Comparison of a three phase single stage PV system in PSCAD and PowerFactory

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Abstract

The main objective of the project is to develop a Photovoltaic (PV) system using three phase Pulse Width Modulation (PWM) converter as the interfacing component in Power factory. Already existing model in Power factory tool uses static generator as the interfacing converter. Moreover the control technique implemented within the PV model is very basic. A working model is already available in PSCAD simulation tool using PWM converter but it is a very detailed one in terms of modeling which results in longer simulation time. Through this project a new PV model is developed in Power factory, an improved version of existing PSCAD and Power factory models. Then a comparison study is carried out between the PSCAD and the new Power factory model in order to validate the created model's functionality. Several case studies with the DC and AC side disturbances are performed to analyze the behavior of two models. The new PV model is found to function very similar to that of the existing PSCAD model, thus proving its credibility. Further improvements and additional functions are also included in the new Power factory model which makes it a better choice to carry out grid studies than the existing model in PSCAD.

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Table of Contents

List of abbreviations

PV: Photovoltaic
R&D: Research and Development
EPIA: European Photovoltaic Industry Association
EU: European Union
GW: Giga Watt
MW: Mega Watt
MPPT: Maximum Power Point Tracking
PWM: Pulse Width Modulation
LV: Low Voltage
HV: High Voltage
VSI: Voltage Source Inverter
CSI: Current Source Inverter
EMC: Electromagnetic Compatibility
THD: Total Harmonic Distortion
LVRT: Low Voltage Ride through
DSL: DIgSILENT Simulation Language
CCP: Common Coupling Point
VSC: Voltage Souce Converter
PLL: Phase Locked Loop
RMS: Root Mean Square

1. Introduction

Green energy, the term is nowadays heard, seen and discussed in almost all the energy related concepts. The world is running out of non-renewable resources, thus the green energy sources gains more importance. Wind energy, solar energy, hydro-power, bio-gas energy etc. are the most popular renewable energy sources. Research and development in each of these areas is being carried out in all parts of the world. Out of which the solar energy is one of the cleanest and the least expensive one. A few years ago the penetration of solar energy into the electricity market was considerably negligible. But the recent statistics show a drastic change in this situation. As per European Photovoltaic Industry Association (EPIA) forecast Photovoltaic (PV) potential of the Sunbelt countries could range from 60 to 250 GW by 2020 and from 260 to 1,100 GW in 2030 [1]. Solar energy is highly promoted; even the governments provide subsidies for the installation of PV systems.

According to the REN21 Renewables 2012 Global Status Report, there was 74% increase in the installation of the PV plants in 2011 thereby increasing the total installed capacity to 70 GW worldwide. Large scale ground mounted systems are continued to be installed in greater numbers which increase the market share of the solar energy to notable numbers. During 2011 in European Union (EU), the solar PV capacity additions were higher than any other energy source installation. Germany and Italy continued to lead the EU solar market when compared with other countries. At the same time 2011 also saw the emergence of China as a strong player in the solar energy sector [2]. A country based table on the installed PV capacity is shown in Fig. 1.1.

	COUNTRY	2011 NEWLY CONNECTED CAPACITY (MW)	2011 CUMULATIVE INSTALLED CAPACITY (MW)
1	Italy	9,284	12,754
2	Germany	7,485	24,678
3	China	2,200	3,093
4	USA	1,855	4,383
5	France	1,671	2,659
6	Japan	1,296	4,914
7	Belgium	974	2,018
8	Australia	774	1,298
9	United Kingdom	784	875
10	Greece	426	631
11	Spain	372	4,400
12	Canada	364	563
13	Slovakia	321	468
14	India	300	461
15	Ukraine	188	190
	Rest of the World	1,371	6,299
	Total	29,665	69,684

Fig. 1.1 Table on worldwide PV system installation [2]

PV market reports published by various organizations clearly show one major trend, the installation of large scale grid connected PV plants in greater numbers. Also people are getting more and more attracted towards solar energy which will result in an increase in the small scale PV installations as well. Such an increase in PV installation can result in high penetration of large amounts of PV energy into the electricity grid. According to the European Photovoltaic Energy Association Report about 29.7 GW of PV systems are connected to the grid in 2011 globally which was 16.8 GW the previous year. Out of 29.7 GW, 21.9 GW is in Europe alone, of which 9.3 GW is in Italy and 7.5 GW in Germany during 2011. Below Fig. 1.2 shows the increase in the amount of grid connected PV systems in Europe till 2011.

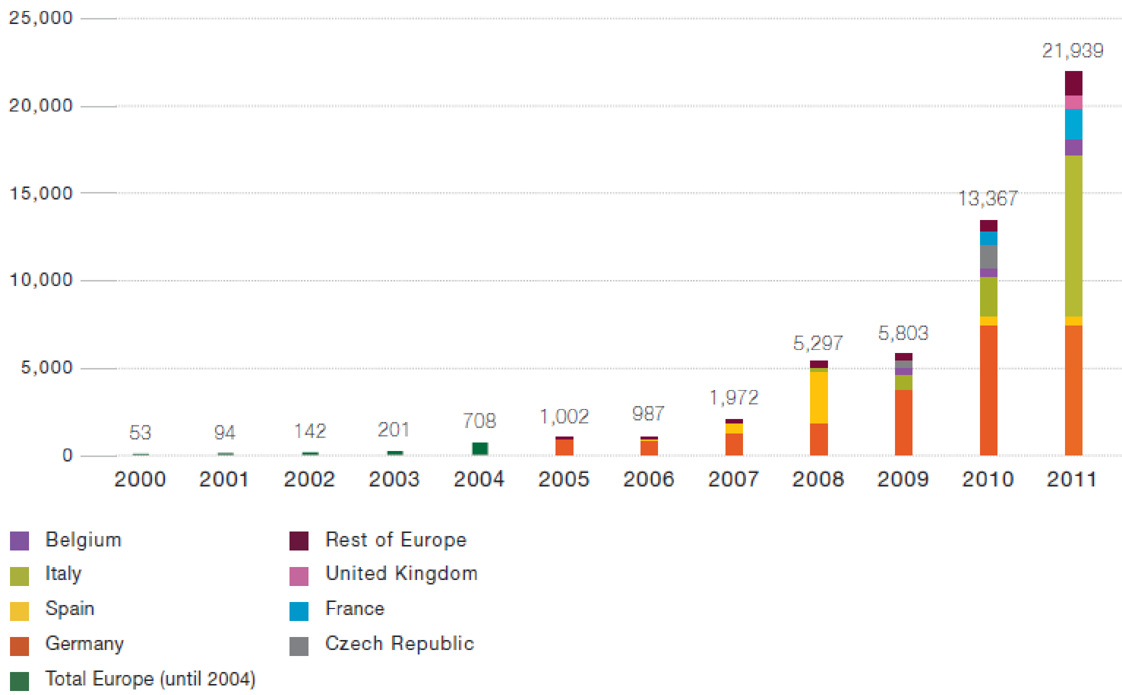

Fig. 1.2 Evolution of new grid connected PV systems in Europe (MW) [2]

In Europe the on-grid capacity is far higher than the off-grid PV capacity of just 1% of the PV installed capacity. But in countries such as USA, Australia and Korea the off-grid capacities come to several megawatt and so considered to play a significant role in the penetration of the solar energy into the total energy market [2].

During 2011 considering the market scenario and energy demand, the contribution of the installed PV capacity to the total electricity demand in Europe is 2%. A clearer picture can be drawn from the Fig. 1.3 given below.

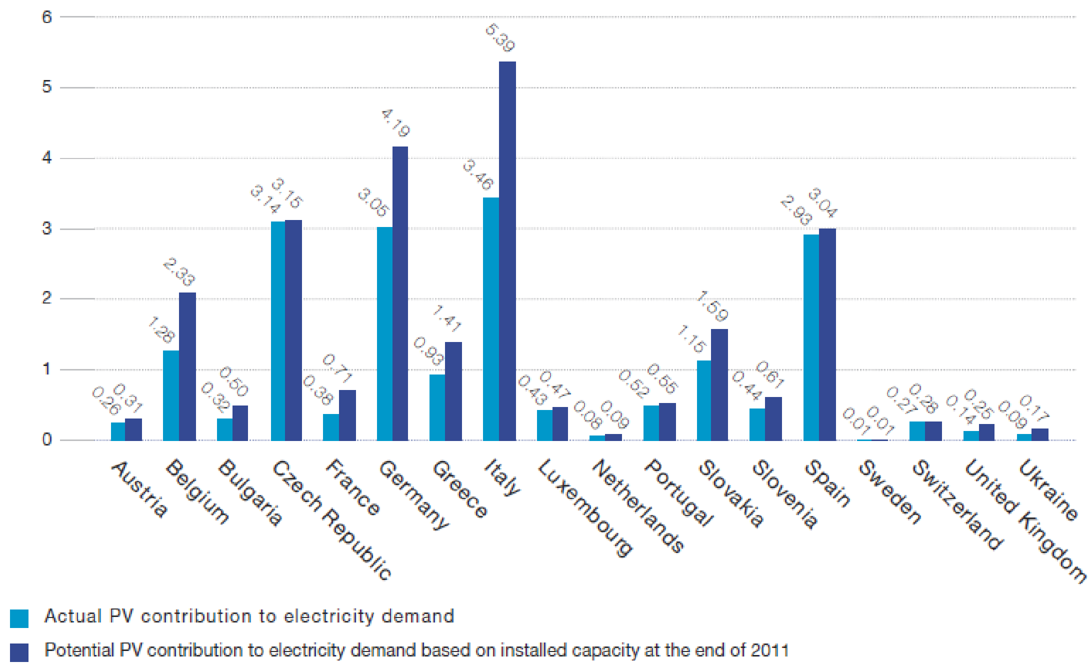

Fig. 1.3 Actual vs. potential PV contribution to electricity demand in 2011(%) [2]

Fig. 1.3 shows what was mentioned earlier, that is Italy and Germany lead the PV race, whereas Belgium, Czech and Spain also show quite impressive numbers. The possible amount of PV contribution to the electricity demand is higher than the current contribution and has not achieved by most of the countries except Czech Republic. For Czech Republic the possible % of contribution from PV towards the electricity demand based upon the installed capacity is 3.15 % in which 3.14% is right now their actual contribution. In case of Sweden, the numbers are not so good and even described as an underestimated PV potential by EPIA. The cumulative installed capacity of PV systems in Sweden by the end of 2011 is just 15 MW and for the year 2011, the annual installed PV power is 3 MW.

Although by the end of 2011, the contribution of PV towards the global electricity demand is 0.5% and towards the peak power demand is 1%, future looks quite promising [3]. Due to the decrease in the PV cell manufacturing costs as compared with the previous years, more and more positive efforts are coming to promote solar energy. So a better R&D and more support schemes by the governing bodies can help this renewable energy source to become a fair player in the world energy market.

1.1 Project objective

The high penetration of PV power into the existing electricity grid demands more study and analysis to enable safe and secure operation. There are several issues pertaining to this. One of the major concerns is the impact of the PV system in the form of overvoltage that can result in voltage fluctuations. Another issue is the impact of one PV system to another PV system as well as its impact on the grid operations. Since the production of solar energy depends upon weather, location and vary over time, PV system impact on the peak demand and energy consumption can also be an area of interest. In order to reduce the impact of PV system on the grid operations several rules termed as grid codes are formulated and issued in countries such as Germany, Spain, Italy etc. that are necessary to be followed during grid connection. Mainly these grid codes are issued for those PV systems which are connected at least to the medium voltage power grid. A more detailed description on grid codes is given in the coming Chapter 2.

The project aims to address and analyze some of the above discussed issues such as voltage fluctuation problems, impact on grid operations etc. For such an analysis and study, a very realistic PV system model which can give more realistic results is required. One of the very well-known PV system model available within the Power industry software is in Power factory. The Power factory model complies with the German Grid code and is simple in terms of design. Another model available in PSCAD is a very detailed model and the simulation using that is a time consuming process. So a much more realistic and detailed model complying with the standards in terms of design in Power factory is the expected outcome of the project. The developed model is then used for utility grid connection studies. The results are then compared with the existing model results available in PSCAD.

When the term Photovoltaic system is mentioned, it consists of two main conversion systems. One is the conversion of solar energy to DC power and the other is the conversion of DC power to AC power. Based on this, the PV system model realization is divided into two main parts, the DC side design of PV system and the inverter controller design that can also be termed as the AC side of the PV system. DC side design includes PV panel modeling as well as the execution of the Maximum Power Point Tracking (MPPT) algorithm which ensure maximum system output power. Converter controller should include various control mechanisms such as DC voltage regulation, AC voltage regulation, Reactive power control, Active power control etc. PV panel and MPPT tracking modeled in another project [20] will be used for the new model in Power factory.

1.2 Project outline

- **Chapter 2** is used to give a brief overview about the general Photovoltaic system as well as electrical characteristics of PV cells. Then an overlook on the inverter technology employed within the PV system is done and finally concluded with the explanation of existing German grid codes.

- The main idea of the project is to create a new PV system model in Power factory and its comparison with the existing model in PSCAD, so it is necessary to be familiarized with the existing PV models. Through **Chapter 3** it is possible to get introduced to the existing PV models in Power factory and PSCAD. A comparison between the existing PV models is also done towards end.

- **Chapter 4** is dedicated to explain about the new PV model in Power factory. It starts with the introduction of the new PV system model diagram in Power factory. Then a more detailed explanation on the DC to AC conversion using PWM technique can be found. This is followed by a familiarization of the PWM converter available in Power factory. Then the control frame of the new model is introduced along with its control technique implementation. Several control methods are employed in order to ensure safe, stable and flexible grid connected operation of the PV system and to regulate the AC power out of the PWM converter. DC voltage regulation, AC voltage regulation, reactive power regulation based on power factor control, active power controls etc. are the controls implemented in the new PV system model. Finally the new PV system frame is explained along with the PV panel, MPPT models and the converter controls to give a complete picture of the new model. For the new PV model development one of the important tasks is to model the PV panel so that the DC output is equal to the actual values of any PV module. Also it is necessary to understand the Maximum Power Point Tracking (MPPT) algorithm and to implement it on the DC side of the PV system. A detailed explanation about the PV panel modeling and the MPPT algorithm can be found in project report [20].

- **Chapter 5** is assigned for the analysis and result comparison between the existing PV model in PSCAD and the newly created PV model in Power factory.

- **Chapter 6** ends the project report with the description of the conclusions drawn from the study and the prospect of the future work possible within the new PV model.

1.3 Project contribution

- ✓ A new PV model in Power factory which can be used for PV system and grid studies.
- ✓ Controller with AC voltage regulation, reactive power control with three different control strategies, active power control etc. is available.
- ✓ DC voltage regulation with two different controller designs is studied in detail.
- ✓ The controller is flexible and can be used along with static generator or PWM converter as per requirement.
- ✓ A detailed comparison between the PSCAD model and the new model developed in Power factory is performed to determine the strength and weakness of both the models.

2. Photovoltaic system

Photovoltaic cells are made of semiconductor materials which have four valence electrons in the outer shell. The most widely used semiconductor for making the PV cells is Silicon. In case of semiconductors the conduction band is empty but the band gap between the conduction band and the valence band is very low. Because of low band gap the easy lifting of electrons from the valence band to the conduction when hit by the charged photons is possible. This phenomenon which is termed as the photovoltaic effect is used to generate the current in the PV cells and is depicted in Fig. 2.1.

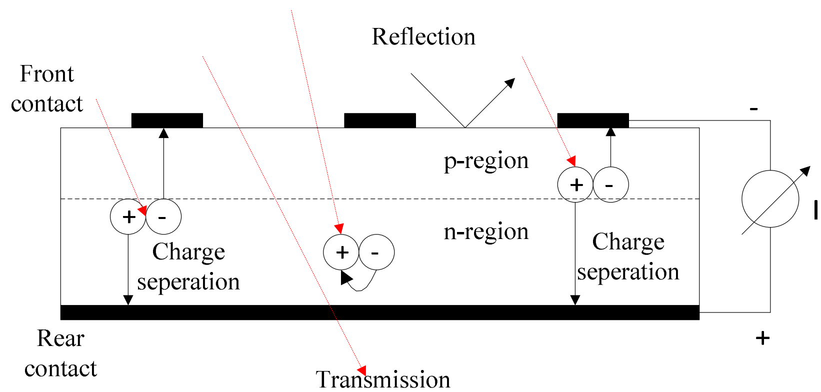

Fig. 2.1 Processes in an irradiated solar cell [3]

2.1 Electrical characteristics of PV system

Equivalent circuit with a single diode is the most popular PV model that describes the characteristics of the photovoltaic system and is shown in Fig. 2.2. The behavior of a non-irradiated solar cell is very much similar to that of a diode. The diode based model with a controlled current source can be used to predict the behavior of the PV system under various levels of irradiation, temperature and load conditions. The series resistance R_s represents the voltage drop during the transfer of charge carriers from the semiconductor junction to the external contacts. The parallel resistance R_{sh} represents the leakage currents at the cell edges. With the variation of irradiation and cell temperature, there will be considerable change in current and voltage which results in the increase or decrease of PV cell power output. It is very much essential to set the PV system to function at MPP (Maximum Power Point) to deliver the maximum possible power and the below model can be used to design, the MPPT (Maximum Power Point Tracking) function, inverter sizing and its control.

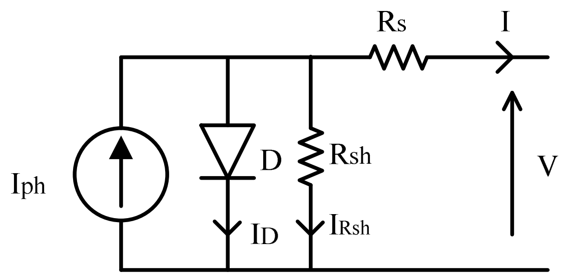

Fig. 2.2 Single diode equivalent circuit of a photovoltaic cell [4]

While describing the I-V characteristics of the PV system, three main measurement points as well as the obtained values are important to be mentioned. They are 1) MPP 2) Short-circuit measurement and 3) Open circuit measurement.
MPP is the Maximum Power Point at which the photovoltaic system delivers the maximum power for a particular irradiance and temperature, from which the voltage at MPP, V_{mpp} and the current at MPP, I_{mpp} can be obtained. Short circuit measurement with a zero voltage can give short circuit current, I_{sc} and the open circuit measurement with a disconnected load can provide open circuit voltage, $V_{oc.}$ All these measurement points can be identified in Fig. 2.3.
The typical I-V and P-V characteristic of the solar cell at Standard Test Conditions (E=1000 W/m2, θ=25 degrees, AM=1.5) is shown in Fig. 2.3.

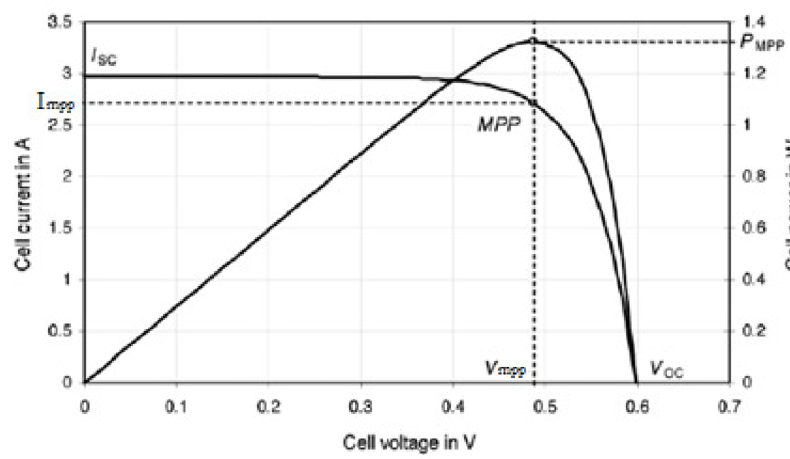

Fig. 2.3 I-V and P-V characteristic of a PV cell with MPP [3]

It can be noticed from the above figure that the value of V_{mpp} is lower than the value of V_{oc} and also the current at maximum power point, I_{mpp} is lower than the short circuit current, I_{sc} . At a particular irradiance and temperature, the cell efficiency while the operating voltage and current are V_{mpp} and I_{mpp} respectively is higher than the cell efficiency at any other operating point.

The voltage and current dependence on the change of irradiation and temperature for general PV cell is shown in Fig. 2.4 and Fig. 2.5. It depicts that the cell voltage has higher temperature dependence whereas the current has got higher irradiance dependence which will also result in the change of MPP.

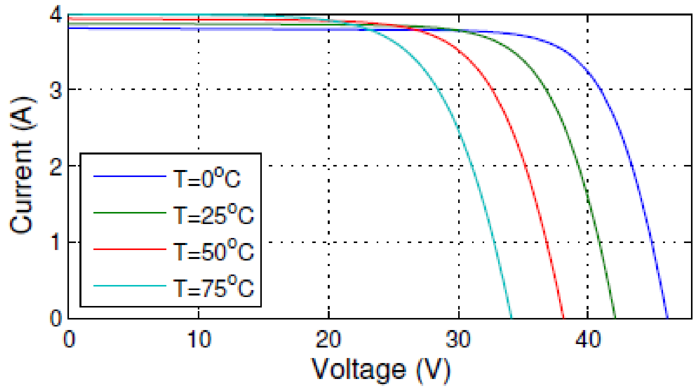

Fig.2.4 Temperature Dependence of Solar Cells [4]

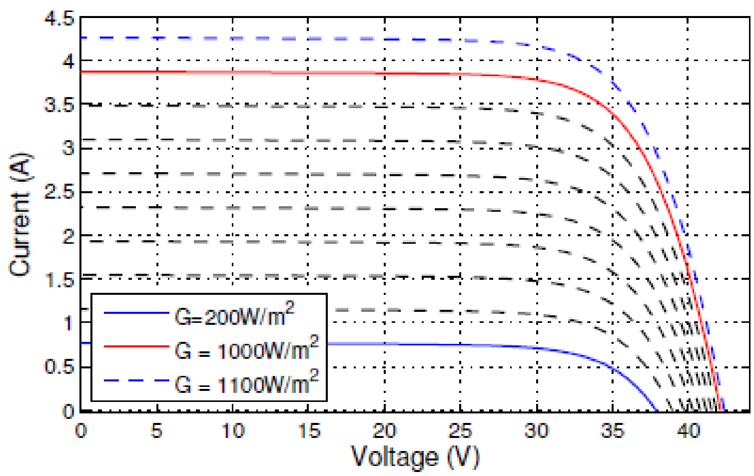

Fig.2.5 Irradiation dependence of Solar cells [4]

2.2 Types of PV systems

There are two major ways in which the photovoltaic system can be implemented for an application

2.2.1 Stand-alone systems

This system can be for a domestic or non-domestic application. Mostly for domestic application there will be battery storage which can act as a hybrid system in order to ensure continuous power supply in case of no irradiance. Off grid domestic application usually are of 1 kW in size and can provide electricity for lighting, refrigeration and other low power loads [15]. Non-domestic application first comes in the form of terrestrial PV systems and later implemented for telecommunication, water pumping, navigational aids etc. In these cases even for small power generation there is a considerable value and is implemented as a better choice than any other power generation method. Stand-alone system can be turned into a more reliable system when combined with wind turbines, diesel generators, battery storage etc. to form a hybrid system and implemented in several applications [15].

2.2.2 Grid connected systems

As the name indicates these are PV systems connected to the utility electricity network and can be distributed or centralized in nature. The distributed PV systems mostly are of roof mounted, can supply power to the grid connected customer or directly to the grid and will be connected to the low voltage transmission network. To be grid connected, a roof-mounted 1 MW PV system is considered to be large enough according to the PV standards [15]. Centralized systems usually are of higher power rating, usually more than 1 MW and normally connected with the medium or low voltage transmission network depending on its rating. These systems are mostly ground mounted and are equipped to supply the maximum power to the grid satisfying the grid codes.

Since the project discuss the grid connected PV system in particular, a brief description about the basic components of such a system is given in the coming section.

Grid connected PV system components

A grid connected system can be divided into two major sections which is the solar power conversion unit and the interfacing unit.
The power conversion unit comes with the solar panels, mounting equipment, DC-DC converters (if necessary) and DC cabling, which helps to convert the solar energy into useful DC power. Next is the inverter which will convert the generated DC to AC and falls in to the interfacing area of the PV system. The interfacing unit plays an important role in the dynamic behavior of the PV system and needs to be designed with special care. Finally using the AC cabling the PV system will be connected to the low or medium voltage transmission grid through an LV/HV transformer. LV/HV transformer acts as an isolation transformer and can be used for voltage adjustment if required.

2.3 Inverters

Inverters are used in a photovoltaic system to convert generated DC power into the useable AC power and to connect PV system to the AC grid. These kinds of inverters are usually fully synchronized in voltage and frequency with the grid. The inverters ensure that PV system should always operate at an optimal power point. For this purpose a special MPPT (Maximum Power Point Tracker) control is used with the PV inverters. The controls ensure that at different operating points because of variable environmental constraints, system will operate on maximum efficiency.

2.3.1 Functions of inverter

When the focus is on the power electronics function of the PV inverter, all the additional constrains like safety, efficiency etc. are ignored. Then the PV inverters can be evaluated with the following basic functions as specified [9].

1. Maximum Power Point Tracking (MPPT)

The inverter controls the DC voltage in order to ensure that the PV system always operates on the point where it gives the maximum possible power point. This MPPT (Maximum Power Point Tracker) function is very important as it is the main factor of efficiency of the PV system. PV system should adapt with the environmental conditions like solar irradiance, environmental temperature and shading conditions, and must shift the operating point to maximum power if any of the above mentioned parameters changes in the system.

2. Grid interface

This is the most important part of the grid connected PV inverters. Usually, Voltage Source Inverters (VSI) is used for the connection of PV generator to the AC grid. This type of inverter has buck characteristics (output AC voltage is always less than input DC voltage) and is connected using a transformer (inductor). There is transformer-less topology exists in the market; which will be explained later in this chapter.

3. Power decoupling between AC and DC side

The power fluctuations between AC and DC side have to be adjusted by some energy storage device which can provide uninterrupted power flow in the system. In this prospective, electrolytic capacitors can be used to provide power decoupling. These electrolytic capacitors form the DC link, and the capacity of this link is very critical with respect to the life time of the inverters.

4. Galvanic isolation between input and output

There are two different types of topologies i.e. with or without galvanic isolation that can be implemented in PV systems. In the first method a proper galvanic isolation is provided, on the other hand there is no isolation in the later method.

a) Conventional transformer with galvanic isolation

Most commonly used method for galvanic isolation is using the conventional transformer operating on grid frequency. This is a tried and tested method and is being used right from the start of the PV technology. But this has some disadvantages like high weight, high cost, additional losses and non-unity power factor. In this topology, MPPT is performed by the main inverter as shown in Fig. 2.6. By controlling AC current the power that is fed into the grid can be controlled [9].

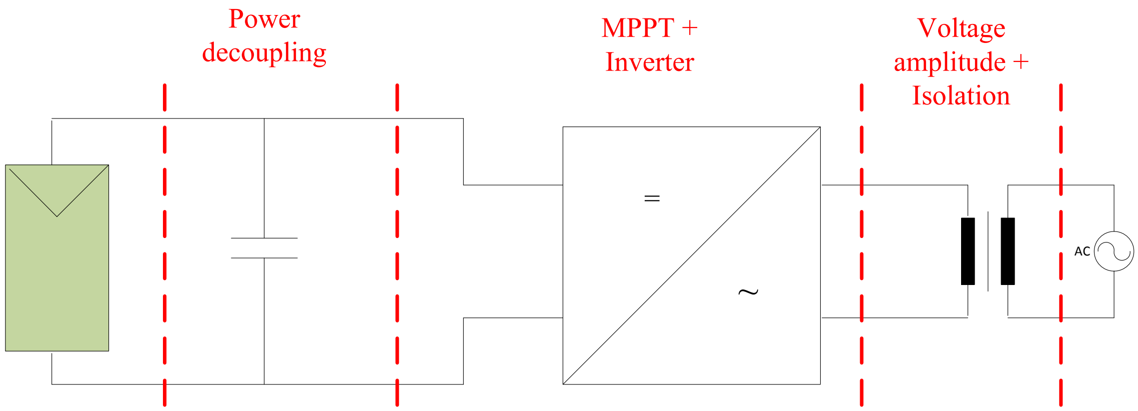

Fig. 2.6 Conventional transformer isolation method [9]

When there is a change in the AC side power of the inverter due to any disturbance in the grid, the DC link capacitor gets charged or discharged which varies the voltage at the DC-link capacitor terminal.

b) High frequency DC-DC converters without galvanic isolation

Due to various drawbacks of conventional transformers, there arises a need to search for an alternative method for galvanic isolation. As a result, `high frequency transformer topology emerged as a new method that does not have any isolation. This method uses high frequency DC-DC converter and does not have any transformer in the system. MPPT and change of voltage magnitude is performed by DC-DC converter. PV system with DC-DC converters are shown in Fig. 2.8 [9].

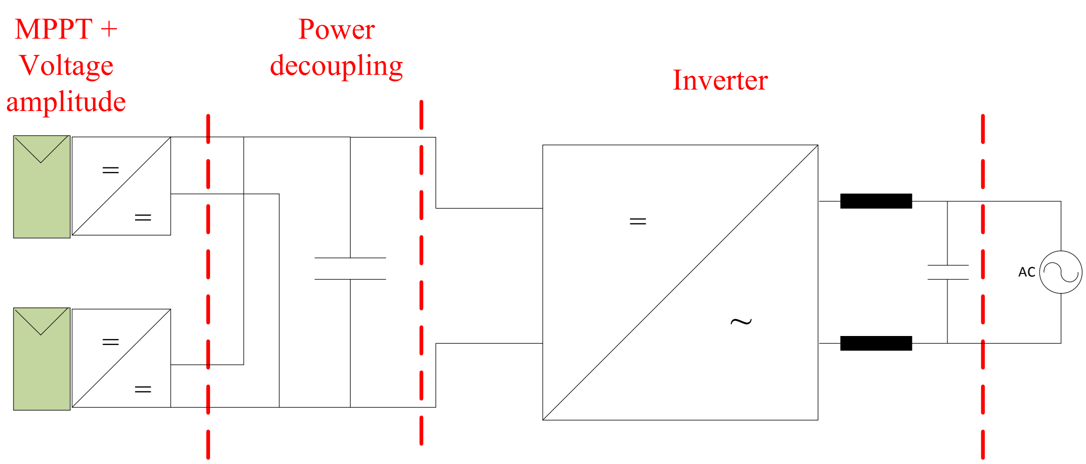

Fig. 2.7 DC-DC converter topology without transformer [9]

Transformer-less topology as shown in Fig. 2.8 is an upcoming technology, and is in development stage. There will be no transformer in the system and switching is done by IGBTs used in the form of a bridge. Neutral conductor of AC side connected to inverter is grounded. This technology is an emerging one as it has less overall losses, lighter in weight and cheaper than conventional grid frequency transformer topology. However there would be some switching losses in this method. In addition, topology without transformer increases the control over the system voltage and power since transformer limits the control of the grid current. When there is no special need of galvanic isolation then this topology is simple, efficient and cheap to implement.

There are still many challenges involved in this type of method due to grounding current problems and safety hazards issues generated due to leakage problem. This demands the need of a special measurement facility for the current. If safety and EMC aspects are considered, current flowing through the earth has to be limited and can be considered as the biggest challenge in this technology. Special Residual Current Devices are used in the inverters to monitor ground leakage current in this respect [9].

2.4 PV system configurations

Generally PV system configurations can be classified into two different categories

I. With respect to the phase configuration of the inverter AC side
II. With respect to the connection of inverter with the PV array and grid

2.4.1 With respect to the phase configuration of the inverter AC side

According to the phase configuration of the inverter AC side, there are single phase and three phase inverter used PV systems.

a) Single phase inverter used PV system

Single phase inverter based PV systems are used for applications like a roof top of a house or office. These types of PV systems are usually available up to 5 kW of rating.

b) Three phase inverter used PV system

Three phase inverter based PV systems are with power rating higher than 5 kW and are usually grid connected. Three phase converters are practically implemented in the PV system using three single phase converters connected to each load terminals. This is because for a three wire topology relatively higher DC voltage value (around 600 V for a 400 V three phase grid) is required and is limited to 1000 V due to safety reasons in installation procedures [8].

2.4.2 With respect to the connection of inverter with the PV array and grid

Depending upon the way in which the inverter, grid and PV array are connected, PV system can be configured in four general ways. There are central inverter, string inverter, multi string inverter and AC module inverter configurations, shown in Fig. 2.8.

