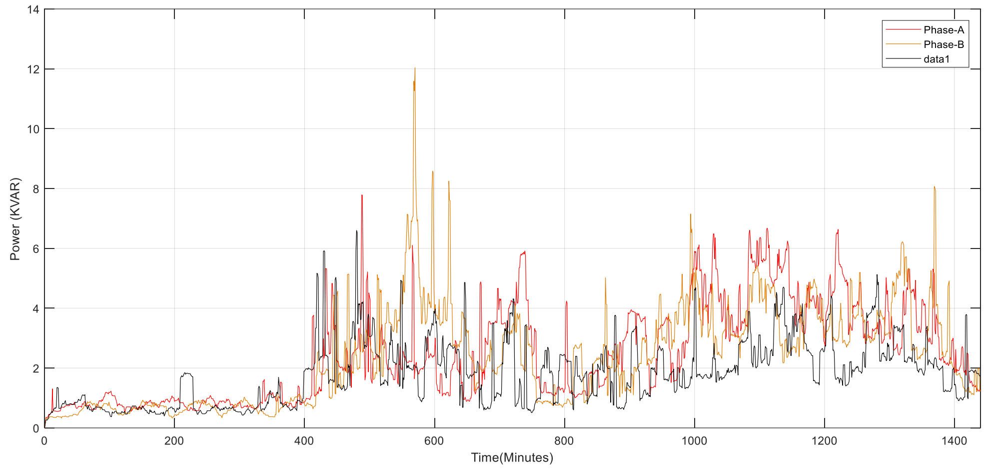

Figure 15 Reactive Power

Figure 14 and Figure 15 shows Active and Reactive power of the distribution network respectively. Loads are having continuously varying load demand which can be observed from above figures. From 55 consumer some of the load demands are shown in Figure. 16. It can be observed that load demand are continuously changing at an interval of 1 minute.

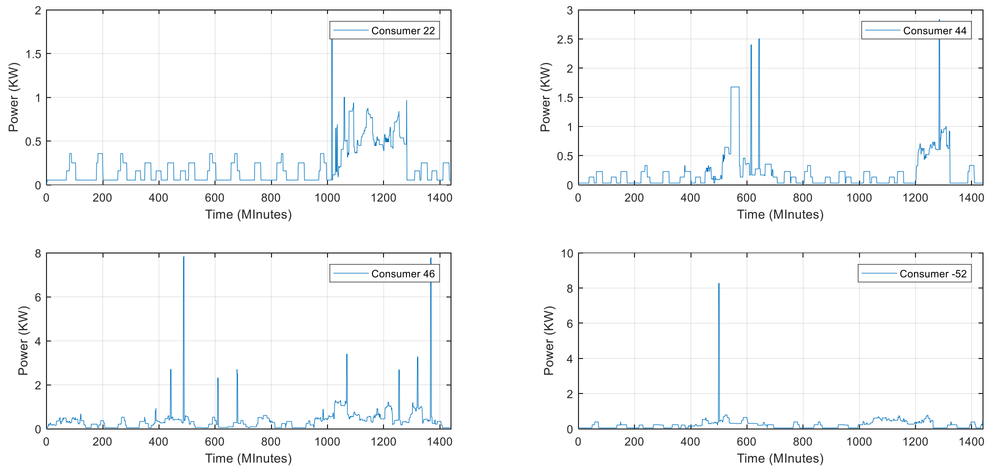

Figure 16 Load Demand

Figure 17, 18, 19 and 20 shows voltage profile of consumer 22, 44, 46 and 52 respectively.

