การควบคุมกำลังไฟฟ้ารีแอคทีฟของอินเวอร์เตอร์เพื่อลดผลกระทบการเปลี่ยนแปลงแรงดัน
เนื่องจากการผลิตไฟฟ้าจากเซลล์แสงอาทิตย์

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REACTIVE POWER CONTROL OF INVERTER FOR REDUCING VOLTAGE DEVIATION DUE TO SOLAR PV GENERATION

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A Thesis Submitted in Partial Fulfillment of the Requirements
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อูดายา เอท : การควบคุมกำลังไฟฟ้ารีแอคทีฟของอินเวอร์เตอร์เพื่อลดผลกระทบการเปลี่ยนแปลงแรงดันเนื่องจากการผลิตไฟฟ้าจากเซลล์แสงอาทิตย์ (REACTIVE POWER CONTROL OF INVERTER FOR REDUCING VOLTAGE DEVIATION DUE TO SOLAR PV GENERATION) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ศ. ดร.บัณฑิต เอื้ออาภรณ์, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: ผศ. ดร.สุรชัย ชัยทัศนีย์, 56 หน้า.

การผลิตไฟฟ้าจากพลังงานหมุนเวียนได้รับความนิยมเป็นอย่างมากในปัจจุบัน เนื่องจากสามารถช่วยลดการปลดปล่อยก๊าซ CO_2 ได้ นอกจากนี้ ได้มีการประยุกต์พลังงานหมุนเวียนเป็นแหล่งพลังงานของการผลิตไฟฟ้าแบบกระจายตัว (Distributed Generation: DG) ซึ่งสามารถใช้เพื่อวัตถุประสงค์ที่แตกต่างกันได้ เช่น การเป็นแหล่งผลิตไฟฟ้าสำรองเพื่อใช้ในกรณีฉุกเฉิน การลดการสูญเสียทางไฟฟ้า การเพิ่มความเชื่อถือได้ของระบบไฟฟ้า และ การชะลอการขยายระบบส่งและระบบจำหน่าย เป็นต้น อย่างไรก็ตาม การผลิตไฟฟ้าแบบกระจายตัวประเภทพลังงานหมุนเวียนโดยเฉพาะอย่างยิ่งระบบผลิตไฟฟ้าจากเซลล์แสงอาทิตย์ (Photovoltaic Generation: PV Generation) ซึ่งมีการจ่ายกำลังไฟฟ้าที่ไม่แน่นอนขึ้นอยู่กับความเข้มแสงอาทิตย์และอุณหภูมิแวดล้อม ความไม่แน่นอนในการจ่ายกำลังไฟฟ้านี้จะส่งผลกระทบต่อการทำงานของระบบไฟฟ้าได้ วิทยานิพนธ์ฉบับนี้มีวัตถุประสงค์ 3 ประการ ได้แก่ 1) การสำรวจกำลังไฟฟ้าจริงที่ผลิตได้ของระบบผลิตไฟฟ้าจากเซลล์แสงอาทิตย์ เมื่อความเข้มของแสงอาทิตย์และอุณหภูมิเปลี่ยนไป 2) การหาตำแหน่งในการติดตั้งระบบผลิตไฟฟ้าจากเซลล์แสงอาทิตย์ในระบบจำหน่ายไฟฟ้าอย่างเหมาะสม และ 3) การคำนวณหาค่ากำลังไฟฟ้ารีแอกทีฟจากอินเวอร์เตอร์ที่เหมาะสมเพื่อทำให้แรงดันไฟฟ้าของระบบดีขึ้นเมื่อกำลังไฟฟ้าจริงนั้นเปลี่ยนแปลงไป

ในทางปฏิบัตินั้นเมื่อแรงดันไฟฟ้าเปลี่ยนไปจนกระทั่งละเมิดพิกัด อินเวอร์เตอร์สามารถที่จะจ่ายหรือรับกำลังไฟฟ้ารีแอกทีฟเพื่อแก้ปัญหาการละเมิดดังกล่าวได้ ค่ากำลังไฟฟ้ารีแอกทีฟจะถูกคำนวณอย่างเหมาะสมเพื่อที่จะลดการเบี่ยงเบนของแรงดันไฟฟ้าของทุกบัสให้น้อยที่สุดด้วยวิธีการคำนวณการไหลของกำลังไฟฟ้าของนิวตัน-ราฟสัน ร่วมกับการใช้ดัชนีความไวของระบบ (Sensitivity Index) วิทยานิพนธ์ฉบับนี้ได้ทำการทดสอบวิธีการที่นำเสนอในระบบไฟฟ้า IEEE 33 บัส เพื่อวิเคราะห์ผลการเบี่ยงเบนของแรงดันไฟฟ้าในกรณีต่างๆ

ภาควิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อ อ.ที่ปรึกษาหลัก	....
ปีการศึกษา	2557	ลายมือชื่อ อ.ที่ปรึกษาร่วม	....

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KEYWORDS: DISTRIBUTION SYSTEM, VOLTAGE PROFILE, PV PLANT, VOLTAGE DEVIATION, OPTIMAL REACTIVE POWER

OUDAYA ETH: REACTIVE POWER CONTROL OF INVERTER FOR REDUCING VOLTAGE DEVIATION DUE TO SOLAR PV GENERATION. ADVISOR: PROF. BUNDHIT EUA-ARPORN, Ph.D., CO-ADVISOR: ASST. PROF. SURACHAI CHAITUSANEY, Ph.D., 56 pp.

Nowadays the electrical generation from renewable energy is extensively promoted because of the concern about greenhouse gas emission. Distributed Generation (DG) can be powered by a variety of renewable energy resources, and can be used for various objectives, for example, reduction of voltage sage, reliability improvement, and the possibility of deferral of the upgrading process of transmission and distribution infrastructure. However, the presence of PV system may have detrimental impacts on the operation of a distribution network because of the variation of solar radiation and ambient temperature. This thesis covers the following three issues 1) Evaluation of active power from PV system related to sunlight and temperature variation 2) Determination of connecting locations for PV system and 3) Calculation of optimal reactive power from inverter to improve voltage profile when active power changes.

In practice, when the voltage changes and exceeds the limits, the inverter of PV system can inject or absorb reactive power to correct the voltage deviation. The optimal reactive power is calculated to minimize voltage deviation of all buses by the proposed method based on Newton-Raphson load flow and sensitivity index. The IEEE 33 bus test system is selected to analyze the voltage deviation in various conditions.

Department:	Electrical Engineering	Student's Signature	....
Field of Study:	Electrical Engineering	Advisor's Signature	....
Academic Year:	2014	Co-Advisor's Signature	....

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Finally, I also would like to express my gratitude to my beloved parents: Mr Borann Eth and Mrs Vanny Chhay, my beloved brother: Mr Ou Dalina Eth for their support and unconditional love throughout my study

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CHAPTER I
INTRODUCTION

1.1 Motivation

Due to the limitation of fossil fuel resources, the growing energy demand and the concerns of greenhouse gas emission in the future, application of renewable energy resources have been extensively promoted. Particularly, application of distributed generation (DG) from renewable energy resources, e.g. wind, solar photovoltaic (PV), biomass, hydroelectric connected to the feeder in distribution system increases continually. In Thailand, solar PV is a huge potential resource of renewable energy. Obviously, some benefits of DG are the emergency backup during sustained utility outages, reduction of voltage sage, loss and harmonics, reliability improvement and the possibility of deferral of the upgrading process of transmission and distribution infrastructure. However, the present of solar PV may have detrimental impacts on the operation of a distribution network. Because of alternative of radiation and temperature in the weather, solar PVs might be a reason of transient stability, high fault current, protection mis-coordination and islanding.

The size and location of solar PVs depend on energy resource and how much the available capacity of the connected system is. There are various applications of PV solar systems, e.g. stand alone, integration with energy storage, building integrated photovoltaic system and power production. In order to synchronize the solar PV system to feeder system, it is usually to be combined with power electronics of advanced technology, e.g. inverters, rectifiers. Therefore, while improving the quality of DG and generated electricity, the voltage profile may face a serious problem. Evidently, voltage deviation always fluctuates because of the contribution of several DG sources and the natural variation of sun light. When the allowable voltage range is violated or the fluctuation limit is exceeded, power quality will be degraded. In some serious cases, the violation may result in disconnection of DGs and activating voltage protection relays to trip and to reduce the reliability index of the whole system as a consequence.

In order to evaluate the impact of solar PVs on voltage, it is essential to consider the operating modes of the power inverter unit. It is well known that when the voltage changes and exceeds the limits, the inverter can inject or absorb reactive power to correct the violation. In this case, an appropriate amount of reactive power from inverter should be determined while reducing the inconvenience for the operation of the inverter. In a real inverter, there are many modes to control reactive power for meeting the requirement of utility operators. The study in this thesis is performed to take those modes into consideration. Fortunately, with a suitable operating condition, PV generators do not much adversely affected system reliability and can possibly help increase the performance of protection coordination devices.

1.2. Research Objectives

The objectives of this research are described as follows:

1. To investigate how the active power from PV system varies with sunlight and temperature,
2. To determine the location of PV for connecting to a given distribution system,
3. To calculate optimal reactive power from inverter to improve voltage profile when active power changes due to variation of sunlight and temperature, and
4. To calculate and discuss the impacts of inverter on voltage profile in the system

1.3. Scope of research

The scope of this research is limited to the following issues.

1. Model of PV modules is based on the well-known single-diode five-parameter model with consideration of radiation and temperature variation,
2. Power from inverter is assumed to be the power from solar PV generator,
3. Solar PV connected bus is treated as a PQ bus, i.e. generating both active power and reactive power.
4. Impacts of solar PV active power variation on voltage profile are analyzed according to steady state analysis and an inverter operation mode, i.e. reactive power injection.

1.4. Methodology

1. Reviewing literature on background knowledge relevant to photovoltaic model and inverter
2. Modeling of PV module
3. Calculating voltage in case of steady state condition in grid-connected photovoltaic using load flow analysis
4. Proposing a method to determine the optimal reactive power in case of active power change
5. Analyzing the impacts of voltage profile with and without inverter

1.5. Expected Contribution

This research is anticipated to provide useful background knowledge on the impact of operating modes of inverter, i.e., reactive power support of inverter on voltage profile during steady state condition. In case of an inverter in operation, it can improve the voltage by injecting or absorbing reactive power to the grid. Consequently it can increase the quality and reliability in the system.

CHAPTER II
BACKROUND KNOWLEDGE

2. 1 Photovoltaic Generation

Photovoltaic (PV) is a direct transformation to convert solar radiation into electricity and based on the photovoltaic effect, which was first observed by Henri Becquerel in 1839 [1] . A key application in the beginning was power supply in space vehicles. In general, countries along the equator can get benefit from their high solar energy. This is the reason that solar photovoltaic attracts a lot of attention in the tropical region. Today PV is a rapidly emerging renewable energy technology for residential and large-scale commercial applications. There are many advantages of solar PV. Especially, there is no mechanical moving parts, no high temperatures, no pollution, long lifetime and free energy resource.

2.1.1 Photovoltaic cell and its characteristic

Photovoltaic cells are mostly made of special materials called semiconductors, e.g. silicon, which has a certain ability to absorb sunlight. It means that all energy of the absorbed sunlight is transferred to the semiconductor. The energy knocks electrons loose, allowing them to flow freely. This flow of electrons is called current and it can draw that current off to use externally by placing metal contacts on the top and bottom of the PV cell. The basic structure of photovoltaic is shown in Fig. 1. The glass cover plate (A) protects the cell from the elements; B is antireflective coating that is applied to the top of the cell to reduce reflection losses to less than 5 percent; C and F are contact grid, and back contact, use for current flow; D and F are N-type and P-type silicon [2].

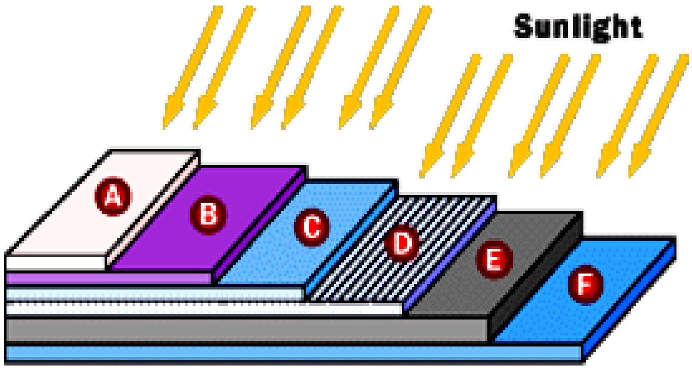
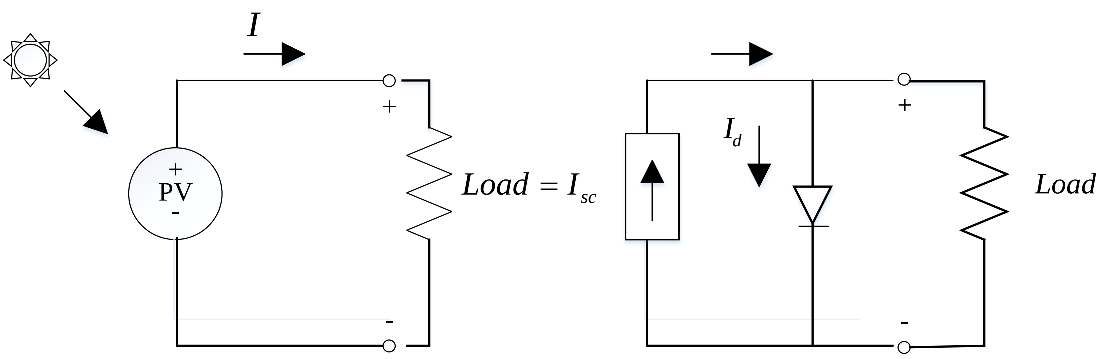


Figure 1 Basic structure of silicon PV Cell [2]

Modeling is a basic tool for simulating a real system. Regarding the photovoltaic system modeling, it is necessary to analyze the influence of different factors on the photovoltaic cells and to consider the characteristics given by manufacturers. Mathematical models of PV arrays are based on the theoretical equations that describe the functions of the PV cells. They can be established using the equivalent circuit of the PV cells [2].

A simple equivalent circuit model of a photovoltaic cell that consists of a real diode in parallel with an ideal current source is shown in Figure 2. Two actual PV characteristics are the short-circuit current, I_{sc}, and the open-circuit voltage, V_{OC}.



