REACTIVE POWER MANAGEMENT IN A DISTRIBUTION SYSTEM BY PHOTOVOLTAIC INVERTER

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ในปัจจุบันการผลิตไฟฟ้าจากเซลล์ไฟฟ้าพลังงานแสงอาทิตย์มีการเพิ่มขึ้นอย่างกว้างขวางเป็นผลอันเนื่องมา จากการตระหนักถึงการเพิ่มขึ้นของปรากฏการภาวะเรือนกระจกหรือการปล่อยก๊าซของเสียเข้าสู่สิ่งแวดล้อมระบบจำ หน่ายของไฟฟ้ากำลังโดยใช้พลังงานแสงอาทิตย์จึงเป็นอีกทางเลือกในการผลิตพลังงานไฟฟ้าอีกทาง และสามารถใช้ประยุกต์เข้ากับวัตถุประสงค์อื่นๆ เช่น ปัญหาการควบคุมแรงดัน และยังลดปัญหาเรื่องการสูญเสียพลังงานไฟฟ้าจริงเมื่อมีการยกระดับกระบวนการของสายส่งและระบบจัดจำหน่าย ถึงอย่างไรก็ตามการปรากฏตัวของระบบโซลาเซลล์ที่มากเกินไปก็อาจจะส่งผลกระทบที่เป็นอันตรายต่อระบบการดำเนินงานของระบบจำหน่าย เนื่องจากความผันผวนการเพิ่มขึ้นของโซลาเซลล์ เป้าหมายของวิทยานิพนธ์นี้คือการหาค่าที่เหมาะสมของการควบคุมพลังงานไฟฟ้าเสมือน โดยพิจารณารูปแบบการทำงานของตัวแปลงกระแสไฟฟ้าในโซลาเซลล์เมื่อมีการละเมิดแรงดันซึ่งส่งผลกระทบต่อระบบจัดจำหน่าย ผลลัพธ์ที่ได้จากการหาที่เหมาะสมที่สุด คือกลุ่มเซตของเพาเวอร์เฟคเตอร์ การคงสถานะเพาเวอร์เฟคเตอร์ และลักษณะรูปแบบการทำงานของแรงดันในกำลังไฟฟ้าเสมือน เมื่อพิจารณารูปแบบการทำงานของตัวแปลงไฟฟ้าในแง่ของการควบคุมกำลังไฟฟ้าเสมือน ซึ่งทดสอบกับระบบจำหน่าย IEEE 33 บัส โดยการใช้กล่องเครื่องมือในโปรแกรมสำเร็จรูปแมทแลป และการจำลองเหตุการณ์เหตุการณ์ในโปรแกรมแมทแลป ดังนั้นการคำนวณค่าที่เหมาะสมที่สุดของกำลังไฟฟ้าเสมือนจากตัวแปลงกระแสไฟฟ้า สามารถยกระดับรูปแบบแรงดันและลดการสูญเสียของกำลังไฟฟ้าจริงเมื่อมีการเปลี่ยนแปลง

ในทางตรงกันข้ามเมื่อมีการเปลี่ยนแปลงของระดับแรงดันและการเกิดละเมิดแรงดัน ตัวแปลงกระแสไฟฟ้าในเซลล์ไฟฟ้าพลังงานแสงอาทิตย์สามารถกำจัดหรือดูดซับพลังงานไฟฟ้าเสมือนได้ รูปแบบการควบคุมการหาค่าที่เหมาะสมที่สุดของกำลังไฟฟ้าเสมือนคือการคำนวณหาค่าความสูญเสียที่น้อยที่สุดของแต่ละบัสในระบบจำหน่าย เป้าหมายของวิธีการนี้อยู่บนพื้นฐานของวิธีการคำนวณการไหลของกระไฟฟ้านิวตัน ราฟสัน ระบบจำหน่ายแบบเส้นเดียว IEEE 23 บัสได้ถูกเลือกเพื่อนำมาวิเคราะห์ปัญหาการลดกำลังสูญเสียและปัญหาการควบคุมแรงดันที่หลากหลายเงื่อนไขในการพิจารณา

สาขาวิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อนิสิต	....
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KEYWORD: DISTRIBUTION SYSTEM VOLTAGE PROFILE PV INVERTER OPTIMAL REACTIVE POWER CONTROL MODES MATPOWER TOOLBOX PSO ALGORITHM NEWTON-RAPHSON POWER FLOW CALCULATION

Akasinh Luangduangsitthideth : REACTIVE POWER MANAGEMENT IN A DISTRIBUTION SYSTEM BY PHOTOVOLTAIC INVERTER. Advisor: Assoc. Prof. SOTDHIPONG PHICHAISAWAT, Ph.D.

Nowadays the electrical generation from the solar photovoltaic resource is extensively promoted because of the concern about greenhouse gas emission. A distribution system can be powered by a variety of solar photovoltaic resources, and can be used for various objectives, it can improve voltage profile problems and can reduce real power losses of the upgrading process of transmission and distribution system. However, presence much of the PV system may have detrimental impacts on the operation of the distribution system because of the variation of solar photovoltaic increases. This thesis proposed the optimal reactive power control modes by PV inverters when the overvoltage impact occurs in the distribution system. The results of these optimal values, there are set to unity power factor, fixed power factor, power factor as , and Q(V) characteristic function. In order the inverter can control Q modes. From tested on IEEE 33 bus radial distribution system and used in MATPOWER toolbox and simulated in MATLAB programs. Therefore, the calculation of optimal reactive power from the inverter can to improve the voltage profile and to reduce real power losses when active power change.

In contrast, the voltage changes and over the limits, the PV inverter can inject or absorb reactive power. The optimal reactive power control mode is calculated to minimize losses of all buses by the proposed method based on Newton-Raphson power flow. The IEEE 33 bus radial distribution system is selected to analyze the loss and voltage profile problem in various conditions.

Field of Study:	Electrical Engineering	Student's Signature ....
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CHAPTER 1
INTRODUCTION

1.1 Background of solar photovoltaic

Due to the limitation of fossil fuel resources, the growing of world energy demand and the environmental concerns of greenhouse gas emission in the future, application of renewable energy resources have been widely promoted. Especially, application of distributed generation (DG) from renewable energy sources such as solar photovoltaic, wind turbine, hydro power connected to the feeder in the distribution system increases continually. Solar photovoltaic (PV) is a fast to growing of renewable source in recent years. The efforts increased in the semiconductor material technology result in the appearance of solar photovoltaic commercial. Consequently, the PV is an important alternative of energy sources [1].

The PV technology is the lack of moving parts that offer the possibility to obtain a long operating time (>20 years) and low maintenance cost. The main drawbacks are the high manufacturing cost and low efficiency (15-20%). As one of the most promising renewable and clean energy resources, PV inverter is development also boosted by favorable governmental support [2-4].

According to Asian Photovoltaic, at the of 2016 the total installed PV capacity more than 51 GW of new PV electricity generation systems, which corresponds to roughly two-thirds of the world widely new PV power installed in 2016. The largest market is China with 35 to 38 GW, followed by Japan with about 8.2 GW, and India with over 4 GW. In 2017, the market exceeding 60 GW is possible [5]. Thailand 15 years renewable energy development plan in early 2009, with a target to increase the renewable energy share to 20% of the country's final energy consumption in 2022. Besides a range of tariff incentives, solar PV systems are eligible for a feed in the premium periods of 10 years. The original THB 8/kWh (facilities in the three southern provinces and those replacing diesel systems are eligible an additional THB 1.5/kWh) reduce to THB 6.5/kWh for those projects not approved before 28 June 2010. The capacity 500 MW is increased to 2 GW begin in 2012, as the original, the target is highly oversubscribed. In addition to the projects are being developed with PPAs.

The 2015-2036, Thailand's Alternative Energy Development Plan (AEDP 2015) is approved by NEPC on 17 September 2015. The plan aims increase of solar energy with installation capacity of 6 GW by 2036. At the end of August 2017, Small Power Producers (SPP) and Very Small Power Producers (VSPP). With an installed solar PV capacity of 2.5 GW have signed delivery contracts according to the Energy Regulatory Commission in Thailand. However, there is a PV rooftop capacity of about 130 MW operational [6].

In Figure 1.1, the total PV power installed in Asian, at the end of 2017. The Figure shows an unbalanced market; where China is leading with 53.1 GW of total installed capacity, Japan with increased PV capacity at a total of 7 GW, India with third 9.6 GW, Thailand with an installed PV capacity of 2.5 GW, and Lao P.D.R with 0.1 GW on the market.

The high penetration of PV technology is inducing to the continuous increase of energy. The price generates in traditional coal and hydropower plant. PV systems have required to reduce costs. In order competed in the energy market but at the same time to provide a good and reliability.

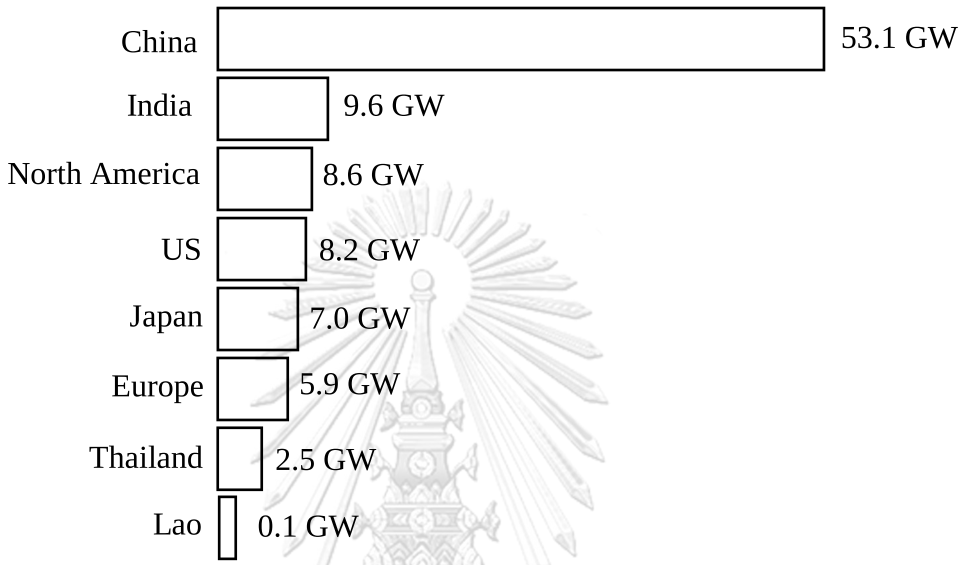

Figure 1.1 Total solar power capacity installed at the end of 2017

Normally, the reliability of the PV system is associated with the inverter topology and main components (semiconductor). The lifetime in the system regarding the PV systems has been estimated to be about 25 years, while inverter sector is expected to improve in the future [7].

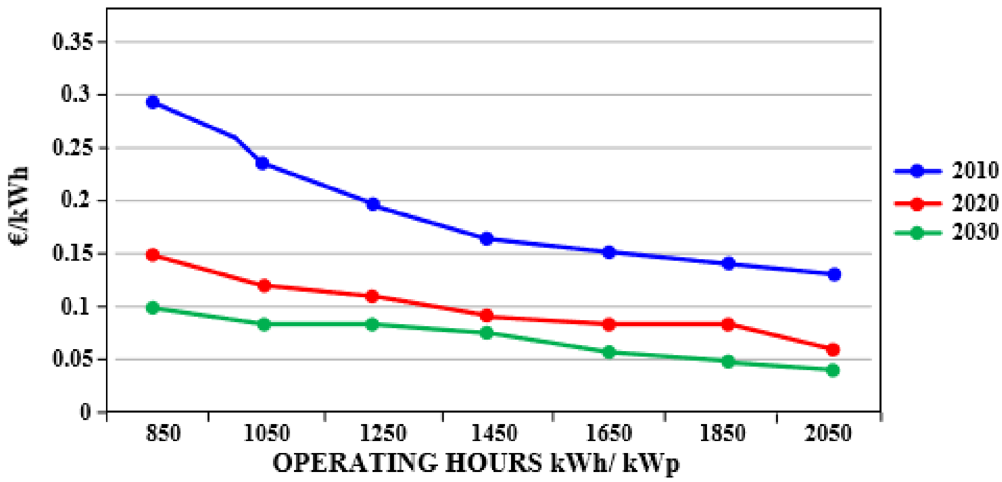

Figure 1.2 Level cost of electricity for large PV systems [7]

The energy production costs in 2010 varied from €0.15/kWh in the north of Europe to €0.12/kWh, the south of Europe and Asia. In 2020 production costs are expected to occur for large PV systems. The difference between €0.07/kWh to €0.17/kWh, the price of residential; PV system is expected to decline significantly in the next 20 years [8].

