Master's Degree

Qualification

Grid Code Proposal for Solar Photovoltaics Power Plant in Indonesia

REPORT

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Abstract

This master thesis deals with the grid code design for solar photovoltaics power plant (PVPP). For this purpose, three approaches are identified: (1) Several sets of international grid codes for large scale solar PVPP are studied from operational perspective such as voltage and frequency boundaries, active power and frequency support, reactive power and voltage support and fault-ride-through. The chosen sets of grid codes are of Puerto Rico, Germany, Denmark and European Union since they are mature enough and well-developed to study. Additionally, the core of this master thesis is to study the existing electricity transmission and distribution system in Indonesia along with current grid codes. The aforementioned research of international grid codes serves as a foundation to propose suitable grid code design or update existing grid code for solar PVPP in Indonesia. (2) the introduction and characteristics of solar photovoltaics power plant (PVPP) in which the basic electrical components (e.g. PV panel, PV inverter and transformer) are discussed. Besides, inverter topology (e.g. central inverter topology, string inverter topology, multistring inverter topology, etc.) and internal collection grid configuration (e.g. radial configuration, ring configuration, star configuration) is explained. In addition, the brief modelling approach for each electrical component is given in this chapter. (3) In the later part of this master thesis, a 1 MW solar PVPP along with the electrical grid is modelled and simulated to test the proposed grid code for solar PVPP in Indonesia. The proposed grid codes that are tested and simulated are active power and frequency regulation particularly absolute production (i.e. power curtailment) through maximum power point tracking (MPPT) function in PV inverter as well as reactive power and voltage support regulation such as function of voltage control, reactive power control and power factor control.

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Thesis Outline

Objectives

The main objective of this master thesis is to propose grid code design or update existing grid codes for 1 MW solar photovoltaics power plant (PVPP) connected to medium voltage (MV) level network in Indonesia. The following tasks are carried out to attain this objective:

- Study some sets of international grid code such as grid codes of Puerto Rico, Germany, Denmark and European Union which permits to analyze the correct trends of connection requirement.
- Describe the existing structure of electricity transmission and distribution system as well as current grid code of Indonesia. Then propose grid code design or update on the existing grid code.
- Discuss the introduction and characteristics of solar PVPP that contains the basic electrical components, inverter topologies as well as internal collection grid configuration.
- Model and simulate a 1 MW solar PVPP together with associated devices to test the proposed grid code design for solar PVPP in Indonesia in terms of active power regulation (absolute production) and reactive power regulation.

Scope

The scope of study in this master thesis are.

- The grid code in this master thesis is presented from operational perspective. It basically consists of requirement of voltage and frequency boundaries, active power and frequency support, reactive power and voltage support and fault-ride-through (FRT) for 1 MW solar PVPP connected to medium voltage (MV) network. In other words, grid codes pertaining to low voltage (LV) network is out of scope of this master thesis.
- In order to test the proposed grid code, a simplified 1 MW solar PVPP with its associated devices is modelled and simulated in Matlab and Simulink.

Organization

This master thesis is organized as follows.

- Chapter 1: introduction to the recent developments of renewable energy sources worldwide including solar power is described along with objectives and scopes of this master thesis.

- Chapter 2: this chapter begins with the necessity of grid code for solar PVPP. In addition, some international grid codes such as grid code of Puerto Rico, Germany, Denmark and European Union are discussed. In the end of this chapter, the summary of operational requirements such as voltage and frequency boundaries, active power and frequency support, reactive power and voltage support and fault-ride-through of each international grid code is given

- Chapter 3: here, the general structure of electrical generation, transmission and distribution system in Indonesia as well as the existing grid code of Indonesia for solar PVPP are discussed. Also, the proposed update on existing grid code for solar PVPP is described.

- Chapter 4: an introduction of solar PVPP is given along with characteristics, basic electrical components (i.e. photovoltaics (PV) arrays, PV inverters and transformer) and inverter topologies together with collection grid configuration of solar PVPP. Additionally, the control theory of solar PVPP is described in the present chapter.

- Chapter 5: in this chapter, the modelling approach for each electrical element in solar PVPP is described. Then the model of each electrical element is simulated. Additionally, a 1 MW solar photovoltaics power plant is modelled and simulated. The model is made up of solar PV arrays, solar PV inverter, transformer and electrical grid.

- Chapter 6: here the results and discussion about grid code proposal for solar PVPP in Indonesia along with the simulation result of a 1 MW solar PVPP for active power and frequency support function particularly MPPT function as well as reactive power and voltage support function are given.

- Chapter 7: in this chapter the conclusions of this master thesis are drawn.

Nomenclature

EU	European Union
FACTS	Flexible Alternating Current Transmission System
FRT	Fault-Ride-Through
GHG	Green House Gas
HVRT	High-Voltage-Ride-Through
IEC	International Electrotechnical Comission
LS-PVPP	Large Scale Photovoltaics Power Plant
LV	Low Voltage
LVRT	Low-Voltage-Ride-Through
MV	Medium Voltage
MPPT	Maximum Power Point Tracking
NA	Not Applicable
NS	Not Stated
PCC	Point of Common Coupling
PPC	Power Plant Controller
PV	Photovoltaics
PVPP	Photovoltaics Power Plant

1. Introduction

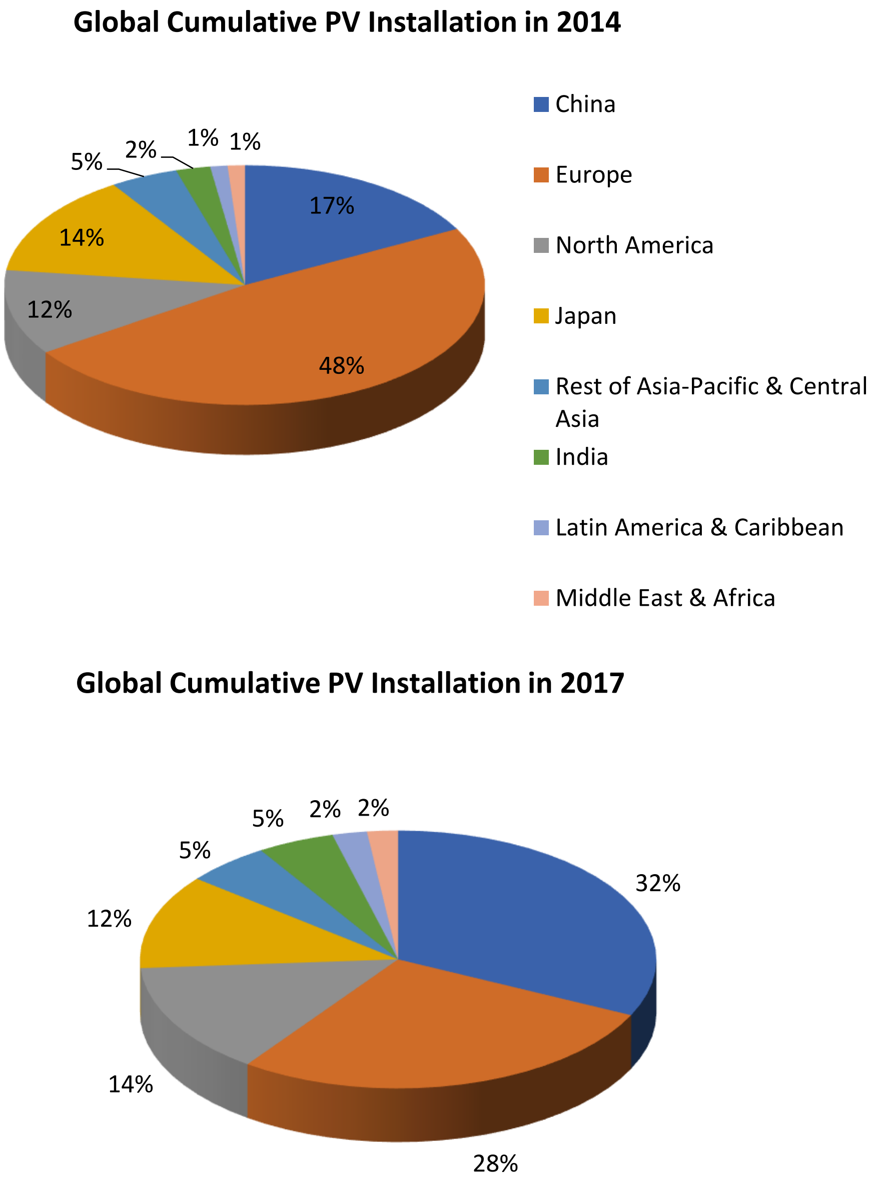
1.1. Overview

It is expected that the energy demand is going to rise by 41% in the next 20 years because of increasing industrial and residential needs [1]. In recent years, over 75% of the electricity demand was met by using fossil fuel sources [2]. Due to its nature, fossil fuels sources cannot be replenished in human time scale and hence it creates a need to meet the growing energy demand using renewable energy source. Moreover, carbon dioxide (CO_2) emissions from fossil fuel combustion and industrial processes contributed approximately 78% of the total greenhouse gas (GHG) emission increase from 1970 to 2010. Without additional efforts to reduce GHG emissions beyond on-going efforts, emission growth is expected to continue due to growth of economic activities and global population. It is estimated that, without additional climate change mitigation, global mean surface temperature will increase between 3.7^{o}C and 4.8^{o}C in 2100 in comparison with pre-industrial level (i.e. period before 1750) [3].

In Europe, the European Union (EU) member states agreed to carry out Horizon 2020 (H2020) plan which sets out 20% of the energy demand comes from renewable energy source, a greenhouse gas emission reduction of 20% as well as the implementation of 20% energy saving in a cost-efficient manner by 2020 in comparison to each respective status in 1990 [4]. In addition, Horizon (H2030) and Horizon (H2050) plan lays down the target of 27% and 75% energy demand comes from renewable energy source, a 40% and 80% greenhouse gas emission reduction along with the energy saving of 27% and 41% in comparison to each respective status in 1990 [5].

Hence, renewable energy has been harnessed more and more in the recent years mainly dominated by wind and solar energy sources. Wind power experienced the fastest growth over the years. In fact, the aggregated wind power installation in the EU by the end of 2014 was 128.8 GW [6] whereas in Asia, US and Latin America was 115 GW [7], 65 GW [8] and 4 GW [7] respectively.

On the contrary, PV power installations did not experience the same growth rate due to prices of photovoltaic panels and the associated technology. According to Fraunhofer ISE, as illustrated in Fig.1.1, the cumulative installed capacity of photovoltaics power in 2014 was 181.25 GW comprising 31.25 GW in China, 87.5 GW in Europe, 20.8 GW in North America, 25 GW in Japan, 8.3 GW in the Rest of Asia-Pacific & Central Asia, 4.2 GW in India, 2.1 GW in Latin America & Caribbean and 2.1 GW in Middle East & Africa. By 2017 the cumulative installed capacity of photovoltaic power rose to 414 GW (i.e. over doubled) comprising 133 GW in China, 115 GW in Europe, 58 GW in North America, 49 GW in Japan, 22 GW in the rest of Asia-Pacific & Central Asia, 20 GW in India, 9 GW in Latin America & Carribean and 8 GW in Middle East and Africa. In 2018, USA solar market expanded by 10.6 GW of PV especially in residential sector [10].


Global Cumulative PV Installation in 2014

Global Cumulative PV Installation in 2017

Figure 1. 1 Global cumulative PV installation in 2014 and 2017 [9]

The dramatic increase of variable renewable energy (e.g. wind and solar energy) source poses a challenge to the electrical grid due to its stochastic nature, particularly on the transmission and distribution level. The wind power plant and solar PVPP is expected not to behave like wind and solar farm (only generate electrical power) but as similar to conventional power plant (provide grid support functions) as possible [11]. Therefore, the need for creating grid codes or updating the existing ones which set outs the grid support requirements defined at the point of common coupling (PCC) for wind power plant and solar PVPP arises [12]. In this sense, wind power plants triggered the grid code development followed by grid codes applied to solar PVPP.

2. Review of International Grid Codes

2.1. Necessity of Grid Code

Generally, a power plant can be defined as a centralized system with the objective of injecting power to the electrical grid (i.e. not to a particular individual customer) [13]. Its main goals are to operate independently and to meet the requirements of electrical system under some regulations. These regulations are in the forms of grid codes and standards that define connection requirements on the MV and LV level for these power plants to the transmission and distribution grid with purpose of increasing its reliability, stability and security. These grid codes were traditionally established to allow interconnection of non-renewable energy power plants to the grid. The contribution of renewable energy power plants to electricity generation was initially very low in comparison with non-renewable energy power plants. However, this situation started to change dramatically in the recent years due to renewable energy sources have been harnessed more and more. As a result, in most countries, the share of renewable energy in electricity generation increased [12].

A couple of years ago, particularly in 2014, Puerto Rico’s electricity generation came from 19.1 TWh fossil fuel energy, 0.4 TWh controllable renewable energy (i.e. any other renewable energy than wind and solar) and 0.48 TWh variable renewable energy (i.e. wind and solar) as illustrated in Fig. 2.1. It is seen that the in 2014 variable renewable energy source held nearly 0% of the Puerto Rico’s electricity generation [14]. However, in 2017 variable renewable energy source emerged in Puerto Rico’s electricity generation up to 0.336 TWh (i.e. 2% of Puerto Rico’s electricity generation) and the rest of Puerto Rico’s electricity generation was composed of 20.58 TWh fossil fuel energy and 0.084 TWh controllable renewable energy. The reduction of controllable renewable energy fraction is presumed to be caused by disaster of Hurricanes Maria and Irma that destroyed much of the electricity generating facilities in 2017 [15]. However, according to Puerto Rico’s energy road map, renewable energy fraction of Puerto Rico’s electricity generation is expected to reach 15% and 20% by 2025 and 2035, respectively [14].

On the other side of the world, as seen in Fig.2.2, in 2010 Germany´s electricity generation came from 352 TWh fossil fuel energy, 193.23 TWh controllable renewable energy, 49.5 TWh variable renewable energy (i.e. wind and solar) and 37.5 TWh others [16]. It is seen that variable renewable energy source held 7% of Germany’s electricity generation in 2010. In 2017 the share of variable renewable energy in Germany´s electricity generation increased to 67 TWh (i.e. 10% of Germany’s electricity generation) and the rest of Germany’s electricity generation came from 328 TWh fossil fuel energy, 224 TWh controllable renewable energy and 30 TWh others [17].

As illustrated in Fig. 2.3, the same situation happened in Denmark where in 2010 Denmark´s electricity generation came from 5.42 TWh controllable renewable energy, 7.81 TWh variable renewable energy and 25.7 TWh fossil fuel energy. It can be observed that in 2010 the variable renewable energy source held 20% of the electricity generation in Denmark. Then in 2016 the fraction of variable renewable energy in Denmark's electricity generation increased drastically to 13.5 TWh (i.e. 44% of Denmark's electricity generation) along with the controllable renewable energy and fossil fuel energy that contributed 5.89 TWh and 11.4 TWh, respectively [18].

Generally, such a situation happened across Europe as depicted in Fig. 2.4 where in 2000, overall EU's electricity generation came from 1,628 TWh fossil fuel energy, 1,382 TWh controllable renewable energy, 22.1 TWh variable renewable energy and 1 TWh others. It is seen that in 2000, variable renewable energy source held 1% of the EU´s electricity generation. In contrast, in 2016 the variable renewable energy source contributed 407 TWh (i.e. 12%) of the overall EU's electricity generation and the rest of EU's electricity generation came from 1,402 TWh fossil fuel energy, 1,439 TWh controllable renewable energy and 5 TWh from the other as described in Fig.2.5 [19].

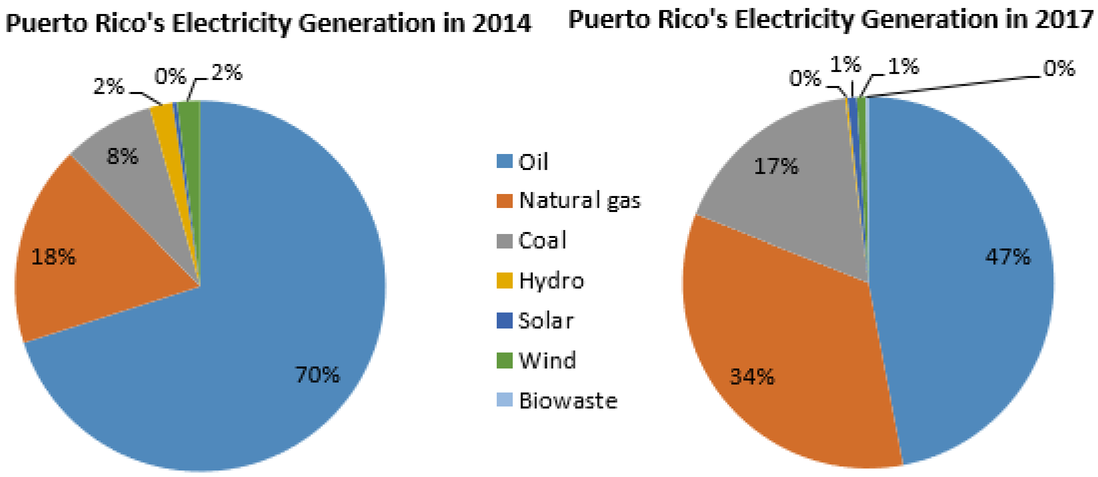


Figure 2. 1 Puerto Rico's electricity generation mix in 2014 and 2017 [14] [15]

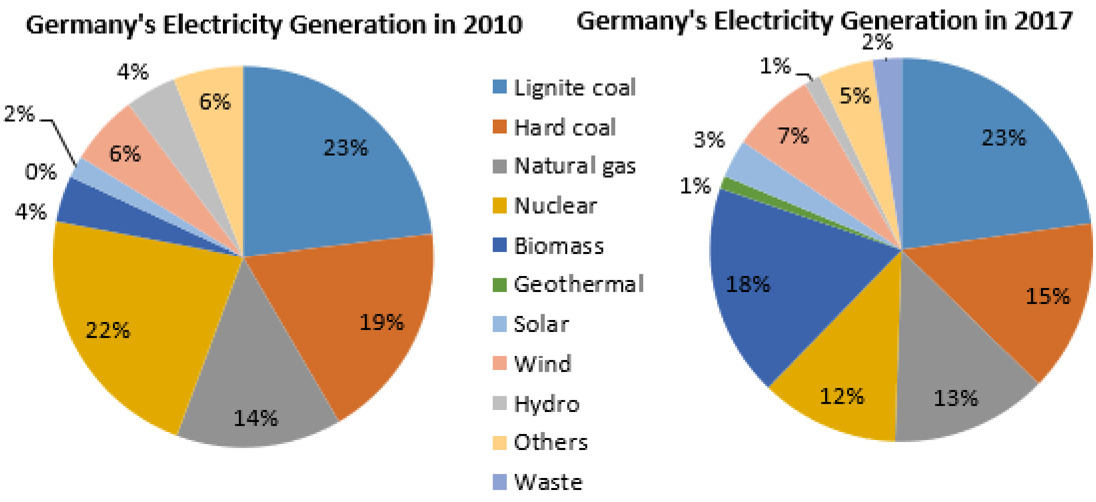


Figure 2. 2 Germany’s electricity generation mix in 2010 and 2017 [16] [17]

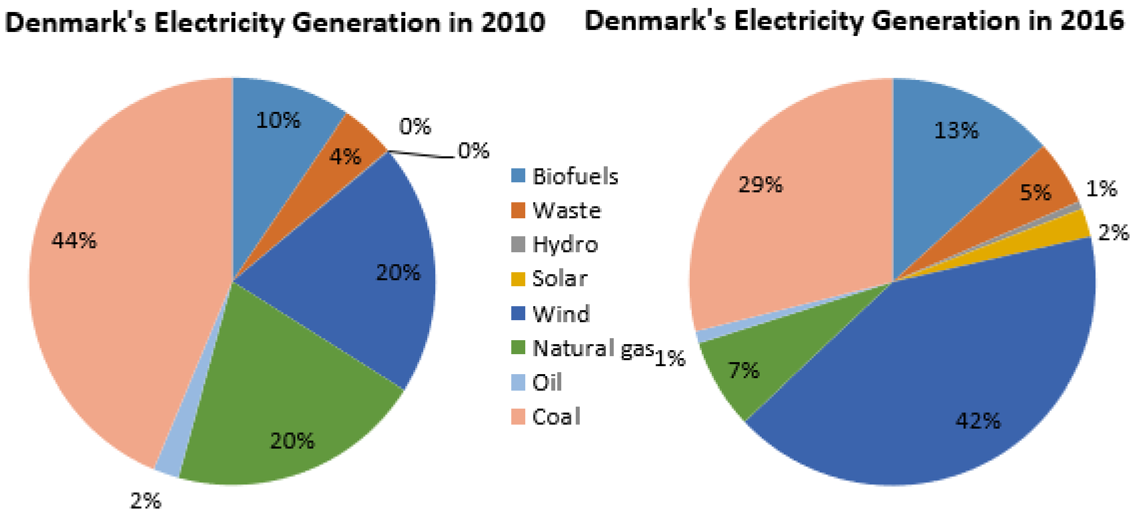


Figure 2. 3 Denmark` electricity generation mix in 2010 and 2016 [18]

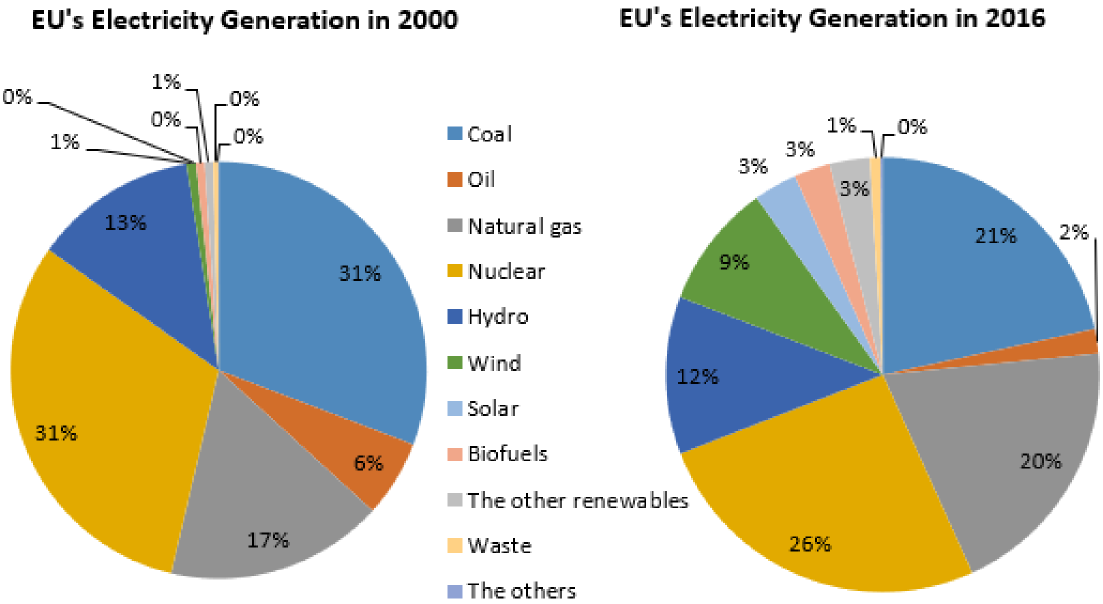


Figure 2. 4 EU’s electricity generation mix in 2000 and 2016 [19]

The growing share of renewable energy in global electricity generation, especially in Europe, is aligned with the increasing share of installed power capacity in Europe. In the last decade, approximately 60% newly constructed power generation is of variable renewable energy generation. As depicted in Fig.2.5, in 2005, the variable renewable energy power generation accounted for 43 GW (i.e. 6%) of the EU´s installed power capacity. Then, the rest is made up of fossil fuel power generation, controllable renewable energy power generation, variable renewable energy power generation and the other type of power generation accounted for 357 GW, 258 GW and 18 GW, respectively. In 2017, the share of variable renewable energy generation rose to 276 GW (i.e. 29%) of the EU´s installed power capacity and the rest is made up of 365 GW fossil fuel power generation, 270 GW controllable power generation and 27 GW other type of power generation [20].

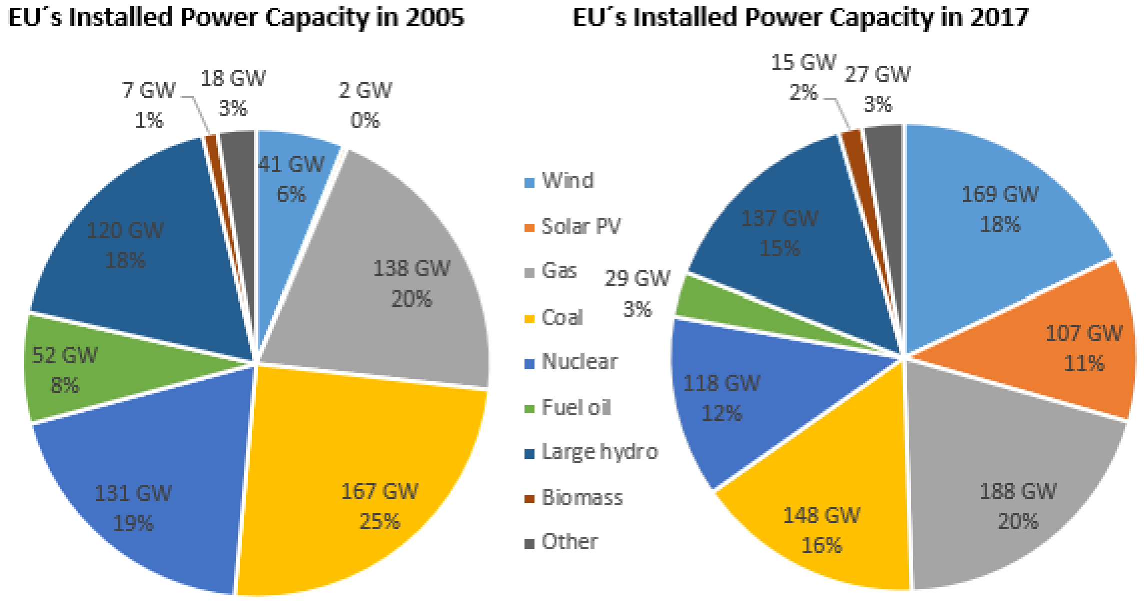


Figure 2. 5 EU´s installed power capacity in 2005 and 2017 [20]

By nature, renewable energy source, particularly variable renewable energy source (i.e. wind and solar photovoltaics) entails intermittency which present problems to the electrical system. These problems can be overcome by the provision of grid support function of the variable renewable energy power generation. The grid support requirement for variable renewable energy power plant is set out in grid codes and standards established by relevant system operator. Therefore, it is necessary to review and update the grid code and standard regularly as the amount of variable renewable energy penetration is growing.

The other motivation for establishment of grid codes and standards is that before the privatization and liberation of electricity market, the electricity network of generation, transmission and distribution could be managed by the same company. After the privatization and liberalization of electricity market that leads to deregulation, different companies may manage each network of transmission and distribution. Consequently, responsible system operators worldwide have prepared grid codes and standards that set out the technical specifications and operational characteristics at the point of connection that power generation must comply. It has the purpose of maintaining uniformity of requirements for each power generation. These grid codes vary by local regulation, legal and technical environment.

In this way, wind power plants first triggered the development of grid codes followed by solar PVPP. According to the electricity system operator of the UK, grid code is the technical code for connection and development of the National Electricity Transmission System (NETS) [21]. Additionally, grid code can be defined as a technical document containing the set of rules governs the operation, maintenance and development of the system at the point of common coupling (PCC) [22].

Thus, this chapter is dedicated for discussion about international grid codes for solar PVPP in selected countries (i.e. Puerto Rico, Germany, Denmark and European Union) since they have common trend of growing share of solar PVPP in their individual installed power capacity. Moreover, their grid codes are mature enough and well-defined to study. Then, an analysis of the main grid code requirements for solar PVPP connected to the electrical system is performed. This analysis is carried out from viewpoint of frequency and voltage boundaries, active power and frequency control, reactive power and voltage control along with fault-ride-through capability.

In following sections, as described in Table. 2.1, each set of grid codes of Germany, Denmark, Puerto Rico and European Union for LS-PVPP connected to medium voltage network managed by relevant system operator in respective country is discussed.

Country / Territory	**Organization**	**Title**	**Version**
USA (Puerto Rico)	PREPA	Technical Requirements for Interconnecting Wind and Solar Generation	August, 2012
Germany	VDE	Summary of the Draft VDE-AR-N 4110:2017:02 – Connection and Operation to Medium Voltage Grid	February, 2017
Denmark	Energinet	Technical Regulation 3.2.2. for PV Power Plants Above 11 kW	July, 2016
European Union	European Comission	EU Directive 2016/631 Establishing a Network Code on Requirements for Grid Connection Generators	April, 2016

Table 2. 1 International grid codes under study

2.2. Contents of Grid Code

In this section, the basic contents of grid code from operational viewpoint are discussed. The first regulations that established the connection requirement for solar PVPP to the electrical network are IEEE 1547 and EN 50160. They are intended for small scale solar PVPPs interconnected to the distribution network for residential, commercial and industrial purpose. In fact, these regulations prevented small scale solar PVPPs from providing ancillary services such as frequency and voltage support as well as reactive power support [23]. However, as discussed earlier, in the coming years the large amount of solar power is expected to penetrate into the electrical grid. This may cause problems due to its intermittency, lack of voltage support, variable active power and power mismatching. Therefore, the grid codes for interconnection of solar PVPP to the electrical network have been developed in a way that capability of fault-ride-through, active power and frequency support along with reactive power and voltage support is required.