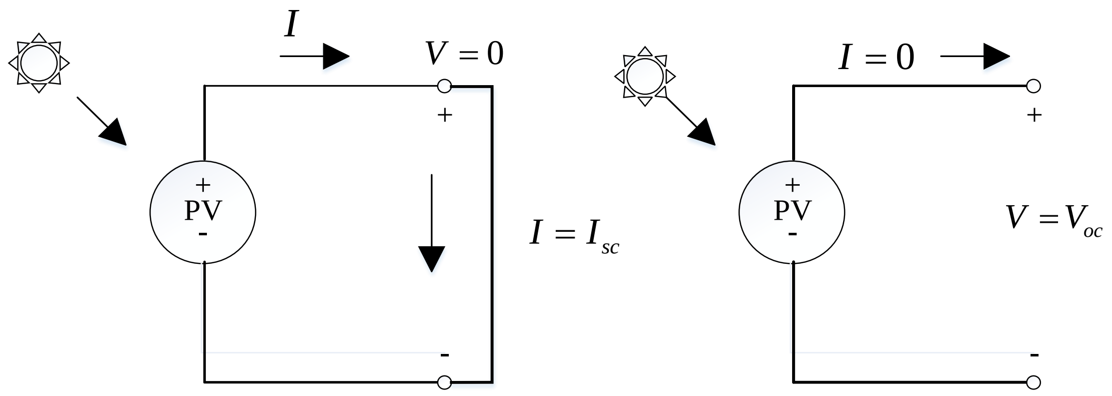


Figure 2 Simple equivalent circuit for PV cell

The characteristic of I_{sc} and V_{oc} can be derived as (1)-(3).

$$I = I_{sc} - I_d \tag{1}$$

$$I_d = I_0(e^{q\frac{V_d}{nkT}} - 1) \tag{2}$$

$$I = I_{sc} - I_0(e^{q\frac{V_d}{nkT}} - 1) \tag{3}$$

where I_{sc} is the photocurrent, a function of irradiation level and junction temperature (A)

I : Cell output current (A)

I_0 : Reverse saturation current of diode (A)

V_d : diode voltage (V)

q: Electron charge (Coulomb)

k : Boltzmann constant (J/$^\circ K$)

n : Diode quality factor, it takes a value between 1 and 2

Under the short-circuit condition, terminal voltage of PV cell is equal to zero. So, I is equal to I_{sc}. In contrast, I is equal to zero under the open-circuit condition. Therefore, the open-circuit voltage can be given by (4).

$$V_{oc} = \frac{nkT}{q}\ln(\frac{I_{sc}}{I_0} + 1) \tag{4}$$

It is worth noting that the second term in the equation (1) is just the diode equation with a negative sign. The curve of current–voltage relationship for a PV cell for no sunlight “dark”, and for an illuminated cell “light” shown in Figure 3 [2].

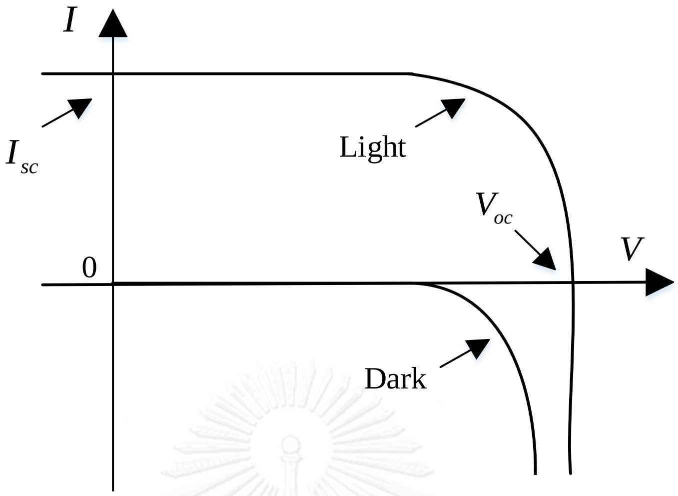


Figure 3 Curve of current–voltage relationship for a PV cell

Some PV cells are wired in series or string to form a PV module. In this case, any cells in that string is in the dark will be considered as shaded cells. Therefore, to improve the accuracy of PV cell equivalent circuit, the parallel or series resistance is added into the PV cell equation shown in Figure 4 and 5 [2]. A modification of PV equivalent circuit by adding parallel resistance, R_p, can cause the current at any given voltage to drop by *V/R* as shown in Figure 6 [2]. Where the adding series resistance, R_s, can cause the voltage at any given current to be shifted to the left by $\Delta V = IR_s$ as shown in figure 7.

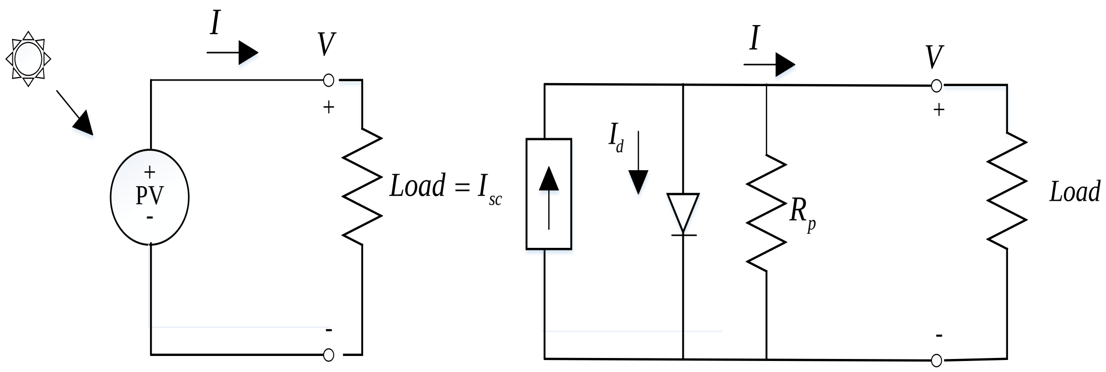


Figure 4 Modification of PV equivalent circuit by adding parallel

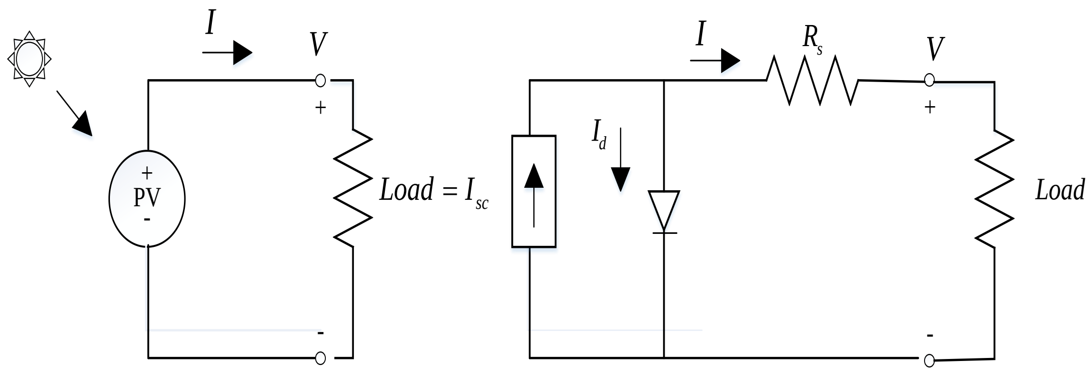


Figure 5 Modification of PV equivalent circuit by adding series resistance

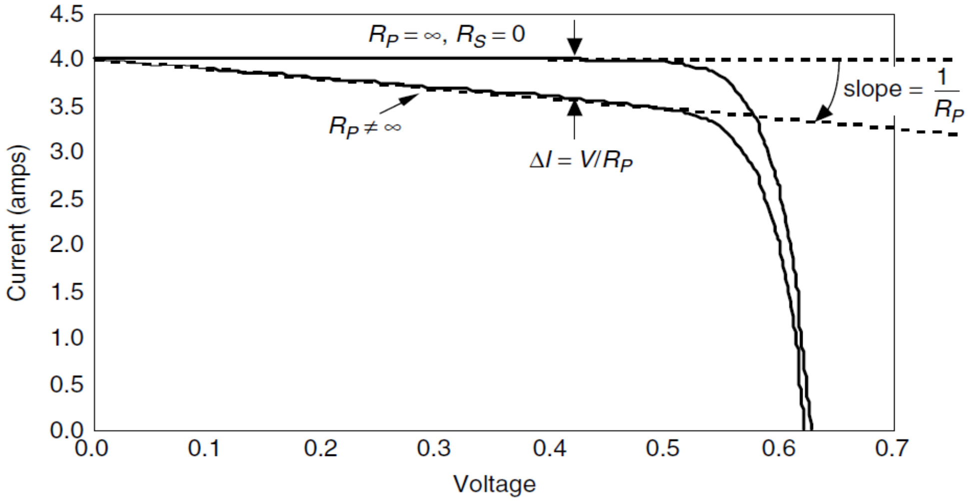


Figure 6 Curve of I-V characteristic of a PV cell by adding parallel resistance [2]

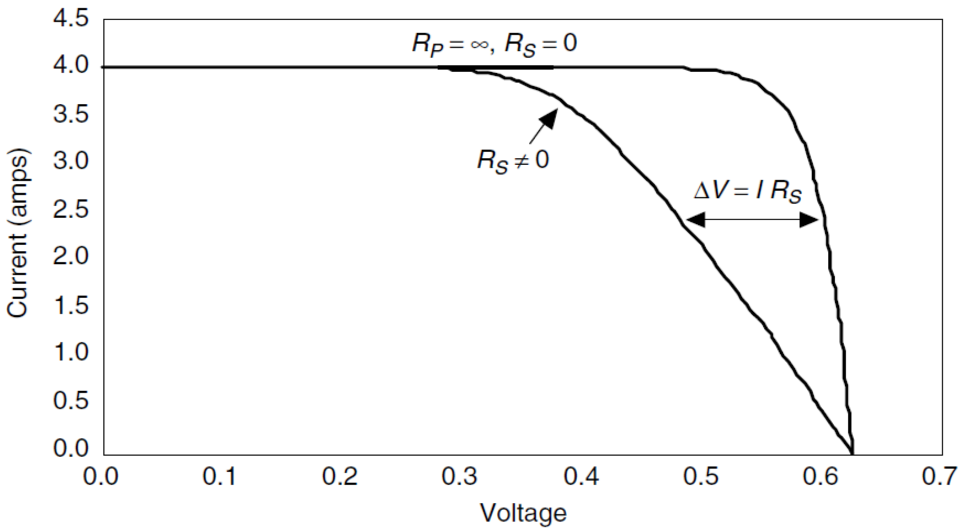


Figure 7 Curve of I-V characteristic of a PV cell by adding series resistance [2]

According to Figure 6, the equation (3) by adding parallel resistance can be derived as (5).

$$I = I_{sc} - I_0(e^{q\frac{V_d}{nkT}} - 1) - \frac{V}{R_p} \quad (5)$$

And the modification of equation (3) by adding series resistance can be also derived as (6).

$$I = I_{sc} - I_0(e^{q\frac{V+I.R_s}{nkT}} - 1) \quad (6)$$

2.1.2 Photovoltaic Module and Array

Replying to the voltage and current requirement in an application system, the PV cells are wired in series to increase the voltage and parallel to increase the current shown in Figure 8 and Figure 10, respectively [2]. A combination of PV cell in both series and parallels is called a PV module, and a combination of PV module in series and parallels is known as an array as shown in Figure 12.
To avoid the shading problem in the PV array, the bypass diode is adding in parallel with each module. In practice, it may not practical to add bypass diodes across every solar cell. Instead, manufacturers may provide at least one bypass diode around a module to help protect arrays or several such diodes around groups of cells within a module. These diodes do not have much impact on shading problems of a single module, but they can be very important when a number of modules are connected in series as shown in Figure 13 [2].

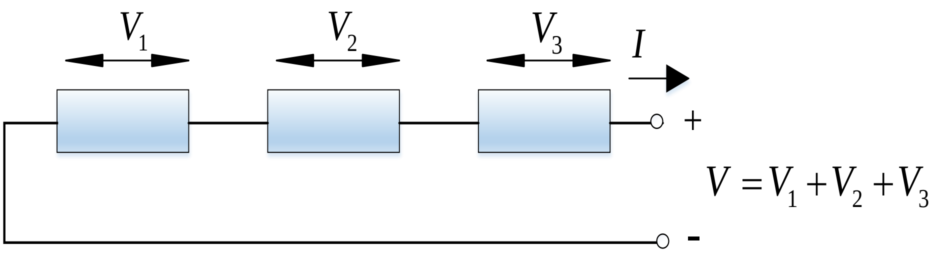


Figure 8 PV module connection in series

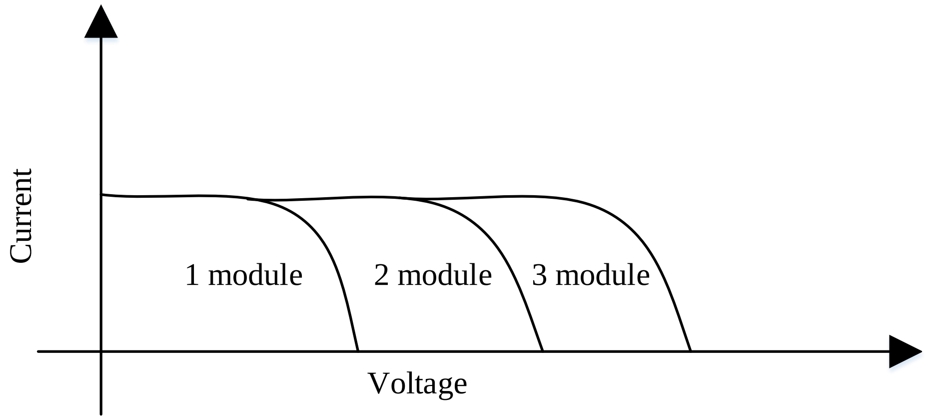


Figure 9 Curve of I-V characteristic by wiring in series

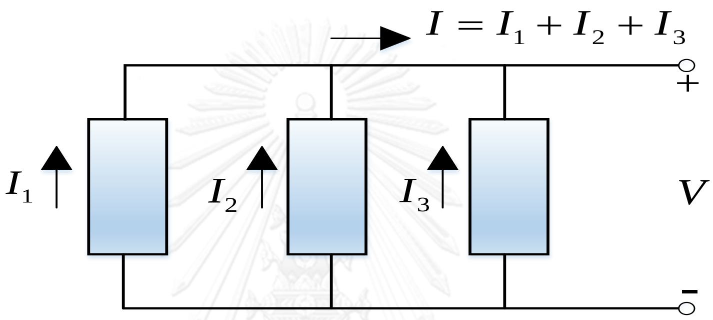


Figure 10 PV module connection in parallels

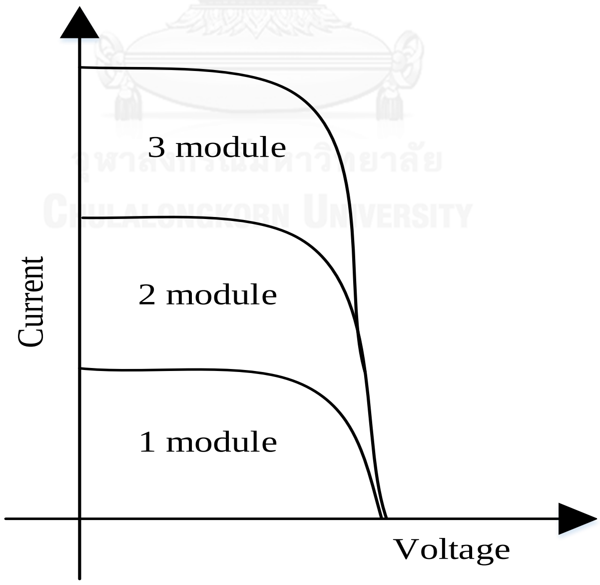


Figure 11 Curve of I-V characteristic by wiring in parallels

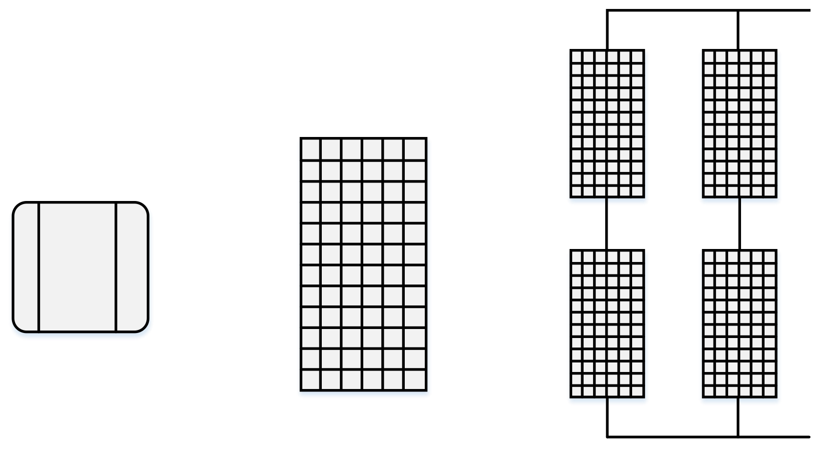


Figure 12 PV cell, module, and array

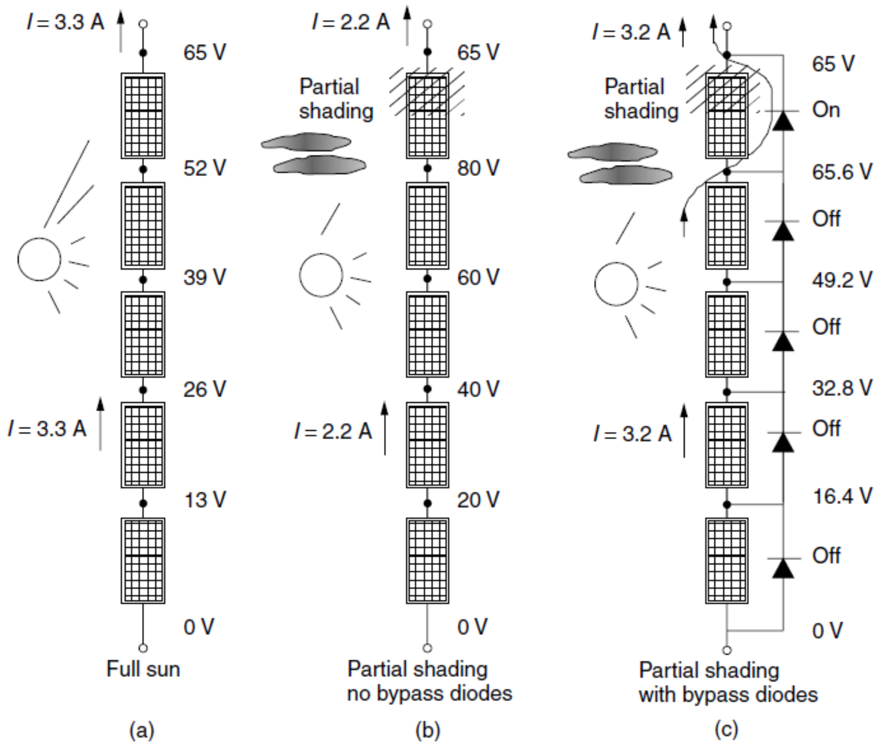


Figure 13 Shading with and without bypass diode [2]