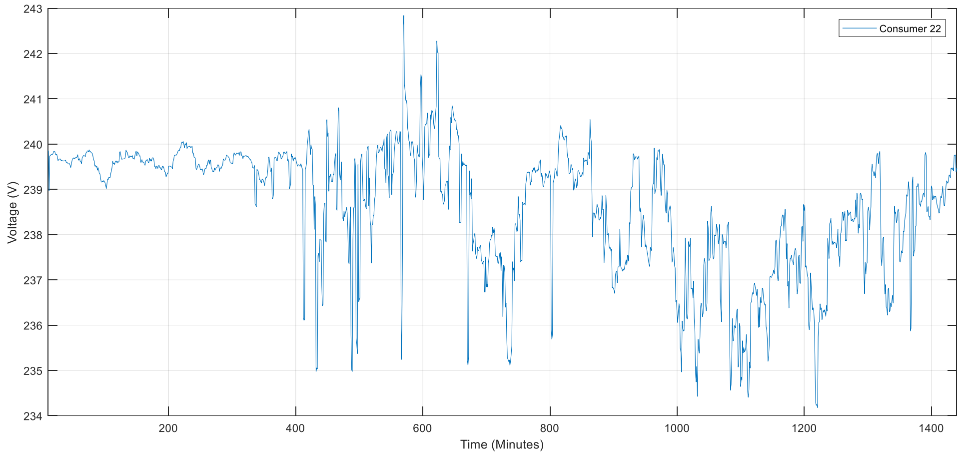

Figure 17 Voltage profile of Consumer 22

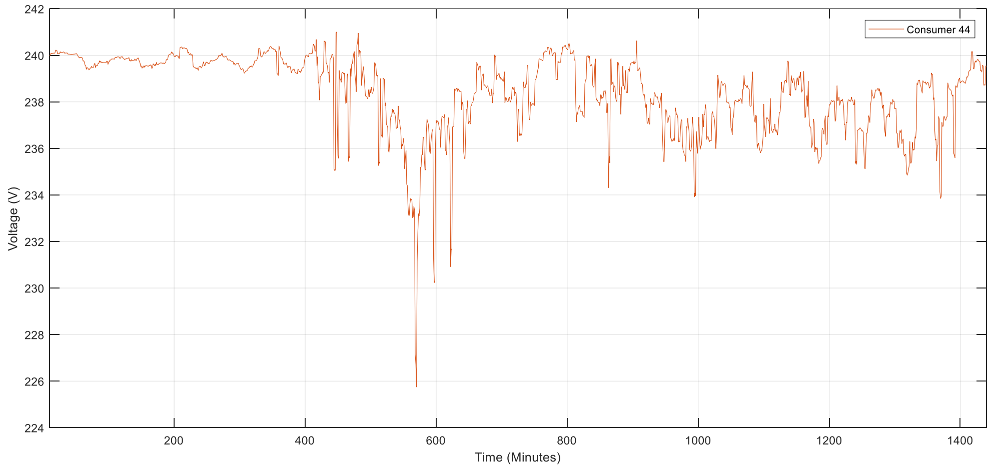

Figure 18 Voltage profile of Consumer 44

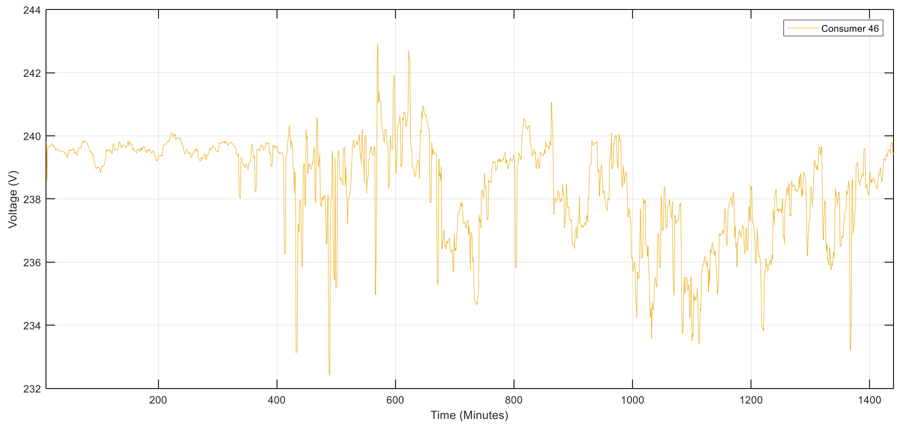

Figure 19 Voltage profile of Consumer 46

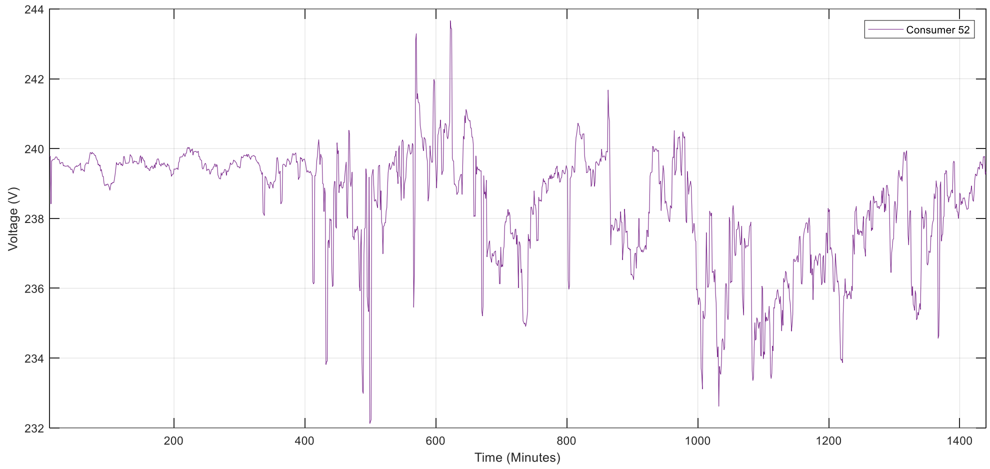

Figure 20 Voltage profile of Consumer 52

Table 2 Minimum and Maximum Voltage of consumer

Consumer	***VL***	***VH***	***Consumer***	***VL***	***VH***	***Consumer***	***VL***	***VH***
1.0	237.9	240.6	21.0	234.5	242.6	41.0	225.2	240.8
2.0	235.2	240.4	22.0	234.2	242.8	42.0	234.0	241.5
3.0	237.6	240.6	23.0	226.8	241.3	43.0	234.0	241.5
4.0	236.5	241.6	24.0	234.3	241.4	44.0	225.8	241.0
5.0	236.5	241.6	25.0	232.3	243.4	45.0	225.2	240.8
6.0	235.2	240.4	26.0	225.2	241.0	46.0	232.4	242.9
7.0	231.0	240.7	27.0	234.3	241.4	47.0	234.0	241.5
8.0	235.2	241.2	28.0	234.3	241.4	48.0	232.8	242.9
9.0	235.4	242.0	29.0	230.6	243.6	49.0	232.8	242.9
10.0	230.7	240.7	30.0	232.3	243.4	50.0	224.4	240.8
11.0	230.7	240.7	31.0	230.9	243.6	51.0	232.8	243.1
12.0	235.3	241.2	32.0	233.8	241.5	52.0	232.1	243.7
13.0	229.6	240.8	33.0	233.1	242.8	53.0	224.2	240.8
14.0	235.5	242.2	34.0	232.9	243.3	54.0	232.9	243.1
