ELECTRICAL ENGINEERING
UNIVERSITY of WASHINGTON

VOLTAGE REGULATION SUPPORT USING PV SMART INVERTERS

Deliverable UW8 of the project:
"Transactive Campus Energy Systems: An R&D Testbed for Renewables Integration, Energy and Grid Services"

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April 2017

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ACKNOWLEDGMENTS

The work presented in this report was carried out as part of the Clean Energy and Transactive Campus project in partnership with the Pacific Northwest National Laboratory (PNNL) and Washington State University (WSU). This project was supported by both the U.S. Department of Energy and the Washington State Department of Commerce Clean Energy Fund. The authors would like to thank PNNL for providing the Energy Plus model of the building and their valuable advice on how to implement the co-simulation environment.

ACRONYMS

PV	:	Photovoltaic
INV	:	Inverter
PF	:	Power factor
IEA	:	International Energy Agency
OLTC	:	On-load tap changer
SVR	:	Step voltage regulator
SC	:	Switchable capacitor
PCC	:	Point of common coupling
FC	:	Fixed capacitor
SCADA	:	Supervisory control and data acquisition

LIST OF SYMBOLS

θ	:	Power factor angle	rad/degree
δ	:	Voltage angle	rad/degree
S_r	:	Rated power of PV inverter	kVA
P_{PV}	:	Real power output of PV inverter	kW
Q_{PV}	:	Reactive power output of PV inverter	kVAr
pf	:	Power factor of PV inverter	-
$\overline{V}$	:	Voltage upper limit	V
$\underline{V}$	:	Voltage lower limit	V

1 INTRODUCTION

1.1 Motivation

Over the last decade, the worldwide PV generation has been increasing exponentially due to the fall in costs, the increased customer awareness and the supporting governments' policies. According to the IEA's 2016's Trends in Photovoltaic Applications report [IEA 16], at the end of 2015 the globally cumulative PV capacity reached 228 GW. It is also predicted that the installed PV capacity will continue to grow over 20% every year in the next 5 year. This rapid growth of PV generation helps the nations fulfil their energy needs without increasing fossil fuel consumption which largely contributes to carbon dioxide emissions.

Although the integrations of PV are promoted worldwide, the current distribution systems were not designed to incorporate this type of generation [Tanaka 10]. Consequently, technical problems may occur as the level of PV penetration increases. One of the most common problems is voltage deviation from the acceptable range defined by the current standards. For example, high PV generation during low demand period might create over-voltage issue while sudden drop in PV generation during peak demand period might create under-voltage issue [Tonkoski 12]. Furthermore, the high intermittency and the reverse power flow from PV generation can interfere with the operations of the existing voltage regulation devices in the system such as on-load tap changers (OLTC), step voltage regulators (SVR), fixed capacitors (FC) and switchable capacitors (SC) [Ravindra 12].

In order to mitigate the aforementioned issues, the following solutions can be applied in practice:

1) **Install network protectors at substations** to prevent reverse power flow to the networks.
2) **Deploy energy storage systems (ESS)** to reduce intermittency and the reverse power flow from PV generation
3) **Utilize the reactive power capability of PV inverters** for voltage regulation support.

The first solution is often used by the utilities. Although this practice can prevent most of the above issues, it increases PV generation curtailment thereby reducing the overall economic gain of PV installations [Walling 08]. The second solution has gained more attention recently as the cost of energy storage devices significantly decrease. This method requires to optimally control the ESSs such that the total economic benefit is maximized [Eyer 10]. Within the scope of this project, we have studied the optimal operations of battery energy storage systems (BESS) in coordination with PV systems, and presented the results in a separate report.

This report focuses on voltage regulation support using PV smart inverters. This practice is rather new in the United States because not until lately did the interconnection standards for distributed generation systems such as IEEE 1547 [Basso 04] allow PV inverters to inject/absorb reactive power. The advantage of an inverter in comparison to the traditional voltage regulators (OLTC, SVR, SC) is that its reactive power output can vary much faster [Liu 08]. To fully take advantage of PV inverter's reactive power capability, a PV inverter must be properly controlled such that it could efficiently regulate the voltage while delivering maximum active power service [Whitaker 08]. In this work, we proposed two algorithms for voltage regulation support using PV smart inverters. A case study is conducted to demonstrate the algorithms' feasibility.

1.2 Organization of the report

- Section 2 reviews the current practices for voltage regulation in distribution network.
- Section 3 presents the reactive power capability of PV smart inverters.
- Section 4 introduces the two methods for voltage regulation support using PV smart inverters.
- Section 5 investigates a case study considering a feeder in UW distribution network.
- Section 6 summarizes the report with conclude remarks.