2.2 Inverter characteristic

Today, power electronics (PE) plays a significant role in distributed energy resource system because they make utility grid interconnection possible for a wide variety of energy sources. In fact, the inverter is really important in PV system. The basic function of this device is to transform the generated DC power into the standard AC current before delivering to utility grids or can be used to couple DC or variable-frequency power sources to the grid [3]. PV inverters are ready to be fully integrated in a smart grid and they are among the smartest devices in the grid. There are three main reasons for this statement [4]:

- Advanced grid features
- Communication
- Future-proof

2.2.1 Advanced grid features

Inverters with their fast and flexible internal control mechanism can be implemented with many functions for supporting system stability. Some functions are for prevent grid problems and therefore can prevent outages. It is really possible to install a lot more PV systems without grid enforcement than it would be without such features. In this research, voltage profile improvement is a main purpose. Normally, voltage in the LV systems is different at any location and in each phase as well. In this case, inverter cannot cause harmful overvoltage because it has the internal interface to protect or disconnect the inverter at that moment to reach a limit. But this disconnection can cause a loss in production for existing PV plants. Inverters also have several possibilities to influence the voltage without losing energy. Actually, inverter characteristic can be simply a reactive power supporter to regulate voltage in any conditions.

There are several methods to control the reactive power. The simplest ways are fixing the displacement factor $\cos(\varphi)$ at the optimal value and voltage-dependent reactive power control functionality. In a combination with communication, these local control functions can be useful during operation. It is possible that even the most complicated reactive power control modes are not enough to guarantee the voltage within the limits. Especially in low voltage grid, active power is the biggest influence on the voltage. Therefore, the influence of active power supply from PV inverter into the grid can prevent from over limit [4]. Typically, the problem of overvoltage is for some moments of days with very high irradiation and peak off load at the same time.

In this case, a smart inverter can reduce losses of produced power from over voltage by absorbing reactive power without disconnection from the grid.

In a grid-connected photovoltaic system, the inverter has a capability of providing reactive power to the grid in addition to the active power generated by the PV cells. In addition, the fast responding speed helps the inverter inject/absorb the reactive power in case of rapid voltage changes. It follows that the inverter can supply positive and negative reactive power. A representation of determining reactive power of inverter is demonstrated by Figure 14. Consequently, the inverter is used as entire rating to supply reactive power if no active power is generated. An advantage compared to a fixed capacitor is that it can vary the supplied reactive power immediately. The maximum reactive power that can be extracted from an inverter is represented by (7) [5]-[6]:

$$\left|q^{pv}\right| \leq q_{\max}^{pv} = \sqrt{\left(S_{\max}^{pv}\right)^2 - \left(p^{pv}\right)^2} \tag{7}$$

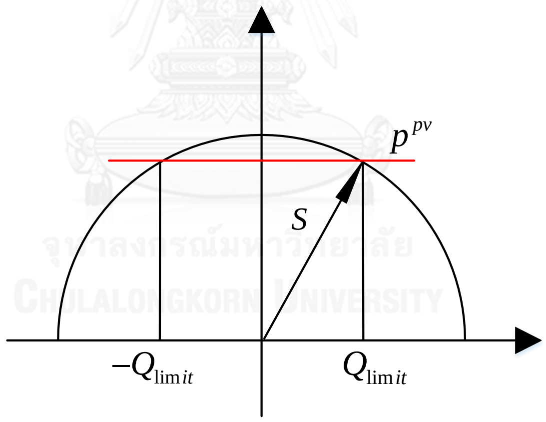


Figure 14 The inverter’s reactive power limits [5]

Obviously, active power p^{pv} depends on solar irradiation. In case the active power output is completely interrupted, i.e., p^{pv}=0, the inverter is capable of generating a maximum reactive power of $S_{\max}^{pv}$. In addition, within that range, the inverter can control the reactive power arbitrarily in a time scale of milliseconds which is much faster than that the utility’s voltage regulation devices. In fact, an inverter can be oversized 10% [7] of apparent power so that $S_{ov} = 1.1 p_{\max}^{pv}$. Thus, even at the maximum active power output mode, the inverter can change reactive power within 46% of the capacity.

In a real inverter, there are many modes to control reactive power for meeting the grid management requirements.

Table 1 shows an example of the operating mode of Sunny Central inverter to control reactive power in difference conditions. There are eleven different modes of reactive power control [8].

Table 1 Difference modes of reactive power control of SMA inverter [8]

Mode	Description
off	The reactive power setpoint is limited to 0 kVAr
VArCtlCom	The reactive power setpoint is transmitted by Modbus protocol to the Sunny Central via the Power Reducer Box or the Power Plant Controller.
PFCtlCom	The reactive power setpoint is transmitted to the Sunny Central via the Power reducer Box or the power Plant Controller. A displacement power factor cos φ is transmitted as the setpoint.
VArCnst	The parameter Q-VAr is used to set the reactive power setpoint in kVAr
VArCnstNom	The parameter Q-VArNom is used to set the reactive power setpoint in % relative to Pmax.
VArCnstNomAnIn	The reactive power setpoint is imported via an analog input. The analog value is converted into a reactive power setpoint
PFCnst	The reactive power setpoint is set via a displacement power factor cos φ.
PFCnstAnIn	The reactive power setpoint is imported via the analog input for setpoint specification. The analog value is converted into a displacement power factor cos φ.
PFCtlW	The displacement power factor cos φ is set as a function of the feed-in power. This dependency is depicted by a configurable characteristic curve

VArCtlVol	The reactive power is configured as a function of the line voltage
VArCtlVolHystDb	The provision of reactive power helps perform voltage-stabilizing measures in the event of overvoltage or undervoltage. The parameterization is carried out by means of a reactive power/voltage characteristic curve.

The main point of control reactive power in this issue is to improve voltage profile in the system. The Volt-Var function control is considered to define the response of inverter based on the voltage levels. To understand clearly about Volt-Var behavior, one example of a Volt-Var curve is shown in Figure 15.

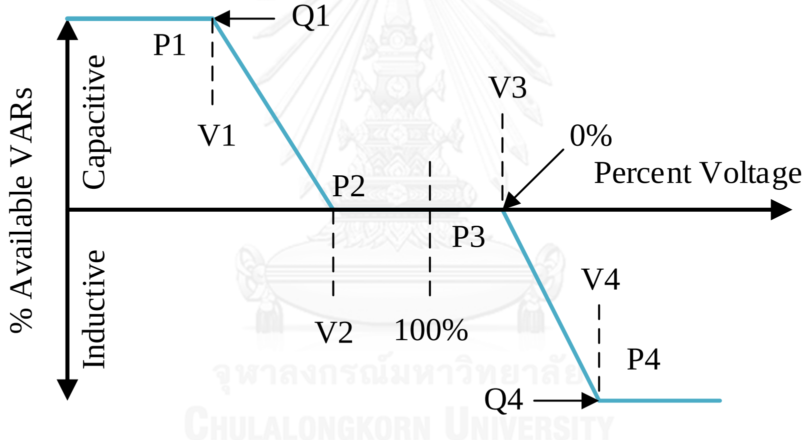


Figure 15 Volt-Var setting Curve [9]

The Volt-Var curve in Figure 15 defines the percentage of available reactive power output level (y-axis) which is determined by the present active power output and inverter apparent power output level.

This curve shows that the percentage of available reactive power output is a function of the voltage at the interconnection point of the grid and the inverter. The voltage (x-axis) is defined as percentage of the normal system voltage rating in the period of time. When the voltage is under the limit, the inverter has to inject reactive power to increase the voltage to within the normal operating range. On the other hand, the inverter has to absorb reactive power when the voltage is over the limit. Actually, the maximum permissible of voltage deviation from normal system voltage at PCC is typically 5% and this is service voltage limits of ANSI C84.1-2006 [10]-[11]. The method to calculate the optimal value is considered later.

2.2.2 Communication

Actually, communication is necessary in smart grid systems. PV inverters are most flexible with communication. There are 2 ways of communicating PV inverters such as those proposed in [4] . Information of inverter can be sent to a control center or an automatic grid controller. In this case, the actual voltage or power at the inverter terminals can help to evaluate the actual situation of the grid and allow measurement.

In any temporary network restrictions, the power output of a PV system can be required to any value. Thus, any reactive and active power set point can be set via communication to reach the limit immediately. There are many types of inverter and the ways of communication for those inverters are also little different.

For example, the following diagram illustrates how the specifications of the grid operator are implemented. The power reducer box or power plant controller sends the specifications of the grid operator to the Sunny Central.

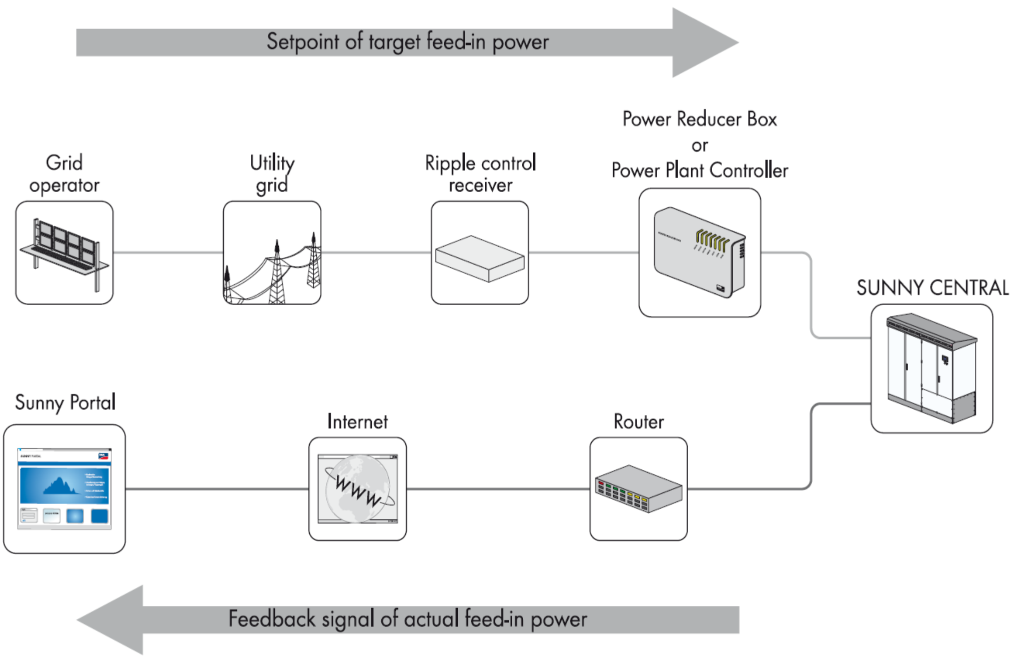


Figure 16 Principle of grid integration [8]

In order to connect the Sunny Central to a computer via the service interface or via the internet the Sunny Central must be integrated in a system network. To enable several Sunny Central inverters in the same network, each Sunny Central has to be assigned unique network address. The following diagram shows the integration of each inverter to computer or internet.

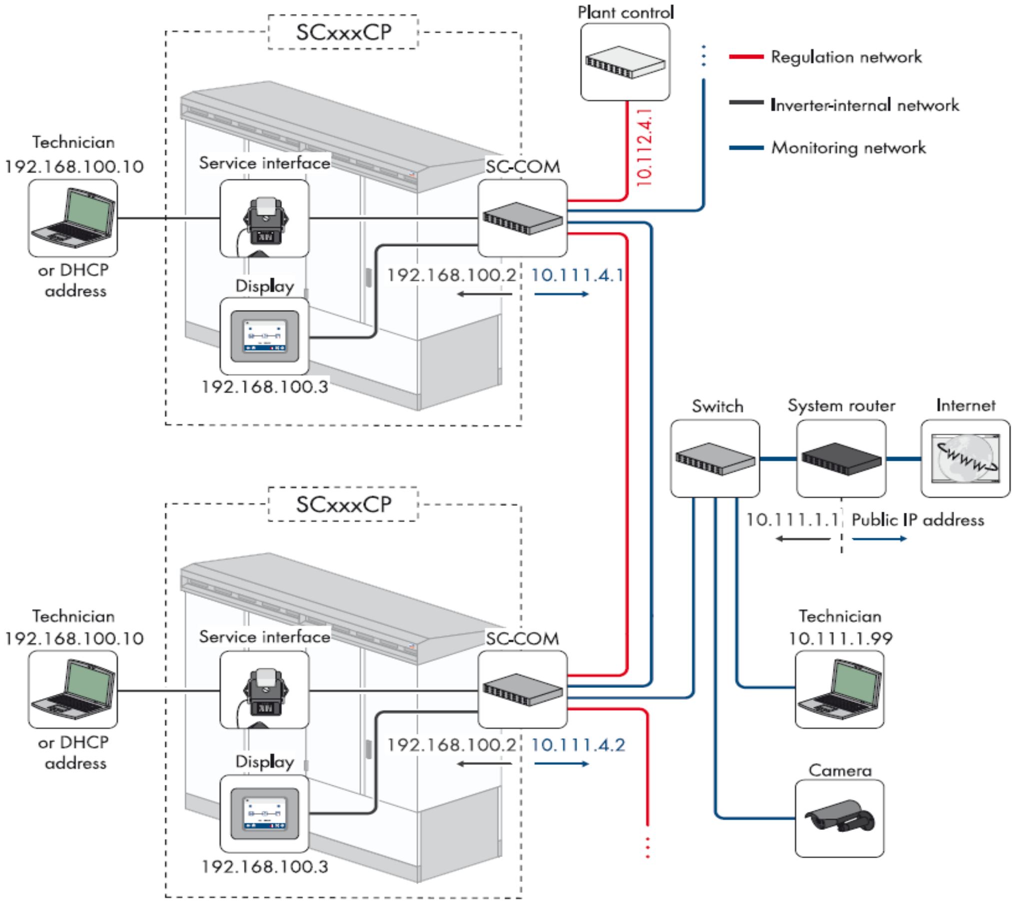


Figure 17 A PV system network with two Sunny Central inverters [8]

2.2.3. Future-proof

In the present, smart grids offer several advantages and grid operators are able to increase more integration of PV systems into an efficient grid. Smart functions and communications are very importance for all size of PV systems in the future. Then, step by step, PV inverters have to do more. All the upgrades are not only software but also hardware as well. Consequently, standards and requirements should be changed. Besides, every customer really objects to have a PV system to get benefit.

