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Market Based Control of PV Inverters in a Distribution System

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MARKET BASED CONTROL
OF PV INVERTERS IN A DISTRIBUTION SYSTEM

By Kumar Rishikesh

THESIS

A dissertation submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering in the College of Engineering at the University of Kentucky

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ABSTRACT OF THESIS

MARKET BASED CONTROL
OF PV INVERTERS IN A DISTRIBUTION SYSTEM

A growing energy crisis, a rapid climate change, and a constant depletion of fossil fuel necessitates the role of renewable energy resources like PV (Photovoltaics) and wind energy to form a group of distributed sources of generation. A group of PV and wind energy generation units may work together as micro players to form smart grid systems and participate in an existing distribution system to meet a portion of the daily energy demand. This will help in minimizing the network losses during transmission and in improving energy efficiency of the overall distribution system. However, owing to the inherent characteristics of power variability of these renewable energy sources which results in voltage variability in the distribution system, there is a need to design a distribution system that minimizes voltage spikes. This thesis examines a potential market-based approach to the control of PV Inverters in a distribution system to stabilize fluctuations in voltage. An algorithm that closely imitates the behavior of an economic system is applied to the system to manage voltage variability. More traditional approaches of mitigating voltage variability are studied and compared to understand the feasibility of the market-based control approach method on this distribution system.

Keywords: *Voltage Variability, Micro players, Market control*

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MARKET BASED CONTROL

OF PV INVERTERS IN A DISTRIBUTION SYSTEM

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November 21st , 2016
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Chapter 1
Introduction and Thesis Objective

1.1. Introduction

In the 1950s, it was found that there is an inherent voltage drop across a p-n junction and power could be harnessed from it. Solar power generation was possible due to this photoelectric effect [1]. Based on statistical data, about 2 billion people still have minimal or no access to electricity, primarily because they are living in rural areas [2]. By the year 2030, this number would be somewhere around 1.4 billion [3]. Since, access to electric grid is limited to these poorer sections and the cost of burning kerosene for light is expensive than the cost of access to lighting via electricity, that is one of the reasons why, the economically poor population around the globe happens to invest a greater percentage share of their income than the wealthier sections [4-5].Across the globe, even in regions experiencing scarcity of natural resources like water, coal and natural gas etc., solar power to some extent has proven to be an effective and environmental friendly substitute, thereby providing electricity at a lower rate than a fossil fuel power generating plant, especially in remote areas. Most importantly, solar energy has helped in sustainable electricity production which has bolstered industrial growth in numerous streams. For instance, the donor model of solar energy generation for meeting the energy demands in rural areas has resulted in a very short payback for the buyers in terms of saving on candles, kerosene and batteries [6-7]. Access to electricity has enabled the middle class shopkeepers and business owners to operate late hours to improve their processes and it has resulted in a marked growth in their income [8]. To cite an example for this, in Bangladesh, long operating hours of electric mills, shops, and cell phone charging and even selling to adjacent establishments is boosting the local economy [9].

However, government intervention for establishing regulations can play a pivotal role in paving the way for a long term and reliable growth of solar energy by streamlining standards and quality of equipment, ensuring codes of selling electricity, and maintaining a healthy competition amongst the sellers [10-11]. Even in developed countries, the government has acted as a catalyst in the expansion of solar power generation through various programs and drives [12].

In spite of the fact that, comparatively solar energy is an inexpensive power generation resource, available with an ever-growing potential since last three decades, one of the major challenges in incorporating PV inverters in an electric distribution system is the power variability caused by the intermittent nature of cloud coverage of the area under renewable energy production. Moreover, since the conventional power distribution sources consist of a lot of switch gears, tap changing transformers and other components intertwined into one another, they fail to keep up with the rapid changing voltage variability affecting the response time and therefore, are prone to frequent maintenance [13]. That is why, even though the costs of clean energy production like PV inverters and wind energy continues to decrease, they still struggle to play a major role in participating in the mainstream of distribution system [14-15]. However, due to the decline in cost, the demand window for solar and wind energy production in the last 20 years has risen to 20% to 25 % [16]. Following this, attempts have been made to encourage better integration of PV and wind energy sources in a distribution system. While in some instances, categorical study based on var control algorithm of a Cyber-Physical System to maintain voltage variation has shown that both voltage variability and power loss can be controlled in a system of PV sources participating in the conventional distributed generation systems [17]. In some other examples, a local feedback control algorithm was applied to an inverter based distributed energy resource to regulate voltage and var values by limiting current [18]. An experiment of deploying energy storage components to mitigate the voltage variability in a distribution system has been studied that would control the ramp rate of a PV Source [19].Various other methods and algorithms of voltage and var controls have also been developed to enable better integration of PV systems and to minimize voltage variability of distribution systems [20]-[23]. Additionally, changes to controllable loads like refrigerators and air conditioners optimal scheduling algorithm have been implemented keeping in mind the demand of the consumer so that voltage variability conditions are minimized [24].

In the wake of increasing participation of renewable energy sources, the economy of the micro players is mostly driven by the market based approach of profit and demand. This calls for a technical and a policy framework in a smart distribution system [25]-[27]. With increasing environmental regulations in mind, there are avenues for the micro players to contribute and are also entitled to produce electricity at the local level using the PV and the wind energy sources that comply with the prosumer behavior [28

Previously, work has been done using price based control approach that would be updated every 5-15 minutes in a market based operating system, to provide a real time varying physical state in response of the voltage imbalances [29]. In this paper, a market based price control algorithm has been developed. Attempts have been made to recognize, decide and therefore, lay out a demand based Voltage pricing that the utility can establish to optimize its resource while making sure that the voltage fluctuation has been contained. Also, this method would provide a better opportunity for the micro players to trade off the extra units of power production to the distribution system per the available pricing scheme [30].

1.2. Proposed Thesis Objectives

The aim of this thesis is to develop and test a price controller algorithm that will enable the utility to buy/sell requisite amount of voltage (V_{mag}) from/to the PV Sources, based on the voltage demand in the distribution network and will also minimize the voltage variation. Simultaneously, advantages of this method will be studied and compared with 2 different control systems previously studied, namely:

- A base line simulation control approach, and
- A sensitivity factor minimization control approach [22]

The paper is distributed in 5 Chapters. Chapter 1 deals with the introduction of solar energy and its role in safeguarding and sustaining the human civilization in different parts of the globe. It also outlines the development and evolution of

Photovoltaics from its early advent. Chapter 2 defines the system setup in which the control algorithm has been developed and other controllers are studied. Additionally, it lays the power flow calculation of a 6 bus distribution system. Chapter 3 describes the three Voltage mitigation controllers namely, Baseline stimulation, Sensitivity minimization and Market based simulation method. Chapter 4 deals with the simulation results of the aforementioned controllers. A detailed comparison is carried out to study the effect of market simulation in particular with /the other 2 controllers and its contribution in achieving a contained voltage fluctuation, hence increasing reliability on photovoltaic cell power production. Chapter 5 deals with a conclusion and explores future scope of work that relates to solar power production and its reliability.

Chapter 2
Network Setup and Power Flow

2.1 Network Setup

We study a single phase, 6-bus distribution system to implement and observe its behavior in all the 3 control systems studied in this paper for instance, by varying the control parameter β in sensitivity minimization method etc. The system is drawn in Fig. 2.1. The base voltage and the base power of the system are 2.9 kV (i.e. 4.16kV/ √3) and 1.4 MVA, respectively. The bus 1 source has a series impedance of 0.01 + j0.08 at 1.05 pu. Buses 3, 5 and 6 carry load with real power of 162 kW and a reactive power of 4.501 kvar. PV Sources are connected on buses 5 and 6 with Complex Power Load of 250 kVA. The unbalanced, series reactance and resistance matrices for line 1-2, 2-4 and 4-6 are:

$$X = \begin{vmatrix} 0.5968 \\ 0.7584 \\ 0.5968 \\ 0.7584 \\ 0.7584 \\ 0.7584 \end{vmatrix} \Omega; \qquad R = \begin{vmatrix} 0.1857 \\ 0.5921 \\ 0.1857 \\ 0.5921 \\ 0.5921 \\ 0.5921 \end{vmatrix} \Omega$$

And the balanced reactance and resistance matrices for line 2-3 and 4-5 are:

$$X = \begin{vmatrix} 13.9691 \\ 13.9691 \\ 13.9691 \end{vmatrix} \Omega; \qquad R = \begin{vmatrix} 28.8427 \\ 28.8427 \\ 28.8427 \end{vmatrix} \Omega$$

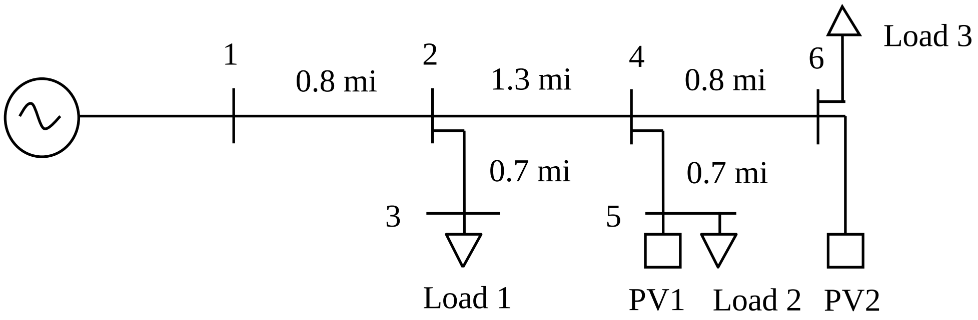


Fig.2.1 A 6-bus distribution system

The data fed into the controller is derived from the 2 irradiance values (irradiance1 and irradiance2) captured by the Solar Measurement Grid of the National Renewable Energy Laboratory (NREL) at Kalaeloa, Oahu, Hawaii [31]. A 15 minute observation for March, 24th 2010, has been simulated from 11:00 am to 11:15 am to collect the global horizontal radiation known as radiance data which practically is the sum of direct and diffuse solar radiation measured in Watt/meter^2 of each of the 2 different locations under observation, viz. DH3 and DH4. We have considered 2 different irradiance data to represent 2 different sites meaning 2 different PV sources (PV1 and PV2) for the purpose of simulating the controller.

2.2 Power Flow

We know from Ohm's law in a DC system:

$$\boldsymbol{V = IR} \tag{1}$$

Where '**V**' is the voltage of the circuit, '**I**' is the current flowing and '**R**' is the resistance across the load of the linear circuit. This can be safely generalized for a single phase AC Circuit with an impedance load '**Z**', as:

$$\boldsymbol{V = IZ} \tag{2}$$

This implies:

$$\boldsymbol{I = \frac{V}{Z}} \tag{3}$$

For a constant impedance '**Z**', a small change in the Load current, 'dI' with respect to a small change in the Real power 'dP' can be expressed as:

$$\boldsymbol{\frac{dI}{dP} = \frac{1}{Z}\frac{dV}{dP}} \tag{4}$$

Similarly, for a constant impedance 'Z', a small change in the Load current, 'dI' with respect to a small change in reactive power 'dQ' can be expressed as:

$$\boldsymbol{\frac{dI}{dQ} = \frac{1}{Z}\frac{dV}{dQ}} \tag{5}$$

We know that, total Source load, '**S**' is the sum of the real and the reactive power of the system, i.e.

$$\boldsymbol{S = P + jQ} \tag{6}$$

And the node current at each node will be computed from the below equation:

$$\boldsymbol{S = VI^{*}} \tag{7}$$

Where $\mathbf{I}^{*}$ is the conjugate of **I.**

Rearranging the above equation implies:

$$\boldsymbol{I^{*}} = \frac{\boldsymbol{S}}{\boldsymbol{V}} \tag{8}$$

Or,

$$\boldsymbol{I} = \left(\frac{\boldsymbol{S}}{\boldsymbol{V}}\right)^{*} \tag{9}$$

Using (6) in (9) yields:

$$\boldsymbol{I} = \left(\frac{\boldsymbol{P + jQ}}{\boldsymbol{V}}\right)^{*} \tag{10}$$

Now, for a source current, load impedance will vary at each bus, therefore a small change in the Source current, ‘dI’ with respect to a small change in Real power ‘dP’ can be expressed as:

$$\frac{\boldsymbol{dI}}{\boldsymbol{dP}} = \frac{\boldsymbol{d}\left(\frac{\boldsymbol{P + jQ}}{\boldsymbol{V}}\right)^{*}}{\boldsymbol{dP}} \tag{11}$$

Applying differentials on product rules using Leibniz notation:

$$\frac{\boldsymbol{dI}}{\boldsymbol{dP}} = \left(\frac{\boldsymbol{P - jQ}}{\boldsymbol{V^{*2}}}\right)\frac{\boldsymbol{dV}}{\boldsymbol{dP}} + \frac{\boldsymbol{1}}{\boldsymbol{V^{*}}} \tag{12}$$

Where **‘V*’** represents the conjugate of **V**.

Similarly, for any source current, load impedance will vary at each bus, therefore a small change in the Source current, ‘**dI**’ with respect to a small change in Reactive power ‘**dQ**’ can be expressed as:

$$\frac{\boldsymbol{dI}}{\boldsymbol{dQ}} = \left(\frac{\boldsymbol{P - jQ}}{\boldsymbol{V^{*2}}}\right)\frac{\boldsymbol{dV}}{\boldsymbol{dQ}} + \frac{\boldsymbol{1}}{\boldsymbol{V^{*}}} \tag{13}$$

For instance,

The Bus Current at Bus 5, say I (5) referring Fig.2.1, will be given by:

$$\boldsymbol{I}(\mathbf{5}) = \frac{\boldsymbol{V}(\mathbf{5})}{\boldsymbol{Z}(\mathbf{5})} - \left(\frac{\boldsymbol{S}(\mathbf{5})}{\boldsymbol{V}(\mathbf{5})}\right)^{*} \qquad (\mathbf{14})$$

Where, **I(5), V(5), Z(5), S(5)** are Bus current, Load Voltage, Load Impedance and total Source load respectively at Bus 5.