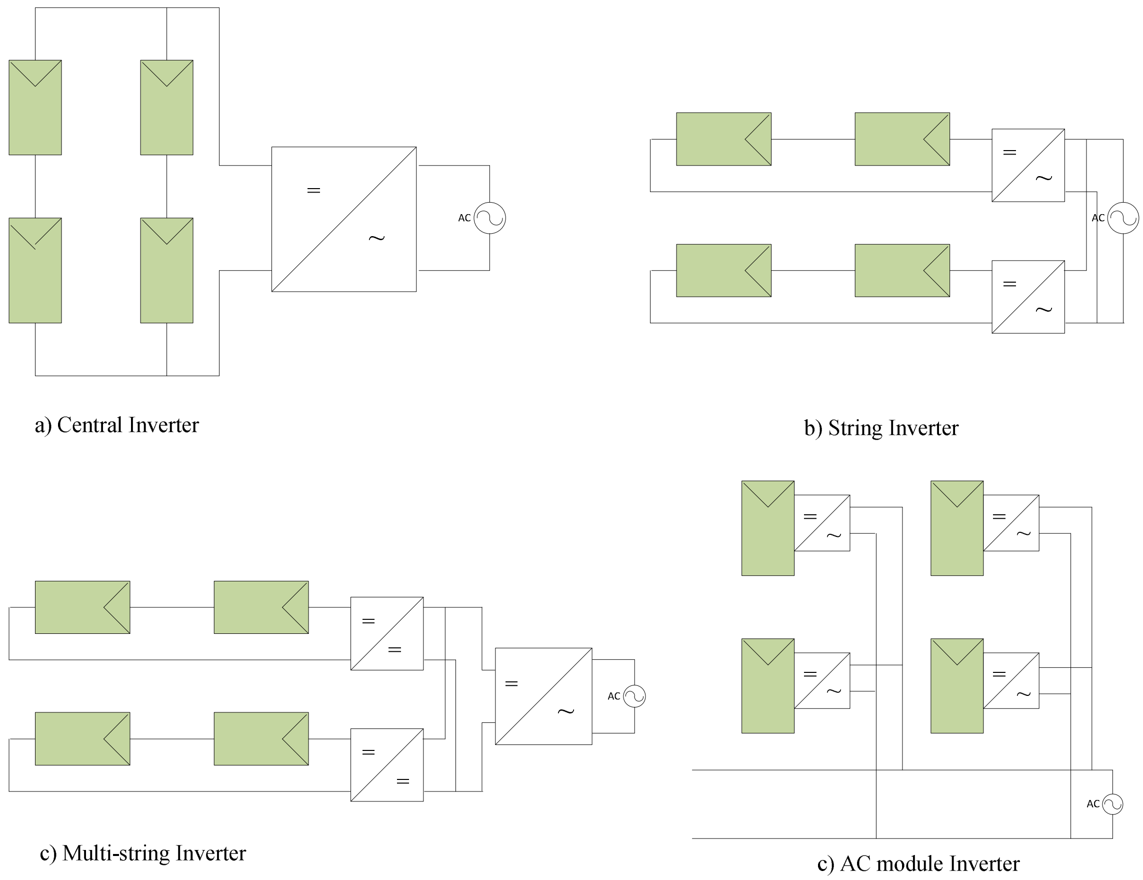

Fig. 2.8 Different configurations for PV system [9]

a) Central inverter configuration

PV modules are connected in series and parallel to get the desired power level and are finally connected to a single converter at the end. Series connection of modules is called a string. This kind of inverters has enough voltage at its DC side i.e. from 150 V to 1000 V and there is no need to use an intermediate DC-DC converter to boost the DC voltage up to a reasonable level. It is available in several kW to 1 MW range of power and can be used for almost all levels of voltage applications.

Central inverter has got the advantage of high inverter efficiency at a low cost per watt. As efficiency is one of the major concerns in the PV system, central inverter based PV system configuration is a better economical choice. Since a single converter is used, this configuration has low total harmonic distortion (THD) losses in the system. Therefore it is the first choice of medium and large scale PV systems. Central inverters are mainly built with three phase full bridges with IGBTs and low frequency system [9]. The structure of the central inverter is shown in the Fig. 2.8 (a).
This kind of inverter configuration has got several disadvantages. With the small roof top application, central inverter based configuration can result in mismatching losses between the modules of string [9]. Also this configuration has high losses in the DC cables. If the inverter

trips, the whole generation is out of the system. Shading effect due to variable irradiance in the system can make it a bad choice within the PV system configurations.

b) String inverter configuration

For those applications where different panel modules cannot be operated on the same orientation as well as the system is subjected to different shading conditions, string inverter configuration is the best choice [9]. As shown in Fig. 2.8 (b), this type of configuration does not have any parallel connection. Each inverter is responsible for each string having its own MPPT control. When the PV array has many strings and each string is different from others in configuration then string inverter configuration is ideal to be employed. This arrangement facilitates to use it under the constraints like different orientation of the parts of the roofs, different shading conditions and types or number of modules in each string. String inverter configuration based PV systems are available from 0.4 kW up to 2 kW of power [9].

String inverter has higher price per kW as compared to central inverters because of its low power per unit. Mostly string inverters are used in low power application with single phase full bridge topology with a low frequency transformer on the AC side for isolation.

c) Multi string inverter configuration

This type of configuration is another type of string inverter configuration with additional DC-DC converter for each string. Basically there are string inverters with two or more inputs. Each string having a DC-DC converter is used as the input to main DC-AC inverter as shown in Fig 2.8 (c). With this kind of arrangement, one can have high inverter power output without sacrificing the advantage of string technology [9].

Multi string inverter configured PV system has two main advantages. First one is that the user can have greater freedom with respect to the input voltage range of the converter because of the additional DC-DC converter. Second advantage is that by having separate MPPT control for each string it is more efficient than a central inverter configured PV system. Multi string inverter configuration has disadvantages due to two power conversion levels. This configuration has more power loss and less efficiency as compared to string inverters. Multi string inverter configuration comes within the power range of 1 kW to 6 kW [9].

d) AC module inverter configuration

With AC module inverter configuration, each module has its own inverter and MPPT control. Several module inverters are used to compensate the high power level as this inverter has lower power handling capability. In this case each inverter can be directly connected to AC grid that is why it is called an AC module inverter configuration. This type of inverter configured PV system is shown in Fig 2.8 (d).

The main advantage of this inverter configuration is that no DC wiring is necessary. Another advantage is that the risk of electric arc and firing is eliminated in this case. But the configuration has got low acceptance due to several disadvantages. Firstly it has low power per unit that leads to low efficiency and high costs. Secondly, this type of inverter technology does not reach the life time of the PV modules [10].

2.5 Important factors to be considered for PV inverter

There are some inverter constraints that should be kept in mind while selecting an appropriate inverter for a PV system. First of all efficiency of PV inverter is most important, since inverter is the interfacing part of the PV system. Inverters are prone to AC as well as DC side disturbances. Any reduction in the inverter efficiency would straight away cause reduction in the overall efficiency of PV system. A PV array normally operates at its rated power for only few hours in a year, because of changing solar irradiance. Due to this condition an inverter predominantly operates under partial load state. Generally the efficiency of inverter increases with increase in its power rating. So it is necessary to determine the inverter efficiency based upon the operating period and conditions.
Euro efficiency or European efficiency of PV inverters is an analytical method to compare the efficiencies of different inverters, and can be expressed by the following equation [13],

$$\eta_{EURO} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.1\eta_{30\%} + 0.48\eta_{50\%} + 0.2\eta_{100\%} \qquad \text{--- (2.1)}$$

The $0.03\eta_{5\%}$ factor means that inverter is operating at 5% efficiency for a period of 0.03 time period out of the total operating time period. Above equation considers amount of time in percentage that the PV inverter is expected to work at partial loads or at different levels of irradiation.

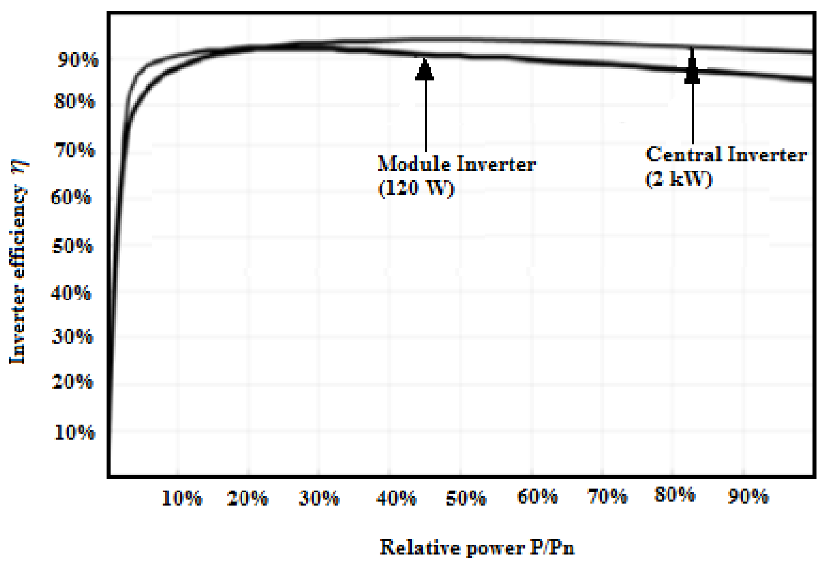

Fig. 2.9 Efficiency over a range of relative photovoltaic generator powers [13]

Another aspect to be considered for PV inverter is anti-islanding protection. The inverter should get disconnected from the grid in case of emergencies to avoid any kind of accident**.** Also the harmonics in the output power supplied by the inverter to the utility should be minimized as much as possible, since these harmonics can cause distortion in the grid voltage and current. Power quality can be improved by minimizing these THD (Total Harmonic

Distortion) contents from the grid voltage. Finally the PV inverter should be compatible with the PV array such that the inverter can perform the MPPT operation efficiently. It should also be able to adjust with the dynamics of the MPPT operation during irradiance changing conditions.

2.6 Grid Codes

Grid connected photovoltaic systems should comply with the grid or the utility requirements for a safe and steady operation. Nowadays it is getting very difficult for the manufacturers and the developers to comply with all these various requirements put forward by various bodies. There are different type of documents like national standards, grid codes, company regulations or rules etc. which will at the end confuse with regard to its realization and compliance. There are several initiatives taken by various organizations to get a unified grid code at least in the European Union and the most notable are as follows [7]:

- European committee for Electro-technical standardization (CENELEC)
- Network of excellence of DER laboratories and pre-standardization (DER-Lab)
- International white book on the grid integration of static converters
- Address project: Active distribution network with full integration of demand and distributed energy resources
- EU-DEEP: The birth of a European distributed energy partnership

Even though the photovoltaic system has not reached a level where it can compete with other conventional energy sources, PV systems with its advanced stage of installation and manufacturing exist in Germany, Italy and Spain. All these countries follow their own grid codes and those are not so uniform. In order to avoid further complications, all the European country specifications are recommended to comply with the European standards [7]:

- EN 50160:Voltage characteristics of electricity supplied by public distribution systems
- EN 50438: Requirements for the connection of micro-generators in parallel with public low-voltage distribution systems

German grid code is found to be used as a reference code for various studies and is the most updated one. So in this section the various requirements that the grid connected PV systems should follow during its installation is presented mainly based upon the German grid code. Existing renewable plants connected to the low and medium grids mostly do not contribute much to the grid stability. But according to the current guidelines PV plants or renewable plants connected to the grid should support the grid to maintain its stability and may also remain connected to the grid during fault. Some of the major and should be mentioned requirements are described in the following sections.

2.6.1 Dynamic grid support

Fault ride through which can also be termed as Low Voltage Ride through (LVRT) is the capability of any electric system to remain connected to the grid in case of temporary voltage drops or load change. So with the dynamic grid support the main aim is to obtain the LVRT capability for the renewable system, which is the PV system.

During LVRT, the system must be capable to carry out any of the following options:

- Remain connected to the grid
- Improve the voltage stability by providing reactive power
- Disconnect during fault and reconnect immediately after the fault clearance

The limiting curves of voltage for the renewable system is shown in Fig. 2.9

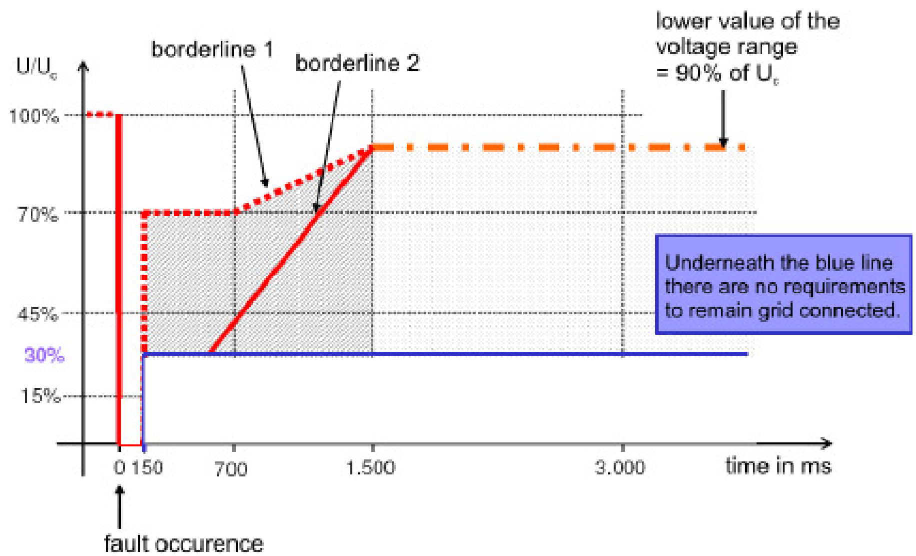

Fig.2.10 Limiting curves of voltage in the event of a network fault [6]

For any voltage drop of ≤ 150 ms, the PV system should not get disconnected from the system. During voltage dips above the borderline 1, the voltage stability will not get affected considerably and need not require a disconnection. When the voltage drop is between the borderlines 1 and 2 then the system must be capable of fault ride through. Once the voltage dip crosses the borderline 2 it is always allowed to have short disconnection and if necessary, longer disconnection as and when agreed by the system operator. There is no requirement for the system to remain connected to the grid if the voltage drop is below the blue line [5].

Next during the event of a network fault, how the voltage support of the renewable system connected to a medium voltage grid should happen is shown in Fig. 2.11. If the system voltage variation is within the dead band of ±10%, no reactive current support is required or enabled. This dead band is to prevent unwanted injection of reactive current. For a voltage drop of more than 10% of the network voltage, the system should support the grid by supplying reactive current, and is recommended to act within a time period of 20ms of the fault. The reactive current support can be even of 100% of the rated current during necessary conditions [5].

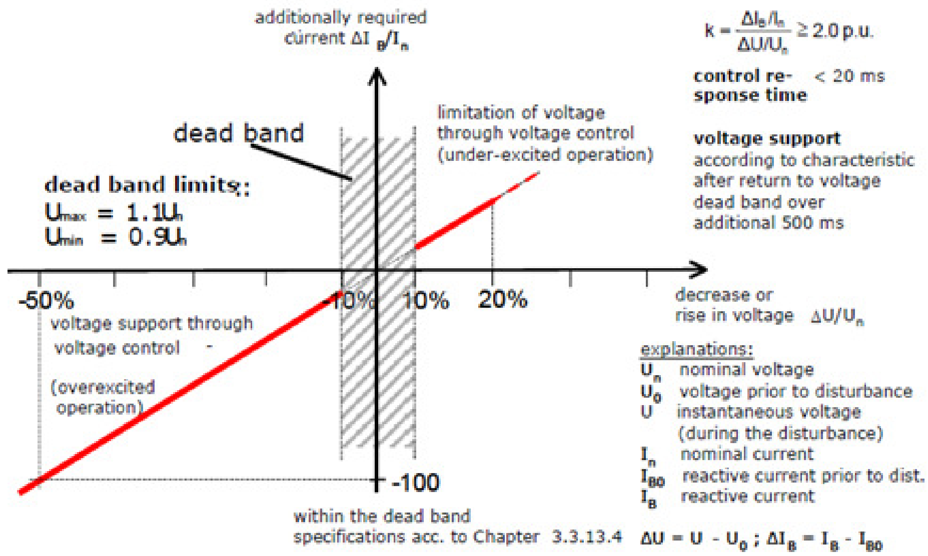

Fig. 2.11 Principle of voltage support at the event of network fault [5]

2.6.2 Active power output

The PV system is recommended to be capable of decreasing its active power output at any operating conditions as and when required by the system operator. These target values can be pre-defined by the system operator at the common coupling point. The active power output should change with at least 10% of the network connection capacity per minute without the disconnection of the plant from the grid [5].

In case of system frequency increase beyond 50.2 Hz, the active power output should reduce with a gradient of 40% of the generator's instantaneously available capacity per Hertz. Once the frequency reach back to ≤ 50.05 Hz then the active power output can be increased such that the system frequency will not exceed 50.2 Hz [5]. Fig. 2.12 clearly shows how the active power output control according to the system frequency can be designed and realized for a renewable system and in this case for the PV system.

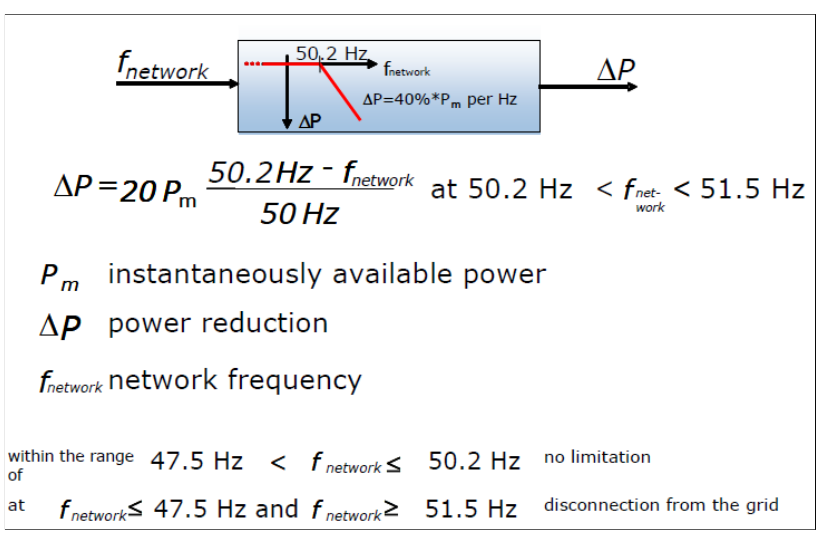

Fig. 2.12 Active power reduction in case of over frequency [5]

2.6.3 Reactive power supply

Current PV systems are designed to provide only active power. But even during normal operation there are possibilities of very slow or low voltage fluctuations in the system which is necessary to be kept within the acceptable limits. In order to ensure the same, the grid codes recommend the exchange of reactive power between the grid and PV system to a very limited extent. In case of PV system normally the inverters are oversized to meet the reactive power requirements [6].

A PV system can carry out the reactive power exchange based upon the three possible operations listed below [5]:

- Power factor based operation- can be constant or dynamic
- Fixed reactive power value(Q in MVaR)
- Variable reactive power depending upon the voltage, Q(U)

In case of constant power factor, the PV system will supply reactive power irrespective of the AC bus voltage. The dynamic power factor operation which is shown in Fig. 2.12 is such that the value of power factor and thus the reactive power varies with the change in active power produced, independent of the AC bus voltage. For the PV plants the recommended variable power factor operation is between 0.95 under-excited and 0.95 over-exited states [5].

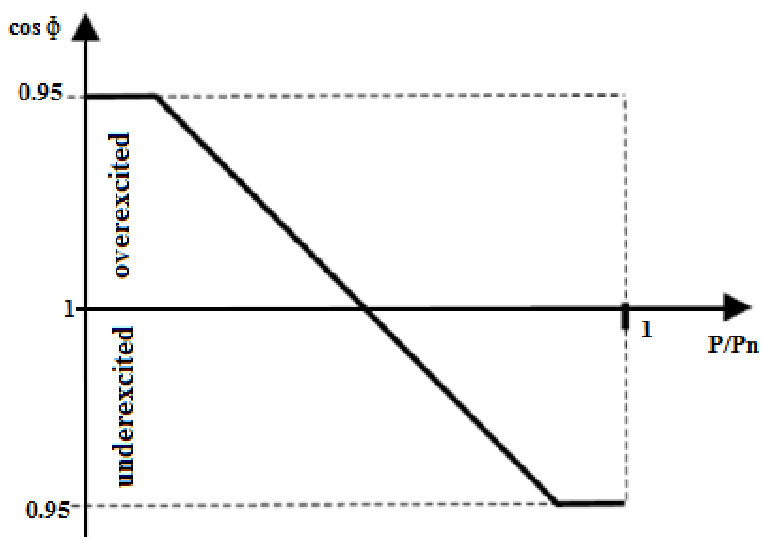

Fig. 2.13 Dynamic power factor operation characteristic [6]

3. PV system models in Power factory and PSCAD

A grid connected PV system without any battery storage mainly consists of a PV array and an inverter with its DC link capacitor as shown in Fig. 3.1.

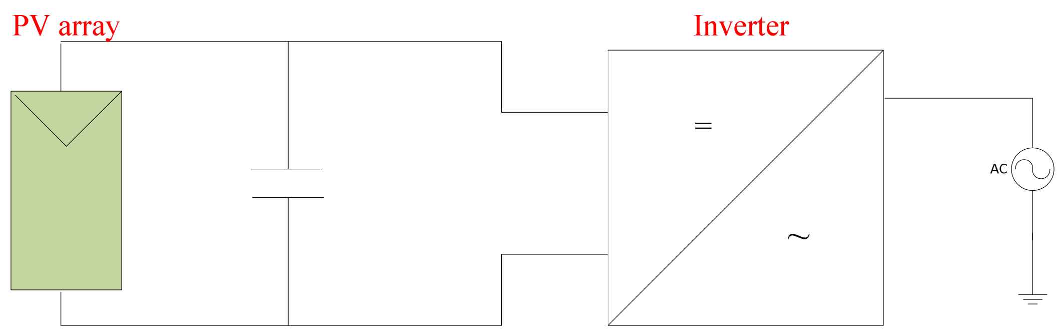

Fig. 3.1 Grid connected PV system model

So while modeling a PV system it is essential to model these basic components. The modeling varies from software to software depending upon the availability of components and requirements.

1. PV array

A PV array can be generally represented as a constant current source. At the same time in order to study the behavior of a PV system it is necessary to include the electrical characteristics of a PV module as discussed in section 2.1. So in almost all the cases the PV array will be modeled based upon PV equations. As shown in Fig. 2.2, a single diode equivalent circuit of a PV module based upon which a PV array equations can be formulated and modeled. Such a PV array model can behave like a realistic PV module, of which the output power varies with the change in system conditions such as change in irradiation, temperature etc. If the requirement is for a much detailed study of PV array, then the two diode based equivalent circuit can be used. So the final output of the PV array is calculated based upon different parameters such as irradiation, temperature, series resistance, parallel resistance, number of parallel modules, number of series modules etc.

2. Interfacing converter

The interfacing converter can be selected from different components based upon the working platform, Power factory or PSCAD. In Power factory the interfacing converter can be represented by a static generator or a PWM converter. In Power factory when the interfacing converter used is a static generator, then the entire PV system is represented by the same static generator. No need to physically represent or include the PV array or the DC link capacitor. So in this case the PV array, DC bus bar and capacitor can be modeled using DSL codes to get associated with the static generator. But in case of a PWM converter, PV array needs to be physically represented with a constant current source connected to a DC bus bar along with a

DC link capacitor. The two different ways of PV system modeling possible in Power factory are shown in Fig. 3.2.

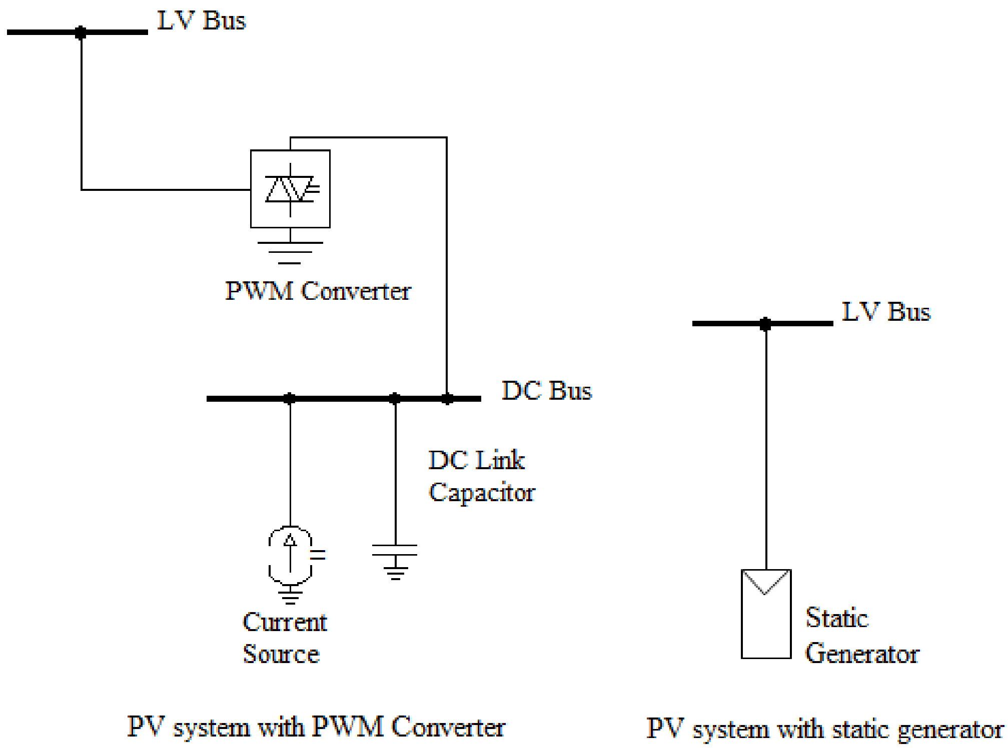

Fig. 3.2 Different PV system modeling in Power factory

In case of PSCAD there is no static generator available therefore an inverter needs to be modeled there. The PV system modeling in PSCAD is very similar to that of the PV system modeling using PWM converter in Power factory. With all these modeling techniques, it is possible to add extra controls with the interfacing converter such as MPPT, active power control, reactive power control etc.

In the Power factory tool there is a PV system module called the PV generator that is available for PV studies which is modeled with the help of a static generator. In PSCAD a PWM converter based PV system is developed and is currently available for grid studies. A brief look through these models is done in the coming sections.

3.1 Generic PV model in Power factory

The basic Photovoltaic system in the generic model is developed using a static generator. This PV system model is available in the newest version of Power factory tool in the form of a template. The template consists of a PV generator along with basic controls and design features. As the name suggests the model is generic and can be modified as per the requirement such as ratings, control etc.

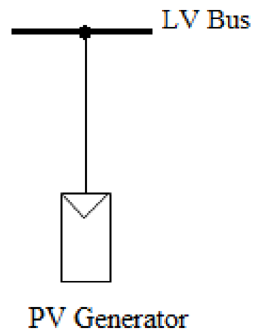

Fig 3.3 Photovoltaic template

3.1.1 Static generator

A typical interface window of the static generator is shown in Fig. 3.4. All values can be changed according to the requirement. The active power tab shows the power rating of the PV system which is the active power output out of the static generator.

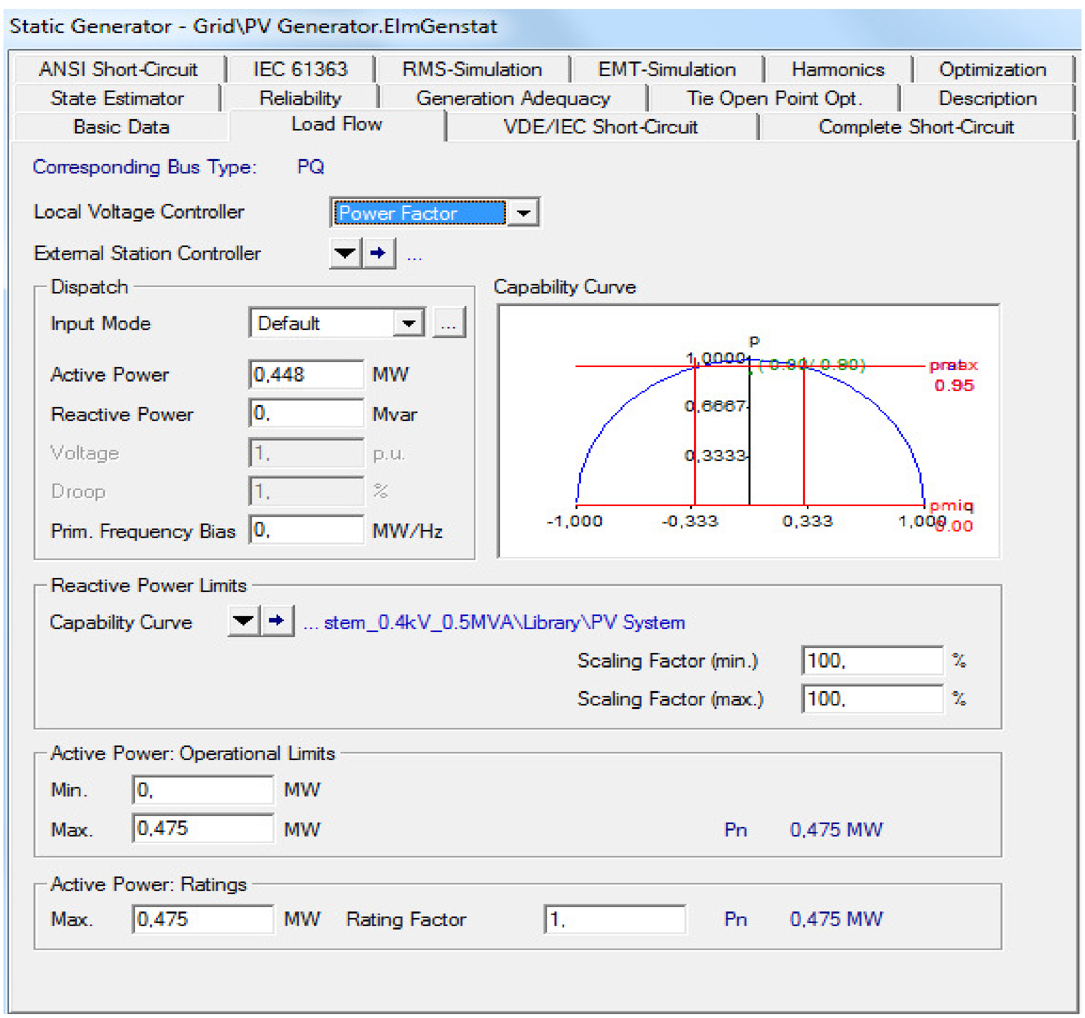

Fig 3.4 Static generator power flow under steady state conditions

The reactive power limits of the PV system are decided based upon the capability curve of the static generator shown in Fig. 3.4.

Capability curve of the static generator has active power on its Y-axis and reactive power is at X-axis. All the values are in per unit. The inverter cannot operate on maximum active and reactive power at the same time. Let's assume that the PV system is expected to work at 0.95 power factor. Then the capability curve of the PV system is shown in Fig. 3.5. The upper red line is the limit of the active power that can be transferred at 0.95 pf. The vertical red lines denote the limits of the reactive power transfer at one specified active power as shown as Qmax and Qmin in the Fig 3.5.According to the system operator, control system and the method used for reactive power control, the reactive power that is to be transferred is decided. The blue line denotes the power limit of the inverter. The inverter cannot operate outside its limit since it is limited by nominal power of the generator.

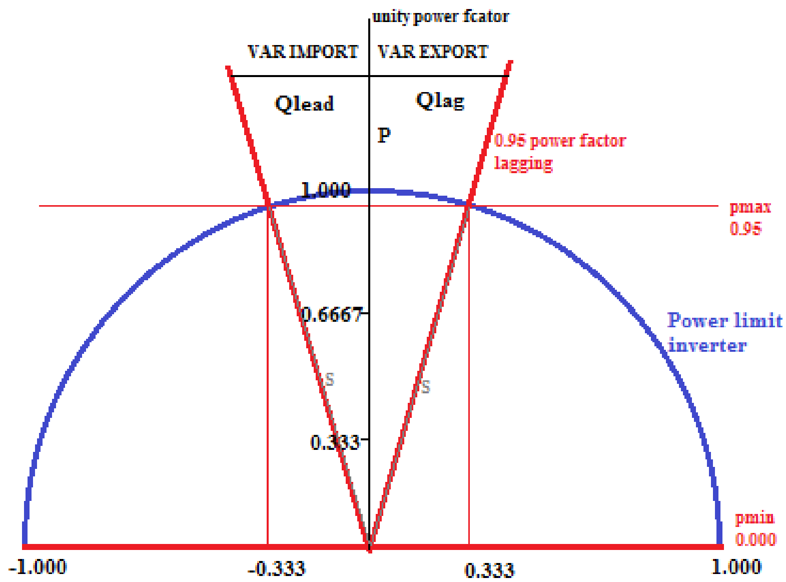

Fig 3.5 Capability curve of the inverter

3.1.2 Control frame of PV system

The control frame of the PV System in generic model is shown in Fig 3.6. As mentioned previously it is necessary to model the PV array, DC link capacitor dynamics by DSL functions. The same can be observed in the control frame and the main blocks will be explained in brief in the following sections.