CHAPTER III
IMPACT OF SOLAR PV SYTEM ON VOLTAGE PROFILE

3.1 Photovoltaic Modeling

In general, a photovoltaic system is designed based on factors such as power consumption demand, capacity of PV module and inverter sizing. In order to produce enough power as required, PV cells are generally connected in a combination of series and parallel configuration. Particularly, a specific amount of cells are arranged to form a module and some modules are connected to form an array.

In this section, the single diode photovoltaic model is utilized to model photovoltaic cell because such model is easy to understand and has a good accuracy. Figure 18 illustrates that model along with complex physical parameters.

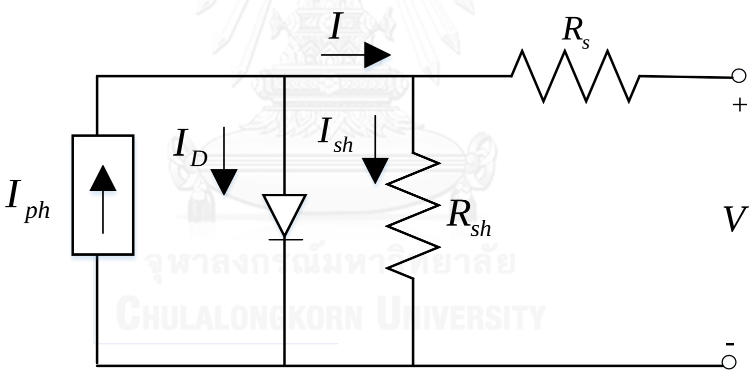


Figure 18 Single diode Photovoltaic model

The circuit parameters are described as follows. I and V are the voltage and current of the PV module, respectively; I_{ph} is the photo generated current ; I_d is the diode current; I_{sh} is current of shunt resistance R_{sh}, R_s is the series resistance that represents the internal resistance to the current flow, R_{sh} is the shunt resistance that is inversely related to the leakage current to ground. From figure 15, the simple current equation by Kirchhoff's law is given by (8).

$$I = I_{ph} - I_D - I_{sh} \tag{8}$$

where I_D is the model using Shockley equation for an ideal diode and described by (9).

$$I_D = I_0\left(exp\left(\frac{V_d}{nV_T}\right)-1\right) \tag{9}$$

where I_0 is the reverse saturation current (A), n is the number of PV cells inside one module, and V_T is the thermal voltage as given by (10).

$$V_T = \frac{kA\left(T_{module}+273\right)}{q} \tag{10}$$

where k is Boltzmann's constant (1.381×10^{-23} J/K), A is the diode quality factor, T_{module} is the module temperature in Celsius scale and q is Coulomb charge (1.602×10^{-19} C). V_d can be represented by (11).

$$V_d = V + IR_s \tag{11}$$

From (9) and (11) , I_D can be written as (12).

$$I_D = I_0\left(exp\left(\frac{V+IR_s}{nV_T}\right)-1\right) \tag{12}$$

According to the circuit model and (11), the current of the shunt resistance is obtained as shown in (13).

$$I_{sh} = \frac{V_d}{R_{sh}} = \frac{V+IR_s}{R_{sh}} \tag{13}$$

From (8), (12) and (13) the voltage-current relationship of PV can be written by the Kirchhoff's law as (14).

$$I = I_{ph} - I_0\left[exp\left(\frac{V+IR_s}{nV_T}\right)-1\right] - \frac{V+IR_s}{R_{sh}} \tag{14}$$

The operating point of PV module provided by the manufacturer is the operating point at the Standard Test Condition (STC). This point is affected directly by the irradiance and the temperature as the following explanations.

Irradiance: the irradiance affects directly the variation of the current generated from the PV module and can be defined by (15)-(16).

$$I_{ph\_new} = I_{ph} \frac{G}{G_{stc}} \tag{15}$$

$$R_{sh\_new} = R_{sh} \frac{G_{stc}}{G} \tag{16}$$

where $I_{ph_new}$is I_{ph}at irradiance G(A), I_{ph} is at standard test condition(A), R_{sh_new} is at irradiance G (ohm), and R_{sh} is at standard test condition (ohm).

Temperature: when the temperature of PV module changes, I_{sc} and V_{oc} are affected through the temperature coefficient as defined by (17)-(18).

$$I_{ph\_new} = I_{ph} + K_i\left(T - T_{stc}\right) \tag{17}$$

$$I_0 = \frac{I_{sc} + K_i(T - T_{stc})}{\exp\left(\frac{V_{oc} + K_V(T - T_{stc})}{nV_T}\right) - 1} \tag{18}$$

where T is present temperature, T_{stc} is at the standard test condition , $I_{ph_new}$is the new photoelectric current, K_i is the current temperature coefficient (A/^{o}C) and K_V is the voltage temperature coefficient (V/^{o}C).

The power generated from the PV module varies on an I-V curve. On this curve, the maximum power point is the point at which the highest efficiency can be obtained. The tool used to find the maximum power point is called Maximum Power Point Tracking (MPPT).

The maximum power point can be found by taking differential of power with respect to voltage and then equating to zero (19).

$$\left.\frac{dP}{dV}\right|_{MPP} = \left.\frac{dIV}{dV}\right|_{MPP} = I_{MPP} + V_{MPP}\left.\left(\frac{dI}{dV}\right)\right|_{MPP} = 0 \tag{19}$$

Typically, the manufacturer’s datasheet provides only the following information: I_{sc}, V_{oc}, P_{MPP}, I_{MPP}, V_{MPP}, K_i, K_V and n. It does not provideI_{ph},I_0, V_T, R_s and R_{sh} which are indispensable for calculating the module output current and voltage. Therefore, these parameters will need to be estimated by proposed method in [12]. We get all parameters as shown in Table 2:

Table 2 All parameters in PV module of KC200GT

From data sheet	
Maximum Power (P_{mpp})	200.143(W)
Maximum power voltage(V_{mpp})	26.3(V)
Maximum power current(I_{mpp})	7.61(A)
Open circuit voltage (V_{oc})	32.9(V)
Short circuit current(I_{sc})	8.21(A)
Temperature coefficient short circuit(K_i)	0.00318(A/C^o)
Temperature coefficient open circuit (K_V)	-0.123 (V/C^o)
Number of cell per module (n)	54
Estimated parameters	
Diode's reverse saturation current (I_0)	7.4267.10^{-10} (A)
Photovoltaic current (I_{ph})	8.22 (A)
Series resistance (R_s)	0.3225(Ω)
Parallel resistance (R_{sh})	169.0952 (Ω)

After getting all parameters from Table 2, the relationship between I module and V module can be expressed by (20).

$$I_{Module} = I_{ph} - I_0\left[exp\left(\frac{V_{Module} + I_{Module}R_s}{nV_T}\right) - 1\right] - \frac{V_{Module} + I_{Module}R_s}{R_{sh}} \quad (20)$$

where I_{Module} is the current of the PV module, V_{module} is the voltage of the PV module, I_{ph} is the photoelectric current in the module, I_0 is diode reverse saturation current in the module, R_s is series resistance in the module, R_{sh} is the parallel resistance in the module and n is the number of cells per module. After a series of equation (21)-(22), the solution to current with Newton-Raphson method can be described as (23).

$$I_{ph} - I_0\left[exp\left(\frac{V_{Module} + I_{Module}R_s}{nV_T}\right) - 1\right] - \frac{V_{Module} + I_{Module}R_s}{R_{sh}} - I_{Module} = 0 \quad (21)$$

$$f(I_{Module}) = I_{ph} - I_0\left[exp\left(\frac{V_{Module} + I_{Module}R_s}{nV_T}\right) - 1\right] - \frac{V_{Module} + I_{Module}R_s}{R_{sh}} - I_{Module} \quad (22)$$

Solution to current with Newton-Raphson method can be described as:

$$I_{K+1} = I_K - \frac{f(I_K)}{f'(I_K)} \quad (23)$$

where I_K is Kth iteration current and I_{K+1} is *(K+1)th* iteration current

It is well known that PV module power equals to value that voltage multiplies current, and can be represented by (24).

$$P = I^M . V^M \quad (24)$$

Irradiance and temperature are the factors which affect the model of PV module. Thus, these two factors are considered in this study.

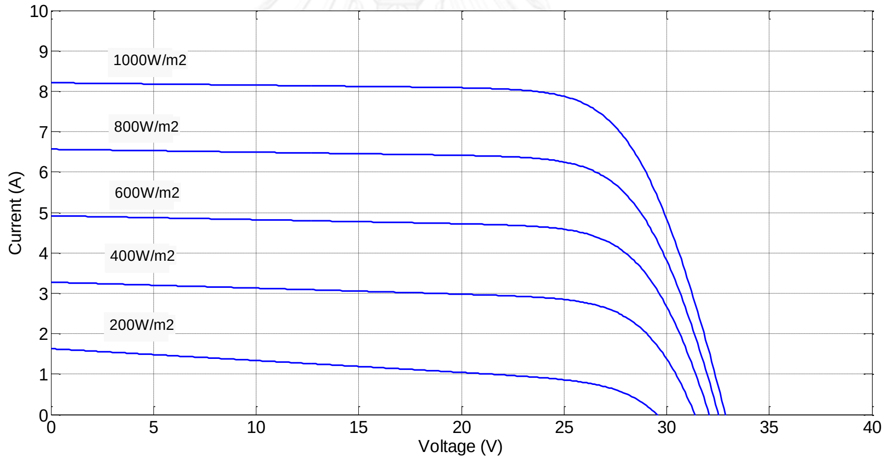


Figure 19 Relation between I and V of PV module with varying irradiation at temperature 25 °C

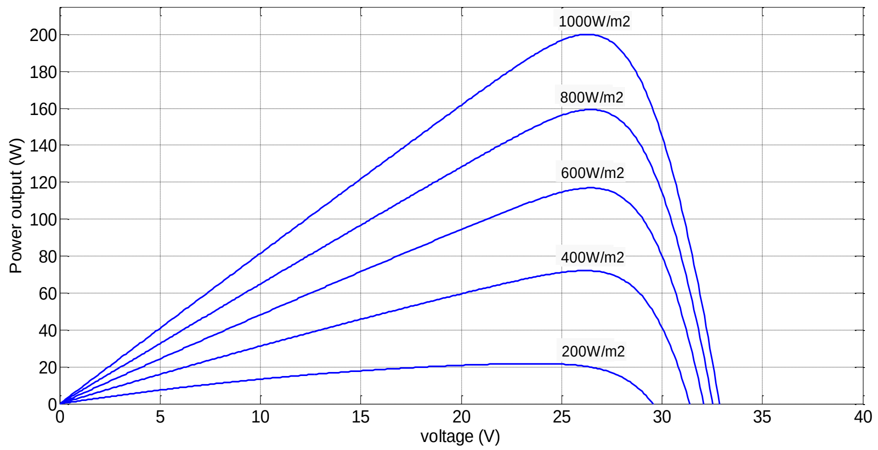


Figure 20 Relation between P and V of PV module with varying irradiation at temperature 25 °C

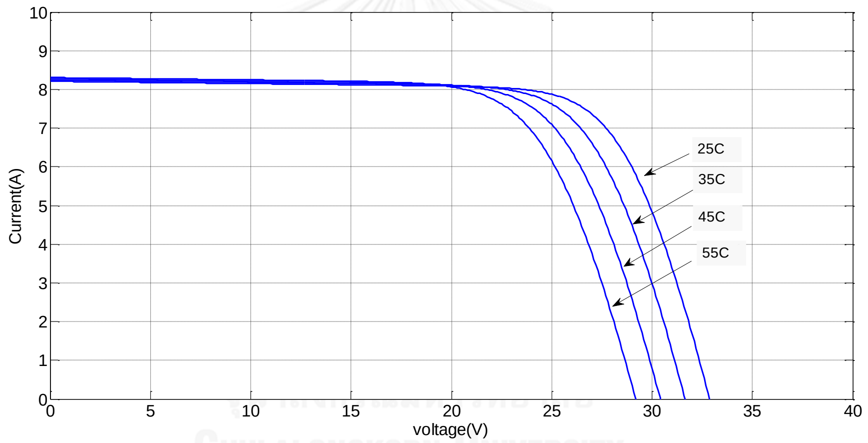


Figure 21 Relation between I and V of PV module with varying temperature at $1000W/m^2$

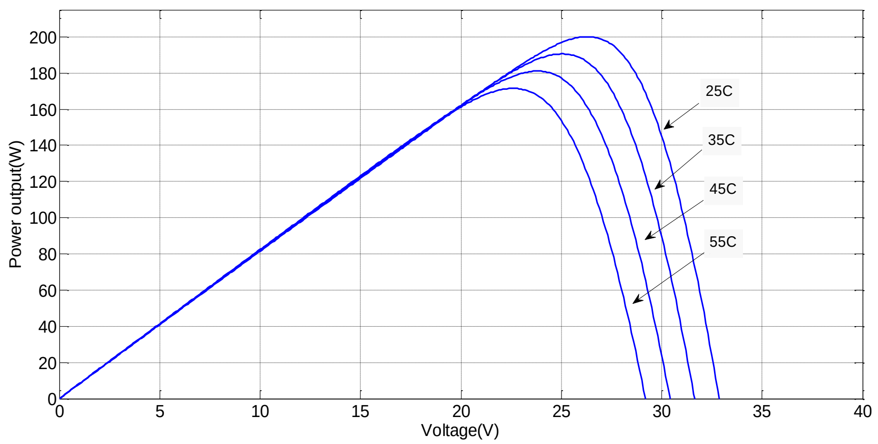


Figure 22 Relation between P and V of PV module with varying temperature at $1000W/m^2$

Actually, the temperature and the irradiance always change every seconds because of cloud moving and changing position of sun. Figure 23 shows an example of the output of one residential solar system during one day. In the morning, the solar system can produce electrical power in the minimum output but in the afternoon, it can produce in the maximum output power. Otherwise, at night no electricity is produced.