15.0	229.6	240.8	35.0	222.8	241.0	55.0	232.4	243.7
16.0	234.9	241.2	36.0	223.9	241.1			
17.0	235.0	241.2	37.0	223.9	241.1			
18.0	233.0	241.6	38.0	225.7	241.0			
19.0	233.6	241.4	39.0	234.0	241.5			
20.0	234.1	242.8	40.0	225.5	240.9			
				Low Voltage				

Table.2 shows minimum voltage and maximum voltage experienced by 55 consumers throughout the day. It can be observed that total 8 number of consumers are experiencing low voltage issue.

4.2 PV Integrated IEEE 906 European LV Network

Table 3 PV Integrated Consumer

Consumer Number		
Phase-A	Phase-B	Phase-C
1	2	8
3	6	12
4	7	16
5	10	17
9	11	18
14	13	**19**
20	15	24
21	23	27
22	26	28
25	35	32
29	36	33
30	37	39
31	38	42
34	40	43
46	41	47
48	**44**	
49	45	
51	50	
52	53	
54		
55		
	X	Consumer without PV
	X	Consumer with PV

Table shows consumer with PV power generation. From the table it has been clear that Phase -A is having maximum PV penetration with 12 number of consumers having PV power generation capacity. Phase -B is having moderate PV Penetration as 4 number of Consumer is capable to inject the power into the network. Whereas Phase C is having only 1 Consumer with PV.