Bus voltage is given by:

$$\boldsymbol{V_b} = (\mathbf{1.04})(\boldsymbol{V_{base}}) - (\boldsymbol{Z})(\boldsymbol{I}) \qquad (\mathbf{15})$$

Where, **“(1.04) (V_{base})”** is the perturbed base voltage in Kilovolts and **‘$\boldsymbol{Z}$’** is the Line impedance and **‘$\boldsymbol{I}$’** is the Line Current in that bus.

2.3 Background of the study

Market simulation has been developed with an intention of optimizing the available resources with the utility and minimizing the voltage variation. It aims at making sure the utilities always meet there minimum voltage demand at any time of the day by incentivizing each producer with an appropriate amount. Each PV source will in turn optimize its own profit on that given price to adjust its production accordingly. Based on the price signal input from the utilities, PV Sources would decide how much Q to output to maximize its own profit.

To elaborate this relationship, for instance, if the cloud comes out at any time of the day, the voltage production would start dropping and the utility would strive to maintain it. This will result in drop of voltages in certain buses, in turn driving the reactive power in those buses and the PV Sources will spring into action knowing they can make money by supplying reactive power to compensate for the total drop in resulting output voltage. In other words, price of the voltage difference bought/sold by the utility to meet the current demand at any instant will amount to the price of the reactive power produced/consumed by the PV Sources.

Therefore, we can say:

$$\boldsymbol{P\Delta V = P\Delta Q} \qquad (\mathbf{16})$$

Such that

P, is the price of Voltage difference per unit set by the utility, and

ΔV is the total voltage difference/drop experienced due to the incoming cloud

ΔQ is the total reactive voltage difference required to compensate for the change in total voltage.

Meanwhile, the controller is removing the surplus and getting the prices to equilibrium. Each time there is a difference, the code drives the source and the utility decision in such a way that the prices decide how much reactive power to produce.

Chapter 3
Voltage Fluctuation Mitigation Methods

There are 3 methods studied in this chapter. Each of them deals with manipulating the real and/or reactive power component of the Voltage required in different ways with an aim of minimizing the voltage variation in the distribution system due to an incoming cloud or a reason that affects Voltage production by the solar power. In all the methods discussed in this paper, we assume common initial parameters namely, P* and Q* as below:

$$\boldsymbol{P}^{*} = \frac{\left|\int_{o}^{t} \boldsymbol{P}_{in}\right|}{\boldsymbol{t}} \qquad (\mathbf{17})$$

Where,

‘**t**’ is 0 – 900 seconds, i.e. duration of experiment reading and

‘$\mathbf{P_{in}}$’ is the input irradiance data collected.

Assuming an initial value for **Q*** as:

$$\boldsymbol{Q}^{*} = \begin{vmatrix} \mathbf{0} \\ \mathbf{0} \end{vmatrix} \qquad (\mathbf{18})$$

Let the maximum apparent power that the PV sources can generate be **'S_{max}'** such that:

$$\boldsymbol{S_{max} = 250\ kvar} \qquad (19)$$

The above equations are used in the three controllers to develop or generate point parameters P and Q over the 15 minute span. To study real time incident solar radiation values, Global Horizontal Irradiance file, '20100324.txt' has been captured from the Oahu Solar Measurement Grid is loaded [31]. The line, load, bus and source parameters are calculated based on these initial data in the function powerflow to establish the expected values.

3.1 Baseline simulation method

In a baseline simulation method, there is no reactive power (var) fed into the system. Only the real power (VA) will be acting as the compensating agent for stabilizing the voltage variation. The practical/usable real power **'P'** will be less than the incident **'P_{in}'** of the sun, as it has to account for the inverter losses, $\boldsymbol{P_{loss}}$ too, which has been calculated using the below equation:

$$\boldsymbol{P = P_{in} - P_{loss}} \qquad (20)$$

Such that,

$$\boldsymbol{P_{loss} = \frac{0.1}{S_{max}} P_{in}^2} \qquad (21)$$

and

$$\boldsymbol{S_{max} \geq P^2 + Q^2} \qquad (22)$$

We define a perturbation parameter '**k**' which is a constant factor used for perturbation and is defined as:

$$\boldsymbol{k = \frac{0.1}{S_{max}}} \qquad (23)$$

Therefore, the real power in baseline simulation would be:

$$\boldsymbol{P = P_{in} - \ kP_{in}^2} \qquad (24)$$

3.2 Sensitivity Minimization Method

In this study a control parameter, β, is introduced to mitigate the voltage variation of a PV distribution system. In this algorithm, the control voltage which is a vector quantity of the system will be a function of the real and the reactive power:

$$\boldsymbol{V = \ f\ (P, Q)} \qquad (25)$$

Using Taylor series expansion, a small change in the '**V**' value can be expressed as:

$$\boldsymbol{\Delta V \ \approx \ \alpha_P \Delta P \ + \ \alpha_Q \Delta Q} \qquad (26)$$

Such that,

$$\boldsymbol{\alpha_P = \left.\frac{\partial f}{\partial P}\right|_{P^*, Q^*}} \qquad (27)$$

$$\boldsymbol{\alpha_Q = \left.\frac{\partial f}{\partial Q}\right|_{P^*, Q^*}} \qquad (28)$$

$$\boldsymbol{\alpha_P \ \epsilon\ \mathbb{R}^{nxm}, \alpha_Q \ \epsilon\ \mathbb{R}^{nxm}} \qquad (29)$$

Where, '$\boldsymbol{\alpha_P}$' and '$\boldsymbol{\alpha_Q}$' are sensitivity factors, And,

$$\boldsymbol{\Delta V} = \boldsymbol{V} - \boldsymbol{V}^* \tag{30}$$

$$\boldsymbol{\Delta P} = \boldsymbol{P} - \boldsymbol{P}^* \tag{31}$$

$$\boldsymbol{\Delta Q} = \boldsymbol{Q} - \boldsymbol{Q}^* \tag{32}$$

The selected controller can be formulated as:

$$\boldsymbol{Q} = \boldsymbol{Q}^* + \boldsymbol{\beta}\,(\boldsymbol{P}^* - \boldsymbol{P}) \tag{33}$$

Substituting the value of Q formulated from **(33)** in equation **(26)**, will yield:

$$\boldsymbol{\Delta V} = \boldsymbol{\Delta P}\,(\boldsymbol{\alpha_P} - \boldsymbol{\alpha_Q}\,\boldsymbol{\beta}) \tag{34}$$

For minimum Voltage perturbations the change in the real output power perturbations have to be minimized, hence:

$$\boldsymbol{\alpha_P} - \boldsymbol{\alpha_Q}\,\boldsymbol{\beta} = \mathbf{0} \tag{35}$$

Therefore,

$$\boldsymbol{\beta} = \boldsymbol{\alpha_Q^{\dagger}\alpha_P} \tag{36}$$

The value of **‘β’** is to be selected such that the perturbation effect on the real power does not throw the output bus voltage off the required upper limit, **‘V_u’** and lower limit, **‘V_l’** of the acceptable voltage range meaning:

$$\boldsymbol{V_l} \leq \boldsymbol{V} \leq \boldsymbol{V_u} \tag{37}$$

Such that **‘V_l’** = 126 V and **‘V_u’** = 118V. For any small change around the operating point, equation **(37)** can be rewritten as:

$$\Delta V_l \leq \Delta V \leq \Delta V_u \tag{38}$$

Such that

$$\Delta V_l = V_l - V^* \tag{39}$$

$$\Delta V_u = V_u - V^* \tag{40}$$

Now, for each bus, the **‘β’** value can be found out by rearranging equations (34) in Constraint optimization environment of equation (37) that yields:

$$\boldsymbol{\beta} = \arg\max|\Delta P| \tag{41}$$

The voltage to be generated and supplied by the PV Source can be decided based on the real and reactive power pricing at the instant when there is a demand from the utility. The real power loss **(P_{loss})** by the PV source at an instant **(P, Q)** is given by:

$$P_{loss} = k(P^2 + Q^2) \tag{42}$$

Substituting value of **P_{loss}** from equation (42) in equation (20) and rewriting Equation (22) yields:

$$[P - k(P^2 + Q^2)]^2 + Q^2 \leq S_{max} \tag{43}$$

Expanding the above equation yields:

$$P^2 + k^2P^4 + k^2Q^4 + 2k^2P^2Q^2 - 2P^3k - 2PkQ^2 + Q^2 \leq S_{max} \tag{44}$$

Now, substituting the **'Q'** obtained in equation **(33)** and applying newton method to obtain a quadratic in **'Q'** will yield:

$$\boldsymbol{\beta k Q^{2} - Q + Q^{*} - \beta P_{in} + \beta k P_{in}^{2} + \beta P^{*} = 0} \tag{45}$$

Solving the above quadratic equation in Q for a real value would arrive at the below Q value:

$$\boldsymbol{Q = \frac{1 - \sqrt{1 - 4\beta k\left(Q^{*} - \beta P_{in} + \beta k P_{in}^{2} + \beta P^{*}\right)}}{2\beta k}} \tag{46}$$

3.3 Market based Simulation method

3.3.1 Profit Calculation

Amount of real power (ΔP) and reactive power (ΔQ) to be produced is directly proportional to their respective prices ($P_{\Delta P}$, $P_{\Delta Q}$**)** set by the utility based on the demand. Mathematically expressed as:

$$\boldsymbol{\begin{vmatrix} P_{\Delta P} \\ P_{\Delta Q} \end{vmatrix} = f_{source}\left(\begin{vmatrix} \Delta P \\ \Delta Q \end{vmatrix}\right)} \tag{47}$$

Such that **'f_{source}'** will be used to determine:

$$\boldsymbol{P_{\Delta P} = \frac{\Delta V_{mag}}{\Delta P} PV_{mag}} \tag{48}$$

And,

$$\boldsymbol{P_{\Delta Q} = \frac{\Delta V_{mag}}{\Delta Q} PV_{mag}} \tag{49}$$

Where, **'ΔV_{mag}'** is the change in the required Voltage and **PV_{mag}** is the Price of the required Voltage required

$$\mathbf{f_{source}}: \mathbb{R}^2 \rightarrow \mathbb{R}^2$$

If $\boldsymbol{P_{\Delta P}^{k}}$ and $\boldsymbol{P_{\Delta Q}^{k}}$ are the step values of the price of change in real and reactive power, it can be expressed as a Jacobian instruction function as below:

$$(\boldsymbol{P_{\Delta P}^{k}}, \boldsymbol{P_{\Delta Q}^{k}}) = \boldsymbol{f_{source}} \, (\boldsymbol{\Delta P^{k}}, \boldsymbol{\Delta Q^{k}}, \boldsymbol{J_{source}^{k}}) \qquad (\mathbf{50})$$

Where the Jacobian matrix assumes the below model:

$$\boldsymbol{J_{source}} = \begin{bmatrix} \dfrac{\boldsymbol{\partial \Delta P}}{\boldsymbol{\partial P_{\Delta P}}} & \dfrac{\boldsymbol{\partial \Delta P}}{\boldsymbol{\partial P_{\Delta Q}}} \\ \dfrac{\boldsymbol{\partial \Delta Q}}{\boldsymbol{\partial P_{\Delta P}}} & \dfrac{\boldsymbol{\partial \Delta P}}{\boldsymbol{\partial P_{\Delta Q}}} \end{bmatrix} \qquad (\mathbf{51})$$

Applying Newton-Raphson method to generate $P_{\Delta P}$ and $P_{\Delta Q}$ values in equation (35) using the Jacobian matrix yields:

$$\begin{vmatrix} \boldsymbol{P_{\Delta P}} \\ \boldsymbol{P_{\Delta Q}} \end{vmatrix} = \begin{vmatrix} \boldsymbol{P_{\Delta P}^{*}} \\ \boldsymbol{P_{\Delta Q}^{*}} \end{vmatrix} + \boldsymbol{J_{source}} \begin{vmatrix} \boldsymbol{P_{\Delta P} - P_{\Delta P}^{*}} \\ \boldsymbol{P_{\Delta Q} - P_{\Delta Q}^{*}} \end{vmatrix} \qquad (\mathbf{52})$$

Where $\boldsymbol{P_{\Delta P}^{*}}$ and $\boldsymbol{P_{\Delta Q}^{*}}$ are the instantaneous previous values of the function and $\mathbf{J_{source}} \in \mathbb{R}^{\mathbf{2mX2m}}$.

We can propose that at any step, ‘k’, a small price change in Voltage ($\boldsymbol{P_{\Delta V}^{k}}$) is a function of a small price change of the real power ($\boldsymbol{P_{\Delta P}^{k}}$) and reactive power ($\boldsymbol{P_{\Delta Q}^{k}}$), expressed as:

$$\boldsymbol{P_{\Delta V}^{k}} = \boldsymbol{f} \, (\boldsymbol{P_{\Delta P}^{k}}, \boldsymbol{P_{\Delta Q}^{k}}) \qquad (\mathbf{53})$$

From the utility perspective, we can say that the price of the Voltage change at a step, k, can be a function of change in Utility voltage ($\mathbf{\Delta V^{k}_{utility}}$) and its Jacobian value ($\boldsymbol{J_{utility}^{k}}$), meaning:

$$\boldsymbol{P_{\Delta V}^{k}} = \boldsymbol{f_{utility}} \left(\boldsymbol{\Delta V_{utility}^{k}}, \boldsymbol{J_{utility}^{k}}\right) \qquad (\mathbf{54})$$

The ‘$\mathbf{f_{utility}}$’ function is similar to the one used in equation (47) and (48)

The price of the change in voltage in K+1th step, using the Taylor series expansion can be expressed as:

$$\boldsymbol{P_{\Delta V}^{k+1} = P_{\Delta V}^{k} - J^{\dagger}\,(P_{\Delta V}^{k})\,F\,(P_{\Delta V}^{k})} \tag{55}$$

Such that:

$$\boldsymbol{F\,(P_{\Delta V}) = \Delta V_{source} - \Delta V_{utility}} \tag{56}$$

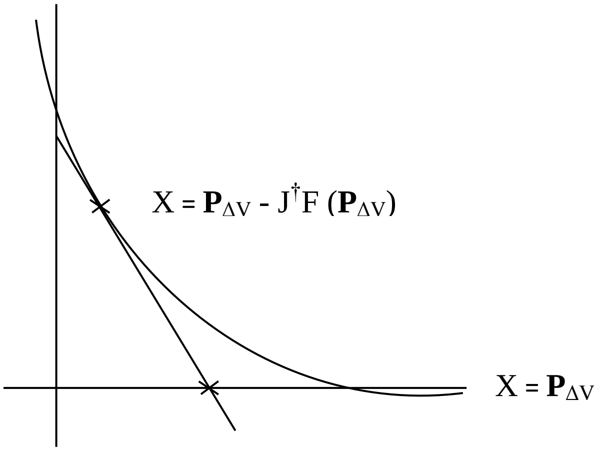


Fig 3.1 Representation for finding the price of voltage, PΔV

The control algorithm is based on a profit oriented price controller that is fed into the economic system. Profit can be expressed as:

$$\boldsymbol{Profit = P_{\Delta V}^{\dagger}\Delta V - P_{\Delta P}^{\dagger}\Delta P - P_{\Delta Q}^{\dagger}\Delta Q} \tag{57}$$

Where, $\mathbf{P^{\dagger}_{\Delta V}}$ is the inverse matrix of the price for a small change in the Voltage

$\mathbf{P^{\dagger}_{\Delta P}}$ is the inverse matrix of the price for a small change in the Real Power

$\mathbf{P^{\dagger}_{\Delta Q}}$ is the inverse matrix of the price for a small change in the Reactive Power

$\mathbf{\Delta P \in \mathbb{R}^m}$, Change in the real power at a value P*

$\mathbf{\Delta Q} \in \mathbb{R}^{\mathbf{m}}$, Change in the reactive power at a value Q*

‘n is the number of buses and ‘m’ is the number of power sources participating in the power distribution system under study in this experiment.