1.1.1 Grid-connected PV systems

PV system is generated energy from the solar photovoltaic to the utility grid. But all power providers face a common set of issues in connecting small renewable energy systems to the grid. They range from small residential and commercial rooftop systems to large utility-scale solar power stations. Unlike stand-alone power systems, a grid-connected system rarely includes an integrated battery solution, as they are still very expensive. When conditions are right. Beyond, consumption by the connected load to the utility grid.

A connection of the solar photovoltaic system can operate only through an interconnection agreement between the consumer and the utility company. The agreement details and the various safety standards are followed during the connection. Figure 1.3 shortly presents the evolution of grid-connected PV systems together with off-grid systems up to the year 2013

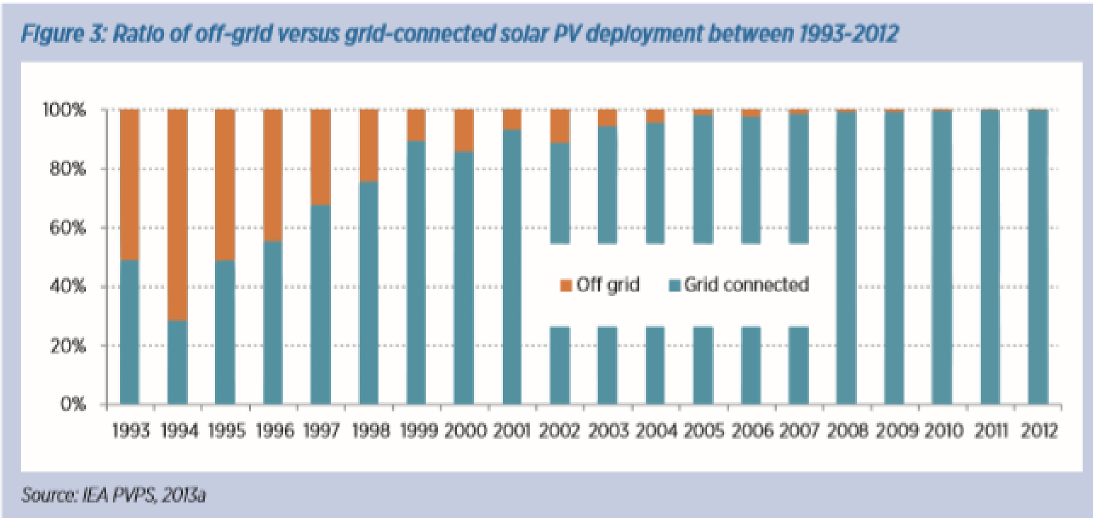

Figure 1.3 Installed grid-connected and off-grid for PV systems in report countries between 1993-2013 [9]

Grid-connected are centralized systems for power plants produce to transform directly to the utility grid. The configuration is to ground mounted and the power rated.

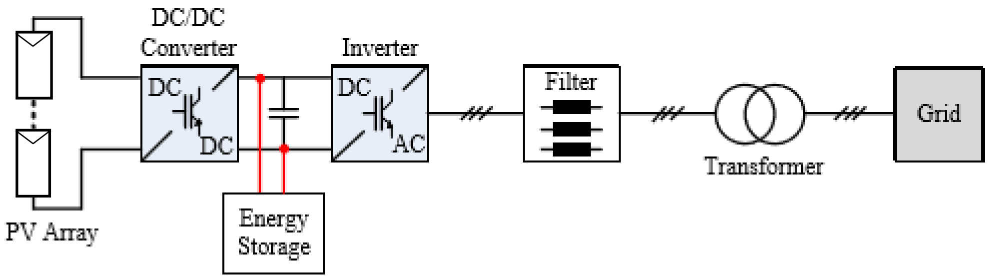

Figure 1.4 Component of a grid-connected PV systems [10]

The typical configuration of the PV system can observe in Figure 1.4 depending on the number of modules, the PV array converts the solar irradiation into specific DC current and voltage. A DC/DC boost converter is using to meet the voltage level required by the inverter. Energy storage devices can include in order to store the energy produced in the case of grid support connection. The power conversion is realized by a three-phase inverter which delivers the energy to the grid. High-frequency harmonic that appear due to power semiconductors switching is reduced by the filter. The transformer is used only for galvanic isolation between the PV system and utility grid [11].

1.1.2 Grid-connected topology for PV systems

The current, a technology of inverters has created and developed rise for solar systems able to divide, follow characteristic of the inverter connected has four types below:

- Central Inverters

In Figure 1.5a, the PV arrays are connected in parallel to one central inverter. The configuration is used for three-phase power plants, with power ranges between 10-1000 kW. The main advantage of a central inverter is high efficiency (low losses in the power conversion stage) and low cost. The drawback of this topology is long DC cables required to PV modules connect. Inverter losses caused string diodes, mismatches between PV module and centralize the maximum power point tracking (MPPT).

- String Inverters

In Figure 1.5b are Compared to central inverters. In the topology of PV strings are connected to separate inverters. If the voltage level before the inverter low, the DC-DC converter can used to boost. For topology string have an inverter connected; string diodes are eliminated to total loss reduction of the system. The configuration allows individual MPPT for each string. Hence, the reliability of the system is improved. Due to the system is no longer dependent on only one inverter compared to the central inverter topology.

- Multi-String Inverters

In Figure 1.5c the power ranges of configuration are maximum 5 kW and strings use an individual DC-DC converter. Before the connection to a common inverter. The topology allows the connection of inverters with different power ratings and PV modules with different current-voltage (I-V) characteristics. MPPT is implemented for each string, thus an improved power efficiency can be obtained.

- Module Inverters

in Figure 1.5d consists of single solar panels connected to the grid through an inverter. The better efficiency is an obtained compare to string inverters as MPPT implemented for each panel. Still, voltage amplification might be needed with the drawback of reducing the overall efficiency of the topology (losses in DC/DC converter). The price per watt is still high compared to the previous configurations.

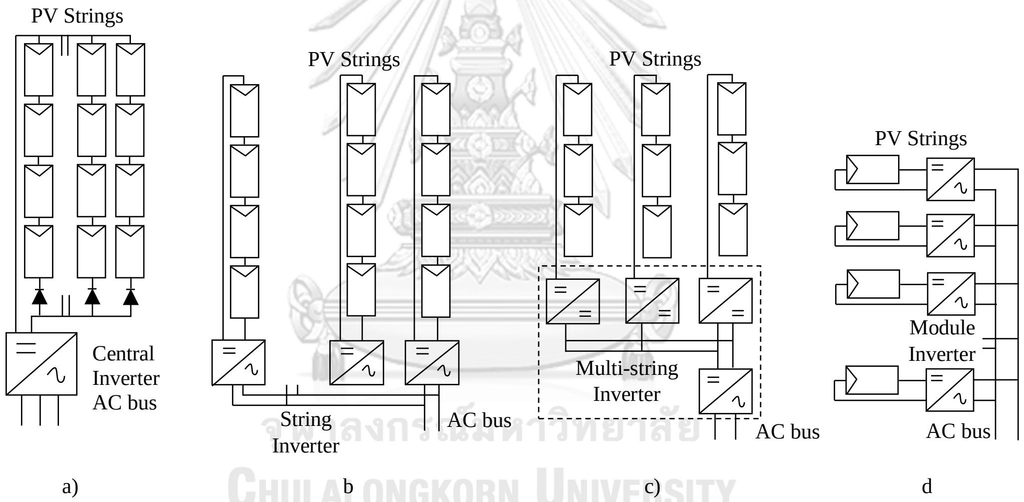

Figure 1.5 PV grid-connected systems configurations (a). Central Inverters; (b). String Inverters; (c). Multi-String Inverters; (d). Module inverters [11]

1.2 Motivation

Over the past several decades, various reasons have a continuous rise in solar photovoltaic systems. Some of them are reduced a price of the PV module product, improve social acceptance of PV parks, or government support for renewable energy. At the same time, the grid-connected systems development requires better understanding, evaluation, and performance of the PV inverters. In case of normal and abnormal conditions on-grid, as well as the quality of generates by the PV systems.

The increasing number of grid-connected, PV inverter has given rise to problem concern the stability and safety of the utility grid. The main problems are:

1.2.1 Voltage rise problem

One of the notable impacts of a high number of the distribution PV systems along in the low voltage distribution systems of voltage rise to problem. The result of offsetting the load from PV generators feed in. when there is the PV generator, the voltage would drop along show that in Figure 1.6 (b) for a simple redial feeder show that in Figure 1.6 (a). With PV, if all loads are perfectly balanced by PV generation at each point connection. Then ideally, no active power would flow through the feeder and voltage profile would be nearly flat as in Figure 1.6 (c). However, if the PV generation exceeds feeder loads, especially at the furthest end of the feeder, then power flows back from feeder to the upstream network and this is caused of the voltage rise, as shown in Figure 1.6 (d) [12].

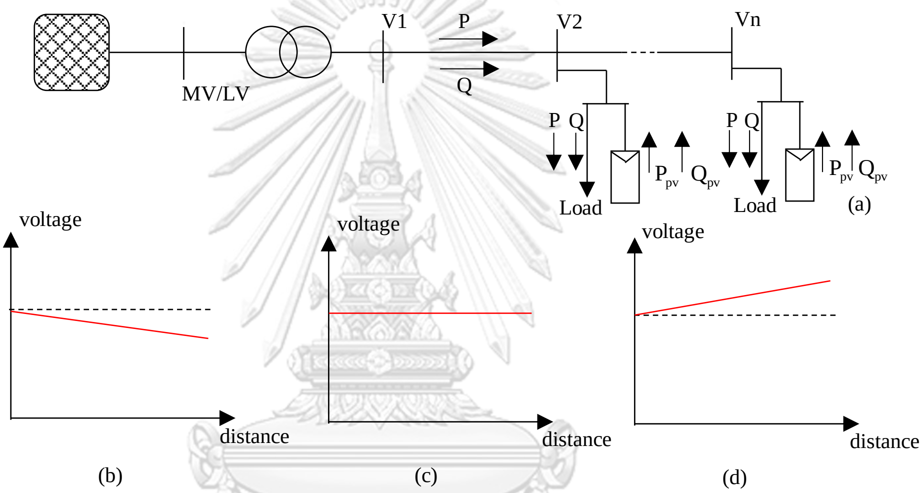

Figure 1.1 Voltage profile along feeder with different PV generation (a) single line diagram of feeder (b) voltage drop (c) flat voltage profile (d) voltage rise

1.2.2 Increased voltage unbalances

Voltage unbalance is considered to one of the most undesirable power quality problems in low voltage networks. The voltage unbalances can be observed in individual customer loads due to phase load unbalances. In the studies, an analysis voltage unbalance is carried out for features of the installed PV systems such as their location and power generation capacity lead to an increase in voltage unbalance. This most the power quality in the distribution networks, due to the random location of the PV installation.