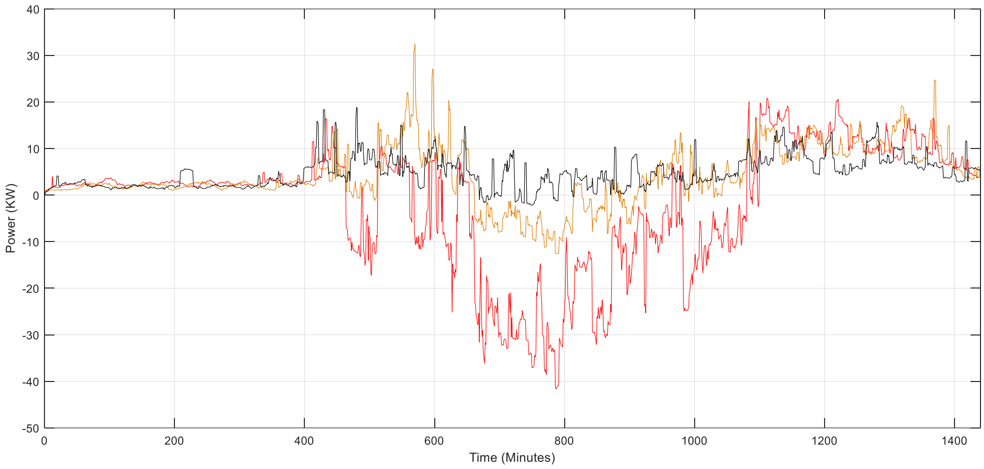

Figure 21 Active Power

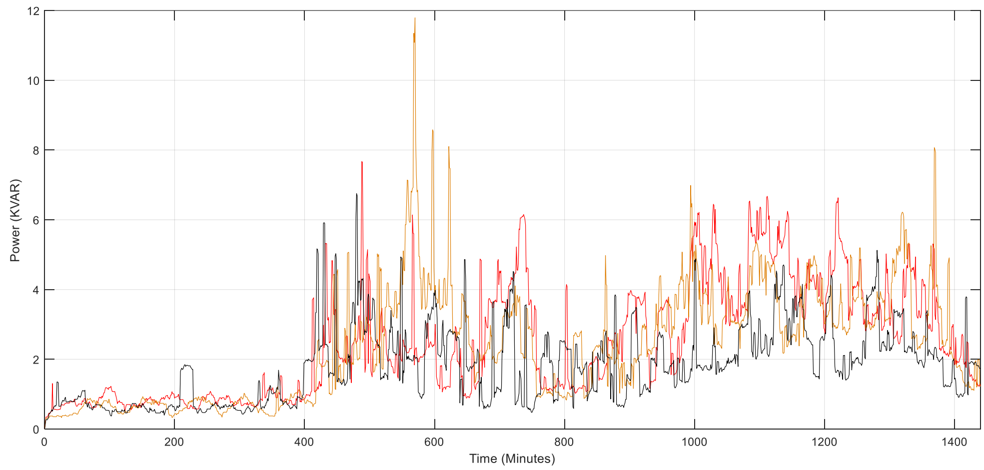

Figure 22 Reactive Power

Figure.21 and Figure 22 shows active and reactive power flow after the PV Integration. It can be observed that Phase -A is showing significant Reverse Power Flow (RPF) due to higher PV Penetration in Phase-A. Phase B and Phase C also showing Reverse Power Flow (RPF) at some point of time due to lower load demand during peak PV hours.