So, the profit now using equation (26), and (57) becomes:

$$\boldsymbol{Profit = P_{\Delta V}^{\dagger}\,(\alpha_P \Delta P + \alpha_Q \Delta Q) - P_{\Delta P}^{\dagger} \Delta P - P_{\Delta Q}^{\dagger} \Delta Q} \qquad (\mathbf{58})$$

Rearranging yields:

$$\boldsymbol{Profit = \Delta P\,(P_{\Delta V}^{\dagger} \alpha_P - P_{\Delta P}^{\dagger}) + \Delta Q\,(P_{\Delta V}^{\dagger} \alpha_Q - P_{\Delta Q}^{\dagger})} \qquad (\mathbf{59})$$

A profit equation should incorporate the profit the PV sources make regularly, and the element that decides the amount of real and reactive power produced that has helped the system or has hurt the system. The desired equation looks like below:

$$\boldsymbol{Profit = P_p \Delta P + P_{\Delta p}\,\Delta P + P_{\Delta Q}\,\Delta Q} \qquad (\mathbf{60})$$

Where, $\boldsymbol{P_p \Delta P}$ **,** is the price that the PV source gets paid on a regular basis for producing a fixed amount that is needed by the utility. Now the $\boldsymbol{P_{\Delta p}\,\Delta P + P_{\Delta Q}\,\Delta Q}$ can add or subtract to the final profit based on the controller decision if it has helped the utility or has hurt it by producing unnecessary Voltage that it never required. So, let’s say if on a day \$1, is regular amount paid by the utility to the PV sources for a fixed amount of power production, and that day if the locate on experienced a lot of cloud hovering over that affected the power generation, so the utility asked for more ΔV injection from the PV sources, it would get the difference amount more over \$1. As a demand from the utility, would mean positive price values. On the other hand, if for some reason, the demand is not there and the utility starts sending the extra voltages back to the PV sources to absorb, the price of the amount of power absorbed will be deducted from the \$1 profit that the PV source consistently made. So the controller is controlling the $\boldsymbol{P_{\Delta p}}, \boldsymbol{P_{\Delta Q}}$ values.

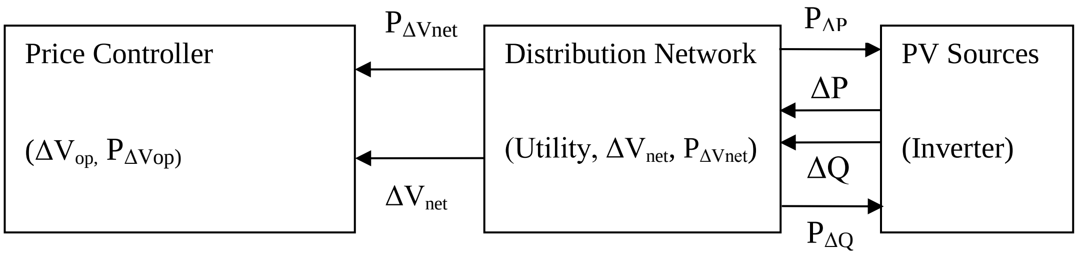


Fig. 3.2 Block Diagram of a market simulation approach

A solar powered production system is affected by irregularities caused by hovering clouds in the production area impacting the generation in no time. In market simulation instead of changing the real and reactive power, we propose to tune the Vmag (magnitude of resultant required Voltage) values to mitigate the voltage variation. In the algorithm developed the distribution system/utility decides how much shortage/excess of voltage it is experiencing based on variation in the bus voltages and then the prices are decided that it can buy from the PV system sources by incentivizing each producer (PV sources) at affordable rates. For instance, if the cloud comes out the voltage in certain buses would drop and the utility would want more, this requirement would then drive the PV system to produce more reactive power to sell to the utility. So, we can safely assume that the rise of voltage drop amounts to price of kvar supplied.

The amount of Voltage required by the utility or the amount supplied by the PV source can be determined by the below equation that involves the contribution of real and reactive powers of the PV source:

$$\boldsymbol{V_{magSource} = V^{*}_{mag} + \left(\frac{dV_{mag}}{dP}\right)(P - P^{*}) + \left(\frac{dV_{mag}}{dQ}\right)(Q - Q^{*})} \qquad (\mathbf{61})$$

Any surplus production, that can be defined as the difference between Source Voltage and the Voltage produced by the utility would not be considered by the controller, making sure that the prices are at equilibrium with the requirement and capacity.

$$\boldsymbol{V_{magSurplus} = V_{magSource} - V_{magUtility}} \qquad (\mathbf{62})$$

3.3.2 Utility Decision:

Utility has to set a voltage deviation in such a way that, if the set price is positive it would try to drive down the demand optimizing the amount of var bought from the PV sources thereby trying to stay within the lower limits of the acceptable range i.e. 118V and when the prices are negative it directs the PV sources to absorb some vars or reactive power so that the operating point is closer and but within the upper limit i.e. 126 V. This phenomenon is better explained in Figure 3.3.

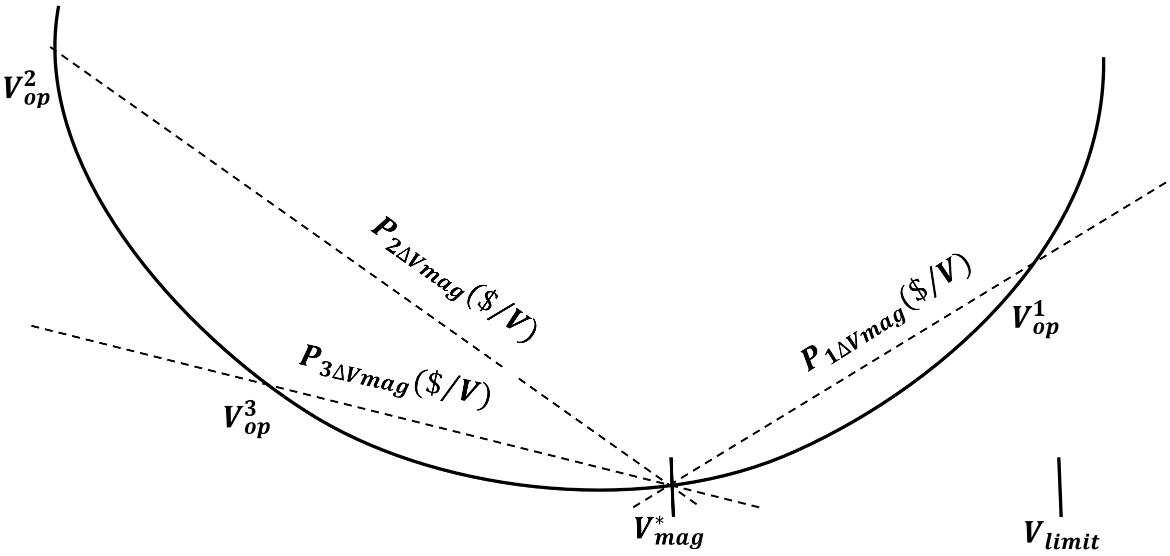


Fig 3.3 Utility decision making pattern diagram on each bus

In a scenario, where the utility is running short of power, it instructs the PV sources to sell some reactive power based on the available pricing scheme. At zero voltage requirement the price would be zero. This pricing scheme at an instant when positive, say $\mathbf{P_{2\Delta Vmag}}$, is favorable for the PV sources, as they get to sell the reactive power and make profit, but the utility would try to optimize to, say $\mathbf{P_{3\Delta Vmag}}$ to guide the PV source while buying its reactive power. If the price variation is low ($\mathbf{P_{3\Delta Vmag}}$), the utility would operate closer to the ideal operating conditions (V_{op}^{3}). Similarly, if there is an excess of available power the utility will try to direct PV Sources to absorb the reactive power so that it can keep the total power under control and pocket that money earned to use it again when it has to buy when the prices shoot up, $\mathbf{P_{1\Delta Vmag}}$. If the utility is presented with a price that would entail crossing the $\mathbf{V_{limit}}$, it would reject the price.

Utility will make a decision on the basis of the amount of Voltage required to compensate for the loss. So, if $\mathbf{V_{magstar}}$ is the Voltage that the utility gets and $\mathbf{V_{mag}}$ is the voltage required, the price that the utility/distribution network is willing to provide say, $\mathbf{P_{\Delta Vmag}}$, a constant multiplier per voltage difference between the $\mathbf{V_{mag}}$ and $\mathbf{V_{magstar}}$, say **c**. The parabola for determining the $\mathbf{V_{mag}}$, can be numerically represented as:

$$-\boldsymbol{P_{\Delta V}\Delta V = c\Delta V^2} \qquad (\mathbf{63})$$

Where**,**

$$\boldsymbol{\Delta V = \left(V_{mag} - V_{magstar}\right)} \qquad (\mathbf{64})$$

Therefore,

$$\boldsymbol{-P_{\Delta Vmag} = c\left(V_{mag} - V_{magstar}\right)} \qquad (\mathbf{65})$$

Rearranging and calculating for $\mathbf{V_{mag}}$ would yield:

$$\boldsymbol{V_{mag} = V_{magstar} - \frac{P_{\Delta Vmag}}{c}} \qquad (\mathbf{66})$$

Where **'c'** is the constant allotted to the utility or the Distribution System to expend to meet the power needs as required.

3.3.3 Source Decision:

Now, based on these prices ($P_{\Delta P}$, $P_{\Delta Q}$) the PV Sources make profit by regulating the Real Power (ΔP) and the Reactive power (ΔQ) components of the Complex Power (Smax) being fed into the distribution network. The distribution network calculates the amount of Voltage required and feeds it to the price controller algorithm that sets the price of the requisite voltage ($P_{\Delta V_{op}}$). It also indicates the surplus Voltage that is the difference between the voltages produced by the source with that of the voltage needed by the utility:

The profit margin for the PV source would be:

$$\boldsymbol{Profit = \left(P_{fixed} + PP\right)(P - P_{loss}) + (PQ)(Q)} \qquad (\mathbf{67})$$

Where, **PP** and **PQ** are the prices of the real and reactive power produced by the PV Source.

The real and reactive power should not be greater than the total power, which means:

$$\boldsymbol{(P - P_{loss})^2 + Q^2 \leq S_{max}^2} \qquad (\mathbf{68})$$

The value **P** must be greater than zero and less than Pin which can be denoted as:

$$\boldsymbol{0 \leq P \leq P_{in}} \qquad (\mathbf{69})$$

Equation (51) and (52) form the constraint for the source decision that it has to satisfy in order to start generating the required real and reactive power.

Chapter 4
Simulation and Results

4.1 Baseline simulation

This chapter outlines the real and reactive voltage and current value of Bus, Source, Load and Line parameter used in the 6 bus distribution network. A table of sensitivity factors used in the sensitivity minimization method is also presented.