1.3 Research objective

The objectives of this research are described as follows:

1) Study the IEEE 33 bus radial distribution system.
2) To implement the voltage regulation strategies contributed by Thailand grid code.
3) To calculate optimal reactive power control modes from PV inverters to improve voltage profile and to reduce real power loss.

1.4 Scopes

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

1) Estimate of the maximum PV inverter capacity in a distribution system.
2) Power from inverter is assumed to be the power from PV generator.
3) PV connected bus is treated as a PQ bus, the generating both are active power and reactive power.
4) Reduces power loss and improves voltage profile by PV inverters are analyzed according to steady state analysis and an inverter operation mode. For example, reactive power injection/absorption.

1.5 Methodology

1) Review literature on background knowledge of solar energy and inverter.
2) Grid code regulation.
3) Calculating real power loss in case of steady state condition in grid-connected PV using load flow analysis.
4) Proposing a method to determine the optimal reactive power control modes in case of active power change.
5) Analyzing the reduces real power loss and the improves voltage profile in case of voltage profile with and without PV inverters by MATPOWER toolbox and MATLAB program.

1.6 Expected contribution

This thesis summarizes the status of reactive power management and compares different global optimization methods. A modified MATPOWER code utilizing particle swarm optimization algorithm is developed to solve the reactive power control mode by the PV inverter in the power systems.

The expected contribution of this mainly includes the following:

- Applying PSO algorithm to adjust the value of control variable (voltage magnitudes), in the power systems to minimize the real power loss.
- Identifying the optimal reactive power control modes of PV inverters in a distribution system.
- Introducing MATPOWER toolbox to calculate the power flow and to manage the equality constraints in the reactive power control modes.

CHAPTER 2

GRID CODES AND REGULATIONS

In the last years, a major number of distributed systems (DGs) have been connected to grids, with the primary aim of increasing renewable energy production. The utility grid is not ideal; therefore, the grid voltage and frequency may be exceed the specified limit, which is undesirable and unacceptable [6]. The power systems require additional services, such as voltage and frequency control, power quality improvement and energy balance to be efficient and reliable. In electrical systems, the distribution system is responsible to maintain the correct operators and can purchase ancillary service directly from the PV generators. Until recently, the inverter requirements in case of the abnormal grid condition and faults to disconnect and wait for fault clearance. The massive development in the PV sector confronted new challenges for the inverter which is now required to contribute to grid stability by providing support function.

It is well known that there may be quality problem in utility grid related to the following fields:

- Magnitude of the supply voltage
- Voltage fluctuations
- Voltage dips and short supply interruptions
- Voltage and current distortion
- Frequency accuracy

In figure 2.1 show that the main challenge of inverters control function

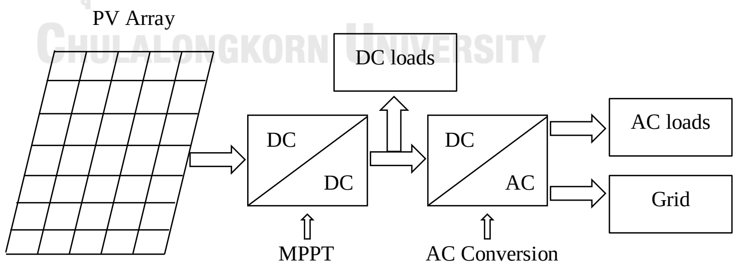

Figure 2.1 PV inverter control function [13]

In the grid-connected inverter, the power is generated by the PV plant is directly supply to the transmission line and distributed. However, the utilize energy of batteries and other energy storage device is not required that makes the arrangement less space, reduced investment cost, and maintenance than a standalone system [14].

Further, in this chapter, the requirements for the grid-connected PV systems will be presented in form a parallel between the Small Power Producer (SPP) and the Very Small Power Producer (VSPP), Thailand grid code for voltage level network [15, 16]. The most relevant requirements concern the grid interface and power quality.

2.1 Inverter characteristic

Currently, power electronics play is significant role in distributed energy resource system because of utility grid interconnection is possible for a wide variety of solar energy resources. In condition, the inverter is important in the system. The basic function of PV inverters is fully integrated in a smart grid. There are two main reasons in grid management.

2.1.1 Advanced grid features

A smart inverter can reduce losses of produced power from overvoltage by absorb reactive power without disconnection from the grid. In a grid-connected PV system, the inverter is a capability of proving reactive power to the grid by the output power from PV systems. Therefore, the fast responding speed helps the inverter (inject/absorb) the reactive power in case of rapid voltage changes. However, the inverter can supply positive and negative reactive power show that in fig.2.2.

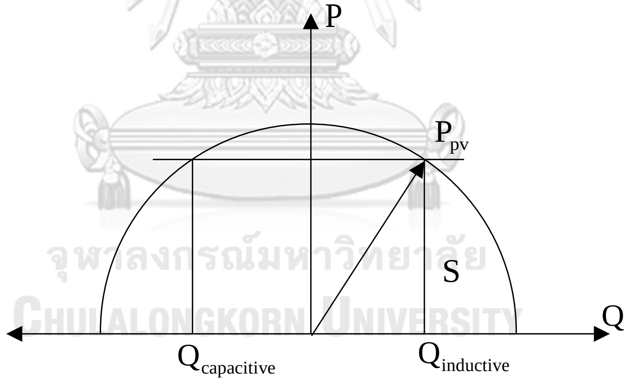

Figure 2.2 The inverter capacity of reactive power limits [17]

Figure 2.2 Consequently, the inverter is used as entire rating to supply reactive power if no active power is generated. The maximum reactive power that can be extracted from an inverter is represented by (2.1).

$$\left|Q_{pv}\right| \le Q_{pv}^{max} = \sqrt{(S_{pv}^{max})^2 - (P_{pv})^2} \tag{2.1}$$

In the real inverter, there are many modes to control reactive power for meeting the grid management requirements. In this thesis will be proposed four reactive power control modes as follows in chapter 3.

2.1.2 Communication

The communication is necessary in smart grid systems. Since PV inverters are most flexible with communication. From information of inverter can be sent to control center or automatic grid controller. In addition, the voltage or power at the inverter terminals can help to evaluate the actual situation of the grid. Therefore, output power of PV systems can be required to values. From any active power and reactive power set point can be set via communication to reach the limit immediately.

The power reducer box or power plant controller sends the specifications of the grid operator to the Sunny Central.

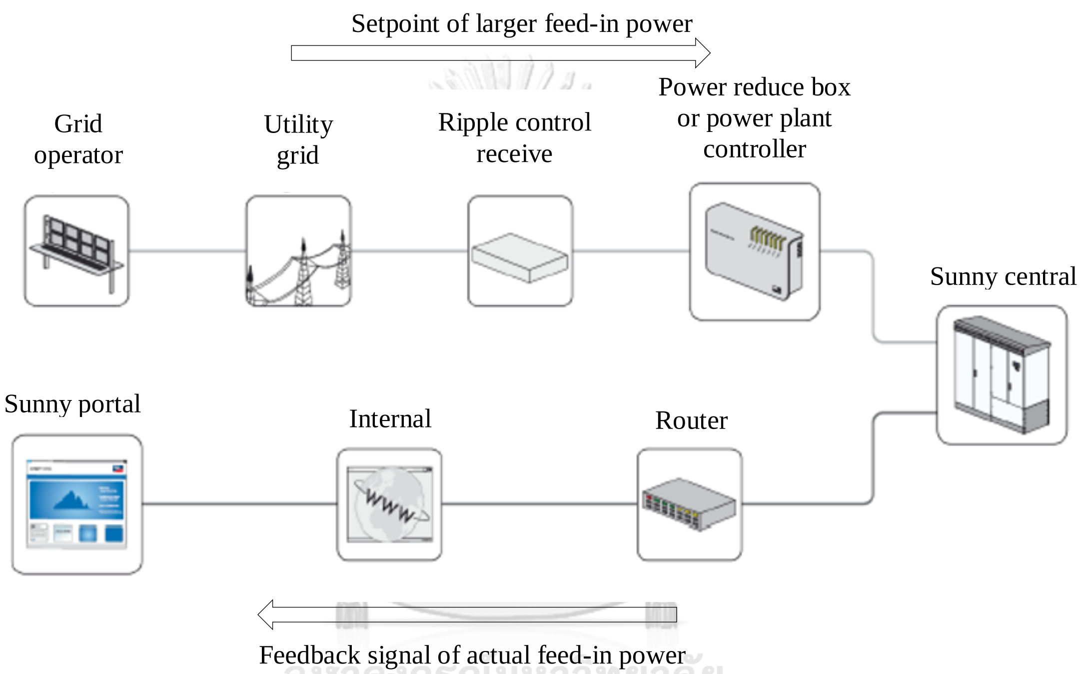

Figure 2.3 Principle of grid integration [18]

In order connect the Sunny Central to a computer via the service interface or via the internet the Sunny Central must be integrated in the system network.

2.2 Grid interface requirements

2.2.1 Undervoltage

Under voltage is defined as a condition where the voltage drops are applied to 90% of rated voltage or at least 1 minute. The depending on the location of the fault occurs in the network. But take note that it is not always a problem of the electric utility not having adequate capacity transformers can act like a choke, restricting how much total power gets through to your systems. Perhaps may be the facility in added new equipment and increased the load beyond what the line could deliver. In isolated cases, will be the facility added a motor with a long cable run, and the voltage drop in that circuits resulted in low voltage at that motor. Brief medium voltage (MV) conditions also happen when someone starts a large load notification in the power company, or when the power is a short circuit to grounded or to another line. Even loose cable connections can cause low voltage [12].

Overvoltage is defined as an increase in the RMS value of the voltage up to a level between 1.1 p.u. to 1.8 p.u. the power frequency for periods ranges from a half cycle to a minute. Overvoltage is lesser common than under voltage but also happen due to system faults. Overvoltage can occur due to a single line to ground fault, which in turn raise the voltage of the other phases. It is can also cause due to disconnection of heavy industrial loads or switching on the capacitor banks. A change in ground reference would give voltage rise to the ungrounded system [12].

2.2.2 Overvoltage

Overvoltage is defined as an increase in the RMS value of the voltage up to a level between 1.1 p.u. to 1.8 p.u. and accepted time duration is up to 1 minute. Overvoltage is lesser common than under voltage but also happen on the system faults. Overvoltage can occur due to a single line to ground faults, which in turn is to raise the voltage of the other phases. It is can also cause due to disconnection of heavy industrial loads or switching on the capacitor banks. A change in ground reference would give voltage rise to the ungrounded in the system [12].

Under normal operating conditions, the voltage variations should not exceed the standard limits table 2.1.

Table 2.1 Supply voltage variation limits from Thailand grid codes [15, 19]

Electricity authority	Installed capacity			Power controls		
	HV	MV	LV	PFC	RPC	APC
MEA	- 90 MW (69 kV) 180 MW (115 kV)	4 MW (12 kV) 8 MW (24 kV) 20 % of transformer	- 5 MW (400/230 V) 15 % of transformer	- - - > 0.85 -	- - - - -	- - - - -
PEA	- - 120 MW 230 MW (115 kV)	8 MW (22 kV) 10 MW (33 kV) 75 % of transformer	- 5 kW (380/220 V) 15 % of transformer	- > 0.90 (< 500 kV) > 0.95 (> 500 kW)	- - Fixed PF Q(V)	- - Decrease 10 %

Note: Standard range can be set 85 % to 110 % for Metropolitan Electricity Authority (MEA) and set 90 % to 110 % Provincial Electricity Authority (PEA)

In table 2.1, the power controls for voltage variations are also available. The voltage deviations are detected to voltage measurement at MEA and PEA, which is the default according to the standards.

2.2.3 Low voltage ride through

In electrical power engineering, fault ride through, sometimes under voltage ride through, is the capability of electric generators to stay connected in short periods of lower electric network voltage. It is need in the distribution level (wind turbine, PV systems, distributed cogeneration, etc.) to prevent a short circuit at HV or EHV level from cause a widespread loss of generation [20].