2 Review of the Current Practices for Voltage Regulation in Distribution Network

2.1 Current standard for voltage regulation

The utilities must maintain the customers' voltages at PCC within an acceptable range as required by the current codes and standards. In the United Sates, the voltage operational ranges are defined by ANSI C84.1 Standard. The latest version of this standard is [ANSI C84.1-2016] in which the voltage limits are set for different service levels as shown in Table I and Table II.

Table I. ANSI C84.1 Voltage Ranges (>600V)

System voltage greater than 600V	Service Voltage Limits		Utilization Voltage Limits	
	Min	Max	Min	Max
Range A	97.5%	105%	90%	105%
Range B	95%	105.8%	86.7%	105.8%

Table II. ANSI C84.1 Voltage Ranges (120V-600V)

System voltage between 120V and 600V	Service Voltage Limits		Utilization Voltage Limits	
	Min	Max	Min	Max
Range A	95%	105%	90%	104.2%
Range B	91.7%	105.8%	86.7%	105.8%

The voltage ranges in ANSI C84.1 specify the steady-state voltage tolerances for an electrical system, where range A is the optimal voltage range and range B is the acceptable voltage range. However, the utilities might have narrower bands for the urban systems and broader bands for the rural systems due to the differences in feeder length and load concentration [Ravindra 12].

2.2 Traditional practices for voltage regulation in distribution systems

Traditional practices for voltage regulation in distribution systems commonly employ OLTC transformers, SVR, FC and SC. The primary function of these devices is to maintain the voltage within the acceptable ranges by adjusting their reactive power outputs. These devices can be described briefly as follows:

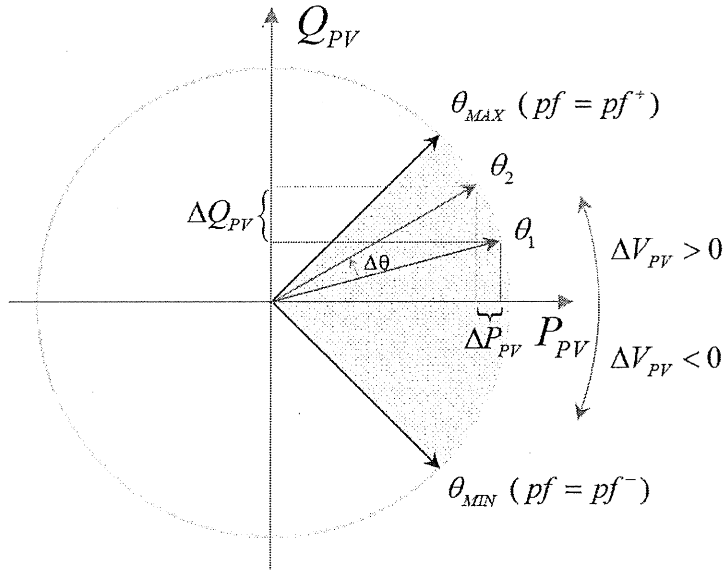
1) **OLTC transformers** are often equipped at substation level. They are capable of changing their voltage tap automatically while carrying the load. The voltage range of an OLTC transformer is often within ±20%. The step size of each voltage tap typically ranges from 1% to 5% depends on the transformers' designs. It is often costly for maintenance or replacement of the OLTC in a transformer, therefore, it is not desired to operate the OLTC frequently.
2) **SVRs** are autotransformers with a large number of taps. Differ from a regular transformer, a SVR is usually installed in series with a feeder. It regulates (mostly boost) the voltage of a long feeder where occurs a large voltage drop.
3) **FCs and SCs** are basically capacitor banks installed at the locations (usually close to large inductive loads) where reactive power support is needed for power factor correction or for voltage boost. The difference between FCs and SCs is that SCs can be automatically switched ON or OFF based on the system's conditions.

In many distribution grids today, the operations of the above devices can be controlled and coordinated utilizing the capabilities of the distribution SCADA systems. Their operations are relatively slow because in most distribution systems the load variations and voltage fluctuations are usually small and slow [Turitsyn 10]. However, with the increasing renewable energy penetration into the distribution systems and the improvement of power electronics technologies will the voltage regulation practices due to change.