TABLE I
SENSITIVITY FACTORS

	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**
	Pin1	**Pin1**	**Pin1**	**Pin1**	**Pin1**	**Pin1**
α_P (10^{-5})	0	9.5274	9.2767	19.465	45.301	20.404
α_Q(10^{-4})	0	2.0461	1.9923	4.1059	6.7685	3.8057
	Pin2	**Pin2**	**Pin2**	**Pin2**	**Pin2**	**Pin2**
α_P (10^{-5})	0	9.5246	9.2914	19.496	20.477	45.325
α_Q(10^{-4})	0	2.0520	1.9980	4.1178	3.8189	6.7890

TABLE II
BUS PARAMETERS

	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Bus 6**
Real Voltage (V)	2497.8	2424.4	2360.4	2382.9	2362.2	2361.7
Reactive Voltage (V)	0	- 0. 5165	- 30.9467	32.1536	67.9830	65.9472
Real Current (Amp)	35.6839	35.6839	65.8680	-30.1840	-16.0779	-14.1060
Reactive Current (Amp)	- 111.899	- 111.899	- 32.974	- 78.924	- 39.918	- 39.006

TABLE III
SOURCE PARAMETERS

	Bus 5	Bus 6
Real Power Produced (P)	197530	192650
Reactive Power Produced (Q)	-17245	-15268
Real Current	83.3409	81.3280
Reactive Current	9.6988	8.7356
Maximum Source Power (Smax)	250000	250000
Constant Factor (e - 07)	4	4

TABLE IV
LOAD PARAMETERS

	Bus 3	Bus 5	Bus 6
Real Power (P)	162000	162000	162000
Reactive Power (Q)	78460	78460	78460
Real Impedance	28.8427	28.8427	28.8427
Reactive Impedance	13.9691	13.9691	13.9691
Real current	65.8680	67.2629	67.2219
Reactive current	-32.9743	-30.2199	-30.2706

TABLE V
LINE PARAMETERS

	From Bus 1 to Bus 2	From Bus 2 to Bus 3	From Bus 2 to Bus 4	From Bus 4 to Bus 5	From Bus 4 to Bus 6
Real Impedance	0.1857	0.5921	0.1857	0.5921	0.5921
Reactive Impedance	0.5968	0.7584	0.5968	0.7584	0.7584
Real current	35.684	65.8680	-30.1840	-16.0780	-141061
Reactive current	-111.90	-32.9743	-78.9249	-39.9187	-39.0062

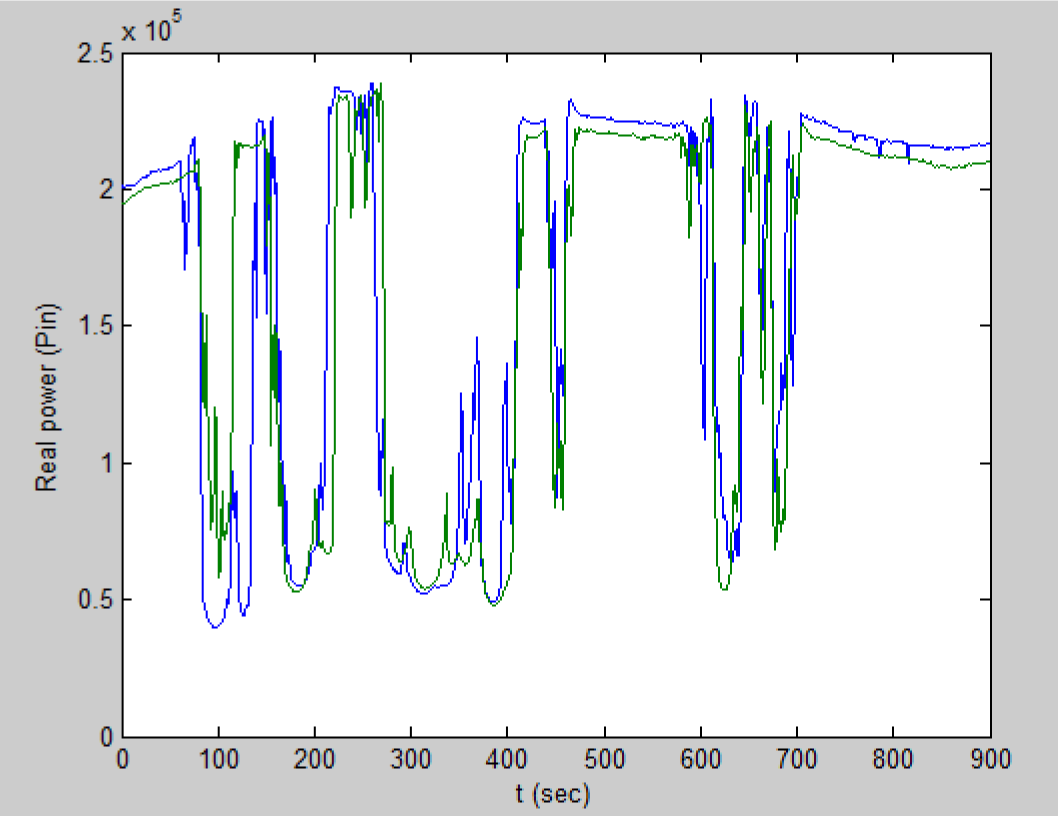


Fig.4.1 PV Input real power in baseline simulation

The 2 input radiance power Pin1 and Pin2 has caused the real power to jump into action as depicted in Fig 4.1 in order to compensate for the loss in the overall Voltage to keep up with accepted range i.e. 118V to – 126 V of utility supplied voltage. It’s quite visible that the compensation for both Pin1 and Pin2 varies almost the same, since the 2 Pin values are close enough, thereby the cloud coverage and exposure to sun should also be nearly be the same in those areas.

From the graph it can be inferred that the real power produced by the PV sources has been absorbed the most from about 275s to 400s in the time frame by the utility and then from about 460s to 590s and from about 710s to 900s the PV sources have absorbed the extra real power input produced by the utility.

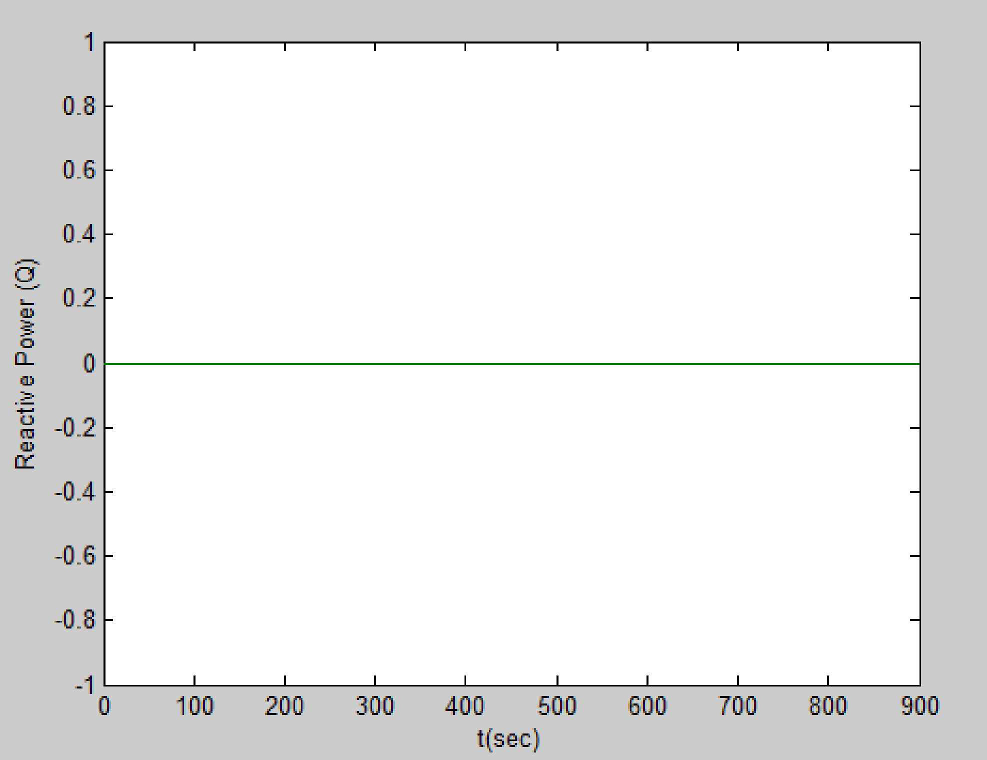


Fig.4.2 PV Input reactive power in baseline simulation

Since baseline simulation does not involve the participation of reactive power (Q), the amount of reactive power absorbed by or released to the PV sources are nil. Only the real power involvement is considered and studied in this simulation.

So the total power is the same as the real power in each bus of the utility.

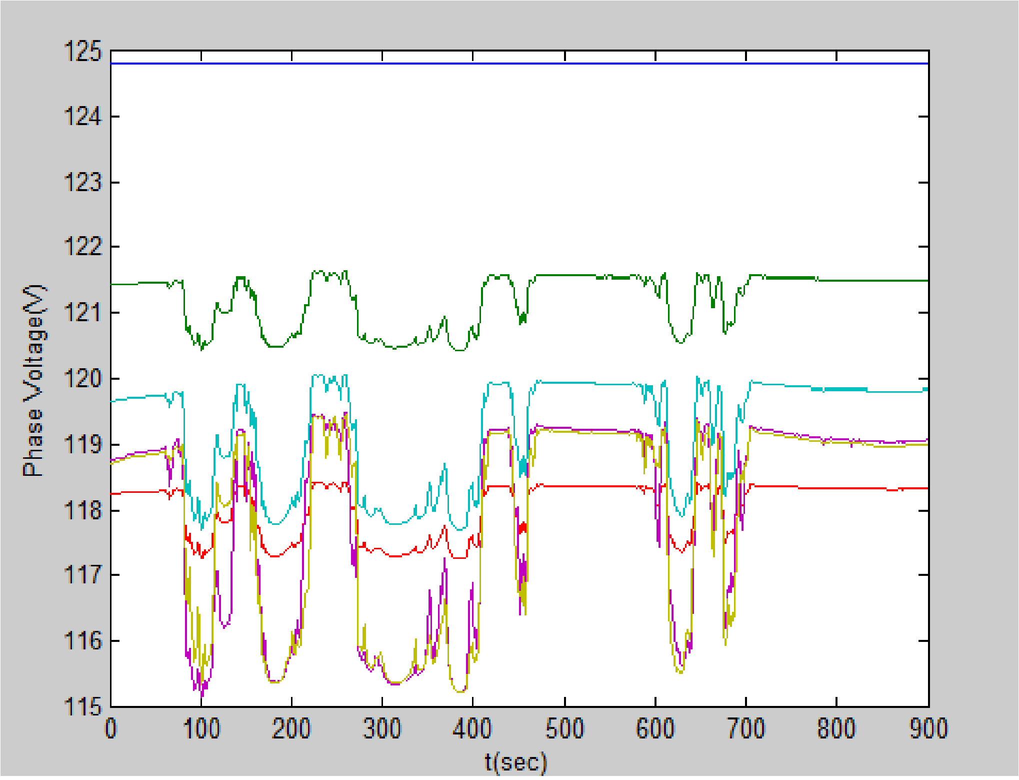


Fig.4.3 Bus phase voltage in baseline simulation

As is evident from the Phase Voltage produced, the individual bus fluctuation has crossed well past the lower limit value i.e. 118V and does not help the utility in maintaining the Voltage variation within the acceptable range. Baseline simulation fails to mitigate the Voltage variation of the PV Sources. The lowest it dips is 115.126 Volts, which is clearly outside the acceptable voltage limit. However, the higher limit is honored; even then this method cannot be used to achieve voltage variation mitigation results.

4.2 Sensitivity minimization results

TABLE VI
CONTROL PARAMETER

β (1)	0.5790
β (2)	0.5785

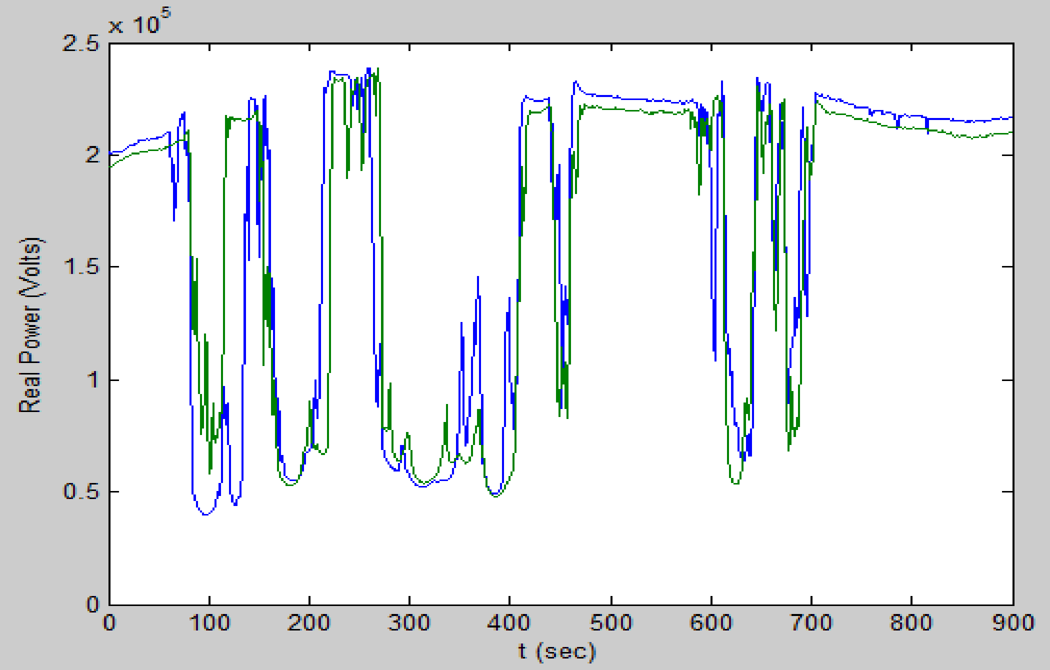


Fig.4.4 PV Input real power using control parameter β

Fig. 4.4 represents the amount of Real Power produced by the PV sources as the utility is experiencing the dearth in Voltage production. The real power produced by the PV sources is positive throughout the observation period implying an active participation of the PV sources in keeping the voltage variation of the supplied voltage by the Utility consistently within the allowable range.

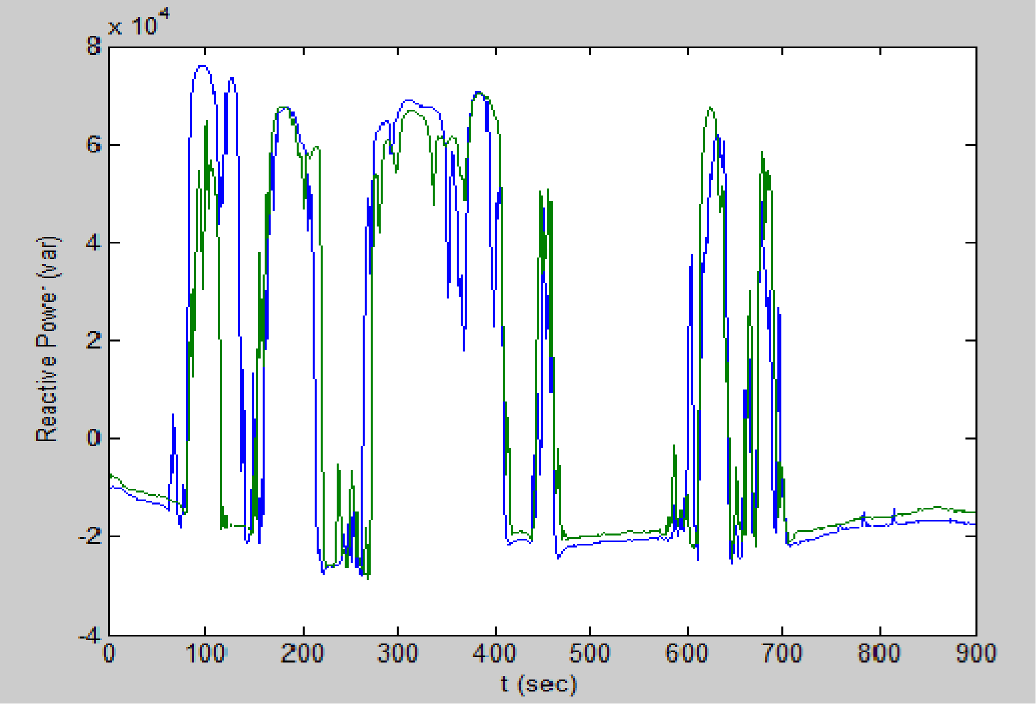


Fig.4.5 PV Input reactive power using control parameter β

Fig. 4.5 depicts the active contribution of the reactive power to the utility throughout the observation period. It can be seen that the reactive power has fluctuated from negative to positive values that implies absorbing excess and releasing the deficit reactive power needed by the utility based on the available Voltage at any instant. From about 470sec to 600sec and about 710sec to 900 sec, the contribution has been registered in the form of absorbing the excessive reactive component of the total power thereby, keeping the fluctuation from overshooting the higher acceptable phase voltage limit, i.e. 124 V.