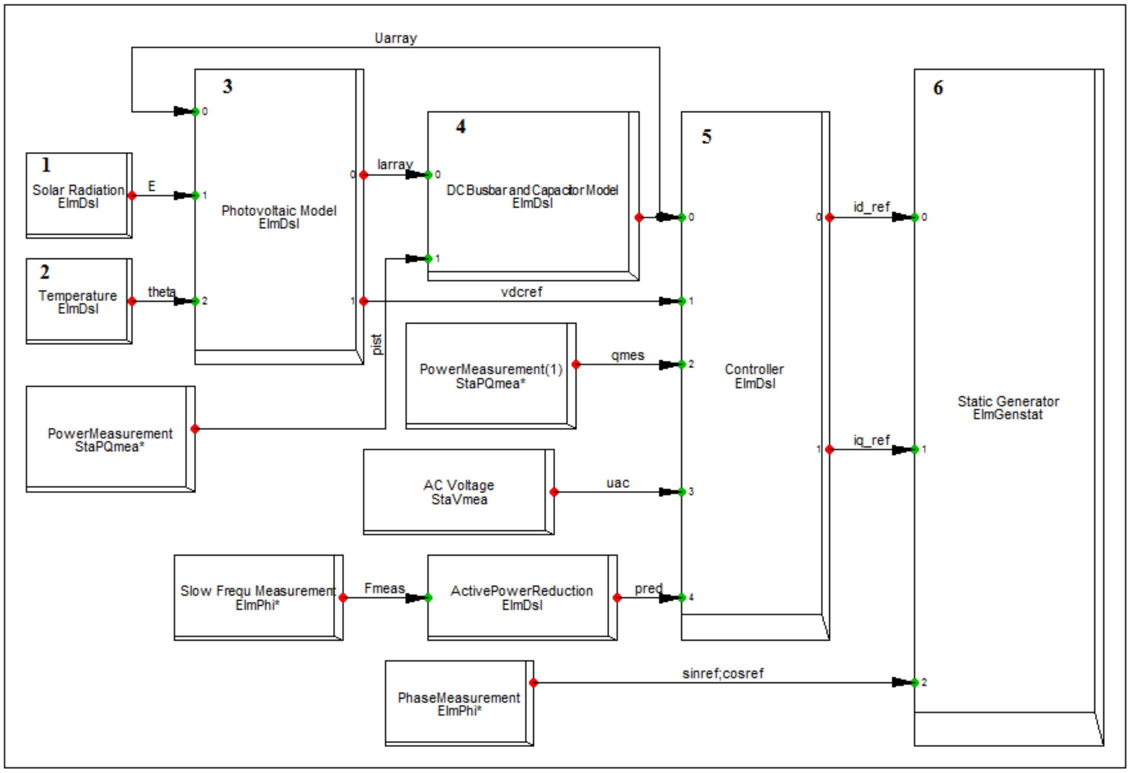

Fig 3.6 Control frame of PV system

Slot 1 & 2: Solar radiation & temperature

Solar radiation & temperature both are modeled as limited time integrators. The purpose of these slots is to accumulate all the changes i.e. change of irradiance per second & change of temperature per second and integrate them over a period of time. The output of these blocks is given to slot 3 which is the photovoltaic model.

Slot 3: Photovoltaic model

Photovoltaic model takes DC voltage, irradiance and temperature as the inputs. Based upon PV equations written as DSL codes, the PV array is modeled and provides array current and reference DC voltage as the outputs.

Slot 4: DC bus bar and capacitor model

This slot is the equation based modeling of DC bus bar and capacitor. With the help of this block the dynamics of the DC side capacitor is included in the PV system. This slot has two inputs i.e. one from the PV model in the form of array current and other from power measurement device in the form of active power signal. The output of the block is the DC voltage across the capacitor considered as the actual DC voltage, which is given as feedback to the PV module as well as the input to the controller.

Slot 5: Controller block

Controller is the one most important part of the PV system and the control frame is shown in Fig. 3.7. It is very much necessary to regulate the active and reactive power outputs of the static generator according to the DC side output of the PV system consisting of the PV array and the DC side capacitor. This purpose is realized with the help of the controller block. Block has four inputs and two outputs. DC voltage from the capacitor model as actual DC voltage, reference DC voltage from PV model, measured AC voltage and active power are the inputs. The reference values of the d-axis and q axis components of the currents in pu are the outputs of this controller. These currents values are given as input to the static generator, which is the interfacing converter.

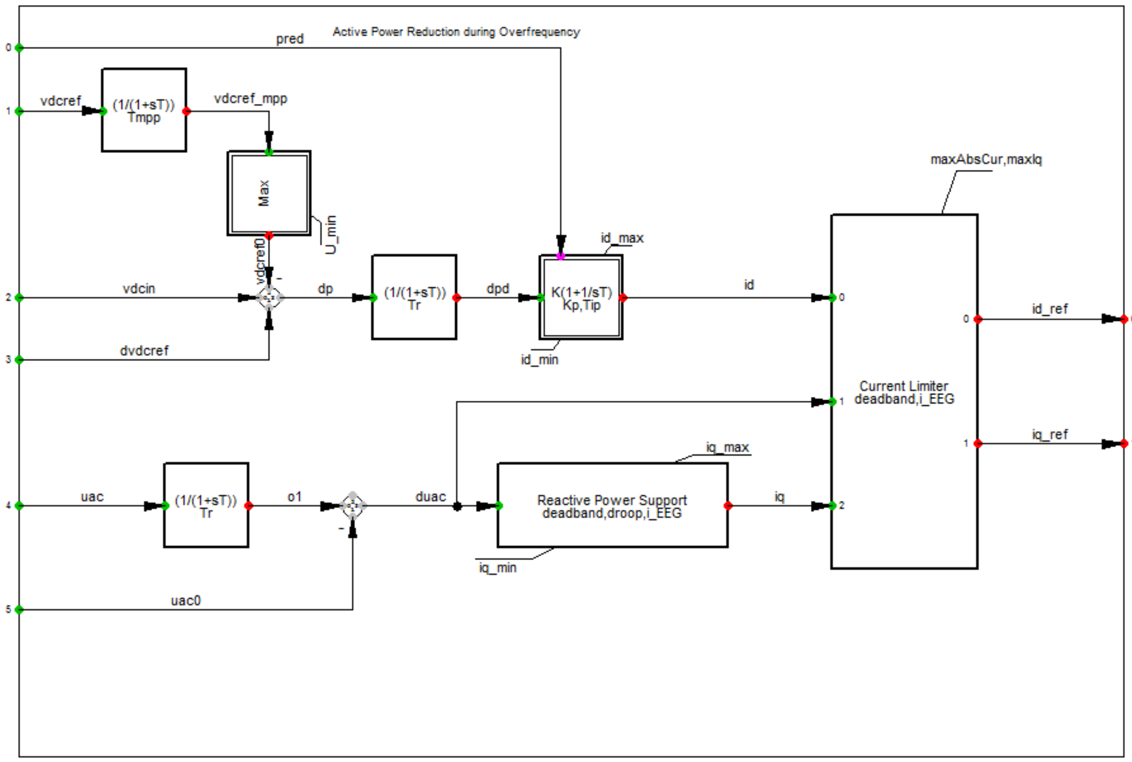

Fig 3.7 Control frame

The upper part of the control frame is the DC voltage regulation which is implemented to control the active power output of the PV system. The inputs are 'vdcref', 'vdcin' and 'dvdcref' and the output is the d-axis component of the reference current, id_ref. The lower part is the reactive power control. For the control the inputs are 'uac and 'uac0' and the output is the q-axis reference current component, iq_ref. Reactive power control is implemented in this model based upon a German grid recommendation shown in Fig. 2.11.

Slot 6: Static generator block

This block represents the static generator in the control frame. The additional inputs that are to be given to the static generator can be given to this block which is internally connected to the actual one. So the output from the controller block that is the d and q axis reference current components as well as the 'cosref' and 'sinref' values from the phase measurement unit are given to slot 6. Based upon which the output of the static generator is regulated.

3.2 PSCAD model overview

As mentioned early the second model currently available to study and understand the PV system behavior as well as grid behavior is in PSCAD software. The schematic diagram of the PSCAD model is shown in Fig. 3.8. The PV system is connected using an LV transformer to the Common Coupling Point (CCP) of the distribution grid. The main components of the PV system consists of PV arrays, DC-link capacitor, PWM Converter as well as external control systems.

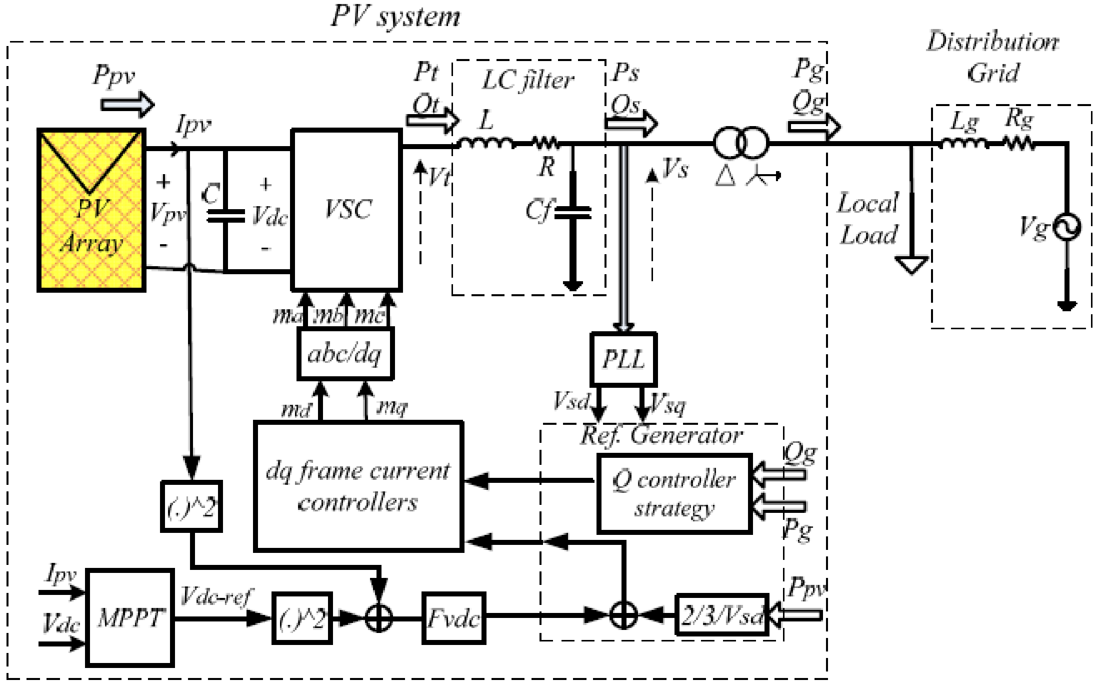

Fig. 3.8 Schematic diagram of the PV system connected to a distribution grid [14]

The PV array model in PSCAD can be chosen between a four parameter and five parameter based PV array design which makes the PV panel behavior very much close to a real PV module. The output of the PV module is given directly to the inverter in form of a current source and also to the MPPT block. MPPT function employed along with the PV array will ensure the maximum power output out of the panel at any operating conditions based on the irradiation and temperature. The MPPT algorithm employs two different methods, Perturbation and Observation method and Incremental Conductance method. Since Incremental Conductance algorithm is much faster and accurate out of two, the final choice of MPPT algorithm for the PSCAD model is Incremental Conductance.

As shown, the Voltage Source Converter (VSC) is connected to an LV transformer and finally to the CCP through the interface reactor, L and R. Here L is the inductance of the series reactor and R is the combined resistance of the reactor as well as the converter switches. Shunt capacitor filter, C_f is added to absorb all the unwanted low frequency current components coming out of VSC. The connection transformer will help to step up the voltage that is required in-order to connect the transformer to the distribution grid. Another function of the transformer is to act as an isolator between the PV system and the grid. Thevenin equivalent model of the distribution grid is used for the analysis along with equivalent resistance Rg and reactance Lg.

The output out of MPPT is used as the reference input voltage for the DC-voltage control employed. The DC-voltage control is introduced as a way to control the active power output of the PV system. Also it should be noted that the Phase Locked Loop (PLL) used will help to transfer the signals of abc or global reference frame to the dq-reference frame. It is known that the d-component is associated with the active power and q-component with the reactive power. So the active and reactive power can be controlled with the d and q axis components as well.

The control of reactive power is implemented in two different ways through AC-voltage regulation as well as reactive power control by which the reference value of the q axis component of the output current can be obtained. Reactive power regulation is implemented based on three different control strategies, such as unity power factor control, dynamic power factor control and Q(U) control. Implemented DC-voltage control will provide with the d-axis component of the output current. These obtained i_{dref} and i_{qref} are then used to generate the modulating index for the PWM converter with the help of current controllers. The modulating signal along with the carrier signal will generate the gate signals for the PWM converter. A feed-forward compensator is also included to the DC-voltage and AC-voltage regulations in order to improve the performances. The feed-forward compensator will eliminate the non-linearity and the destabilizing effect of the PV power output [14].

3.3 Comparison between Power factory and PSCAD models

- Power factory is more generic and is more flexible for modification than the PSCAD model
- Power factory model has got the PV panel modeled based upon several assumptions which make the result less accurate or as less real as the output. In case of PSCAD model, the PV panel is designed based upon real PV equations and the results lie very close to the actual output.
- In the current Power factory model there is no MPPT algorithm implemented which is a major drawback. PSCAD model is implemented with incremental conductance based MPPT algorithm which tracks the maximum power operating point at all the operating conditions.
- Power factory PV model is equipped with static generator instead of PWM converter whereas in case of PSCAD model actual PWM converter is used. Since static generator is used, the DC bus bar and capacitor are modeled using DSL functions in Power factory. But in case of PSCAD model, physical DC side capacitor is used.
- The active power control in both the Power factory and PSCAD is accomplished with DC voltage regulation. In Power factory an additional grid requirement of active

power reduction according to the system frequency is implemented. This feature is not available in current PSCAD model.

- In Power factory model reactive power control is established with AC-voltage based reactive power injection. In-order to avoid unwanted or unnecessary reactive power injection, a droop based control according to the German grid codes and the Transmission code 2007 is implemented. In case of PSCAD model, reactive power control is implemented through AC voltage regulation as well as reactive power control. Along with reactive power control, 3 different choices of operation are also provided to choose from. The choices are: unity power factor operation, dynamic power factor operation and Q(U) control strategy.

4. New PV model in Power factory

In the new Power factory model the PV system is modeled using a DC current source, a DC-link capacitor and an interface converter for the grid connection as shown in Fig. 4.1

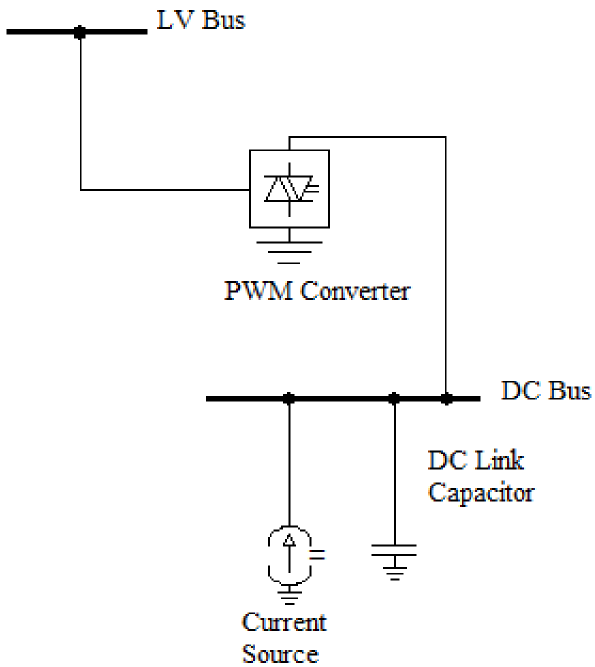

Fig. 4.1 PV system

The DC current source is having the 'I_{mpp}' value of PV array as its current rating. Since the PV system is connected to an infinite bus on the AC side, to ensure the flow of power from PV side to the grid side it should be noted that the current set point inside the DC current source is set to -1 pu.

The rating of the PV array is 0.0101 MW with a V_{mpp}=0.471 kV and I_{mpp}=0.0214 kA at STC for the current project. The DC-link capacitor connected is having a capacitance value of 10000 µF which is in parallel with the interfacing converter. The interfacing converter used here is a 3-phase PWM Voltage Source Converter. The AC voltage output of the inverter terminal is 0.18 kV with a power rating of 0.0112 MVA.

4.1 Interfacing converter

The DC/AC converter or inverter is as one of the most important components of a grid connected PV system. As the name suggests the inverter converts the DC power to AC power which enables the connection of PV system into the grid. When the inverter input DC is a voltage source then the inverter is called Voltage Source Inverter (VSI) in which the inverter has got direct control over the output AC voltage. Similarly when the input DC is current source then the inverter is called Current Source Inverter (CSI) and the CSI has control over the output AC current. For the current study, the chosen one is VSI which is the most popular one in the PV industry. A well-known example in which the voltage source inverter is used is the Uninterruptable Power Supply (UPS) whereas the battery bank used here is an example for a DC voltage source [17].

4.1.1 Voltage source inverters

Voltage Source Inverter can be classified based upon various criterions. VSI's can be classified according to their ability in controlling the magnitude of the output parameters like, frequency, voltage, harmonic content etc. Some inverters are designed to output fixed magnitude, variable frequency voltage whereas some inverter output voltage is of variable frequency, variable magnitude in nature. If classified according to the phases they output- there are single-phase and three-phase inverters.

The three general VSI's based upon their ability in controlling are as follows [18]:

1. Pulse Width Modulated (PWM) Inverters: Inverters that can produce AC voltages of variable magnitude as well as variable frequency with an input DC voltage of constant magnitude. The output is realized with the help of PWM of the inverter switches from which it got the name PWM inverter. There are several PWM techniques which will enable to get an output of near sinusoidal ac voltage, the important ones are: - sinusoidal PWM technique, Space Vector based PWM technique, selective harmonic elimination technique etc. These inverters can be either of single-phase or three-phase and a much detailed description of three-phase sinusoidal PWM inverter is explained later.

2. Square-wave inverters: Inverter output is of square waveform in nature of which the magnitude is determined by adjusting the magnitude of the input DC voltage. Hence the inverter's ability is to control the frequency of the output voltage and can be employed as single-phase or three-phase inverters.

3. Single-phase inverters with voltage cancellation: As the name indicates this is a single phase inverter with the combined characteristics of the other two inverters. The inverter is designed to control both the magnitude as well as frequency of the output ac voltage even with constant DC input voltage and without the PWM inverter switches.

4.1.2 Three phase sinusoidal PWM inverter

PWM technique is the most widely used one out of the three explained above, which is used in the current project and gives a three-phase output voltage. The principle of operation remains same for both the single-phase and three-phase PWM inverters.

Equivalent circuit of a three-phase inverter which is used for the project is shown in the below Fig. 4.2.

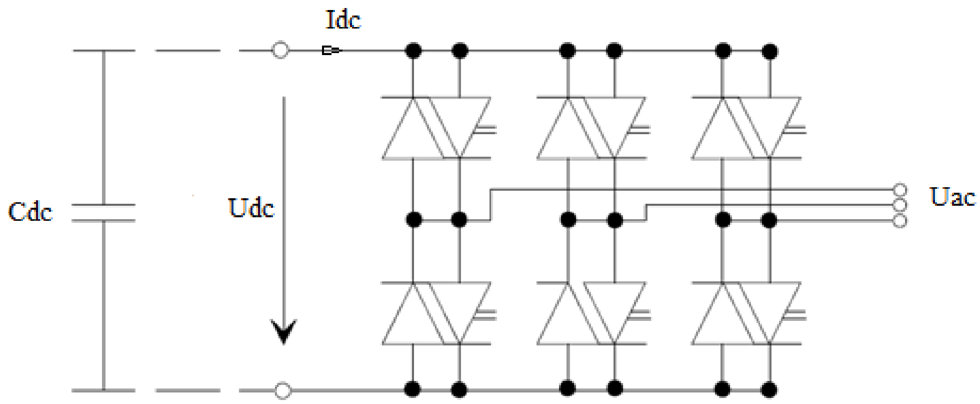

Fig. 4.2 Equivalent circuit with DC-link capacitor [19]

As shown in Fig. 4.2, 'Udc' is the input DC supply across the inverter and the current to the inverter is the DC link current 'Idc'. Also a large DC link capacitor (C_{dc}) is put across the input terminals of the inverter. In case of an ideal DC supply with no series impedance the DC link capacitor does not have any role. But almost all the practical voltage supply has got considerable series impedance and it is necessary to bypass it. If not, then the impedance can cause considerable voltage spike at the DC bus during inverter operation which will result in the deterioration of output voltage. Moreover it can cause the malfunctioning of the inverter switches because this high voltage can appear across the non-conducting switches of the inverter. Here comes the importance of DC link capacitor which can eliminate the effect of supply line impedance. Also the DC link capacitor can help in the quick build up or fall of supply current as per the demand of the inverter circuit [17].

The main idea of the circuit is to produce a sinusoidal output voltage with controllable magnitude and frequency. So it is necessary to generate the switching signals for the inverter to get the desired output. To generate the switching signals, a sinusoidal control signal of desired frequency is compared with a triangular waveform.
According to the generated switching signals the inverter switches are controlled to get a three phase output voltage. The three sinusoidal modulating signals should be balanced to get a balanced three phase output and also it is important that the carrier waveform for all the three legs may remain identical. In this context it is important to mention the term modulation index which is the ratio of the peak magnitudes of the modulating waveform and the carrier waveform [17].

The magnitude of the modulation index is normally limited below 1, i.e. $0<m<1$ and is termed as linear modulation. In this case the fundamental frequency component of the output voltage varies linearly with the modulation index [17]. When the modulation index is above 1, then it is called over modulation. In case of over modulation the fundamental components of the output voltage vary slightly with the variation of the modulation index such that the linear relationship no longer exits. Moreover due to the introduction of the lower frequency harmonics which causes the distortion of the output voltage, over modulation is generally not preferred.

4.2 Power factory PWM converter [19]

The equivalent circuit of the PWM converter used for the study is shown in Fig. 4.2. For the Power factory built-in model a number of options are available to carry out various steady state and transient studies. In this section only the used and relevant options of the PWM converter used for the current PV system study is explained. The DC capacitance which is shown is not part of the built-in model, so a capacitance 10000 µF is added externally to the grid to act as the DC link capacitor. The given PWM converter model is a self-commutated voltage source inverter with the circuit valves realized by GTO's or IGBT's with turn-off capability. The inverter supports sinusoidal as well as rectangular modulation of which the selected modulation is sinusoidal.

The PWM converter characteristic based on the Pulse Width Amplification factor P_m is shown in Fig. 4.3 according to which the converter ratings and controls can be determine to avoid the converter saturation. Once the converter enters saturation lower order harmonics starts to increase which can distort the output voltage, at the same time low levels of saturation are usually allowed for this model.

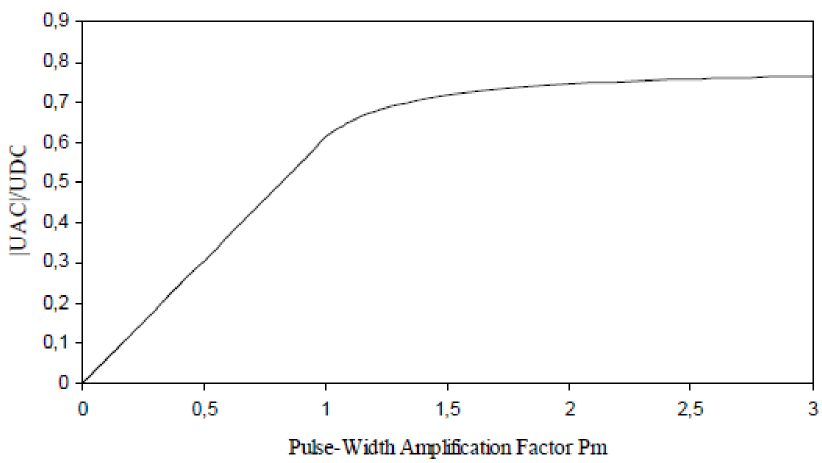

Fig. 4.3 PWM Converter characteristic [19]

The main loss associated with an inverter is the switching losses which is the V^2-loss and is one of the inputs along with the copper losses. Even though there is no series reactor externally connected to the inverter an inductance of 4 mH and a resistance including the switching resistance equal to 3 mΩ is assumed to calculate the controller parameters as well as losses. Since the grid connected PWM converters are usually connected to the AC system through a reactance, which is already included in the built-in model to simplify further modeling.

4.2.1 Load flow analysis

In the load flow analysis section instead of the control variables, the controlled variables are specified for which several options are available and are shown in Fig. 4.4. The control-variable-modulation index is then obtained from the load flow calculation performed during the model execution. Out of the available options, the selected one is V_{DC}-Q as shown below.

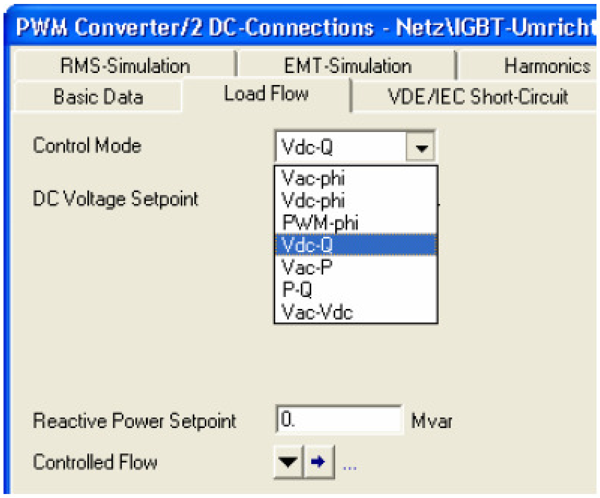

Fig. 4.4 Load Flow tab of PWM converter

4.2.2 Stability analysis

The input/output definition of the stability model or the RMS model of the PWM converter is shown in Fig. 4.5.

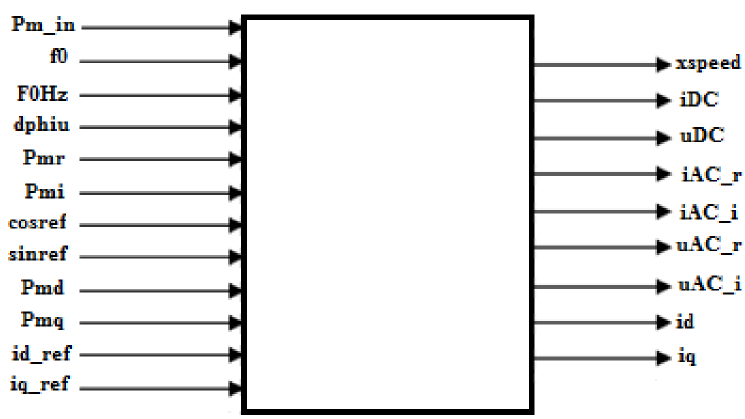

Fig. 4.5 Input/output definition of Stability Model [19]

According to the above inputs/outputs and application various options/ input combinations are available to determine the modulation index of the model [19]:

- *Pmr, Pmi: Real and imaginary part of the pulse width modulation index. Reference system is here the global reference-frame, which is usually defined by a reference-machine, external network or voltage source (or even a PWM-converter) why this set of inputs must always be used in combination with phase measurement devices (e.g. PLL) and reference-frame transformations.*
- *Pmd, Pmq, cosref, sinref: This set of input variables is convenient in grid-connected applications. It allows specifying a pulse-width modulation index-vector, with reference to a reference-system that is defined by cosref and sinref. A very common*

application is to measure the voltage angle using a PLL and to connect the output of a dq-current controller to Pmd and Pmq. The output of the PLL must be connected to cosref, sinref. This set of input variables avoids the explicit definition of reference-frame transformations.

- *id_ref, iq_ref, cosref, sinref: as input variables reference values for the d- and q-axis currents can be used, when an internal current controller is defined on the RMS-simulation tab. Similar to the previous set of input variables, the currents are defined with reference to a reference-system that is defined by cosref and sinref. Also here the explicit definition of transformation from local to global reference-frame is not needed.*
- *Pm_in, dphiu: Magnitude and phase of the pulse-width modulation index. This representation is fully equivalent to Pmr and Pmi (dphiu is expressed with reference to the global reference-frame).*
- *Pm_in, f0 (F0Hz): Pm_in defines the magnitude of the pulse-width modulation index. The frequency f0 allows varying the frequency of the output voltage. This is especially useful in variable speed-drive applications, in which a PWM-converter is used for driving an induction machine. The variable F0Hz can be used alternatively to f0 and defines the frequency in Hz (f0 is in p.u.).*

For the current PV system the option with the inputs: id_ref, iq_ref, cosref, sinref is used to determine the modulation index in the dq-reference frame. An inbuilt current controller is available within the PWM converter as shown in Fig. 4.6.

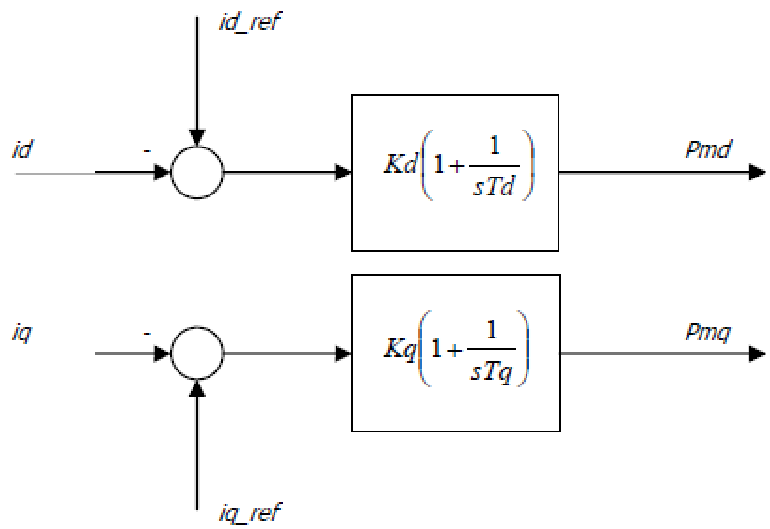

Fig. 4.6 Built-in current controller [19]

From the output definition of the RMS model it is clear that the converter output current is projected on the dq-reference frame which is iq and id. So it is necessary to obtain the reference values also in the dq-frame for which an outside controller is designed to obtain the values of id_ref and iq_ref. Then the input reference values are compared with the actual converter output current id and iq. Finally using the built-in current controllers, the d-axis and q-axis components of the modulation index are calculated. The use of the built-in current controller is optional.

The proportional gain and the time constants of the PI controller can be calculated using the equations [16],

$$K_p = K_d = \frac{L}{\tau} \quad \text{--- (4.1)}$$

$$T_p = T_d = \frac{\tau}{R} \quad \text{--- (4.2)}$$

where L and R are the inductance and resistance of the inverter series reactor. It is also possible to determine the gain and time constant values using hit and trial method.

Time constant 'τ' is selected based upon the desired speed of response from the range of 0.5 to 5ms, which is 0.5ms in this case. It is important to note in this context is that the value of L, R and τ used to calculate the value of gain, K and time constant, T should be in pu. For the new model the current controller is enabled but the values of K_p and T_p are initialized to zero. This is because during short circuit studies, non-zero values of K_p and T_p generates convergence problems during simulation.

Further to obtain the values of cosref and sinref, a phase measurement unit is employed along with the PWM converter in Power factory. So based upon these reference angles the output signals Pmd and Pmq are transformed back to the global (abc) reference frame.

4.3 External control of PWM converter

The external control scheme will enable to obtain the reference value of the output current in the dq-reference frame so that the desired ac output can be obtained from the PV system. So the main idea of the additional control is to provide an extra control over the output components. For the current PV system several control techniques are implemented in Power factory for the regulation of DC voltage, AC voltage, reactive power output and active power output.

As explained previously the current generic Power factory PV model is equipped with active power control based on the DC voltage regulation and the reactive power control based upon the AC-voltage regulation. Along with those controls, extra controls are implemented in the new model with options to choose depending upon the requirement. Nowadays various grid codes and transmission regulations demand various requirements to be met by the grid connected PV systems, which can be realized using these control techniques.