Germany is the first country that launched grid codes for solar PVPP connected to MV and HV level network in 2008 [22]. 4 years after Denmark´s grid code for wind power plant was released. This grid code has been an inspiration for the other grid codes by several other countries in Europe. After Germany´s grid code, South Africa [24], China [25] and Romania [26]

Grid code from operational perspectives basically contains voltage and frequency boundaries, active power and frequency control function, voltage and reactive power control function, and FRT capability and they are summarized one by one in following subsections.

2.2.1 Voltage and Frequency Boundaries

Grid code essentially states the electrical boundaries under which the solar PVPP must operate continuously. The electrical boundaries consist of range of normal operating voltage and frequency at the PCC. Each range consists of several sub-ranges in which the solar PVPP must remain online for particular period of time. The voltage and frequency boundaries are established uniformly by relevant system operator for each solar PVPP.

2.2.2 Active Power and Frequency Control Functions

As the solar energy varies throughout the day, the need for controlling the active power of solar PVPP arises. Active power and frequency control is essentially made up of function of frequency response or control, absolute production (i.e. power curtailment), delta production (i.e. power reserve) and power gradient (i.e. ramp rate). Frequency response or frequency control can be defined as the capability of a solar PVPP to adjust its active power output (P) in response to a measured deviation at the point of common coupling of system frequency (Δf) from a setpoint with a view to stabilize the grid. The permissible variation of active power due to the change of frequency is described by droop. Droop constant is expressed by the ratio of change in frequency (Δf) over nominal frequency (f_n) to change of actual active power output (ΔP) over nominal output power (P_n) or actual active power output (P_{ac}) depending on the grid code. The frequency response or control is illustrated in Fig.2.6. The frequency response or control is composed of upward droop (line from f_2 to f_1), dead band (the range where no change in active power), downward droop (line from f_3 to f_{max}) and control band (the range comprises upward droop, dead band and downward droop). In addition, the active power output is allowed to rise again after the frequency f_4 is reached. Please note that f_n represents nominal frequency.

Absolute production is the adjustment of active power (P) to maximum level at the point of common coupling as indicated by setpoint. The purpose of absolute production is to protect the electrical grid from overloading in critical situations. Then, delta production is the power reserve that a solar PVPP creates out of the difference between the available active power output (P_{av}) and actual active power output (P_{ac}). The purpose of delta production is to establish a regulating reserve for upward regulation related to the delivery of ancillary service (i.e. frequency response or control). In addition, power gradient is used to limit the maximum speed by which the active power (ΔP) can be changed in the event of changes in power or the set points for a plant. Its unit is power over time. The purpose of power gradient is to prevent the changes in active power from adversely impacting the electrical grid. Fig.2.7. Illustrates the function of absolute production, delta production and power gradient.

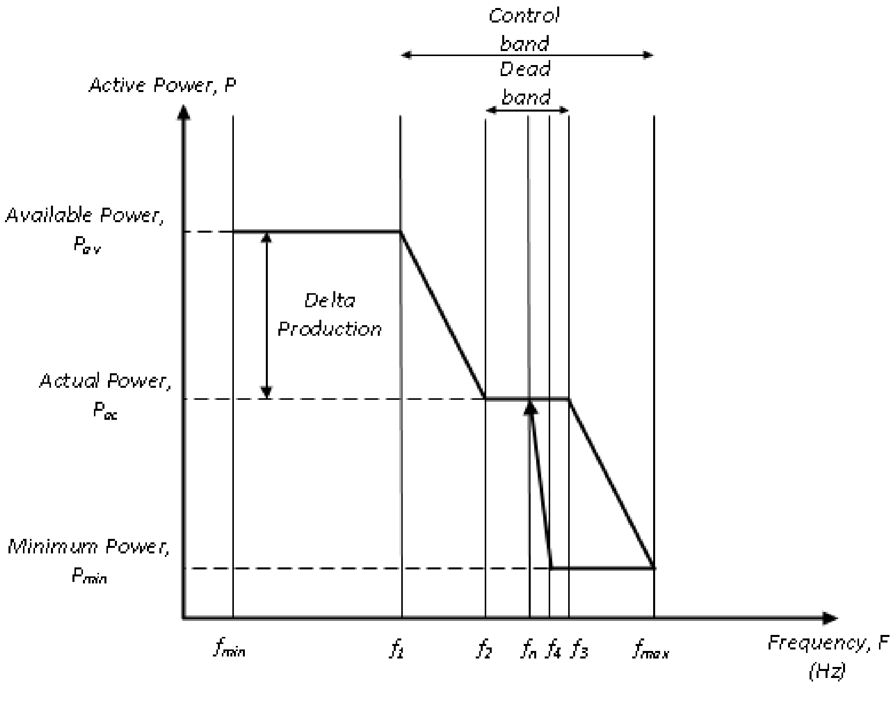


Figure 2. 6 Frequency response or control [adapted from [12]]

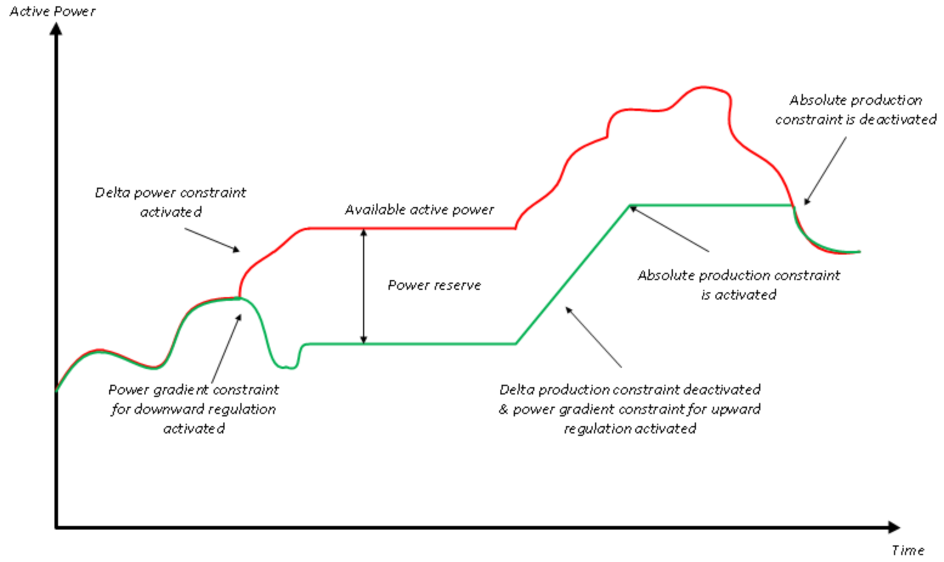


Figure 2. 7 Absolute production, delta production and power gradient [adapted from [27]]

2.2.3 Reactive Power and Voltage Control Functions

Solar PVPP must be capable of overcoming voltage deviations and providing reactive support to the grid as conventional power plants. Thus, grid codes establish the minimum reactive power requirement that solar PVPP must comply with. In the past, PV inverters were not designed considering this requirement but recently some PV inverter manufacturers considering this requirement in PV inverters specification. The capability of reactive support in PV inverters varies in function of the solar irradiance and temperature. To accommodate the connection of solar PVPP to the electrical network and collaborate smoothly, the relevant system operator encounters two challenges: (1) the voltage has to be kept inside within the dead band regulated by relevant system operator. (2) the solar PVPP must follow the capability curve given by the relevant system operator that defines the relation between reactive and active power [12].

There are four methods to regulate the reactive power and voltage: (1) voltage (V) control, (2) power factor (PF) control, (3) automatic power factor (PF) control and (4) reactive power (Q) control. Voltage control regulates the voltage based on the droop function that is defined as the ratio of variation of voltage (ΔV) over nominal voltage (V_n) due to the change of reactive power (ΔQ) over instantaneous power (actual power (P_{ac}) in case no delta production) as illustrated in Fig.2.8. The power factor control regulates the reactive power (Q) based on the value of active power (P) whereas automatic power factor (PF) control regulates the reactive power with a variable PF depending on the generated active power as illustrated in Fig.2.9. When the ratio of actual power (P_{ac}) to available power (P_{av}) reaches X_1 then the solar PVPP starts supplying reactive power (Q) following a linear gradient until it reaches power factor (PF) of 1. And the last method is reactive power control that regulates directly the reactive power (Q) at the PCC. The solar PVPP must be capable of regulating the reactive power and voltage using any of these controls. The most commonly used functions are combination of voltage control and reactive power control as well as voltage control and power factor control. However, in some grid code the reactive power control, power factor control and voltage control are mutually exclusive which implies that only one of the three functions can be performed at a time [27]. Fig.2.10 depicts normal operating zones of solar PVPP as functions of power factor (PF) and reactive power (Q). There are two types of operating zones: (1) rectangular-shaped zone in which solar PVPP must be capable of providing reactive power between Q_1 and Q_2 with no regard to power factor (2) triangle-shaped zone in which solar PVPP must be capable of providing reactive power between Q_1 and Q_2 with regard to power factor in the range of PF_1 and PF_2. Additionally, in some international grid codes, below particular active power (P_1) solar PVPP is not required to deliver reactive power (Q).

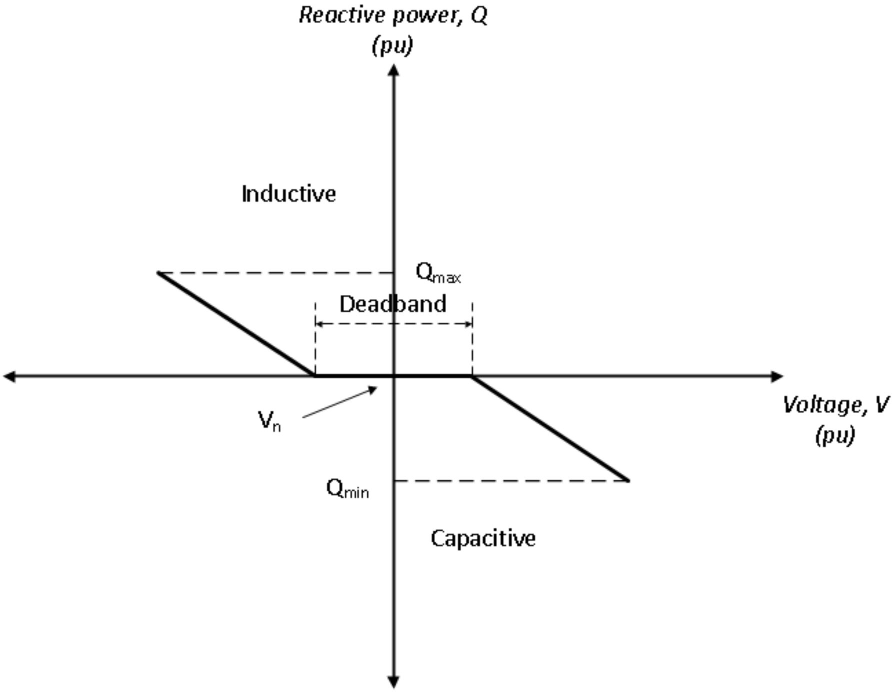


Figure 2. 8 Voltage control with droop function [adapted from [28]]

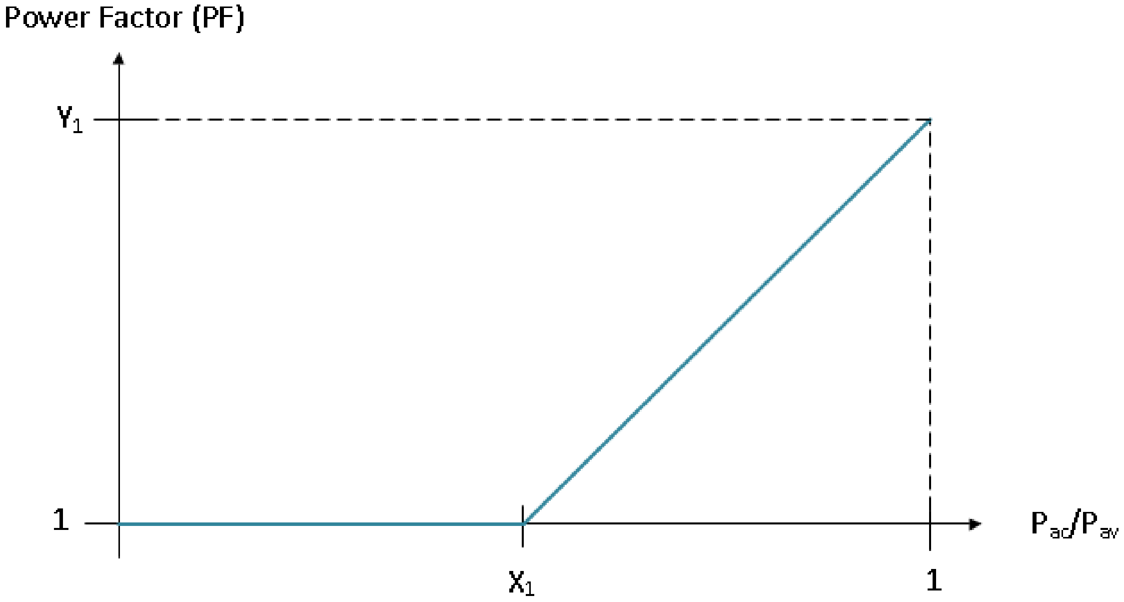


Figure 2. 9 Automatic power factor control [adapted from [27]]

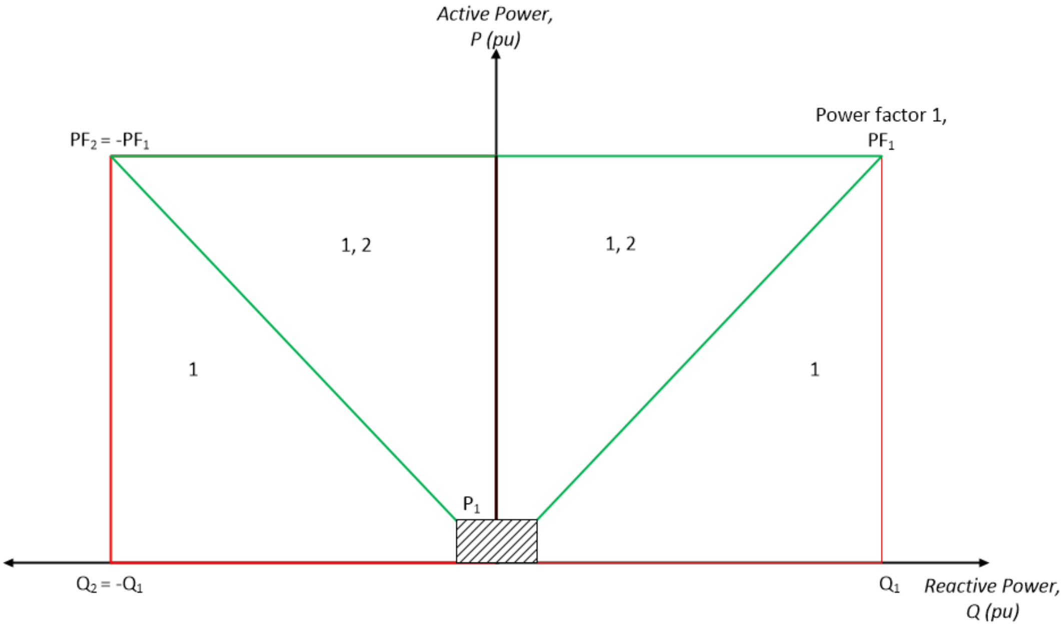


Figure 2. 10 Normal operating zones as functions of power factor and reactive power

[adapted from [12]]

2.2.4 Fault-Ride-Through (FRT) Capability

Fault-ride-through (FRT) capability is a capability normally possessed by solar PVPP to remain online in the event of symmetrical and/or asymmetrical fault. FRT capability is composed of low-voltage-ride-through (LVRT) capability and high-voltage-ride-through (HVRT) capability along with reactive current injection (I_q) capability.

Low-voltage-ride-through (LVRT) capability is a capability by which solar PVPP remains online in undervoltage situation for certain period of time. This capability is illustrated in Fig.2.11. In case of the normal voltage profile at the PCC (i.e. in zone A) the solar PVPP must remain online continuously whereas in case of voltage profile is located in zone B the solar PVPP must remain online for certain period of time and perform reactive current injection to help stabilizing the network. In addition, the solar PVPP is not required to remain online in case the voltage profile is located in zone C.

High-voltage-ride-through (HVRT) capability is a capability by which solar PVPP remain online in overvoltage situation for certain period of time. This capability is required in several international grid codes. Fig.2.12 depicts this capability. In case the voltage profile at the PCC is located in zone A then the solar PVPP must stay connected to the network continuously. In contrast, in case the voltage profile is located in zone B then the solar PVPP must remain online for determinate periods of time. Additionally, in case the voltage profile is located in zone C then the solar PVPP is not required to remain online.

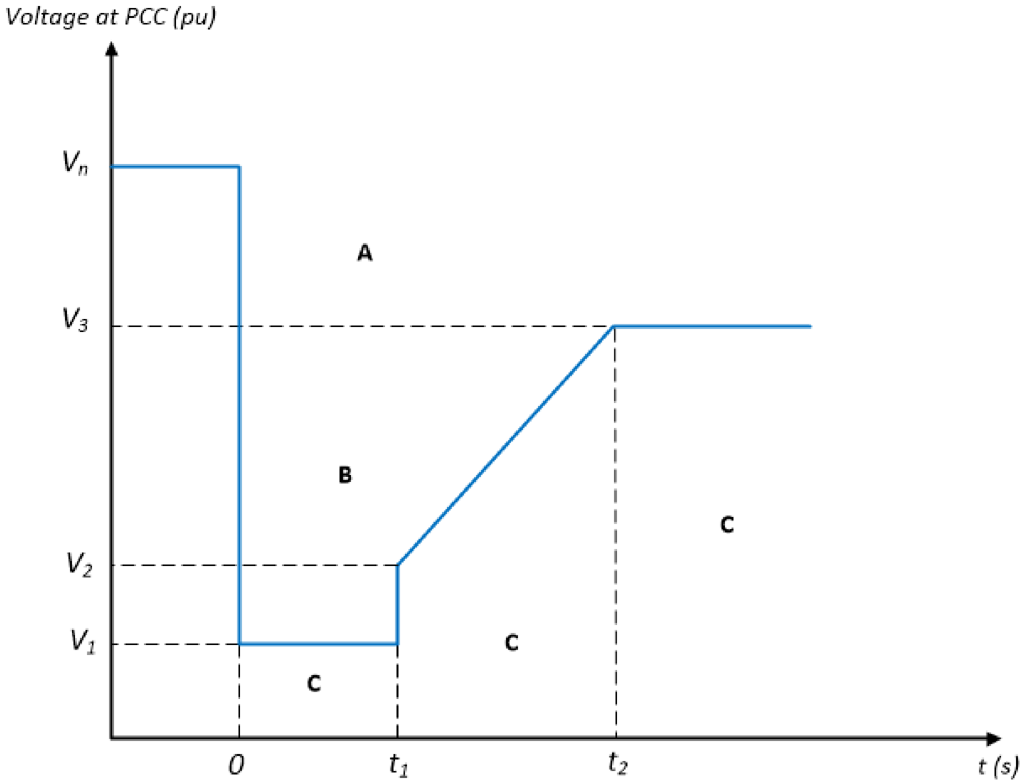


Figure 2. 11 LVRT Capability [12]

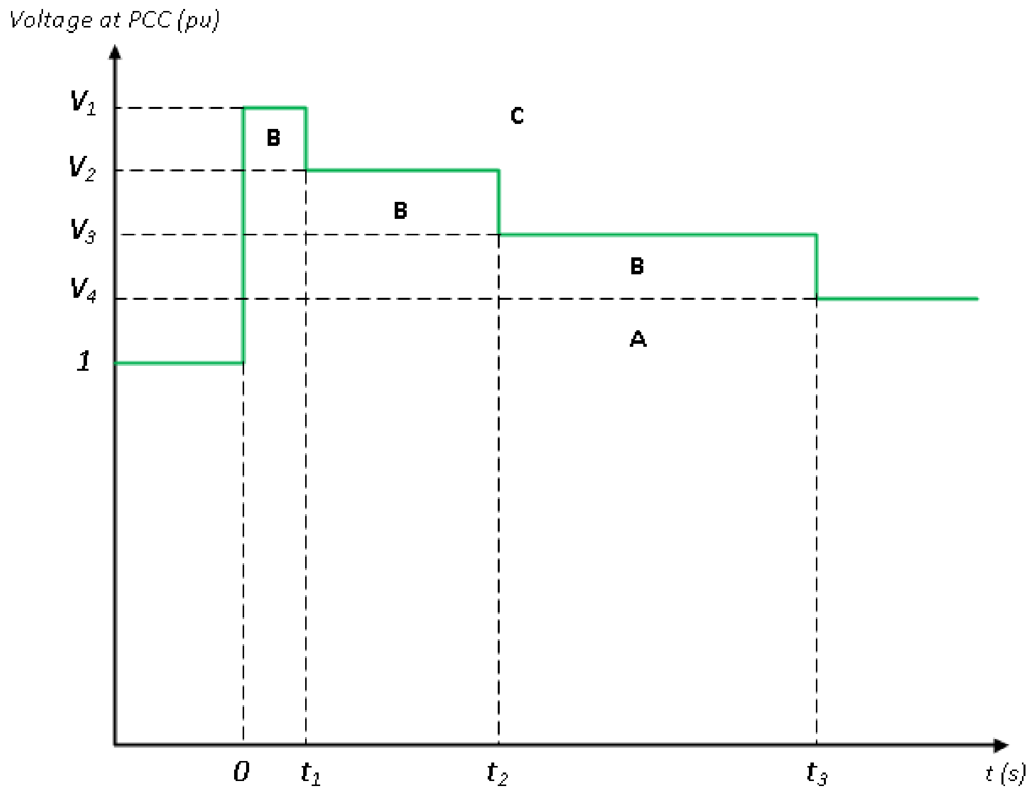


Figure 2. 12 HVRT capability [12]

Besides LVRT capability and HVRT capability, reactive current injection capability is required in undervoltage situation in several international grid codes. This requirement defines the reactive current injection in function of voltage as shown in Fig.2.13. This capability essentially consists of deadband (i.e. a range without reactive current injection), droop constant (i.e. ratio of change of reactive current (ΔI_q) over nominal current (I_q) to change of voltage (ΔV) over nominal voltage (V_n), voltage deviation setpoint 1 (X_1) where solar PVPP begin injecting 100% reactive current as well as the voltage deviation setpoint 2 (X_2) where the solar PVPP start absorbing 100% reactive current.

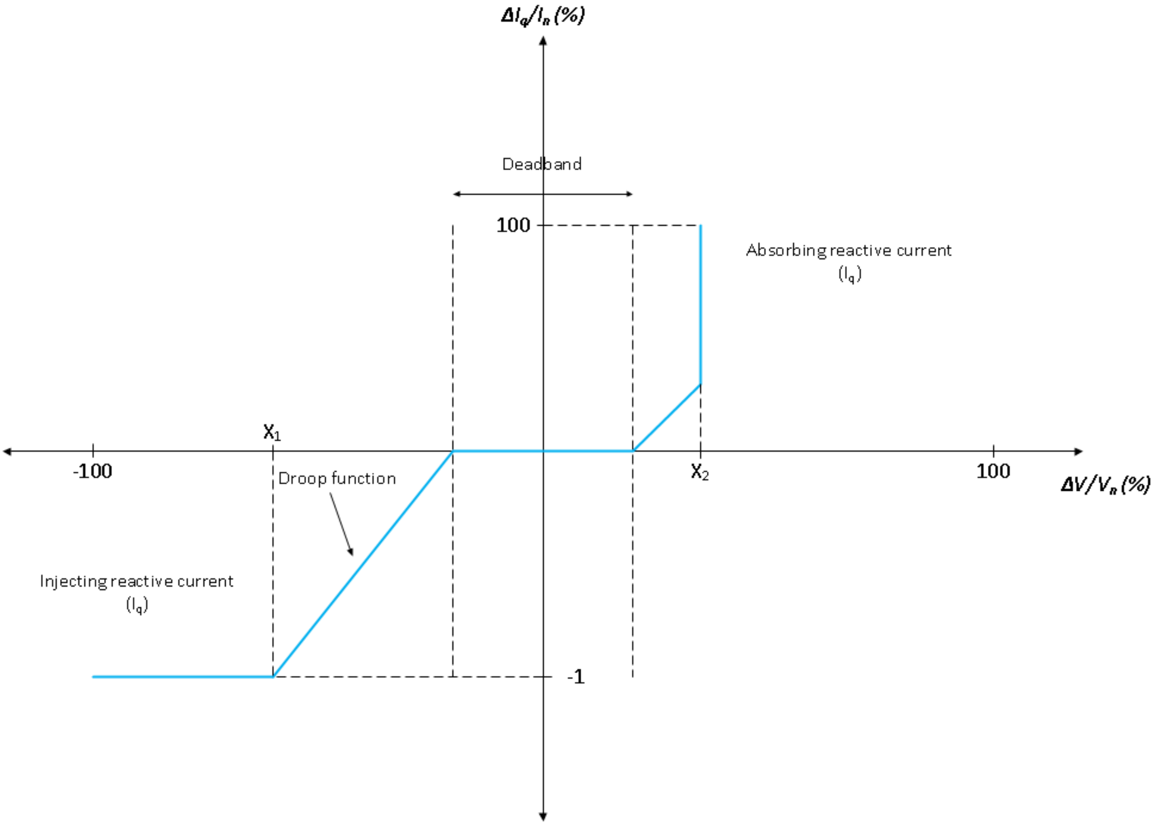


Figure 2. 13 Reactive current injection

2.3. Grid Codes of Puerto Rico

2.3.1 Voltage and Frequency Boundaries

According to the latest regulation of Puerto Rico, the range of normal operating frequency along with minimum duration to remain online of a solar PVPP and the range of normal voltage are listed in Table 2.2 and Table 2.3, respectively.

Nominal Frequency, f_n (Hz)	Range of Normal Operating Frequency (Hz)	Minimum Duration
60	x<56.5	Instantaneous trip
	56.5≤x<57.5	10 sec

	57.5≤x≤61.5	Continuous
	61.5<x≤62.5	30 sec
	x>62.5	Instantaneous trip

Table 2. 2 Range of normal operating frequency

Range of Normal Operating Voltage (pu)	**Minimum Duration**
0.85-1.15	Continuous

Table 2. 3 Range of normal operating voltage

2.3.2 Active Power and Frequency Support

Table 2.4 outlines the active power and frequency support requirements for solar PVPP.

Requirements for a 1 MW solar PVPP	**Response**
Frequency response or control. frequency response or control is detailed below	Yes
Absolute production. absolute production or power curtailment is detailed below	Yes
Delta production. delta production or power reserve is detailed below	Yes
Power gradient. power gradient or ramp rate or is detailed below	Yes

Table 2. 4 Active power and frequency support requirements

Frequency Response

In the latest Puerto Rico´s grid code, there are two cases in regards to frequency response or control.

(1) For small frequency deviations (i.e. less than 0.3 Hz), the parameters illustrated in Fig.2.6 are listed in Table 2.5.

Parameter	Value
f_{min}	56.5 Hz
f_1	≥59.694 Hz
f_2	59.994 Hz
f_3	60.006 Hz
f_4	≤60.306 Hz
f_{max}	62.5
Upward droop constant	5% as a function of nominal output power (P_n)
Downward droop constant	5% as a function of nominal output power
Response time for both droops	<1 s
Actual power	NS

Table 2. 5 Parameter in case 1

NS : not stated

(2) For large frequency deviations (i.e. greater than 0.3 Hz), the parameters illustrated in Fig.2.6 are illustrated in Table 2.6.

Parameter	Value
f_{min}	56.5
f_1	<59.694 Hz
f_2	59.994 Hz
f_3	60.006 Hz

f_4	>60.306 Hz
f_{max}	62.5
Upward droop constant	5% a function of nominal output power
Downward droop constant	5% a function of nominal output power
Response time for both droops	<1 s
Settling time for both droops	NS
Actual power	≥10% of nominal output power

Table 2. 6 Parameter in case 2

Constraint Functions

The type of constraint functions is listed in Table 2.7.