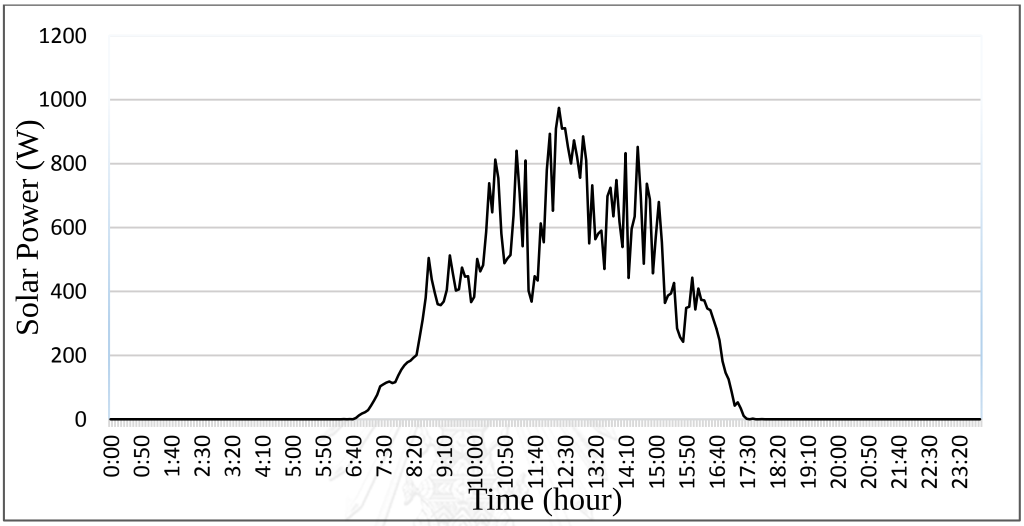


Figure 23 Solar power over the course of one day

It is well known that solar power may fluctuates when clouds pass over and shade the solar array, power output also drops sharply, then increases again when cloud passes away. At a high penetration level, such fluctuation has significant impacts on the system voltage. In this case, it is a problem for utility to control power output during connecting to the grid because the voltage level of electricity system is impacted. Sometime, level of voltage can exceed the regulatory range.

3.2 Voltage Profile Improvement

The presence of distributed generation may result in a significant impact on distribution networks, such as system reliability, power flow, relay protection, voltage profile and stability. Voltage level around the rated value is a basic demand for electrical equipment and it is the utility's responsibility for keeping the customer's service voltage within the acceptable range [5]. Therefore, Voltage regulation is an important subject in electrical distribution [5]. Two of fundamental methods to control the voltage on the feeder by using on-load tap-changing transformers and fixed or switched capacitors [5].

1. On-load tap changing transformer: It is called voltage regulator and is typically constructed as autotransformers. Automatically adjustable OLTCs are commonly used at distribution substation to raise the starting voltage for a feeder under load, so that some points along the feeder experience the desired voltage. If the load is near the voltage regulator so the amount of permissible voltage increase is limited. In this case, additional voltage regulators along the feeder might be necessary.

2. Switched Capacitor: Actually, load requires both active power and reactive power. The reactive power supplied by the capacitor banks helps offset the reactive power of the load and consequently reduces the amount that needs to come from the substation that causes the associated voltage to drop. Overcompensation of the feeder leads to voltage rise on the feeder, and it might require the voltage regulator in the substation to take action to lower the voltage to accommodate the rise due to overcompensation by the capacitors. In general there are three type of reactive compensation from capacitor [13]: single-, bulk- and central- type compensations.

Actually, in large plants, there are mixture of these three types and the location of compensation bank should be close to the customers. The figures below show the type of these compensation:

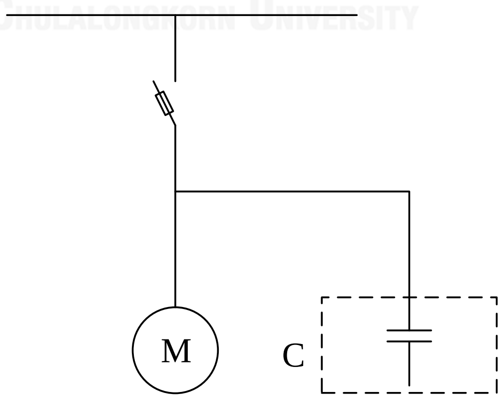


Figure 24 Single-type compensation

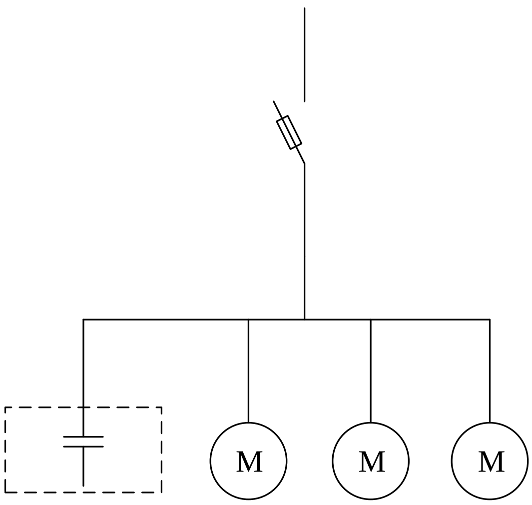


Figure 25 Bulk type-compensation

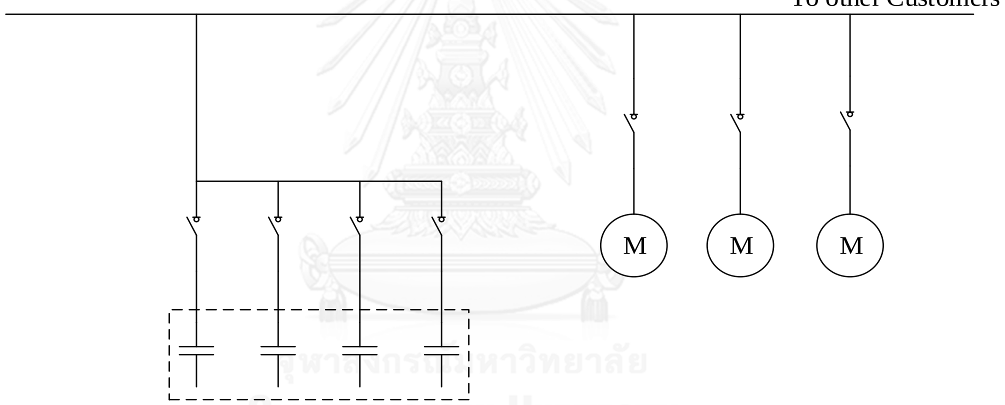


Figure 26 Central type-compensation

Normally, in a distribution system with grid-connected PVs, voltage profile is one of the most important issues to be considered. Grid-connected PVs can affect the distribution system voltage in two ways [10]:

- If power from distribution system is injected into power system, it will offset load current and reduce voltage drop. When distribution system can offset the load current, the voltage profile will rise as well.
- If the grid-connected PVs inject reactive power into the system or absorbs reactive power from the system, it will affect the voltage profile on that area. If the grid-connected PVs injects reactive power, the voltage drop will reduce. On

the other hand, if the grid-connected PVs absorbs reactive power, the voltage drop will increase.

Consequently, the power from the substation must adapt to meet the demand of load, and then keep power balance in the whole system. Most of PV systems are designed to operate at unity power factor because it maximizes real power and will not affect to voltage control of the utility [5]. Furthermore, many inverters also have a capability of providing reactive power to the grid. In Germany, PV system connected to the low voltage distribution system aims to supply reactive power at their points of common coupling [14]. Point of common coupling is accessible by both the utility and the customer for direct measurement [15]. In this case, optimal reactive power injection to the system has to be considered to regulate voltage profile inside the limit. A method is proposed to minimize voltage deviation in the system as shown in the next section.

3.3 Proposed Method

Integration of renewable energy-based generation really provides a lot of benefits to the conventional distribution system. The power injections from these generations located near the load can provide an opportunity for reduction in energy losses, voltage profile and improvement of reliability in the system. Thus, the location of those generations should be necessarily determined with different conditions. This section present a method to calculate the optimal location of distribution generations based on a voltage sensitivity index. The optimal location is chosen to object the best voltage profile. In this method, it could be calculated by injecting 25% of distribution generator capacity at each node and get the voltage index by using (25) [16]:

$$VSI_i = \sqrt{\frac{\sum_{k=1}^{n}(1-V_k)^2}{n}} \tag{25}$$

Where V_k is the voltage at the kth node and n is the number of nodes.

The optimal location for distribution system is the node with the least VSI.

After the best location is selected, solar PV generator power can be located to improve the voltage profile as well. Due to the solar power fluctuation, control center can use inverter to inject/absorb reactive power to regulate voltage level within the limit.

In this section, a method is proposed to calculate the optimal reactive power from the inverter in case of solar PV power changes. This principle guarantees the minimal value of system voltage deviation within limit in a distribution network [17]:

$$\text{Voltage deviation minimization: } F_V = \sum_{i=1}^{n} (V_i - V_{nom})^2 \rightarrow \min \tag{26}$$

In Newton-Raphson based power flow calculation, the Jacobian matrix gives the linearized relationship between small change of voltage angle $\Delta\delta$ and voltage magnitude ΔV with the small changes of active and reactive power, ΔP and ΔV is usually written as [18],[19] and [20].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{27}$$

In the n bus system with one slack bus, if m buses are voltage-controlled, m equations involving ΔQ and ΔV and the corresponding columns of the Jacobian matrix are cut out. There are n-1 real power constraints and n-1-m reactive power constraints and the Jacobian matrix is of order $(2n-2-m)\times(2n-2-m)$. The order of $J_{P\delta}, J_{PV}, J_{Q\delta}$ and J_{QV} are $(n-1)\times(n-1)$, $(n-1)\times(n-1-m)$, $(n-1-m)\times(n-1)$ and $(n-1-m)\times(n-1-m)$, respectively. For shortly expressing equations hereinafter, let us denote *N=n-1* and *M=n-1-m*.

From a view point of sensitivity analysis, (27) can be interpreted as how the voltage changes in corresponding to a small change of power. Assume that the system is operating at a point V_0 with power injection P_0+jQ_0. A small change of power $\Delta P + j\Delta Q$ causes a voltage change $\Delta V \angle \Delta\delta$ computed by solving (27) with the Jacobian matrix evaluated at V_0.

After a change ΔP, the system voltage can be mathematically constant $(\Delta V = 0)$ if suitable ΔQ at all buses is adjusted as (29). Substituting for ΔV in (27) yields (28).

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ 0 \end{bmatrix} \tag{28}$$

Eliminating $\Delta\delta$ yields (29) which is an equation for the necessary amount of ΔQ

$$\Delta Q = J_{Q\delta} J_{P\delta}^{-1} \Delta P \tag{29}$$

Equation implies all buses in the system including load buses must be capable of varying reactive power. In the case of this research, we considered a change ΔP at only one PV plant at a time and only this plant is expected to change its reactive power to support the system voltage. Obviously, the system voltage cannot go back to the right value as before the change ΔP by adjusting reactive power at only one bus.

However, a minimum voltage deviation can be obtained. Assuming that the PV plant at bus k has power change $\Delta P_k + j\Delta Q_k$ and the other buses have no power change. The linear equation can be solved directly by optimally ordered triangular factorization and Guassian elimination to obtain $\Delta\delta$ and ΔV. To represent equations more comfortable, Inversion symbols are used. The inversion of the Jacobian matrix in (27) is denoted by K as given in (30). Then voltage change ΔV is achieved in (31) by substituting (30) for J in (27):

$$K = J^{-1} = \begin{bmatrix} K_{P\delta} & K_{PV} \\ K_{Q\delta} & K_{QV} \end{bmatrix} \tag{30}$$

$$\Delta V = K_{Q\delta} \Delta P + K_{QV} \Delta Q \tag{31}$$

As mentioned before, only ΔP_k and ΔQ_k are the non-zero elements of ΔP and ΔQ. The changing voltage compared to the initial voltage at bus i, (i=1,...M), is expressed by:

$$\Delta V_i = K_{Q\delta(ik)} \Delta P_k + K_{QV(ik)} \Delta Q_k \tag{32}$$

where $K_{Q\delta(ik)}$ and $K_{QV(ik)}$ indicate the elements at row *ith*, column *kth* of matrices $K_{Q\delta}$ and K_{QV}, respectively.

At the initial state, we assume $V_{0i} - V_{nom} = \varepsilon_{0i}\, p.u$ where ε_{0i} may be zero, positive or negative, V_{oi} is the voltage of each bus at initial state before reactive control and V_{nom} is nominal voltage 1 p.u.

As denoted before $\Delta V_i = V_i - V_{0i}$ where Vi is voltage of each bus after reactive power injection. Therefore the objective function (26) can be represented by ΔV_i and ε_{0i} given by (33).

$$F_V = \sum_{i=1}^{n} (\Delta V_i + \varepsilon_{0i})^2 \rightarrow \min \tag{33}$$

Substituting (32) for ΔV_i in (33) yields (34)

$$F_V = \sum_{i=1}^{n} (\varepsilon_{0i} + K_{Q\delta(ik)} \Delta P_k + K_{QV(ik)} \Delta Q_k)^2 \rightarrow \min \tag{34}$$

Subject to:

$$\left| V_i - V_{nom} \right|_{i=1,\ldots M} \leq \varepsilon\, p.u \tag{35}$$

Constrain (35) is rewritten by (36):

$$\left| \varepsilon_{0i} + K_{Q\delta(ik)} \Delta P_k + K_{QV(ik)} \Delta Q_k \right|_{i=1,\ldots M} \leq \varepsilon\, p.u \tag{36}$$

where ε is voltage variation which is set 0.05 p.u.

Generally, constraints of an optimization power flow problem may consist of power flow equality, physical limits of the control and state variables, and other limits such as power factor range [21]. Under the scope of this research, the power flow equality constraint is fully met because the objective function was derived from the power balance equation (27). The control variable ΔQ_k is restricted by the capability of PV plants as shown in (37). The state variable of line flow can be neglected within the duration of the concerned fluctuation because the PV plant adjusts its reactive power strictly within its installed capacity which was already planned by the utility.

$$\left| Q_{PVk} \right| \leq Q_{PVk\max} = \sqrt{\left(S_{PVk\max} \right)^2 - \left(P_{PVk} \right)^2} \tag{37}$$

where $Q_{PV} = Q_{PVk0} + \Delta Q_k$; Q_{PVk0} is the generated reactive power of the PV plant at the operating point V_0; ΔQ_k is the adjusted Var amount. In case the active power is completely interrupted, ie., $P_{PV} = 0$, the inverter is capable of generating a maximum

Var of the rated capacity $S_{PV\max}$. In addition, within that range, Var output is controlled arbitrarily with responding time in a time scale of milliseconds. Consequently, the inverter can serve Var at a much faster than timescale with finer resolution than utility's regulation devices. In fact, an inverter can be oversized 10% of apparent power so that $S_{ov} = 1.1 S_{PV\max}$ [1]. Thus, even at maximum active power output mode $(P_{PV} = S_{PV\max})$, the inverter can vary its reactive power within 46% of the capacity.

Note that $K_{Q\delta}$ and K_{QV} are known because they are evaluated at V_0, so (36) can be reduced to one equality for a given ΔP_k.

$$\Delta Q_{k\min V} \le \Delta Q_k \le \Delta Q_{k\max V} \quad (38)$$

where "minV" and "maxV" subscribts imply the minimum and maximum requirement of the additional reactive power ΔQ_k to satisfy the voltage limit. If the PV_k is operating at Q_{PVk0}, the requirement reactive power is limited by (39):

$$Q_{PVk\min V} \le Q_{PVk} \le Q_{PVk\max V} \quad (39)$$

Where $Q_{PVk\min V} = Q_{PVk0} + \Delta Q_{k\min V}$ and $Q_{PVk\max V} = Q_{PVk0} + \Delta Q_{k\max V}$. An unsuccessful support comes in two cases produced from comparing (34) and (39). Case 1 is $Q_{PVk\min V} > Q_{PVk\max}$ and case 2 is when $Q_{PVk\max} < -Q_{PVk\max}$. In these case, controlling reactive power at only PV_k to keep all bus voltages within limits is beyond the capacity of PV_k. There is no choice in such situation for any control methods to pull/push the voltage back to within limit except partly sacrificing active power of PV_k as recommended by [22]-[23]. Additionally, fluctuation of PV's active power does not cause the voltage to go far from the limits. A sufficiently large PV plant allowed by the utility can carry out the task successfully. In case of successful control, (37) and (39) can be combined to produce a final reactive power constraint given in (40) where the subscript "f" implies the final calculated value.

$$Q_{PVk\min f} \le Q_{PVk} \le Q_{PVk\max f} \quad (40)$$

The minimum point of equation (34), which is a quadratic function of ΔQ_k, is the root of the derivative and that point is given by (41). Considering the constraint (39), if

$Q_{PVkopt} = Q_{PVk0} + \Delta Q_{kopt}$ is not inside the range, the optimal point is displaced as presented by (43).