The below Fig. 4.7 shows the main control frame designed for the PV system and will be explained in detail in the coming sections.

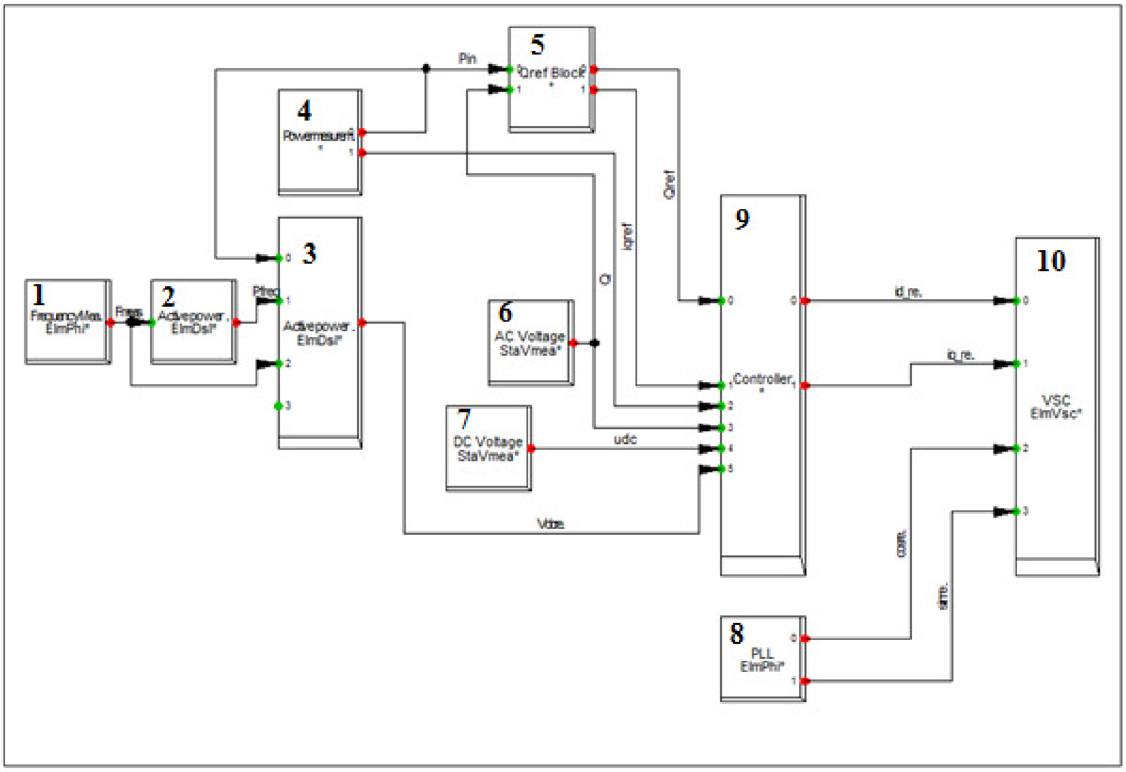

Fig. 4.7 The main control frame

Slots 1, 2, 3 and 4 are for the active power control of the PV system. Slot 1 is the frequency measurement unit and slot 2 is the active power reduction block. Slot 3 is the active power control block. Slot 4 is the power measurement unit which will provide the measured AC power from the AC side of the PV system. Both active power as well as reactive power are measured and are given to various slots for further controller design. Slot 5 is the Qref block which is designed to provide the 'Q_{ref}' value to the controller (slot 9). The obtained 'Q_{ref}' value out of the Qref slot is used inside the controller for reactive power regulation. Slot 6 is the AC voltage measurement unit and slot 7 is the DC voltage measurement unit. Slot 9 is the main controller inside which the DC voltage regulation, AC voltage regulation and reactive power control are implemented.

It should be kept in mind that for the new model controller the measured voltage and the power values used inside the active power control (slot 3), Qref block (slot 5) and controller (slot 9) are in kV and MW/MVaR respectively. The output out of the controller (slot 9) is given to the VSC (slot 10) which is directly associated with the PWM inverter employed in the PV system.

As explained earlier, the chosen stability mode of operation of the PWM inverter is *Pmd, Pmq, cosref, sinref* combination. The values of *cosref, sinref* are obtained from the phase measurement unit (slot 10) employed inside the control frame. In order to simplify the analysis and design, the variables are expressed in dq-frame instead of the abc-reference frame in the PV model. Further using the obtained values of *cosref, sinref,* the variables are transformed back to the abc- reference frame inside the controller.

4.3.1 Active power control (slot 3)

Active power control as the name indicates will regulate the actual active power output out of the inverter according to the reference value of the active power. The active power control is mainly employed in order to decrease externally the power while the PV system is operating around its maximum power output by varying the voltage. The below block diagram, Fig. 4.8 shows the active power control technique employed within the system.

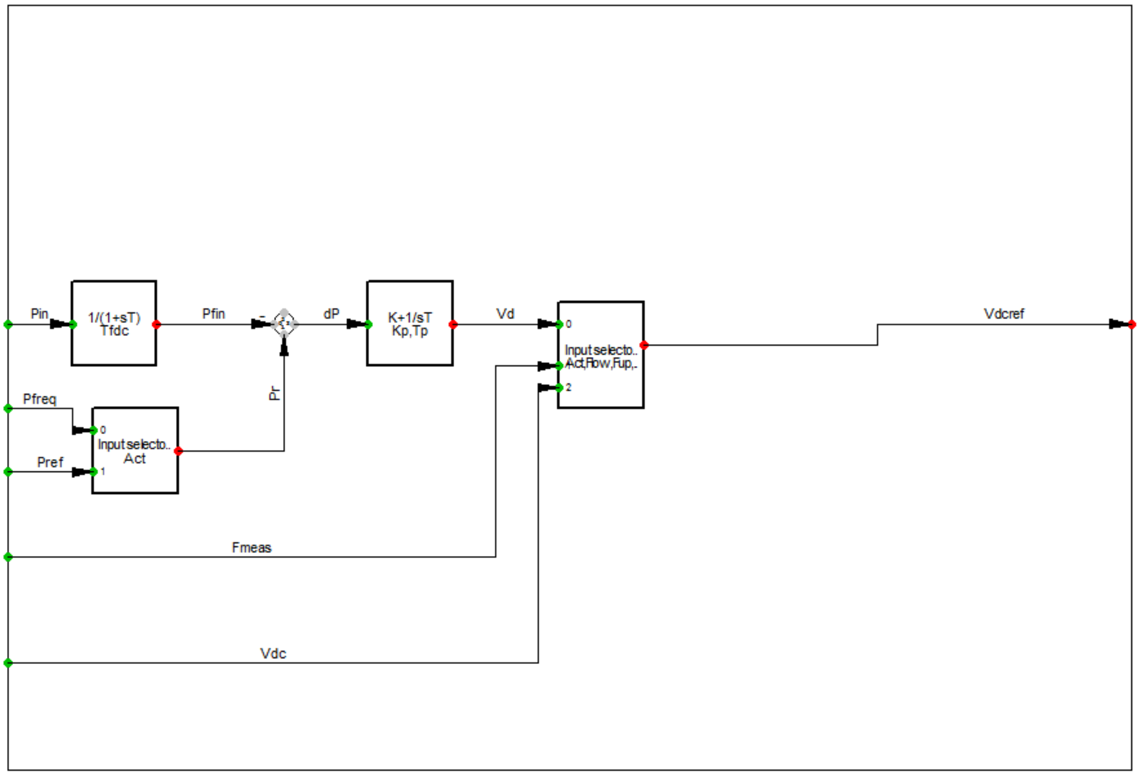

Fig. 4.8 Active Power Control

As seen in figure there are two options available to determine the value of ‘P_r’. First option is to manually input the desired value which is given by ‘P_{ref}’ and will be enabled if the parameter ‘Act’ inside the Active Power controller is set to 1. The next option is to obtain the active power based upon ‘P_{freq}’ value.

‘P_{freq}’ is the active power reference value obtained out of the active power reduction block which is shown in Fig. 4.9.

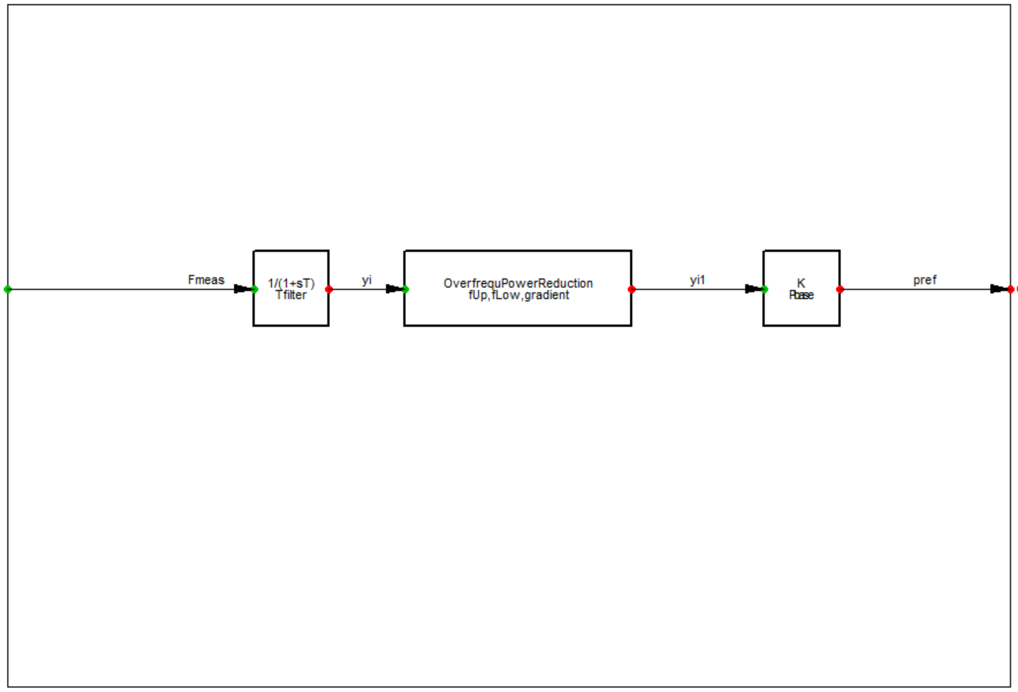

Fig. 4.9 Active power reduction block

In the grid-code there is a recommendation to reduce the active power in case of over frequency as explained in Fig. 2.12. The same is realized in the active power reduction block where the actual system frequency ‘Fmeas’ is compared with the limits. Based upon which the ‘P_{freq}’ is calculated and is then given to the active power controller which will be used further for the calculation of ‘i0dc’. For any ‘Act’ parameter value (here it is set to 0) other than 1, ‘P_{freq}’ option is enabled and is the usual choice during the normal operating condition.

The output out of the active power control block is into the main controller in the form of ‘Vdcref’. An MPPT connected system will have the value of ‘Vdcref‘ coming out of the MPPT function block. In case if there is requirement for constant ‘Vdcref’ then the value of ‘Vdcref’ into the controller can be set as ‘Vmpp’. When the requirement is to reduce the active power at maximum power output state as per the operator wish, then the required ‘Vdcref’ can be obtained using the PI controller from ‘Pref’.

During all the operating conditions other than ‘Pref’ option, if there is any frequency increase in the system then the active power will be reduced with the help of active power reduction block. So to choose from all these various options such as MPPT based ‘Vdcref’, constant ‘Vdcref’ and ‘Pref’ or ‘Pfreq’ based ‘Vdcref’, a selector switch with parameter ‘Act’ is employed. When the switch parameter Act=0, then the output ‘Vdcref’ comes out of the MPPT block. For Act=1, then the manual ‘Pref’ option is enabled which allows to increase or decrease the value of active power as per requirement. When the switch parameter Act=2 then the value of ‘Vdcref’ out of active power control block is a constant which is normally ‘Vmpp’.

Further to obtain the value of 'Vdcref' based upon 'Pref' or 'Pfreq' the PI controller employed is having the equation:

$$F_p(s) = K_p + \frac{1}{T_p s} \quad \text{--- (4.3)}$$

Where, K_p is the gain of the active power controller

T_p is the time constant of the active power controller in sec

4.3.2 Controller (slot 9)

The block diagram of the controller implemented to obtain the values of 'iq_ref' and 'id_ref' is shown in Fig. 4.10.

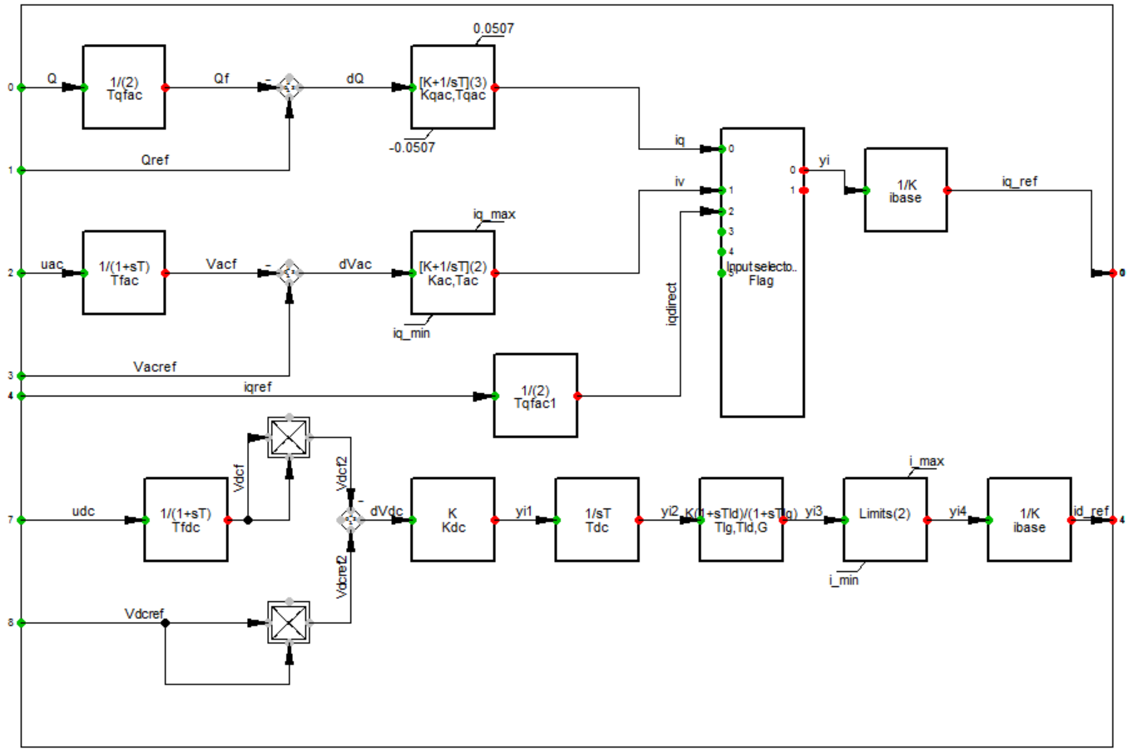

Fig. 4.10 Controller block diagram

The topmost part is the reactive power control with 'Q' and 'Qref' as input and 'iq' as output. Down to reactive power control is the AC voltage regulation with 'uac' and 'Vacref' as inputs and 'iv' as output. Next is ' iqref' which is a directly calculated 'iq_ref' value and is an output of the Power factor block (Slot 6). In order to choose from the three different 'iq_ref' calculation method available, an input selector is provided with a parameter named 'Flag'. Since the value of 'iq_ref' that is to be given to the VSC should be in pu, the chosen value out of the input selector is converted to pu by dividing it by 'ibase'.

The value of 'ibase' is calculated using the equation,

$$ibase = \frac{2S_{base}}{3V_{sd}} \quad \text{--- (4.4)}$$

where, S_{base} is the inverter rating in MVA and V_{sd} is the peak value of the line-ground inverter AC side voltage in kV

.

The lower part of the control is for the DC voltage regulation with 'udc' and 'Vdcref' as inputs and 'yi4' as the output. The output 'yi4' is further converter to pu using 'ibase' to obtain the desired value of 'id_ref' in pu.

a) DC voltage regulation

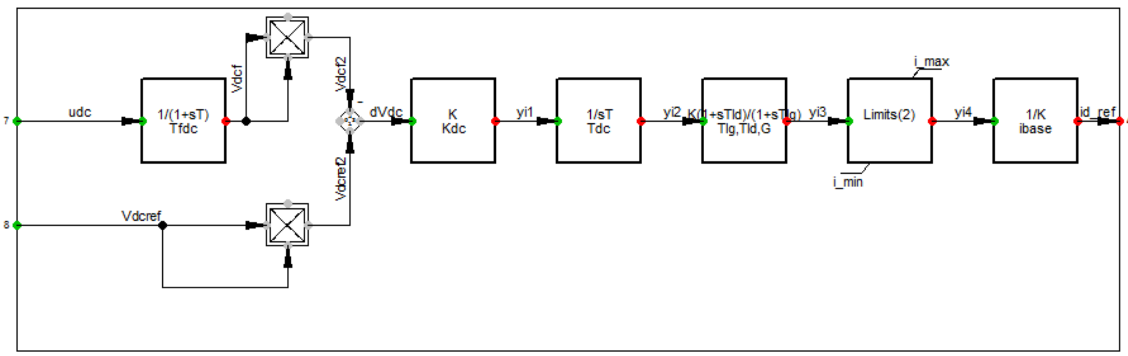

Fig. 4.11 DC voltage regulation

As shown in Fig. 4.11 the DC voltage regulation is implemented which is an alternative way to provide a control over the active power output out of the converter. The actual DC output voltage, udc which is measured using a voltage measurement unit is first passed through a low pass filter to attenuate any high frequency components. Then the error of the squared values of DC reference value, V_{dcref} and the output from the low pass filter was found, which is dV_{dc}. The value of dV_{dc} then passed through the compensator, $F_{dc}(s)$ to get the value of id_ref as the input to the inverter [16].

Where,

$$F_{dc}(s) = K_{dc} \frac{1}{T_{dc}s} \frac{1+T_{ld}s}{1+T_{lg}s} \quad \text{--- (4.5)}$$

Here, K_{dc} is the gain of the DC voltage compensator

T_{dc} is the time constant of the DC voltage compensator in sec.

T_{ld} is the lead time constant of the lead-lag compensator in sec.

T_{lg} is the lag time constant of the lead-lag compensator in sec.

To get an idea of the possible values of the gains and time constants for all the controllers described above and further, a Matlab code is given in Appendix 8.4. The limit i_max and i_min are ibase and 0 respectively.

DC voltage regulation using PI controller

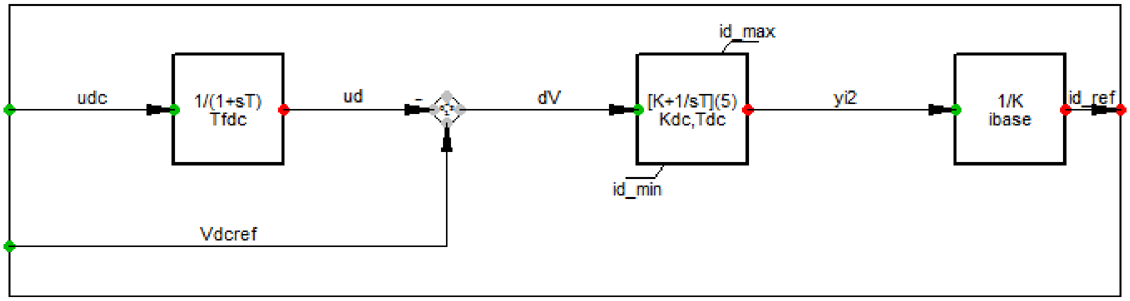

Fig. 4.12 DC voltage regulation

DC voltage regulation can also be realized with the help of a PI controller which is the most widely used method as shown in Fig. 4.12. In the previous model the squared values of 'Vdcref' and 'udc' are used to determine 'id_ref'. But in this case the inputs 'Vdcref' and 'udc' are used as it is, to determine the error. Then the error is passed through the PI controller to obtain the value of 'id_ref' which is the input to the PWM converter. The PI controller implemented is having the equation,

$$F_{dc}(s) = K_{dc}(1 + \frac{1}{T_{dc}s}) \quad \text{--- (4.6)}$$

Where, K_{dc} is the gain of the DC voltage regulator

T_{dc} is the time constant of the DC voltage regulator in sec.

For the PI controller, the values of K_{dc} and T_{dc} are determined by trial and error method to get the desired output.

b) AC voltage regulation

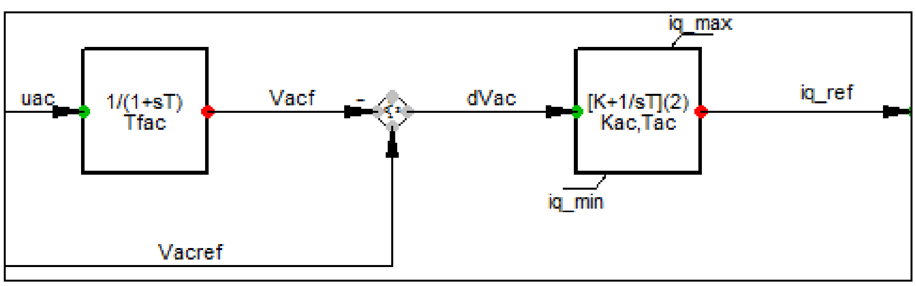

Fig. 4.13 AC voltage regulation

The main idea behind the introduction of a separate control for the AC voltage is to keep the voltage at the coupling point within the steady state voltage limits. If there is an increase or decrease in grid voltage then the ac-voltage control will act to return back the system voltage to the normal operating voltage or V_{acref}. V_{acref} can be assigned with the desired AC voltage, which is to be maintained at the regulation point after the PV system gets connected to the grid. The regulation is achieved with the injection or absorption of reactive power by the inverter according to its capability/limits. Nowadays for the medium voltage PV system grid connections, grid codes allow or demands the PV system to operate within 0.95 lead or lag power factor. So within these limits as well as depending upon the inverter ratings the AC voltage control can be utilized for a better control over the output AC voltage.

As shown in Fig. 4.13 the error of the AC reference voltage, V_{acref} and the actual AC-voltage from the inverter V_{ac} is passed through a PI controller, $F_{ac}(s)$ to obtain the iq_ref. Then with the help of the in-built current controller the modulation index is calculated which can be used to generate the switching pulses for the inverter. The PI controller has got the equation:

$$F_{ac}(s) = K_{ac} + \frac{1}{T_{ac}s} \quad \text{--- (4.7)}$$

where, K_{ac} is the gain of the AC voltage controller

T_{ac} is the time constant of the AC voltage controller in sec.

The limits, iq_max and iq_min are determined using the formula,

$$Q_s = -\frac{3}{2}V_{sd}i_q \quad \text{--- (4.8)}$$

where, Q_s is the maximum possible reactive power of the PV system in MVaR (reactive power corresponding to 0.9 power factor in this model)

V_{sd} is the peak value of the line-ground inverter AC side voltage in kV

i_q is the q-axis component of the reference current in kA

c) Reactive power control

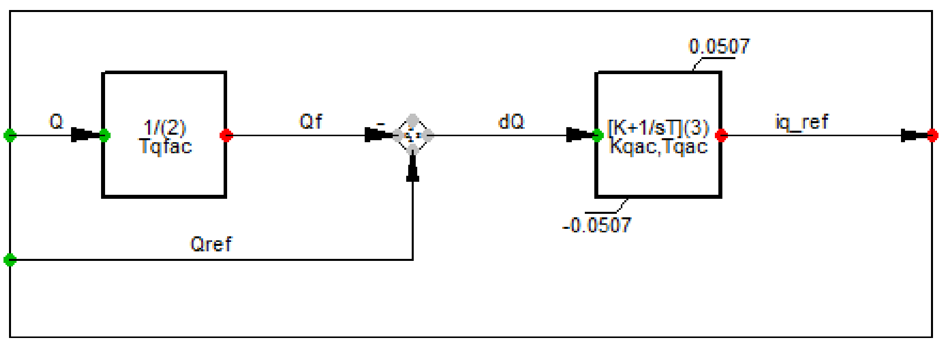

Fig. 4.14 Reactive power control

The actual reactive power termed here as 'Q' in Fig. 4.14 is regulated to follow the 'Q_{ref}' value which is the desired reactive power. The 'Q_{ref}' variable to the main controller comes from the Qref block which will be explained in the immediate section. Then the actual reactive power output of the converter is compared with the obtained reactive power reference value to get the error. The error is then passes through the controller, Fq(s) to obtain the value of iq_ref which is the input to the PWM converter. Here,

$$F_q(s) = K_q + \frac{1}{T_q s} \quad \text{--- (4.9)}$$

where, K_q is the gain of the reactive power controller

T_q is the time constant of the reactive power controller in sec

The current limits given for the controller is ±ibase.

4.3.3 Qref block (slot 5)

The ‘Qref’ input shown in Fig. 4.14 comes from the Qref block. The block diagram of the Qref block employed along with the inverter control, in order to obtain the value of Qref based upon different strategies is shown in the below Fig. 4.15.

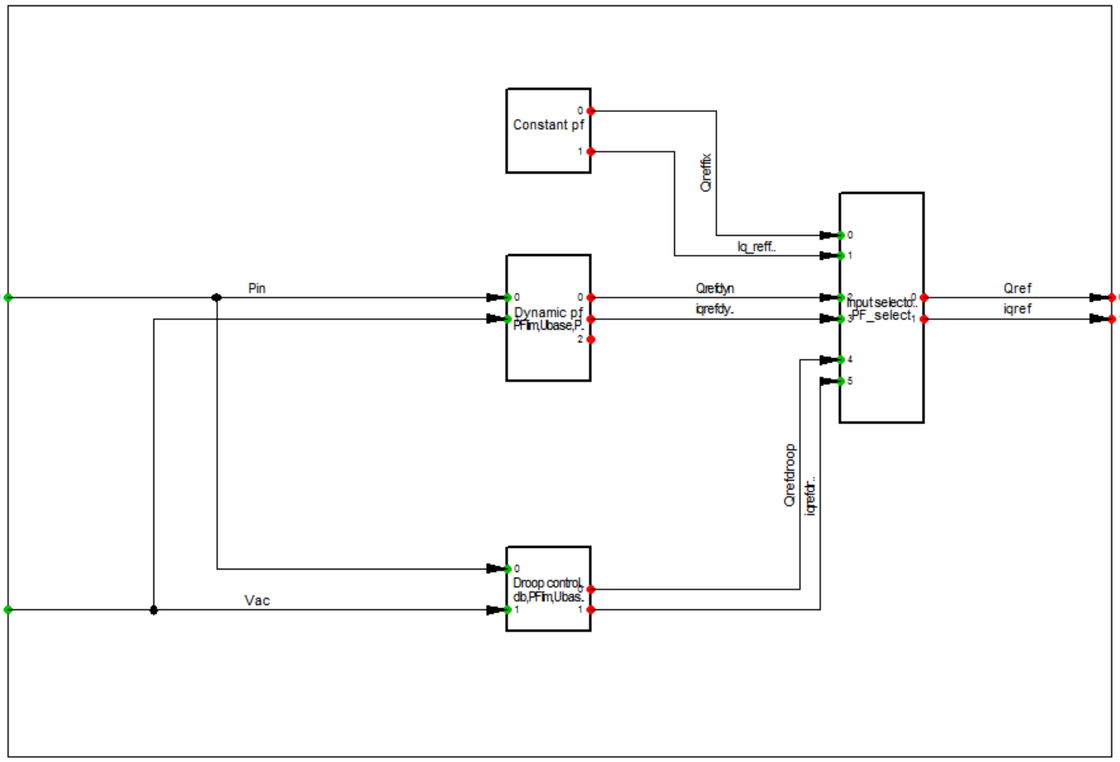

Fig. 4.15 Qref block

The Qref block outputs the ‘Q_{ref}’ value based upon the choice selected from three options. The options available are unity power factor, dynamic power factor and Q(U) operation, which in turn decides the ‘Q_{ref}’ value.

In case of unity power factor operation, there will not be any reactive power support, ie. ‘Q_{ref}’ is equal to zero. This case of unity power factor operation is nowadays not advised rather dynamic power factor operation is recommended. Dynamic power factor operation will enable the PV system to take part in the grid-voltage support in case of disturbances. Since the PV panel does not provide any reactive power support the inverter is oversized to meet the reactive power grid requirements.

Fig. 2.13 demonstrates the dynamic power factor operation implemented for the new PV system. According to the active power output, the power factor of the PV system is varied to obtain the required reactive power support independent of the system voltage.

Droop based reactive power control is the third option such that the ‘Q_{ref}’ is calculated based on the variation in the system voltage. If the grid voltage change is within the entered dead-band ‘D’ there will not be any reactive power injection which will eliminate the unnecessary reactive power absorption or injection. If the variation of system voltage is beyond this dead-band, then there will be reactive power injection or absorption according to the control curve shown in Fig. 4.16.

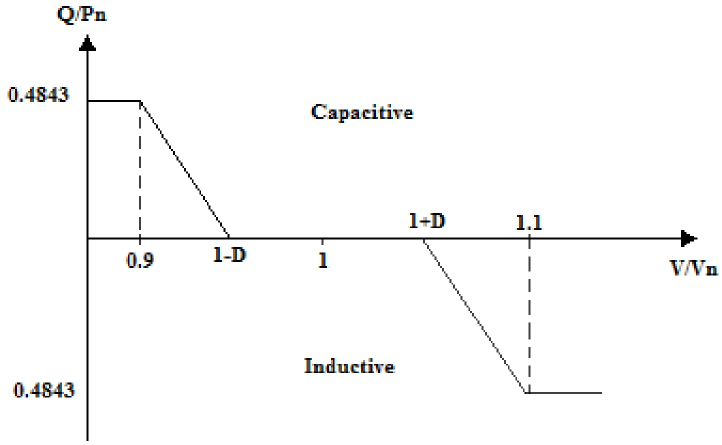

Fig. 4.16 Q(U) curve

Out of the Qref block it can also be noted that an output 'iqref' is available and is valid for unity power factor, dynamic power factor and Q(U) operation.

The value of 'iqref' is calculated based upon the equation

$$Q_s = -\frac{3}{2} V_{sd} i_q \qquad \text{--- (4.10)}$$

where, Q_s is the maximum reactive power of the PV system in MVaR (reactive power corresponding to 0.9 power factor in this model)

V_{sd} is the peak value of the line-ground inverter AC side voltage in kV

i_q is the q-axis component of the reference current in kA

Obtained 'iqref' and 'Qref' are given to the controller block and is used further to get the desired value of 'iq_ref' in pu.

4.4 New PV model frame

The PV system will be complete only when the PV array and the MPPT come together with the control frame discussed till last section. The complete frame of the new PV system model is shown in Fig. 4.17.

The new additions to the control frame given in Fig. 4.7 are slots 11, 12, 13, 14 and 15. **Slot 11** is the irradiation block and **slot 12** is the temperature block. Irradiation and temperature effects are modeled inside these blocks. The outputs from these blocks are given to **slot 13** which is the PV module block.

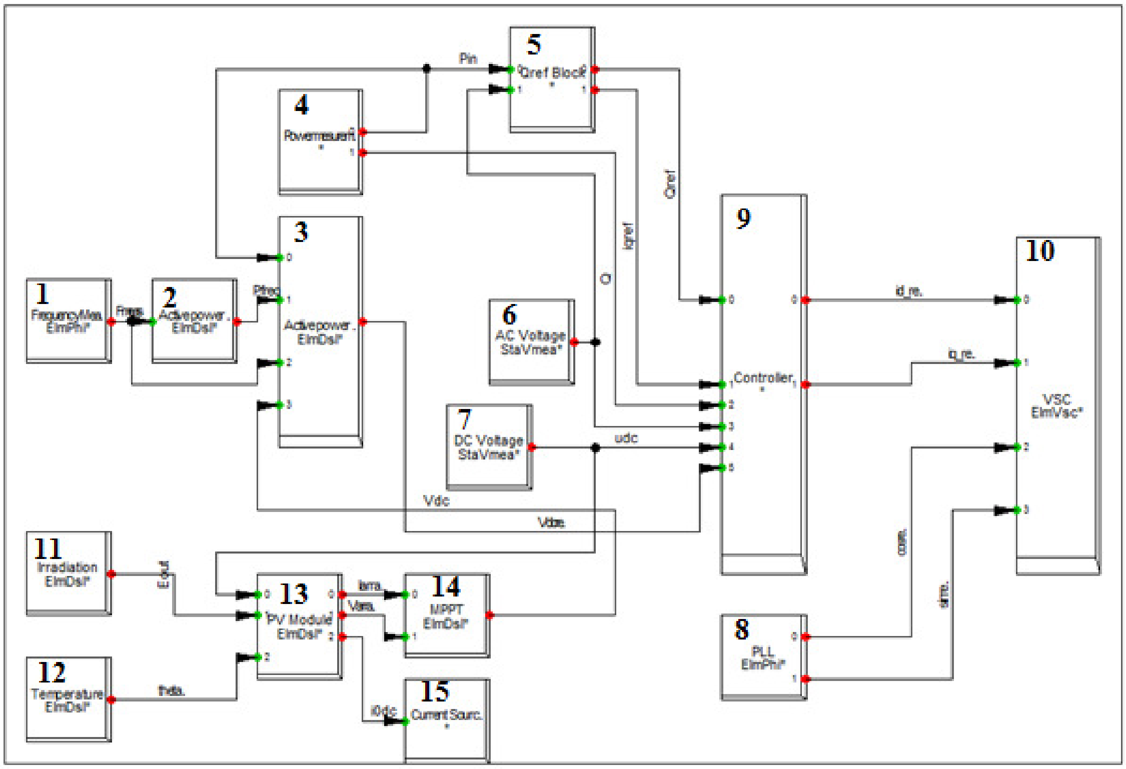

Fig. 4.17 New PV system frame

4.4.1 PV module block (slot 13)

The PV module is modeled based on the equivalent circuit of the solar cell shown in Fig. 4.18.