Type of Constraint Functions	**Value**
Absolute production	aw-TSO
Delta production	10% nominal output power ≤ x ≤ 100% nominal output power
Ramp rate Rate of increase of power Rate of decrease of power Rate of increase of power when an absolute production constraint turns off Rate of decrease of power when an absolute production constraint turns on	10% of nominal output power per minute with tolerance of 10%

Table 2. 7 Constraint functions

*aw-TSO: agreed with transmission system operator

2.3.3 Reactive Power and Voltage Support

Table 2.8 summarizes the reactive power and voltage support requirements for a solar PVPP according to the latest Puerto Rico´s regulation.

Requirements for a 1 MW solar PVPP	**Response**
Voltage control. voltage control is detailed below	Yes
Reactive power control.	No
Power factor control.	No
Automatic power factor control.	No

Table 2. 8 Reactive power and voltage support requirements

Voltage Control

Table 2.9 illustrates parameters with regards to voltage control function as depicted in Fig.2.8.

Parameters	**Value**
Deadband	0.999pu≤x≤1.001pu
Upward droop function	0%<x≤10%
Downward droop function	0%<x≤10%
Time response	1s for 95% total reactive power
Upper limit of reactive power delivery	0.62 of actual active power (P_{ac})
Lower limit of reactive power delivery	-0.62 of actual active power (P_{ac})

Table 2. 9 Parameters in voltage control function

2.3.4 Fault-Ride-Through Requirement

Table 2. 10 lists the requirement of FRT for a 1 MW solar PVPP.

Requirements for a 1 MW solar PVPP	**Response**

LVRT capability due to symmetrical and asymmetrical fault	Yes
HVRT capability due to symmetrical and asymmetrical fault	Yes
Reactive current injection	Yes

Table 2. 10 Fault-ride-through requirement

Table 2.11 explains the parameters in LVRT requirement described in Fig.2.11.

Parameters	**Value**
V_1	0
V_2	0.1 pu
V_3	0.85 pu
t_1	600 ms
t_2	3 s

Table 2. 11 Parameters in LVRT requirement

In addition, Table 2.12 describes the parameters with regards to high-voltage-ride-through requirement depicted in Fig. 2.12.

Parameters	**Value**
V_1	1.4 pu
V_2	1.3 pu
V_3	1.15 pu
t_1	150 ms
t_2	1 s
t_3	3 s

Table 2. 12 Parameters in HVRT requirement

During undervoltage fault condition, solar PVPP must operate on reactive current injection mode as parameters listed in Table 2.13 and depicted in Fig.2.13.

Parameters	**Value**
Droop constant	1%≤x≤5%
Deadband	15%
X_1	aw-TSO
X_2	NS

Table 2. 13 Parameters in reactive current injection requirement

*aw-TSO: agreed with transmission system operator

NS: not stated

2.4. Grid Codes of Germany

The latest regulation of Germany for grid codes for power plants connected to MV level network is based on that for HV level network. The scope of this regulation is explained in Table 2.14.

Parameter	**Value**
Grid Voltage (kV) [29]	1-60
Type of Power Generation [30]	Type 1 – power generation with synchronous generation and its associated storage
	Type 2 – power generation with asynchronous generator and its associated storage
Typical Size of Power Generation [31]	500 kW to 100 MW

Table 2. 14 The scope of the latest Germany´s regulation for grid code

In this section the requirements for type 2 is focused since in this master thesis, emphasis is put on a 1 MW solar PVPP.

2.4.1 Voltage and Frequency Boundaries

The range of normal frequency and voltage for solar PVPP connected to MV level network is described in Table 2. 15 and Table 2. 16, respectively [29].

Nominal Frequency (Hz)	**Range of Normal Operating Frequency (Hz)**	**Minimum Duration**
50	x<47.5	Instantaneous trip
	47.5≤x<49	30 minutes

	49≤x≤51	Continuous
	51<x≤51.5	30 minutes
	x>51.5	Instantaneous trip

Table 2. 15 The range of normal operating frequency

Range of Normal Operating Voltage (pu)	Minimum Duration
x<0.85	Instantaneous trip
0.85≤x<0.9	60 seconds
0.9≤x≤1.1	Continuous
1.1<x≤1.15	60 seconds
x>1.15	Instantaneous trip

Table 2. 16 The range of normal operating voltage

Normal operation is defined as the condition where voltage gradient is less than 5% per minute and frequency gradient is less than 0.5% per minute. In addition, voltage gradients over 5% is acceptable in the voltage range of 0.9 pu - 1.1 pu.

2.4.2 Active Power and Frequency Support

Table 2. 17 outlines active power and frequency support requirement.

Requirements for a 1 MW Solar PVPP	**Response**
Frequency response or control. frequency response or control is specified below	Yes
Absolute production. absolute production or power curtailment is detailed below	Yes
Delta production. delta production or power reserve is detailed below	Yes
Power gradient. power gradient or ramp rate or is detailed below	Yes

Table 2. 17 Active power and frequency support requirements

Frequency Response

The relevant parameters in frequency response or control function depicted in Figure 2. 6 is listed in Table 2. 18.

Parameter	**Value**
f_{min}	47.5 Hz
f_1	48.8 Hz
f_2	49.8 Hz
f_3	50.2 Hz
f_4	50.1 Hz
f_{max}	51.5 Hz
Upward droop constant	5% as a function of nominal output power (P_n)
Downward droop constant	5% as a function of actual output power (P_n)
Response time for both droops	2 s
Settling time for both droops	20 s
Actual power	NS

Table 2. 18 Parameters in frequency response or control

Constraint Functions

Table 2. 19 describes the types of available constraint function.

Type of Constraint Functions	**Value**
Absolute production	aw-TSO
Delta production	aw-TSO

Ramp rate Rate of increase of power Rate of decrease of power Rate of increase of power when an absolute production constraint turns off Rate of decrease of power when an absolute production constraint turns on	19.8% of nominal output power per minute ≤ x ≤39.6% of nominal output power per minute

Table 2. 19 Constraint functions

2.4.3 Reactive Power and Voltage Support

Table 2. 20 summarizes reactive power and voltage support requirement for solar PVPP.

Requirements for a 1 MW solar PVPP	**Response**
Voltage control. voltage control is detailed below	Yes
Reactive power control. reactive power control is detailed below	Yes
Power factor control. power factor control is detailed below	Yes
Automatic power factor control.	No

Table 2. 20 Reactive power and voltage support requirement

Voltage Control

Table 2. 21 illustrates parameters with regards to voltage control function as depicted in Figure 2. 8.

Parameters	**Value**
Deadband	NA
Upward droop function	0%<x≤8.333%
Downward droop function	0%<x≤8.333%
Ramp rate	aw-TSO

Table 2. 21 Parameters in voltage control function

*NA : not applicable

Reactive Power Control

Solar PVPP must be capable of providing the reactive power from Q_1 to Q_2 with regard to the power factor between PF_1 to PF_2 (i.e. zone 2). In fact, solar PVPP is not required to supply reactive power below determinate active power (P_1). Table 2. 22 establishes the parameters illustrated in Figure 2. 10.

Parameters	Value (pu)
PF_1	0.9
PF_2	-0.9
Q_1	0.48
Q_2	-0.48
P_1	0.05
Time Response	NS

Table 2. 22 Parameters in reactive power control

Power Factor Control

Solar PVPP must be capable of delivering reactive power as a function of active power. As listed in Table 2. 22, solar PVPP must be capable of operating at power factor between PF_1 and PF_2 depicted in Figure 2. 10.

2.4.4 Fault-Ride-Through Capability

Table 2. 23 outlines the FRT requirement.

Requirements for a 1 MW Solar PVPP	Response
LVRT capability due to symmetrical and asymmetrical fault	Yes
HVRT capability due to symmetrical and asymmetrical fault	Yes
Reactive current injection	Yes

Table 2. 23 Fault-ride-through requirement

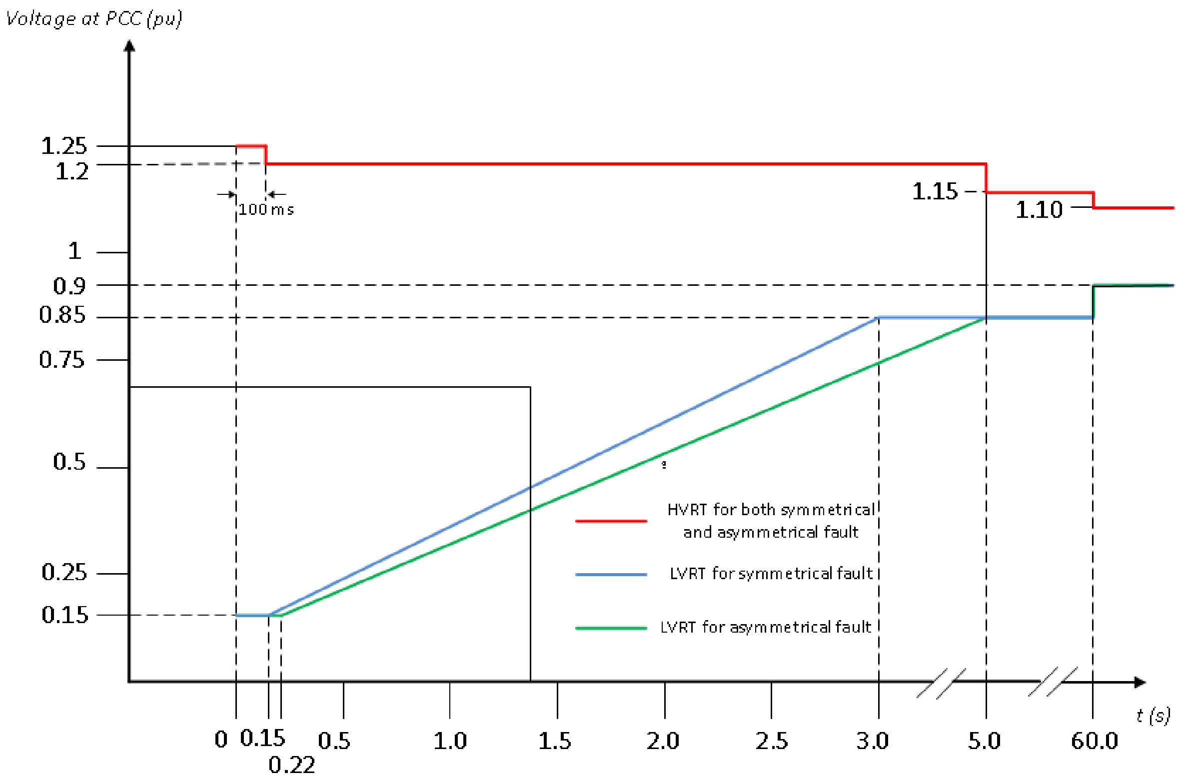


Figure 2. 14 FRT requirement [adapted from [29]]

Figure 2. 14 depicts FRT requirement comprising HVRT for both symmetrical and asymmetrical fault as well as LVRT for individual symmetrical and asymmetrical fault. The criteria for fault start are voltage at PCC ≥ 1.1 of nominal voltage (U_n) or ≤ 0.9 U_n. Furthermore, the criteria for fault end is 5 s after the fault starts and all line-to-line voltages should be restored in the range between 0.9 U_n and 1.1 U_n.

For reactive current injection requirement, it is set out in the latest grid code of Germany. However, its value is not explicitly specified.

2.5. Grid Codes of Denmark

Denmark’s regulations classify power plants based on the voltage at the PCC and nominal output power (i.e. active power) into 5 types. Table 2. 24 lists the voltage level and nominal output power for each type of power plants.

Parameters	Type A1	Type A2	Type B	Type C	Type D
Rated power	x ≤11 kW	11 kW < x ≤ 50kW	50 kW < x ≤ 1.5 MW	1.5 MW < x ≤ 25 MW	x>25 MW
Voltage level	x≤100 kV	x≤100 kV	x≤100 kV	x≤100 kV	x>100 kV

Table 2. 24 Voltage level and nominal output power for each type of power plants

Moreover, the Denmark's regulations are made up of five technical regulation according to the nature of power plant as follows.

- The first technical regulation applies to all generation plants (excluding battery plants) that are up to and including 11 kW [32].
- The second technical regulation applies to connection requirement pertaining to solar PVPP over 11 kW [27].
- The third technical regulation describes connection requirement for thermal power plants over 11 kW [33].
- The fourth regulation defines the connection requirement for wind power plants above 11 kW [34].
- The fifth regulation details the connection requirement for battery plants [35].

In this section, the second technical regulation that defines that connection requirement for power plants type B is more focused since this master thesis deals with a 1 MW solar PVPP.

2.5.1 Voltage and Frequency Boundaries

The range of normal operating voltage at the PCC is U_n±10% and the nominal frequency is 50 Hz as well as the range of normal operating frequency is from 47.00 Hz to 52.00 Hz in which the solar PVPP must remain connected to public electricity grid.

The range of normal operating voltage is derived from nominal voltage (U_n) as listed in Table 2. 25. The operating voltage should lie between the minimum (U_{min}) and maximum voltage (U_{max}) listed in Table 2. 25.

Voltage Level Descriptions	**Nominal Voltage U_n [kV]**	**Minimum Voltage U_{min} [kV]**	**Maximum Voltage**

			U_{max} [kV]
High voltage [HV]	60	54	72.5
	50	45	60
Medium voltage [MV]	33	30	36
	30	27	36
	20	18	24
	15	13.5	13.5
	10	9	12
Low voltage [LV]	0.69	0.62	0.76
	0.4	0.36	0.44

Table 2. 25 Nominal voltage, minimum voltage (U_{min}) and maximum voltage (U_{max})

2.5.2 Active Power and Frequency Support

Table 2. 26 outlines the active power and frequency support requirements.

Requirements for a 1 MW Solar PVPP	**Response**
Frequency response or control. frequency response or control is detailed below	Yes
Absolute production. absolute production or power curtailment is detailed below	Yes
Delta production.	No
Power gradient. power gradient or ramp rate is detailed below	Yes

Table 2. 26 Active power and frequency support requirements

Frequency Response

The relevant parameters in frequency response or control function described in Figure 2. 6 is listed in Table 2. 27.

Parameter	Major Islands
f_{min}	47.0 Hz
f_1	NA
f_2	NA
f_3	50.0-52.0 Hz (aw-TSO) 50.2 Hz (standard value)
f_4	NA
f_{max}	52.0 Hz
Upward droop constant	NA
Downward droop constant	2-12% (aw-TSO) 4% as a function of actual output power (standard value)
Response time for downward droop	2 s
Settling time for downward droop	15 s
Actual power	NA

Table 2. 27 Parameters in frequency response or control

Constraint Functions

Table 2. 28 describes the constraint functions stated in the technical regulation.

Type of Constraint Functions	Value
Absolute production	aw-TSO
Delta production	NA
Ramp rate Rate of increase of power Rate of decrease of power Rate of increase of power when an absolute production constraint turns off Rate of decrease of power when an absolute production constraint turns on	100 kW/s

Table 2. 28 Constraint functions

The response and settling time for both absolute production and ramp rate constraints are 2 seconds and 10 seconds, respectively.

2.5.3 Reactive Power and Voltage Support

Table 2. 29 lists the reactive power and voltage support requirements. In fact, the control functions of voltage control, reactive power control and power factor control are mutually exclusive, meaning only one of the three functions can be activated at a time.

Requirement for a 1 MW solar PVPP	Response
Voltage control	No
*Reactive power control**. reactive power control is detailed below	Yes
*Power factor control**. power factor control is detailed below	Yes
*Automatic power factor control**. automatic power factor control is detailed below	Yes

Table 2. 29 Reactive power and voltage support requirements

Nb : *reactive power control, power factor control and automatic power factor control must not be performed in the absence of agreement with transmission system operator

Reactive Power Control

Solar PVPP is responsible of providing the reactive power from Q_1 to Q_2 with regard to the power factor between PF_1 to PF_2 (i.e. zone 2). Table 2. 30 establishes the parameters illustrated in Figure 2. 10.

Parameters	Value (pu)
PF_1	0.9
PF_2	-0.9
Q_1	0.48
Q_2	-0.48
P_1	NA
Time response (100% of steady-state response)	10 s

Table 2. 30 Parameters in reactive power control

Power Factor Control

Solar PVPP must be capable of delivering reactive power as a function of active power. As listed in Table 2. 30, solar PVPP must be capable of operating at power factor between PF_1 and PF_2 depicted in Figure 2. 10. Additionally, the solar PVPP must reach power factor setpoint by 10 s (i.e. time response of 10 s).

Automatic Power Factor Control

The activation and deactivation levels for this function are normally 105% and 100% of the nominal voltage (U_n), respectively and they both must be adjustable via setpoints. Table 2. 31 lists the parameters in automatic power factor control function depicted in Figure 2. 9.

Parameter	Value

X_1	0.5
Y_1	0.9

Table 2. 31 Parameters in automatic power factor control function

2.5.4 Fault-Ride-Through Capability

Table 2. 32 lists the FRT requirement.

Requirement for 1 MW solar PVPP	**Response**
LVRT capability due to symmetrical and asymmetrical fault	No
HVRT capability due to symmetrical and asymmetrical fault	No
Reactive current injection	No

Table 2. 32 Fault-ride-through requirement

The FRT requirements for solar PVPP type B are not set out in the second technical regulation.

2.6 Grid Codes of European Union

In the latest grid codes of European Union, power plants are essentially classified into four types on the basis of voltage level at PCC along with their nominal output power listed in Table 2. 33.

- Type A : the voltage level at PCC is below 110 kV and the capacity is below limit stated in Table 2. 33.
- Type B : the voltage level at PCC is below 110 kV and the capacity is located within the range defined in Table 2. 33.
- Type C : the voltage level at PCC is below 110 kV and the capacity falls within the range stated in Table 2. 33.
- Type D : the voltage level at PCC is equal to or above 110 kV or the capacity is stated within the range stated in Table 2. 33.

Synchronous Area	**Capacity Range of Type A**	**Capacity Range of Type B**	**Capacity Range of Type C**	**Capacity Range of Type D**

Continental Europe	x<0.8 kW	0.8 kW≤x≤1 MW	1 MW<x≤50 MW	50 MW<x≤75 MW
Great Britain	x<0.8 kW	0.8 kW≤x≤1 MW	1 MW<x≤50 MW	50 MW<x≤75 MW
Nordic	x<0.8 kW	0.8 kW≤x≤1.5MW	1.5 MW<x≤10 MW	10 MW<x≤30 MW
Ireland and Northern Ireland	x<0.8 kW	0.8 kW≤x≤0.1MW	0.1 MW<x≤5 MW	5 MW<x≤10 MW
Baltic	x<0.8 kW	0.8 kW≤x≤0.5MW	0.5 MW<x≤10 MW	10 MW<x≤15 MW

Table 2. 33 Capacity range

Synchronous area is defined as an area covered by synchronously interconnected TSOs, for instance synchronous areas of Continental Europe, Great Britain, Ireland-Northern Ireland and Nordic along with the power system of Lithuania, Latvia and Estonia which forms Baltic synchronous area. This is illustrated in Figure 2. 15.

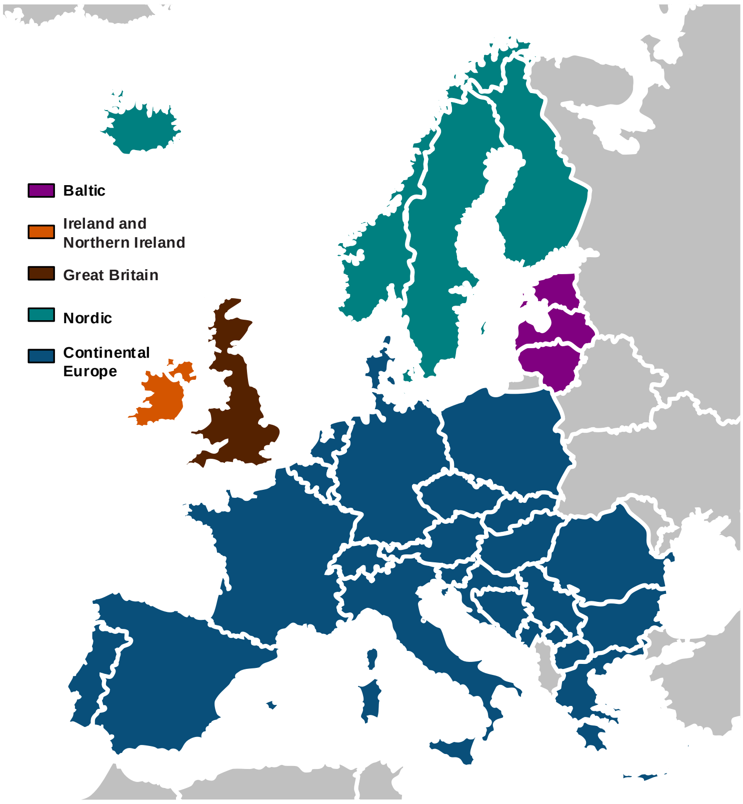


Figure 2. 15 The map of synchronous areas in Europe [36]

2.6.1 Voltage and Frequency Boundaries

In regards to range of normal operating voltage and frequency, the relevant solar PVPP must be capable of remaining online and operate normally when the voltage decreases to 0.85 pu and in ranges of normal operating frequency with minimum duration as listed in Table 2. 34.

Synchronous Area	Nominal Frequency (Hz)	Range of Normal Operating Frequency	Minimum Duration
European Union (Continental Europe)	50	x<47.5	Instantaneous trip
		47.5≤x<48.5	Not less than 30 minutes [a]
		48.5≤x<49	Not less than period for 47.5Hz≤x<48.5Hz

		49≤x≤51	Unlimited
		51<x≤51.5	30 minutes
		x>51.5	Instantaneous trip

Table 2. 34 Range of normal operating frequency

[a] : to be agreed with relevant system operator

2.6.2 Active Power and Frequency Support

Table 2. 35 outlines active power and frequency support requirement.

Requirements for a 1 MW solar PVPP	**Response**
Frequency response or control. frequency control is detailed below	Yes
Absolute production.	No
Delta production.	No
Power gradient. power gradient or ramp rate is detailed below	Yes

Table 2. 35 Active power and frequency support requirements

Frequency Response or Control

In the latest grid code of European Union, the parameters in frequency response or control function described in Figure 2. 6 is listed in Table 2. 36.

Parameter	**Value**
f_{min}	47.5 Hz
f_1	NS
f_2	aw-TSO

f_3	50.2-50.5 Hz (aw-TSO)
f_4	NA
f_{max}	51.5 Hz
Upward droop constant	2% as a function of nominal output power (P_n) (in case $f_2 < 49$ Hz) 10% as a function of nominal output power (P_n) (in case 49 Hz $< f_2 <$ 49.5 Hz
Downward droop constant	2-12% as a function of actual active power (P_{ac}) or nominal output power (P_n) (aw-TSO)
Response time for downward droop	≤ 2 s
Settling time for downward droop	NS
Actual power	NS

Table 2. 36 Parameters in frequency response or control

Constraint Functions

Table 2. 37 describes the constraint functions.

Type of Constraint Functions	**Value**

Absolute production	NA
Delta production	NS
Ramp rate Rate of increase of power	NS

Table 2. 37 Constraint functions

2.6.3 Reactive Power and Voltage Support

Table 2.38 lists the reactive power and voltage support requirement.

Requirement for a 1 MW solar PVPP	**Response**
Voltage control.	No
Reactive power control. reactive power control is detailed below	Yes
Power factor control.	No
Automatic power factor control.	No

Table 2. 38 Reactive power and voltage support requirement

Reactive Power Control

In the latest grid code of EU, reactive power control requirement is set out. However, the provision range of reactive power and the time response are not specified.

2.6.4 Fault-Ride-Through Capability

Table 2. 39 outlines the FRT requirement.

Requirement for a 1 MW solar PVPP	**Response**
LVRT capability due to symmetrical and asymmetrical fault	Yes
HVRT capability due to symmetrical and asymmetrical fault	No
Reactive current injection	Yes

Table 2. 39 Fault-ride-through requirement

The LVRT requirement due to symmetrical fault is depicted in Fig.2.16 below.

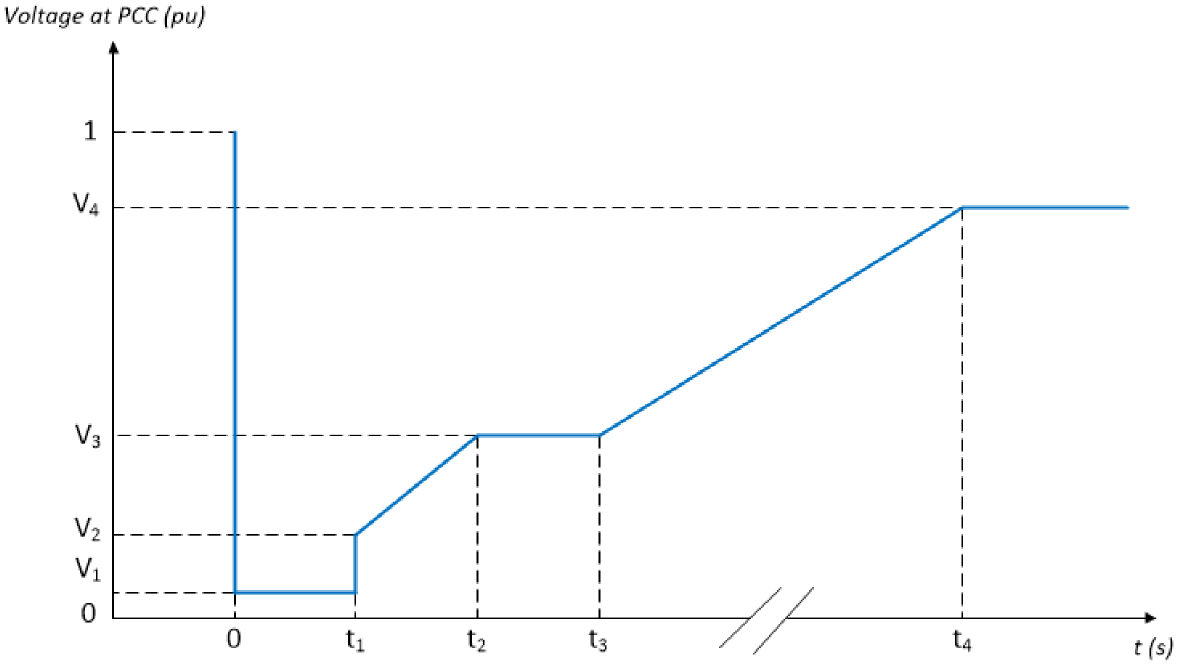


Figure 2. 16 LVRT requirement due to symmetrical fault

Table 2. 40 lists parameters in Fig.2.16.

Voltage Parameters (pu)		**Time Parameters (seconds)**	
V_1	0.05-0.15	t_1	0.14-0.25
V_2	V_2-0.15	t_2	t_1
V_3	V_2	t_3	t_2
V_4	0.85	t_4	1.5-3.0

Table 2. 40 Parameters in LVRT

In addition, the LVRT requirement due to asymmetrical fault must be specified by relevant TSO on case-by-case basis. The reactive current injection requirement is set out in the latest grid code of EU. However, its details are not specified.

2.7 Summary

In the present section, the summary of grid codes of Puerto Rico, Germany, Denmark and European Union pertaining to 1 MW solar PVPP connected to medium voltage (MV) level network is given from different perspectives as follows.

- Classification based on type and voltage level at PCC is listed in Table 2. 41

Country	Type	Voltage Level	Lower Limit (kV)	Upper Limit (kV)
Puerto Rico	NS	NS	NS	NS
Germany	2	Medium Voltage	1	60
Denmark	B	Medium Voltage	-	33
European Union	B for Continental Europe, B for Great Britain, B for Nordic, C for Ireland and Northern Ireland & C for Baltic	NS	-	110

Table 2. 41 Classification based on type and voltage level at PCC

- Table 2. 42 describes normal operating frequency based on each grid code

Grid code	Frequency (Hz)	Limits (Hz)	Minimum Duration
Puerto Rico	60	x<56.5	Instantaneous trip
		56.5≤x<57.5	10 sec
		57.5≤x≤61.5	Continuous

		61.5<x≤62.5	30 sec
		x>62.5	Instantaneous trip
Germany	50	x<47.5	Instantaneous trip
		47.5≤x<49	30 minutes
		49≤x≤50	Continuous
		50<x≤51	30 minutes
		x>51.5	Instantaneous trip
Denmark	50	x<47	Instantaneous trip
		47≤x≤52	Continuous
		x>52	Instantaneous trip
European Union	50		
• Continental Europe		x<47.5	Instantaneous trip
		47.5≤x<48.5	Not less than 30 minutes [1]
		48.5≤x<49	Not less than period for 47.5Hz≤x<48.5Hz
		49≤x≤51	Unlimited
		51<x≤51.5	30 minutes
		x>51.5	Instantaneous trip
[1] Specified by relevant system operator			

Table 2. 42 Normal operating frequency

- Table 2. 43 illustrates normal operating voltage in each grid code

Grid code	Range of Voltage (pu)	Minimum Duration
Puerto Rico	x<0.85	Instantaneous trip
	0.85<x≤1.15	Continuous
	x>1.15	Instantaneous trip
Germany	x<0.85	Instantaneous trip
	0.85≤x<0.9	30 minutes
	0.9≤x≤1.1	Continuous
	1.1<x≤1.15	30 minutes
	x>1.15	Instantaneous trip
Denmark	x<0.9	Instantaneous trip
	0.9≤x≤1.1	Continuous
	x>1.1	Instantaneous trip
European Union (Continental Europe)	x<0.85	Instantaneous trip
	x≥0.85	Continuous

Table 2. 43 Normal operating voltage

- Table 2. 44 summarizes the active power and frequency support requirement in each grid code

Requirements for 1 MW Solar PVPP	Puerto Rico's regulation	Germany's regulation	Denmark's regulation	EU's regulation
Frequency response or control	Yes	Yes	Yes	Yes
Absolute production	Yes	Yes	Yes	No
Delta production	Yes	Yes	No	No

Power gradient	Yes	Yes	Yes	Yes

Table 2. 44 Active power and frequency support requirement

- Reactive power and voltage support requirement are outlined in Table 2. 45.