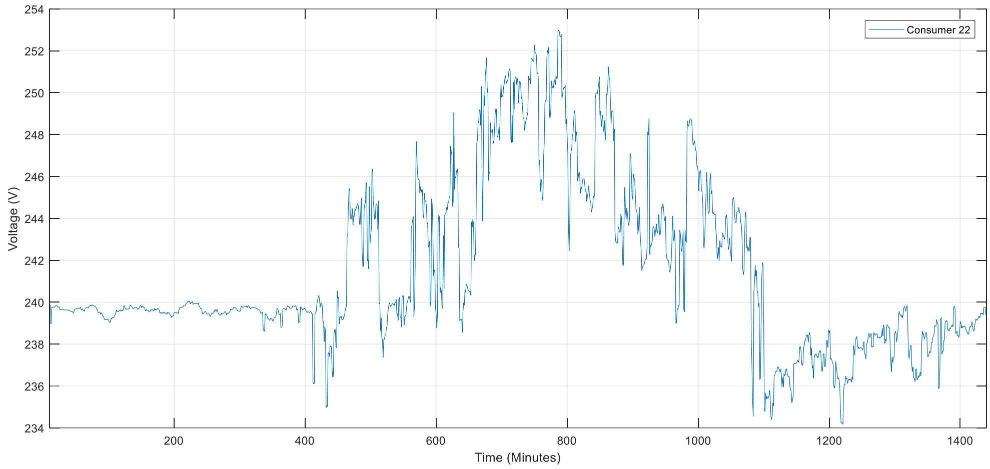

Figure 23 Voltage profile of consumer 22

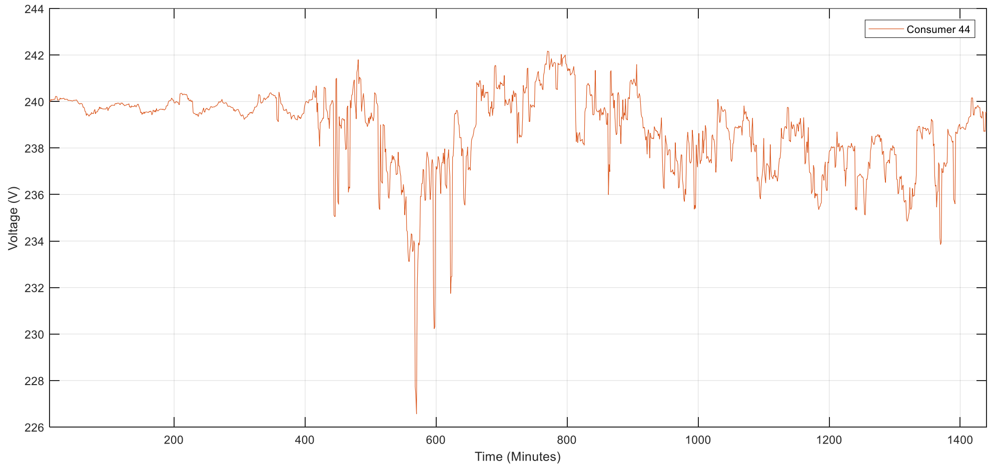

Figure 24 Voltage profile of consumer 44

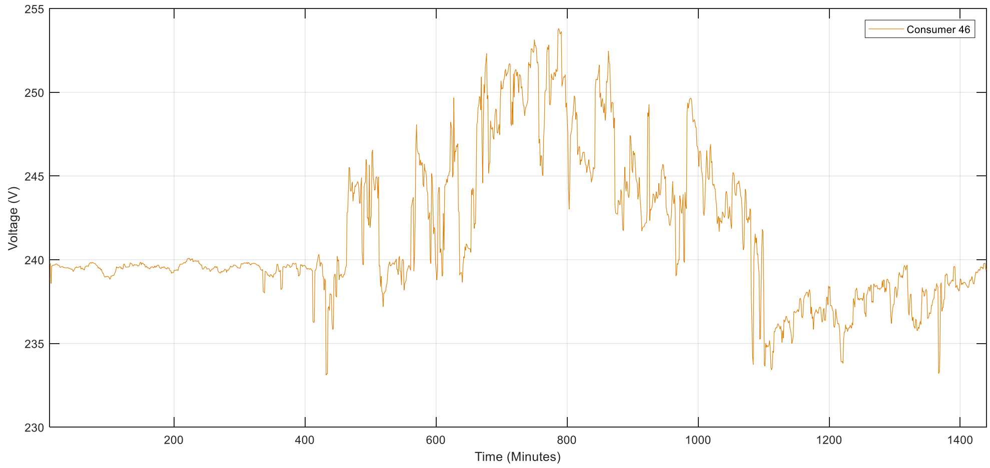

Figure 25 Voltage profile of consumer 46

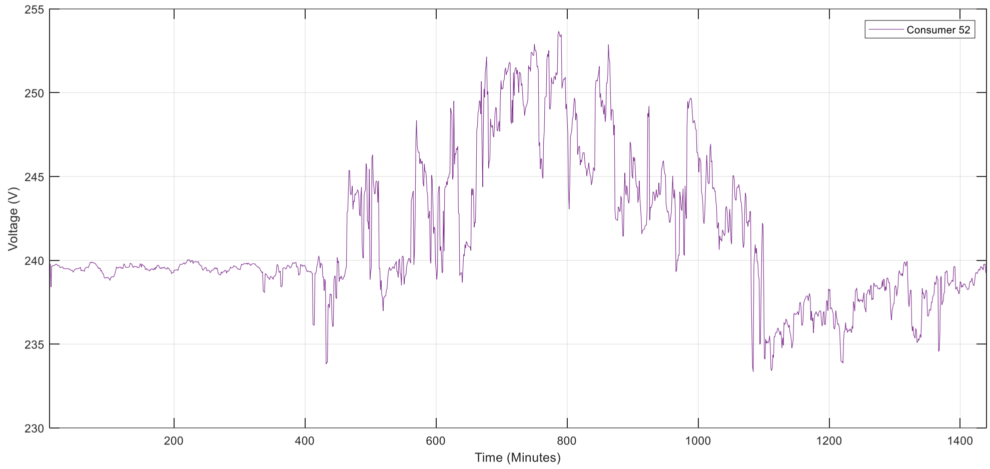

Figure 26 Voltage profile of consumer 52

Table 4 Voltage at consumer PCC

Consumer	VL	VH	Consumer	VL	VH	Consumer	VL	VH
1.0	238.4	243.7	21.0	234.5	254.4	41.0	225.9	241.8
2.0	235.4	240.7	22.0	234.2	255.6	42.0	232.6	240.9
3.0	238.4	243.7	23.0	227.3	241.5	43.0	232.9	240.9
4.0	236.5	249.3	24.0	232.8	240.7	44.0	226.3	241.5
5.0	236.5	249.3	25.0	233.6	257.6	45.0	225.9	241.9
6.0	235.4	240.7	26.0	225.8	241.5	46.0	233.1	257.4
7.0	231.4	241.1	27.0	232.7	240.8	47.0	232.8	240.9
8.0	234.1	240.6	28.0	232.7	240.8	48.0	232.9	257.4
9.0	235.4	250.6	29.0	233.7	258.3	49.0	233.0	257.3
10.0	231.0	241.1	30.0	233.6	257.7	50.0	224.9	241.4
11.0	231.1	241.1	31.0	233.7	258.3	51.0	233.3	258.4
12.0	234.2	240.6	32.0	232.4	240.9	52.0	233.4	259.6
13.0	230.1	241.4	33.0	229.9	241.5	53.0	224.7	241.4
14.0	235.5	251.9	34.0	233.6	257.0	54.0	233.3	258.5
15.0	230.2	241.5	35.0	223.5	242.2	55.0	233.3	259.6
16.0	233.6	240.5	36.0	224.7	242.4			
17.0	233.7	240.5	37.0	224.8	242.5			
18.0	232.6	240.8	38.0	226.4	241.8			
19.0	232.1	240.8	39.0	232.6	240.9			
20.0	234.1	255.5	40.0	226.1	241.6			
				Low Voltage				
				High Voltage				