3 Reactive Power Capability of PV Smart Inverters and Existing Control Methods

3.1 Reactive power capability of PV smart inverters

In order to enable the reactive power capability of PV inverters, it is required that the inverter power rating is oversized. In other words, the apparent power S of the inverter must be greater than the real power output P of the PV arrays to allow the excess capability for providing reactive power. It is important to note that, the storage capacitor inside the inverter must also be suitably oversized to handle the voltage ripple while injecting/absorbing reactive power. Therefore, the reactive power capabilities of the PV smart inverters are often limited when the small size capacitors are required to reduce the cost and the dimensions of the inverter. This is reflected in the power factors of the inverters. For example, the power factor of a 300VA micro inverter might be only as low as 0.7. This means the micro inverter can only provide as much reactive power as its real power, thus this inverter cannot provide reactive power at night when there is no PV generation. The relationship between different output powers of a smart inverter is illustrated in Figure 1 in which pf is the power factor and limited by pf^{+} (leading) and pf^{-} (lagging). The power factor can be adjusted to change the reactive power output. The blue (red) arrow in the figure shows the direction toward an increase (decrease) when more (less) reactive power is injected into the grid. For example, by changing the power factor from θ_1 position to θ_2 position, the reactive power injection increases by ΔQ_{PV} thereby increasing the voltage by $\Delta V>0$. Correspondingly, the active power output decreases by ΔP_{PV}



$$\begin{cases} \Delta P_{PV} = S_{PV}(\cos\theta_2 - \cos\theta_1) \\ \Delta Q_{PV} = S_{PV}(\sin\theta_2 - \sin\theta_1) \end{cases}$$

Figure 1. Smart inverter's real and reactive power.

The reactive power limits of the smart inverters are functions of real PV power, and calculated as follows:

$$Q_{PV}^{MAX} = \min\{P_{PV}\tan(\theta_{MAX}), S_r \sin(\theta_{MAX})\} \text{ : Positive} \quad \textbf{Eq.1}$$

$$Q_{PV}^{MIN} = \max\{P_{PV}\tan(\theta_{MIN}), S_r \sin(\theta_{MIN})\} \text{ : Negative} \quad \textbf{Eq.2}$$

3.2 Existing methods for reactive power control of PV inverters

In the literature, the reactive power control of PV inverters have been studied. Many of them are droop-based controls described as follows:

1) **Constant Q** [Demirok 11] **:**

In this control method, the reactive power output is fixed. The power factor limit and the apparent power limit must be met, therefore the reactive power output must be selected between Q_{PV}^{MAX} and Q_{PV}^{MIN}.

2) **Constant *pf*** [Braun 08, Smith 11, Demirok 11] **:**

In this control method, the power factor is kept constant. Thus, the reactive power output is proportional to the real PV power:

$$Q_{PV} = P_{PV}\tan(\theta) \text{ with } P_{PV} \le S_r.\cos(\theta) \quad \textbf{Eq.3}$$

As seen in **Eq.3** the real power output is bounded. Therefore when PV generation is high, it can be curtailed to maintain constant power factor. This method can be applied when voltage violation is always on one direction (i.e., either undervoltage or overvoltage). For example, in a network with high PV penetration, the voltage is often higher than the acceptable limit.

3) ***pf(P)*** [Demirok 11, Smith 11, Stetz 14, Malekpour 16, Wang 17]:

In some cases, the real PV power can be consumed locally and there is no need to control the reactive power. In these case, the previous control methods fail to drive the reactive power output to zero. In ***pf(P)*** method, the power factor of the inverter is predefined as a piecewise linear function of real power. Therefore, it has the flexibility to decide when to provide reactive power to the grid.

$$pf(P_{PV}) = \begin{cases} pf_1 & \text{if } P_{PV} < P_1 \\ \dfrac{pf_1 - pf_2}{P_1 - P_2}(P_{PV} - P_1) + pf_1 & \text{if } P_1 \le P_{PV} \le P_2 \\ pf_2 & \text{if } P_{PV} > P_2 \end{cases} \quad \textbf{Eq.4}$$

4) ***Q(V)*** [Braun 09, Demirok 11, Smith 11, Stetz 14, Velasco 15, Malekpour 16, O'Connell 17]:

In the above methods, the voltage is regulated indirectly as the reactive power control only takes PV real power as input. This might lead to high control error and in some cases might move the voltage to the wrong direction. In ***Q(V)*** (or volt-var) method, the reactive power output is controlled based on the voltage. The voltage thresholds are often selected based on the voltages at different locations along the feeder.

$$Q_{PV}(V) = \begin{cases} Q_{PV}^{MAX} & \text{if } V < V_1 \\ \dfrac{Q_{PV}^{MAX}}{V_1 - V_2}(V - V_1) + Q_{PV}^{MAX} & \text{if } V_1 \le V \le V_2 \\ 0 & \text{if } V_2 \le V \le V_3 \\ \dfrac{Q_{PV}^{MAX}}{V_3 - V_4}(V + V_3) & \text{if } V_3 \le V \le V_4 \\ -Q_{PV}^{MAX} & \text{if } V > V_4 \end{cases} \quad \textbf{Eq.5}$$