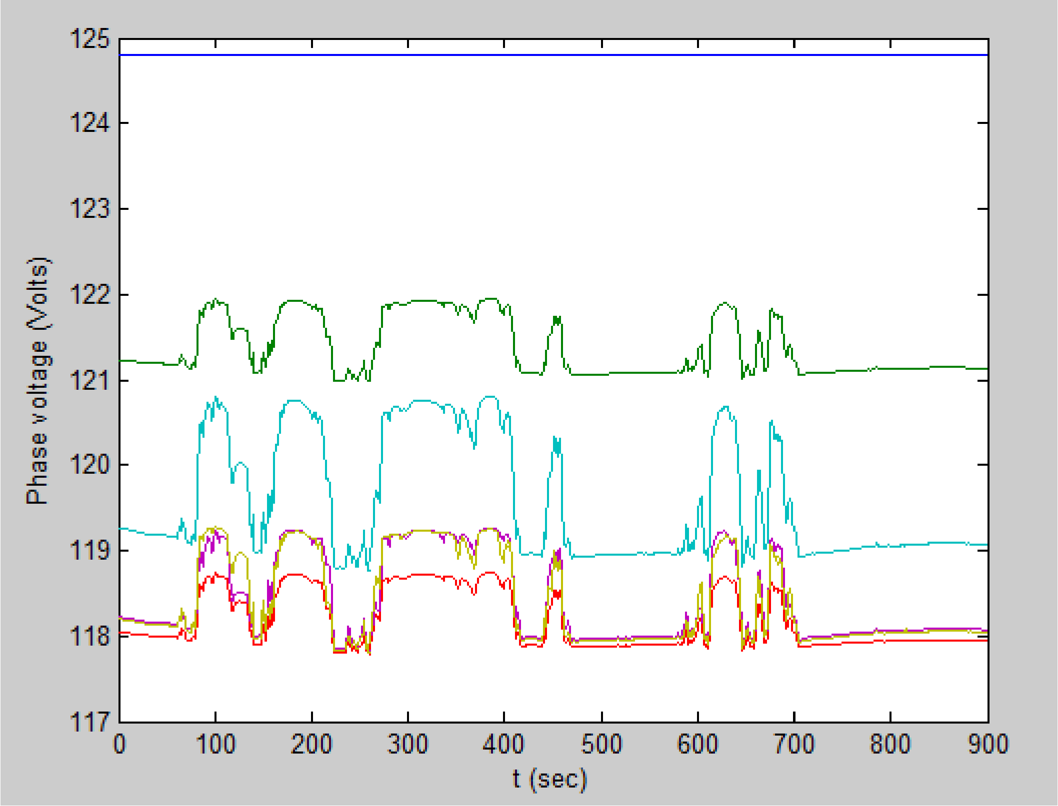


Fig.4.6 Phase voltage of each bus using control parameter β

The phase voltage study reveals that the voltage mitigation achieved with sensitivity minimization method has enabled the utility in achieving its goal. It can be observed that the Phase voltage spikes to upper limit with the reactive power requirements but the real power requirements falls. Similarly, the observed phase voltage when starts dipping towards the lower limit the reactive power requirement dips but the real power contribution by the PV source starts growing.

4.3 Market simulation results

In market simulation, unlike the sensitivity minimization method, the algorithm perturbs the Vmag values instead of the P and the Q values of the PV source. The market settlement is achieved by instructing the PV source to produce real/reactive power in case of a dearth of Power at the utility and thereby make some profit.

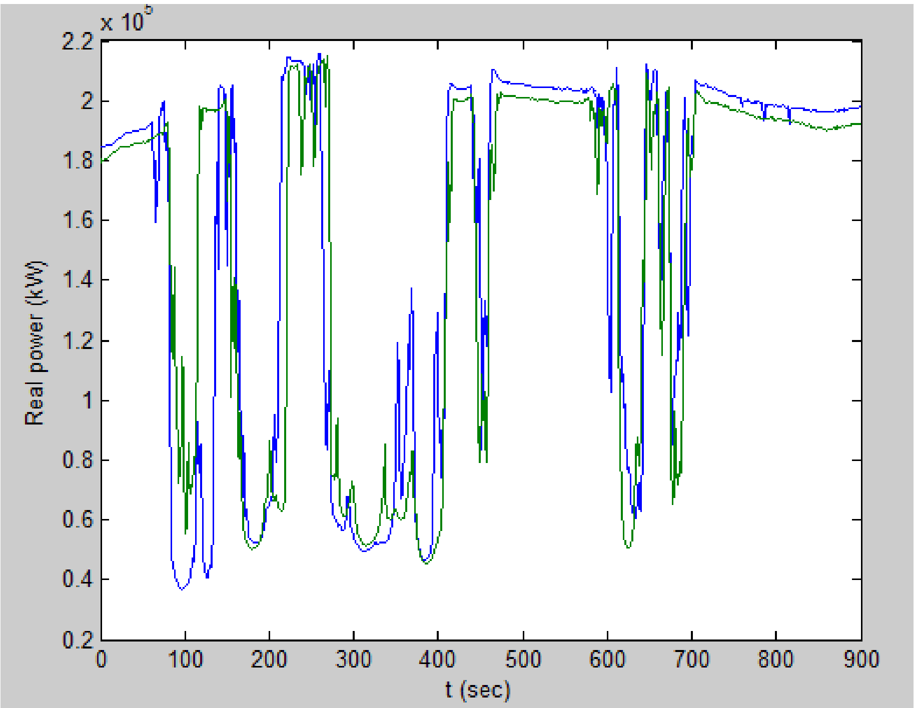


Fig.4.7 Real power (kW) mapping with time in market simulation

The real power can be seen actively participating in contributing to the utility in Fig. 4.7 by continuously producing and selling Real power for the entire time span of observation. The minimum and maximum produced are 36.73kW and 215 kW.

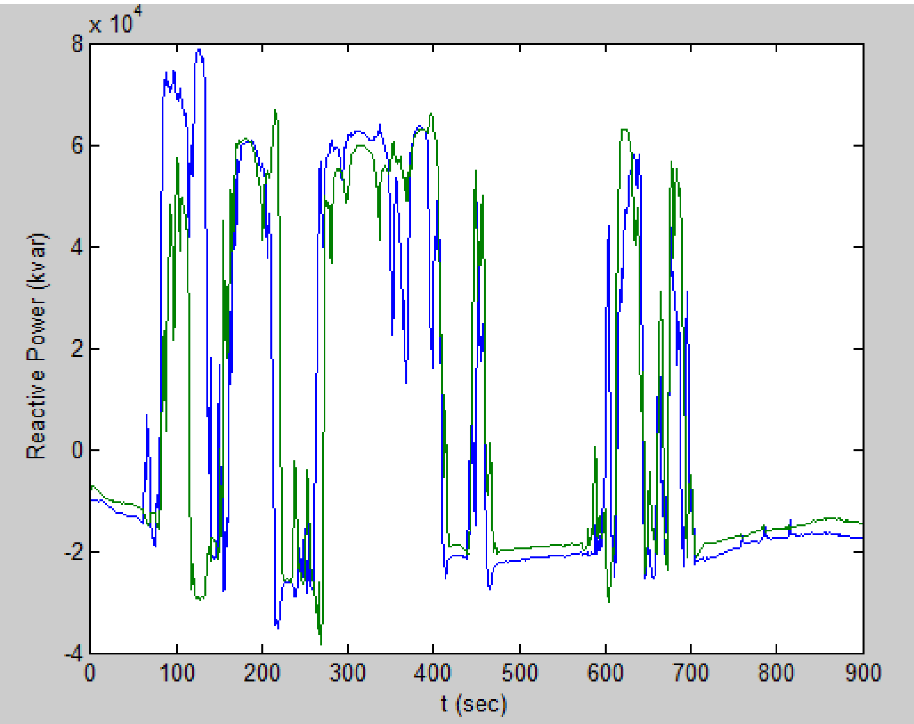


Fig.4.8 Reactive power mapping with time in market simulation

The reactive power produced in market simulation varies like the Phase voltage. It is both produced and consumed as the system demand varies. The real power follows the

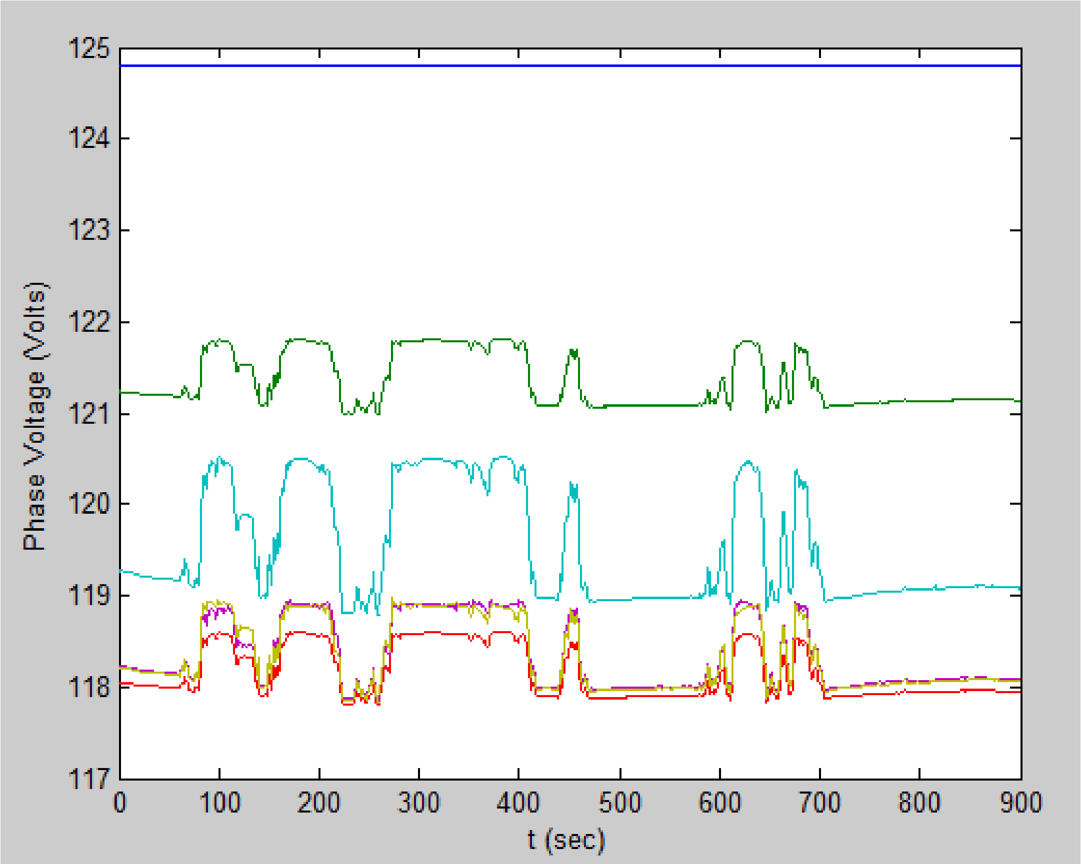
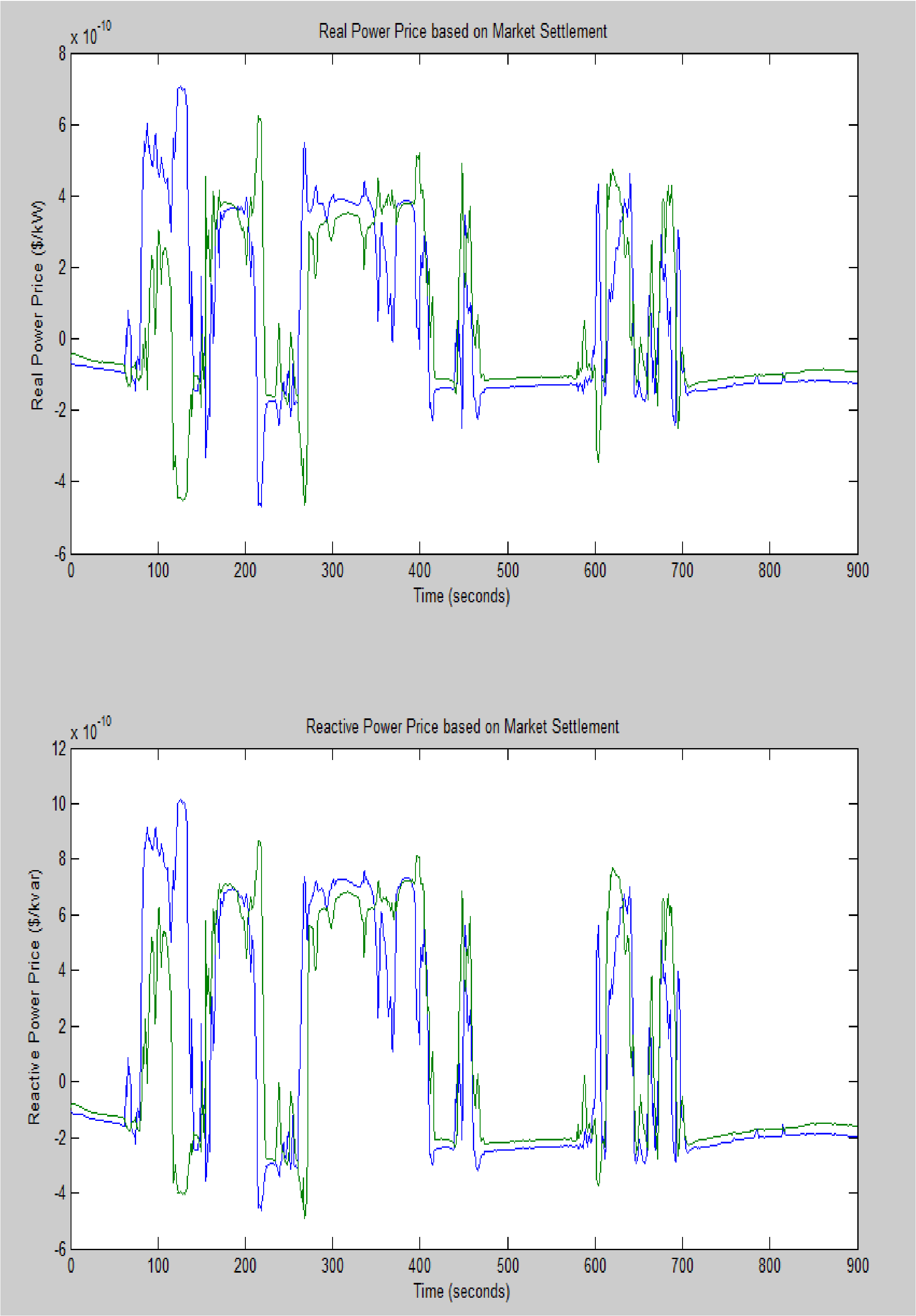


Fig.4.9 Phase voltage of each bus in market simulation

The market simulation controller manages to provide a fairly steady phase voltage in each bus optimizing the amount of Voltage bought from the PV sources. The variation observed has been quite successful in limiting it to the acceptable range. The behavior is similar to the graph plotted for sensitivity minimization plotted for all the six buses’ phase voltages.