Figure 23, Figure 24, Figure 25 and Figure 26 shows the voltage profile of consumer 22,44,46 and 52 respectively after the PV integration. It can be observed that Consumer residing in Phase A (22,46,52) are experiencing very significant voltage rise due to higher PV penetration.

Whereas consumer 44 which is connected on Phase B are not experiencing voltage rise as the PV penetration in Phase B is not that much high as on Phase A.

Table.3 shows minimum voltage and maximum voltage experienced by 55 consumers throughout the day. It can be observed that due to PV Integration less number of consumers are experiencing low voltage (6% below rated) issue. But, PV integration introduce voltage rise issue. Total number of 15 consumers are experiencing high voltage (6% above rated) issue. All of the consumer experiencing high voltage issue are from Phase-A due to higher PV penetration in Phase-A compared to Phase-B and Phase-C.

4.3 PV Integrated IEEE 906 European LV Network with Voltage Optimization Technique

Voltage optimization technique has been used to prevent voltage rise in PV Integrated IEEE 906 European LV Network. PV System with reactive power support has been considered for the mitigation of voltage rise. In this manner PV system regulate the reactive power in following manner.

Figure.27 shows the performance of reactive power controller. For the greater insight only the peak PV hours are shown. It can be observed that reactive controller absorbing the reactive power as per the PCC voltage variation.