Equation (41) is a controlling principle that helps a PV plant responds to its active power change. This principle guarantees the minimal value of system voltage deviation. The controlling method is deployable if the system configuration and load condition are known and informed the PV plant. Therefore, after detecting a change ΔP_{PV}, the PV's controller can compute very fast how much reactive power to inject/absorb into/from the system.

At bus i:

$$F_{Vi} = \left(\varepsilon_{0i} + K_{Q\delta(ik)}\Delta P_k + K_{QV(ik)}\Delta Q_k\right)^2$$

$$F_{Vi} = \left(\varepsilon_{0i} + K_{Q\delta(ki)}\Delta P_k\right)^2 + 2\left(\varepsilon_{0i} + K_{Q\delta(ki)}\Delta P_k\right)K_{QV(ik)}\Delta Q_k + \left(K_{QV(ik)}\Delta Q_k\right)^2$$

$$F_V = \sum_{i=1}^{M}\left(\varepsilon_{0i} + K_{Q\delta(ki)}\Delta P_k\right)^2 + 2\left[\sum_{i=1}^{M}\left(\varepsilon_{0i} + K_{Q\delta(ki)}\Delta P_k\right)K_{QV(ik)}\right]\Delta Q_k + \left(\sum_{i=1}^{M}K_{QV(ik)}^2\right)\left(\Delta Q_k\right)^2 \quad (41)$$

The equation (41) is the form of quadratic function $f(x) = ax^2 + bx + c$ where a, b and c are the real number and $a \neq 0$. The graph of a quadratic function $f(x) = ax^2 + bx + c$ is open upward when the leading coefficient a>0. In this case, the vertex is the minimum point on the graph or for the function.

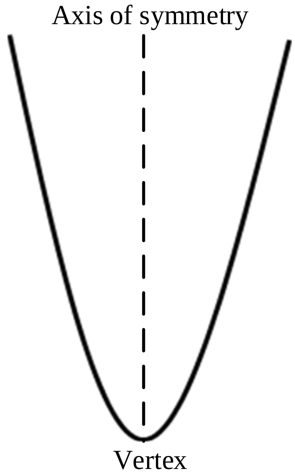


Figure 27 Minimum point of a quadratic function

The graph of a quadratic function $f(x) = ax^2 + bx + c$ is open upward when the leading coefficient a<0. In this case, the vertex is the maximum point on the graph or for the function.

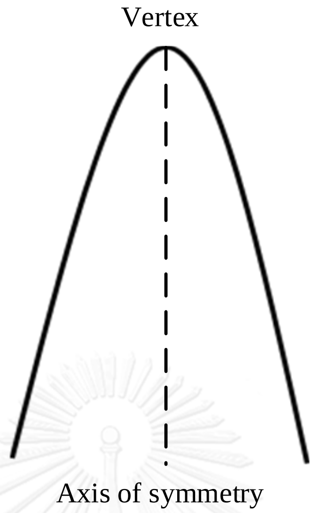


Figure 28 Maximum point of a quadratic function

The equation of the axis of symmetry is $x = -\dfrac{b}{2a}$. The b and a come from $f(x) = ax^2 + bx + c$ and the minimum or maximum value is $f\left(-\dfrac{b}{2a}\right)$.

Thus, the minimum value of (41) can be written as (42).

$$\Delta Q_{kopt} = -\frac{\sum_{i=1}^{M}\left(\varepsilon_{0i} + K_{Q\delta(ik)}\Delta P_k\right)K_{QV(ik)}}{\sum_{i=1}^{M} K_{QV(ik)}^2} \tag{42}$$

Where ΔQ_{kopt} is limited by this constraints $\left|\varepsilon_{0i} + K_{Q\delta(ik)}\Delta P_k + K_{QV(ik)}\Delta Q_{kopt}\right|_{i=1,\ldots M} \le \varepsilon\, p.u$

Reactive power capacity of inverter $\left|Q_{PVk}\right| \le Q_{PVk\max} = \sqrt{\left(S_{PVk\max}\right)^2 - \left(P_{PVk}\right)^2}$

The final reactive power constraint is from (40) $Q_{PVk\min f} \le Q_{PVk} \le Q_{PVk\max f}$.

The optimal reactive power of inverter can be calculated by as follow:

- $Q_{PVkopt} = Q_{PVk0} + \Delta Q_{kopt}$ if $Q_{PVkopt} \in \left[Q_{PVk\min f}, Q_{PVk\max f}\right]$

- $Q_{PVkopt} = Q_{PVk\min f}$ if $Q_{PVkopt} < Q_{PVk\min f}$

- $Q_{PVkopt} = Q_{PVk\max f}$ if $Q_{PVkopt} > Q_{PVk\max f}$

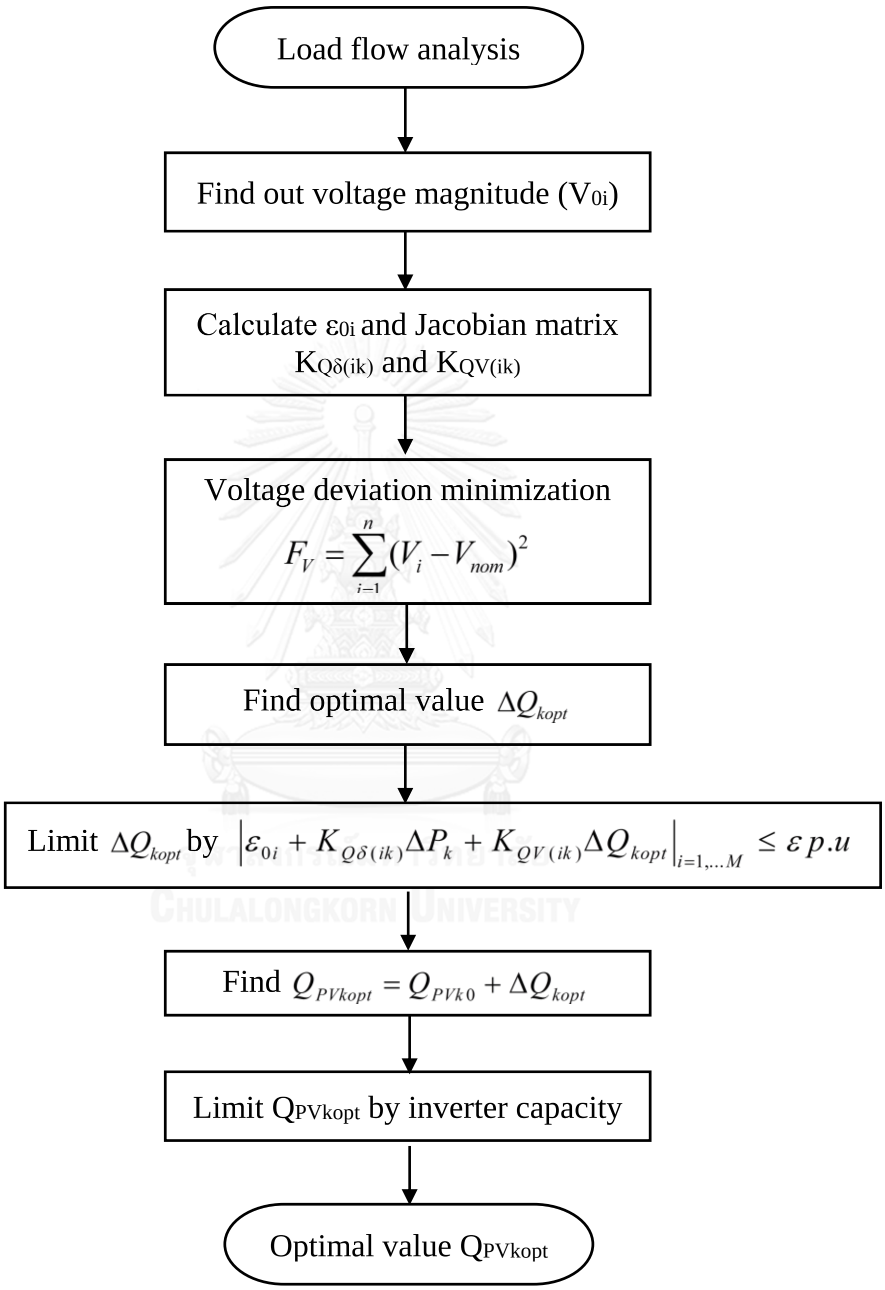


Figure 29 Optimal reactive power calculation scheme

CHAPTER IV
TEST RESULTS AND DISCUSSION

4.1 Testing system model

This section describes a test system IEEE 33- bus distribution network with a substation of 12.66 kV [24]. The network consists of 33 buses with 2 solar PV generators, in which bus 1 is considered as slack bus. The remaining nodes are viewed as PQ buses in load flow program. The total loads for this test system are 3.72 MW and 2.3 MVAr.

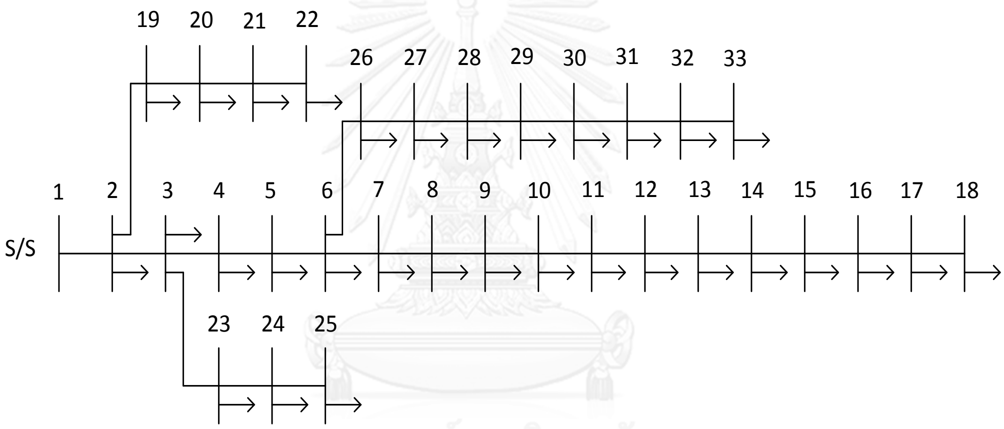


Figure 30 IEEE 33-bus radial distribution system

4.2 Optimal location of PV based on voltage sensitivity index

In order to calculate optimal location of PV generators to the system, load flow with PV capacity of 25% of the total feeder loading (i.e 0.93 MW) is carried out to find VSI (voltage sensitivity index) at various buses by using (25). Figure 31 shows the variation of VSI along the feeder. As seen from that figure, bus number 17 is the lowest VSI compared to other buses because it is very far from the substation. On the other hand, bus 33 is lowest VSI compared to other buses in the same lateral feeder. Thus, bus 17 and bus 33 are considered as candidates for the PV placement to improve voltage profile in the system.

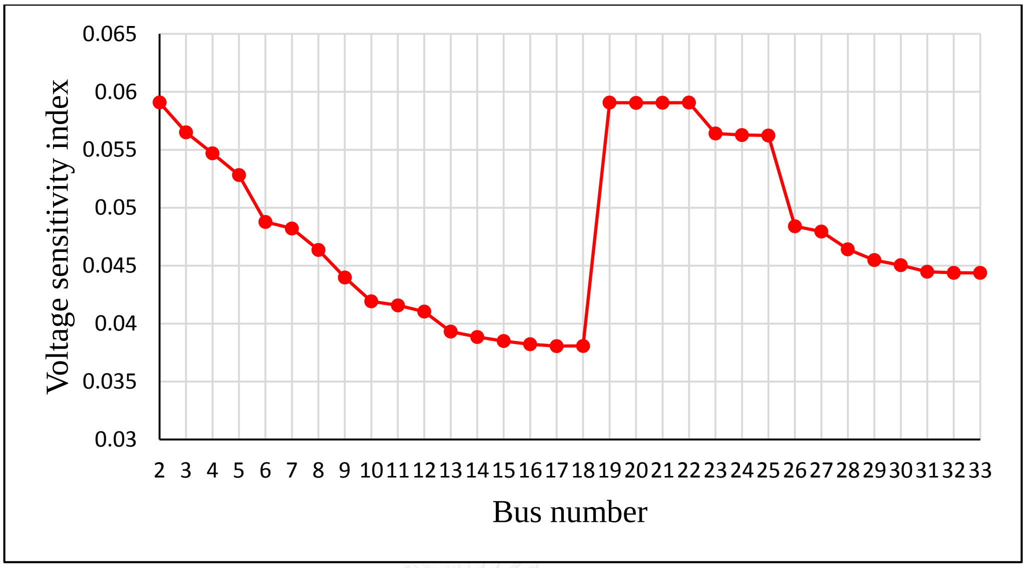


Figure 31 Voltage sensitivity index at different buses

4.3 Impact of Solar PV System on voltage profile

According to the technical rule for connecting distributed generators to the grid, the maximum allowable penetration of distribution generators is approximately 25% [5]. However, due to the impact of voltage profile, power supply capacity and network structure in different distribution system, the interconnection of distribution system will cause different influence on voltage quality and the maximum penetration level will be different as well [25]. In [26] 86% of all PV penetration scenarios for all feeders, the maximum PV penetration was always above 30%. For several researches, the maximum PV penetration that considered only steady state voltage and overcurrent can be above 50% unless the feeders have maximum load voltage already and in two-third cases, the maximum of PV penetration can over than 90%. In western Denmark, penetration level of renewable energy is 100% already even in transmission line [26].

Because of the low voltage level of the feeder, the maximum PV penetration of this study is selected up to 90% of total load feeder to improve voltage quality. From the test system of IEEE 33 bus, the total load is 3.72 MW and 2.3 MVAr but for the lateral feeders which are selected to place PV system, the total load 1322.46 KVA in the lateral feeder 2 (bus 26-33) and 1677.088 KVA in the lateral feeder 3 (bus 1-18). The penetration level is defined as [8].

PV Penetration = (Peak PV Power)/ (Peak load apparent power)

Thus, for feeder 2 and 3, the maximum PV penetration injection (90% of peak load) is 1190.214 KW and 1509.379 KW respectively.

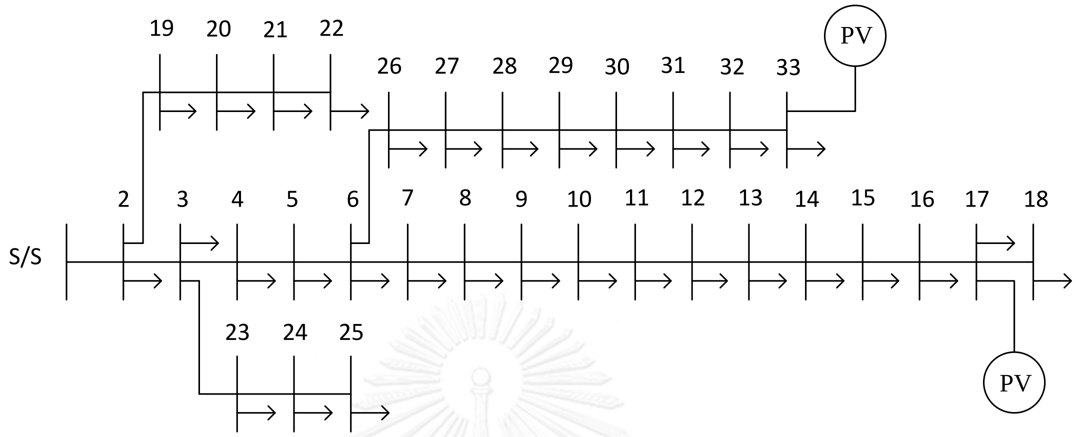


Figure 32 IEEE 33 bus system with PV penetration

A base case for load flow analysis is done to calculate the bus voltage magnitude and network power loss of the test system. Furthermore, load flow analysis with power input from PV can show voltage profile improvement in the system. Figure 33 shows the variation of voltage along the feeder.