2.3 Grid code in Germany

2.3.1 Active power control

Demand for real power control from a medium voltage (MV) and low-voltage (LV) networks connection. It is dependent on the installed capacity of the PV system show that in table 2.2.

2.3.2 Reactive power control

According, an installed capacity of PV system on the grid connected in MV and LV networks. The controller's distribution system operator (DSOs) defined, the PV system is necessary to regulate reactive power show that in table 2.3.

Table 2.2 Requirements for active power curtailment of PV systems [21]

System size (kW)	Requirements
$P_n \geq 100$	Remote control interface for DSO
$30 \leq P_n < 100$	
$P_n < 30$	A choice between remoted control interface for DSO or permanent feed-in limitation to 70 % PN

Note: P_n – quantity of installed capacity

Table 2.3 Requirements for reactive power control of PV systems [21]

Voltage level	System size	Technical requirements
MV	Any size	A minimum power factor of 0.95 (leading/lagging)
LV	S_N < 3.68 kVA	No requirements
	3.68 kVA ≤ S_N ≤ 13.8 kVA	Minimum power factor of 0.95 (leading/lagging) if P(t) ≥ 20 % S_N
	S_N > 13.8 kVA	Minimum power factor of 0.9 (leading/lagging) if P(t) ≥ 20 % S_N

2.3.3 Power factor control

The requirement of power factor control in Germany for PV systems can be defined three methods following:

Step 1: The fixed power factor characteristic (cos φ) method. The PV system is operated at a static power factor supplied by the distribution networks (see Figure 2.4). The method is primarily suitable for systems where the active output generation is constant.

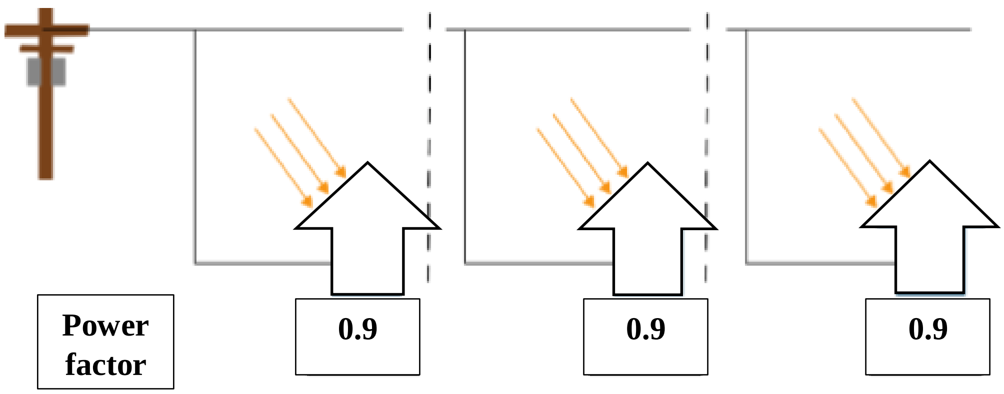

Figure 2.4 The reactive power/voltage characteristic method; system operate at different power factors due to different local voltage [22]

Step 2: With the power factor characteristic cos φ (P) method, the reactive power provided depends on the active power fed in by the generator at its point of connection to the grid show that in Figure 2.5. The distribution system is experienced a different level of insolation and presumably outputting. The different amount of active powers, each as operation systems is a different power factor.

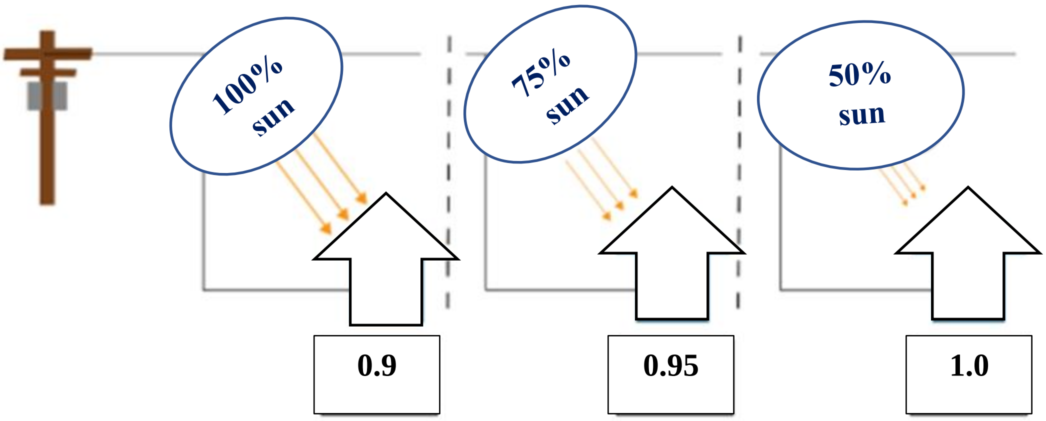

Figure 2.5 The fixed power factor method; each system operates at the same set power factor [22]

Step 3: Unlike the previous two methods, the reactive power/voltage characteristic or Q(V) method relies on local voltage information on the reactive power control process. Under this method, the reactive power output by a generator's inverter is proportional to the voltage level at grid connected. See in Figure 2.6.

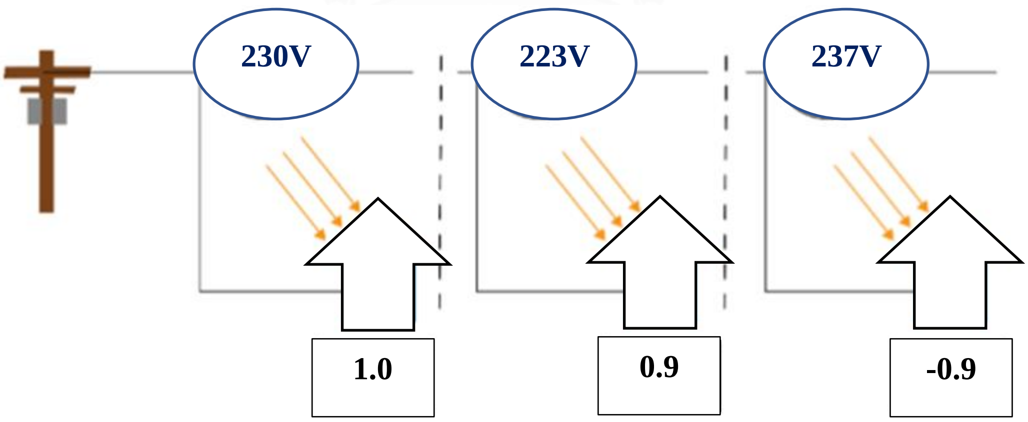

Figure 2.6 The power factor characteristic method; systems operate at different power factor due to deferent active power output [22]

2.4 Grid code in Austria

In Austria, the fundamental technical of the grid connected on distributed generation (DG) is similarly rather of grid-connected in Germany.

2.4.1 Active power control

Generation plants is a system capacity of more than 100 kW needs to implement active power control on demand of the distribution network operators (DNOs). For smaller plants, there are no common requirements for active power control. However, some DNOs required an external control unit for smaller plants above 5 kW.

2.4.2 Reactive power control

Depending on the capacity of the generation plant, the different requirements apply to the provision of reactive power.

Table 2.4 Requirements for reactive power control of PV systems [21]

The capacity of the generation plant	Requirement
$S_N < 3.68$ kVA	No control requirement (power factor shall be > 0.95)
3.68 kVA $\leq S_N \leq$ 13.8 kVA	A minimum power factor of 0.95 (over/under excited), a setpoint defined by DNO
$S_N > 13.8$ kVA	A minimum power factor of 0.95 (0.90 if required due to local needs) (over/under excited), a setpoint defined by DNO

The reactive power control strategies are defined to set point by the DNO and depended on local grid condition.

2.5 Grid code in Thailand

Applicants are needed to design and install a power control system from the generator to be maintain the quality of power supply at the connection point. There are conditions following:

2.5.1 Voltage regulation and power factor

Applicants are required to control the voltage level from the generator with the highest and lowest voltage standards MEA from table 2.5, 2.6 and PEA from table 2.7.

Table 2.5 The highest and lowest voltage level standards of MEA in case the applicant without use the feed-in systems [19]

Voltage levels	Normalcy		Emergency	
	Highest	Lowest	Highest	Lowest
115 kV	117.6 kV	106.4 kV	123.0 kV	96.0 kV
69 kV	70.4 kV	63.6 kV	72.5 kV	57.3 kV
24 kV	23.6 kV	21.8 kV	24 kV	21.6 kV
12 kV	11.8 kV	10.9 kV	12.0 kV	10.8 kV
400 V	410 V	371 V	416 V	362 V
230 V	237 V	214 V	240 V	209 V

Table 2.6 The highest and lowest voltage level standards of MEA in case the applicant using the feed-in systems [19]

Voltage levels	Normalcy		Emergency	
	Highest	Lowest	Highest	Lowest
115 kV	118.0 kV	113.0 kV	123.0 kV	113.0 kV
69 kV	71.0 kV	67.0 kV	72.5 kV	67.0 kV
24 kV	23.6 kV	21.8 kV	24 kV	21.6 kV
12 kV	11.8 kV	10.9 kV	12.0 kV	10.8 kV
400 V	410 V	371 V	416 V	362 V
230 V	237 V	214 V	240 V	209 V

MEA's have a reserve the right control to give connection reduces to power electric produced down or close circuits out systems, if the connections transfer impact voltage level and stability systems.

PEA has a define, Small Power Producers and Very Small Power Producers use grid-connected and power supplies in the network. The voltage regulates at maximum power point give consistently with voltage level highest and lowest in PEAs defined. Therefore, regulate normalcy and emergency as shown in Table 2.7.

Table 2.7 The highest and lowest voltage level standards of PEA in case the applicant using the feed-in systems [15]

Voltage levels	Normalcy		Emergency	
	Highest	Lowest	Highest	Lowest
115 kV	120.7 kV	109.2 kV	126.5 kV	103.5 kV
33 kV	34.7 kV	31.3 kV	36.3 kV	29.7 kV
22 kV	23.1 kV	20.9 kV	24.2 kV	19.8 kV
380 V	418.0 V	342.0 V	418.0 V	342.0 V
220 V	240.0 V	200.0 V	240.0 V	200.0 V

MEA and PEA have a reserve the right allows in the connected producer to adjust the power factor of the generator. According, MEA and PEA are defined to control and maintain quality voltage level in the system. Therefore, power factor defines changed according to necessary of the system network at the time.

- In the case of rotating machine, it can be adjusted power factor between at 0.85 leading to 0.85 lagging.
- In the case of inverter base, it can be adjusted the power factor between at 0.95 leading to 0.95 lagging. If connection in the system network, the voltage level 230/400 V or between at 0.9 leading to 0.9 lagging.

2.5.2 Frequency range

The inverters must open circuit from the grid system within 0.1 second if the frequency of the grid differs from 49-51 Hz.