Real Power Price based on Market Settlement

Reactive Power Price based on Market Settlement

Fig.4.10 Price of real and reactive power in market simulation

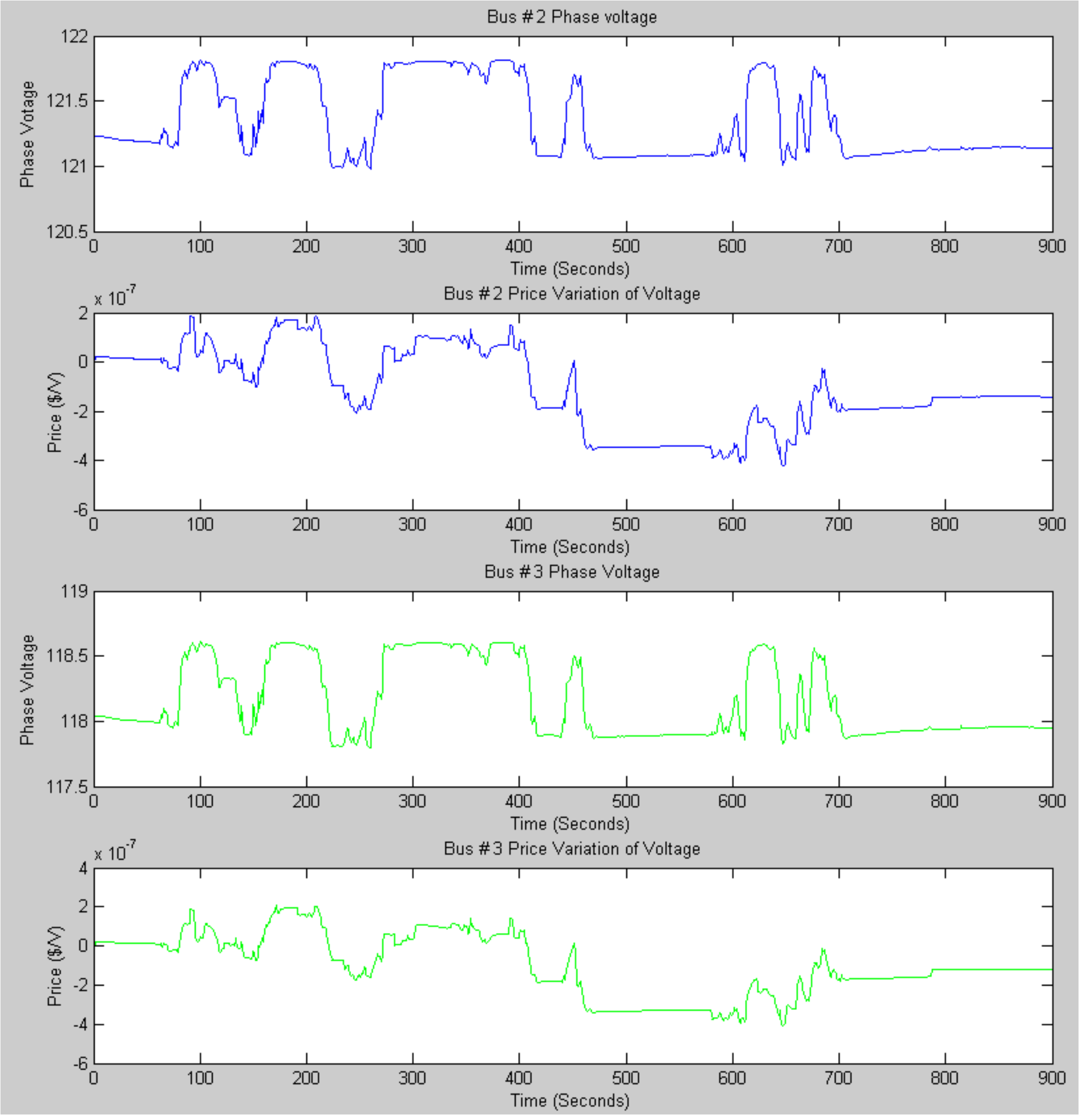


Fig.4.11 Price and Phase Voltage Comparison on Bus 2 and 3

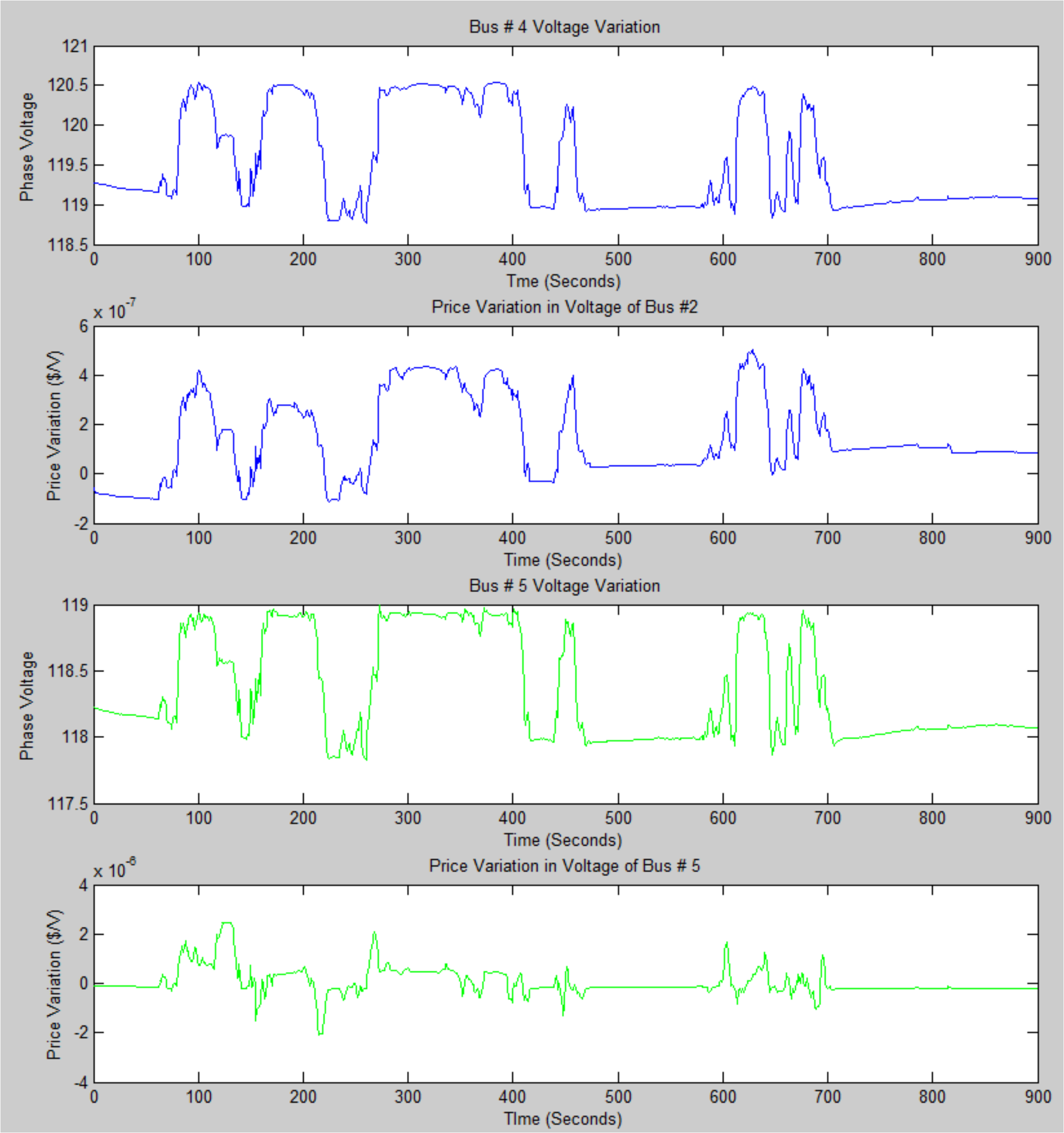
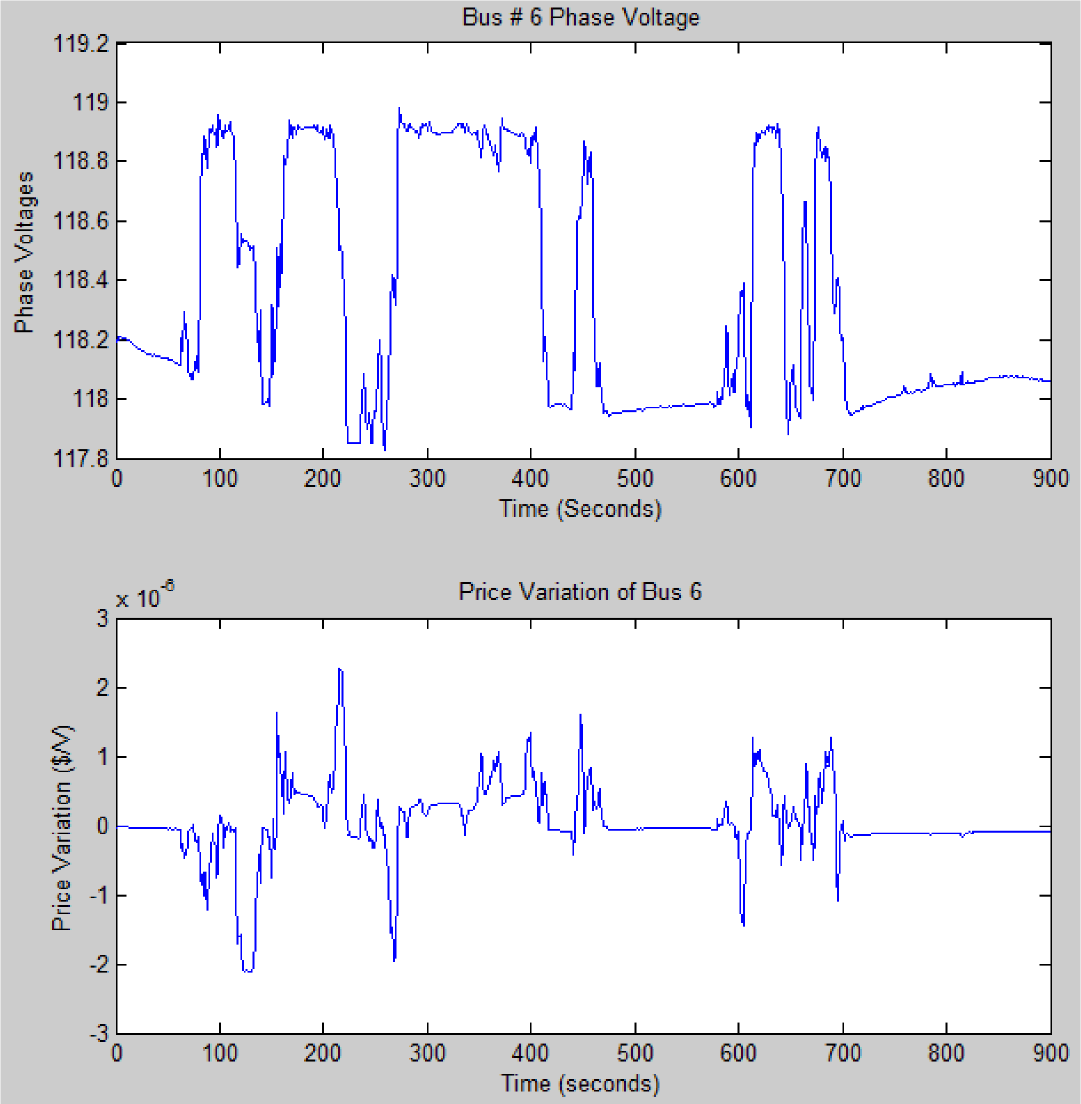


Fig.4.12 Price and Phase Voltage Comparison on Bus 4 and 5



Bus # 6 Phase Voltage

Price Variation of Bus 6

Fig.4.13 Price and Phase Voltage Comparison on Bus 6

Fig 4.11 – 4.13 depicts the Voltage variation with the Price of the Voltage required at each bus. For a given Price of ΔV, the utility decides how much Voltage to buy/sell from/to the PV Sources per the equation (53). If the bus voltage is high, pushing it low will cost money to the Utility, but if it is already low, pushing it lower will not save money nor will it be able to maintain the lower limit constraint, so it goes up by not selling it back to the PV sources anymore. If the required voltage on any bus, Vmag is high, the utility will buy the voltage from the PV sources and thereby the price would start going down as the demand for it decreases. As depicted in Fig 4.14, it is interesting to note that in bus 6, while the Bus Voltage magnitude is rising in the time interval 75 - 90 seconds and immediately after the 200 seconds (around 201- 207 seconds) , the Price continues to dip. However, in the third line of observation, while the voltage is dropping, the Price keeps rising up. This indicates the decision making ability of the Utility.