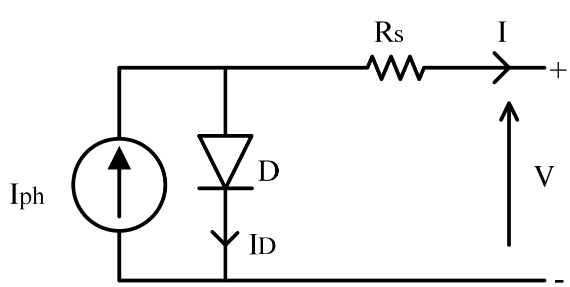

Fig. 4.18 Equivalent circuit of the solar cell

As mentioned in Chapter 3 depending upon the project requirement, the PV array can be modeled based upon the equivalent circuit of the solar cell of our choice.
Based on the selected equivalent circuit shown in Fig. 4.18, the output current of the PV module is,

$$I = I_{ph} - I_D \quad \text{--- (4.11)}$$

where, I_{ph} is the photoelectric current due to irradiation in Ampere

I_D is the diode current in Ampere

Further substituting the values of I_{ph} and I_D in (4.11), the end equation based upon which the output current, I of the PV module is calculated can be determined and is given by [20],

$$I = I_{sc} - I_0 * exp(\frac{V+IRs}{V_t}) \quad \text{--- (4.12)}$$

where, I_{sc} is the short circuit current at STC in Ampere

I_0 is the dark current of the PV cell in Ampere

V is the actual DC voltage of the PV module (DC-link voltage) given as measurement to the block in Volts

R_s is the series resistance in Ω in order to include the loss due to the poor conductivity of the solar cells and,

V_t is the thermal voltage and is around 2.824 V per cell at STC for this project which can be different for different PV modules.

The short circuit current for the PV cell is calculated using the equation [20],

$$I_{sc} = I_{sc2} * (\frac{E_{out}}{E_{STC}}) \quad \text{--- (4.13)}$$

where,

$$I_{sc2} = I_{sc1} * \left(1 + \frac{KI}{100}\right) * (thetaout - Tref) \quad \text{--- (4.14)}$$

Here KI- temperature correction factor for current(from PV module data sheet), Isc1- short circuit current of the PV module (from PV module data sheet), Tref – temperature at STC which is 25 °C, E_{STC}- irradiation at STC which 1000 W/m^2 are given as parameters to the PV module block. E_{out} in W/m^2 and thetaout in °C are the inputs from the irradiation (slot 11) and temperature (slot 12) blocks respectively.

Further the value of dark current can be calculated using the equation [20],

$$I_0 = \frac{I_{sc2}}{\exp(\frac{V_{oct}}{V_t})} \quad \text{--- (4.15)}$$

where,

$$V_{oct} = V_{oc1} + [KV * (thetaout - Tref)] \quad \text{--- (4.16)}$$

Here, KV- temperature correction factor for voltage (from PV module data sheet), Voc1- open circuit voltage of the PV module (from PV module data sheet), Tref – temperature at STC which is 25 °C are parameters of the PV module block. ‘thetaout’ in °C is the input from the temperature (slot 12) block.

The DSL code written to design the PV module [20] based on the current equation (4.12) is given in Appendix 8.2. The block diagram of the PV module block (slot 13) is given in Appendix 8.3 (Fig. 8.3). The measured actual DC voltage ‘udc’ from the DC terminal (see Fig. 4.17) given to the PV module block is divided by the number of series modules (nSerialModules) of the PV array inside the block in order to obtain the DC voltage for a single PV module for current calculation. Further using the input signals- E_{out}, thetaout, V and the parameters of the PV module block, the output current of the PV module is calculated using the DSL codes. The output current, 'I' calculated is for a single PV module which needs to be multiplied by the number of parallel modules (nParallelModules) to get the total output current, 'Iarray' out of the PV array. The outputs of the PV module block are the array current, 'Iarray' and the actual DC voltage, 'Varray'. The output array current, 'Iarray' in Amperes is then converted to signal 'i0' in pu and is given as an input to the constant current source (slot 15) in order to vary the current value according to the change in system conditions such as irradiation change, grid voltage variations etc. Also it is important to note here is that the constant current source (slot 15) takes the current value in pu under the variable name, 'i0dc'.

4.4.2 MPPT block (slot 14)

The PV module outputs, array current as 'Iarray' and actual DC voltage as 'Varray' are given to the MPPT block (slot 14) to perform the MPPT function. The function of MPPT is to determine the optimum DC voltage from the P-V characteristic curve shown in Fig. 2.3 for a given irradiation and temperature. The P-V characteristic curve varies with the change in irradiation and temperature. Thus by using MPPT function, the optimum DC voltage is found which will ensure the maximum power out of the PV system in turn increasing the efficiency of the system. Several MPPT techniques are available, but for the current model MPPT is implemented based on the Incremental Conductance algorithm [21] as shown in Appendix 8.3 (Fig. 8.4). The output out of the MPPT block is the reference DC voltage 'vdcref' and is given to the controller block (slot 9) through the active power control block (slot 3). Thus obtained reference voltage value is then used inside the controller block under the variable name 'Vdcref' for the DC voltage regulation of the PV system which is explained in section 4.3.2 (a). For a more detailed description on how the PV array is modeled as well as the execution of MPPT function, refer to project report [20] and the block diagrams of the slots 11, 12, 13 and 14 are given on Appendix 8.3.

The calculations inside slots 13 and 14 are performed in nominal values of current in A and voltage in V. The output of the measurement devices are in kV and kA. So the conversion from kV to V and kA to A and vice versa are performed inside the blocks upon requirement.

5. Model analysis and comparison between Power factory and PSCAD PV models

5.1 Single-line diagram of the system

The single line diagram of the power system that is used in both Power factory and PSCAD for analysis and result comparison is shown in Fig. 5.1.

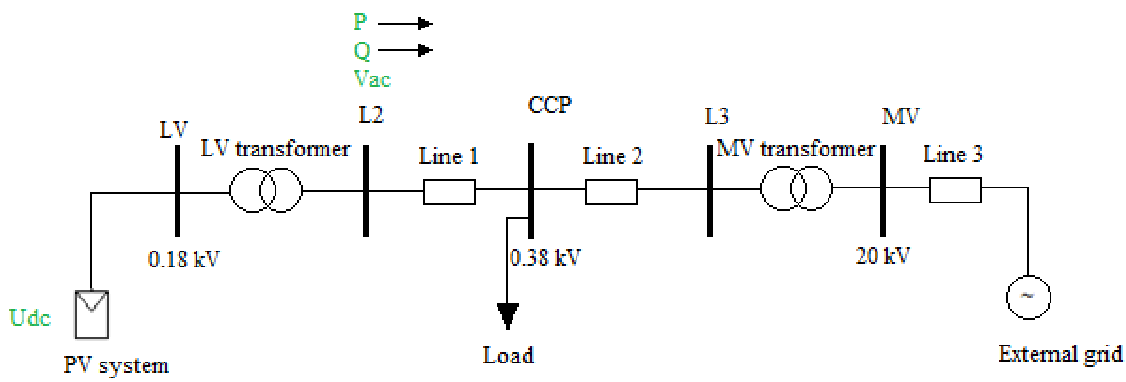

Fig. 5.1 Single-line diagram of the grid connected PV system

The measurement points of the result variables can also be noted in Fig. 5.1 .System specification of the above power system is given in Appendix 8.1.

5.2 Comparison and evaluation of the Power factory model with the PSCAD model with MPPT function

5.2.1 Scenario 1: Irradiation change in PV system

The current case study enables to understand the PV system behavior in case of irradiation change, expressed as ‘G’ W/m^2 shown in Fig. 5.2. At 6th second of the simulation time the irradiation given to the system is reduced from 1000 W/m^2, initial condition to 500 W/m^2 which is half of the irradiation. Then during 10th second irradiation is returned back to the normal value 1000 W/m^2. The current simulation provides the following results in case of DC voltage, ‘Udc’ and AC power ‘P’ as shown in Fig. 5.3 and Fig. 5.4.

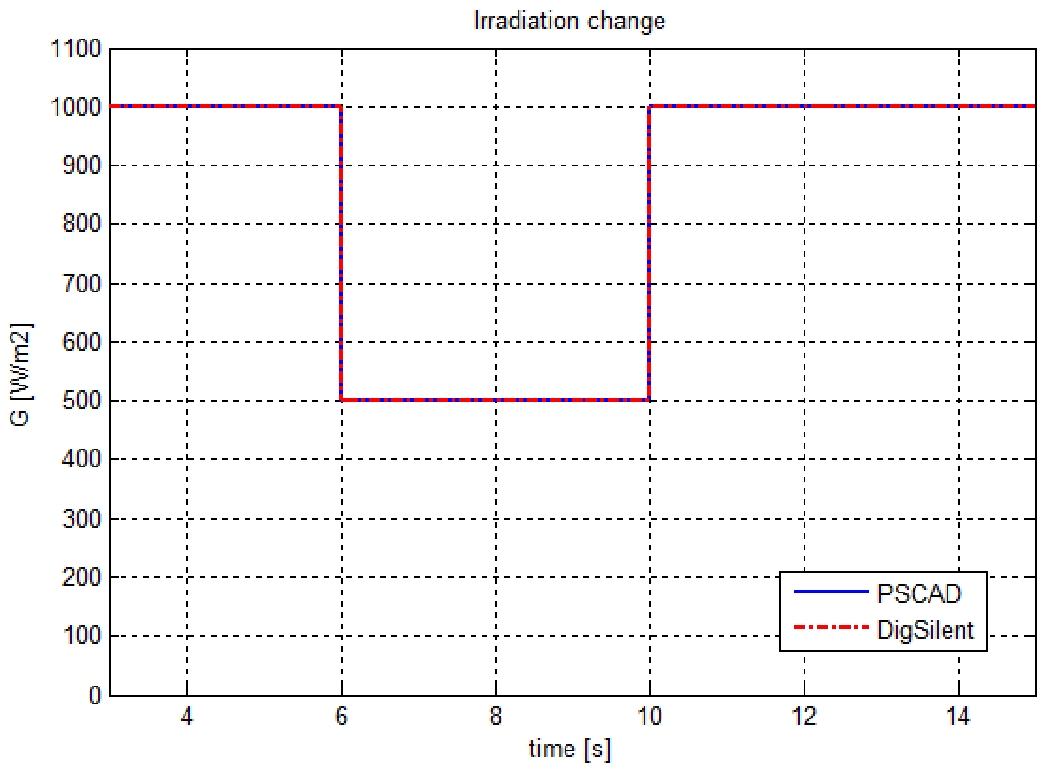

Fig. 5.2 Irradiation change in the PV system

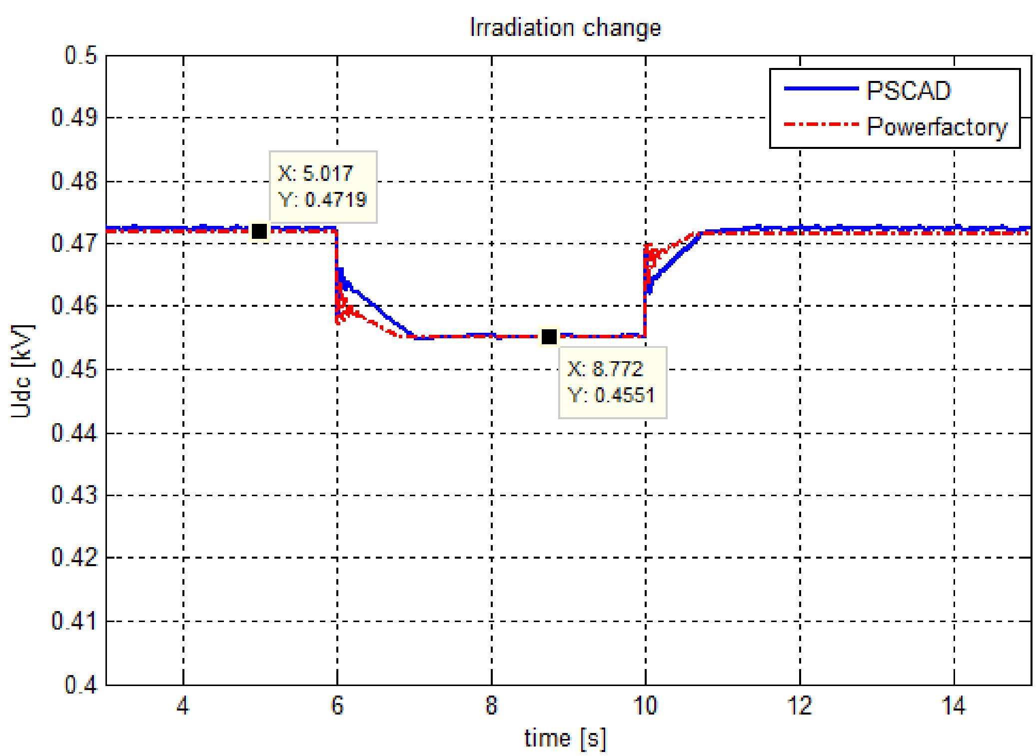

Fig. 5.3 DC voltage of the PV system

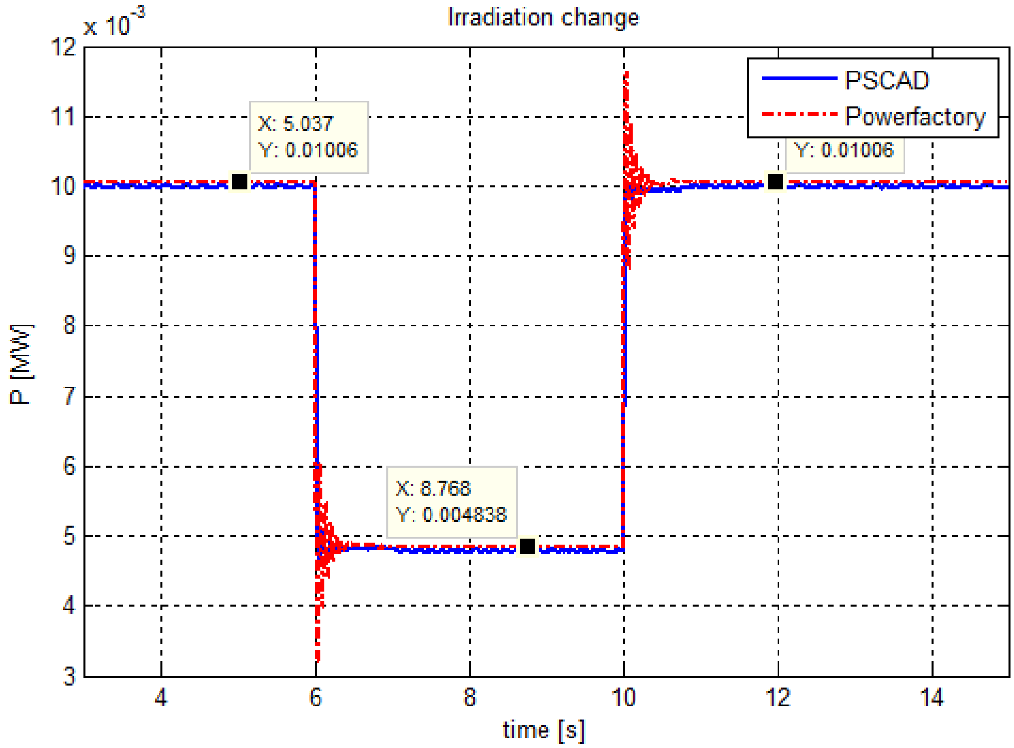

Fig. 5.4 Active power of the PV system

According to Fig. 5.3 the DC voltage 'Udc' decreases due to the decrease in irradiation from 1000 to 500 W/m^2 in both Power factory and PSCAD. With the help of the MPPT function employed in both the models the system finds the best possible DC voltage output that will ensure the maximum power output out of the PV system for a particular condition. Due to the change in DC voltage and current out of the PV module the active power or the DC power decreases during the time of irradiation decrease. As shown in Fig. 5.4 for the standard test condition, the active power output out of the PV system is 0.0101 MW which got decreased to 0.00484 MW when the irradiation decreased to 500 W/m^2.

From the graphs it is clear that for the current disturbance or change in the system, both the Power factory as well as the PSCAD PV models behave in a similar way. The steady state values at different irradiance are more or less the same even though there are differences in the dynamic behavior of the system. Although the two models are designed very much the same way, the difference in the solvers that are used in Power factory and PSCAD can be one reason of the difference in dynamic behavior. Another reason is the way in which the MPPT is being realized in both the systems. In both PSCAD and Power factory the MPPT algorithm used is the Incremental Conductance. But the implementation technique used to realize the algorithm is not exactly the same which is another reason for the different dynamic behavior. The impact of MPPT in the dynamic behavior of the system is verified and discussed in section 5.4.

As discussed earlier various reactive power control techniques are designed to control the AC and DC side outputs according to the requirement. For the same irradiation decrease how this controls behave is discussed further.

1. Unity power factor operation- QControl 1

Next possible reactive power control is the unity power factor control, in which at any operating condition the PV system power factor remains unity. Unity power factor operation is accomplished by initializing the value of 'Qref' to be equal to zero. Based upon 'Qref', the reactive power out of the PV system is controlled with the help of PI controller implemented inside the main controller. The AC voltage and reactive power waveforms are shown in Fig. 5.7 and Fig. 5.9 respectively.

As shown in Fig. 5.7, the reactive power output of the PV system is zero irrespective of the irradiation change or any other variation keeping the power factor to unity as shown in Fig. 5.8. So during this reactive power regulation, there will not be any control over the AC voltage as shown in Fig. 5.9. The voltage gets decreased and increased according to the disturbance in the system.

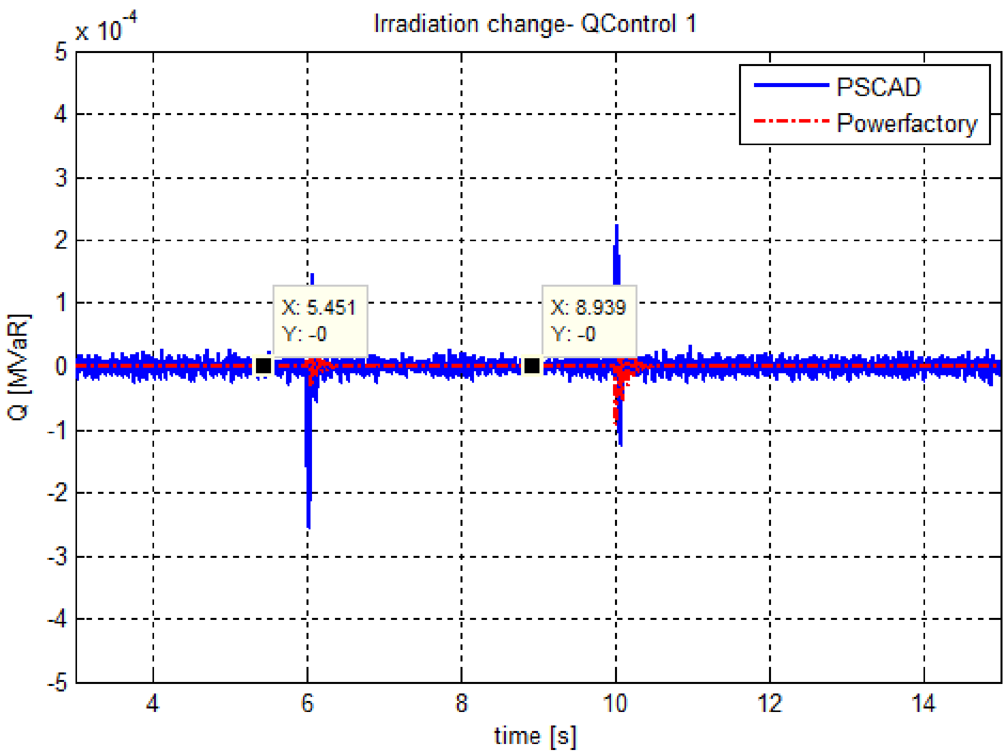

Fig. 5.7 Reactive power of the PV system

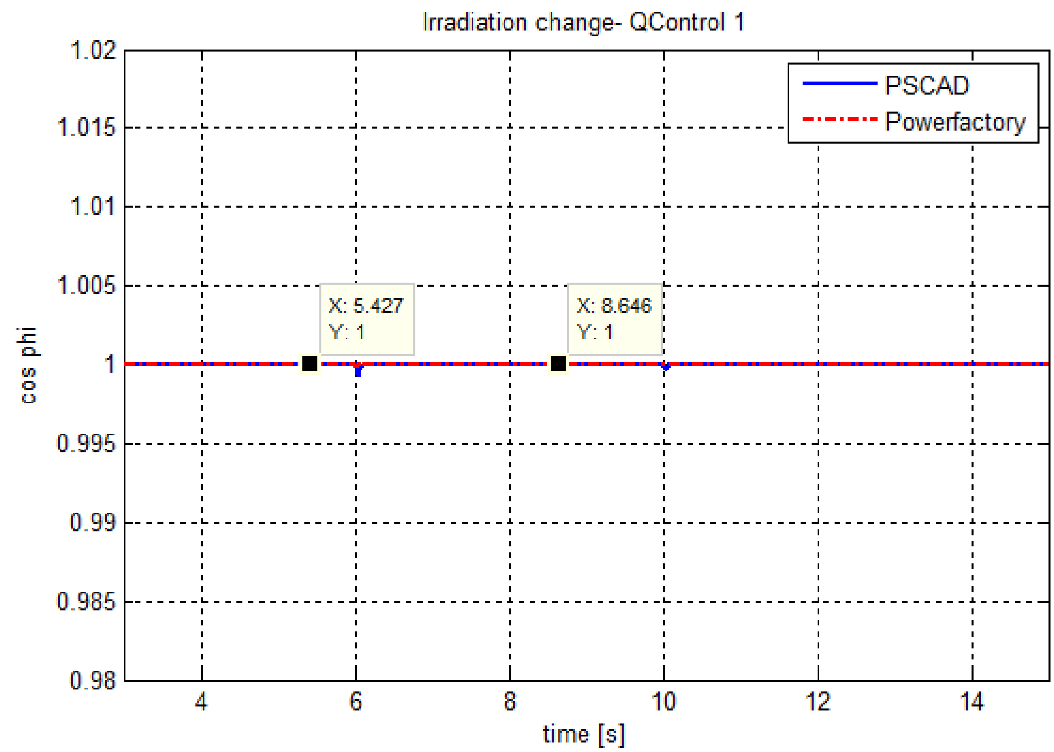

Fig. 5.8 Power factor of the PV system

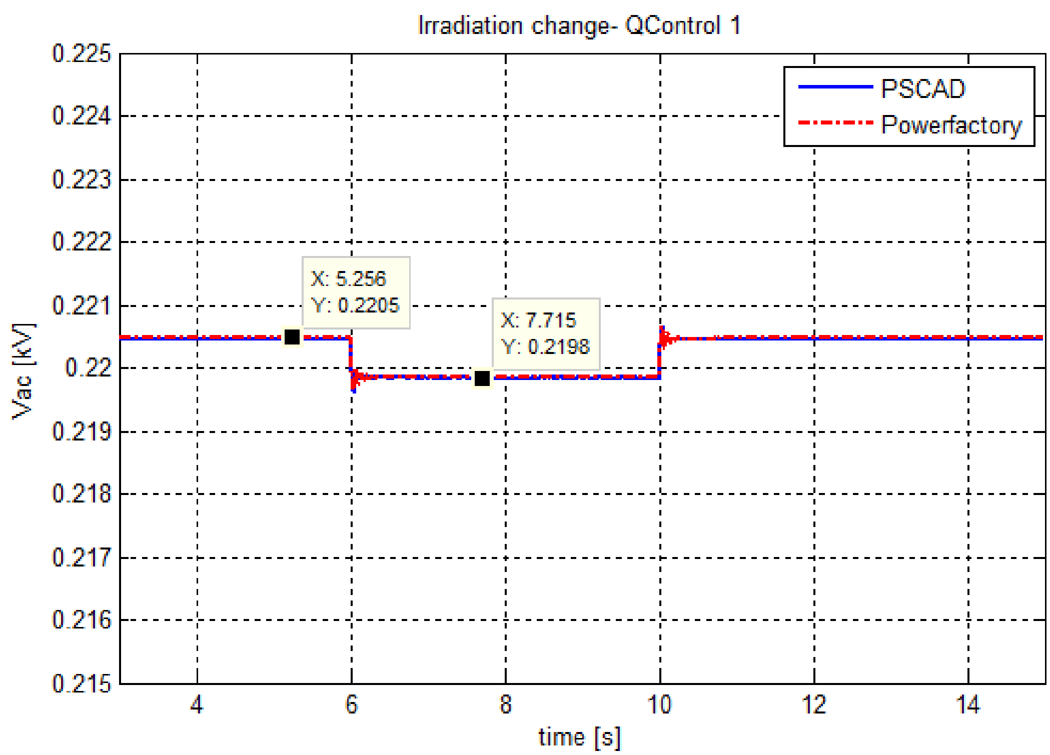

Fig. 5.9 AC voltage at terminal L2

2. Dynamic power factor operation- QControl 2

According to the power factor curve discussed in Fig. 2.13 the reactive power varies to keep the PV system power factor within 0.9 inductive and capacitive. When the PV system operates at STC then according to the curve the system should operate at 0.9 inductive power factor. The same response can be observed in Fig. 5.10 which shows the reactive power output of the PV system. During 0.0101 MW active power output of the PV system which is the STC state, the reactive power is absorbed from the grid making the PV system power factor to 0.9 inductive. Then during the irradiation change interval from 6-10 seconds, less active power output. According to the curve when the active power output is half the maximum then the power factor output is unity. So the absorption of reactive power from the grid is decreased to get a near unity power factor and can be observed the same in Fig. 5.11 which is the power factor curve of the PV system.

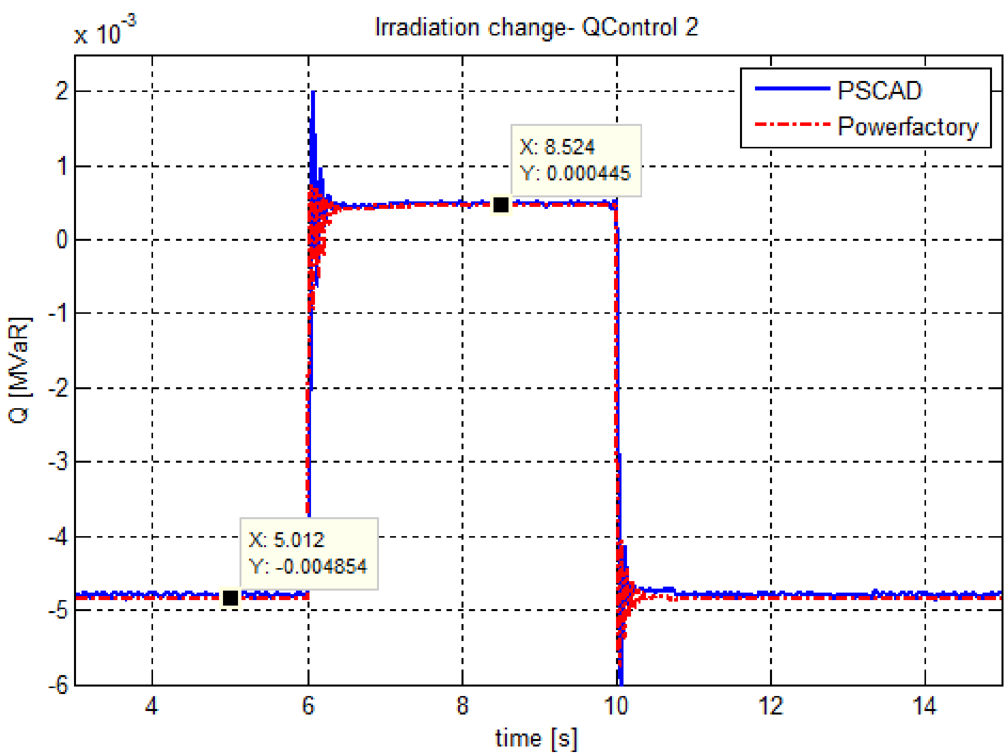

Fig. 5.10 Reactive power of the PV system

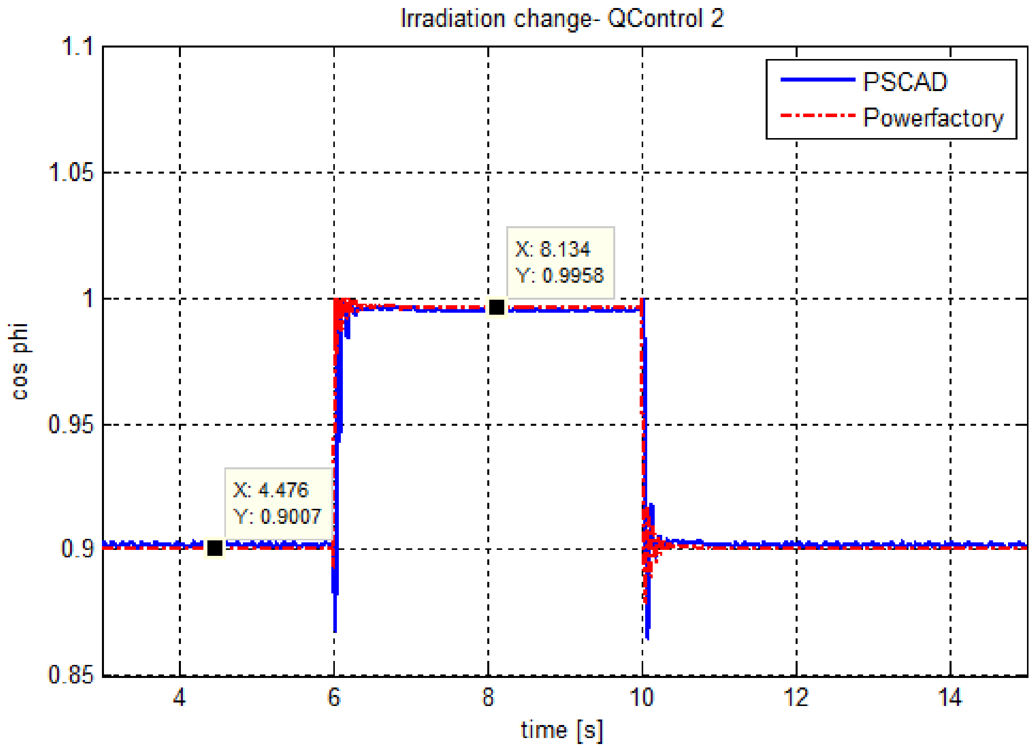

Fig. 5.11 Power factor of the PV system

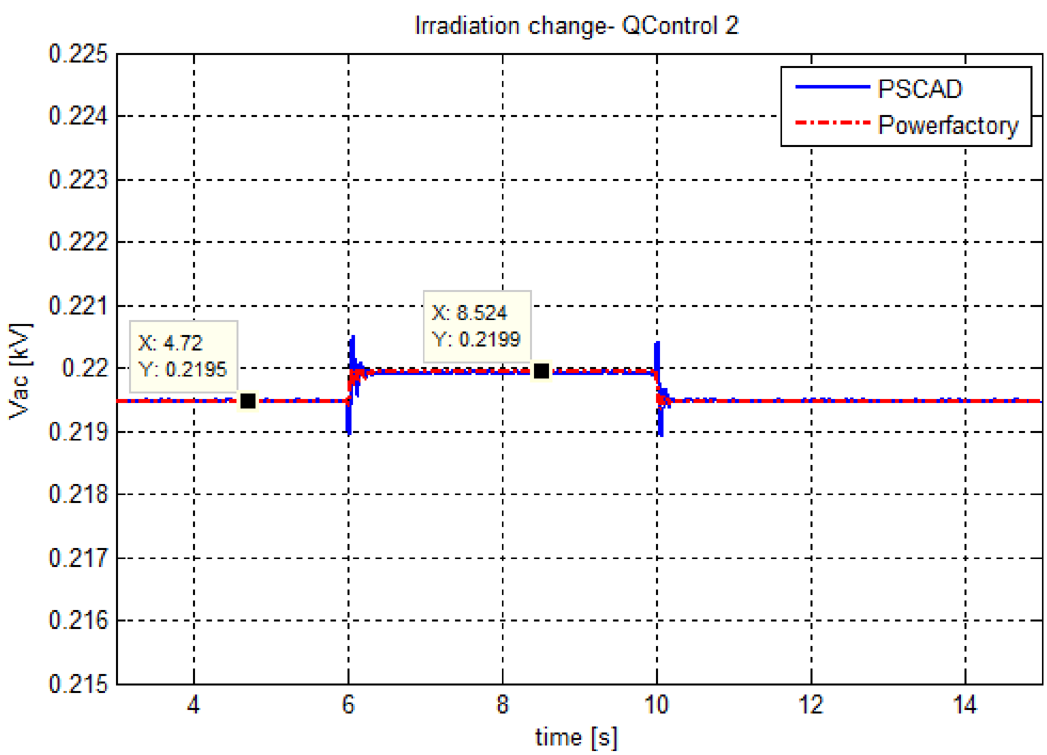

Fig. 5.12 AC voltage at L2 terminal

Fig. 5.11 shows that initially the PV system operates at 0.9 inductive power factor and during irradiation change the power factor of the system reaches unity. Finally once the irradiation reached back to 1000 W/m^2 from 500 W/ m^2 the power factor once again returns back to 0.9 inductive. During this mode of reactive power control, the AC voltage is not controlled which is free to vary and the response of the AC voltage is shown in Fig. 5.12.