2.5.3 Voltage range

An inverter must open the circuit from the grid system if the voltage of line or line to Neutral in the grid system differs from 345-416 V and 200-240 V chronologically in the duration listed below:

Table 2.8 Voltage level line to line and line to neutral (voltage 230/400 V) [19]

Voltage range (Volt)		Maximum time of open circuit (second)
Line to line	Line to neutral	
V < 199	V < 115	0.1
119 ≤ V < 346	115 ≤ V <200	2.0
346 ≤ V ≤ 416	200 ≤ V ≤ 240	Continue to run (no pen circuit)
416 < V < 539	240 < V < 311	2.0
V ≥ 539	V ≥ 311	0.05

The inverters must open circuit from the grid system at the time defined. If the voltage in the grid system is oversize voltage listed in the table below:

Table 2.9 Voltage limits of an inverter for MEA (voltage exceed 12 kV) [19]

The nominal voltage of inverter (%)	Maximum time of open circuit (second)
V < 50 %	0.1
50 % ≤ V < 85 %	2.0
85 % ≤ V ≤ 100 %	Continue to run (no pen circuit)
110 % < V < 135 %	2.0
V ≥ 135 %	0.05

Table 2.10 Voltage limits of inverter for PEA (voltage exceed 12 kV) [15]

Nominal voltage of inverter (%)	Maximum time of open circuit (second)
V < 50 %	0.3
50 % ≤ V < 90 %	2.0
90 % ≤ V ≤ 110 %	Continue to run (no pen circuit)
110 % < V < 120 %	1.0
V ≥ 120 %	0.16

2.5.3 DC current injection

In the design test refer to the method evaluation in IEEE 1547 standard 2005, designates to test DC value when the inverter operated at 33%, 66% and 100% of current rating.

According, the requirement of electrical network connection for (MV) network and (LV) network. In the standard range of operating voltages of the electrical network is determined by the connection of the photovoltaic inverter system, ranging from 85 to 110 percent of normal voltage. By there are methods voltage at the point connected with operation of function characteristic in an inverter is included function Q(V) and $\cos\varphi(P)$ which is used to calculated reactive power by voltage level connected and power supply by Photovoltaic inverter.

CHAPTER 3
VOLTAGE REGULATION STRATEGIES

The voltage and frequency are levels in the utility system represent a fundamental criterion to determine the quality of the power delivered to customers. The voltage has to be controlled to remain within the prescribed limits; therefore, devices such as the on-load tap transformer, shunt capacitor, and compensators are responsible with the voltage regulation process [23].

The diverse of distribution generator systems in distribution networks are raised stability problems. The expect that DGs will a take partly of the regulation process, it is operating between active and reactive power concurrently with a result in a benefit for the utilities as well as for customers.

3.1 Conventional voltage regulation methods

If the distribution generator system connection effect is not considered, the voltage is maintained within prescribed limits based on the power flow from substation towards load. The current flow in transformer and load impedance causes a voltage drop. Therefore, voltage regulation devices are needed to keep the deviations in the acceptable range. The common voltage control methods are discussed more details.

The on-load tap-changing transformer (OLTC) represents are used mainly the voltage regulation method in distribution networks. The work bases are similarly to an autotransformer with automatically tap changes. The control variables are the voltage and current. On the other hand, the tap change is triggered until the voltage returns within the desired bound. Another technique to regulate the voltage along the feeder is by means of capacitor banks which are designed to supply reactive power and consequently compensate the lagging power factor of the loads. The capacitor banks connection can be fixed or switched. In order of avoid the overcompensation to reactive power and voltage rise along in the feeder which is not required tap change of the transformer, control algorithms are used [24].

Static Synchronous Compensator (STATCOM) is a Voltage Source Inverter (VSI) connected to the grid for reactive power compensation and power factor improvement purpose. STATCOM can be seen as a current source; therefore, active and reactive power exchange between Distribution Static and STATCOM is possible by controlling the magnitude and the phase angle of the output voltage of the VSI [24].

3.2 Proposed method

Reactive power improvement in power systems by PV inverters with different goals. It can minimize the real power loss and can improve the voltage profile. In this thesis, the aim of the reactive power control modes from the PV inverter is to reduce the real power loss.

The real power loss in the system equals the sum of the real power loss on each branch as follows:

$$P_{loss} = \sum_{j=1}^{N} g_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\theta_{ij}) \tag{3.1}$$

Where N is the number of branches

g_{ij} is the conductance of the branch at node bus i and bus j

V_i is the voltage magnitude at bus i

V_j is the voltage magnitude at bus j

θ_{ij} is the difference of phase angle between bus i and bus j

The reactive power improvement problem has equality constraints to process. The load flow problem can be solved by the Newton-Raphson method using a set of nonlinear equations to express the specified real and reactive powers in terms of bus voltages [25].

There are n buses in the system which there are m load buses. The power flow equations are

$$P_{gi} - P_{di} - V_i = \sum V_i(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \tag{3.2}$$

$$Q_{gi} - Q_{di} - V_i = \sum V_i(G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij}) = 0 \tag{3.3}$$

Where P_{gi} is the real power generation at bus i

P_{di} is the real power demand at bus i

Q_{gi} is the reactive power generation at bus i

Q_{di} is the reactive power demand at bus i

In Newton-Raphson based power flow calculation, the Jacobian matrix gives the linearized relationship between small change of voltage angle $\Delta\theta$ and voltage magnitude ΔV with the small change of active power and reactive power, ΔP and ΔQ is usually written as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} = \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{3.4}$$

In the n bus system with one slack bus, if m buses are voltage controlled, m equations involving ΔQ and ΔV, the corresponding columns of the Jacobian matrix are cut out.

There are (n-1) the real power constraints and (n-1-m) reactive power constrains and the Jacobian matrix [26] is $(n-1)\times(n-1)$, $m\times m, (n-1)\times m,$ and $m\times(n-1)$.

$$J^{-1}=\begin{bmatrix} -(J_{P\theta}+J_{PV}J_{QV}^{-1}J_{Q\theta})^{-1} & (J_{P\theta}+J_{PV}J_{QV}^{-1}J_{Q\theta})^{-1}J_{Q\theta}J_{QV}^{-1} \\ (J_{QV}+J_{Q\theta}J_{P\theta}^{-1}J_{PV})^{-1}J_{Q\theta}J_{P\theta}^{-1} & -(J_{QV}+J_{PV}J_{P\theta}^{-1}J_{PV})^{-1} \end{bmatrix} \tag{3.5}$$

Such that

$$\Delta V = VP\cdot\Delta P + VQ\cdot\Delta Q \tag{3.6}$$

Where

$$\begin{cases} VP=(J_{QV}+J_{Q\theta}J_{P\theta}^{-1}J_{PV})^{-1}J_{Q\theta}J_{P\theta}^{-1} \\ VQ=-(J_{QV}+J_{PV}J_{P\theta}^{-1}J_{PV})^{-1} \end{cases} \tag{3.7}$$

The sensitivity matrices in (3.7) can use to estimate voltage of the PV inverter (active and reactive power) injection.

Reverse power flow in the electrical power grids limit the distributed generator (DG) absorption capacity and bring additional problems such as voltage rise and limited PV penetration. The problems can be overcome by injection/absorption of reactive power by each PV inverter [26, 27]. In this thesis, the voltage regulation methods for the PV generators are

3.2.1 Unity power factor

When PV generator is working on unity power factor, $\Delta Q = 0$, voltage variation of all the load buses because of power injection from PV generators is expressed by:

$$\Delta V = VP1\cdot\Delta P \tag{3.8}$$

3.2.2 Fixed power factor

When PV generator is working on fixed power factor as $\cos\varphi$, $\Delta Q \neq 0$, the PV generators can be estimated by:

$$\Delta Q = -\sqrt{1-\cos\varphi^2}\cdot\Delta P \tag{3.9}$$

$$\Delta V = VP2\cdot\Delta P + VQ2\cdot\Delta Q \tag{3.10}$$

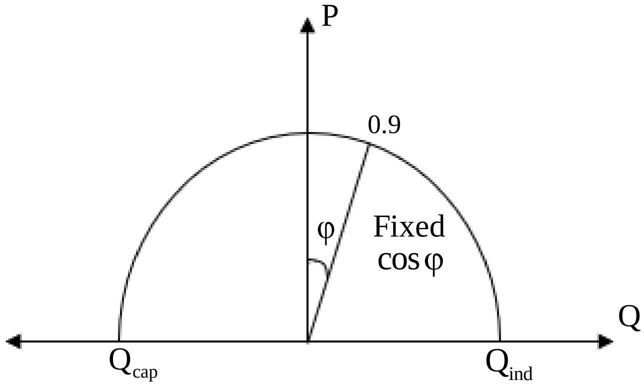

Figure 3.1 Fixed power factor

3.2.3 Power factor as $\cos\varphi(P)$

When the PV generator is working on power factor as $\cos\varphi(P)$,

$$\Delta Q = -\sqrt{1-\left[\cos\varphi(\Delta P)\right]^2}\cdot\Delta P \tag{3.11}$$

$$\Delta V = VP3\cdot\Delta P + VQ3\cdot\Delta Q \tag{3.12}$$

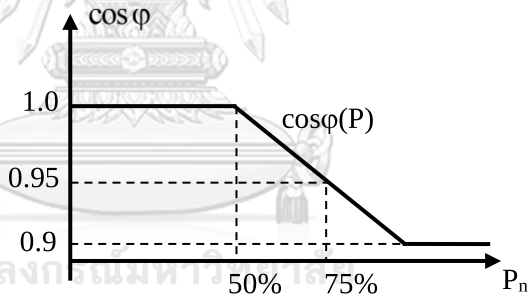

Figure 3.2 Power factor as $\cos\varphi(P)$

3.2.4 Reactive power as function of Q(V)

When the PV generator is working on reactive power as function of Q(V), reactive power inject/absorb by PV is the function of Q(V) in (3.13) as follows:

$$Q = \begin{cases} Q_{max} & V < V_1 \\ (V-V_1)\cdot\dfrac{Q_{max}}{V_1-V_2}+Q_{max} & V_1 \le V \le V_2 \\ 0 & V_2 \le V \le V_3 \\ (V-V_3)\cdot\dfrac{Q_{max}}{V_3-V_4} & V_3 \le V \le V_4 \\ -Q_{max} & V > V_4 \end{cases} \tag{3.13}$$

Based on operation point V3, the voltage sensitivity in terms of active power derived by absorb in fig. 3.3.

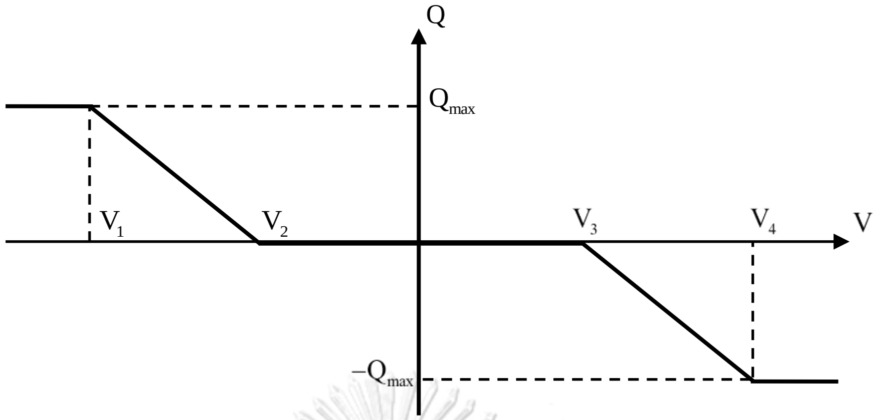

Figure 3.3 Reactive power as function of Q(V)

Therefore, the voltage sensitivity matrices are modified by equation (3.14). system voltage variation because of active power injection is estimated as

$$\Delta V = VP4 \cdot \Delta P \tag{3.14}$$

The reactive power reference is calculated using the value of the voltage variation found in (3.15).

$$Q = \tan(a\cos\varphi) \cdot P \tag{3.15}$$

Therefore, the total reactive power absorption by the inverters can be considerably reduced within the modes of weaker voltage support with the unity power factor, fixed power factor, power factor as $\cos\varphi$(P), and Q(V).