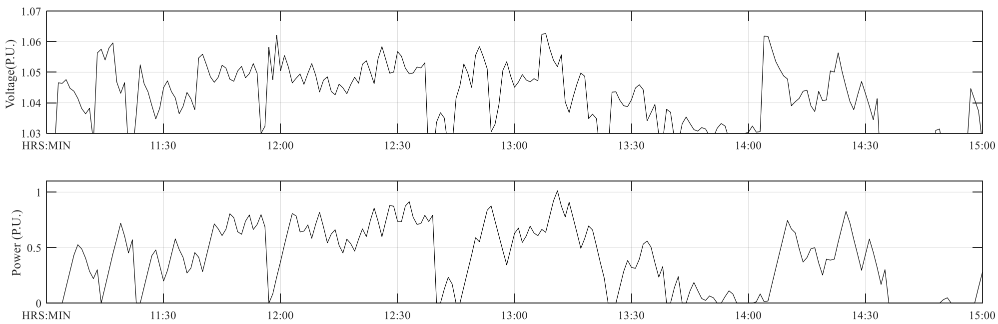

Figure 27 Performance of reactive power controller

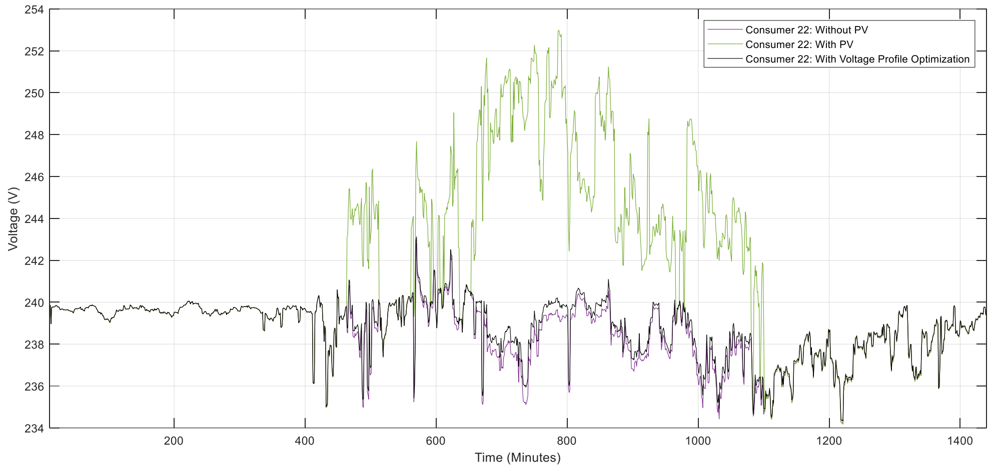

Figure 28 Voltage profile improvement for Consumer: 22

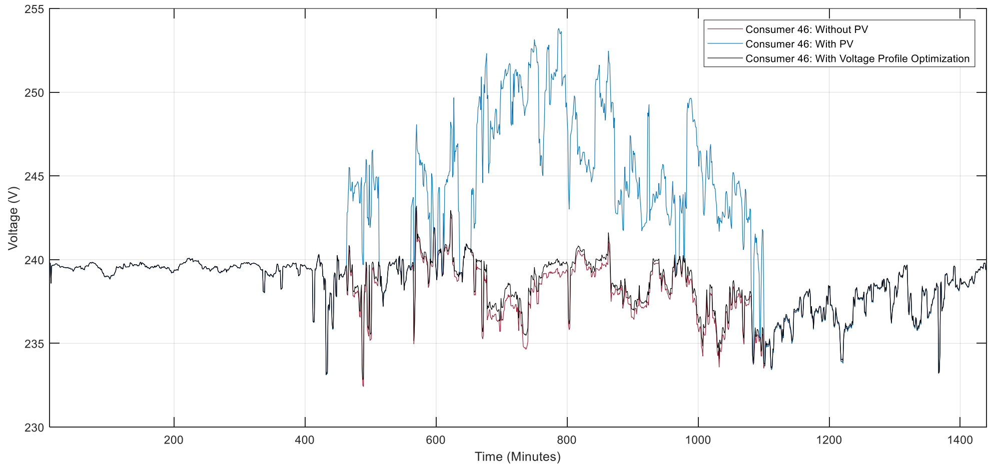

Figure 29 Voltage Profile Improvement for Consumer: 46

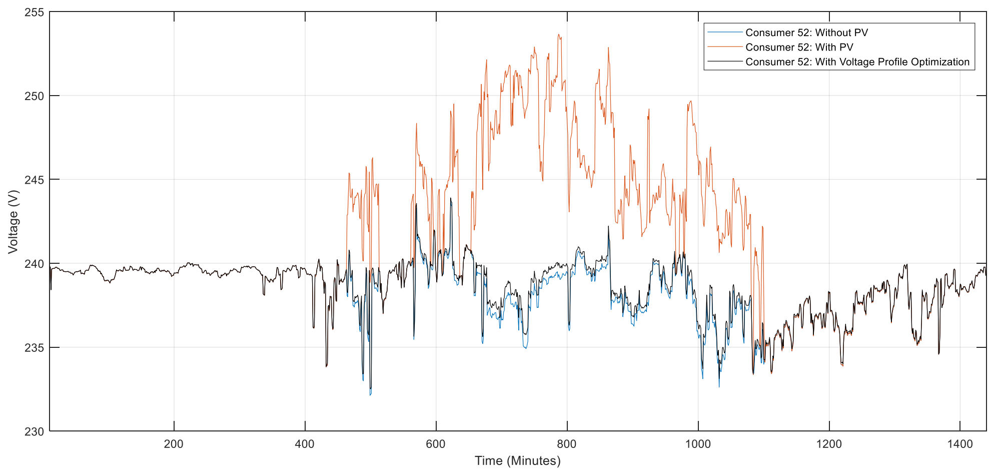

Figure 30 Voltage Profile Improvement for Consumer: 52

As the voltage rise problem only experienced in Phase-A. Consumer 22, 46 and 52 are only shown over here. It can be observed that significant voltage profile improvement has been achieved through reactive power absorption.

Table 5 Minimum and maximum voltage at Consumer PCC

Consumer	VL	VH	Consumer	VL	VH	Consumer	VL	VH
1.0	238.1	240.8	21.0	234.7	242.9	41.0	225.2	240.9
2.0	235.2	240.4	22.0	234.3	243.1	42.0	234.0	241.3
3.0	237.8	240.8	23.0	226.7	241.3	43.0	234.0	241.4
4.0	236.7	242.0	24.0	234.2	241.2	44.0	225.7	241.0
5.0	236.7	241.9	25.0	232.5	243.7	45.0	225.2	240.9
6.0	235.2	240.4	26.0	225.2	241.0	46.0	232.8	243.2
7.0	231.0	240.8	27.0	234.2	241.2	47.0	234.0	241.4
8.0	235.1	240.9	28.0	234.2	241.2	48.0	232.9	243.2
9.0	235.5	242.3	29.0	230.8	243.8	49.0	233.1	243.2
10.0	230.6	240.8	30.0	232.5	243.7	50.0	224.4	240.8
11.0	230.7	240.8	31.0	231.1	243.8	51.0	233.2	243.4
12.0	235.2	240.9	32.0	233.7	241.2	52.0	232.5	243.9
13.0	229.6	240.8	33.0	232.9	242.7	53.0	224.2	240.8
14.0	235.6	242.5	34.0	233.1	243.6	54.0	233.3	243.4
15.0	229.6	240.9	35.0	222.7	241.1	55.0	232.8	243.9
16.0	234.8	240.9	36.0	223.9	241.1			
17.0	234.9	241.0	37.0	223.9	241.1			
18.0	232.9	241.4	38.0	225.7	241.0			
19.0	233.6	241.1	39.0	234.0	241.3			
20.0	234.2	243.1	40.0	225.5	240.9			