For the sake of observing the voltage variation of each feeder, Figure 34 and 35 show the curves of voltage variation of feeder 2 and 3 respectively. It can be observed that the voltage of PV bus is strongly increased compared to other buses that are far from the PV bus. From this result, the PV provides positive impact on voltage profile.

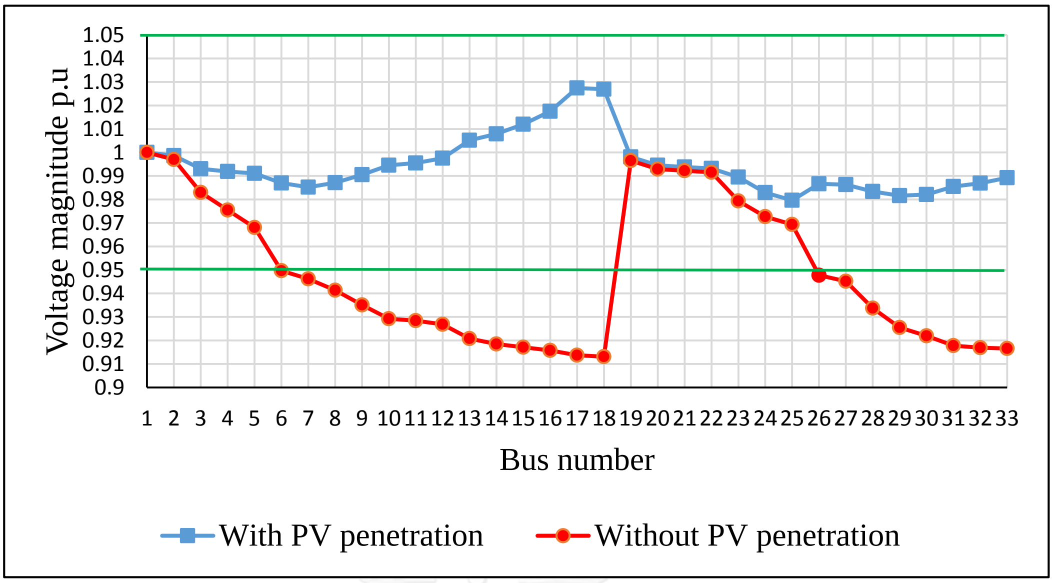


Figure 33 Variation of voltage at each bus

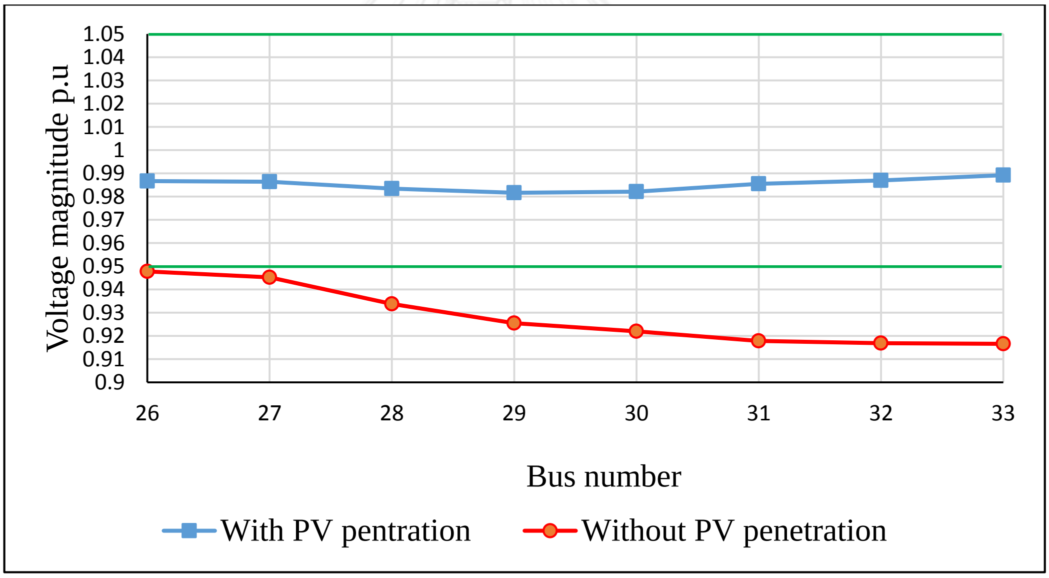


Figure 34 Voltage variation of each bus at feeder 2

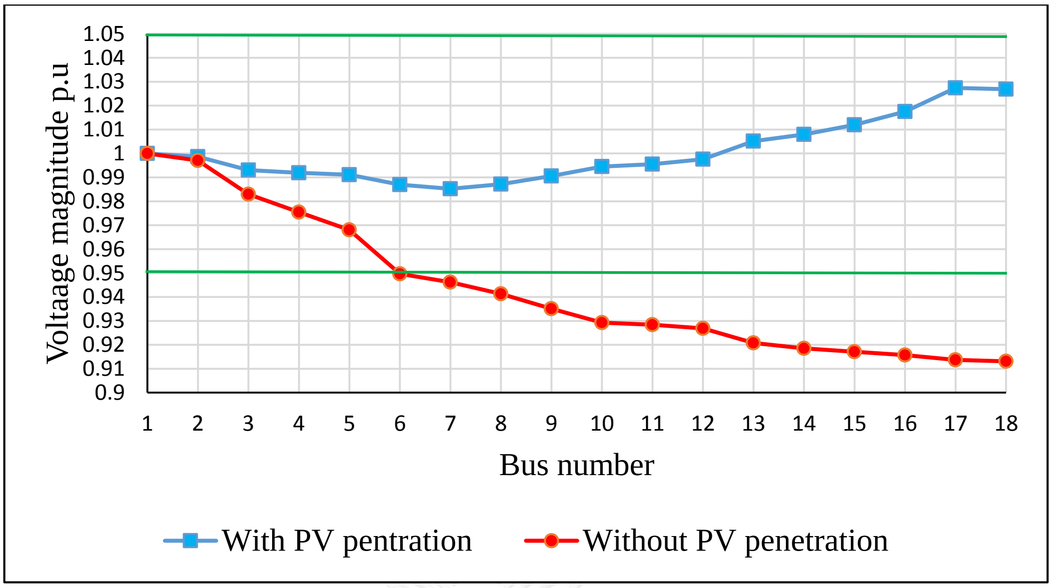


Figure 35 Voltage variation of each bus at feeder 3

The main objective of this research is to analyze the impacts of solar PV system on voltage profile in difference cases. Actually, in low voltage networks, active power is the biggest influence on the voltage profile. Consequently, when the active power varies, the voltage profile also varies as well. Every seconds of the day, the power from PV always fluctuate because of irradiance of sunlight. Sometimes, voltage of the grid network decrease under the limit when the active power from the PV drops. The typical problem is overvoltage for only some moments at days with very high irradiance and the low load consumption at the same time. In these case, just a little over produced power can make a complete disconnection from PV system. Inverters have several possible solution to solve the problem and influence the voltage without losing energy. Through supplying reactive power, inverter can influence the grid voltage. The voltage can be lowered by consuming reactive power and can be raised by reactive power injection. With a proper design, PV system can operate reactive power without causing losses of energy. In this section, 2 cases are considered to calculate the optimal reactive power from PV to maintain voltage profile within the limit.

1. Active power of PV changing during maximum load
2. Active power of PV changing during minimum load

4.3.1 Active power of PV changing during maximum load

It is simply understood that the sun is not always shine. On cloudy day, the solar irradiance may vary wildly. The variability of this input leads to changes at the output of a PV plant. Consequently, the power from the substation must adapt to meet the demand of load, then to keep power balance in the whole system. In this case, active power of PV from feeder 3 is reduced to 50% of total capacity (1.509 MW) to analyze the voltage variation of each bus and the optimal reactive power Q_{PV} is calculated by the proposed method to improve voltage profile when PV power changes.

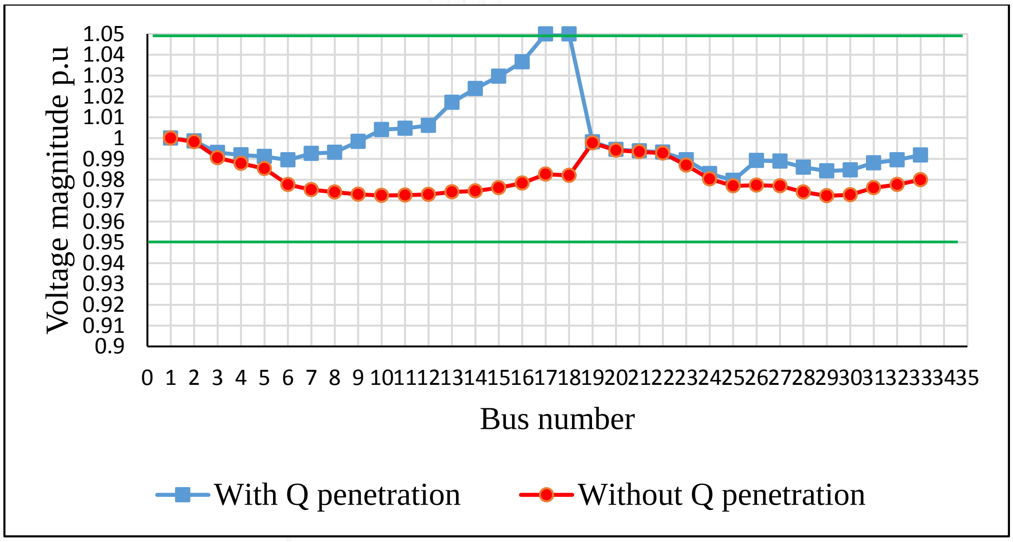


Figure 36 Variation of voltage of each bus during maximum load

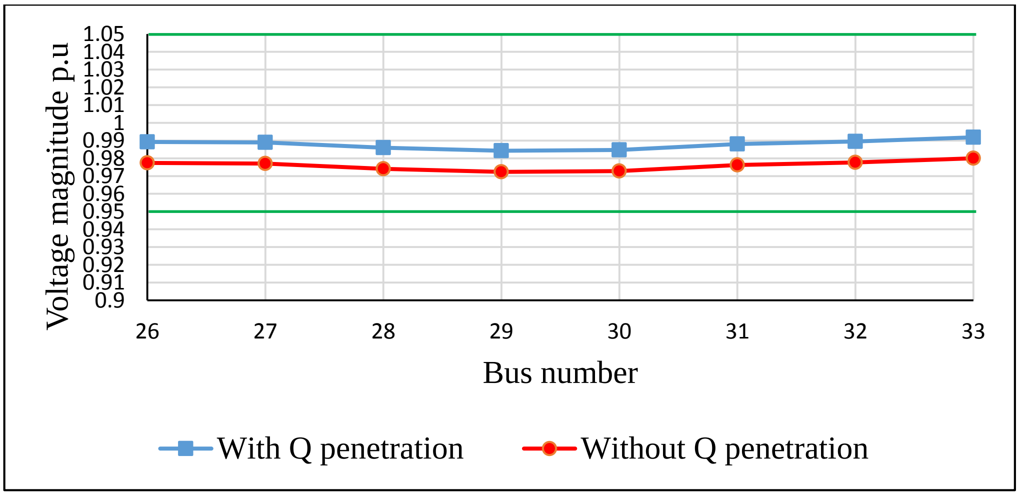


Figure 37 Voltage variation of each bus at feeder 2 during maximum load

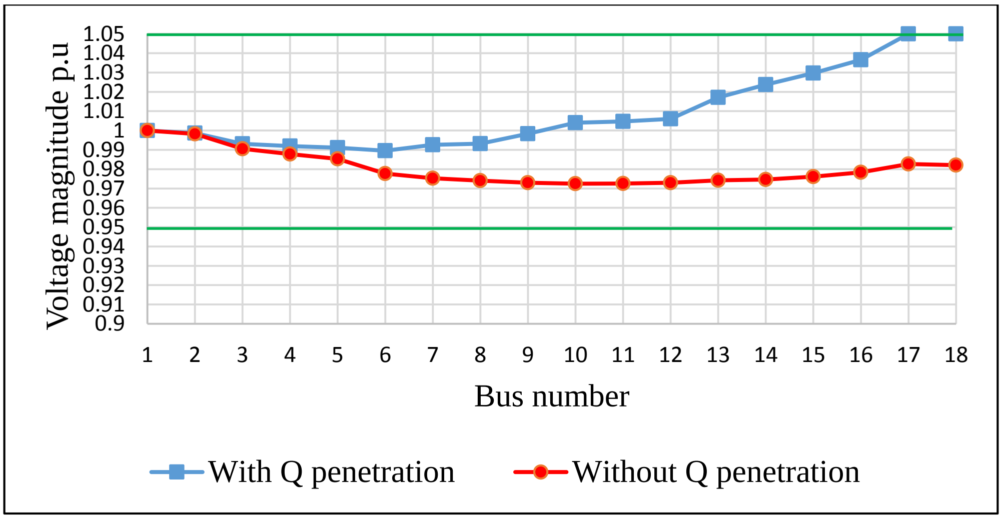


Figure 38 Variation of voltage at each bus at feeder 3 during maximum load

Figure 36 shows that the voltage at each bus without Q penetration is lower than voltage profile with Q penetration. In Figure 37, voltage at each bus at feeder 2 is increased as well when reactive power from PV 17 is injected but increasing level is still lower than bus voltage of feeder 3 because it is far from the PV 17. In this case, the optimal reactive power is calculated by the proposed method to improve voltage after reducing active power from PV. Typically, reactive power injection not only depends on not only rating of inverter, but also limitation of voltage profile in the system. In some cases, over reactive injection can cause voltage profile to be out of bound and it can make problem to customer too.

By using the proposed method, when the power from PV 17 reduces to 50% of its capacity (0.7545MW), it has to inject reactive power at the optimum value 1.7234 MVAr to increase voltage profile and minimize voltage deviation in the system. Due to the limitation capacity of this PV 17 and the constraint limitation voltage, inverter can inject reactive power only Q_{PV}=1.4785 MVAr. Thus, the final reactive power of PV 17 that can inject to system is the maximum capacity of rating inverter.