In all of the above methods, the voltage control are open loop and based on a predefined set of rules. The advantage of these methods is their simple implementations. Nevertheless, these controls might need tuning frequently as the PV generation profiles change seasonally and annually. Different methods to optimally choose the droop settings for method 3 and method 4 have been studied in [Smith 11, Demirok 11, Wang 17, O'Connell 17]

Beside the droop-based methods, other methods have also been studied. In [Tanaka 10, Turitsyn 10, Cagnano 11], distributed optimal controls of PV inverters' reactive power was performed to regulate the voltage while minimizing the Ohmic loses of the distribution radial systems. Least square method was used in [Bonfiglio 14] to find the optimal references for PV inverters' reactive control which minimize the differences between real and targeted voltages. [Weckx 14] presented a method which combine centralized and distributed control for PV inverters in unbalanced distribution system. [Kekatos 15] presented a stochastic reactive power management which considered uncertainties and delays in the system states.

4 PROPOSED METHODS FOR VOLTAGE REGULATION SUPPORT USING PV SMART INVERTERS

The aforementioned methods often neglected the power factor limits of the PV inverters. Furthermore, most of them only studied the impact of a single PV inverter on a feeder. In this section, we proposed two control algorithms for voltage regulation through reactive power control of the PV smart inverters. Power factor adjustments and voltage measurements are used to maintain the voltages within a predefined range. Multiple PV systems on a single feeder are also considered in these algorithms.

4.1 Trail-and-error (TnE) method

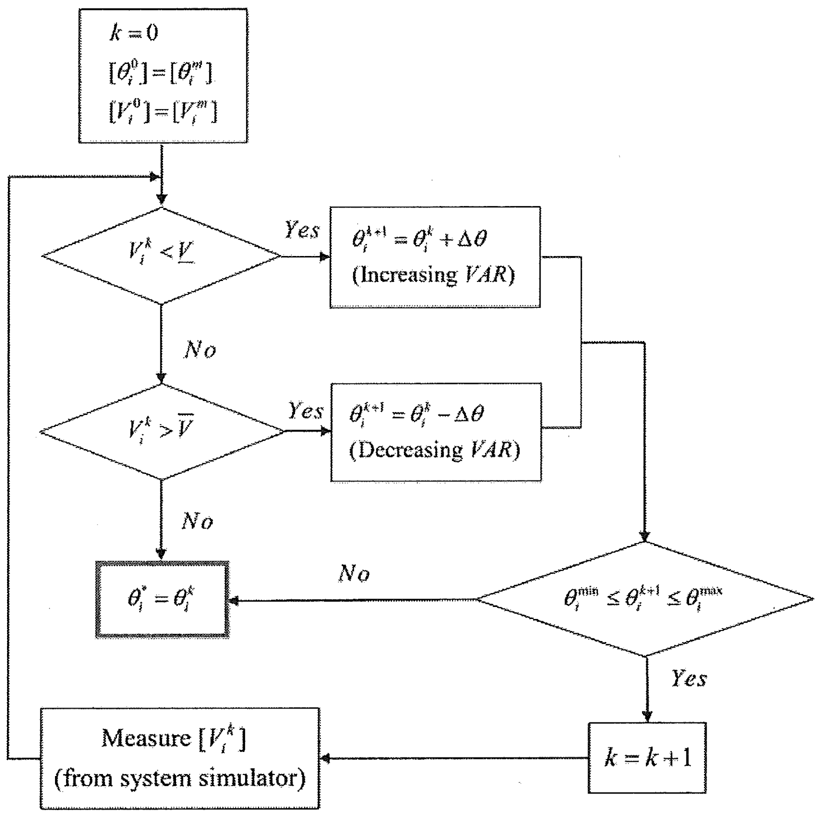


Figure 2. Trail-and-error control algorithm

Figure 2 shows the trail-and-error control algorithm in which voltage measurements are acquired periodically (typically every 5 minutes). The voltage is compared to the limits and the power factor angle is adjusted accordingly to increase or decrease the amount of reactive power injected to the grid. Before sending the power factor reference to the inverter's control, the voltage is estimated by system simulator to ensure the voltage after the power factor adjustment does not violate the limits. The system simulator can be a power flow solver or a sophisticated real time digital simulator.

This algorithm only take the local voltage as the input, therefore it can be used locally without complicated communication system. The drawback of this control method occurs when the voltages at different inverter nodes are strongly dependent such as in a rural network with long feeders. Therefore, this control method should only be applied in the networks where the feeders are short.