3.3 Particle swarm optimization

Particle swarm optimization (PSO) is a computational method that optimizes a problem by iteratively trying to improve a candidate solution regarding to give measure of quality. The idea of PSO comes from a simplified social system like bird flocking or fish schooling. In PSO, each single solution can view as a bird. The position of each particle is expressed as $x_i = (x_{i1}, x_{i2}, ..., x_{in})$. the initial solutions in PSO are randomly selected and then PSO will continually search for optimal value by updating the solutions in each iteration. The fitness value of the particle is related to the objective function and the velocity of the particles $v_i = (v_{i1}, v_{i2}, ..., v_{in})$ is related to the velocity, global best position [32]. However, in the formula (3.16) and formula (3.17) describe below, the principle of the PSO algorithm are

$$v_{d+1} = k*(w*v_d + \varphi_1 \cdot rand()*(p_{best} - x_d) + \varphi_2 \cdot rand()*(g_{best} - x_d)) \qquad (3.16)$$

$$x_{d+1} = x_d + v_{d+1} \qquad (3.17)$$

Where w is the inertia weight factor,

φ_1 and φ_2 are acceleration factors,

Rand () is a random value between 0 and 1

k is the constriction factor

The acceleration factors handle the step size of the particles in the next iteration. The maximum velocity is specified by users depending on different problems. The advantages of PSO is summarized in fig. 3.6.

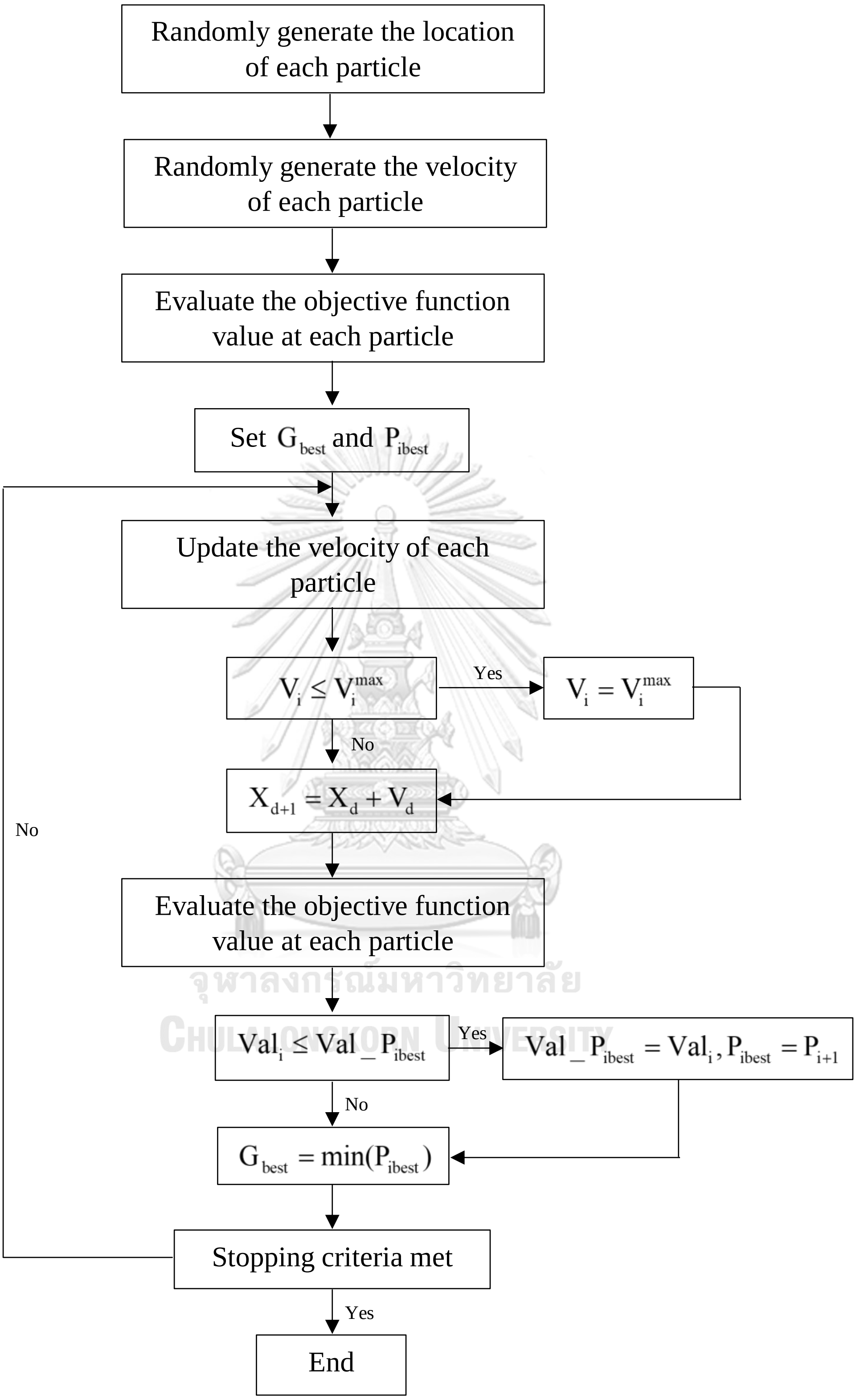

Figure 3.4 Flow chart of the particle swarm optimization [33]

CHAPTER 4
TEST SYSTEM AND DISCUSION

4.1 Test system

This part describes a test IEEE 33 bus radial distribution system with the substation of 12.66 kV [29]. In the system consists of 33 busses with 3 PV generators, upon which two variables specify, the buses can be categorized into three categories as well slack bus (swing or reference bus), PQ bus (sometimes called as a load bus), and PV bus. The total loads for this test system are 3.72 MW and 2.3 MVAr.

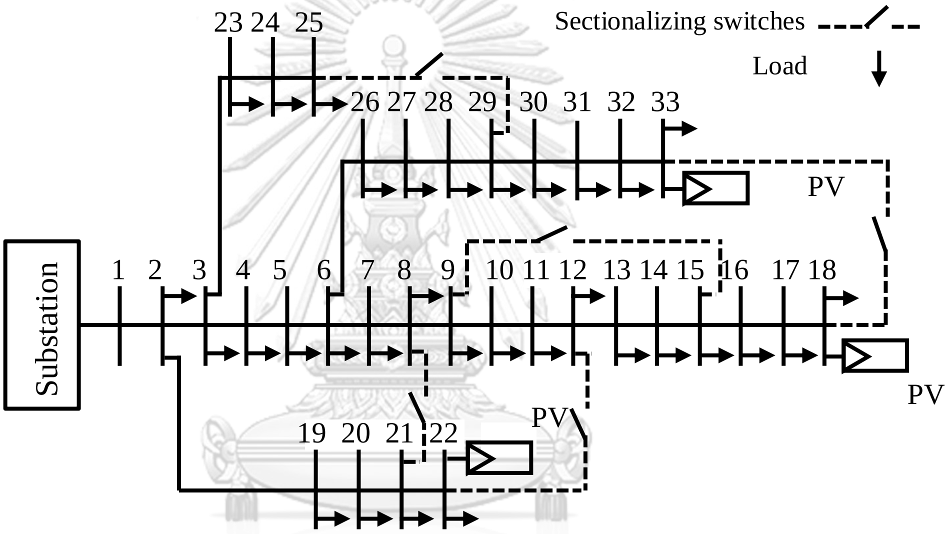

Figure 4.1 IEEE 33 bus radial distribution system with PV generators

The reactive power is critical to operate of power systems on both safety aspects and economic aspects. Therefore, reactive power management in distribution systems by PV generators can improve voltage profile and reduce the real power loss.

4.2 Reactive power management without PV generators

Figure 4.2 shows that the optimization process of reactive power management without installing PV generator. At the beginning of the optimization process, the positions of the particles are randomly selected. The global optimal real power loss is about 0.1646 MW at that time. As the particles continually updated their positions toward the best solution, the real power loss keeps decreasing. After 200 iterations, no obvious improvement can be observed. Finally, the real power loss converges to 0.163 MW.

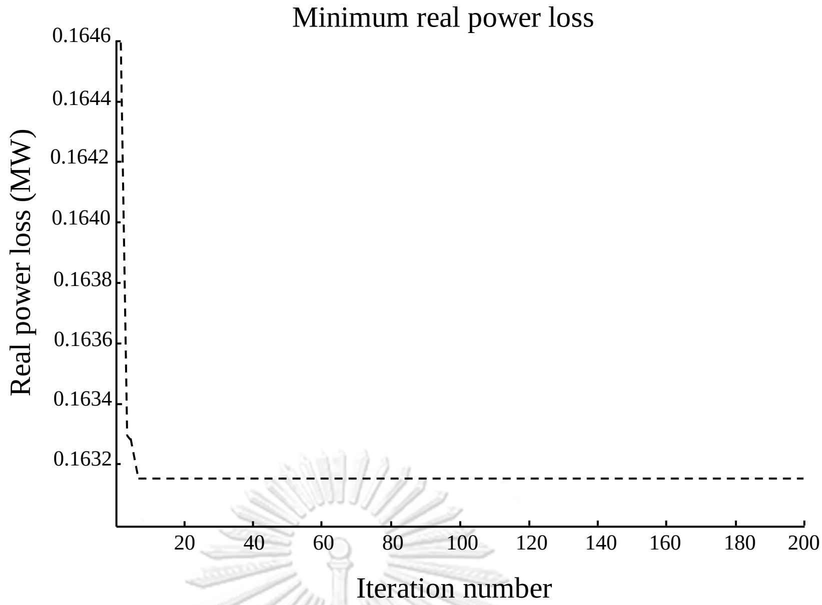

Figure 4.2 Real power loss without PV generation

Table 4.1 shows that the real power loss on each branch before and after the optimization. Although, the real power loss in some branches are slightly increased, the overall real power loss of the 33 buses system is significantly reduced.

Table 4.1 Comparison real power losses at each branch

Branch number	Before optimization (MW)	After optimization (MW)
1-2	0.012	0.010
2-3	0.052	0.042
3-4	0.020	0.016
4-5	0.019	0.015
5-6	0.038	0.031
6-7	0.002	0.002
7-8	0.005	0.004
8-9	0.004	0.003
9-10	0.004	0.003
10-11	0.001	0.000
11-12	0.001	0.001
12-13	0.003	0.002
13-14	0.001	0.001
14-15	0.000	0.000
15-16	0.000	0.000
16-17	0.000	0.000

17-18	0.000	0.000
2-19	0.000	0.000
19-20	0.001	0.001
20-21	0.000	0.000
21-22	0.000	0.000
3-23	0.003	0.003
23-24	0.005	0.004
24-25	0.001	0.001
6-26	0.003	0.002
26-27	0.003	0.003
27-28	0.011	0.009
28-29	0.008	0.006
29-30	0.004	0.003
30-31	0.002	0.001
31-32	0.000	0.000
32-33	0.000	0.000
21-8	0.000	0.000
9-15	0.000	0.000
12-22	0.000	0.000
18-33	0.000	0.000
25-29	0.000	0.000

Real power losses are compared before and after optimization (see table 4.1). It changes the area of different branches respectively, the corresponding system changes of the general power loss in the system.

4.3 Optimized Q(V) method

The main objectives when talking about systems are supposed to find optimal solutions to problems that minimize loss. The optimization problem explained in this thesis refers to the reactive power management problem with the focus on developing an algorithm with the following purposes:

- Unity power factor
- Fixed power factor
- Power factor as $\cos\varphi\,(P)$
- Reactive power as a function of voltage Q(V)

The best candidate from the regulation methods proposed by the distribution system, Q(V) was compared with the optimized algorithm shows in 4.4.

4.4 Implementation of optimized Q(V) method

The local reactive power absorption methods can be divided mainly into four categories as well unity power factor, fixed power factor, power factor as a function of $\cos\varphi\,(P)$, and reactive power as a function of voltage Q(V). These methods are shown results as follows.

- Unity power factor (PF=1.0 p.u.)

In this case with three small power producers can provide the real power supply in the system by PV inverters. There are located producers at buses 18, 22, and 33 with PV capacities are 0.25 MW, 0.25 MW, and 0.5 MW respectively. The results for case as follow in Table 4.2.