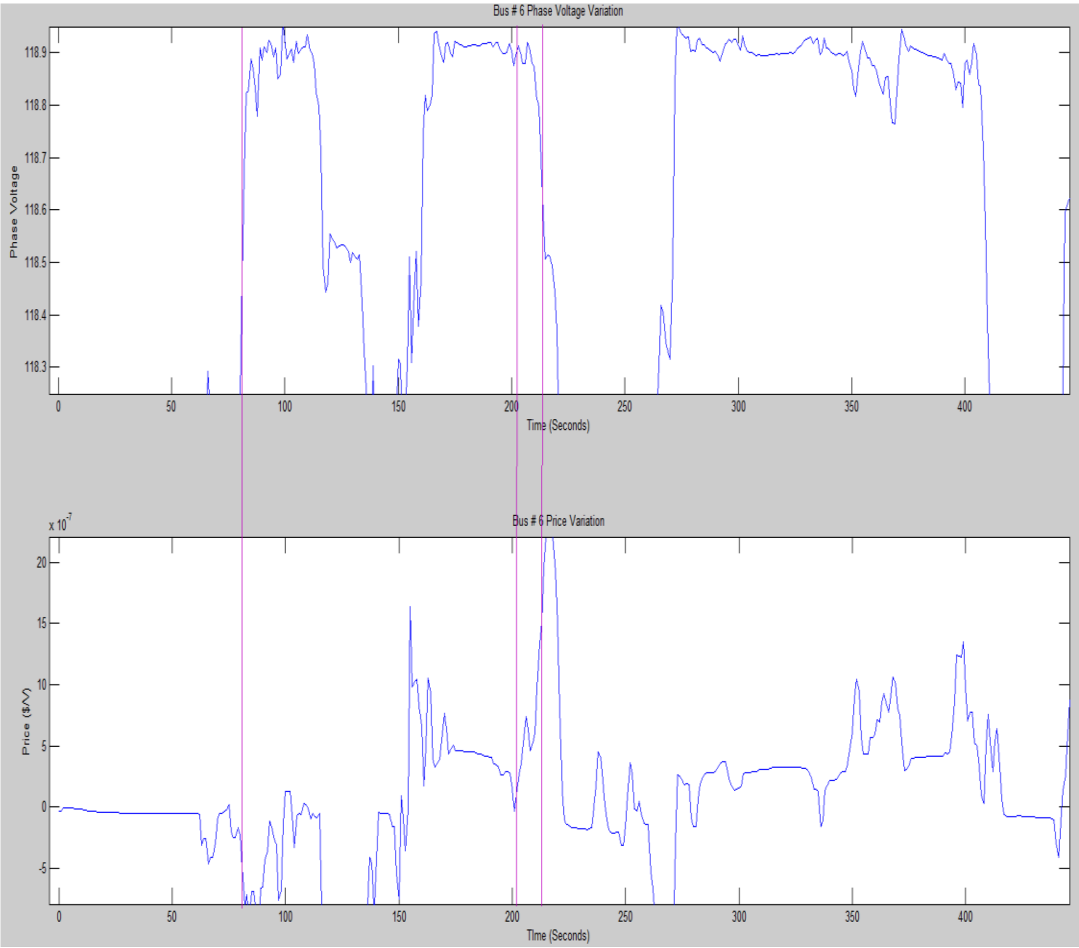


Fig.4.14 Price and Phase Voltage relationship study on Bus 6

Chapter 5
Conclusion and Future Scope of Work

5.1 Conclusion

5.1.1 Baseline method

It is evident that the baseline simulation fails to accomplish any necessary adjustments (Fig 4.3), to tune the phase voltage within the allowable upper limit and the lower limit range of 126 V to 118 V. The lower limit of the allowable phase voltage is being crossed way over the tolerance limit. This is partly due to the fact that there has been no recognition of reactive power (var) contribution in resulting output Voltage and the rest is because there is no control algorithm to regulate the real power (kW).

5.1.2 Sensitivity minimization method

Even though the allowable magnitude limits of a bus voltage is 126V to 118 V for an ideal operating voltage of 120V, the control parameter β, fails to restrict the voltage within the boundary, as reflected in Fig.4.3 above. However, this adjustment seems to contain the voltage better than the baseline simulation precisely in terms of restricting the phase voltages and limiting the drastic voltage variation.

5.1.3 Market based simulation method

Normative economics, generally termed as welfare economics that deals with the study of the ‘measure’ of the society as a whole, states two fundamental theorems.

The first theorem states that in a free market where there happens to be no monopoly, the solution for a market problem that is converging can also be optimal under given conditions [32] [33]. In this paper, an attempt has been made to come up with a converging solution from a utility and a PV source perspective that trade power in a way that the overall system is balanced. The power sold to the utility and the charges levied by the utility on the PV sources are doing the balancing act in the market.

With market simulation algorithm described above, it can be concluded that the Voltage mitigation achieved is better than the voltage minimization method and the baseline simulation, as the required Voltage stays within the allowable limits (126 V to 118 V). This is due to the profit based control introduced in the system that directs the PV Sources to decide if they need to produce real/reactive power and helps the utility to fairly invest in buying the shortage power that they encounter when there is a cloud hovering and affecting the power production. Per the Fig. 4.11, Fig. 4.12 and Fig. 4.13, prices paid/charged to/from the PV sources on buses 5 and 6 for the real and reactive powers are developed by the market simulation algorithm.

In introspection, the market simulation is definitely better than the baseline simulation in terms of successfully mitigating the voltage variation. In comparing with the sensitivity minimization method, it is observed that the even though both attain substantial success in keeping the voltage variation within the allowable range, the voltage variation itself has decreased a little in Market simulation, thereby keeping the voltages more in the acceptable stable range in each phase.

In the subsequent figures, an extensive graph comparison of voltage variation on each bus among the three controllers has been studied in this paper that intensifies the impact of each on the utility/distribution system.