4.2 Modified-power-flow (MPF) method

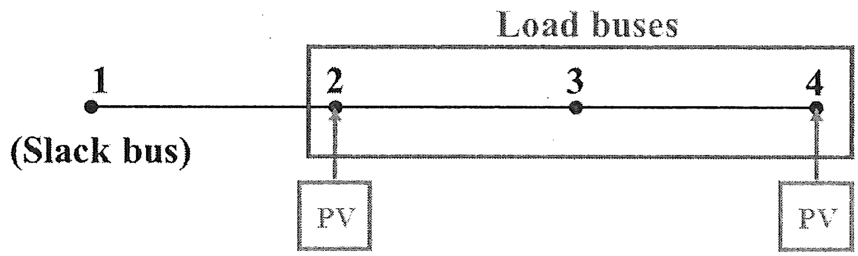


Figure 3. 4-bus example

In this method, the power factor angles of the inverters are introduced into the power flow equations as unknowns. Therefore, a new set of equations are also introduced:

$$\begin{cases} f_P^i = P_i - P_{PVi} + P_{Di} = 0 \\ f_Q^i = Q_i - Q_{PVi} + Q_{Di} = 0 \\ f_V^i = V_i - V_i^* = 0 \end{cases} \Leftrightarrow \begin{cases} f_P^i = P_i(V,\delta) - S_{PVi}\cos\theta_{PVi} + P_{Di} = 0 \ (1) \\ f_Q^i = Q_i(V,\delta) - S_{PVi}\sin\theta_{PVi} + Q_{Di} = 0 \ (2) \\ f_V^i = V_i - V_i^* = 0 \ (3) \end{cases} \quad \textbf{Eq.6}$$

In **Eq. 6** θ_{PVi} are the new variables and (3) is the new set of equations in which V_i^* are the target voltage at bus i where PVi is installed. This equation system can be solved using Newton-Raphson method:

$$\begin{bmatrix} \Delta\delta \\ \Delta V \\ \Delta\theta_{PV} \end{bmatrix}^{(k)} = -\left[J_M^{(k)}\right]^{-1} \begin{bmatrix} f_P \\ f_Q \\ f_V \end{bmatrix}^{(k)} ; \begin{bmatrix} \delta \\ V \\ \theta_{PV} \end{bmatrix}^{(k+1)} = \begin{bmatrix} \delta \\ V \\ \theta_{PV} \end{bmatrix}^{(k)} + \begin{bmatrix} \Delta\delta \\ \Delta V \\ \Delta\theta_{PV} \end{bmatrix}^{(k)} \quad \textbf{Eq.7}$$

where $J_M^{(k)}$ is the augmented Jacobian matrix calculated as follows:

$$J_M^{(k)} = \begin{bmatrix} \frac{\partial f_P}{\partial \delta} & \frac{\partial f_P}{\partial V} & \frac{\partial f_P}{\partial \theta_{PV}} \\ \frac{\partial f_Q}{\partial \delta} & \frac{\partial f_Q}{\partial V} & \frac{\partial f_Q}{\partial \theta_{PV}} \\ \frac{\partial f_V}{\partial \delta} & \frac{\partial f_V}{\partial V} & \frac{\partial f_V}{\partial \theta_{PV}} \end{bmatrix} \quad \textbf{Eq.8}$$

Augmented Jacobian J_M

$$J_M^{13} = \left[\frac{\partial f_P}{\partial \theta_{PV}}\right]_{(Npv+Npq)\times Ninv}$$

$$J_M^{23} = \left[\frac{\partial f_Q}{\partial \theta_{PV}}\right]_{Npq\times Ninv} \quad \textbf{Eq.9}$$

$$J_M^{31} = [0]_{Ninv\times(Npv+Npq)}, J_M^{32} = \left[\frac{\partial f_V}{\partial V}\right]_{Ninv\times Npq}, J_M^{33} = [0]_{Ninv\times Ninv}$$

An illustrative example is shown in Figure 3. The simplified feeder has load buses. The PV inverters are located at bus 2 and bus 4. The variables, equations and Jacobian matrix are formulated as follows:

$$x = \begin{bmatrix} \delta_2 \\ \delta_3 \\ \delta_4 \\ V_2 \\ V_3 \\ V_4 \\ \theta_{PV2} \\ \theta_{PV4} \end{bmatrix} \quad \textbf{Eq.10}$$

$$f = \begin{bmatrix} P_2 - P_{PV2} + P_{D2} \\ P_3 + P_{D3} \\ P_4 - P_{PV4} + P_{D4} \\ Q_2 - Q_{PV2} + Q_{D2} \\ Q_3 + Q_{D3} \\ Q_4 - Q_{PV4} + Q_{D4} \\ V_2 - V_2^* \\ V_4 - V_4^* \end{bmatrix} \quad \textbf{Eq.11}$$

$$J_M^{13} = \left[\frac{\partial f_P}{\partial \theta_{PV}}\right]_{3\times2} = \begin{bmatrix} S_{PV2}\sin\theta_{PV2} & 0 \\ 0 & 0 \\ 0 & S_{PV4}\sin\theta_{PV4} \end{bmatrix}$$

$$J_M^{23} = \left[\frac{\partial f_Q}{\partial \theta_{PV}}\right]_{3\times2} = \begin{bmatrix} -S_{PV2}\cos\theta_{PV2} & 0 \\ 0 & 0 \\ 0 & -S_{PV4}\sin\theta_{PV4} \end{bmatrix} \quad \textbf{Eq.12}$$

$$J_M^{31} = [0]_{2\times3}, J_M^{32} = \left[\frac{\partial f_V}{\partial V}\right]_{2\times3} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, J_M^{33} = [0]_{2\times2}$$