Requirement for 1 MW solar PVPP	**Puerto Rico's regulation**	**Germany's regulation**	**Denmark's regulation**	**EU`s regulation**
Voltage control	Yes	Yes	No	No
Reactive power control	No	Yes	Yes	Yes
Power factor control	No	Yes	Yes	No
Automatic power factor control	No	No	Yes	No

Table 2. 45 Reactive power and voltage support requirement

- FRT requirement is listed in Table 2. 46.

Requirement for 1 MW solar PVPP	**Puerto Rico's regulation**	**Germany's regulation**	**Denmark's regulation**	**EU´s regulation**
Low-voltage-ride-through capability due to symmetrical and asymmetrical fault	Yes	Yes	No	Yes
High-voltage-ride-through capability due to symmetrical and asymmetrical fault	Yes	Yes	No	No
Reactive current injection	Yes	Yes	No	Yes

Table 2. 46 FRT requirement

3. Grid Code Proposal for Solar PVPP in Indonesia

In chapter 3 the growing share of renewable energy in electricity generation and installed power capacity in Puerto Rico and Europe is discussed. As depicted in Figure 3. 1 Indonesia´s installed power capacityFigure 3. 1, an opposite situation happened in Indonesia where in 2009 Indonesia´s installed power capacity was made up of 4.9 GW controllable renewable energy power generation (i.e. 16%) and 26.5 GW fossil fuel power generation [37]. Then in 2015 the share of controllable renewable energy power generation in Indonesia´s installed power capacity increased slightly in size to 7 GW (i.e. 14%) and fossil fuel power generation held 43 GW of Indonesia´s installed power capacity [38].

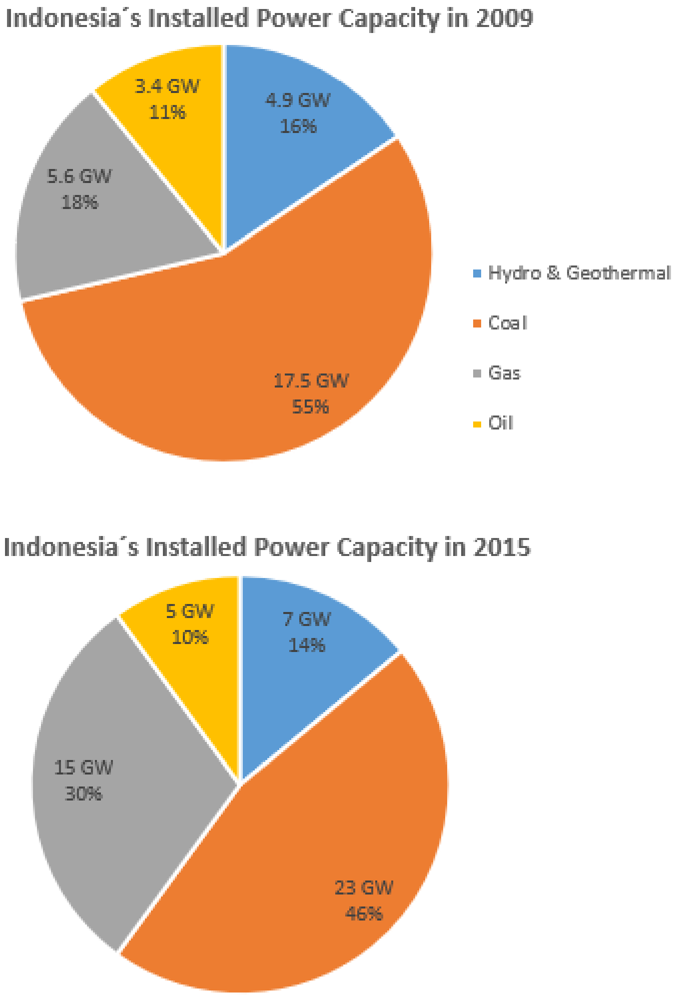


Figure 3. 1 Indonesia´s installed power capacity

in 2009 and 2015 [adapted from [37] and [38]]

However, according to Indonesia´s energy policy by 2025 the energy demand is planned to be met by 332 TWh fossil fuel energy, 95.3 TWh controllable renewable energy (i.e. 21%) and 4.3 TWh solar (1%) and 4.3 TWh wind (1%) as illustrated in Figure 3. 2 [39].

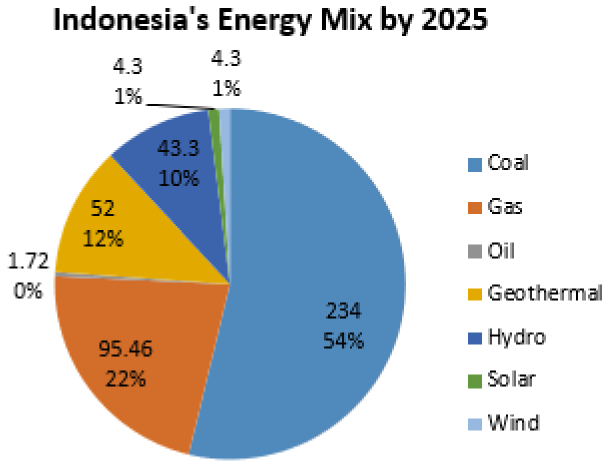


Figure 3. 2 Indonesia´s energy mix by 2025 [39]

Recently a number of solar PVPPs came into operation in Indonesia amounts to 17.02 MW [40] and on average each solar PVPP has capacity of 300 kW [41].

Since Indonesia´s government begun to construct a large number of solar PVPPs to follow their energy policy and by nature solar PVPP entails intermittency, it is necessary to review the current regulation and existing grid code of Indonesia to ensure the integration of large amount of solar power into the grid smoothly.

3.1 Existing Electricity Transmission and Distribution System

Generally electrical power system is made up of

1. Power station

   This is the place where electrical power is generated in which turbine (i.e. prime mover) and generator in case of conventional power plant and PV array, PV inverter and LV-MV transformer in case of solar PVPP can be found. The generated electricity has a medium voltage level in the range of 6 kV to 24 kV with frequency of 50 Hz.

2. Electricity transmission system

   Is a system whose function is to transmit electrical power from power station to electricity distribution system.

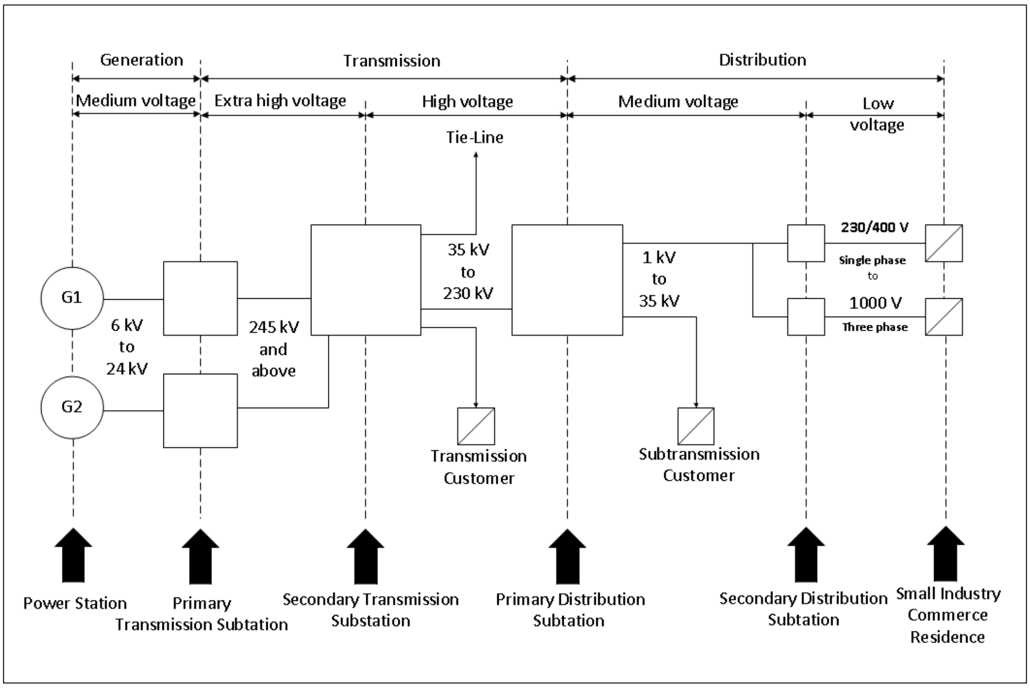


Figure 3. 3 Illustrative single line diagram of generation, transmission and distribution system in Indonesia [Adapted from [42]]

Figure 3. 3 illustrates the single line diagram of power generation, transmission and distribution system. It starts with two power stations (G1 and G2) where the electricity is generated. Then the electricity is forwarded to transmission system comprising primary and secondary transmission substations, tie-line and transmission customer. The transmission system serves to adjust and regulate the voltage in transmitted electricity. According to International Electrotechnical Comission (IEC), extra high voltage is characterized by any nominal voltage above 245 kV and high voltage is any nominal voltage in the range of 35 kV to 230 kV. Besides, medium voltage is any nominal voltage in the range of 1 kV to 35 kV as well as low voltage is any nominal voltage below 1 kV [43]. Indonesia's regulation defines the voltage level in the same manner with IEC [44]. In electric power system, long distance between power station and load causes instability which creates the need for utilization of ancillary services such as flexible alternating current transmission system (FACTS) or capacitor banks [45]. In electricity transmission system, transmission substations serve to connect multiple transmission lines. The simplest case is where all transmission lines operated at the same voltage. In such cases, substation houses high-voltage switches that enables lines to be connected or isolated for fault clearance or maintenance. A small substation may be a little more than a bus and several circuit breakers. A normal size substation may houses transformer, voltage control or power factor correction devices such as FACTS as well as phase shifting transformer to regulate power flow between two adjacent power systems and some circuit breakers.

Indonesia’s electricity transmission system is not interconnected across the nation [46] [47]. In fact, Indonesia is currently split into several electrically synchronous areas as listed in Table 3. 1.

No.	Electrically Synchronous Area
1.	Sumatra island
2.	Java island, Madura Island and Bali island

Table 3. 1 Electrically Synchronous Area

While the other major islands such as Sulawesi island, Kalimantan island, Papua island don´t have individual electricity interconnection system across the island. In addition, smaller islands have their own transmission electricity and disconnected from each other [46].

3. Electricity distribution system

The present system serves to deliver electricity from electricity transmission system to end-user. In addition to changing the voltage, the task of distribution substation is to isolate faults in either the transmission or distribution system. At primary distribution substation, the voltage is stepped down from high voltage level to medium level. Then, the electrical power is forwarded from primary distribution substation to secondary distribution system via primary distribution line at medium voltage. The electricity reaches small industrial and commercial customers in the form of three phase at low voltage via secondary distribution line. In case of residential customer, the electricity reaches them in the form of single phase via secondary distribution line at low voltage. One of main elements in electricity transmission and distribution system is power line. Two most widely used types of transmission and distribution line in Indonesia: (1) Overhead lines which has upsides such as low initial and repairment cost. On the other hand, it has downsides such as prone to storm and wind as well as has low aesthetics. (2) Underground lines which offer advantages like not affected by storm and wind and high aesthetics. On the other hand, it has disadvantages such as high initial and repairment cost and vulnerable to storm surge and flooding from corrosive saltwater, rainfall or melting ice and snow [42].

3.2 Current Grid Codes of Indonesia

The regulation of Indonesia for renewable energy power plant connected to electricity distribution system is based on IEEE technical guidance. One of them is IEEE 1547 [48]. Moreover, the summary of Indonesia´s grid code is based on regulations stated in Table 3. 2.

Organization	Title	Version
PLN (TSO & DSO in Indonesia)	Pedoman Penyambungan Pembangkit Listrik Energi Terbarukan ke Sistem Distribusi PLN (Guideline for Renewable Energy Power Plant Connected to Electricity Distribution System of PLN)	July, 2014
PLN (TSO & DSO in Indonesia)	Persyaratan Umum dan Metode Uji Inverter Untuk Pembangkit Listrik Tenaga Surya (PLTS) (General Requirement and Compliance Test Methodology for PV inverter)	November, 2012

Table 3. 2 Regulation and grid code under study

The scope of above-mentioned regulation is explained in Table 3. 3.

Parameter	Value
Grid Voltage (kV)	Up to 20 kV
Collection Grid Topology of Network	Radial
Size of Power Generation	Up to 10 MW

Table 3. 3 The scope of regulation for grid code

3.2.1 Voltage and Frequency Boundaries

The range of normal operating frequency and voltage along with minimum duration to remain online are listed in Table 3. 4 and Table 3. 5, respectively.

Nominal Frequency, f_n (Hz)	Range of Normal Operating Frequency (Hz)	Minimum Duration
50	x<49	0.2 s
	49≤x≤51	Continuous
	x >51	0.2 s

Table 3. 4 Range of normal operating frequency

Range of Normal Operating Voltage (pu)	**Minimum Duration**
x<0.5	0.1 s
0.5≤x<0.85	2 s
0.85-1.10	Continuous
1.1<x≤1.35	2 s
x≥1.35	0.1 s

Table 3. 5 Range of normal operating voltage

3.2.2 Active Power and Frequency Support

Table 3. 6 outlines the active power and frequency support requirements. It can be deduced that active power and frequency support requirement is not stated in Indonesia’s regulation.

Requirements for a 1 MW solar PVPP	**Response**
Frequency response or control.	No
Absolute production. absolute production or power curtailment is not stated	No
Delta production. delta production or power reserve is not laid down	No
Power gradient. power gradient or ramp rate or is not stated	No

Table 3. 6 Active power and frequency requirement

3.2.3 Reactive Power and Voltage Support

Table 3. 7 outlines the reactive power and voltage support requirements.

Requirements for a 1 MW solar PVPP	Response
Voltage control.	No
Reactive power control.	No
Power factor control. power factor control is detailed below	Yes
Automatic power factor control.	No

Table 3. 7 Reactive power and voltage support requirements

Power Factor Control

Solar PVPP must be capable of providing the reactive power from Q1 to Q2 with regard to the power factor between PF1 to PF2 (i.e. zone 2). Table 3. 8 establishes the parameters illustrated in Figure 2. 10.

Parameters	Value (pu)
PF_1	0.85
PF_2	-0.9
Q_1	0.62
Q_2	-0.48
P_1	NA

Table 3. 8 Parameters in reactive power control

3.2.4 Fault-Ride-Through Capability

Table 3. 9 lists fault-ride-through requirement. It is deduced that fault-ride-through requirement is not stated in Indonesia's regulation.

Requirements for a 1 MW Solar PVPP	Response
Low voltage fault-ride-through capability	No

due to symmetrical and asymmetrical fault	
High voltage fault-ride-through capability due to symmetrical and asymmetrical fault	No
Reactive current injection	No

Table 3. 9 Fault-ride-through requirement

3.3 Grid Code Proposal

There are there approaches for proposing grid code design:

1. Geographic approach
   Table 3. 10 summarizes the geographic condition of Indonesia based on relevant parameters.

Parameter	**Response**
Type of Nation	Archipelago
Number of Major Islands	Five (5) Sumatera island (land area of 480,793 km^2) Java island (land area of 129,438 km^2) Kalimantan island (land area of 544,150 km^2) Sulawesi island (land area of 188,522 km^2) Papua island (land area of 418,707 km^2)
Number of Small Islands	17,504 (average land area per island of 5,000 km^2)
Number of Land Borders	Three (3) With Malaysia in Kalimantan island With Timor Leste in Nusa Tenggara island With Papua New Guinea in Papua island

Table 3. 10 The geographic condition of Indonesia [49]

Furthermore, Table 3. 11 and Table 3. 12 summarize the geographic condition of Puerto Rico and Denmark based on relevant parameters, respectively.

Parameter	**Response**
Type of Nation	Archipelago
Number of Major Islands	One (1) with land area of 8,868 km^2
Number of Small Islands	Three (3) with average land area per island of 30 km^2
Number of Land Borders	None

Table 3. 11 The geographic condition of Puerto Rico [50]

Parameter	Response
Type of Nation	Archipelago
Number of Major Islands	One (1) with land area of 42,916 km^2
Number of Small Islands	Four hundred (400)
Number of Land Borders	One (1) with Germany in the south

Table 3. 12 The geographic condition of Denmark [51]

In addition, Table 3. 13 and Table 3. 14 summarize the geographic condition of Germany and European Union based on relevant parameters, respectively.

Parameter	Response
Type of Nation	Non-archipelago
Number of Major Islands	One (1) (land area of 357,104 km^2)
Number of Small Islands	Ten (10)
Number of Land Borders	Ten (10) countries with the Netherlands, Belgium, Luxemburg, France, Switzerland, Liechteinsten, Austria, Czechia, Poland and Denmark.

Table 3. 13 The geographic condition of Germany [52]

Parameter	Response
Type of Nation	Non-archipelago
Number of Major Islands	One (1) (land area of 4,369,364 km^2)
Number of Small Islands	Hundreds
Number of Land Borders	Five (5) countries that are Russia, Belarus, Ukraine, Moldova and Turkey

Table 3. 14 The geographic condition of European Union [53]

Based on description above, it is noted that Puerto Rico and Denmark have similar geographical condition with Indonesia´s geographical condition.

2. Electricity generation mix approach

Table 3. 15 summarizes the fraction of solar power in electricity generation described in chapter 2. It is expected that Indonesia´s landscape of electricity generation by 2025 will be similar to Puerto Rico´s electricity generation in 2017 and Denmark´s electricity generation in 2016.

Nation	Percentage of Solar Power in Electricity Generation
Indonesia	1% based on Energy Policy by 2025
Puerto Rico	1% in 2017
Denmark	1% in 2016
Germany	3% in 2017

European Union	3% in 2016

Table 3. 15 Solar power percentage in electricity generation

Electricity interconnection system approach

Table 3. 16 summarizes the status of Indonesia´s electricity interconnection system.

Parameter	Response
Domestic interconnection	One (1) interconnection that links Java island, Madura island and Bali island
International interconnection	None

Table 3. 16 Status of Indonesia´s electricity interconnection system [46] [47]

Table 3. 17 and Table 3. 18 list the status of Puerto Rico and Denmark´s electricity interconnection system.

Parameter	Response
Domestic interconnection	Interconnection across the nation
International interconnection	None

Table 3. 17 Status of Puerto Rico´s electricity interconnection system [54]

Parameter	Response
Domestic interconnection	Interconnection across the nation
International interconnection	Three (3) interconnections that links the nation to Norway, Sweden and Germany

Table 3. 18 Status of Denmark´s electricity interconnection system [55] [56]

And Table Table 3. 19 and Table 3. 20 summarizes the status of Germany's and EU's electricity interconnection system.

Parameter	Response
Domestic interconnection	Interconnection across the nation

International interconnection	Nine (9) interconnections that link the nation to Poland, Czechia, Austria, Switzerland, Luxemburg, Belgium, the Netherland, Denmark and Sweden

Table 3. 19 Status of Germany´s electricity interconnection system [56]

Parameter	**Response**
Domestic interconnection	Interconnection across the region
International interconnection	Five (5) interconnections that connects the region to Russia, Belarussia, Ukraine, Turkey and Morocco

Table 3. 20 Status of EU´s electricity interconnection system [56]

Considering above approaches, international grid codes under study that suits the most current condition of Indonesia´s electricity system during the transition period to renewable energy are grid codes of Puerto Rico and Denmark. Moreover, both sets of grid codes are aligned with Indonesia´s energy policy to attain 1% solar power in electricity generation by 2025. Accordingly, the grid code proposal for solar PVPP in Indonesia especially in major and small islands will be based on grid codes of Denmark and Puerto Rico. Note that Denmark and Puerto Rico have an average closest individual area of the higher and smaller islands in Indonesia and similar electricity generation mix to the expected one of Indonesia in 2025.

3.3.1 Voltage and Frequency Boundaries

Table 3. 21 and Table 3. 22 summarize the range of normal operating frequency for major islands and small islands, respectively.

Nominal Frequency (Hz)	**Range of Normal Operating Frequency (Hz)**	**Minimum Duration**
50	x<47	Instantaneous trip
	47≤x≤52	Continuous
	x>52	Instantaneous trip

Table 3. 21 Normal operating frequency for major islands

Nominal Frequency (Hz)	**Range of Normal Operating Frequency (Hz)**	**Minimum Duration**
50	x<47.1	Instantaneous trip
	47.1≤x<47.9	10 sec

	47.9≤x≤51.3	Continuous
	51.3<x≤52.1	30 sec
	x>52.1	Instantaneous trip

Table 3. 22 Normal operating frequency for minor islands

Table 3. 23 lists the normal operating voltage for major island and small islands.

Range of Normal Operating Voltage (pu)		**Minimum Duration**
Major Islands	Small Islands	
0.90-1.10	0.85-1.15	Continuous

Table 3. 23 Normal operating voltatge for small islands

3.3.2 Active Power and Frequency Support

Table 3. 24 summarizes the active power and frequency support for solar PVPP in major islands and smalls islands.

Requirements for a 1 MW Solar PVPP	**Major islands**	**Small islands**
Frequency response or control. frequency response or control is detailed below	Yes	Yes
Constraint functions. absolute production or power curtailment is detailed below	Yes	Yes
Constraint functions. delta production or power reserve is detailed below	No	Yes
Constraint functions. power gradient or ramp rate is detailed below	Yes	Yes

Table 3. 24 Active power and frequency support requirements

Frequency Response

Table 3. 25 lists the parameters for frequency response or control depicted in Figure 2. 6 for solar PVPP in major islands, small islands with small frequency deviation (i.e. less than 0.25 Hz) and large frequency deviation (i.e. larger than 0.25 Hz).

Parameter	**Major Islands**	**Small Islands**	**Small Islands**

		(small frequency deviation)	**(large frequency deviation)**
f_{min}	47.0 Hz	47.1 Hz	47.1 Hz
f_1	NA	≥49.745 Hz	<49.745 Hz
f_2	NA	49.995 Hz	49.995 Hz
f_3	50.0-52.0 Hz (aw-TSO) 50.2 Hz (standard value)	50.005 Hz	50.005 Hz
f_4	NA	≤50.255 Hz	>50.255 Hz
f_{max}	52.0 Hz	52.1	52.1
Upward droop constant	NA	5% as a function of nominal output power (P_n)	5% as a function of nominal output power (P_n)
Downward droop constant	2-12% (aw-TSO) 4% as a function of actual output power (P_{ac}) (standard value)	5% as a function of nominal output power (P_n)	5% as a function of nominal output power (P_n)
Response time for both droops	2 s (only downward droop is applicable)	<1 s	<1 s
Settling time for both droops	20 s (only downward droop is applicable)	NS	NS

Actual power	NA	NS	≥10% of nominal output power

Table 3. 25 Parameters in frequency response or control for major islands and small islands

Constraint Functions

Table 3. 26 describes the types of constraint functions applied to solar PVPP in major islands and small islands.

Type of Constraint Functions	Major Islands	Small Islands
Absolute production	aw-TSO	aw-TSO
Delta production	NA	10% nominal output power ≤ x ≤ 100% nominal output power
Ramp rate • Rate of increase of power • Rate of decrease of power • Rate of increase of power when an absolute production constraint turns off • Rate of decrease of power when an absolute production constraint turns on	100 kW/s	10% of nominal output power per minute with tolerance of 10%

Table 3. 26 Types of constraint functions

*aw-TSO: agreed with TSO

3.3.3 Reactive Power and Voltage Support

Table 3. 27 lists the reactive power and voltage support for solar PVPP in major islands and small islands, respectively. For the major islands, the control functions are exclusive meaning only one of three functions can be activated at a time.

Requirement for a 1 MW solar PVPP	**Major Islands**	**Small Islands**
Voltage control. voltage control is detailed below	No	Yes
*Reactive power control**. reactive power control is detailed below	Yes	Yes
*Power factor control**. power factor control is detailed below	Yes	Yes

Table 3. 27 Reactive power and voltage support for solar PVPP in major islands and small islands

Nb: * for solar PVPP in major islands, reactive power control, power factor control and automatic power factor control must not be performed in the absence of agreement with transmission system operator

Reactive power and power factor control requirements are thought to be also needed for solar PVPP in small islands to ensure security, stability and reliability of the electrical grid as electrical grid in small islands are naturally less robust than that in major islands.

Voltage Control

Table 3. 28 illustrates parameters with regards to voltage control function for small islands as depicted in Figure 2. 8.

Parameters	**Value**
Deadband	$0.999pu \le x \le 1.001pu$
Upward droop function	$0\% < x \le 10\%$
Downward droop function	$0\% < x \le 10\%$
Time response	1s for 95% total reactive power
Upper limit of reactive power delivery	0.62 of actual active power (P_{ac})
Lower limit of reactive power delivery	-0.62 of actual active power (P_{ac})

Table 3. 28 Parameters in voltage control function

Reactive Power Control

Table 3. 29 lists the parameters in reactive power control depicted in Figure 2. 10 for solar PVPP in major islands and small islands.

Parameters	Value
Type of zone	2
PF_1	0.9
PF_2	-0.9
Q_1	0.48
Q_2	-0.48
P_1	NA
Time response (100% of steady-state response)	10 s

Table 3. 29 Parameters in reactive power control

Steady-state mode turns on under the condition where voltage droop is not taking action whereas dynamic mode turns on under the condition where voltage droop is being applied.

Power Factor Control

As illustrated in Table 3. 29, solar PVPP in both major and small islands must be capable of operating at PF between 0.9 and -0.9. In addition, the solar PVPP must reach power factor setpoint by 10 s (i.e. time response of 10 s).

3.3.4 Fault-Ride-Through Capability

Table 3. 30 lists the fault-ride-through requirement for solar PVPP in major islands and small islands.

Requirement for 1 MW solar PVPP	Major Islands	Small Islands

Low-voltage-ride-through capability due to symmetrical and asymmetrical fault	No	Yes
High-voltage-ride-through capability due to symmetrical and asymmetrical fault	No	Yes
Reactive current injection	No	Yes

Table 3. 30 Fault-ride-through requirement

Table 3. 31 explains the parameters in low-voltage-ride-through (LVRT) requirement described in Fig.2.11 for solar PVPP in small islands.

Parameters	**Value**
V_1	0
V_2	0.1 pu
V_3	0.85 pu
t_1	600 ms
t_2	3 s

Table 3. 31 Parameters in LVRT requirement

Furthermore, Table 3. 32 describes the parameters with regards to high-voltage-ride-through (HVRT) requirement depicted in Fig. 2.12 for small islands.

Parameters	**Value**
V_1	1.4 pu
V_2	1.3 pu
V_3	1.15 pu
t_1	150 ms
t_2	1 s

t_3	3 s

Table 3. 32 Parameters in HVRT requirement

During undervoltage fault condition, solar PVPP in small islands must operate on reactive current injection mode depicted in Figure 2. 13 with parameters listed in Table 3. 33.