Table 4.2 Reconfiguration results without and with PV generators

No	case	PV buses installed	PV generators (MW)	Real power losses (MW)
1	without PV	-	-	0.163
2	with 1 PV	18	0.5	0.124
3	with 2 PV	18, 22	0.5, 0.25	0.123
4	with 3 PV	18, 22, 33	0.5, 0.25, 0.25	0.104

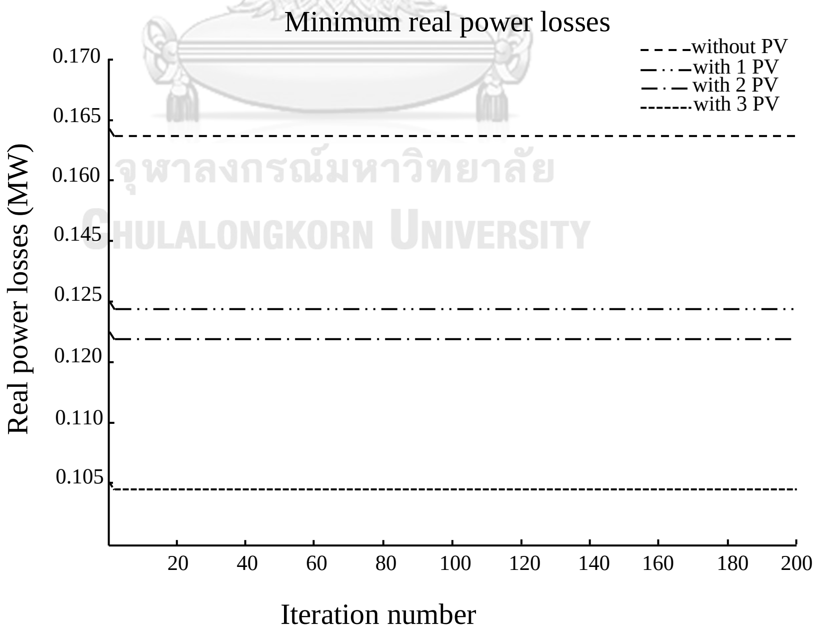

Figure 4.3 Real power losses reduction process without and with PV generators

In figure 4.3 PV generators at buses 18, 22, and 33 are active power increased as well when the PV generator is supplied real power into the system. In this case, PV generators can improve voltage profile problems and can reduce power losses in the system.

Table 4.3 Optimization results voltage magnitude and angle for mode 1

Bus	Before optimization		After optimization	
	Mag (p.u.)	Ang (deg)	Mag (p.u.)	Ang (deg)
1	1.000	0.000	1.100	0.000
2	0.997	0.014	1.097	0.012
3	0.983	0.096	1.085	0.078
4	0.975	0.162	1.078	0.131
5	0.968	0.228	1.071	0.185
6	0.950	0.134	1.055	0.108
7	0.946	-0.096	1.052	-0.078
8	0.941	-0.060	1.047	-0.049
9	0.935	-0.133	1.042	-0.108
10	0.929	-0.196	1.037	-0.158
11	0.928	-0.189	1.036	-0.152
12	0.927	-0.117	1.034	-0.143
13	0.921	-0.269	1.029	-0.216
14	0.919	-0.347	1.027	-0.279
15	0.917	-0.385	1.026	-0.309
16	0.916	-0.408	1.025	-0.328
17	0.914	-0.485	1.023	-0.390
18	0.913	-0.495	1.022	-0.397
19	0.997	0.004	1.097	0.003
20	0.993	-0.063	1.094	-0.052
21	0.992	-0.083	1.093	-0.068
22	0.992	-0.103	1.092	-0.085
23	0.979	0.065	1.081	0.053
24	0.973	-0.024	1.075	-0.020
25	0.969	-0.067	1.072	-0.056
26	0.948	0.173	1.053	0.140
27	0.945	0.229	1.051	0.185
28	0.934	0.312	1.041	0.253
29	0.926	0.390	1.033	0.315
30	0.922	0.496	1.030	0.400
31	0.918	0.411	1.026	0.332
32	0.917	0.388	1.026	0.314
33	0.917	0.380	1.025	0.307

- Fixed power factor (PF=0.9 p.u.)

Under the fixed power factor method of the PV inverter is approached in order a suitable for the static power factor supply on the system. This method is using the fixed power factor characteristic.

Table 4.4 Reconfiguration results without and with PV generators

No	case	PV buses installed	PV generators (MW)	Real power losses (MW)
1	without PV	-	-	0.163
2	with 1 PV	18	0.5	0.122
3	with 2 PV	18, 22	0.5, 0.25	0.111
4	with 3 PV	18, 22, 33	0.5, 0.25, 0.25	0.085

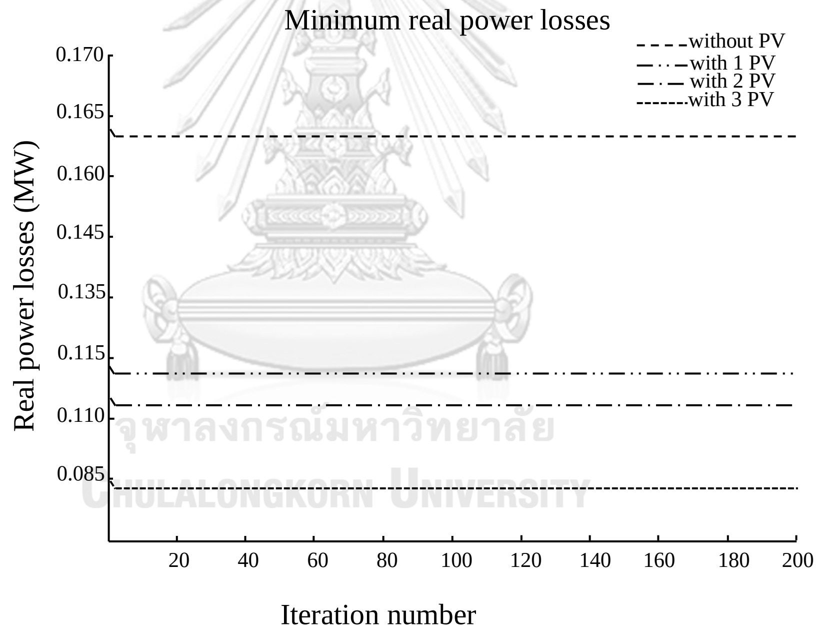

Figure 4.4 Real power losses reduction process without and with PV generators

Fig. 4.3 shows that the power losses at buses without and with PV generators. This method is primarily suitable for the system where the active power output generation is constant. An unstable of PV generators in the system, the PV system recommend using the power factor characteristic fixed $\cos\varphi$ or fixed reactive power characteristic.

Table 4.5 Optimization results voltage magnitude and angle for mode 2

Bus	Before optimization		After optimization	
	Mag (p.u.)	Ang (deg)	Mag (p.u.)	Ang (deg)
1	1.000	0.000	1.100	0.000
2	0.997	0.014	1.098	0.012
3	0.983	0.096	1.088	0.079
4	0.975	0.162	1.084	0.132
5	0.968	0.228	1.079	0.186
6	0.950	0.134	1.068	0.184
7	0.946	-0.096	1.067	0.087
8	0.941	-0.060	1.065	0.098
9	0.935	-0.133	1.064	0.079
10	0.929	-0.196	1.063	0.068
11	0.928	-0.189	1.062	0.069
12	0.927	-0.117	1.062	0.068
13	0.921	-0.269	1.063	0.070
14	0.919	-0.347	1.064	0.082
15	0.917	-0.385	1.065	0.092
16	0.916	-0.408	1.067	0.104
17	0.914	-0.485	1.071	0.219
18	0.913	-0.495	1.074	0.246
19	0.997	0.004	1.098	0.009
20	0.993	-0.063	1.098	0.000
21	0.992	-0.083	1.098	0.005
22	0.992	-0.103	1.099	0.033
23	0.979	0.065	1.085	0.054
24	0.973	-0.024	1.079	-0.018
25	0.969	-0.067	1.076	-0.054
26	0.948	0.173	1.067	0.215
27	0.945	0.229	1.065	0.259
28	0.934	0.312	1.057	0.358
29	0.926	0.390	1.052	0.444
30	0.922	0.496	1.050	0.526
31	0.918	0.411	1.048	0.501
32	0.917	0.388	1.048	0.500
33	0.917	0.380	1.049	0.524

- Power factor as $\cos\varphi\,(P)$

The low voltage level of the feeder, when the PV buses 18, 22, and 33 are reduces to 50% and 75% of the total load feeder to improve voltage. From fig. 4.1, the total loads for this test system are 3.72 MW and 2.3 MVAr but for the lateral feeders with two cases as follows:

$$\sum_{i=1}^{n_{pv}} P_{pv,max} = 50\% \times \sum_{i=1}^{N_{load}} P_{load,max} = 0.5 \times 1.505\text{MW} = 0.753\text{MW}$$

Case 1: For the feeder 2 (bus 26-33), the total load is 0.92 MW and 0.95 MVAr, feeder 3 (bus 1-18), the total load is 1.505 MW and 0.74 MVAr and feeder 4 (bus 19-22), the total load is 0.36 MW and 0.16 MVAr. The output power from PV penetration is to reduce 50% of peak load. Therefore, bus connected there are 0.46 MW, 0.753 MW, and 0.18 MW respectively.

Case 2: For the feeder 2 (bus 26-33), the total load is 0.92 MW and 0.95 MVAr. Eeder 3 (bus 1-18), the total load is 1.505 MW and 0.74 MVAr and feeder 4 (bus 19-22), the total load is 0.36 MW and 0.16 MVAr. The output power PV penetration is to reduce 75% of peak load. Therefore, bus connected there are 0.69 MW, 1.129 MW, and 0.27 MW respectively.

Table 4.6 Reconfiguration results with PV operate 50% and 75%

No	case	PV buses installed	PV generators (MW)	Real power losses (MW)
1	with PV 50%	18, 22, 33	0.46, 0.753, 0.18	0.0894
2	with PV 75%	18, 22, 33	0.69, 1.129, 0.27	0.064

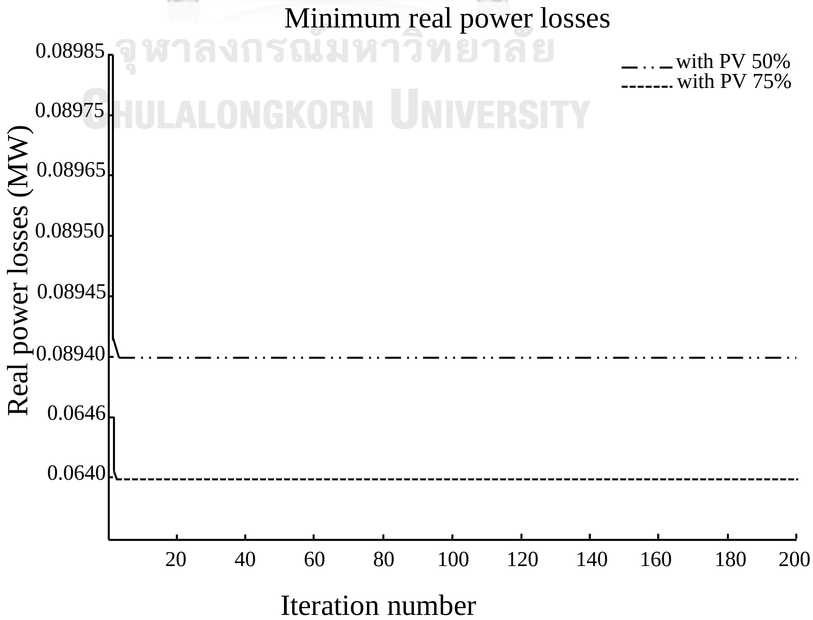

Figure 4.5 Real power losses reduction process with PV generators 50% and 75% rated power

In figure 4.5, shows that the power losses when power from buses 18, 22, 33 reduces to 50%, 75% of capacity. It can absorb reactive power from the system the optimal real power losses value 0.089 MW and 0.064 MW to minimize losses.