During STC, the AC voltage of the system during dynamic power factor operation decreases as compared with the AC voltage of the system during unity power factor operation shown in Fig. 5.9. This is due to the inductive power factor operation of the PV system which absorbs reactive power from the grid.

3. Droop based reactive power control Q(U)- QControl 3

Droop based control is designed to avoid unwanted injection of reactive power when the voltage variation at the grid is within the dead-band and is designed based on the control curve shown in Fig. 4.16. For the current system the dead-band is given to be 0.03 which means 3% voltage variation with respect to the actual grid voltage is allowed. Fig. 5.13 shows the reactive power output and Fig. 5.14 shows the AC voltage at terminal L2.

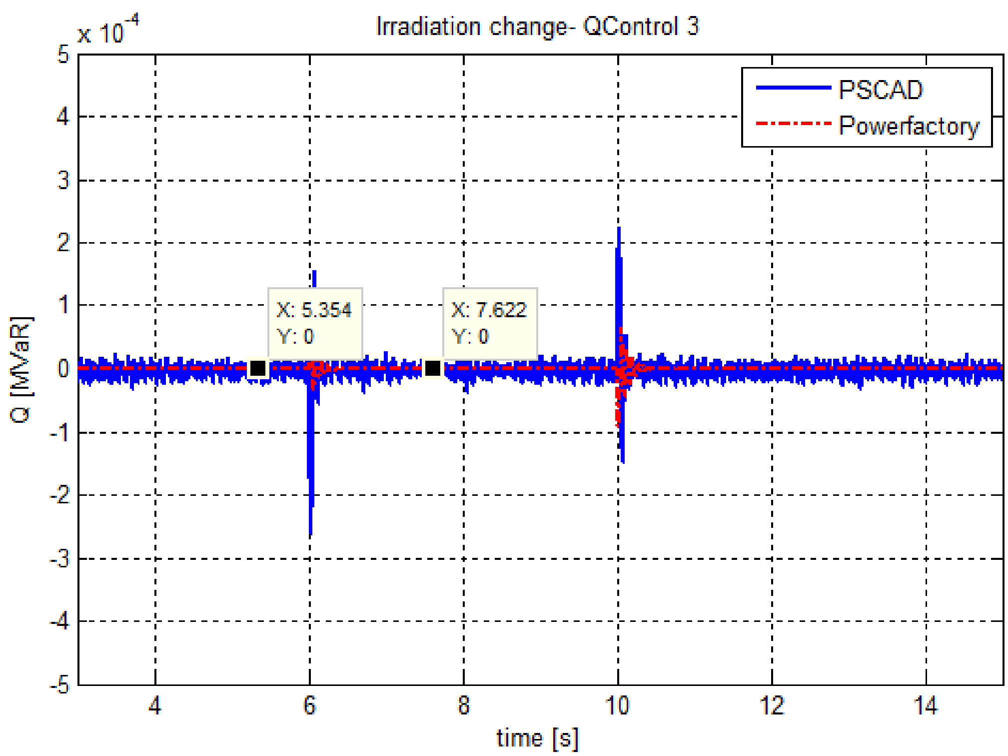

Fig. 5.13 Reactive power output of the PV system

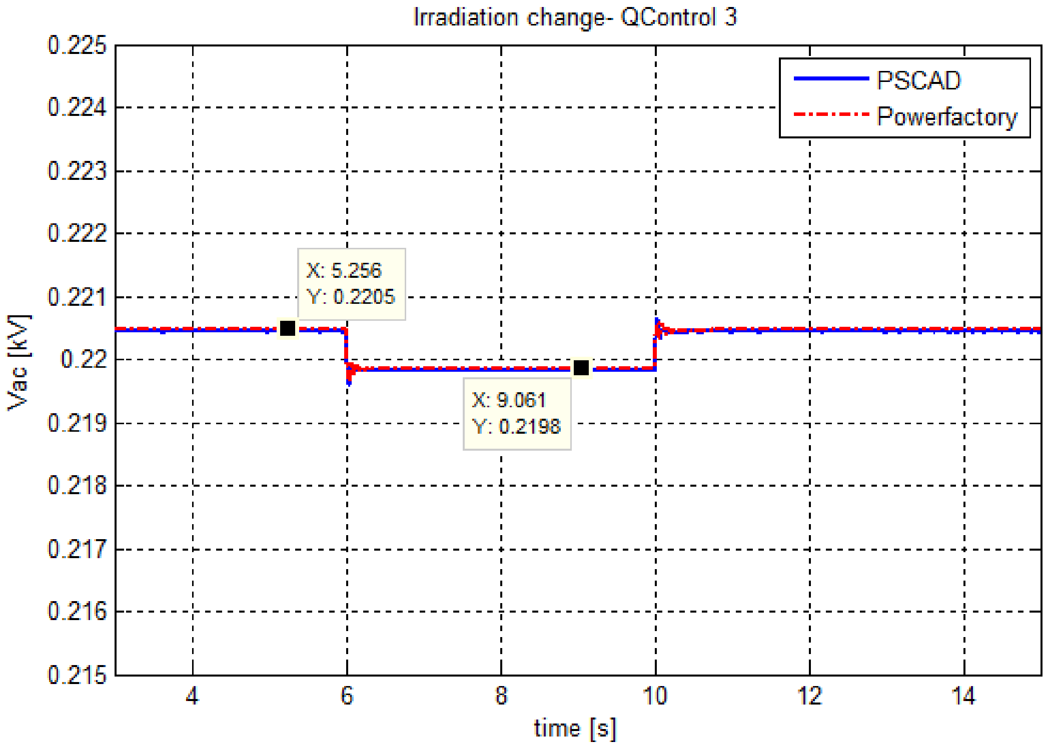

Fig. 5.14 AC voltage at terminal L2

As shown in Fig. 5.13 the reactive power injection is zero at all the simulation time since the voltage variation is within the dead-band of 3%. The AC voltage varies according to the disturbance in the PV system as shown in Fig. 5.14 but is not high enough to initiate any reactive power injection/absorption.

4. AC voltage regulation – QControl 4

Fig. 5.5 and Fig. 5.6 shows the system behavior when the reactive power control is implemented through AC voltage regulation. Through AC voltage regulation it is tried to keep the voltage at L2 at a certain defined level. In this case the pre-defined voltage level is the voltage of the grid at half the rated power of the PV. To be clear the current rated output power at STC out of PV system is 0.0101 MW and half of that will be 0.0055 MW. So at any operating condition, the voltage at the grid should be equal to the voltage during 0.055 MW PV output power. This value was found to be equal to 0.22 kV line-ground at L2. So through the current control the voltage should remain at 0.22 kV during disturbance provided sufficient reactive power limits are there.

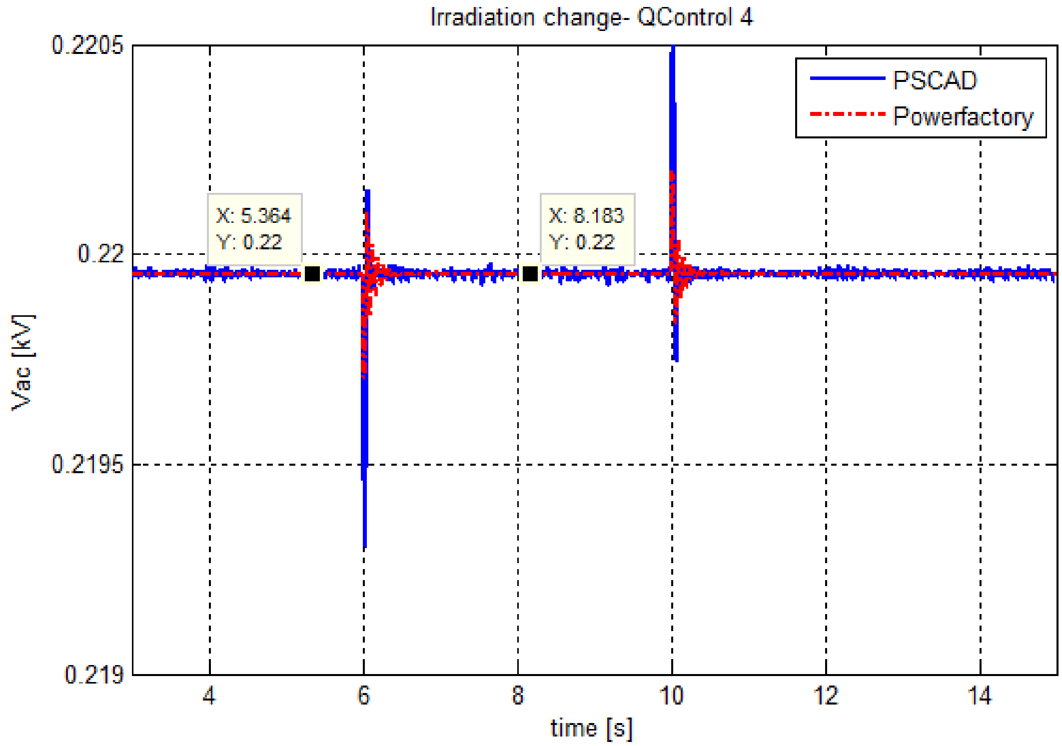

Fig. 5.5 AC voltage at L2 terminal

From Fig. 5.5 it is clear that the voltage at CCP is kept at 0.22 kV because of AC voltage control. Initially due to the connection of the PV system into the grid the voltage at CCP increases, which is then brought back to the set value of the AC voltage 0.22 kV. This is accomplished with the absorption of reactive power from the grid and is clearly shown in Fig. 5.6. During the 6^{th} second, with the decrease in active power due to the change or decrease in irradiation the voltage get decreased. In this case in order to keep the voltage within 0.22 kV it is not required to absorb that much reactive power as it was required for 0.0101 MW PV output. Fig. 5.6 shows a similar behavior as explained, i.e. during the time interval 6-10 sec, the amount of reactive power absorbed from the grid got reduced and is less as compared with other time during which there is maximum PV output into the grid.

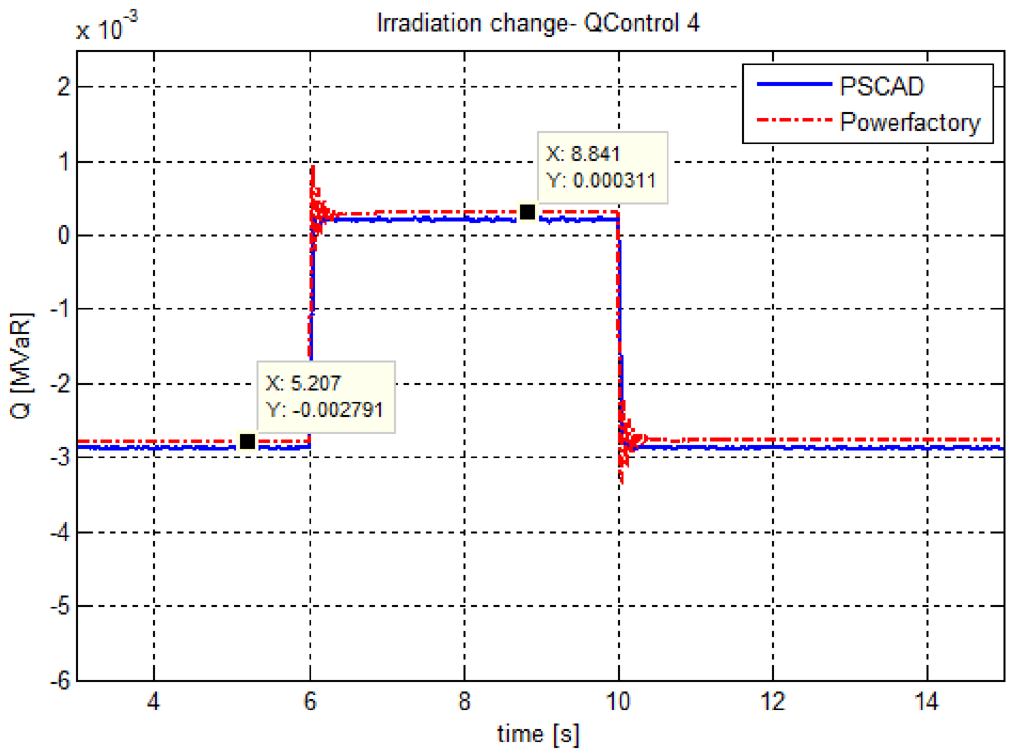

Fig. 5.6 Reactive power of the PV system

5.2.2 Scenario 2: Change in external grid voltage

The second case study is executed to understand how the PV system will behave when there is disturbance in the AC side of the system. The disturbance in the AC side is the change in the external grid voltage. The decrease or increase of external gird voltage is achieved by a parameter event in Power factory. In PSCAD the external grid voltage can be changed directly according to the requirement. The case study is carried out for two different voltage variation levels and the reactive power controls used are QControl 3 and QControl 4.

1. Grid voltage decrease by 1% with QControl 4

When the grid voltage is decreased by 1%, i.e. from 20 to 19.8 kV the response of the DC voltage and the active power output of the PV system is shown in Fig. 5.15 and Fig. 5.16 respectively.

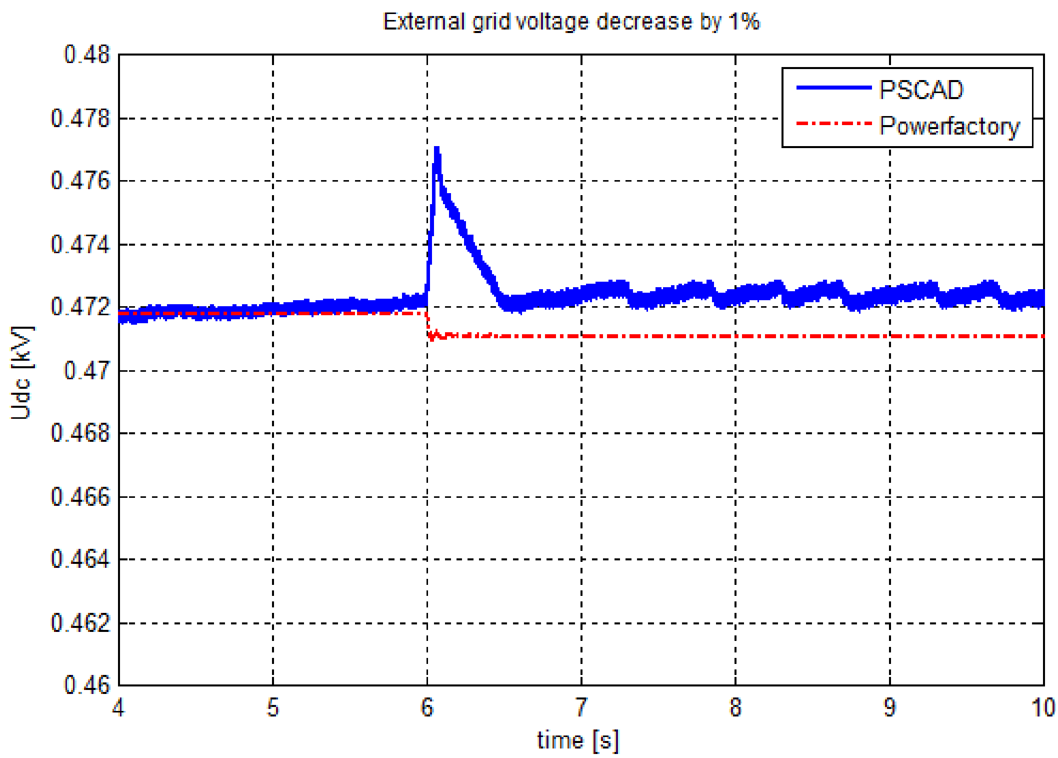

Fig. 5.15 DC voltage of the PV system

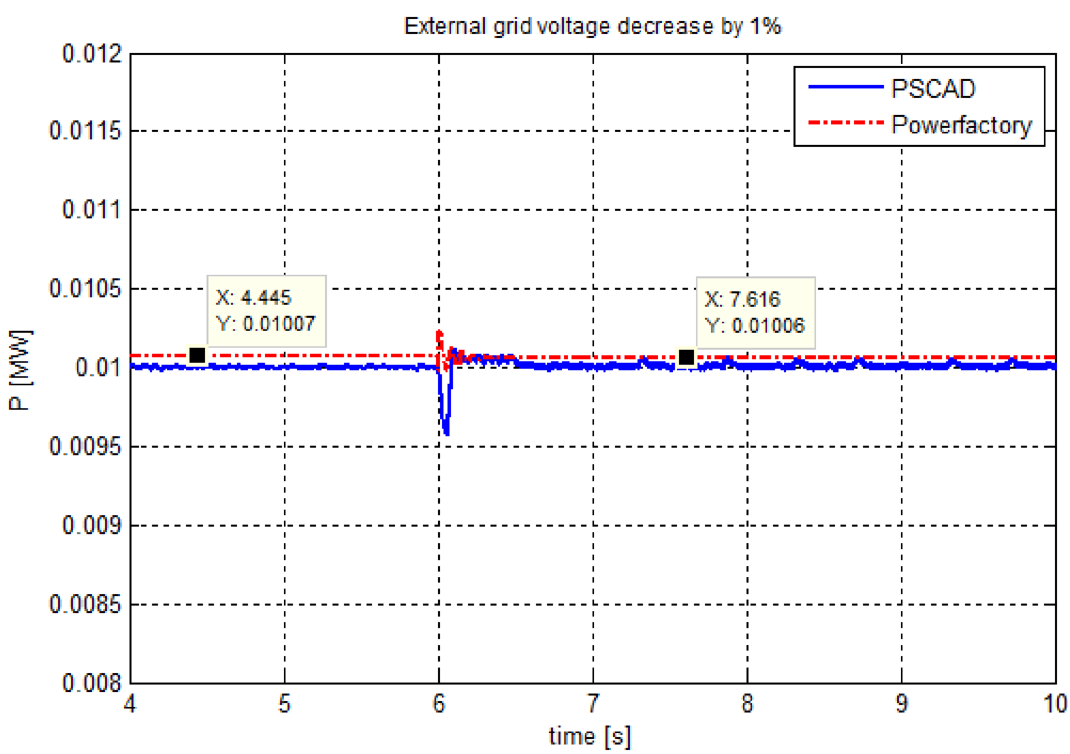

Fig. 5.16 Active power of the PV system

The DC voltage shown in Fig. 5.15 shows a difference in response. In case of Power factory model the DC voltage increases, then decreases and settles at a lower value. But in case of PSCAD model the DC voltage increases and then comes back to the original value. This difference is due to the discrepancy in the realization of MPPT in the two models. When the active power curve Fig. 5.16 is examined it is clear that in both Power factory and PSCAD the active power decreases initially due to the decrease in voltage and then settles back to the original or actual value. So the discrepancy in the DC voltage waveform can be neglected in this situation. Fig. 5.17 and Fig. 5.18 show the AC voltage and reactive power waveforms and will be explained further.

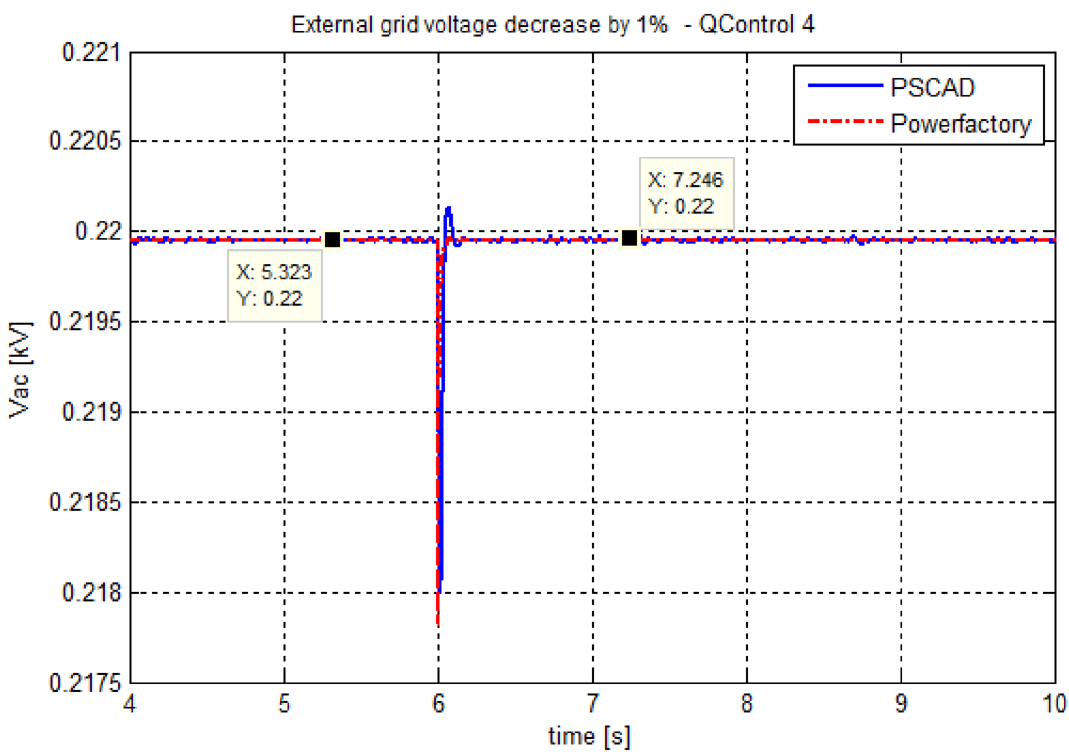

Fig. 5.17 AC voltage at terminal L2

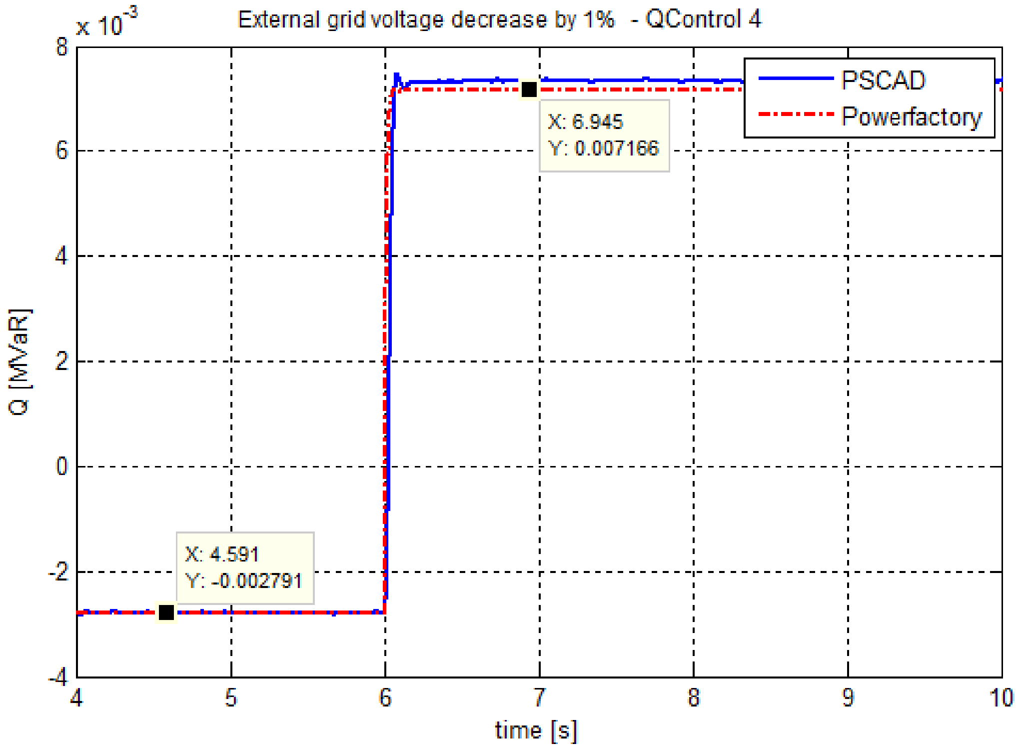

Fig. 5.18 Reactive power of the PV system

As expected the AC voltage shown in Fig. 5.17 decreases during external grid voltage drop, but QControl 4 helps to reach back the voltage to its original value. Due to QControl 4 it is necessary to keep the voltage at the predefined voltage level of 0.22 kV during disturbance in the system. So the reactive power which is absorbed from the grid as shown in Fig. 5.18 from 4-6 seconds is released during the voltage drop. This release or injection of reactive power helps to maintain the AC voltage at the grid to 0.22 kV as defined in the system during voltage drop. For this particular case the limits of the control is removed to examine the credibility of the QControl 4.

2. External grid voltage increase by 5% with QControl 3

In this case, the external grid voltage increases by 5% i.e. from 20 to 21 kV during the time interval 6^{th} -7^{th} second. The response of the PV system with the change in DC voltage and active power output is shown in Fig. 5.19 and Fig. 5.20. The DC voltage of the PV system decreases due to the initial increase in the active power of the PV system as a result of the increase in the AC voltage of the grid in case of Power factory. For PSCAD the DC voltage decreases and then comes back to its original value during the disturbance as expected due to MPPT action.

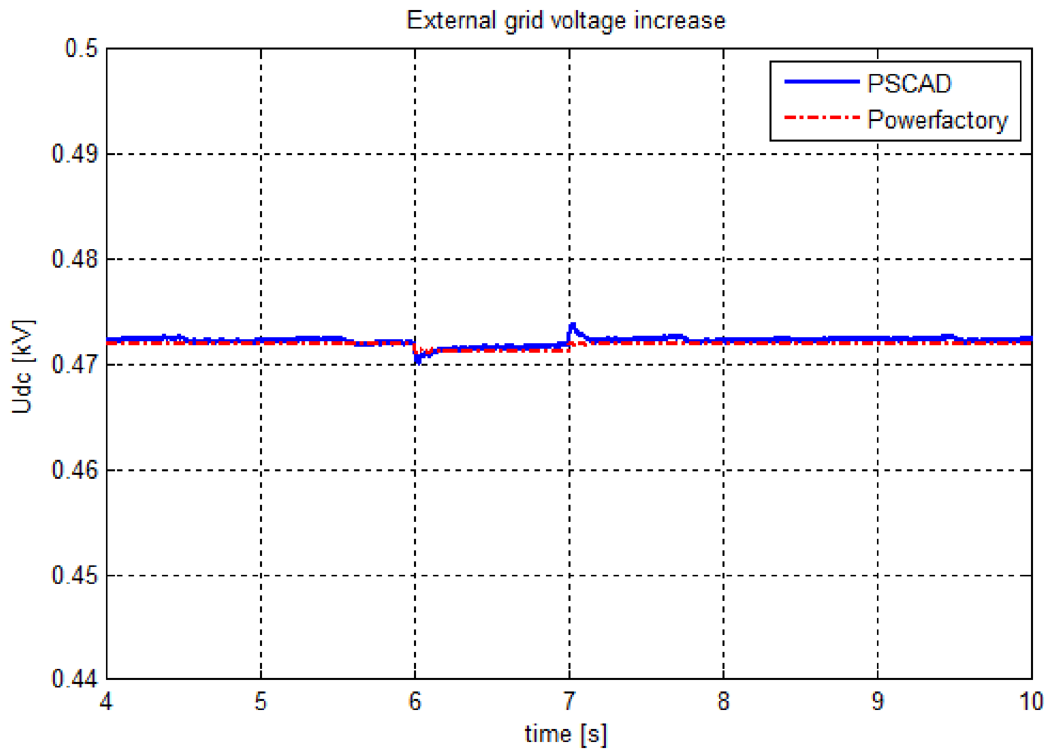

Fig. 5.19 DC voltage of the PV system

The active power output of the PV system in both Power factory and PSCAD models increases and then comes back to the original value, as shown in Fig. 5.20

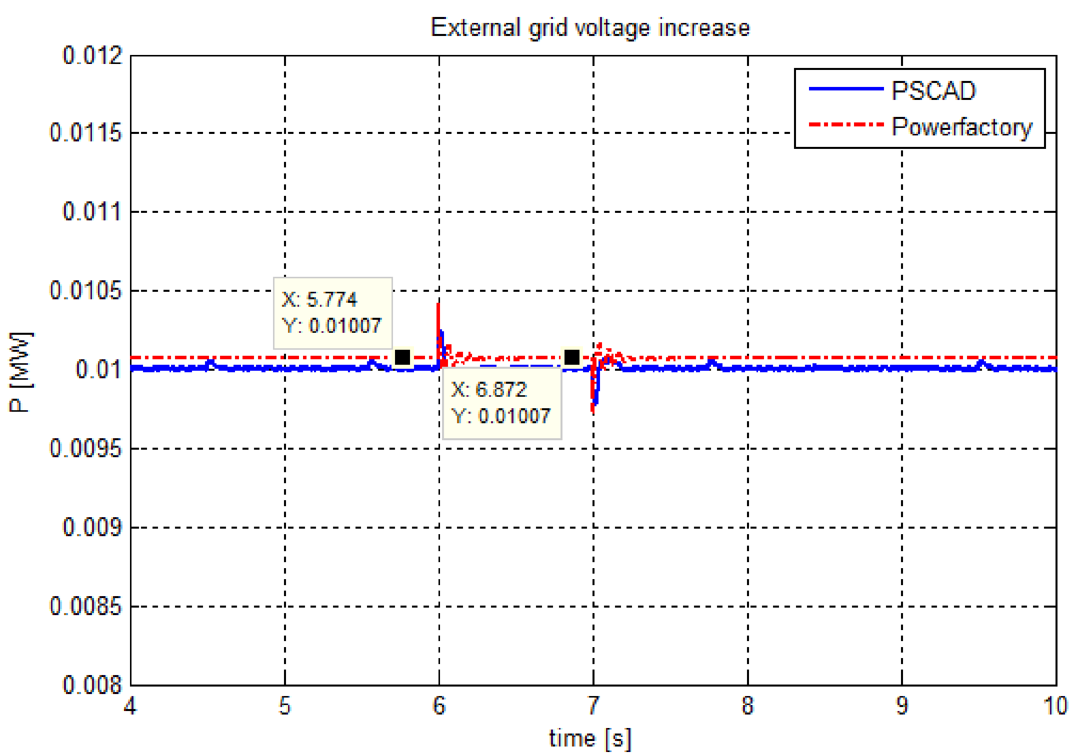

Fig. 5.20 Active power of the PV system

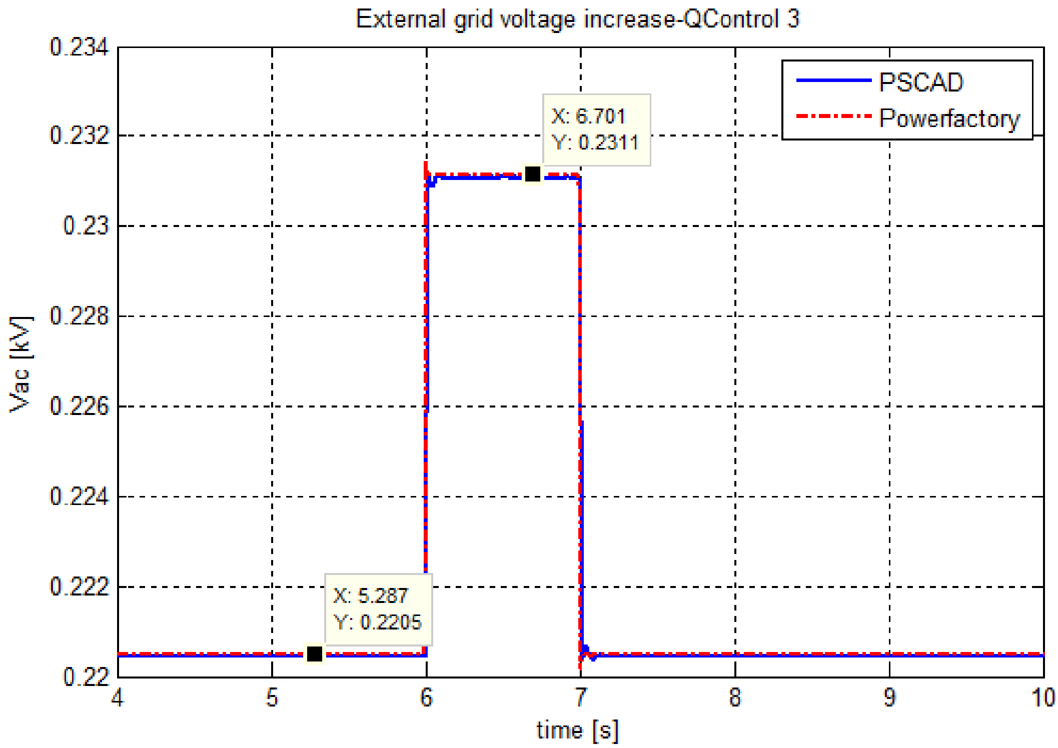

Fig. 5.21 AC voltage at terminal L2

The reactive power control used here is the QControl 3 which is the droop curve based reactive power injection. The AC voltage at terminal L2 is shown in Fig. 5.21 in which the AC voltage increases during the disturbance. Based upon this variation in AC voltage the reactive power injection happens and is shown in Fig. 5.22.