Parameters	**Value**
Droop constant	1%≤x≤5%
Deadband	15%
X_1	aw-TSO
X_2	NS

Table 3. 33 Parameters in reactive current injection requirement

*aw-TSO: agreed with transmission system operator

NS: not stated

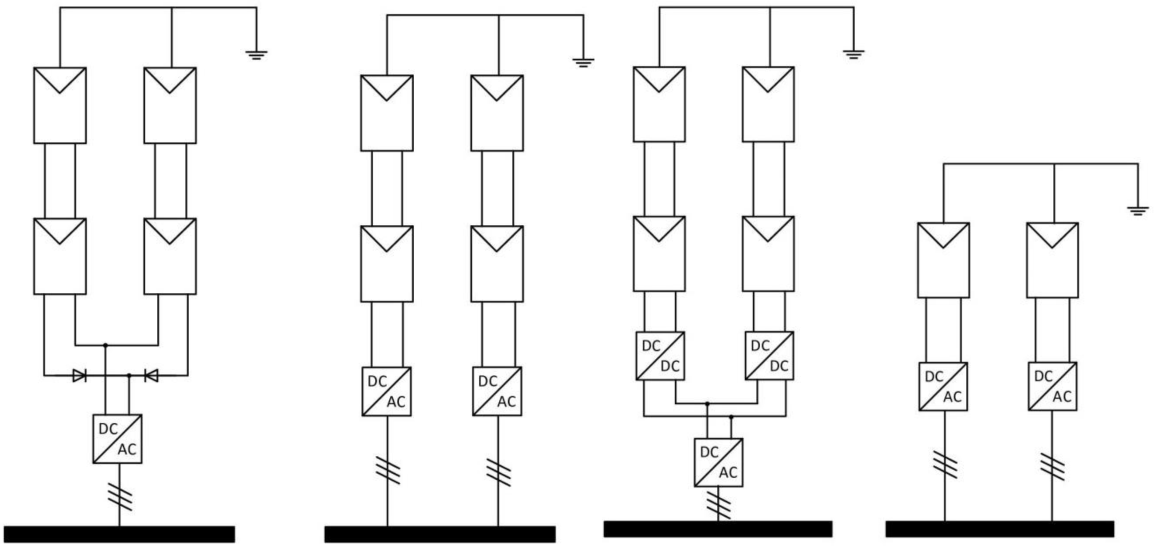
4. Introduction and Control of Solar Photovoltaics Power Plant

4.1. Introduction

Solar photovoltaics power plant is generally split into three sizes which are small scale, large scale and very large scale. According to International Energy Agency, the power rating of small scale photovoltaics power plant (PVPP) ranges from 25 kW to 1 MW, large scale photovoltaics power plant (LS-PVPP) from 1 MW to 100 MW and very large scale photovoltaics power plant (VLS-PVPP) from 100 MW to GW [57]. Electrical components are the basis of solar PVPP. They are basically assigned to [58]: (1) to transform solar energy into electricity. (2) to connect the PVPP to electrical grid in grid-connected PVPP application. (3) to ensure appropriate performance.

The basic electrical components basically deployed in solar PVPP are: PV panels, PV inverters and transformers. PV panel is a block where the sunlight arrives on. A PV string is a set of PV panels that are electrically connected in series whereas a PV array is a set of PV strings that are electrically connected in parallel. The objective of PV string and PV array structure is to generate desired current and voltage that a single PV panel might not.

PV inverter is an electrical component whose function is to transform the dc current to ac current. Basically, there are four (4) basic inverter topologies in solar PVPP as shown in Figure 4. 1. Inverter topology number one is called central inverter in which the whole set of PV arrays is linked to a single PV inverter. Inverter topology number two is called string inverter where each PV string is connected to a single PV inverter. Inverter topology number three is called multistring topology in which each PV string is linked to a single dc-dc converter then several dc-dc converters are connected to a single PV inverter (dc-ac inverter). And the last inverter topology is called module integrated inverter in which each PV panel is connected to a single PV inverter. As for central topology inverter, since a lot of PV strings are connected in parallel it will create high dc voltage variation. However, due to its robustness and low number of inverters needed in central inverter topology, it makes central inverter topology most widely used in solar PVPP. Therefore, most solar PVPPs are based on central inverter topology [58].



1) central inverter 2. string inverter 3. multistring inverter 4. module integrated

Figure 4. 1 PV inverter topologies [adapted from [58]].

Solar PVPP is also classified based on the internal collection grid and how the PV generator is connected to electrical grid. A PV generator is referred to a set of PV arrays and PV inverters along with the transformers. In radial collection topology, several PV generators connected to one feeder as shown in Figure 4. 2. This topology is most used in LS-PVPPs since it is the cheapest and simplest. However, its disadvantage is low reliability. In case a PV inverter fails, the total power production will not be affected significantly [58].

In order to improve the reliability of LS-PVPPs in general, ring collection topology is used. The connection is built on radial collection topology but it adds another feeder that connects the other side of PV generators (Figure 4. 3). In case one of the PV generators is lost, then the PV generators connected to the other side of the feeder can still give power to the LS-PVPP. The downside is the cost and complexity of the installation.

In star collection topology, each PV generator is connected to the main collector. Normally, the collector is placed in the middle of the LS-PVPP to have the same proximities with all PV generators that result in the same losses between them (Figure 4. 4). The star collection topology has the highest reliability among the grid collection topologies. Its downside is one feeder for each generator results in high total cost.

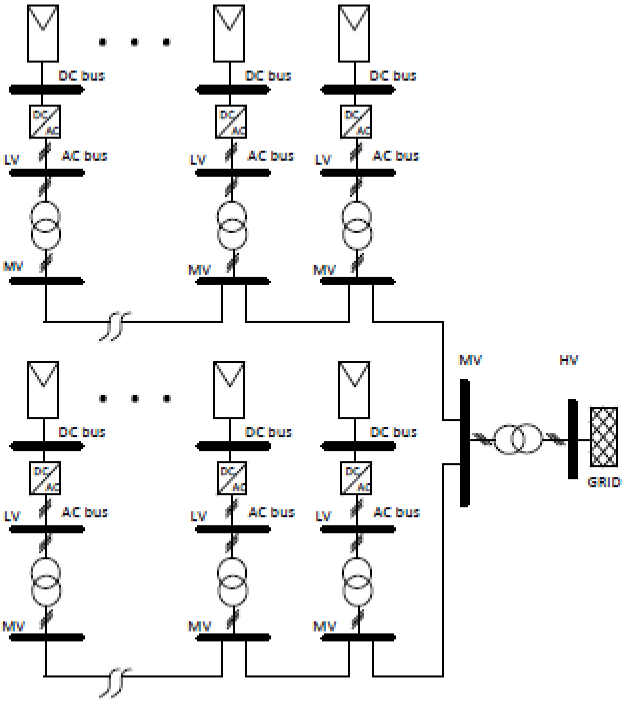


Figure 4. 2 Radial collection grid topology [58]

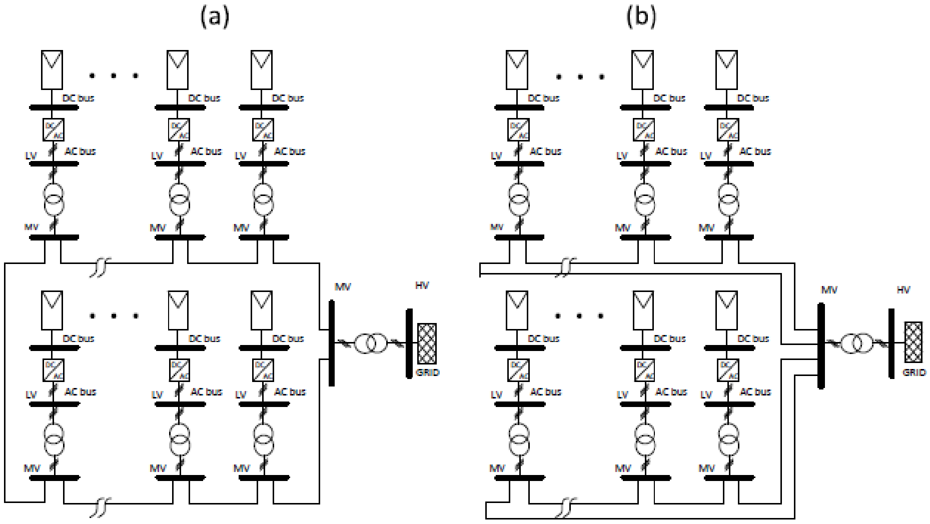


Figure 4. 3 Ring collection grid topology [58]

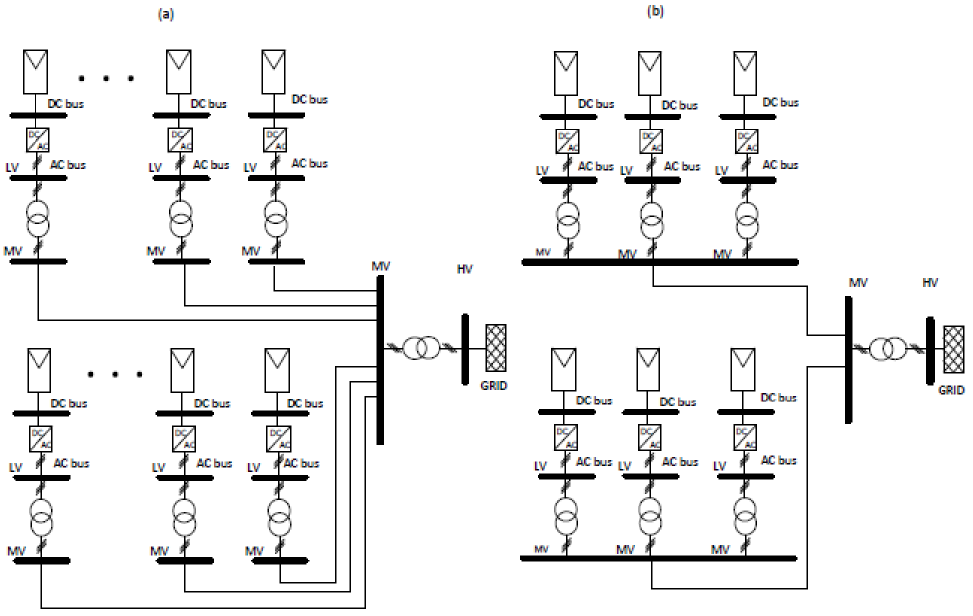


Figure 4. 4 Star collection grid topology [58]

To understand more about function of each electrical component and modelling approach in solar PVPP, following sections are devoted to describe basic electrical components one by one in solar PVPP.

4.2. PV Panels

PV panel is composed of solar cells. The function of solar cells is to transform solar energy into electricity [59]. A set of solar cells are connected in series and then enclosed in a special frame to build the PV panel [60].

There are various materials of solar cells that have different overall efficiencies of the PV panels. The elementary type, crystalline (c – Si) and multicrystalline (m – Si) silicon, offers efficiency of approximately 20 % [61]. Other type, thin film solar cells constituting amorphous silicon (a-Si) offer efficiency approximately from 6.9% to 9% [61] [62]. Thin film solar cells constituting other material like copper indium diselenide (CuInSe2 – CIS) and Cadmium telluride (Cd-Te) presents efficiency approximately 15% [59] and 12% [61] respectively.

The power generation by solar PVPP starts with the incidence of light on the solar cell. It results in charge carriers that originates an electric current if the cell is short-circuited [63] Adequate energy of the incident photon produces the charges that lead to the detachment of the covalent electrons of the semiconductor - this phenomenon depends on the semiconductor material and on the wavelength of the incident light.

The general model of solar cell circuit is illustrated in Figure 4. 5. This circuit is made up of the photovoltaic current (I_{pv}), a diode, a series resistance (R_s) and a parallel resistance (R_p).

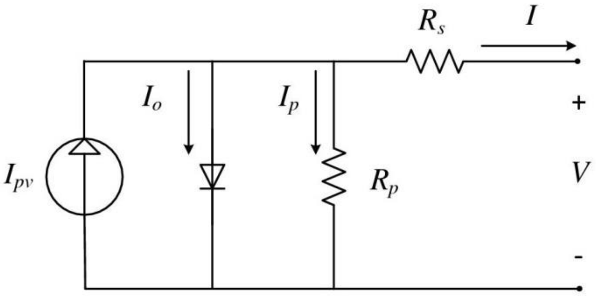


Figure 4. 5 General model of solar cell circuit [adapted from [[64]]

The generated current (I) can be obtained by

$$I = I_{pv} - I_o\left[exp\left(\frac{V+R_S I}{V_t a}\right) - 1\right] - \frac{V+R_S I}{R_p} \quad (4.1)$$

Where I_{pv} and I_0 represents the photovoltaic (PV) and saturation currents, respectively of the array and V is the working voltage, $V_t = N_{ss}kT/q$ is the thermal voltage of the array and N_{ss} is 1 in case of solar cell and N_{ss} is number of series-connected cells in case of solar panel, T is the working voltage, q (= 1.6 $\times 10^{-19}$C) represents the electron charge, k (= 1.38 $\times 10^{-23}$J/K) is a Boltzmann's constant, α is ideality diode factor.

The solar radiation and temperature affects linearly the light-generated current of the PV cell as expressed by Eq.4.2. [65]-[68]

$$I_{pv} = \left(I_{pv,n} + K_I \Delta_T\right)\frac{G}{G_n} \quad (4.2)$$

Notice that $I_{pv,n}$ (in amperes) is the light-generated current under normal condition (normally 25◦C and 1000 W/m^2), K_I is short circuit temperature coefficient, $\Delta T = T - T_n$ (T and T_n being the working and nominal temperatures [i.e. 25◦C], respectively), G (watts per square meters) is the irradiance on the device surface, and G_n is the nominal irradiance [i.e. 1000 W/m^2] [69].

The saturation currents with the influence of temperature is expressed as follows

$$I_o = \frac{I_{sc,n} + K_I \Delta_T}{exp\left(\left(V_{oc,n} + K_v \Delta_T\right)/\alpha V_t\right) - 1} \quad (4.3)$$

Where K_I and K_v represent short circuit current-temperature and open circuit voltage-temperature coefficient.

The PV cell efficiency is affected significantly by variation in series resistance (R_S) but not by variation in parallel resistance (R_p). The PV cells are generally connected in series configuration to build a PV module with purpose of attaining desired working voltage in most commercial PV products. Then PV modules are configured in parallel structure to form PV string. Finally, the combination of PV strings and series-connected PV modules is called PV array that results in the generation of desired output power. A general equivalent circuit for all PV cells, module and array is illustrated in Figure 4. 6 [64].

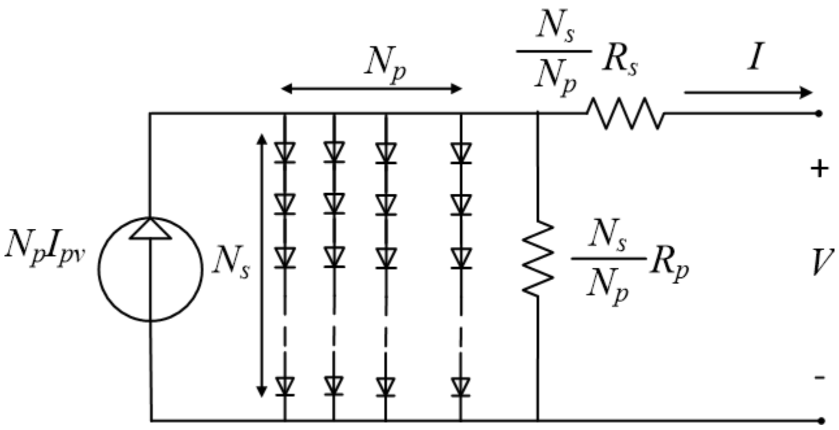


Figure 4. 6 General equivalent circuits of PV [64]

Note that for a PV cell, *Nss* = *Ns* = *Np* = 1 and for a PV module *Nss* is number of cells per module, *Ns* = *Np* = 1 and. For a PV array, *Nss* is number of cells per module, *Ns* represents the number of series-connected PV module and *Np* represents the number of parallel connections (i.e. PV string) of PV module. The mathematical formula of general model can be expressed as follows.

$$I = N_p I_{pv} - N_p I_o\left[exp\left(q\left(V/N_S + IR_S/N_p\right)/N_{ss}kTa\right) - 1\right] \quad (4.4)$$

4.3. PV Inverters

PV inverters are electronic devices that enable the conversion from dc to ac power and are employed in different solar PVPP applications. Essentially a PV array produces dc power, then the PV array is connected to a PV inverter to produce ac power [60]. PV inverter also has the other function of connecting the PV array to internal ac grid.

In this master thesis, the PV inverter is modelled according to [70]. The function of central PV inverter is to interconnect PV arrays with the 3-phase ac grid and commonly modelled as voltage source inverter (VSI) type. At first, a PV array produces dc current and is connected to PV inverter whose function is to convert dc current into 50 or 60 Hz ac current using local control. The electrical scheme is illustrated in Figure 4. 7.

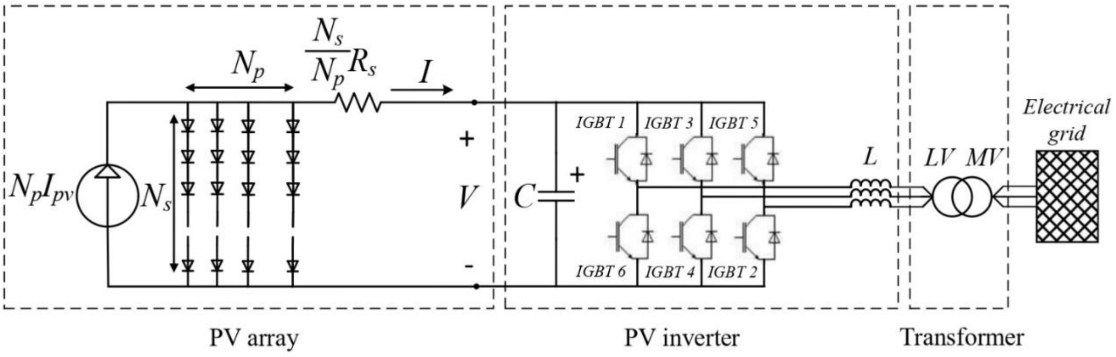


Figure 4. 7 Electrical scheme of on-grid solar PVPP under study [adapted from [70]]

In this scheme, the dc side is modelled as a capacitor that acts as a voltage source and the ac side is modelled as a filter which is made up of three phase inductance which acts as a current source.

Due to limited resources, in this master thesis an average equivalent model as in [45] is used. The average model is based on the concept of ideal switching modulation and particularly technique of space vector pulse width modulation (SVPWM). Consequently, the converter model is decoupled and has 2 (two) sides. The dc side is modelled as a capacitor which acts as current source and the ac side is modelled as an ac voltage source. The equation that connects dc side with ac side will be described in later part. The average model is described in Figure 4. 8.

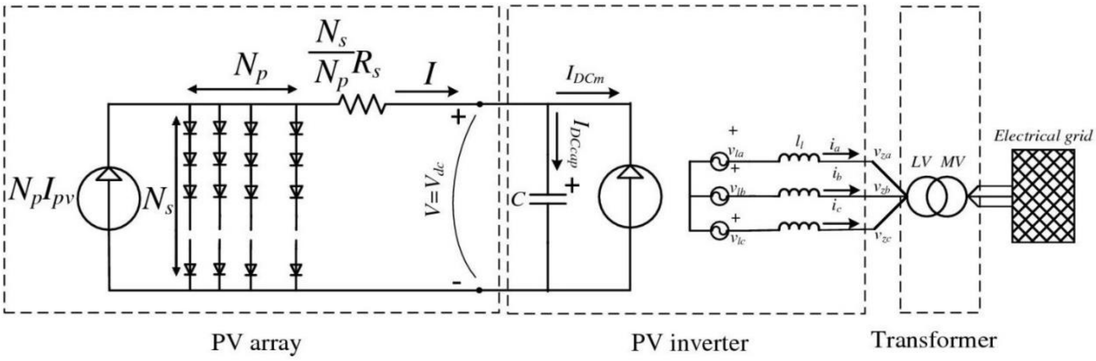


Figure 4. 8 Electrical scheme of average on-grid solar PVPP model under study [adapted from [45]]

In order to analyze the model of PV inverter, the PV array is represented as a current source and the low voltage side of the transformer is represented by three voltage sources, v_{za}, v_{zb} and v_{zc} respectively as sketched in Figure 4. 9.

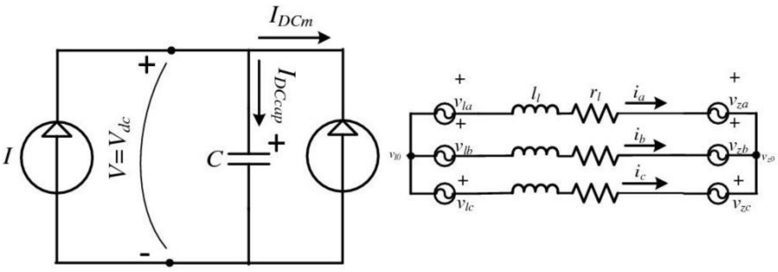


Figure 4. 9 Electrical scheme of average PV inverter model under study [adapted from [45]]

4.3.1 Local Control of PV Inverter

Park transformation plays an important role in the general control scheme in a way simplifying the control algorithm. The general control of PV inverter is sketched in Figure 4. 10.

First of all, v_{zq} component is obtained by means of phase locked loop (PLL) with PI controller calculating the angle θ that results in $v_{zd} = 0$. Considering $v_{zd} = 0$, the active (P_z) and reactive power (Q_z) delivered to the grid can be calculated based on equation 4.5 and 4.6 as follows.

$$\mathrm{P}_z = \frac{3}{2}\left(v_{zq} i_q\right) \quad (4.5)$$

$$\mathrm{Q}_z = \frac{3}{2}\left(v_{zq} i_d\right) \quad (4.6)$$

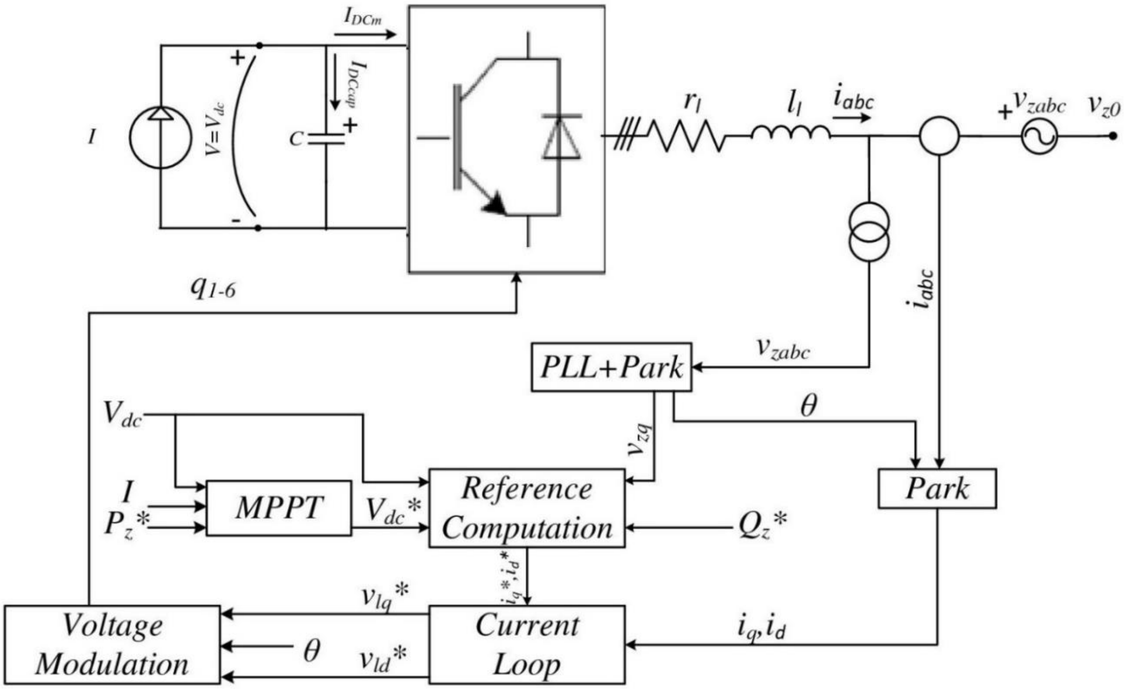


Figure 4. 10 General control scheme of PV inverter

Active (P_z) and reactive power (Q_z) can be controlled separately by means of control of i_q and i_d components, respectively. Based on the dc voltage measurement (V_{dc}) and the dc voltage setpoint (V_{dc}^*), the reference computation block calculates the desired current in the q axis (i_q^*) and d axis (i_d^*) using PI controller as given in equation 4.7 and 4.8, respectively.

$$i_q^* = \frac{2}{3}\frac{P_z^*}{v_{zq}} \quad (4.7)$$

$$i_d^* = \frac{2}{3}\frac{Q_z^*}{v_{zq}} \quad (4.8)$$

P_z^* and Q_z^* are the setpoints of active and reactive power delivered to the grid, respectively. The main function of MPPT is to generate the dc voltage setpoint (V_{dc}^*) and V_{dc}^* is related to the active power. It is not always the case the PV array has to work at the maximum power point (MPP) since in some cases PV array is expected to generate necessary voltage that leads to the desired active power.

The main function of current loop block is to compute the voltage (v_{lq}^*, v_{ld}^*) in qd0 frame to be applied by the PV inverter by taking into account the desired current (i_q^*, i_d^*) and current measurement (i_q,i_d) in qd0 frame. Then the SVPWM technique is used to modulate these voltages. In fact, these voltages are applied directly to three voltage sources by using the anti-

Park transformation (i.e. the technique of anti-park transformation is embedded in voltage modulation block) since average model is used in this master thesis.

MPPT

Two functions that MPPT may have are (1) in case there is no PPC in the solar PV facility, it is to calculate the dc voltage setpoint (v_{dc}^{*}) to produce maximum power based on PV array behavior and environmental conditions (i.e. MPP mode). (2) in case there is PPC in the solar PV facility, MPPT can perform power curtailment by computing the dc voltage setpoint (v_{dc}^{*}) to generate a desired active power (i.e. active power setpoint mode). MPPT algorithms are essentially based on heuristic technique. The most widespread algorithm is so-called perturb and observed (P&O).

Regarding the first function, this method measures the generated active power (P_z) of PV array and changes the voltage supplied (v_{dc}) by PV array to the PV inverter. Then, the system will measure the generated active power again ($P_{z(k)}$) and compare it to the previous generated active power ($P_{z(k-1)}$). In case the increment of v_{dc} results in the increment of $P_{z(k)}$ then the system will increase v_{dc} again until MPP is reached ($v_{dc} = v_{dc}^{*}$). However, in case the increment of v_{dc} results in the decrement of $P_{z(k)}$ then the system will lower the v_{dc} in the next step. On the other hand, in case the decrement of v_{dc} results in the increment of $P_{z(k)}$ then the system will decrease v_{dc} again until MPP is reached. Then, in case the decrement of v_{dc} results in the decrement of $P_{z(k)}$ then the system will raise the v_{dc} in the next step.

With regards to the second function, when the PV array is expected to deliver certain amount of active power (P_z) according to active power setpoint (P_z*) (i.e. not maximum power), the PV array must operate outside of its MPP. It is required to operate the PV array in the right zone of maximum power point to prevent V_{dc} is lower than V_{dcmin}. In case the active power setpoint (P_z^{*}) is lower than P_z then voltage increment must be applied. When the P_z is equal to the P_z^{*} the aforementioned MPPT algorithm is implemented which leads to the condition of $P_z^{*} > P_z$ and supplied voltage (v_{dc}) increases. The other observation is in case P_z cannot reach P_z^{*}, the algorithm will be continuously performing the MPPT. In the end, P_z^{*} is greater than maximum active power (P_z) of the PV array. The corresponding flowchart for active power setpoint mode (i.e. not MPP mode) is illustrated in Fig. 4.11.

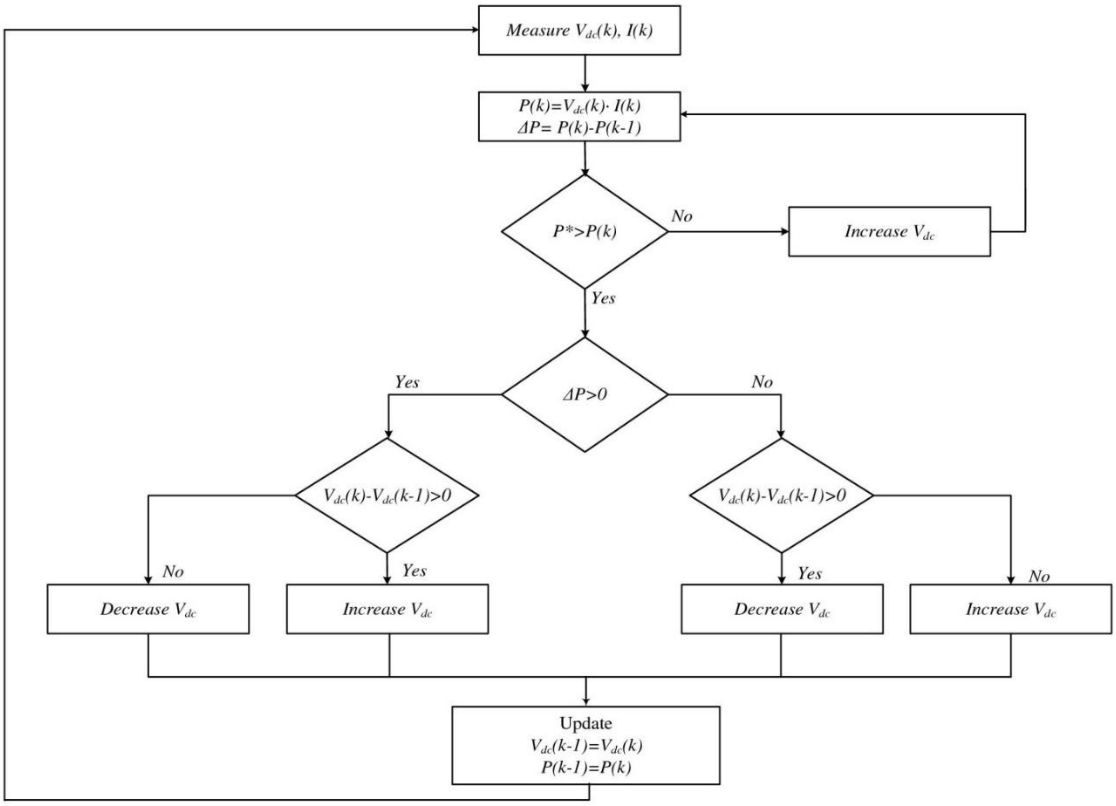


Fig.4.11 MPPT algorithm for active power setpoint mode

4.4. Master Control by Power Plant Controller

The PV inverters are capable of performing their own local controls in compliance with the active power and reactive power setpoints established by PPC. These setpoints contain desired value of each active and reactive power to be met at the PCC. Hence, PPC is the responsible device to drive the active power and frequency action as well as reactive power and voltage regulation action described below. In contrast, FRT requirement is satisfied by the local controls built in the PV inverters.