Table 3 Q optimal value responding to percentage of PV penetration from feeder3 during maximum load

PV penetration (% of total capacity)	Q optimal value (MVAr) without constraint limitation	Q optimal value (MVAr) with constraint limitation	Power factor with constraint limitation
10%	3.1925	1.653	0.0909
20%	2.8308	1.6322	0.1818
30%	2.4651	1.597	0.2727
40%	2.0959	1.5463	0.3636
50%	1.7234	1.4785	0.4545
60%	1.3480	1.3480	0.5575
70%	0.9699	0.9699	0.7365
80%	0.5895	0.5895	0.8985
90%	0.2069	0.2069	0.9885
100%	-0.1776	-0.1776	0.9931

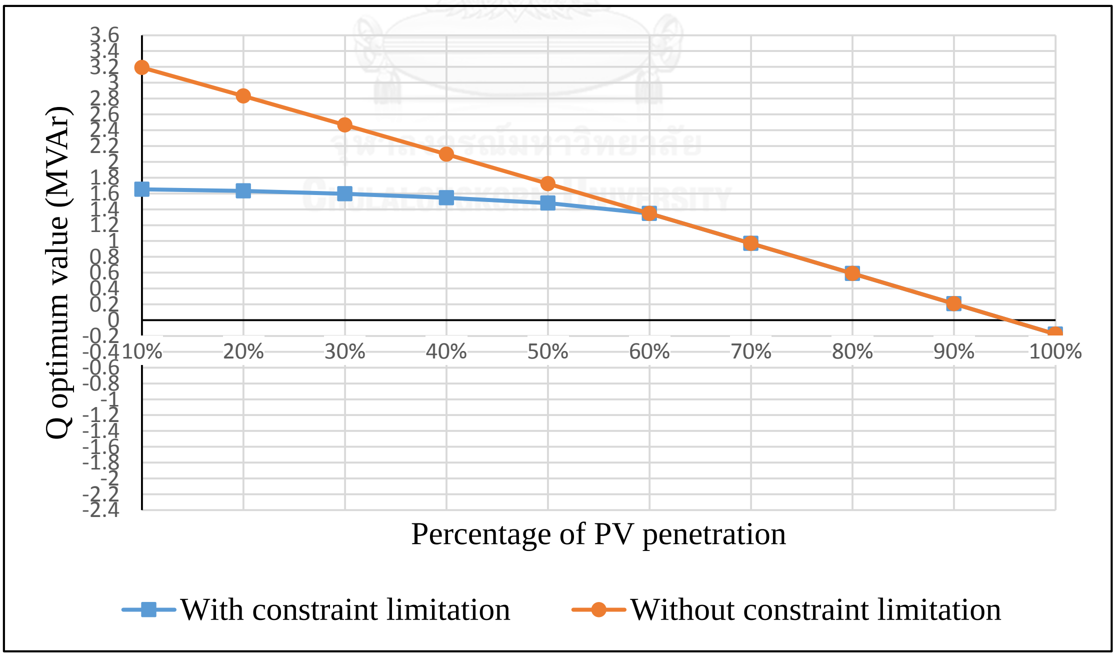


Figure 39 Curve of Q optimal value responding to percentage of PV penetration from feeder3 during maximum load

Figure 39 shows that inverter has to inject reactive power as much as it can to improve voltage profile. Only 100% of PV penetration, inverter has to absorb reactive power to to decrease over voltage profile and maintain voltage level within the limit.

4.3.2 Active power of PV changing during minimum load

It is similar to what have been done in the previous section except the minimum load condition in this section. The minimum load is chosen as 25% [27]-[28] of peak load 3.72MW and 2.3MVAr. The following cases are considered in this study to analyze the voltage variation in difference conditions and from these cases, the optimal reactive power Q_{PV} is calculated by the proposed method to improve voltage profile when PV power changes.

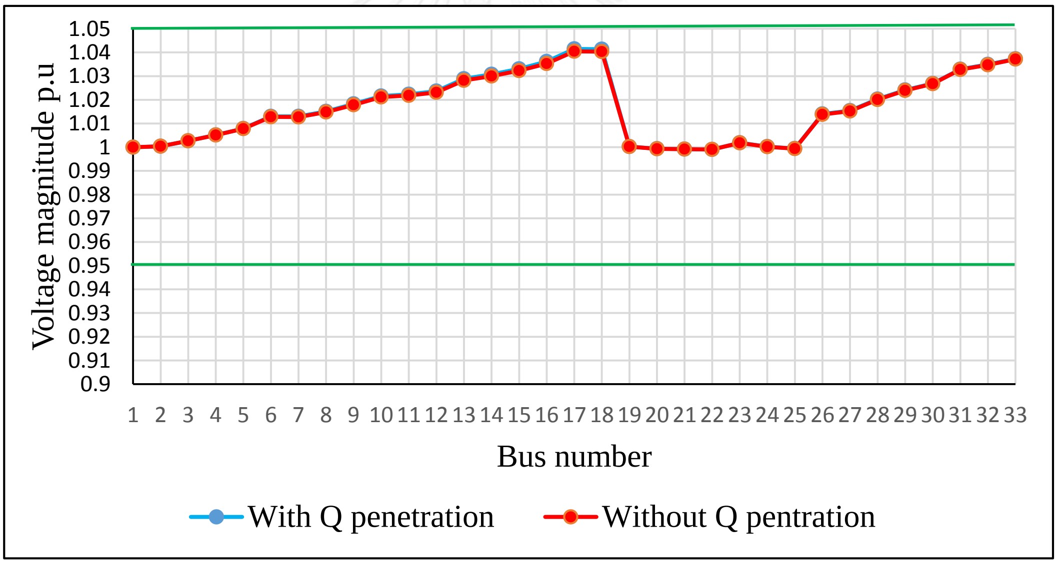


Figure 40 Variation of voltage at each bus during minimum load

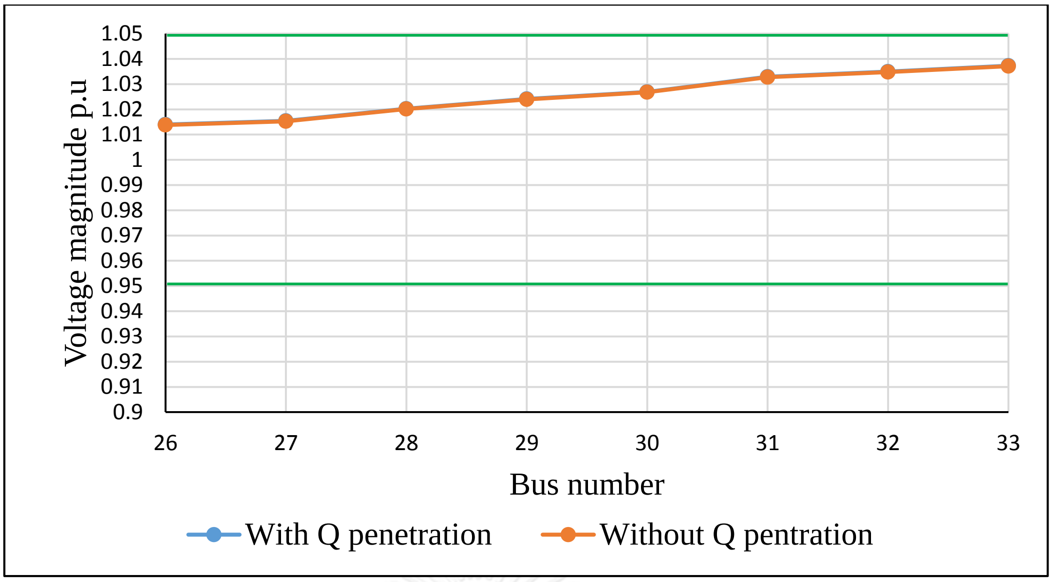


Figure 41 Voltage variation of each bus at feeder 3 during minimum load

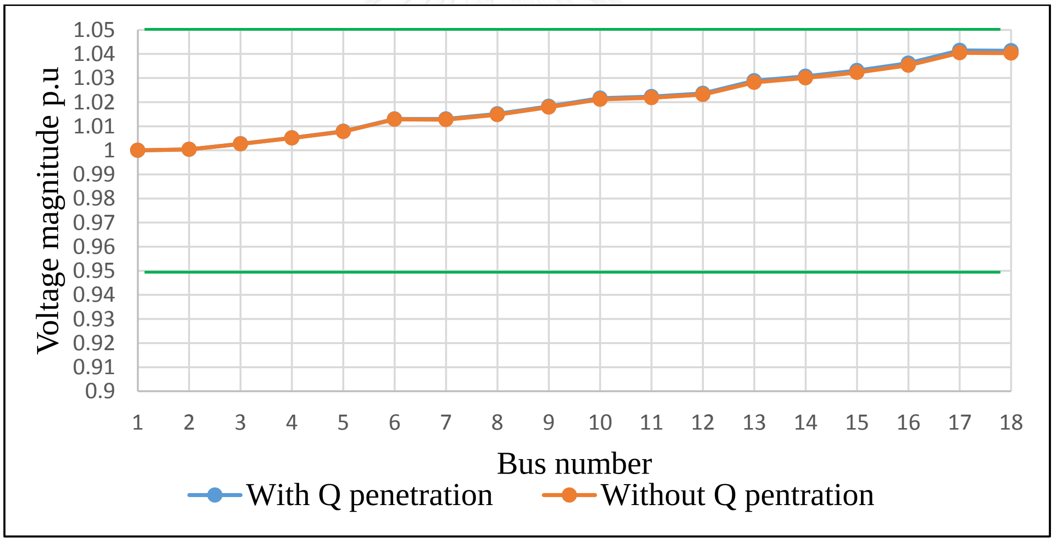


Figure 42 Voltage variation of each bus at feeder 2 during minimum load

Figure 40 shows that the voltage profile of each bus without Q penetration is higher than voltage profile with Q penetration. In this case, PV inverter has to absorb reactive power from the system to minimize the voltage deviation.

By using the proposed method, when power from PV 17 reduces to 50% of its capacity (1.509 MW) , it has to absorb reactive power from the system the optimum value -0.0198 MVAr to minimize voltage deviation. On the other hand, the limitation of $Q_{PVk\min f}$ = -0.9317 MVAr and $Q_{PVk\max f}$ = 1.0832 MVAr. This optimal value is between $Q_{PVkminf}$ and $Q_{PVkmaxf}$, so the optimal value of Q_{PV}= -0.0198 MVAr.

From this result, it is observed that reactive power control is really important to maintain the voltage within limitation and reduce voltage deviation that can influence to the customers. Figure 43 will show the reactive power control to respond the variation of active power in the system.

Table 4 Q optimal value responding to percentage of PV penetration from feeder 3 during minimum load

PV penetration (% of total capacity)	Q optimal value (MVAr) without constraint limitation	Q optimal value (MVAr) with constraint limitation	Power factor with constraint limitation
10%	1.5764	1.5764	0.0952
20%	1.1807	1.1807	0.2476
30%	0.7827	0.7827	0.5006
40%	0.3824	0.3824	0.8447
50%	-0.0198	-0.0198	0.9996
60%	-0.4238	-0.4238	0.9056
70%	-0.8293	-0.8293	0.7865
80%	-1.2362	-1.1393	0.7272
90%	-1.6444	-0.9544	0.8181
100%	-2.0538	-0.6915	0.9090

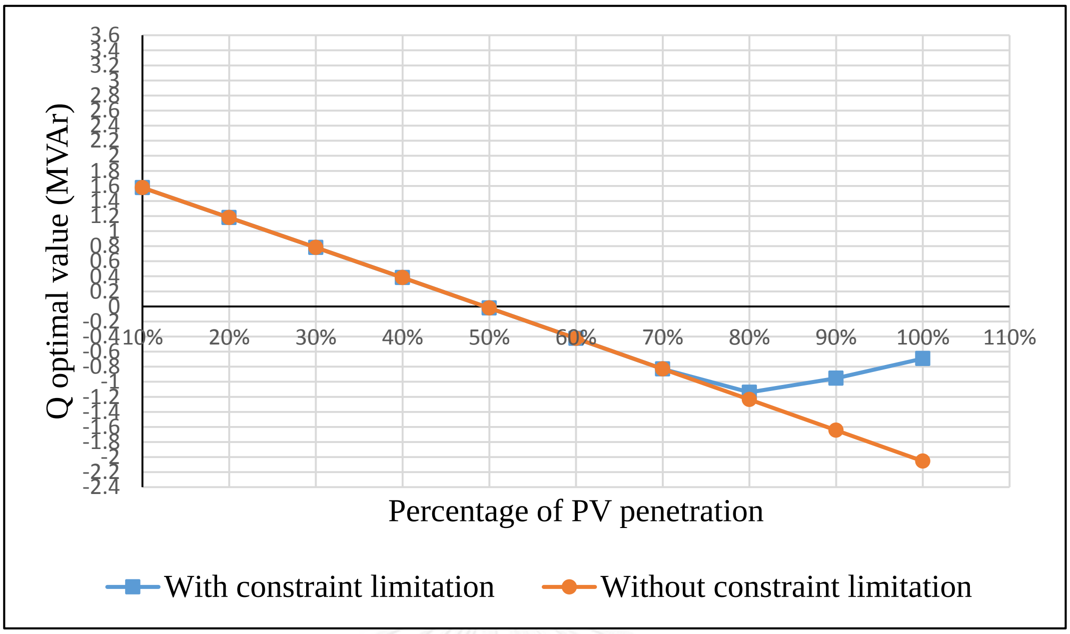


Figure 43 Optimal Q value responding to variation of PV penetration

Figure 43 shows that inverter has to decrease reactive power to improve voltage profile in the system when percentage of PV penetration increases. It can be observed that amount of reactive power from inverter is nearly zero when 50% of PV penetration is supplied to the power system. After that point, inverter has to absorb reactive power to decrease over voltage profile and maintain voltage level within the limit.

CHAPTER V
CONCLUSION

5.1 Conclusion

This research has examined the impacts of solar PV on voltage profile by considering reactive power injection of inverter. PV system modeling shows that power from PV varies every minute due to irradiance and temperature. The variation can make voltage profile to be out of the normal limitation in the power system. Proposed algorithm can be used to calculate the optimal reactive power from PV to minimize voltage deviation in the system. If the system voltage profile is low compared to the nominal voltage, thus inverter can inject reactive power as much as it can to increase voltage when PV power change because of variation of sunlight or night time. On the other hand, if the system voltage profile is over the limit if comparing to nominal voltage, thus inverter has to absorb reactive power from the system to decrease voltage. It is worth nothing that sometimes voltage fluctuates inside the regulatory limit at the PCC but the voltage at the far end of the feeder maybe out of the allowable bound. It is really hard to cope with this situation by using utility's voltage regulation devices. The proposed method, fortunately, is applicable and effective in this case.

5.2 Future work

According to this research, the optimal reactive power from one PV system can improve voltage profile because of fluctuation of sunlight and load level based on the proposed method. It can be found that the impact of PV plants to distribution system depends on all PV systems connected and only one PV system cannot control reactive power to improve all voltage buses. So the future research should consider the impact of all PV systems connected and find out a method to calculate the optimal reactive power of all PV systems. Finally, it should observe not only the impacts of PV system to the distribution system but also other renewable energy sources, like wind generators or other inverter-based distributed generations to investigate its advantages and disadvantages.

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APPENDIX

Table 5 Load data for IEEE 33 bus distribution system

Bus-No	P_load(KW)	Q_Load(KVAr)	Bus_No	P_load(KW)	Q_load(KVAr)
1	0	0	18	90	40
2	100	60	19	90	40
3	90	40	20	90	40
4	120	80	21	90	40
5	60	30	22	90	40
6	60	20	23	90	50
7	200	100	24	420	200
8	200	100	25	420	200
9	60	20	26	60	25
10	60	20	27	60	25
11	45	30	28	60	20
12	60	35	29	120	70
13	60	35	30	200	600
14	120	80	31	150	70
15	60	10	32	210	100
16	60	20	33	60	40
17	60	20			

Table 6 Branch data for IEEE 33 bus distribution system

Branch number	Sending end bus	Receiving end bus	R(Ω)	X(Ω)
1	1	2	0.0922	0.0470
2	2	3	0.4930	0.2512
3	3	4	0.3661	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	0.7115	0.2351
8	8	9	1.0299	0.7400
9	9	10	1.0440	0.7400
10	10	11	0.1967	0.0651
11	11	12	0.3744	0.1298
12	12	13	1.4680	1.1549
13	13	14	0.5416	0.7129
14	14	15	0.5909	0.5260
15	15	16	0.7462	0.5449
16	16	17	1.2889	1.7210
17	17	18	0.7320	0.5739
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3555
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3084
23	23	24	0.8980	0.7091
24	24	25	0.8959	0.7071
25	6	26	0.2031	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0589	0.9338
28	28	29	0.8043	0.7006
29	29	30	0.5074	0.2585
30	30	31	0.9745	0.9629
31	31	32	0.3105	0.3619
32	32	33	0.3411	0.5302

VITA

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