Since the variation of AC voltage is within the dead band range there is no reactive power injection during steady state. During the disturbance which is the increase of external grid voltage by 5%, the variation of AC voltage is clearly outside the dead band which will initiate some reactive power injection based upon the Q(U) curve shown in Fig.4.16. So with an increase in AC voltage there is a decrease in reactive power i.e. the reactive power is absorbed from the grid.

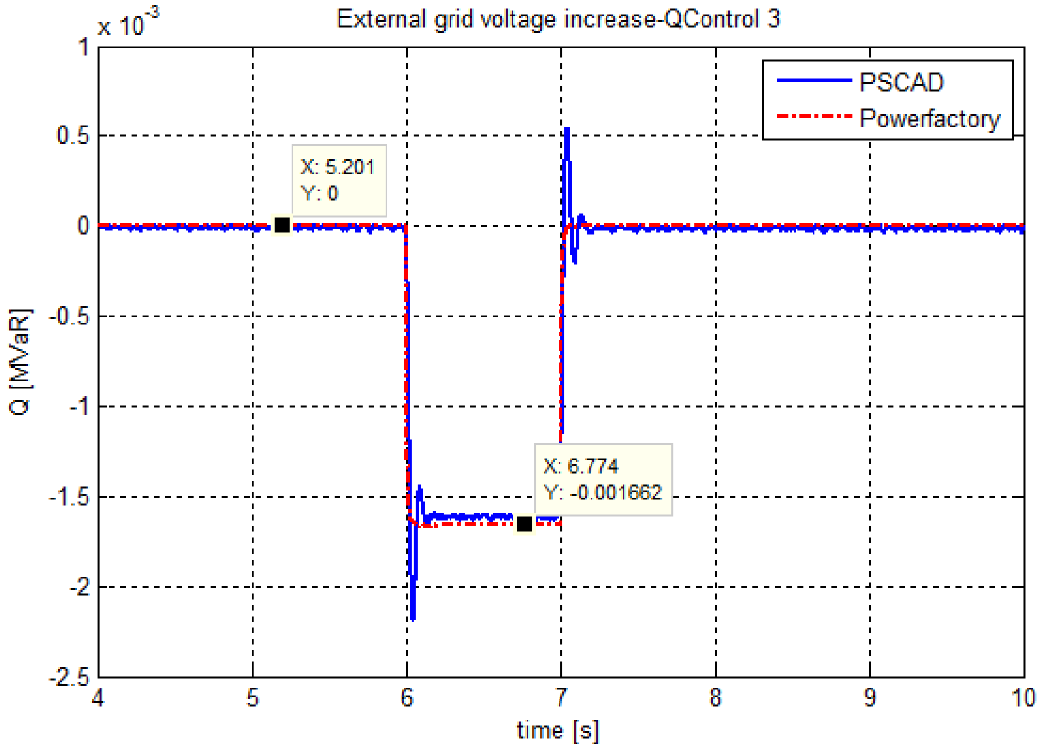

Fig. 5.22 Reactive power of the PV system

5.2.3 Scenario 3: Three-phase short circuit at CCP

Scenario 3 is to understand the new PV model response when high intensity and fast disturbance like short circuit happens in the power system. A three phase short circuit of impedance 0.008 Ω is created at terminal CCP using a short circuit event in Power factory. The three-phase circuit happens at 6th second and is cleared after 100 milliseconds. A similar disturbance is also created in PSCAD model in order to compare the results. The AC voltage of the system during short circuit is shown in Fig. 5.23, in which the AC voltage at terminal L2 drops to near zero value.

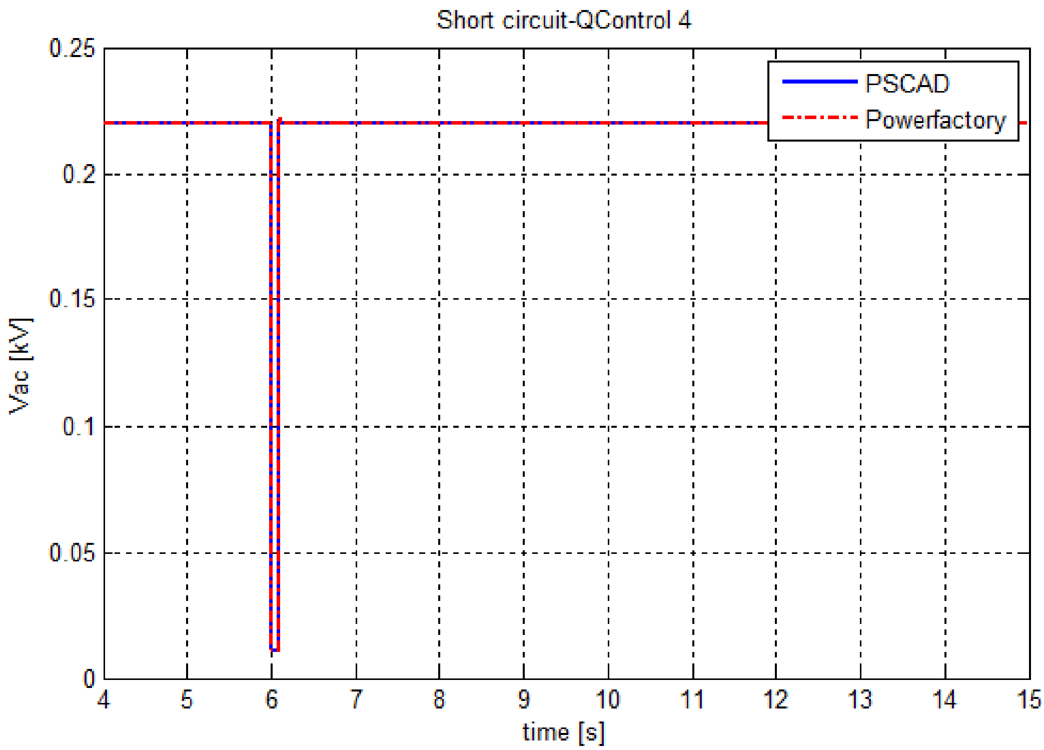

Fig. 5.23 AC voltage at terminal L2

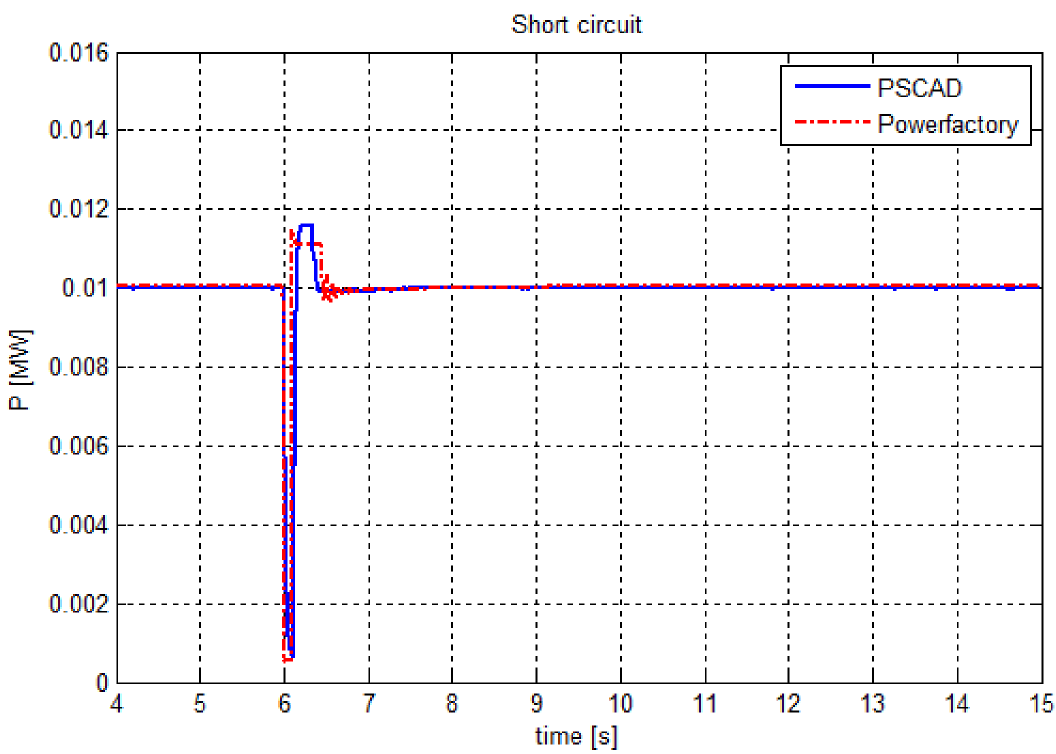

Fig. 5.24 Active power of the PV system

The active power of the PV system during disturbance is shown in Fig. 5.24. Due to the drop of AC voltage of the grid the active power of the PV system also decreases and reaches to a very low value near zero. Once the short circuit is removed from the system then the PV system returns back to its original value. There is an increase of active power for a short duration of nearly 200 ms after the removal of short circuit which can be explained when the DC voltage of the PV system shown in Fig. 5.25 is examined.

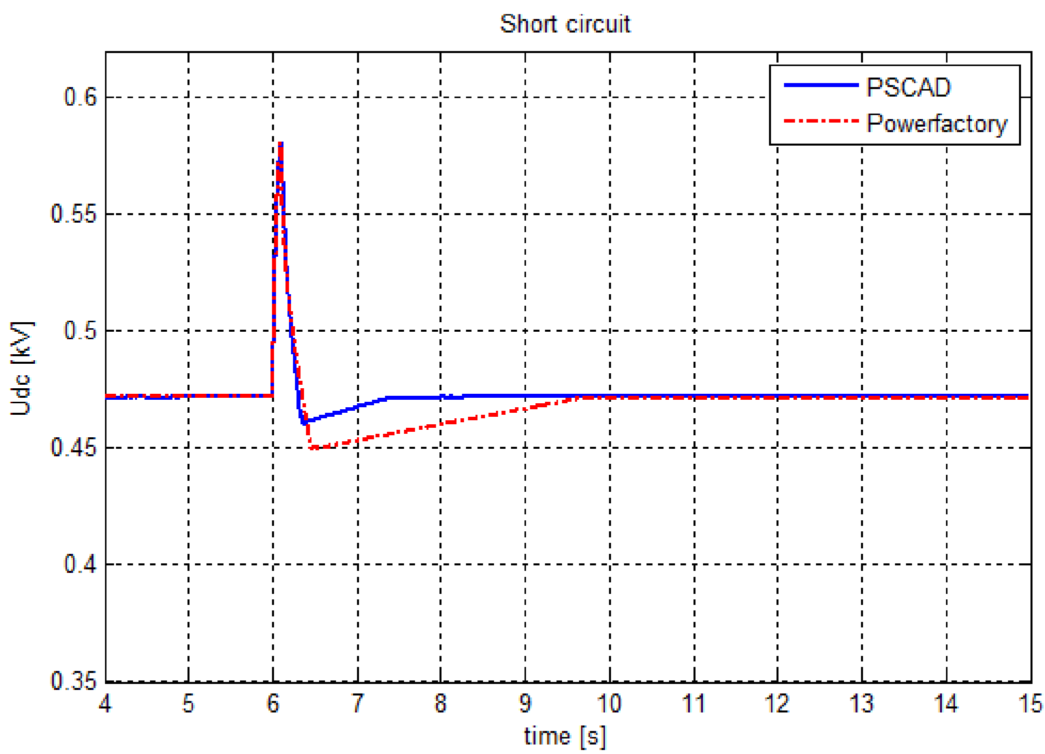

Fig. 5.25 DC voltage of the PV system

The DC voltage of the PV system increases due to the decrease in the active power output of the PV system during short circuit and almost reaches its open circuit voltage value of 0.589 kV. After removing the disturbance there is sudden increase of active power out of the PV system which causes a sudden drop of DC voltage and an increase of DC current of the PV system. Due to this increase of DC current the active power of the PV system increases for 200 ms after the removal of short circuit. The DC voltage as well as the active power of the PV system reaches back to its original value due to MPPT action after some time in both Power factory and PSCAD models. In case of PSCAD, the time within which the DC voltage reaches back to its original value is less as compared with the Power factory model. But the nature of response is same in both the models.

The reactive power out of the PV system is shown in Fig. 5.26. During disturbance the reactive power of the PV system reaches near zero value due to the drop of both AC voltage and active power of the PV system. Once the short circuit is removed, initially there is an injection of reactive power for a short duration. After that due to QControl 4 it is necessary to maintain the defined voltage level at terminal L2 which results in the absorption of reactive power from the grid.

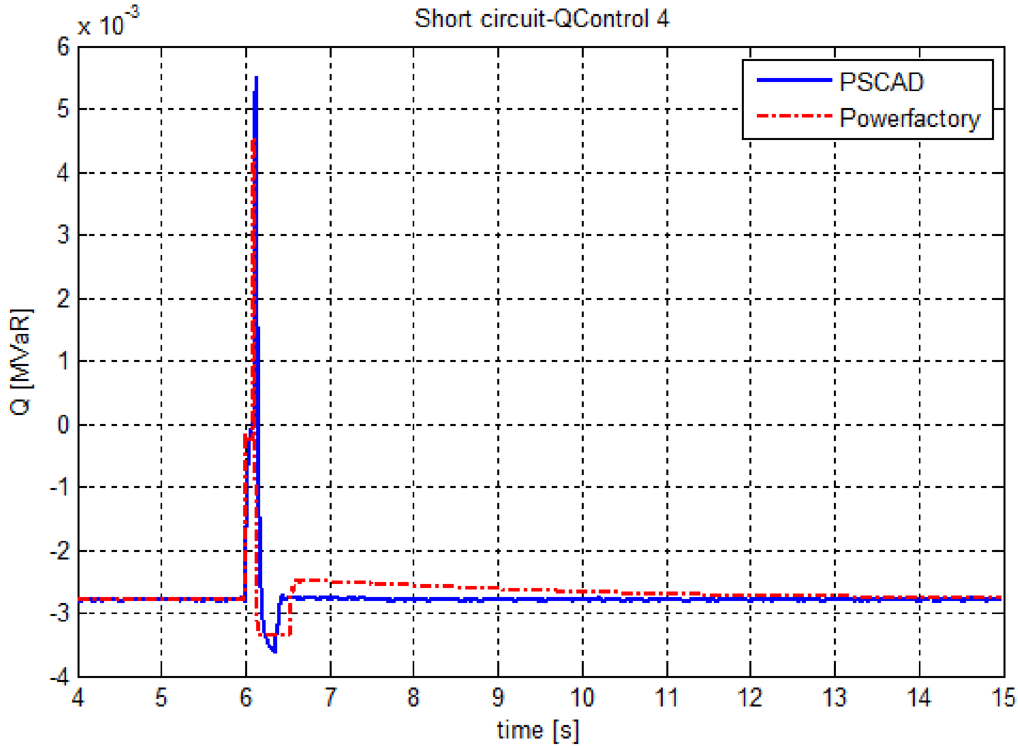

Fig. 5.26 Reactive power of the PV system

5.3 Validation of active power control

Active Power control method implemented especially for the Power factory model ensures the operator to reduce the active power out of the PV system when the PV system operates around its maximum rated power. The study is carried out to ensure the operation of this control. The switch included inside the active power block shown in Fig. 4.8 helps to decide in which mode the PV system should work. So in this case with a parameter event at time, t=2 seconds the parameter 'Act' is set to 1 which switches the active power mode to the mode in which it is possible to give the 'Pref' value. At 6^{th} second, the 'Pref' value is given as 0.00808 MW which is 80% of the rated PV output power of 0.0101 MW. Then at 10^{th} second 'Pref' is again inputted to be 0.0101 MW, back to the original active power output. Fig. 5.27 shows the variation of DC voltage output and Fig. 5.28 shows the active power output of the PV system.

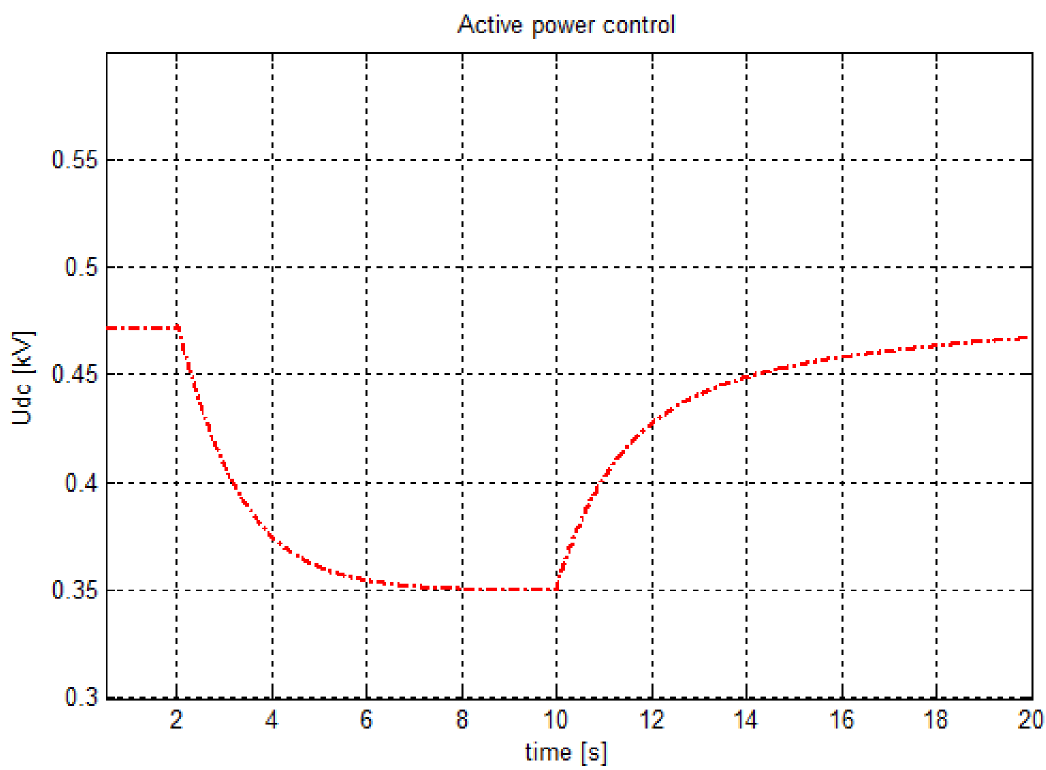

Fig. 5.27 DC voltage during active power control

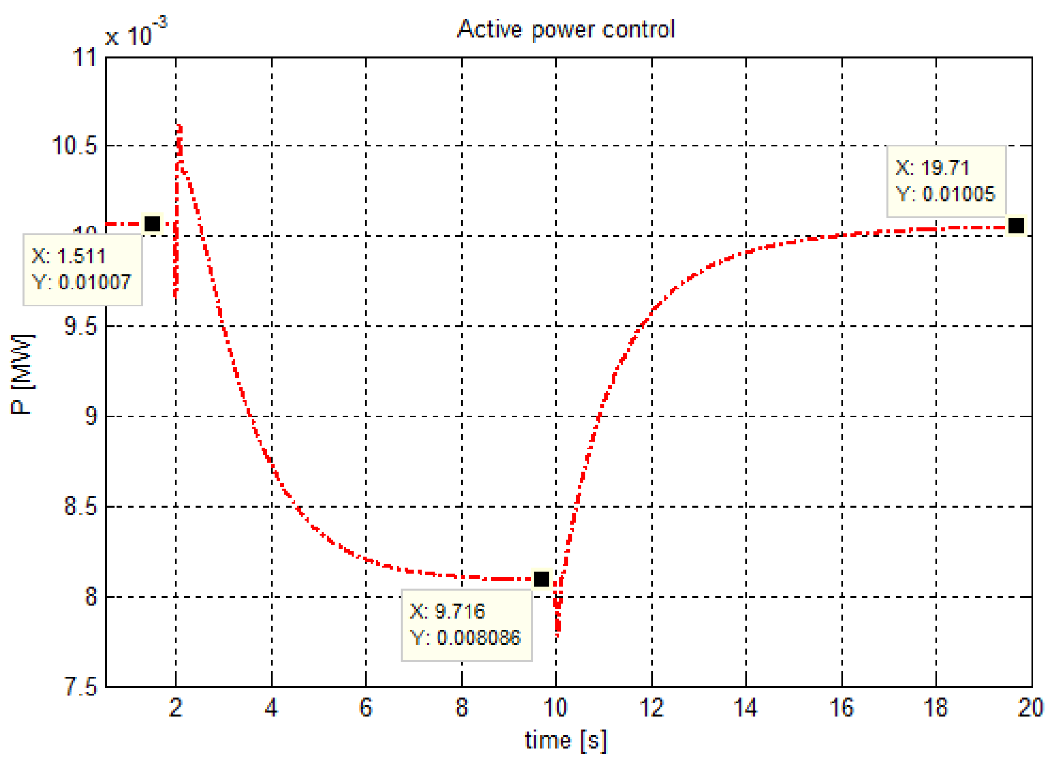

Fig. 5.28 Active power of the PV system

According to the above figures the active power control works fine according to the input power given. The active power decreases to the required value of 0.00808 MW during disturbance by decreasing 'Vdcref' and then again at 10th second controller ensures to bring back the active power to 0.0101 MW as given. During active power control, AC voltage regulation is used and the simulation results for AC voltage and reactive power are given in Appendix. 8.5.1.

5.3.1 Active power control based on system frequency

System frequency based active power control implemented along with the manual active power control is evaluated here. The system frequency is manually increased to 51 Hz from 50 Hz at time t=2 seconds. According to the regulation given in Fig. 2.12 the active power has to be decreased to 0.00686 MW for 51 Hz. Once the system frequency is back to 50 Hz then the actual active power output with MPPT should be supplied. Here with a parameter event supplied to the external grid the system frequency is decreased and then removed the event at 15th second. Fig. 5.29 shows the system frequency and Fig. 5.30 shows the variation of active power output of the PV system.

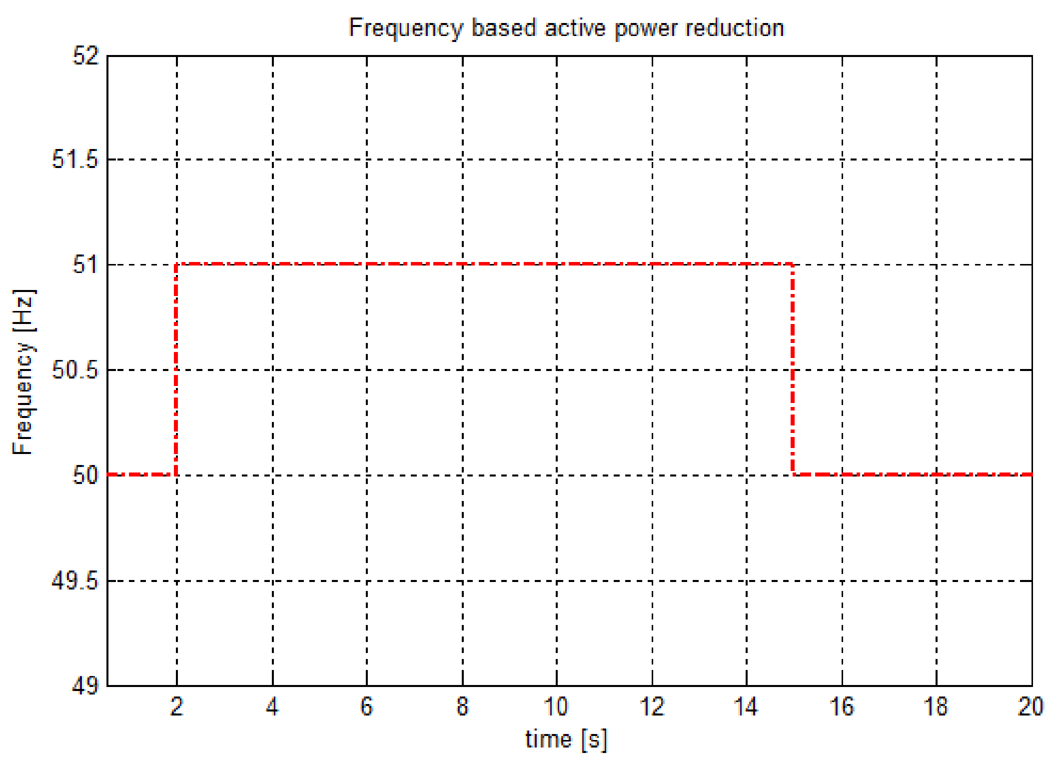

Fig. 5.29 System frequency

The active power of the PV system shown in Fig. 5.30 decreases to the value 0.006847 MW for an increase of frequency to 51 Hz at t=2 seconds. At 15th second once the frequency is back to 50 Hz the active power output comes back to its actual value of 0.0101 MW. The active power takes some time to reach its steady state values after disturbance due to MPPT and slow control mode.

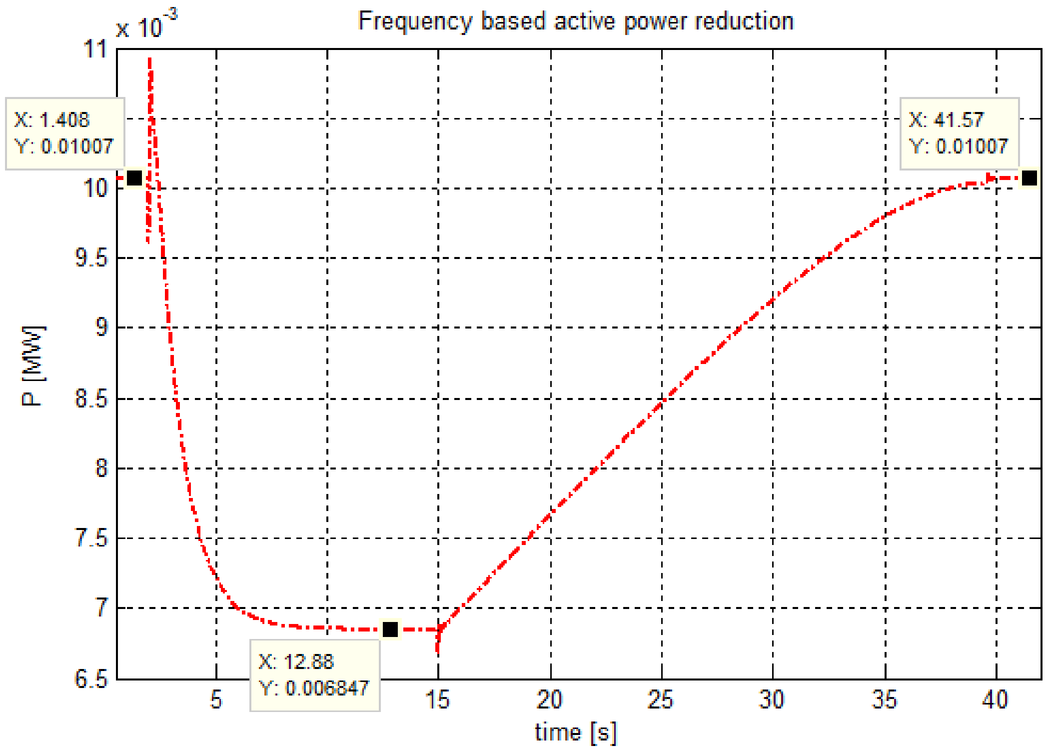

Fig. 5.30 Active power of the PV system

5.4 Evaluation of the effect of MPPT on the dynamic behavior of the system

In section 5.2.1 it is explained that one of the reasons for the difference in the dynamic behavior variation in the Power factory model is due to the difference in the realization of the MPPT in the two models. So this case study is performed to evaluate the same by removing the MPPT out of the system, keeping the 'Vdcref' constant. When 'Vdcref' is kept constant then 'Udc' will be constant at all conditions due to the DC voltage regulation included in the controller. The scenario used to evaluate the effect is the irradiation change which is the decrease of irradiation from 1000 to 500 W/m^2 at 6th second. Then at 10th second the irradiation is brought back to 1000 W/m^2. Fig. 5.31 shows the DC voltage and Fig. 5.32 shows the active power output waveforms.