Grid code requirements from operational perspective that are satisfied by PPC are.

1) Active power and frequency regulation action.

   The frequency support is used to sustain the grid frequency in determinate ranges around its nominal value by regulating active power output of solar PVPP. The active power and frequency regulation action can be in the following form.

- Active power curtailment: the responsible system operator sends the active power setpoint that must be satisfied at PCC.

- Frequency regulation by droop curve: the responsible system operator establishes a curve which preset an increase or decrease of the active power output delivered at PCC as a function of the measured frequency.

- Ramp rate restriction: the active power variation may be limited by a ramp rate when transitions (such as absolute production and power reserve) occur. This may also apply to reactive power output.

2) Reactive power and voltage regulation action

The solar PVPP is required to help sustaining the grid voltage level. Hence, a minimum reactive power capability is established and ancillary devices (e.g. FACTS or capacitor banks) can help to meet the capability limit. The reactive power and voltage regulation action may be in the following form.

- Reactive power setpoint: the responsible system operator sends reactive power setpoint that must be satisfied by solar PVPP at the PCC.

- Voltage regulation by droop curve: the responsible system operator establishes a droop curve that consists of preset the reactive power depending on the voltage level at the PCC.

- Power factor setpoint: the responsible system operator sends power factor that must be met by solar PVPP at the PCC.

The active power control scheme in this master thesis is adopted from [28] and limited to active power curtailment using MPPT function in the PV inverter. As depicted in Figure 4. 11, the control scheme is split into reference computation block, the controller and the dispatch system. The reference computation block calculates the active power setpoints (P^*) that must be satisfied at PCC.

Once P^* is calculated, the controller computes the aggregated power (P_{tot}) that must be delivered by all PV inverters. This controller is based on a typical PI controller that ensures no error (i.e. error = 0) between P^* and the measured power (P) at PCC in normal operating condition.

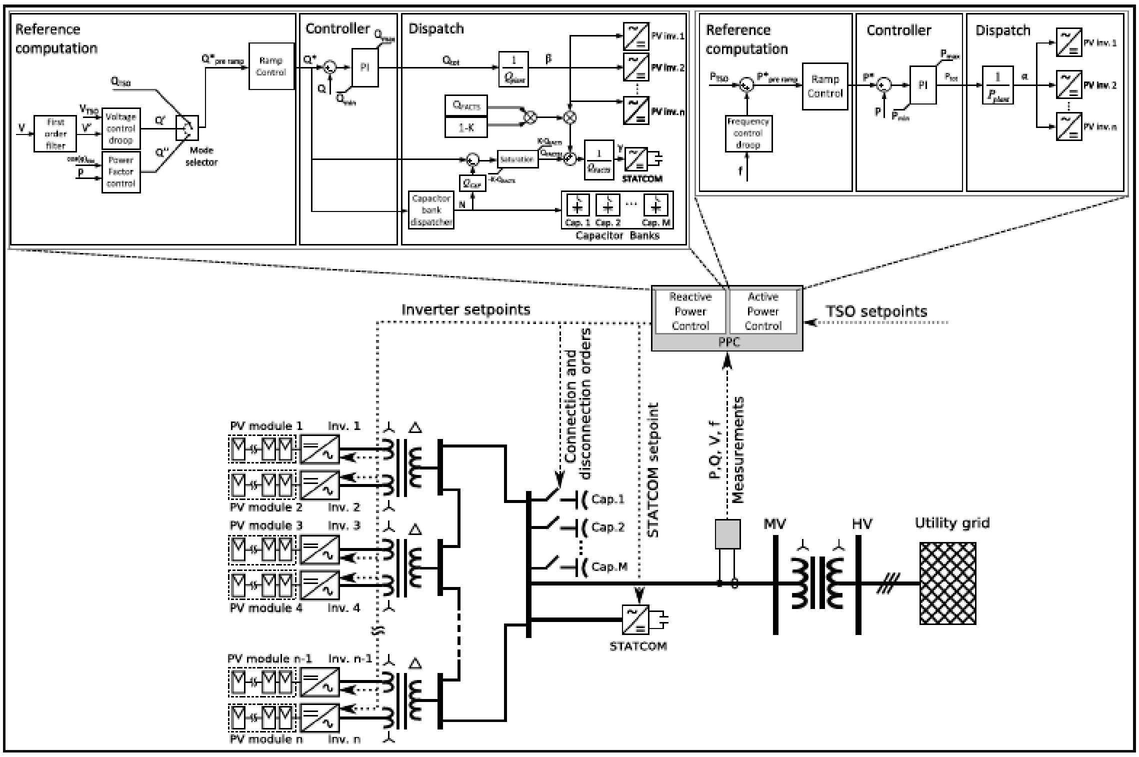


Figure 4. 11 Typical LS-PVPP layout including power plant control scheme [28]

The reactive power control is carried out in a similar way with active power control as illustrated in Figure 4. 11. In this master thesis, ancillary devices (i.e. FACTS device and capacitor banks) are not employed in the model.

In contrast to the active power and frequency regulation action, the reactive power and voltage regulation action does not require simultaneous operations such as reactive power setpoint and voltage control. Thus, a mode selector is employed to choose the way to compute desired reactive power setpoint (Q^*) from three options that are reactive power control, voltage control and power factor control.

In case reactive power control is chosen, the responsible system operator sends a reactive power setpoint (Q_{TSO}) and $Q^* = Q_{TSO}$. In case power factor control is chosen, the corresponding desired reactive power is expressed in Eq. 4.9.

$$Q_{TSO} = P \cdot \frac{\sin(\varphi)_{TSO}}{\cos(\varphi)_{TSO}} \quad (4.9)$$

Where P represents the measured active power at PCC and $\cos(\varphi)_{TSO}$ represents the power factor setpoint.

In case the voltage control is chosen, Q_{TSO} is computed according to voltage droop curve illustrated in Figure 4. 12. In this context, due to the entire plant operation, it is needed to filter the voltage measurement (*V*) to obtain droop input (*V´*).

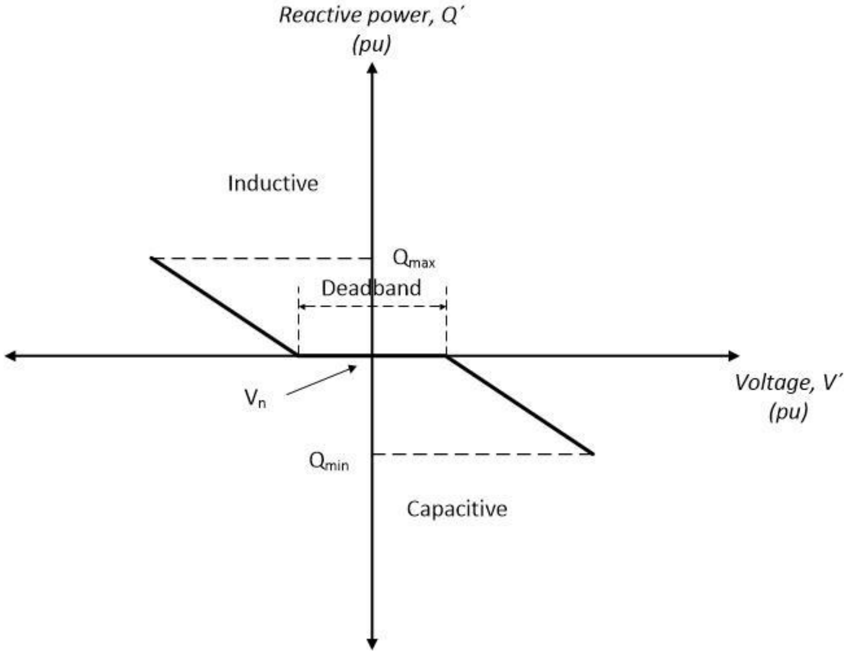


Figure 4. 12 Voltage control function [28]

Next, the controller computes the reactive power (Q_{tot}) that PV inverters have to deliver by means of PI controller as depicted in Figure 4. 12. The corresponding p.u. value of β signal is obtained by dividing Q_{tot} by Q_{plant}. Where Q_{plant} represents the nominal reactive power of the solar PVPP. Each PV inverter *i* receives *β* signal and computes its local reactive power setpoint as follows.

$$Q_{inv,i}^{*} = \beta \cdot Q_{nom,i} \quad (4.10)$$

Notice $Q_{inv,i}^{*}$ and $Q_{nom,i}$ represents the local reactive power setpoint and the nominal reactive power of the inverter *i*, respectively.

5. Modelling and Simulation of Solar PVPP

The modelling approach for each electrical element is described one by one below.

5.1. PV Arrays

The PV module constituting the PV arrays in this model is KC200 GT solar module from Kyocera company. This module possesses characteristics listed in Table 5. 1 under standard test condition (STC) in which the working temperature (T) is 25°C and solar irradiance (G) is 1000 W/m^2 [71].

No.	**Electrical characteristics**	
1.	Maximum power (P_m)	200 W
2.	Current at maximum power point $(I_{MPP_{module}})$	7.61 A
3.	Voltage at maximum power point $(V_{MPP_{module}})$	26.3 V
4.	Short circuit current $(I_{sc,n})$	8.21 A
5.	Open circuit voltage $(V_{oc,n})$	32.9 V
	Thermal characteristics	
6.	Short circuit current – temperature coefficient (K_I)	3.18x10^{-3} V/°C
7.	Open circuit voltage – temperature coefficient (K_V)	-1.23x10^{-1} A/°C
	Physical characteristics	
8.	Dimensions	1425 mm x 990 mm x 36 mm
9.	Weight	18.5 kg
10.	PV cell type	Multicristalline silicon
11.	Number of cells per module	54 cells in series

Table 5. 1 Characteristics of PV module [71]

In the solar PVPP system under study, there are two (2) PV arrays and each of them consists of ninety two (92) PV strings ($N_p = 92$) and each PV string is made up of twenty seven (27) PV modules ($N_m = 27$) resulting in 4,968 pieces of PV module. The nominal power of each PV array is expressed by equation 5.1.

$$P_{array} = N_p \cdot N_m \cdot P_m \quad (5.1)$$

P_{array} represents the nominal power of each PV array and it is 496.8 kW. Hence, two PV arrays result in total nominal power of 993.6 kW.

The nominal short circuit current and the open circuit voltage of each PV array are given in equation 5.2 and 5.3, respectively. They result in 755.32 A and 888.3 V, respectively.

$$I_{sc_{array}} = N_p \cdot I_{sc,n} \quad (5.2)$$

$$V_{oc_{array}} = N_m \cdot V_{oc,n} \quad (5.3)$$

The current and voltage at maximum power point of each PV array can be calculated by equation 5.4 and 5.5. They give 700.2 A and 710.1 V, respectively.

$$I_{MPP_{array}} = N_p \cdot I_{MPP_{module}} \quad (5.4)$$

$$V_{MPP_{array}} = N_m \cdot (V_{MPP_{module}}) \quad (5.5)$$

Figure 5. 1 and Figure 5. 2 illustrates characteristic curve of the PV module and PV array, respectively under STC. The discrepancies in most important characteristics between simulation model and information given by the PV module manufacturer for a PV module and two (2) PV arrays are summarized in Table 5. 2 and Table 5. 3. As seen in Table 5. 2 and Table 5. 3, the simulation results are similar to the information given by PV module manufacturer.

Figure 5. 3 and Figure 5. 4 describe the PV array characteristics under variations of working temperature (*T*) and irradiance (*G*), respectively. It is seen that the working temperature (*T*) affects the open circuit voltage ($V_{oc,n}$) and open circuit voltage at MPP ($V_{MPP_{module}}$) in an inverse way as well as short circuit current ($I_{sc,n}$) and current at MPP ($I_{MPP_{module}}$) slightly in a linear way. On the contrary, irradiance (G) influences short circuit current ($I_{sc,n}$) and current at MPP ($I_{MPP_{module}}$) significantly in a linear way and the open circuit voltage ($V_{oc,n}$) and open circuit voltage at MPP ($V_{MPP_{module}}$) slighlty in a linear way.

As observed in Figure 5. 3 and Figure 5. 4 that maximum PV power changes with variation of working temperature (*T*) and irradiance (*G*). This is summarized in Figure 5. 5 and Figure 5. 6 Therefore, it is needed to deploy maximum power point tracking (MPPT) function to search for the maximum PV power under particular working temperature (*T*) and irradiance (*G*)

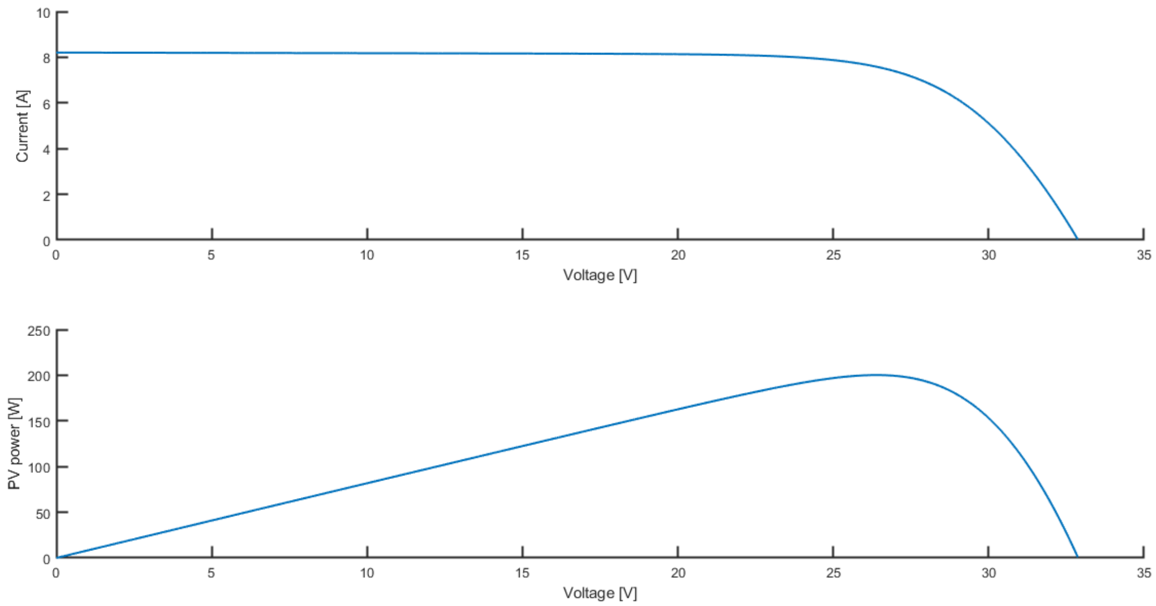


Figure 5. 1 V-I and V-P characteristic curves of PV module at T = 25^{o}C and G = 1000 W/m^2

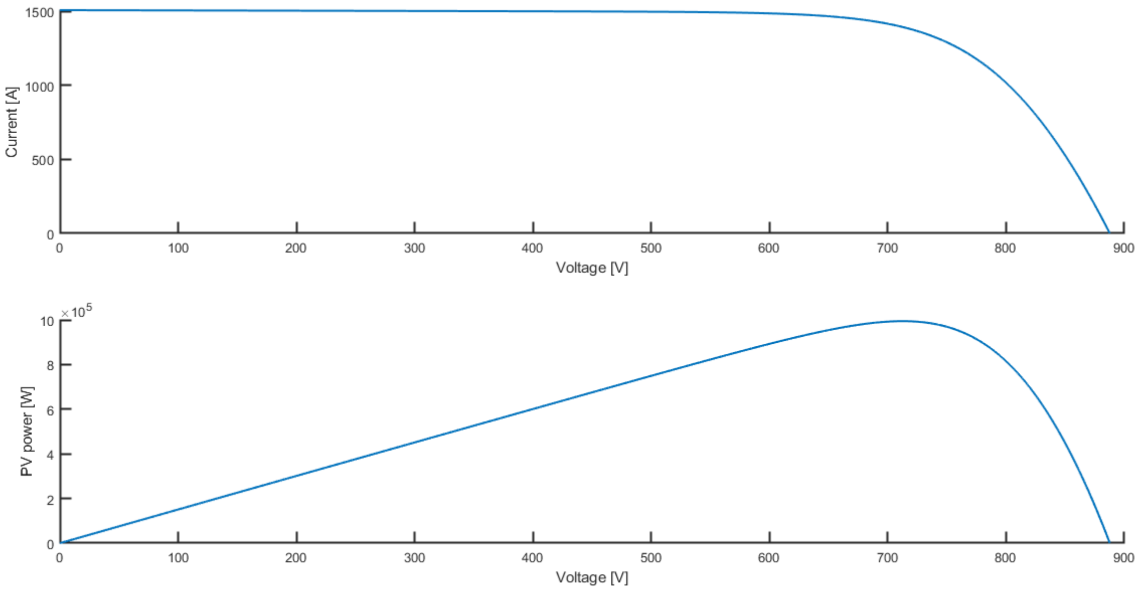


Figure 5. 2 V-I and V-P characteristic curves of two (2) PV arrays

at T = 25^{o}C and G = 1000 W/m^2

No.	PV module	Simulation Result	Error (%)
1.	Maximum power (P_m)	200.16 W	0.08
2.	Current at maximum power point ($I_{MPP_{module}}$)	7.58 A	-0.39
3.	Voltage at maximum power point ($V_{MPP_{module}}$)	26.38 V	0.30
4.	Short circuit current ($I_{sc,n}$)	8.26 A	0.61
5.	Open circuit voltage ($V_{oc,n}$)	32.87 V	-0.09

Table 5. 2 Simulation results of PV module

No.	Two (2) PV arrays	Simulation Results	Error (%)
1.	Maximum power (P_m)	994,389.83 W	0.08
2.	Current at maximum power point ($I_{MPP_{module}}$)	1395.79 A	-0.32
3.	Voltage at maximum power point ($V_{MPP_{module}}$)	712.42 V	0.33
4.	Short circuit current ($I_{sc,n}$)	1509.75 A	-0.06
5.	Open circuit voltage ($V_{oc,n}$)	887.75 V	-0.06

Table 5. 3 Simulation results of two (2) PV arrays

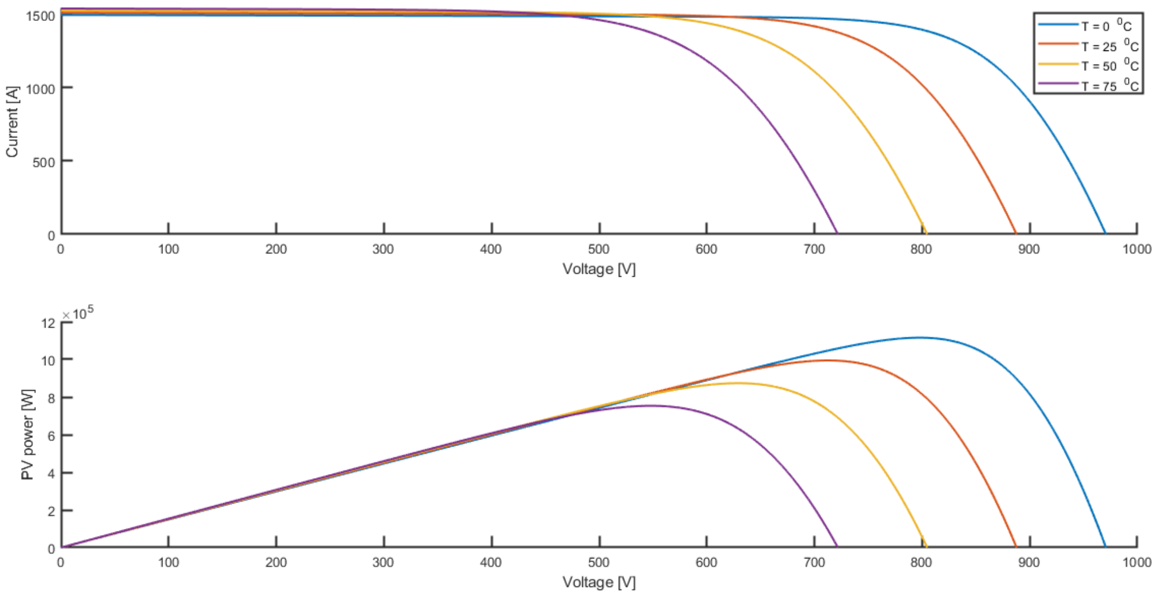


Figure 5. 3 PV arrays characteristics in function of working temperature (T)

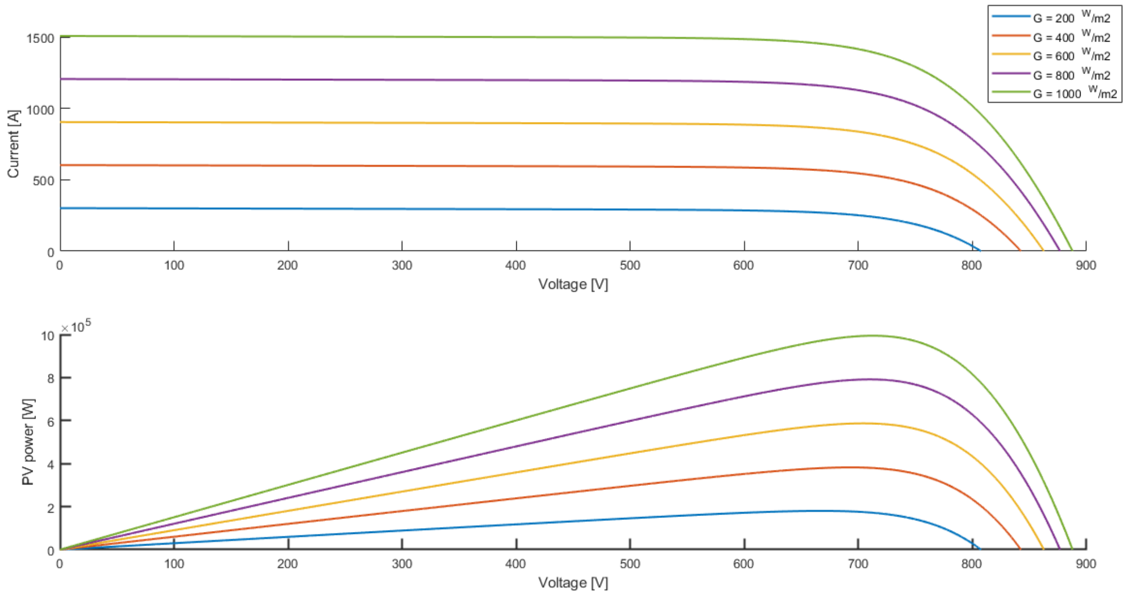


Figure 5. 4 PV arrays characteristics in function of irradiance (G)

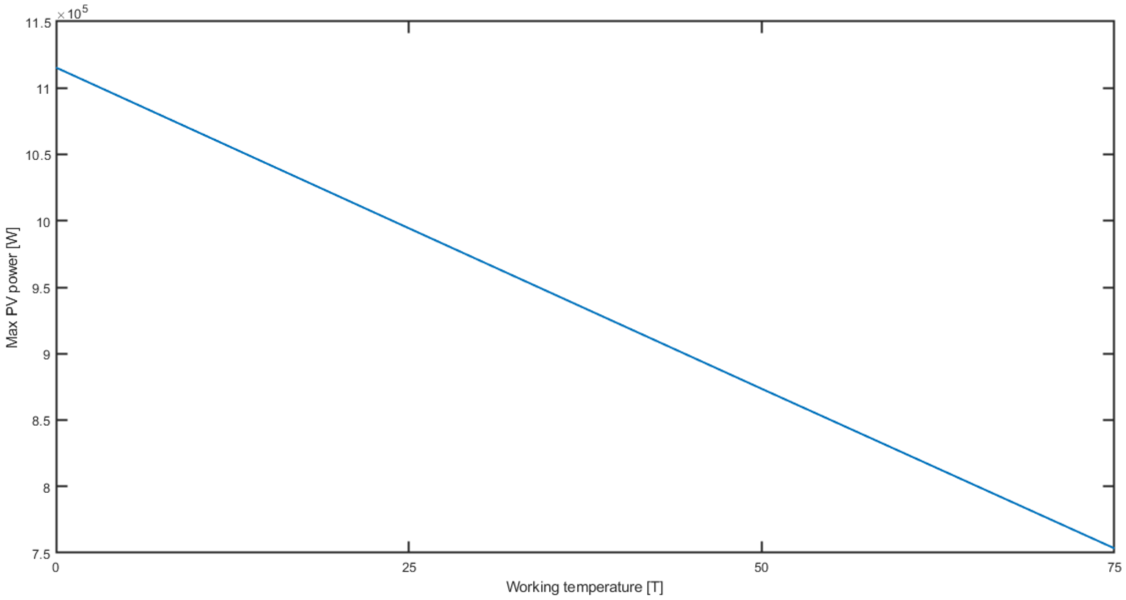


Figure 5. 5 Max PV power in function of temperature (T) and

at constant irradiance (G) of 1000 W/m^2

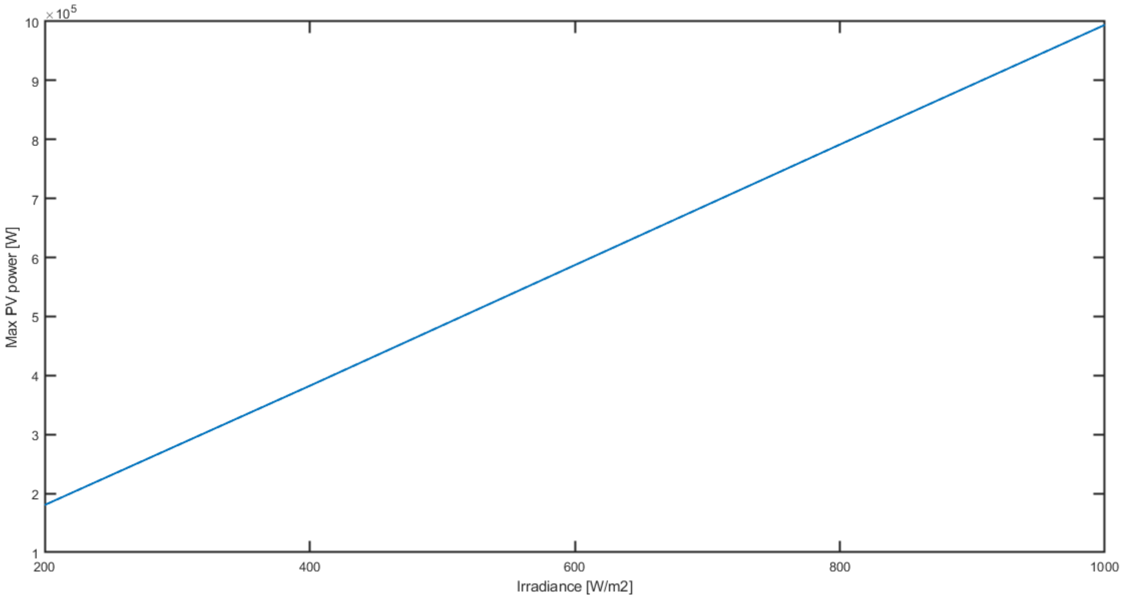


Figure 5. 6 Max PV power in function of irradiance (G) and

at constant working temperature (T) of 25^{o}C

In addition, three parameters to take into account for sizing the correct inverter linked to each PV array is (1) $V_{min_{MPPT}} \leq 712.42\ \mathrm{V} \leq V_{max_{MPPT}}$, (2) $I_{input_{max}} \geq 697.9\ A$ and (3) $P_{nom} \geq 497{,}190\ W$ [72].

5.2. PV Inverters

The solar PVPP is modelled as in Figure 4. 8 and the PV inverter model is a ready-to-use model that can be coupled directly with the PV arrays and the integration of transformer and electrical grid. Each PV array is linked to a single central PV inverter resulting in the total number of PV inverters is two (2).

In the PV inverter model, instead of one (1) PV array of approximately 1 MW linked to a single central PV inverter, two (2) PV arrays of each maximum PV power of 500 kW connected to two (2) central PV inverters separately are deployed. Some underlying motives for that are (1) easy maintenance. Solar PVPP requires less maintenance than the other power plants since it has a few moving parts. However, solar PVPP still requires little maintenance that must be performed for determinate intervals. In case of maintenance, one (1) PV array can be isolated at a time. As a result, the other PV array may still be online that results in the generated maximum PV power of approximately 500 kW. (2) Higher reliability. In the event of fault that happens to one PV array, it results in the isolation of the corresponding PV array, the other PV array may still be in operation and produces maximum PV power of approximately 500 kW [73]. The PV inverter model is depicted in Figure 5. 7.