Table 4.7 Optimization results voltage magnitude and angle for mode 3

Bus	PV operate 50%		PV operate 75%	
	Mag (p.u.)	Ang (deg)	Mag (p.u.)	Ang (deg)
1	1.100	0.000	1.100	0.000
2	1.098	0.031	1.099	0.017
3	1.089	0.186	1.091	0.113
4	1.085	0.306	1.089	0.187
5	1.081	0.430	1.087	0.263
6	1.071	0.620	1.081	0.382
7	1.069	0.586	1.080	0.397
8	1.068	0.670	1.081	0.427
9	1.067	0.789	1.084	0.513
10	1.066	0.917	1.087	0.605
11	1.066	0.938	1.087	0.611
12	1.067	0.976	1.089	0.621
13	1.068	1.182	1.095	0.786
14	1.068	1.291	1.098	0.909
15	1.069	1.387	1.102	0.994
16	1.072	1.499	1.106	1.078
17	1.075	1.844	1.116	1.449
18	1.078	1.971	1.122	1.551
19	1.098	0.030	1.098	0.013
20	1.096	0.048	1.097	-0.009
21	1.096	0.057	1.097	-0.010
22	1.096	0.091	1.098	0.005
23	1.086	0.161	1.088	0.088
24	1.080	0.089	1.082	0.016
25	1.077	0.054	1.079	-0.019
26	1.070	0.666	1.080	0.413
27	1.068	0.730	1.078	0.456
28	1.061	0.931	1.073	0.577
29	1.056	1.094	1.069	0.679
30	1.055	1.212	1.067	0.758
31	1.054	1.291	1.068	0.764
32	1.054	1.327	1.068	0.777
33	1.054	1.399	1.069	0.823

- Reactive power Q(V)

The Q(V) strategy of voltage regulation presented in fig.3.3, it is calculating to amount of reactive power present in each PV inverter will depend on the voltage magnitude. In the case, power factor as *cosφ(P)* method is used local voltage information in the regulation process with the reactive power consumption of the voltage level. For mode 4, V3 = 1.02 p.u., V4 = 1.05 p.u., the Q(V) regulation method can be implemented in the optimal reactive power.

Table 4.8 Reconfiguration results with PV operate 50% and 75%

No	case	PV buses installed	PV generators (MW)	Real power losses (MW)
1	Before Q absorb	18, 22, 33	0.69, 1.129, 0.27	0.064
2	After Q absorb	18, 22, 33	0.69, 1.129, 0.27	0.147

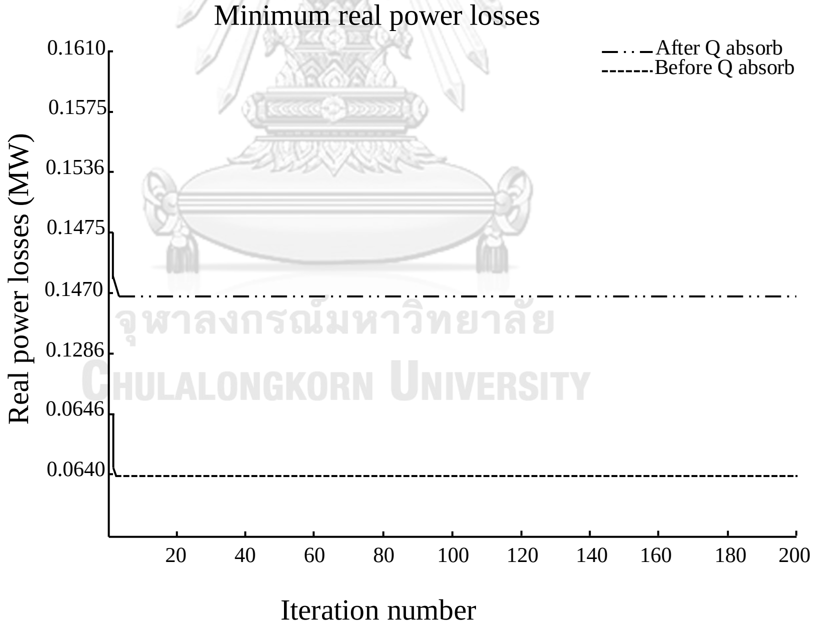

Figure 4.5 Real power losses reduction process with before and after Q absorb

Fig. 4.6 shows that the power loss of each bus before Q absorption is high than voltage profile after Q absorption. In this case, PV inverters can absorb reactive power from the system to minimize losses. By using the proposed methods when power from PV 18, PV 22, and PV 33 reduces to 50% and 75% of capacity, it can absorb reactive power from the system the optimal real power losses value 0.064 MW and 0.147 MW to minimize losses. At any given output the PV generators may be requested to inject active power help manage voltage profile in the system. On the other hand, the limitation of Q in Q(V) (absorb) reactive power help the optimal value of reactive power. From fixed power factor and power factor as $\cos\varphi\,(P)$ are reduced power losses in the system, unity power factor can be reduced power loss but no inject reactive power.

Table 4.9 Optimization results voltage magnitude and angle for mode 4

Bus	Before optimization		After optimization	
	Mag (p.u.)	Ang (deg)	Mag (p.u.)	Ang (deg)
1	1.100	0.000	1.100	0.000
2	1.099	0.017	1.098	0.055
3	1.091	0.113	1.089	0.330
4	1.089	0.187	1.085	0.540
5	1.087	0.263	1.081	0.757
6	1.081	0.382	1.070	1.182
7	1.080	0.397	1.067	1.238
8	1.081	0.427	1.066	1.436
9	1.084	0.513	1.066	1.764
10	1.087	0.605	1.066	2.103
11	1.087	0.611	1.066	2.155
12	1.089	0.621	1.067	2.254
13	1.095	0.786	1.068	2.767
14	1.098	0.909	1.068	3.022
15	1.102	0.994	1.070	3.249
16	1.106	1.078	1.072	3.511
17	1.116	1.449	1.075	4.204
18	1.122	1.551	1.078	4.481
19	1.098	0.013	1.098	0.059
20	1.097	-0.009	1.095	0.116
21	1.097	-0.010	1.095	0.136
22	1.098	0.005	1.095	0.189
23	1.088	0.088	1.086	0.305
24	1.082	0.016	1.080	0.233
25	1.079	-0.019	1.077	0.197
26	1.080	0.413	1.069	1.242
27	1.078	0.456	1.067	1.327
28	1.073	0.577	1.058	1.606
29	1.069	0.679	1.052	1.829
30	1.067	0.758	1.050	1.986
31	1.068	0.764	1.048	2.138
32	1.068	0.777	1.048	2.198
33	1.069	0.823	1.048	2.297

Due to the fact the optimized Q(V) method is absorbing less reactive power than the Q(V) method, it can be started that the transformer does not exceed the 100% loading in this case also. In addition, the optimized Q(V) method presents the advantage of less stressing the transformer.

4.5 Discussions

The best candidate from the reactive power control modes proposed by PV inverters operation, Q(V) are compared with the optimized algorithm. The performance is evaluated based on their ability to maintain the voltage profile with limits and to minimize the real power losses by the reactive power absorption.

The main difference between the reactive power control modes is the fact that while for the operation, each PV inverter absorbs a calculated value of reactive power corresponding to the local voltage magnitude, for the fourth strategy, the amount of reactive power values are computed based on all the PCC voltages of the system. In the result, the optimized Q(V) algorithm makes in the distribution system by PV systems. Even though the voltage levels using the optimized Q(V) method are higher, but with limits compared to the voltage using the Q(V) algorithm, the benefit of the optimized method is the minimization of the real power losses by the reactive power absorption from PV inverters operation.

This thesis uses the IEEE 33 bus radial distribution system. Both MATPWOER toolbox and PSO algorithm are applied to reduce the real power loss in the system as follows:

- PSO algorithm shows excellent searching ability in solving nonlinear optimization problems. Applying the PSO algorithm to solve the reactive power management problems is technically feasible and achieve considerable economic benefits.
- MATPWOER toolbox is introduced to calculate the power flow and manage the equality constraints in PSO based reactive power control modes

CHAPTER 5
CONCLUSION

5.1 Conclusion

This research is examined the increases of solar PV on voltage profile by considering reactive power control modes injection of inverter. PV inverters array shows that the output power from PV changes every day due to irradiance and temperature. The proposed methods are inherited from four methods: unity power factor, fixed power factor, $\cos\varphi\,(P)$, and Q(V). The variation can make voltage profile to be out of the normal limitation in the distribution system. The PSO algorithm can be used to calculate the optimal reactive power control modes from PV inverters to reduce real power losses and to improve voltage profile 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. On the other hand, if the system voltage profile is high the limit if compare to nominal voltage, thus inverter can absorb reactive power from the system to decrease voltage. Therefore, reactive power management is a nonlinear optimal problem in each mode of PV inverters. The reactive power control modes are applied to reduce the power losses and to improve voltage profile in the distribution system. The inverters can share local data for the minimization of distribution losses by reactive power control.

5.2 Future work

According to this research, the optimal reactive power control modes from PV inverters can improve voltage profile and can reduce real power losses. Therefore, the future research should consider the impact of all PV systems connected, the PV power change of mode in nighttime and find out a method to compare the optimal reactive power of all PV inverters. Finally, it should compare for the inverters can share local data for the minimization of network losses and distribution losses of reactive power which one is better from PV systems operation.

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APPENDIX

Table A. 1 IEEE 33 bus system loads parameters [29]

Bus number	Nominal load	
	P(kW)	Q(kVAr)
1	0	0
2	100	60
3	90	40
4	120	80
5	60	30
6	60	20
7	200	100
8	200	100
9	60	20
10	60	20
11	45	30
12	60	35
13	60	35
14	120	80
15	60	10
16	60	20
17	60	20
18	90	40
19	90	40
20	90	40
21	90	40
22	90	40
23	90	50
24	420	200
25	420	200
26	60	25
27	60	25
28	60	20
29	120	70
30	200	600
31	150	70
32	210	100
33	60	40
Total	**3,715**	**2,300**

Table A. 2 IEEE 33 bus system branch parameter [29]

From bus	To bus	R (Ω)	X (Ω)	B (p.u.)
1	2	0.0922	0.0470	0
2	3	0.4930	0.2511	0
3	4	0.3660	0.1864	0
4	5	0.3811	0.1941	0
5	6	0.8190	0.7070	0
6	7	0.1872	0.6188	0
7	8	0.7114	0.2351	0
8	9	1.0300	0.7400	0
9	10	1.0440	0.7400	0
10	11	0.1966	0.0650	0
11	12	0.3744	0.1298	0
12	13	1.4680	1.1550	0
13	14	0.5416	0.7129	0
14	15	0.5910	0.5260	0
15	16	0.7463	0.5450	0
16	17	1.2890	1.7210	0
17	18	0.7320	0.5740	0
2	19	0.1640	0.1565	0
19	20	1.5042	1.3554	0
20	21	0.4095	0.4784	0
21	22	0.7089	0.9373	0
3	23	0.4512	0.3083	0
23	24	0.8980	0.7091	0
24	25	0.8960	0.7011	0
6	26	0.2030	0.1034	0
26	27	0.2842	0.1447	0
27	28	1.0590	0.9337	0
28	29	0.8042	0.7006	0
29	30	0.5075	0.2585	0
30	31	0.9744	0.9630	0
31	32	0.3105	0.3619	0
32	33	0.3410	0.5302	0
21	8	2.0000	2.0000	0
9	15	2.0000	2.0000	0
12	22	2.0000	2.0000	0
18	33	0.5000	0.5000	0
25	29	0.5000	0.5000	0

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