Figure 3 shows the MPF control algorithm in which load and system states are given as inputs at each time period. The inverters start at unity power factor. Voltages at the initial step can be measured or calculated using a regular power flow solver. The target voltages are adjusted if any of the inverter voltages are out of range and the MPF is run to find the inverters' power factor angles. If the power factor at an inverter node reaches its limit, this power factor angle will eliminated from the MPF equations. The process is iterated until all voltages are within acceptable range or all power factors reach their limits.

This method required a communication system to collect measurements and send command signals to the inverters. In this project, we propose the use of VOLTTRON platform for this purpose. Load, weather, and system information are sent to the control center where high-performance computers calculate the control references and send the command signals to all devices. The latency of the communication might impact the optimal operation of the system. However, it is not considered in this project.

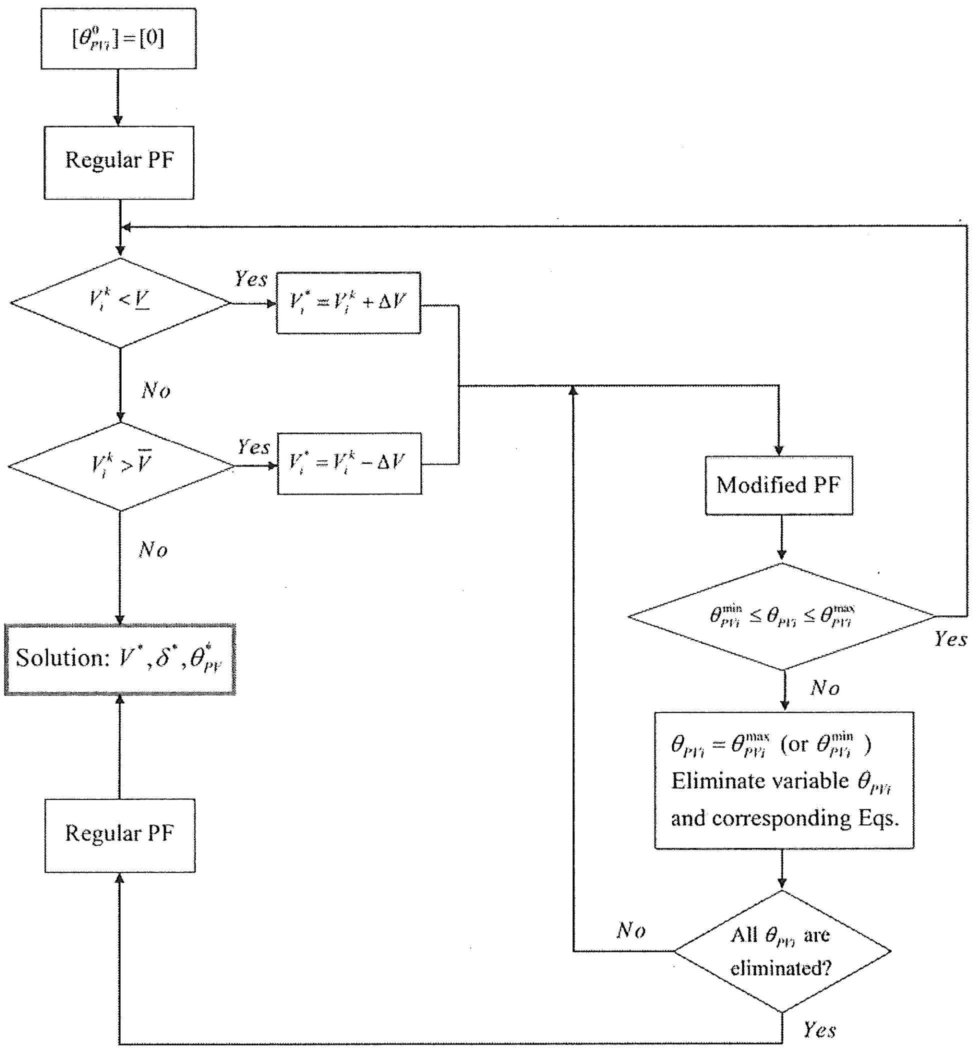


Figure 4. MPF control algorithm

5 A CASE STUDY FOR UW DISTRIBUTION NETWORK

5.1 Input data

In this section, we investigate feeder WD8 of UW distribution network where three PV systems are installed. The feeder is modelled in Gridlab-d and Matlab. The MPF algorithm is implemented in Matlab with Matpower 6.01b. To better evaluate the feasibility of the proposed method, the capacities of the three PV systems are assumed to be five larger than their design values. Each PV system is equipped with smart inverters with power factor adjustable within 0.7 leading and 0.7 lagging. Load and weather data are imported from historical data of May-01-2016. Voltage acceptable range is assume to be [0.99,1.01]