In the PV inverter simulation, the grid along with the transformer are represented by three phase ideal voltage source 400 kV (phase to phase) at 50 Hz. The maximum active power of the PV inverter is not limited due to an approximation model is used in this master thesis. Table 5. 4 summarizes the characteristics of the PV inverter model in this master thesis. The simulation model is run under STC.

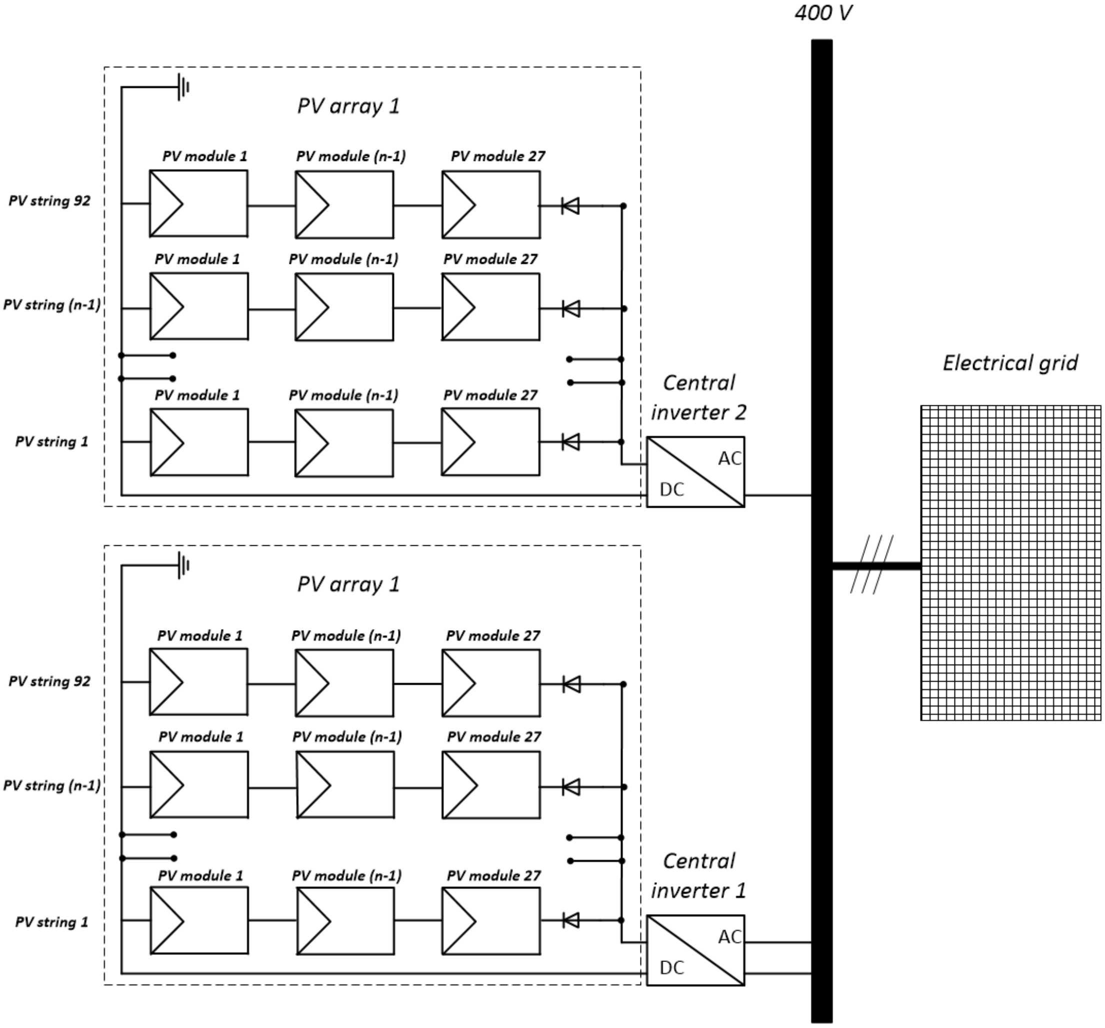


Figure 5. 7 The layout of PV inverter model

No.	Characteristics	Value
	Phase Lock Loop	
1.	Admitted peak voltage (E_{mPLL})	16.33x10^3 V
2.	Kp gain (K_{ppll})	0.0272
3.	Ki gain (K_{Ipll})	6.0439
4.	Time constant (τ_{PLL})	4.5 ms
	Current loop	

5.	Kp gain (K_{pi})	0.0395
6.	Ki gain (K_{Ii})	0.5333
7.	Time constant (τ_i)	1 ms
	Reference computation	
8.	Kp gain (K_{pdc})	31.1002
9.	Ki gain (K_{Idc})	1.3817×10^4
10.	Time constant (τ_{dc})	10 ms
11.	Initial dc voltage reference (V_{dcref})	800 V

Table 5. 4 Characteristics of PV inverter model

5.2.1 Aggregated PV Inverter Model

Due to high computer system requirements to perform simulation of two PV arrays linked to each individual PV inverter, in this master thesis, an aggregated PV inverter model is used. The aggregated PV inverter model is characterized by a single PV inverter connected to one PV array of approximately 1 MW.

As explained earlier in section 4.3.1 Local Control of PV inverter particularly about MPPT that based on dc voltage measurement (V_{dc}) and dc voltage setpoint (V_{dc}^*), MPPT controller computes desired current in the q axis (i_q^*) and d axis (i_d^*). Since dc voltage measurement (V_{dc}) is dependent on the power profile of PV array (i.e. work temperature (T) and irradiance (G)), in the simplified PV inverter model the current setpoint in the q axis (i_q^*) can be calculated by.

$$i_q^* = \frac{2}{3}\frac{P_z^*}{v_{zq}} \text{ if } P_z^* \leq P_{av} \quad (5.6)$$

Or

$$i_q^* = \frac{2}{3}\frac{P_{av}}{v_{zq}} \text{ if } P_z^* \geq P_{av} \quad (5.7)$$

Where P_z^* is active power setpoint and P_{av} is available power.

5.3. PV Plant Model

The PV plant model is a ready-to-use model for the purpose of master control simulation. It consists of one aggregrated PV array linked to a single central PV inverter. The PV inverter is connected directly to electrical grid. The internal impedance of electrical grid includes the inductor-equivalent model of LV/MV transformer. Figure 5. 8 and Table 5. 5 depicts the PV plant model and lists the parameter in PV plant model, respectively.

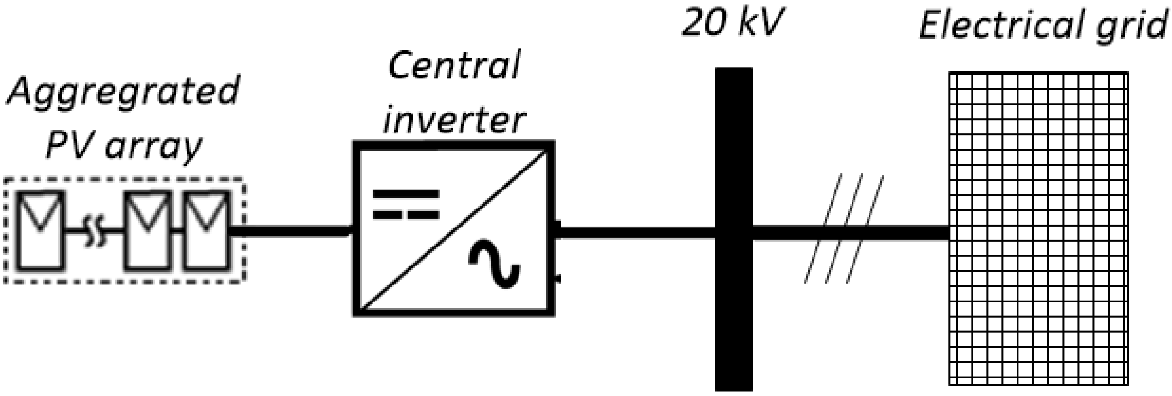


Figure 5. 8 The layout of PV plant simulation model

Voltage (kV)	Short circuit power (MVA)	Reactance to resistance (X/R)
20	500	1/3

Table 5. 5 Equivalent grid data

6. Results and Discussion

6.1. Maximum Power Point Tracking (MPPT)

6.2.1 Maximum Power Point (MPP) Mode

In this section, the maximum power point tracking (MPPT) function of PV inverters developed by the student is tested for each particular working temperature (*T*) and irradiance (*G*). The simulation result of MPTT function for variation of working temperature (*T*) and at constant irradiance (*G*) of 1000 W/m^2 as well as variation of irradiance (*G*) and at constant working temperature of (*T*) of 25^{o}C is depicted in Figure 6. 1 and Figure 6. 2, respectively.

As seen in Figure 6. 1, due to inizialitation period that is unrelated to the observation of MPP, the simulation result is shown from second 1. Table 6. 1 compares the maximum PV power in function of working temperature (*T*) and at constant irradiance (*G*) of 1000 W/m^2 based on PV array characteristics depicted in Figure 5. 5 with maximum PV power based on MPPT function in PV inverter depicted in Figure 6. 1. Additonally, Table 6. 2 compares the maximum PV power in function of irradiance (*G*) and at constant working temperature (*T*) of 25^{o}C based on PV array characteristics illustrated in Figure 5. 6 with maximum PV power based on MPPT function in PV inverter illustrated in Figure 6. 2.

As observed in Table 6. 1 and Table 6. 2, the MPPT function developed by the student fits the PV array characteristics well. The MPPT function creates little discrepancy because of the pertubation in MPPT algorithm during maximum power point (MPP) searching.

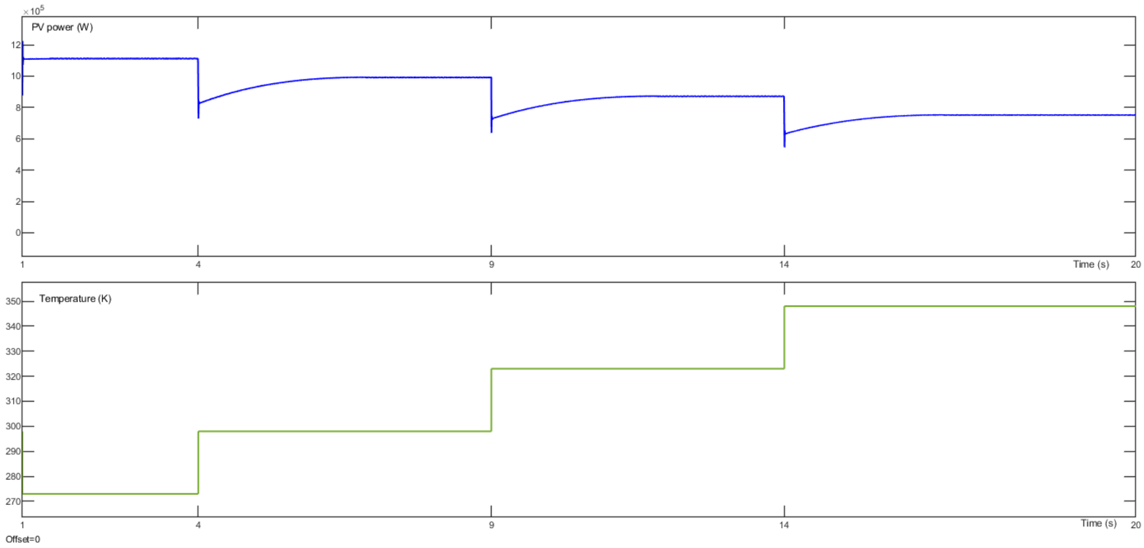


Figure 6. 1 PV power in function of working temperature (*T*) and

at constant irradiance (*G*) of 1000 W/m^2

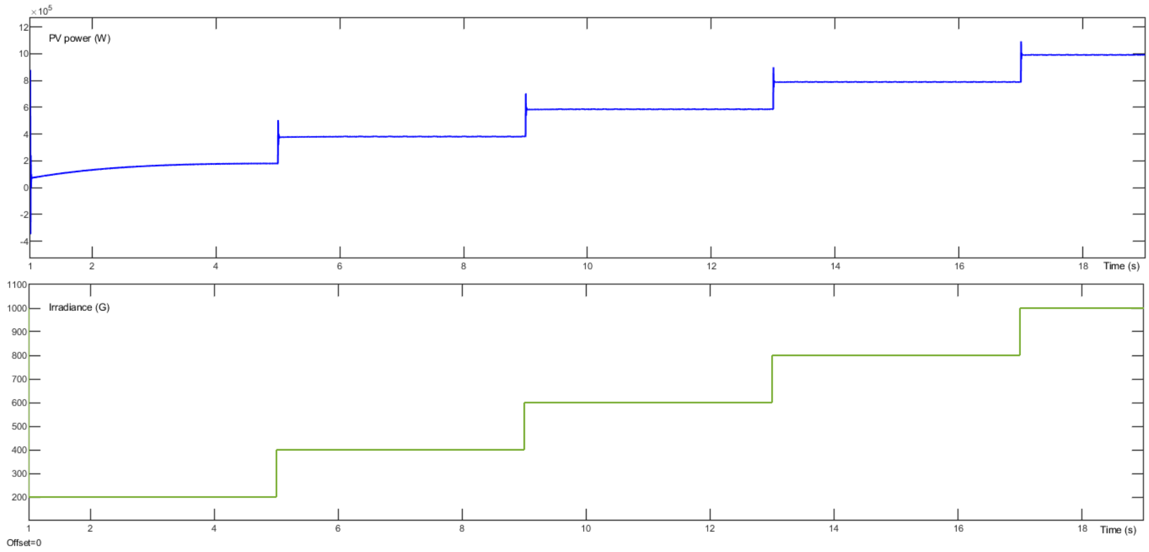


Figure 6. 2 PV power in function of irradiance (*G*) and

at working temperature (*T*) of 25^{o}C

No.	Period (s)	Working Temperature (^{o}C)	Maximum PV Power Based on PV Array Characteristics (Watt)	Maximum PV Power Based on MPPT function (Watt)	Discrepancy (%)
1.	1≤t<4	0	1,115,386	1,117,000	0.14

2.	4≤t<9	25	994,390	996,000	0.16
3.	9≤t<14	50	873,537	875,300	0.20
4.	14≤t<20	75	753,388	755,100	0.23

Table 6. 1 Maximum PV power in function of working temperature (*T*) and at constant irradiance (*G*) of 1000 W/m^2

No.	Period (s)	Irradiance (W/m^2)	Maximum PV Power Based on PV Array Characteristics (Watt)	Maximum PV Power Based on MPPT function (Watt)	Discrepancy (%)
1.	1≤t<5	200	180,325	185,200	2.63
2.	5≤t<9	400	382,422	386,900	1.16
3.	9≤t<13	600	587,034	590,800	0.64
4.	13≤t<17	800	791,442	794,200	0.35
5.	17≤t<20	1000	994,390	996,100	0.17

Table 6. 2 Maximum PV power in function of irradiance (*G*) and at constant working temperature (*T*) of 1000 W/m^2

6.2.1 Active Power Setpoint Mode (i.e. Power Curtailment)

As mentioned in section 4.3.1 Local Control PV Inverter particularly about MPPT function, MPPT function can carry out power curtailment by calculating the dc voltage setpoint (v_{dc}^*) to generate a desired active power (P_z^*). In this mode there are two (2) options which are (1) In case active power setpoint (P_z^*) is greater than available power (P_{av}) (i.e. maximum power based on PV array characteristics), then the MPPT function computes the dc voltage setpoint (v_{dc}^*) that corresponds to the available power (P_{av}). (2) In case active power setpoint (P_z^*) is lower than available power (P_{av}), then MPPT function computes the dc voltage setpoint (v_{dc}^*) that corresponds to the active power setpoint (P_z^*).

Option 1 is depicted in

Figure 6. 3, the active power setpoint mode is activated at second 0.5. Hence, the simulation result is displayed from second 0.5. When the active power setpoint (P_z^*) is set to 1.5 MW, then the MPPT function computes the dc voltage setpoint (v_{dc}^*) of approximately 713 V that leads to the available power (P_{av}) of around 1 MW under STC as verified earlier. It is observed

that at second 0.5 the measured voltage (v_{dc}) starts to decrease gradually from initial dc voltage reference (V_{dcref}) of 800 V to dc voltage setpoint (v_{dc}^*) of approximately 713 V. At second 3.4, measured voltage (v_{dc}) reaches dc voltage setpoint (v_{dc}^*) of approximately 713 V that makes generated active power equal to available power (P_{av}) of around 1 MW.

Option 2 is illustrated in Figure 6. 4, in a similar manner, the active power setpoint mode is engaged in second 0.5. Hence, the simulation result is displayed from second 0.5. The active power setpoint (P_z^*) is depicted in brown line whereas the generated active power is represented by blue line. When the active power setpoint (P_z^*) is set to 0.5 MW, then the MPPT function computes the dc voltage setpoint (v_{dc}^*) of 845 V that corresponds the active power setpoint (P_z^*) of approximately 0.5 MW. It is seen that measured voltage (v_{dc}) starts rising from initial dc voltage reference (V_{dcref}) of 800 V to dc voltage setpoint (v_{dc}^*) of approximately 845 V. At second 2, the measured voltage (v_{dc}) reaches dc voltage setpoint (v_{dc}^*) that makes the generated power equal to the active power setpoint (P_z^*) of around 0.5 MW.

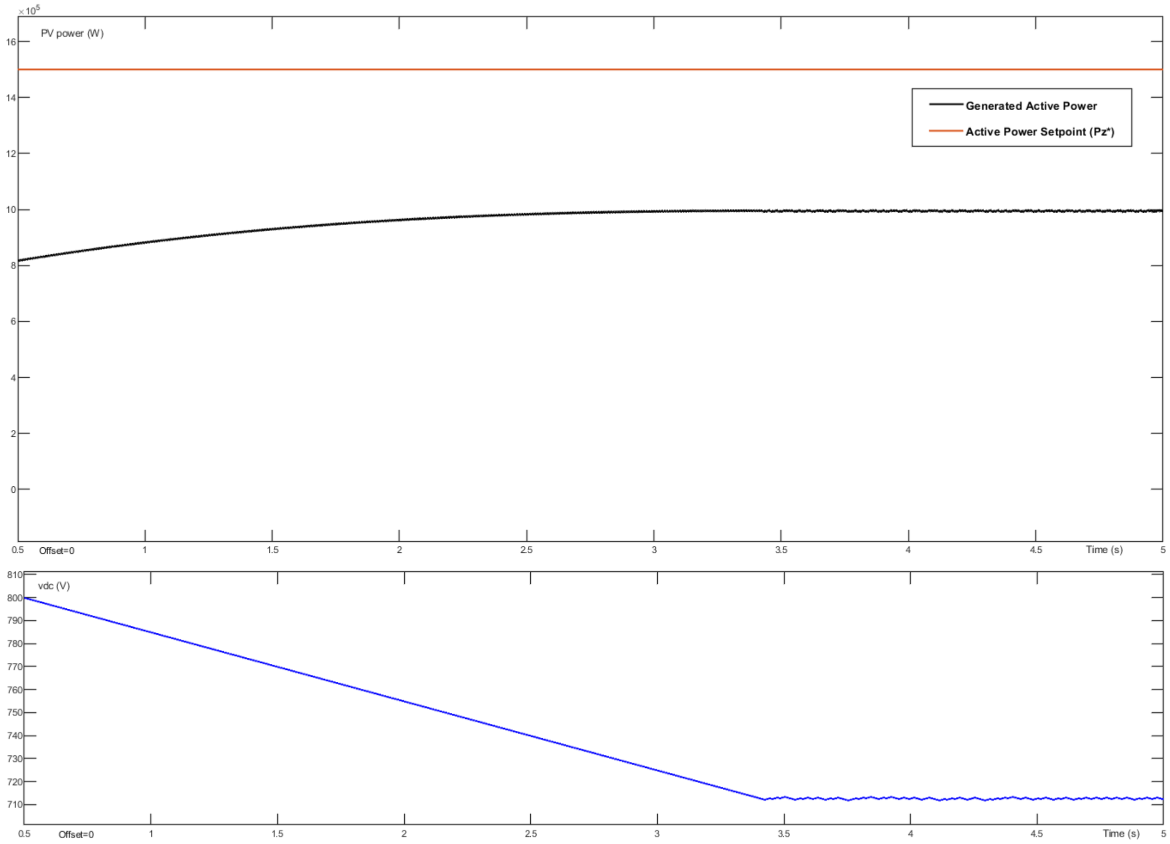


Figure 6. 3 Option 1 in active power setpoint mode

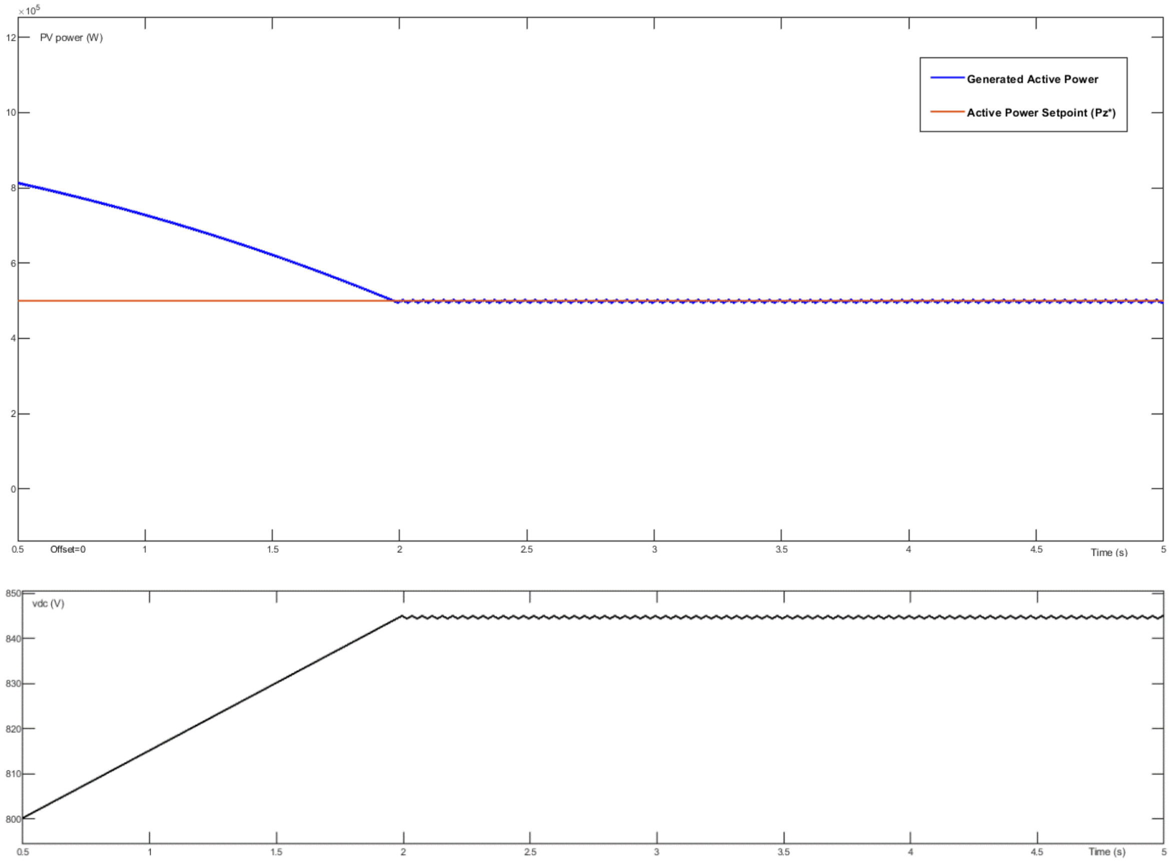


Figure 6. 4 Option 2 in active power setpoint mode

6.2. Voltage Control and Reactive Power Regulation Action

As described in section 4.4 Master Control by Power Plant Controller, voltage control and reactive power regulation action can be in the form of (1) reactive power control, (2) voltage control by droop curve and (3) power factor control. In this section, the reactive power and voltage control regulation set out in grid code proposal for solar PVPP in major islands and small islands in Indonesia described in section 3.3.3 Reactive Power and Voltage Support is simulated. Furthermore, the response to this regulation is observed and explained.

6.2.1 Voltage Control

As explained earlier in section 3.3.3 Reactive Power and Voltage Support especially in Table 3.28, the grid code proposal sets out voltage control regulation for solar PVPP in small islands. The proposed voltage control is adopted from Puerto Rico´s grid code.

Figure 6. 5 depicts the response to voltage control function. In this simulation, the MPPT particularly maximum power point mode and the voltage control are engaged concurrently. The simulation result is displayed from second 0.2 since the mode of maximum active power in MPPT and voltage control turn on at second 0.2. Hence, initialization takes place that is unrelated to the simulation analysis lasts until second 0.2. In order to see the response under the strictest requirement, the maximum allowable and minimum allowable voltage droop gradient of 10% and -10% are applied in turn. Table 6. 3 lists the parameters in response to voltage control function.

As observed in Figure 6. 5, at second 0.2 the solar PVPP starts to produce active power from approximately 815 kW and at second 2.5 it eventually attains the maximum power point (MPP) of 993.6 kW. In fact, due to perturb and observe method in MPPT algorithm, the generated active power oscillates around the maximum power point (MPP) (i.e. not remains at 993.6 kW).

Regarding the reactive power output, as stated in Table 6. 3, from second 0.2 to 3.1, by default the solar PVPP absorbs reactive power in the range of -2.2 W to -11,020 W due to the voltage at the PCC of between 20,030 V and 20,040 V that is supposed to be absolute 20,000 V. The deviated voltage at the PCC is because of the existence of internal impedance that leads to the higher voltage than nominal voltage at the PCC. From second 3.1 to 5, a voltage perturbation is simulated that leads to the voltage at the PCC of absolutes 20,000 V that places the operating point within the deadband in voltage droop curve depicted in Figure 2. 8. As a result, solar PVPP delivers reactive power in the range of -10,950 W to 13 W whereas theoretically no reactive power. From second 5 to 7, another voltage perturbation is simulated that leads the voltage at the PCC to 19,500 V that puts the operating point in the left zone of voltage droop curve. As a result, solar PVPP produces reactive power between 125,400 W to 236,800 W. Additionally, from second 7 to 9, another voltage perturbation is simulated that leads to the voltage at PCC of 20,540 V that puts the operating point in the right zone of voltage droop curve. As a result, the solar PVPP absorbs reactive power in the range of -40,080 W to -258,300 W. The generated reactive power fluctuates since the transient condition takes place every time a voltage perturbation is simulated and it stays oscillating due to the perturb and oscillation method in MPPT algorithm that affects the generated reactive power.

Table 6. 4 summarizes the parameters at a determinate point for each period. It is observed that generated reactive powers are similar to theoretical reactive powers according to the equation for voltage droop function described in section 2.2.3 Reactive Power and Voltage Control Functions. The proposed voltage control function gives acceptable time response since it takes less than 1 s to reach the 95% of steady-state response (i.e. 95% of final value of reactive power) as listed in Table 6. 4.

In the next simulation, the minimum allowable voltage at the PCC and maximum voltage droop function of 0.85 pu and 10% as well as the maximum allowable voltage at the PCC and minimum allowable voltage droop function of 1.15 pu and -10%, respectively, are applied separately.

As seen in Figure 6. 6, at the second 0.2, the solar PVPP starts producing active power of 814,900 kW and at second 2.5, the solar PVPP achieves the maximum power point (MPP) of 993,600 kW. In fact, due to perturb and observe method in MPPT algorithm, the generated active power keeps oscillating around the maximum power point (MPP) (i.e. not remains at 993.6 kW).

Concerning reactive power output, as listed in Table 6. 5, the response to voltage control function for periods of second 0.2 to 3.1 and second 3.1 to 5 remains the same as stated in Table 6.3. Additionally, from second 5 to 7, another voltage perturbation is simulated that leads the voltage at the PCC to 0.85 pu (i.e. 17,000 V) that puts the operating point in the left zone of voltage droop curve. As a result, solar PVPP delivers reactive power between 370,800 W and 618,400 W. Since stated in the grid code proposal that the upper limit of reactive power output of solar PVPP is 0.62 of actual power (P_{ac}). Hence, the maximum reactive power that solar PVPP can produce is 618,400 W despite the voltage drop at the PCC is over 0.062 pu (in fact, the actual voltage drop is 0.15 pu that corresponds to the reactive power production of 1.49 MW). Then from second 7 to 9, another voltage perturbation is simulated that leads to the voltage at PCC of 1.15 pu (i.e. 23,000 V) that puts the operating point in the right zone of voltage droop curve. As a result, the solar PVPP absorbs reactive power in the range of -241,600 W to -619,300 W. As stated in the grid code proposal that lower limit of reactive power output of solar PVPP is -0.62 of actual power (P_{ac}). Thus, the maximum reactive power output that solar PVPP can absorb is -619,300 W despite the voltage spike at the PCC is greater than 0.062 pu (in fact, the actual voltage spike is 0.15 pu that corresponds to the reactive power absorption of 1.49 MW). The generated reactive power keeps fluctuating since the transient condition occurs every time a voltage perturbation is simulated and it keeps oscillating due to the perturb and oscillation method in MPPT algorithm that affects the generated reactive power.