Table.2 shows minimum voltage and maximum voltage experienced by 55 consumers throughout the day. It can be observed that voltage increment with Volt/VAR control is very small as compared to without Volt/VAR control. Any of the consumer are not experiencing higher voltage with inclusion of Volt/VAR control.

5 Conclusion

Injection of active power from a PV grid into the delivery network alters the voltage profile significantly. PV penetration of a certain level is advantageous to the distribution network because it eliminates power loss and the load on the distribution transformer. Injecting PV power into the distribution network at the far end will raise the voltage above a safe level. Any delivery network's PV hosting capability is limited by this voltage spike. The distance between the PV system and the distribution transformer is critical. If the PV device is close to the distribution transformer, more power can be pumped without exceeding the voltage cap. During periods of low demand, reverse power flow may occur in PV-penetrated distribution networks.

PV system with reactive power support can maintain the voltage profile of distribution network. This technique can be used to avoid voltage rise beyond the maximum voltage. As the voltage rise issue is one of the limiting factor for the maximum integration capacity of the distribution network. This technique also helpful to increase PV integration capability of any distribution network.

6 Future Scope

Further, coordinated control of smart PV system along with DSTATCOM, OLTC, DVR can be considered. Active power curtailment is also an option to control power injection in the distribution network. Inclusion of battery energy storage can also provide control over injected active power.

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