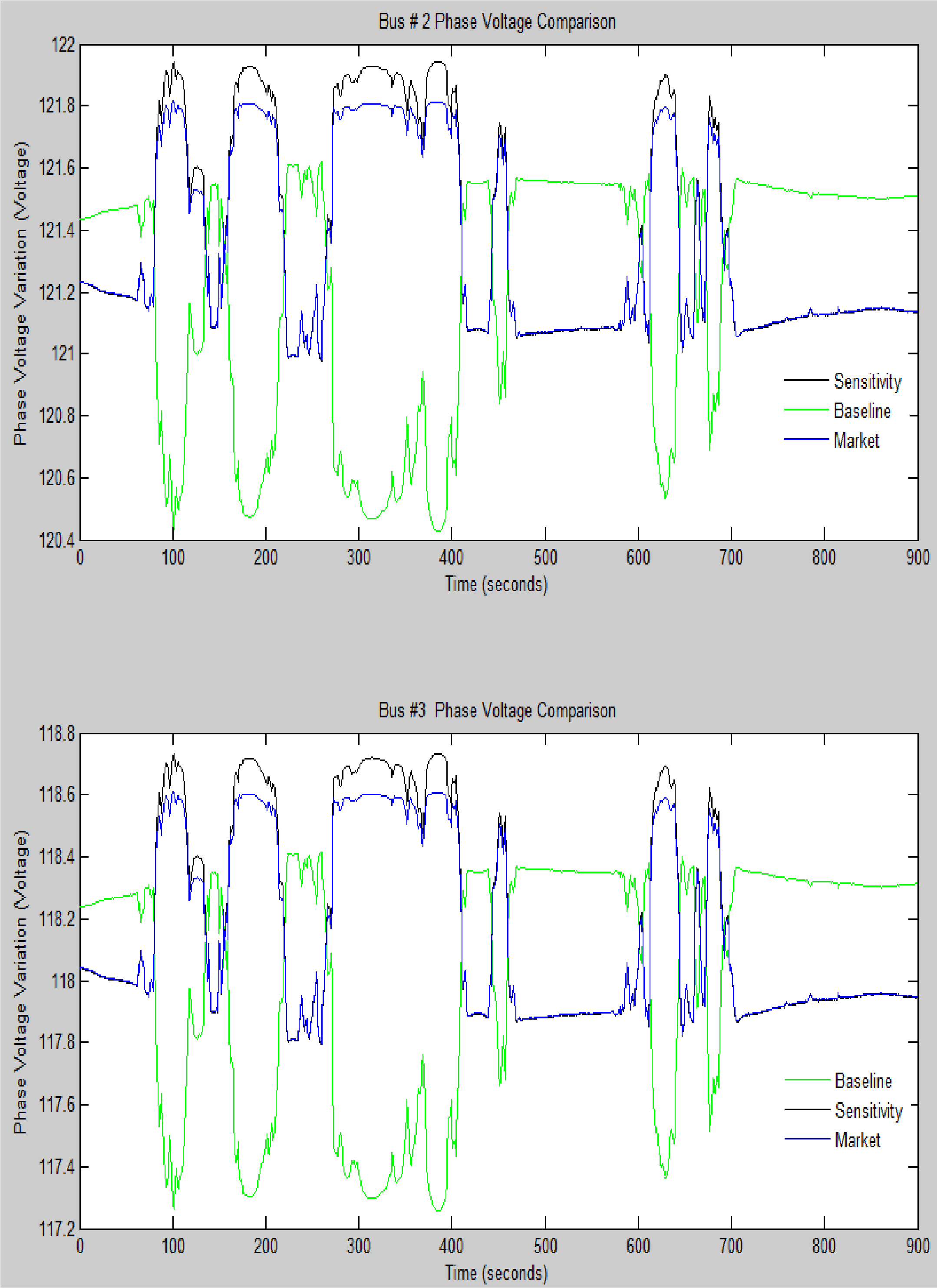


Fig. 5.1 Bus 2 and 3 Single Phase Voltage comparisons

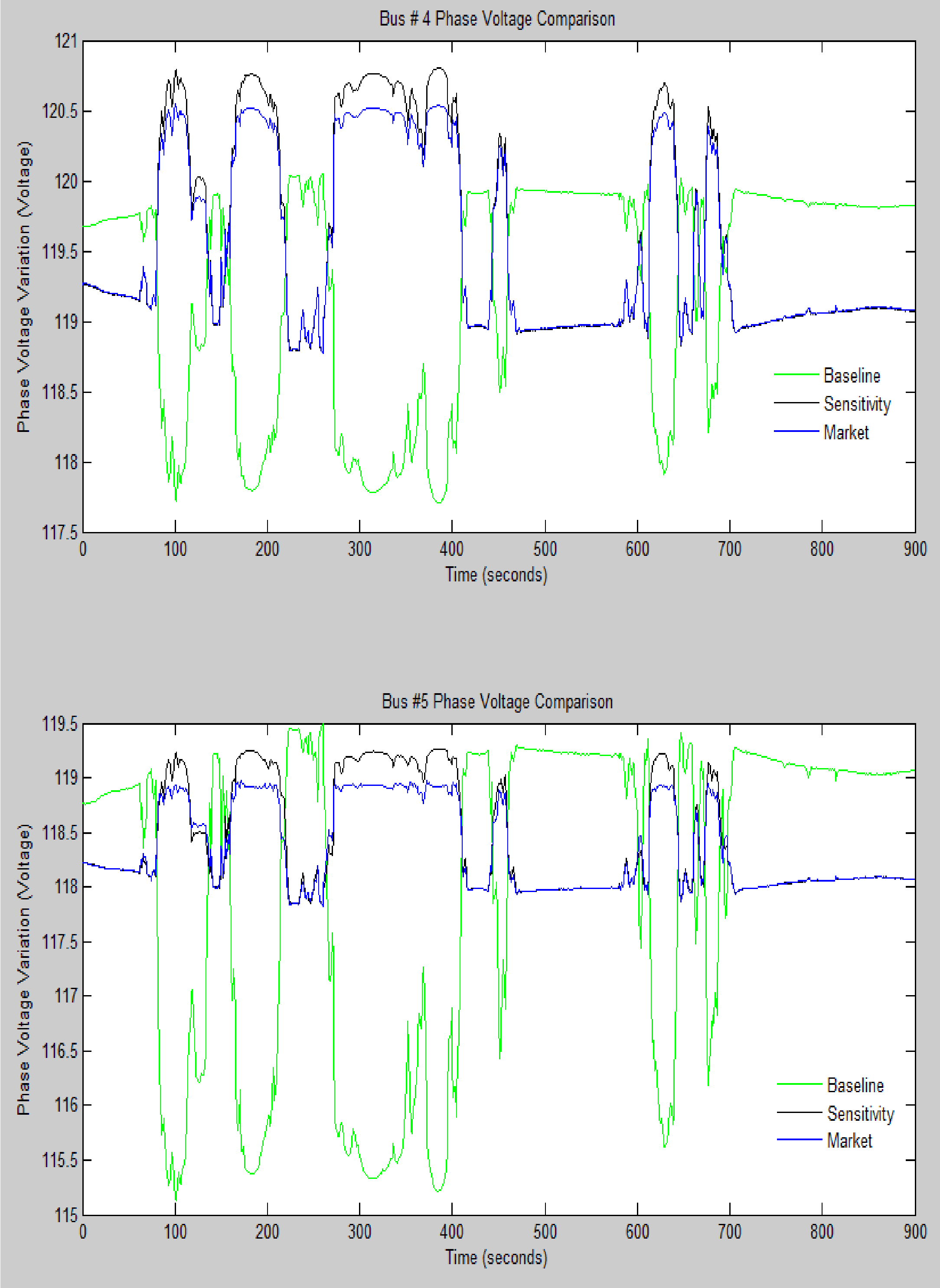


Fig. 5.2 Bus 4 and 5 Single Phase Voltage comparisons

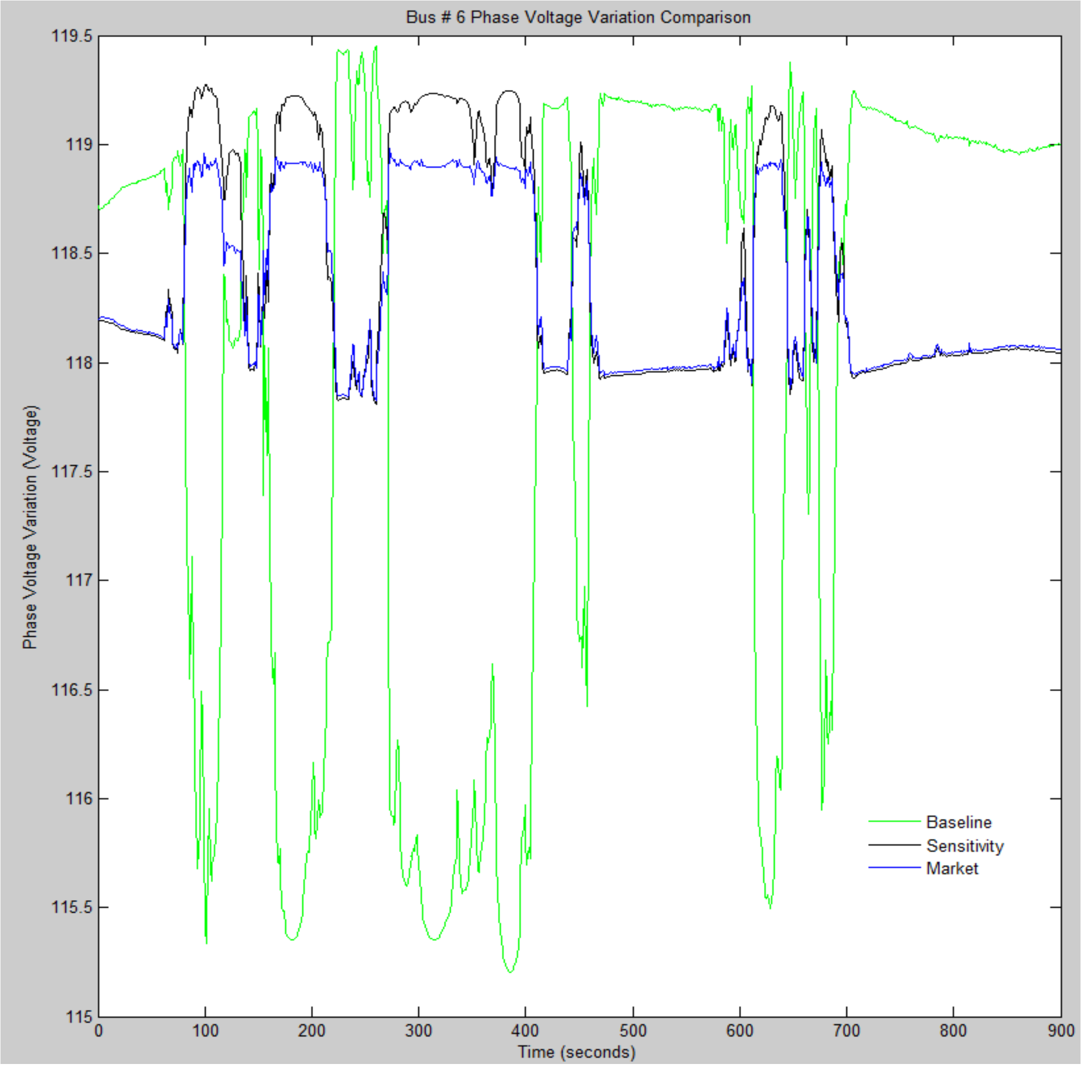


Fig. 5.3 Bus 6 Single Phase Voltage comparisons

From Fig. 5.1 to 5.3, it can be inferred that the baseline simulation controller fails to meet the voltage variation requirement, but the market simulation and the sensitivity minimization do the job staying pretty within the limits for the most part. A close observation tells us that in fact, market simulation does a better job in decreasing the voltage variation than the sensitivity minimization method as it stays closer to the steady state voltages in all the buses.

TABLE VII
STANDARD DEVIATION

	Baseline Simulation	Sensitivity Minimization	Market Simulation
Bus 1	0.0000	0.0000	0.0000
Bus 2	0.4135	0.3394	0.2973
Bus 3	0.4026	0.3304	0.2895
Bus 4	0.8141	0.7119	0.6256
Bus 5	1.5117	0.5029	0.3957
Bus 6	1.4767	0.5111	0.3921

Table VII shows the standard deviation of all the three controllers studied in this paper. For each bus it can be inferred that the maximum deviation has occurred in the baseline simulation and minimum deviation was observed in the market simulation method. So the market simulation does achieve a better mitigation of voltage variation in all the buses as compared to the baseline and the sensitivity minimization method. Basically, the market simulation has achieved the following 2 goals:

1. Optimize the amount of ΔV to buy from the PV sources based on the demand
2. Achieved a better result in minimizing the Voltage variation on each bus.

5.2 Future scope of work

The paper might be helpful in realizing the practical behavioral challenges in a grid system or in a system of PV inverters. The algorithm was applied on a 6 bus voltage distribution system containing 2 PV sources. With a healthy comparison of the baseline simulation, voltage optimization method and the market simulation, it was observed that the best voltage control on possible voltage fluctuation is provided by the market simulation method. Future scope involves spreading this control algorithm application over a bigger system for testing the veracity and universality of the algorithm.

There are some unexplored avenues for selecting the controller algorithm that can be more robust and include some more practical conditions. The profit controller designed has considered the investment of the utility in letting the PV sources produce the shortage power. If a controller is designed that involves the investment made out of the profit earned by the utility, that can be an option for choosing a controller. Another design avenue for a controller would be an algorithm that allows maximum participation from PV Sources on a daily basis and the produced energy is stored in large storage batteries and or being used by the producer and then fed to the utility on a demand and supply basis so that more PV sources participation is encouraged.

BIBLIOGRAPHY

[1] Cuauhtemoc Rodriguez and Gehan A. J. Amaratunga," Analytic Solution to the Photovoltaic Maximum Power Point Problem," IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—I: REGULAR PAPERS, VOL. 54, NO. 9, SEPTEMBER 2007

[2] Report of the World Summit on Sustainable Development Johannesburg, South Africa, 26 August- 4 September 2002 http://cisdl.org/natural-resources/public/docs/WSSD_rept.pdf

[3] "World Energy Outlook 2002," http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo2002_part2.pdf

[4] The Energy Challenge for Achieving the Millennium Development Goals http://www.unep.org/training/programmes/Instructor%20Version/Part_2/Activities/Innovations_and_Technology/Energy/Core/The_Energy_Challenge.pdf

[5] H.J.Corsair and Debora Ley, "The Commercialization of Solar Energy as a Means for Rural Development", IEEE Energy 2030 Atlanta, Georgia, USA, 17-18 November 2008

[6] Energy Policy Vol. 24, No. I, pp. 81 - 111. 1996 Elsevier Science Ltd, “The quiet (energy) revolution Analyzing the dissemination of photovoltaic power systems in Kenya”, Richard H Acker, M Kammen

[7] Energy Policy, Vol. 26, No. 4, pp. 295— 305, 1998 Published by Elsevier Science Ltd, “Solar electricity in Africa: a reality”, Robert J van der Plasa, and Mark Hankinsb

[8] D. Ley, H. Martinez, E. Lara, R. Foster, & L. Etsrada 2006, “Nicaraguan renewable energy for rural zones program initiative”, ASME International Solar Energy Conference – Solar Engineering 2006

[9] Renewable Energy 22 (2001) 205-210, “Strategy for promotions and development of renewable technologies in Bangladesh: experience from Grameen Shakti”, Dipal C. Barua

[10] Eric Martinot, Akanksha Chaurey, Debra Lew, Jose Roberto Moreira and Njeri Wamukonya, “Renewable Energy Markets In Developing Countries” Annual Review of the Energy and the Environmental 2002. 27:p 309–48 doi: 10.1146/annurev.energy.27.122001.083444

[11] F.D.J. Nieuwenhout, A. van Dijk, P.E. Lasschuit, G. van Roekel, V.A. P. van Dijk, D. Hirsch,H. Arriaza, M. Hankins, B.D. Sharma and H. Wade, "Experience with Solar Home Systems in Developing countries: A review", Progress in Photovoltaics: Research and Applications. Prog. Photovolt: Res. Appl. 2001; 9: 455- 474

[12] Charles Hanley, Michael Ross, Octavio Montufar, Chris Rovero, Robert Foster, "Introducing Photovoltaics to new markets through government development programs: The FIRCO example in Mexico"

[13] Esa Aleksi Paaso, Yuan Liao & Aaron M. Cramer (2015) "Dual layer Voltage and VAR Control Approach with Active Participation from Distributed Solar Generations, Electric Power Components and Systems," 43:8-10, 854-865, DOI:10.1080/15325008.2015.1026006

[14] Ward T. Jewell and Timothy D. Unruh, "Limits on Cloud-Induced Fluctuation in Photovoltaic Generation," IEEE Transactions on Energy Conversion, Vol. 5, No.1, March 1990.

[15] Wan, Y. H."Long-Term Wind Power Variability". Rep. no. NREL/TP-5500-53637. N.p., Jan. 2012. Web.

[16] Jeyraj Selvaraj and Nasrudin A. Rahim, Senior Member, IEEE, “ Multilevel Inverter For Grid-Connected PV System Employing Digital PI Controller”, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 56, NO. 1, JANUARY 2009

[17] Yuan Liao, Wen Fan, Aaron Cramer, Paul Dolloff, Zongming Fei, Meikang Qui, Siddhartha Bhattacharyya, Larry Holloway, Bob Gregory, “Voltage and Var Control to Enable High Penetration of Distributed Photovoltaic Systems”, in 2012 North American Power Symp., 2012, pp. 1–6.

[18] D. Tom Rizy, Yan Xu, *Member*, Huijuan Li, *Member*, Fangxing Li, Phil Irminger, “ Volt/Var Control Using Inverter-based Distributed Energy Resources”, Rizy, D.T.; Yan Xu; Huijuan Li; Fangxing Li; Irminger, P. Power and Energy Society General Meeting, 2011 IEEE,Year: 2011,Pages: 1 - 8, DOI: 10.1109/PES.2011.6039020

[19] M. J. E. Alam, *Student Member, IEEE,* K. M. Muttaqi, *Senior Member, IEEE,* and D. Sutanto*, Senior Member, IEEE, “A Novel Approach for Ramp-Rate Control of Solar PV Using Energy Storage to Mitigate Output Fluctuations Caused by Cloud Passing,” IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 29, NO. 2, JUNE 2014*

[20] Teleke, S., Baran, M., Bhattacharya, S., and Huang, A., "Rule based control of battery energy storage for dispatching intermittent renewable sources," IEEE Trans. Sustain. Energy, Vol.1, No. 3, pp. 117–124, August 2010.

[21] Hund, T., Gonzalez, S., and Barrett, K., "Grid-tied PV system energy smoothing," 35th IEEE Photovoltaic Specialist Conference, Honolulu, HI, 20–25 June, 2010.

[22] Xiao Liu; Cramer, A.M., "Inverter power control to support distribution system voltage variability mitigation", Energy Conversion Congress and Exposition (ECCE), 2014 IEEE Pages: 689 - 694, DOI: 10.1109/ECCE.2014.6953462

[23] Jong-Fil Moon and Jin-Seok Kim, "Voltage Sag Analysis in Loop Power Distribution System With SFCL", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

[24] Abdulelah H Habib, Zachary K Pecenak, Vahid R Disfani, Jan Kleissl and Raymond A. de Callafon, " Reliability of Dynamic Load Scheduling with Solar Forecast Scenarios" arXiv:1512.09017v1 [cs.SY] 30 Dec 2015

[25] R. E. Brown, "Impact of smart grid on distribution system design," in Proc. IEEE Power Energy Soc. Gen. Meeting, 2008, pp. 1–4.

[26] N. D. Hatziargyriou, A. L. Dimeas, A. G. Tsikalakis, J. A. Pecas Lopes, G. Kariniotakis, and J. Oyarzabal, “Management of MicroGrids in market environment,” presented at the IEEE Int. Conf. Future Power Syst., Amsterdam, the Netherlands, 2005.

[27] L. Meeus,M. Saguan, J.-M. Glachant, and R. Belmans, “Smart Regulation for Smart Grids”, 2010, EUI Working Paper no. 45, EUI RSCAS 2010/45.

[28] Ettore F. Bompard, Member, IEEE, and Bei Han, “Market-Based Control in Emerging Distribution System Operation,” IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 28, NO. 4, OCTOBER 2013

[29] A. Jokic, R. M. Hermans, M. Lazar, and P. P. J. van den Bosch, “Distributed, price-based controls approach to market-based operation of future power systems,” presented at the 6th Int. Conf. Eur. Elect.Market, Leuven, Belgium, May 2009.

[30] Luca Ferrarini and Giancarlo Mantovani, Giuseppe Tommaso Costanzo, “A Distributed Model Predictive Control approach for the integration of flexible loads, storage and renewable”

[31] Sengupta, M.; Andreas, A. (2010). Oahu Solar Measurement Grid (1-Year Archive):1-Second Solar Irradiance; Oahu, Hawaii (Data); NREL Report No. DA-5500-56506.

http://dx.doi.org/10.5439/1052451

[32] The Efficiency Theorems and Market Failure Peter J. Hammond Department of Economics, Stanford University, CA 94305-6072, U.S.A.

http://web.stanford.edu/~hammond/effMktFail.pdf

[33] Stiglitz, Joseph E. (March 1991), The invisible Hand an Modern Welfare Economics.

http://www.nber.org/papers/w3641.pdf

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AutoCAD, Mat lab, MS Office, PLC (Allen Bradley) and DCS (Schneider) software.

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Responsibilities include designing low voltage electrical control panel in adherence to the industry standards viz. NEC, NFPA etc., Ladder logic writing in Allen Bradley PLC (CCW, Control Logix), developing HMI for the automated process, programming and interfacing YASKAWA Robots with Allen Bradley PLC.