Table 6. 6 lists parameters at a determinate point for each period. It is seen that generated reactive powers are similar to theoretical reactive powers according to the equation for voltage droop function described in section 2.2.3 Reactive Power and Voltage Control Functions. The proposed voltage control function gives acceptable time response since it takes less than 1 s to reach the 95% of steady-state response (i.e. 95% of final value of reactive power) as listed in Table 6. 5.

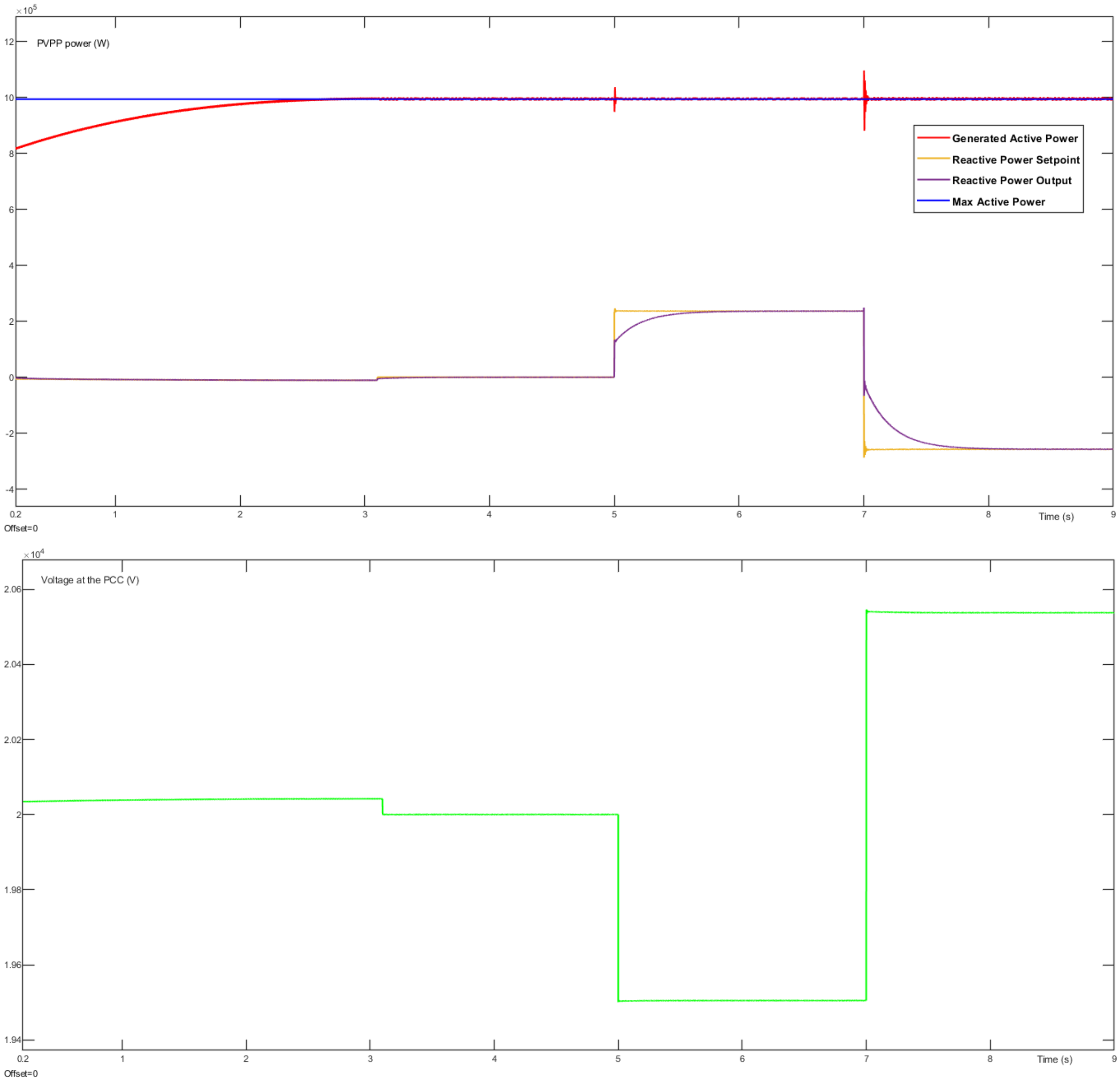


Figure 6. 5 Response to voltage control function

No.	Period (*s*)	Voltage at the PCC (*V*)	Reactive Power (*W*)	Time Response (s)
1.	3.1≤t<5	20,000	-10,950 to 13	0.7 (i.e. at second 3.8)
2.	5≤t<7	19,500	125,400 to 236,800	0.5 (i.e. at second 5.5
3.	7≤t<9	20,540	-40,080 to -258,300	0.6 (at second 7.6)

Table 6. 3 Parameters in response to voltage control function

No.	Time (*s*)	Voltage at the PCC (*V*)	Active Power (*W*)	Theoretical Reactive Power (*W*)	Generated Reactive power (*W*)	Reactive Power Discrepancy (%)
1.	3.09	20,040	995,600	-10,930	-10,970	0.037
2.	4.99	20,000	992,700	0	-14.2	-
3.	6.99	19,500	995,300	236,600	236,500	-0.04
4.	8.99	20,540	995,500	-256,800	-256,900	-0.04

Table 6. 4 Parameters in determinate points for each period

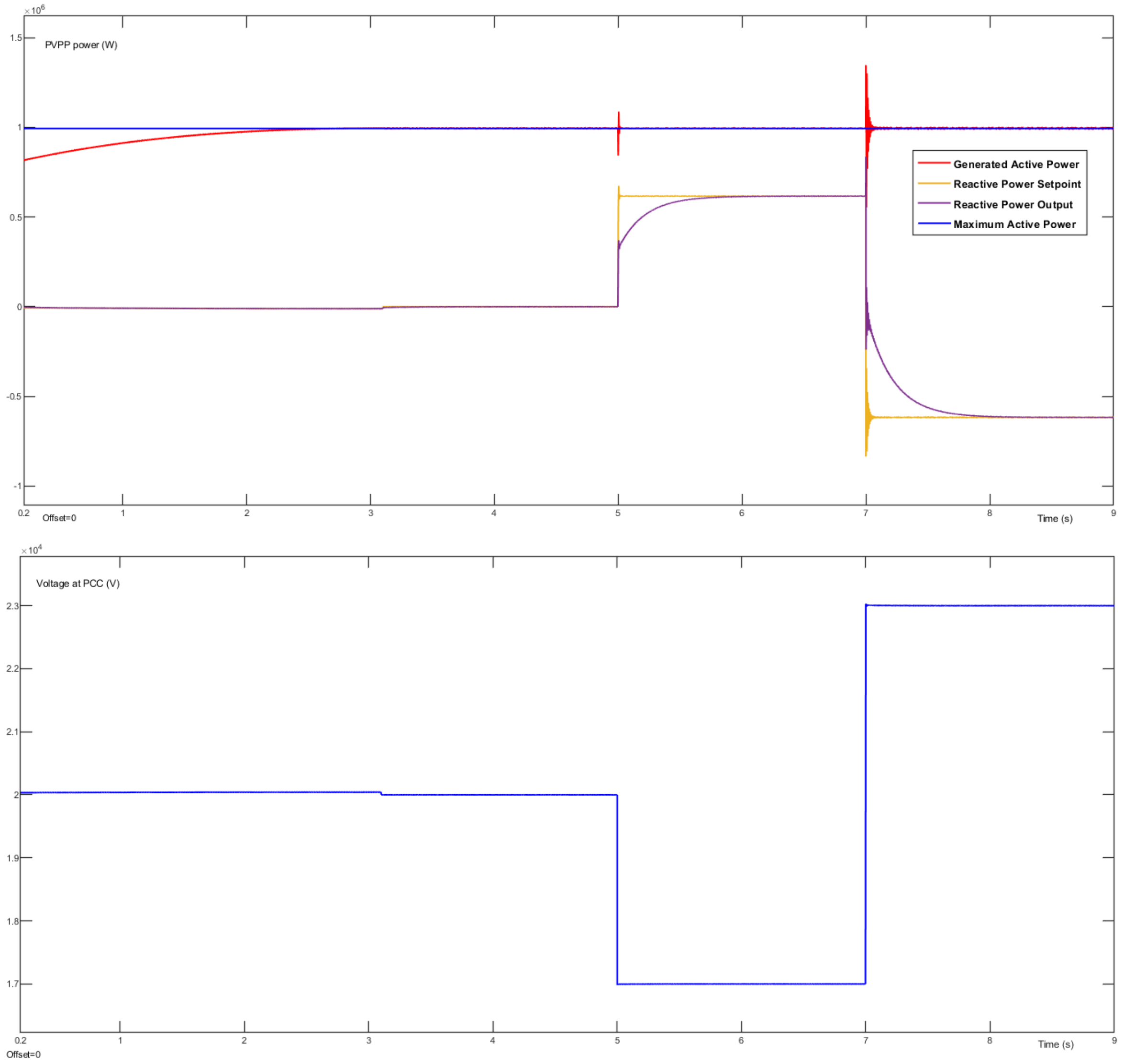


Figure 6. 6 Response to voltage control function with different parameters

No.	Period (*s*)	Voltage at the PCC (*V*)	Reactive Power (*W*)	Time Response (s)
1.	3.1≤t<5	20,000	-10,950 to 13	0.7 (i.e. at second 3.8)
2.	5≤t<7	17,000	370,800 to 618,400	0.5 (i.e. at second 5.5
3.	7≤t<9	23,000	-241,600 to -619,300	0.7 (at second 7.7)

Table 6. 5 Parameters in response to another voltage control function

No.	Time (*s*)	Voltage at the PCC (*V*)	Active Power (*W*)	Theoretical Reactive Power (*W*)	Generated Reactive power (*W*)	Reactive Power Discrepancy (%)
1.	3.09	20,040	995,600	-10,930	-10,970	0.37
2.	4.99	20,000	992,700	0	-14.2	-
3.	6.99	17,000	995,000	616,100	616,200	0.02
4.	8.99	23,000	995,500	-618,300	-617,800	-0.08

Table 6. 6 Parameters in determinate points for each period

6.2.2 Reactive Power Control

As described earlier in section 3.3.3 Reactive Power and Voltage Support particularly in Table 3.29, the grid code proposal contains reactive power regulation for solar PVPP in major islands and small islands in Indonesia.

The proposed reactive power control is adopted from Denmark´s grid code and it is applied to solar PVPP in both major islands and small islands. As set out in the grid code proposal, the 1 MW solar PVPP must be capable of delivering reactive power ranging from 0.48 pu to -0.48 pu with respect to power factor from 0.9 to -0.9.

In this simulation, the maximum and minimum allowable reactive power setpoint of 0.48 pu and -0.48 pu, respectively, are separately applied. At the same time, the MPPT mode particularly maximum active power is engaged. As depicted in Figure 6. 7, the simulation results are shown from second 0.2 because initialization that is unrelated to the simulation analysis takes place until second 0.2. It is observed that at second 0.2 solar PVPP starts to increase active power from 814,900 W and at second 2.5 solar PVPP attains the maximum PVPP power of 993,600 W. Concurrently, the reactive power setpoint (Q^*) is set to 0.48 pu at second 0.2 then the solar PVPP starts delivering reactive power gradually from 273,100 W. Then solar PVPP attains the reactive power setpoint (Q^*) of 476,928 W at second 1.8. In other words, it takes 1.6 s for solar PVPP to attain the reactive power setpoint (i.e. time response of 1.6 s).

Additionally, as illustrated in Figure 6. 8, when the reactive power setpoint is established at -0.48 at second 0.2 then the solar PVPP starts absorbing reactive power of -272,800 W. The solar PVPP reaches the reactive power setpoint (Q^*) of -476,928 W at second 1.7 s. In other words, it takes 1.5 s for solar PVPP to reaches the reactive power setpoint (i.e. time response of 1.5 s). At the same time, at second 0.2 the MPPT mode particularly maximum power point is engaged. The solar PVPP begin producing active power 814,900 W and reaches the active power setpoint of 993,600 W at second 2.5. It is concluded that the proposed reactive power controller meets the requirement as it gives time response shorter than that in the requirement (i.e. time response of 10 s).

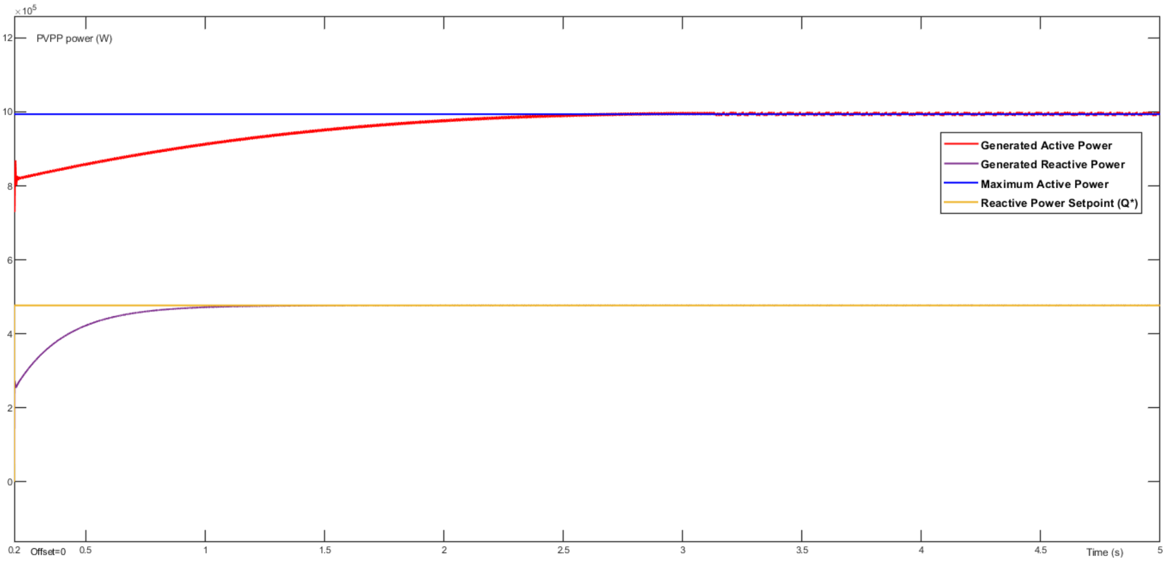


Figure 6. 7 Response to maximum allowable reactive power setpoint

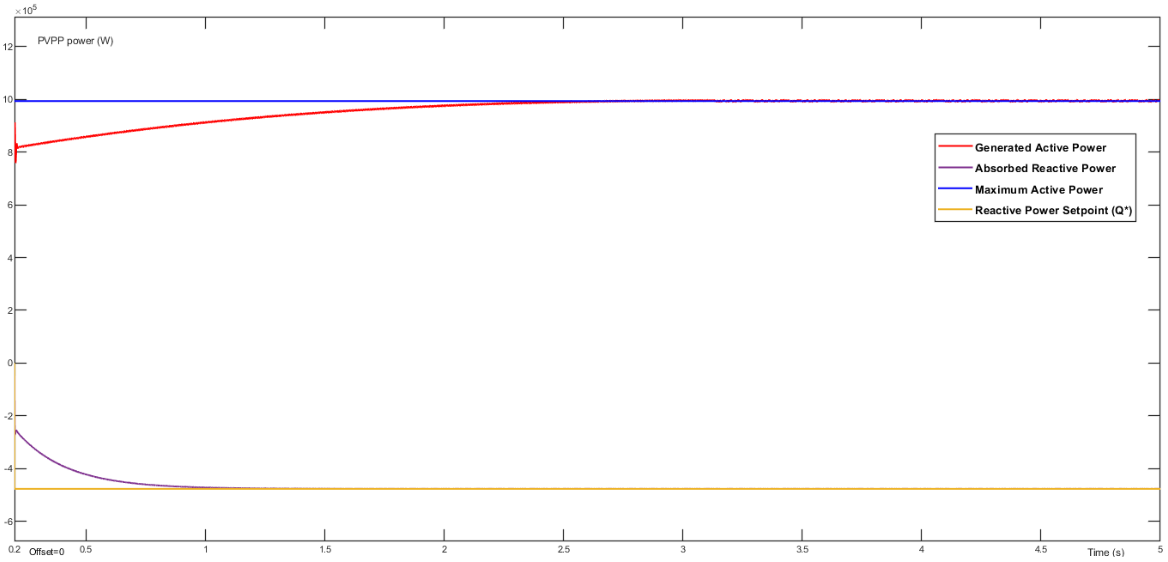


Figure 6. 8 Response to minimum allowable reactive power setpoint

6.2.3 Power Factor Control

As explained in section 3.3.3 Reactive Power and Voltage Support, solar PVPP both in major islands and smalls islands must be capable of operating at power factor in the range of 0.9 to -0.9. In this simulation, the maximum and minimum permissible power factor setpoint of 0.9 and -0.9 are applied separately. At the same time, MPPT particularly MPP mode is activated.

As depicted in

Figure 6. 9, the simulation results are shown from second 0.2 because initialization that is unrelated to the simulation analysis takes place until second 0.2. At second 0.2, it is observed that the solar PVPP starts to increase active power from 814,900 W and at second 2.5 solar PVPP attains the maximum PVPP active power of 993,600 W. And at second 0.2, when the power factor setpoint is established at 0.9, the solar PVPP also starts delivering reactive power gradually from 208,400 W. Then eventually the solar PVPP attains the desired reactive power of 476,928 W at second 2.3. Regarding the response to power factor setpoint, at second 0.2, solar PVPP operates at power factor of 0.96 and eventually at second 2.9, it attains the reactive power setpoint of 0.9. In other words, the solar PVPP attains the steady-state response of power factor setpoint in 2.7 s (i.e. time response of 2.7 s).

In addition, as illustrated in Figure 6. 10, the simulation results are displayed from second 0.2 because of unrelated transient condition that lasts until second 0.2. At second 0.2, the solar PVPP begins to deliver active power gradually from 814,900 W and at second 2.5 solar PVPP reaches the maximum active power of 993,600 W. At second 0.2, when the power factor setpoint is established at -0.9, the solar PVPP starts to absorb reactive power from -249,100 W. Then finally the solar PVPP reaches the desired reactive power of -476,928 W at second 2.4. Concerning response to power factor setpoint, at second 0.2, solar PVPP runs at power factor of -0.96 and finally at second 2.7, the solar PVPP attains the power factor setpoint of -0.9. In other words, the solar PVPP reaches the steady-state response of reactive power in 2.5 s (i.e. time response of 2.5 s). It is concluded that proposed power factor controller meets the requirement as it yields time response less than 10 s as stated in the requirement.

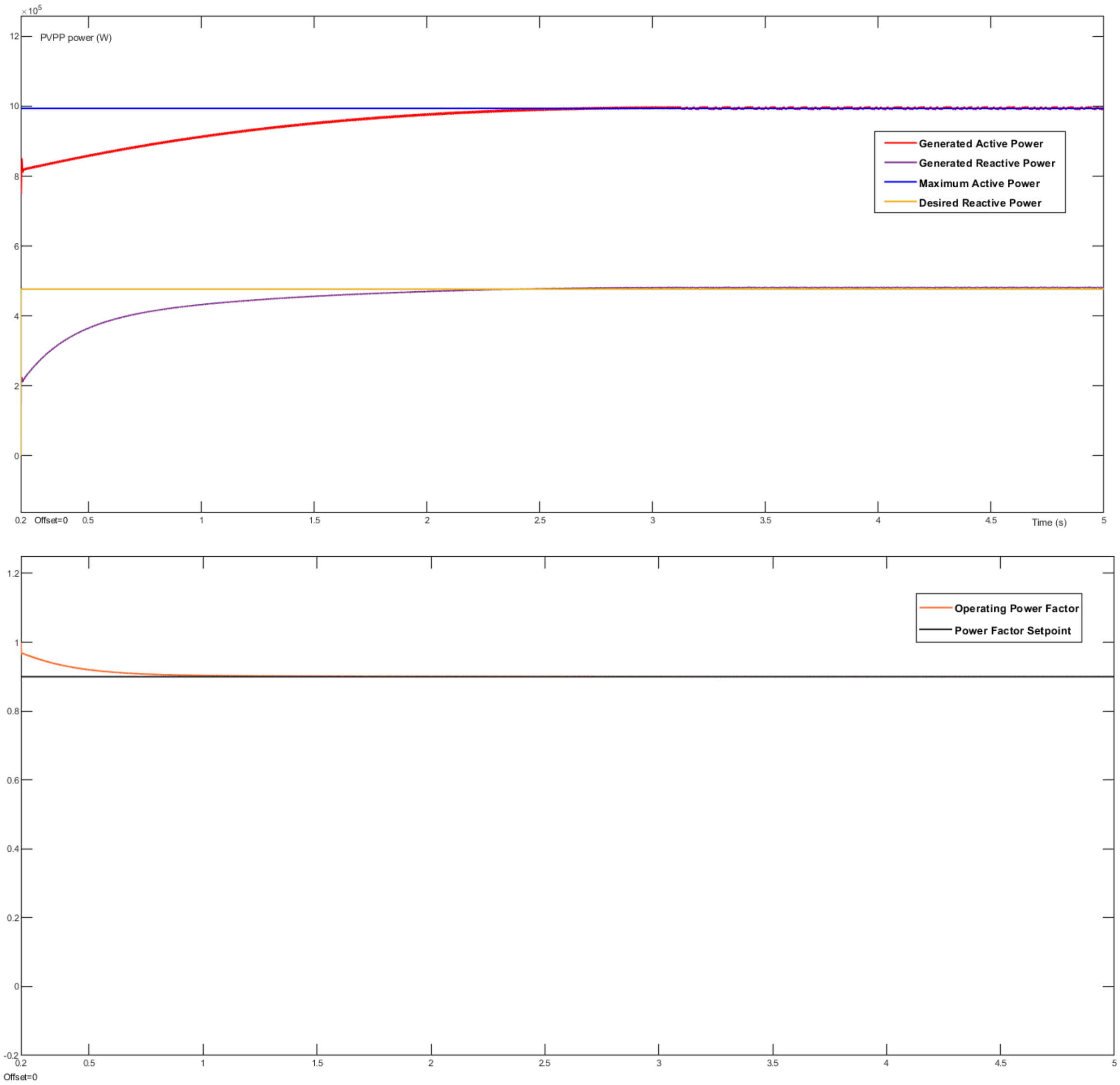


Figure 6. 9 Response to maximum allowable power factor setpoint

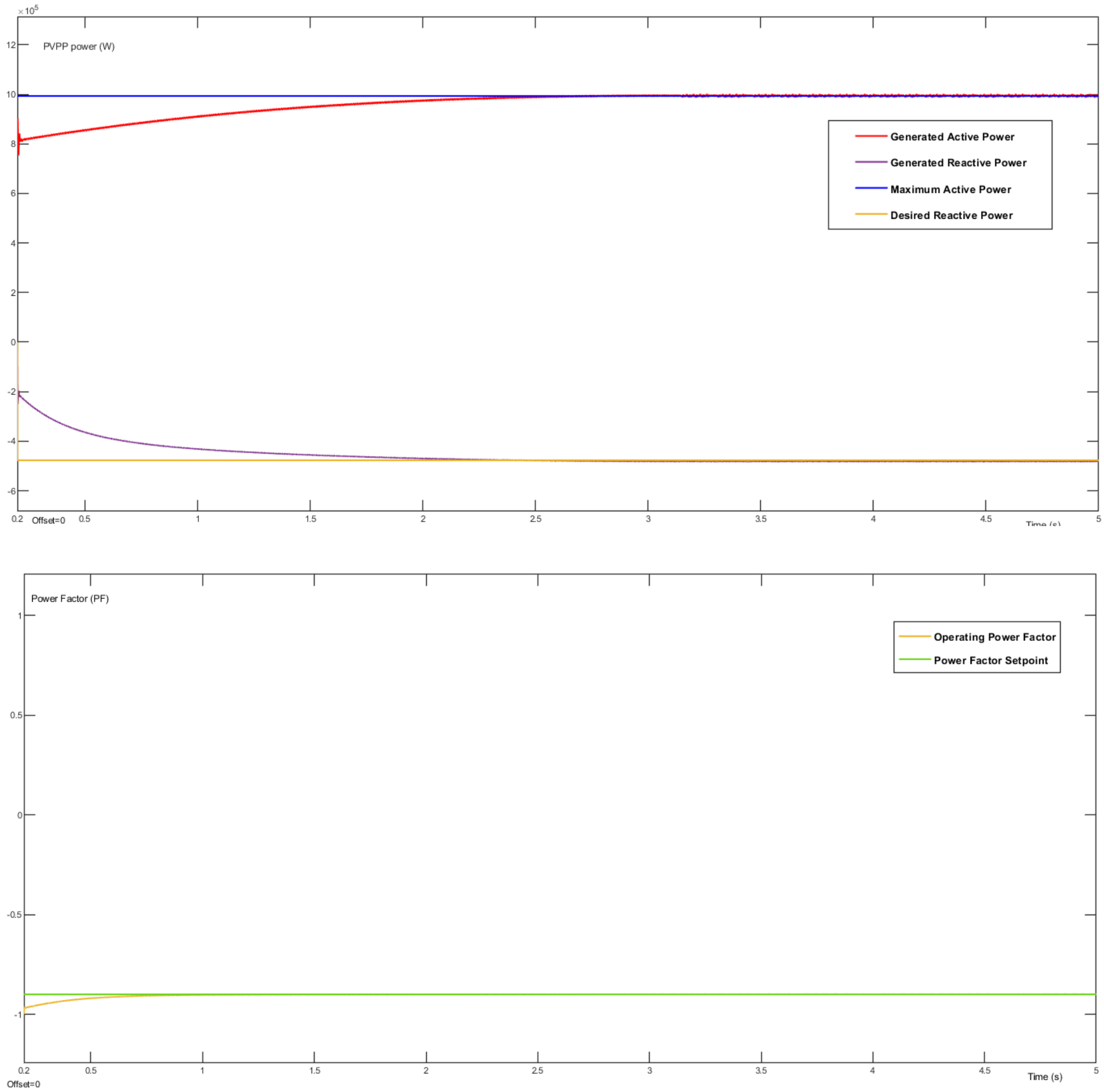


Figure 6. 10 Response to minimum allowable power factor setpoint

7. Conclusion

In this master thesis, the study of several international grid codes from operational perspectives are performed as a foundation to create grid code proposal for 1 MW solar PVPP in Indonesia. The grid code proposal consists of regulation of voltage and frequency boundary, active power and frequency support, reactive power and voltage support as well as fault-ride-through (FRT). Moreover, to comply with the grid code proposal, power plant controller (PPC) is modelled and simulated using Matlab and Simulink to see the response. Particularly, MPPT function in PV inverter and voltage control, reactive power control and power factor control have been verified. Following conclusions can be drawn from all works carried out in this master thesis.

- At present, Indonesia is using IEEE series of standard and one of them is IEEE 1547 as the guidance on interconnection of solar PVPP to electricity grid. The current policies in Indonesia are leading to promote the connection of new PV generation facilities, which will change the electricity mix of the country. Accordingly, new regulations regarding the PV power plants interconnection will be required.

- This study can serve as a starting point for developing a new regulation for the connection of PVPP in Indonesia. From the viewpoint of geography, electricity generation mix and electricity interconnection system those grid codes that best suit the solar PVPP in major island and small islands are grid code of Denmark and Puerto Rico, respectively. Moreover, based on these two international grid codes, the grid code proposal is created along with some modifications to adapt to the existing electricity system of Indonesia and projection of solar PV growth in the electricity mix.

- As working temperature (T) and solar irradiance (G) affects the active power output of solar PVPP, it is necessary to use MPPT function to continuously search for the maximum power point (MPP). Maximum power point (MPP) mode in MPPT function is modelled and simulated under variation of working temperature (T) and solar irradiance (G). It is validated that MPP mode helps to produce maximum active power in each scenario.

- In order to comply with the grid code proposal such as active power and frequency regulation as well as reactive power and voltage regulation, MPPT function and power plant controller (PPC) is modelled and developed. MPPT function can be modified in order to achieve a desired power production. This modification can be used to comply with those requirements affecting the active power (e.g. power curtailment) as shown by the simulation results.

- The voltage, reactive power and power factor control requirements can be fullfilled thanks to a central controller based on a PI controller, which have been validated through simulations complying with the required time response.

In order to obtain more comprehensive and accurate result, the following works can be carried out in the future.

- In order to see the dynamic response and effect of individual electrical device, the current solar PVPP model can be developed to detailed solar PVPP model comprising LV-MW transformer and MV-MV transformer.

- In order to see the response to active power and frequency regulation, the active power and frequency support controller comprising function of frequency response (i.e. frequency control), absolute production (i.e. power curtailment), delta production (i.e. power reserve) and power gradient (i.e. ramp rate) can be modelled and simulated.

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