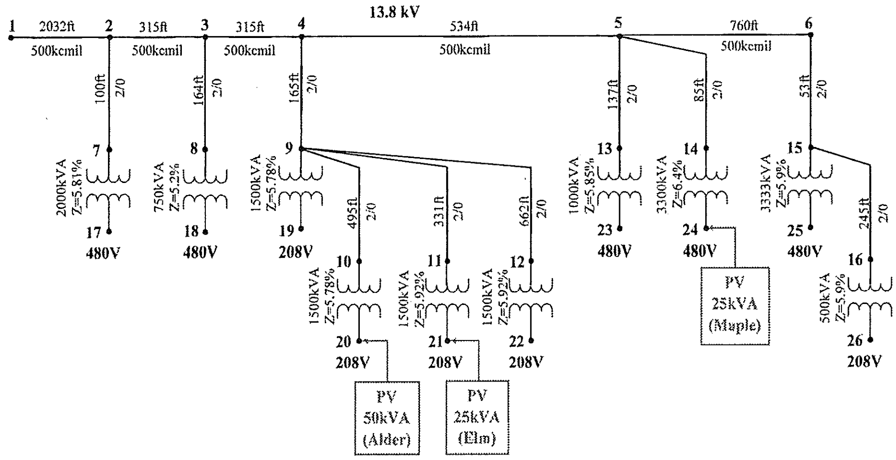


Figure 5. WD8 feeder

5.2 Results

The results for bus 20 are shown in Figure 6, 7, 8, 9.

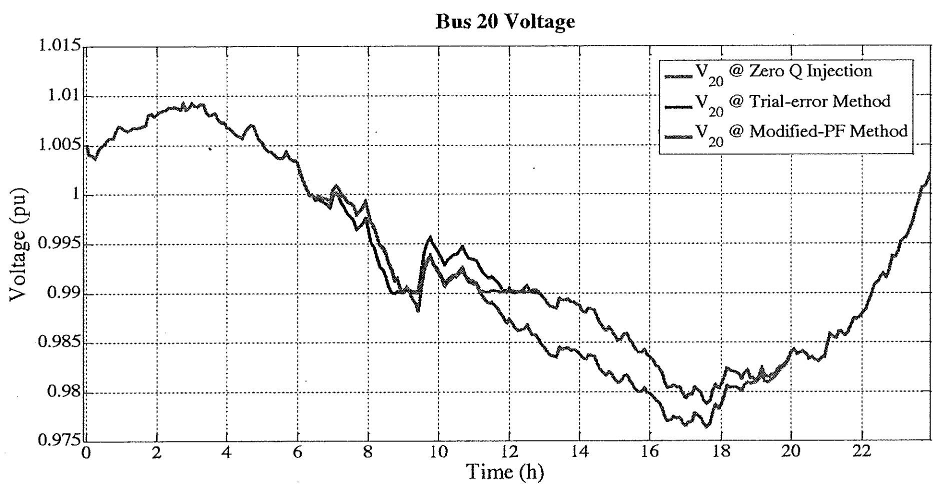


Figure 6. Voltage profile of bus 20.

As seen in the figures, the control methods are successful only when PV generation is high. In this case the power factor limits of the inverters only allow to provide as much reactive power as the real power. Therefore, when there is no or low PV generation the voltage regulation support from the inverters is not effective. It is also observed that the real power output is reduced significantly during peak sun in order to inject reactive power to the grid.

The reactive power output from the MPF method is just enough to keep the voltage inside the acceptable range when possible. This is to maximize the PV real power output. On the other hand, The TnE method utilizes the reactive power capability of the inverters. When the PV generation is low the solutions of the two methods are the same because the power factor angle reaches it limits.

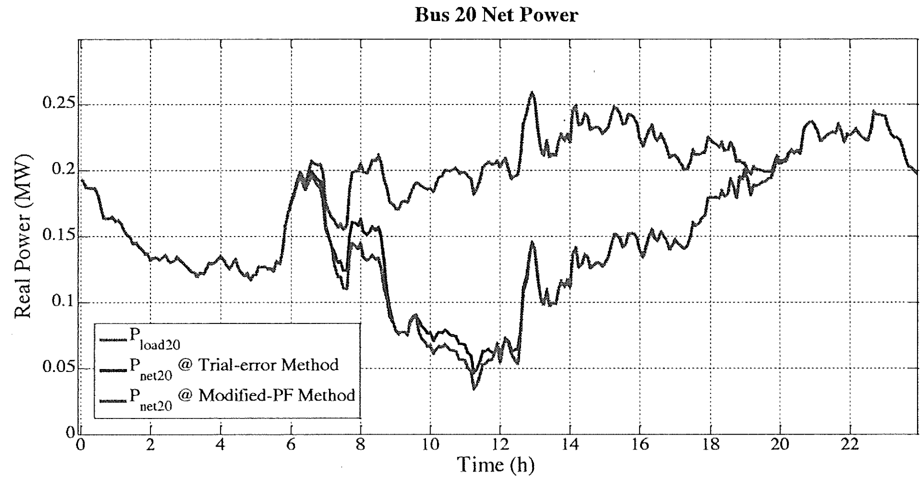


Figure 7. Active power profile of bus 20.

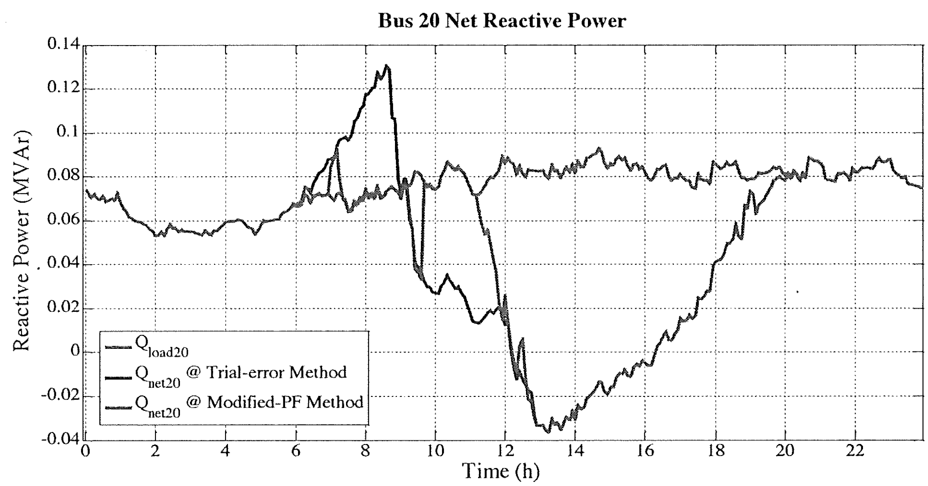


Figure 8. Reactive power profile of bus 20.

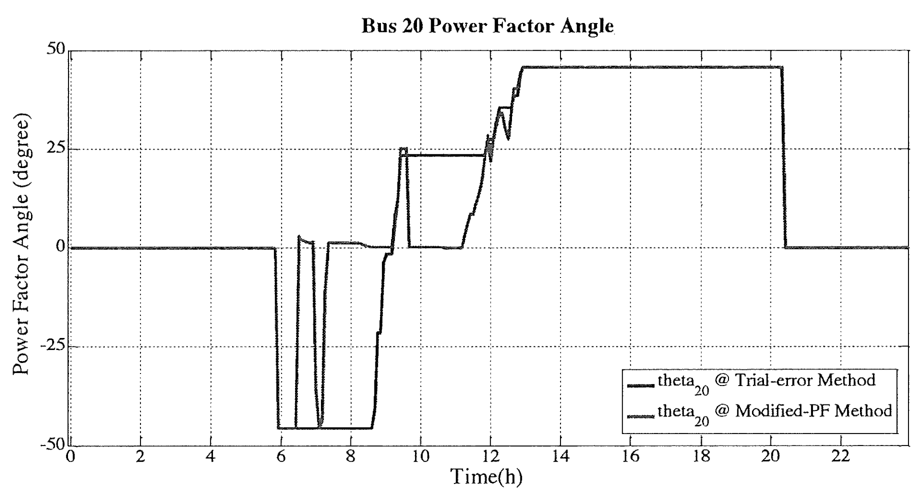


Figure 9. Power factor angle at bus 20.

6 Conclusions

In this report, current practices for voltage regulation have been described. The reactive power capability of PV smart inverters and existing control methods have been reviewed. In this work, we proposed two algorithms for voltage regulation support using PV smart inverters. A case study is conducted to investigate a feeder in UW distribution network. The results show the feasibility of the proposed methods. Future work in this area would involve the integration of energy storage systems to utilize the reactive power capability of PV inverters.

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