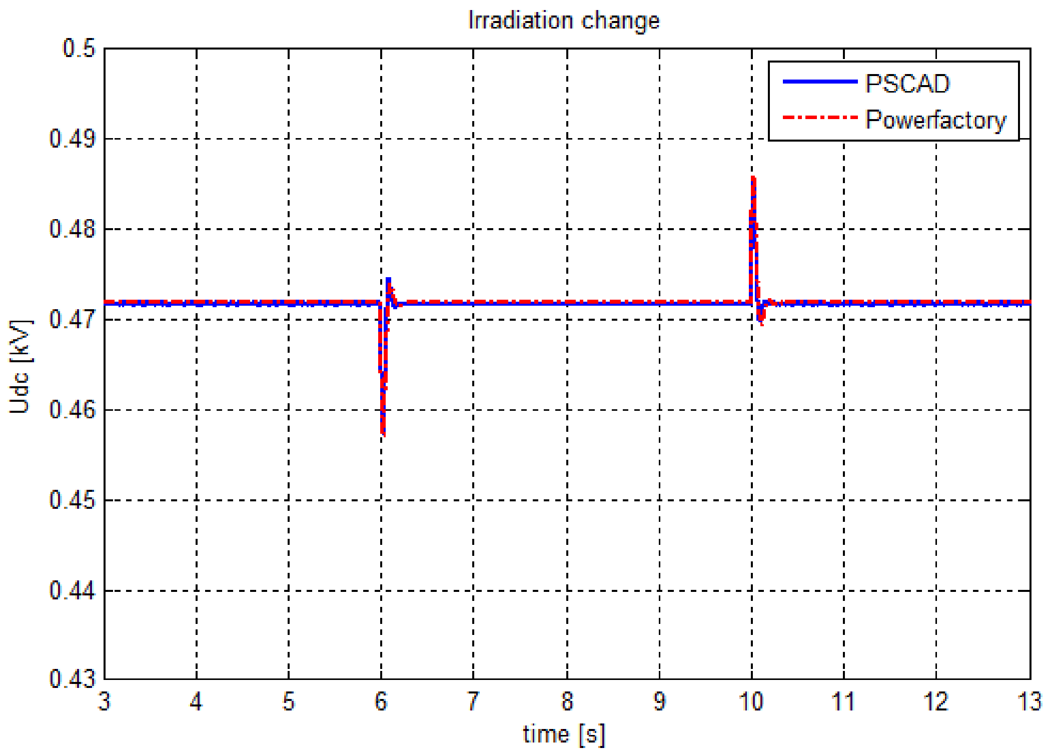

Fig. 5.31 DC voltage of the PV system

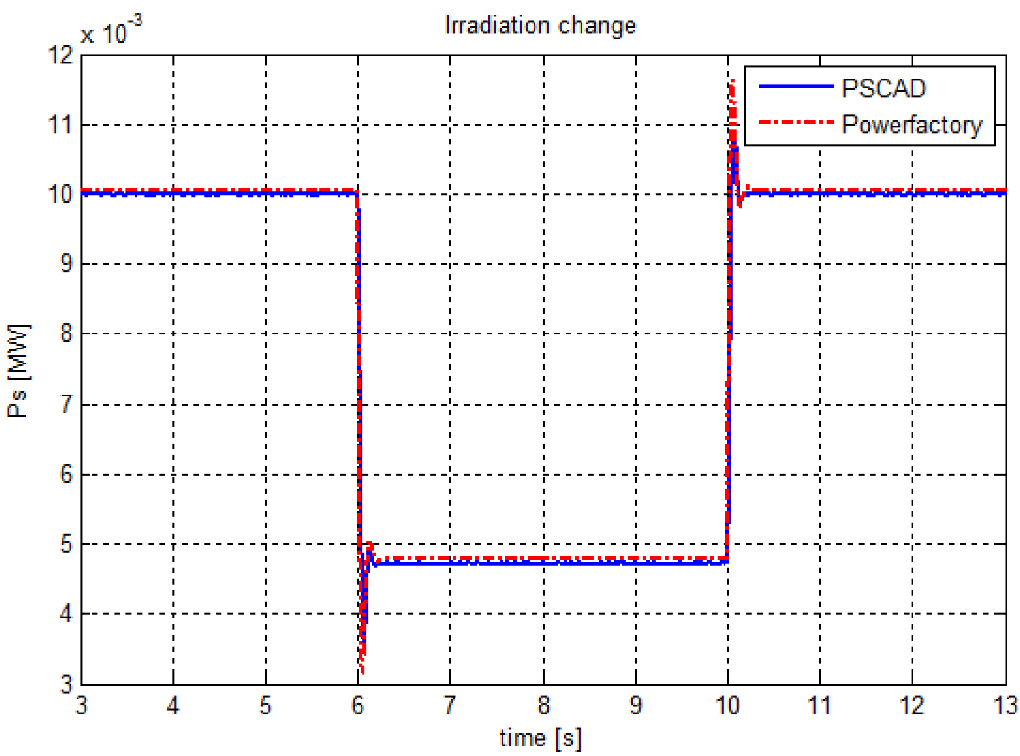

Fig. 5.32 Active power of the PV system

As seen in Fig. 5.32 the active power output decreases due to the irradiation change due to the decrease in DC current. To be noted here is the dynamic behavior during change in active power. In section 5.2.1 as compared with the PSCAD model the Power-factory model has got more oscillation during active power variation. But in Fig 5.32 the dynamic response of both the models are almost the same with less oscillation.

When the active power output of the system that are shown in Fig. 5.4 and Fig. 5.32 are analyzed more closely, another question arises here. What is the need of MPPT? Because both the active power output figures show almost the same output for the irradiation change. Without MPPT function also the system provides its maximum output, then why MPPT is required which is one of the reasons for dynamic oscillation. Fig. 5.33 shown below justifies the MPPT function in this context. The active power of the PV system during an increase of PV module temperature from 25 °C to 40 °C keeping the irradiation constant at 1000 W/m^2 is shown in Fig.5.33.

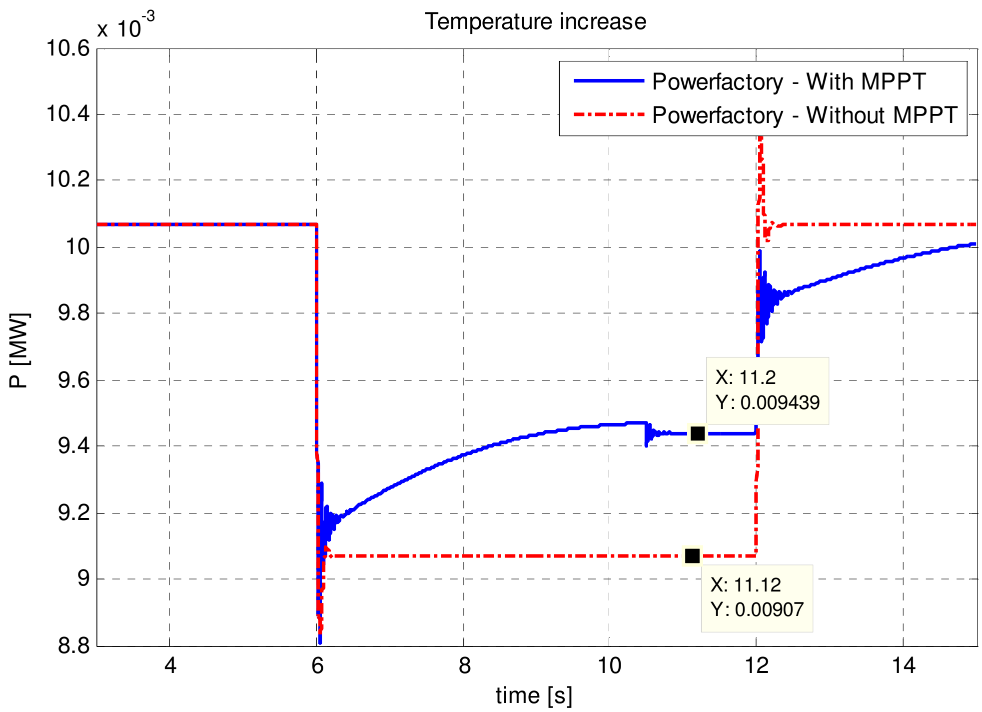

Fig. 5.33 Active power of the PV system

As shown in Fig. 5.33 the active power output of the PV system without MPPT function is lower than the active power output of the PV system equipped with MPPT function. During temperature variation that has got a direct influence on the DC output voltage, PV system with MPPT ensures maximum active power of the system as compared with the one without MPPT.

There are several parameters such as MPPT frequency, step, epsilon etc. that are required to be decided for the MPPT module. One of these variables that have got high impact on dynamic oscillation is the MPPT frequency. For the scenarios described in section 5.2 the MPPT frequency is 20 Hz, which is now changed to a higher value of 30 Hz to study the response. The scenario used to evaluate the system response is the change in irradiation and the DC voltage and active power outputs of the PV system in Power factory are shown in Fig. 5.34 and Fig. 5.35 respectively.

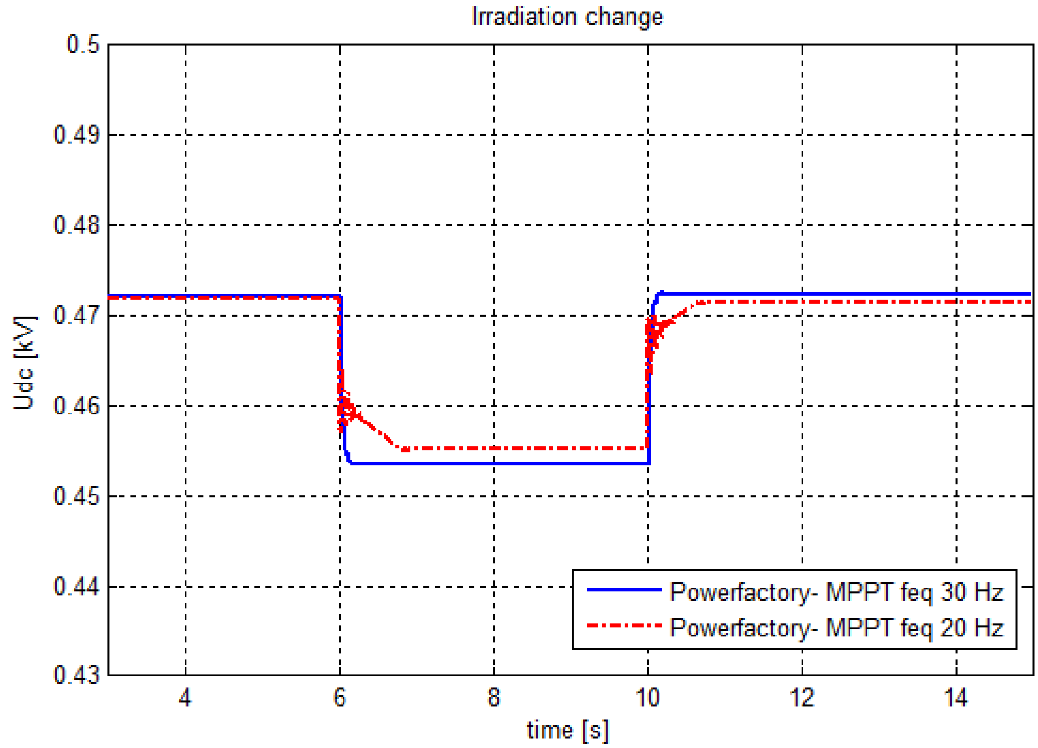

Fig. 5.34 DC voltage of the PV system

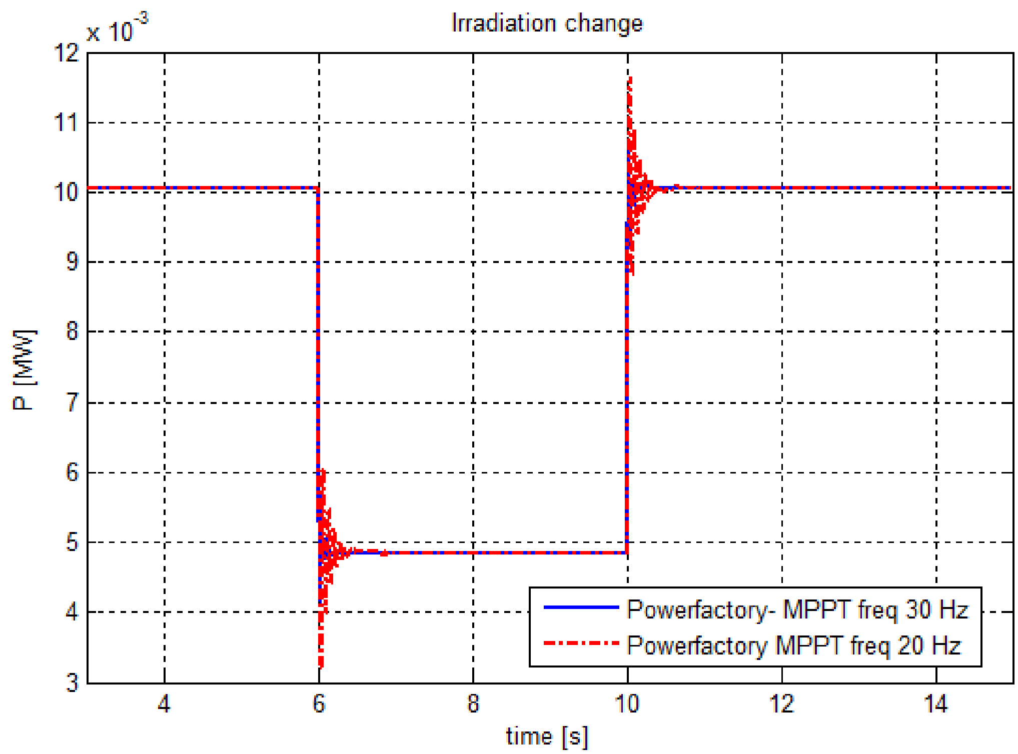

Fig. 5.35 Active power of the PV system

When the dynamic behavior of the model with two different MPPT frequency are compared, the model with an MPPT frequency 30 Hz has got less oscillation as compared with the model with an MPPT frequency of 20 Hz. Since MPPT frequency decides the speed of maximum power tracking it should also be noted here is the steady state value of the DC voltage shown in Fig. 5.34. Although the active power output of the PV system shown in Fig. 5.35 is same for both the frequencies there is discrepancy in the DC voltage output. DC voltage after removing the disturbance, that depends upon the 'Vdcref' coming out of the MPPT block settles to a value that is not equal to the previous steady state DC voltage. Hence if it is necessary to obtain a consistent DC voltage response during steady state, MPPT frequency needs to be equal to 20Hz for the Power factory model. Moreover it is to be mentioned here is that the PSCAD model does not work for MPPT frequencies higher than 26 Hz.

5.5 Effect on PV output with the change in design parameter of the DC voltage regulator

Another approach to reduce the oscillation during the dynamic response in the Power factory model is to change the design parameters of the DC voltage regulator. The design parameter that are changed from the previous design were K_{dc}- the gain of the DC controller, T_{ld}-the lead time constant of the lead-lag compensator and T_{lg}- the lag time constant of the lead-lag compensator given in Eqn. 4.5. The cross over frequency, WcV used in the Mat lab code given in Appendix 8.4 for the new controller design is 130 Hz which was 200 Hz and the phase margin, PM (Mat lab code given in Appendix 8.4) for the new controller is 70-Pm, was 60-Pm for the previous design. Based upon which the new controller parameters are obtained and the new results are simulation. Again the scenario used is the change in irradiation. DC voltage and active power output waveforms are shown in Fig. 5.36 and Fig. 5.37 respectively.

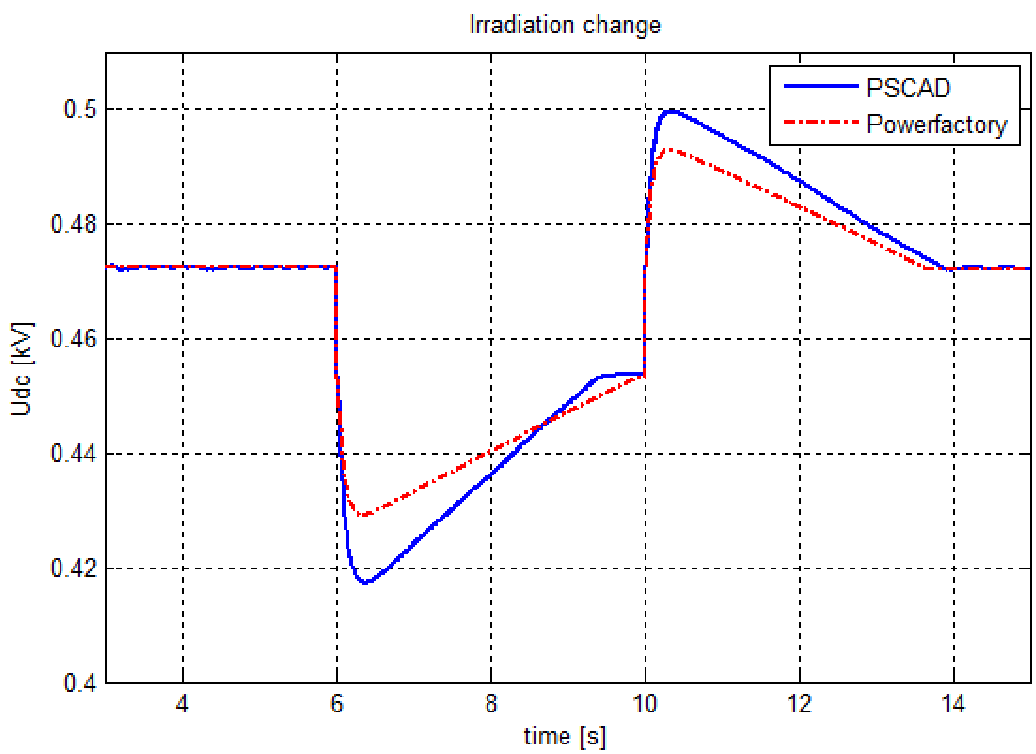

Fig. 5.36 DC voltage of the PV system

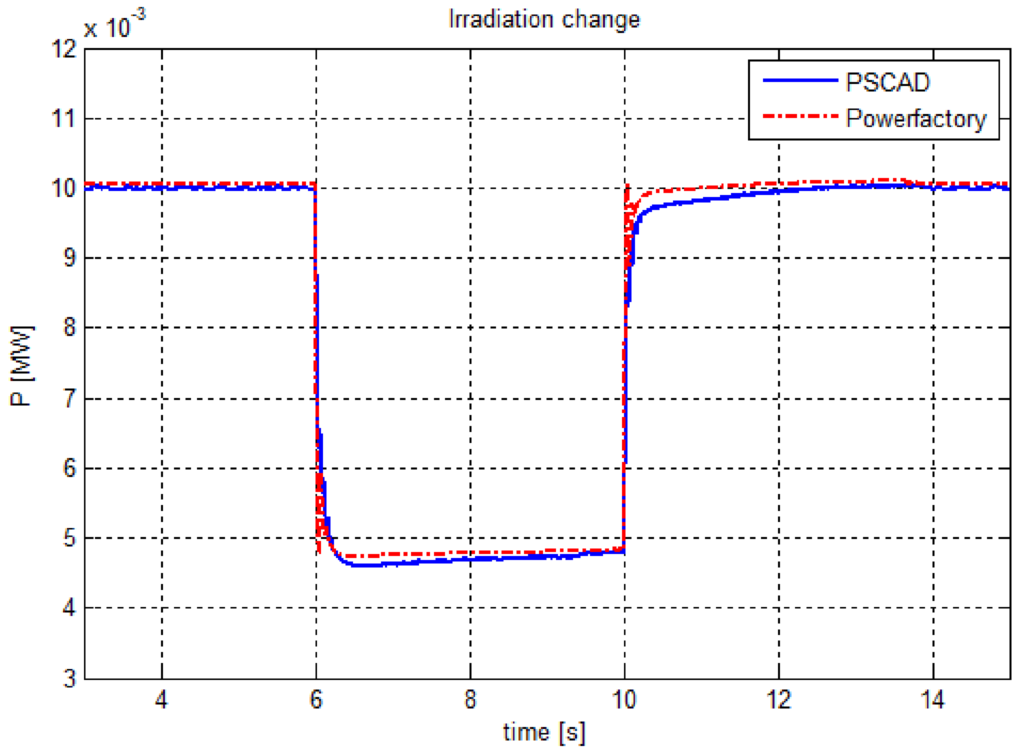

Fig. 5.37 Active power of the PV system

The DC voltage for the new controller design is smooth without oscillation but takes time reach the steady state value as compared with the previous controller design. When the gains are compared within the two controller designs, new controller has got less gain as compared with the actual controller design. The decrease in gain is a reason for the longer time the controller takes to reach the steady state value after disturbance. When the active power waveforms shown in Fig. 5.37 are compared, the oscillation during disturbance in the system got reduced to a considerable level in the new controller. So this approach to reduce the oscillation during disturbance can be utilized during system studies.

5.6 Result analysis for new DC voltage regulator using PI controller

In section 4.3.2 (a) the new DC voltage regulation using a simple PI controller is discussed. The result analysis for various scenarios using the new PI controller is performed in the current section. The scenarios mentioned here is exactly the same as explained in sections 5.2.1, 5.2.2 and 5.2.3. **DC control design 2 is the DC regulation with PI controller and DC control design 1 is the DC regulation with the lead-lag compensator.**

5.6.1 Scenario 1: Change in irradiation

The DC voltage and active power output of the PV system are shown in Fig. 5.38 and Fig. 5.39 respectively.

The responses clearly show the decrease in oscillation in both DC voltage and active power output of the PV system. DC regulator with the PI controller takes time to reach the steady state value after disturbance than the DC regulator with the lead lag compensator.

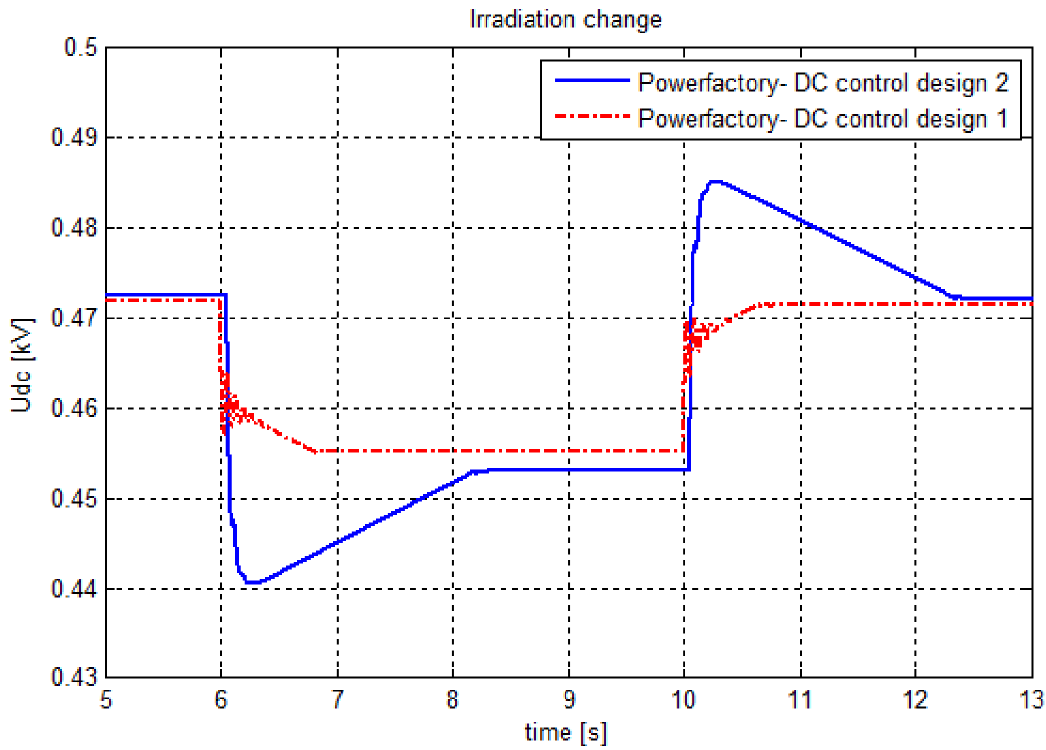

Fig. 5.38 DC voltage of the PV system

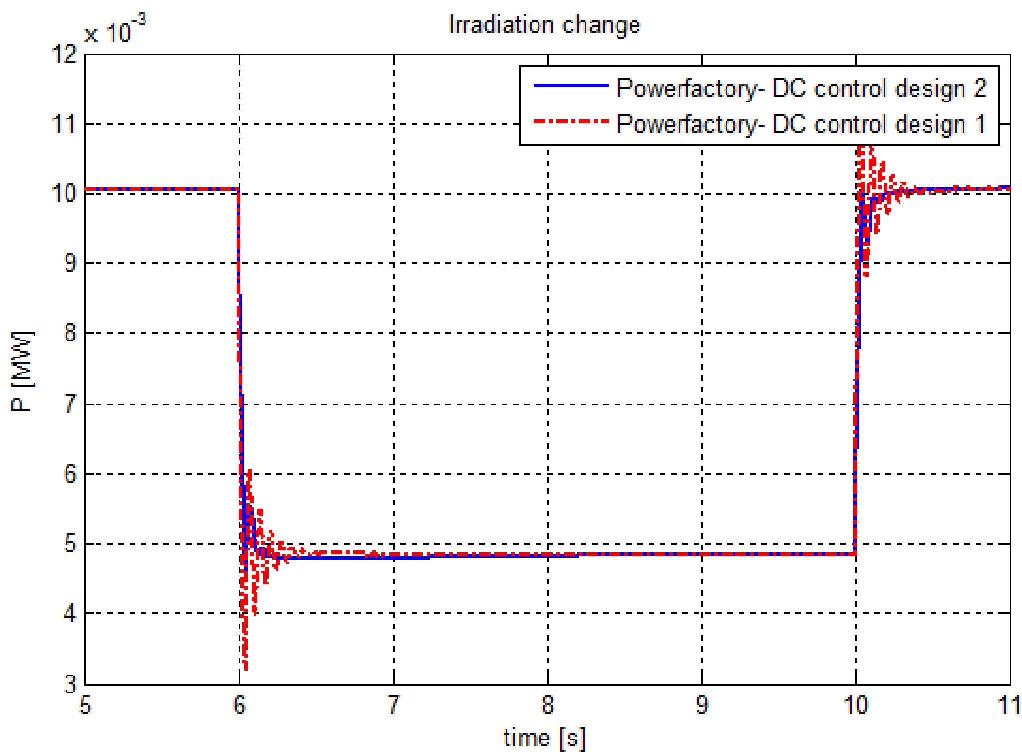

Fig. 5.39 Active power of the PV system

The active power output of design 2 shown in Fig. 5.39 comes out with a better response than design 1 without much oscillation. The controller with design 1 has got much faster dynamic response than the one with design 2 and attains the steady state value much early. It is necessary to mention here the similarity in the response of the new PI controller and the response of the lead-lag compensator controller with the new design parameter mentioned in section 5.4. The DC voltage and active power output waveforms when compared are very much similar in behavior.

When the reactive power and AC voltage at terminal L2 for both the designs are compared as shown in Fig. 5.40 and Fig. 5.41 respectively, of which the steady state values are exactly the same.

The reactive power control used is dynamic power factor control i.e. QControl 2. For both the designs during the maximum PV array output the system works at 0.9 inductive power factor with the absorption of reactive power from the grid. The only change is the dynamic response with a much smoother waveform for design 2 than design 1. The AC voltage at terminal L2 shown in Fig. 5.41 also responds the same way for both the controllers but the only change is again the reduced dynamic oscillation in case of design 2.

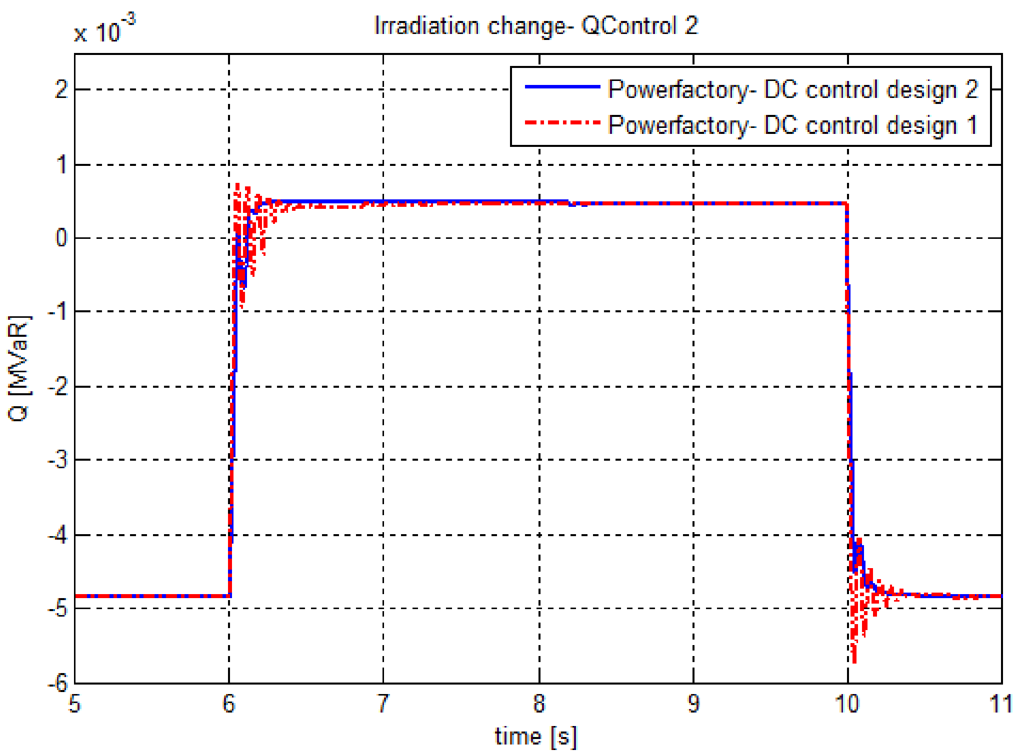

Fig. 5.40 Reactive power of the PV system

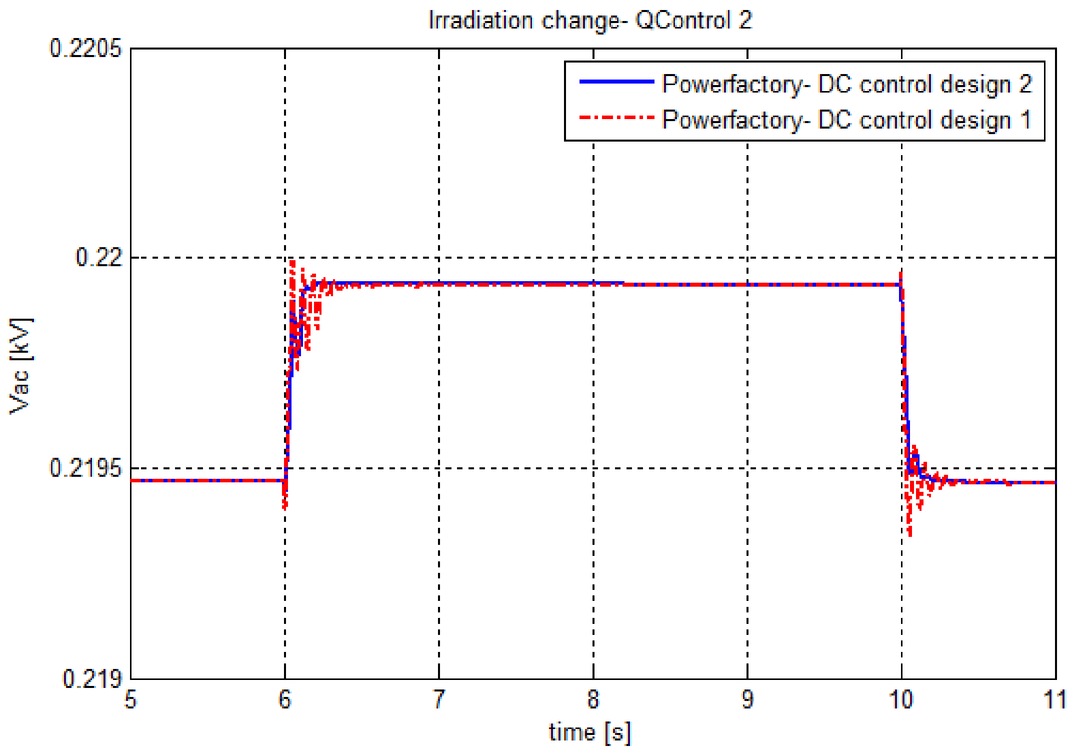

Fig. 5.41 AC voltage at terminal L2

From these figures it is clear that for any disturbance in the DC side of the PV system, the dynamic response of the PV system has got considerable influence of the DC voltage regulator. In case of design 1 the dynamic response is very fast and attains its steady state value much faster, but at the expense of dynamic oscillations. For design 2 the oscillations got reduced, at the expense of much higher time to reach the steady values.

The comparison waveforms of the PV system responses for 1% drop of external grid voltage (scenario 2) and three-phase short circuit at CCP (scenario 3) with design 1 and design 2 are given in Appendix 8.5. For both the scenarios the reactive power control used is the AC voltage regulation, QControl 4 with current limits enabled.

6. Project summary

The project targets to create a new PV model in Power factory using PWM converter as the interfacing converter along with MPPT function so that a comparison study can be done between the new model and the existing PSCAD model. The initial challenge was to create the new model in Power factory very similar to the PSCAD so that a better comparison is possible. Even though the general modeling approach remains the same, working on new software was quite demanding. New PV panel and MPPT function modeled separately is combined with the control mechanism implemented for the PWM converter in this report to obtain a new PV model in Power factory. A comparison study was then carried out between the two models in Power factory and PSCAD, from which the following conclusions are drawn.

- PSCAD PV model, a very detailed one which takes considerable time for simulation even for very small power system network, can be replaced by the new model developed in Power factory. The first reason why the Power factory model can be used instead of the PSCAD model is that it takes less simulation time. The time for simulating the power system network (shown in Fig. 5.1) in Power factory is just 20 seconds compared to 120 seconds in PSCAD for the same simulation running time and step size.
- Even though the Power factory model is very fast, it captures all the dynamics during disturbances in both the DC and AC side of the PV system, just like the PSCAD model. The results when compared, shows similar steady state responses in both the models. Since the PSCAD is already a validated model, similar response of the new Power factory model for the same disturbances validates the new models credibility.
- Even though same modeling techniques and methods are used for the realization of PV panel, MPPT and control techniques, the difference in solvers employed in Power factory and PSCAD creates discrepancies in the dynamic responses of the two models. The pattern of response is same, but for the same controller design Power factory model gives more dynamic oscillation than the PSCAD model.
- The MPPT function employed along with the inverter in order to track the maximum power point is found to have considerable effect on the dynamic response of the PV system during DC side disturbance. Increasing the MPPT frequency of the MPPT algorithm can reduce the dynamic oscillations but can generate discrepancy in the steady state values.
- Another solution found to reduce the dynamic oscillations in the new model is to adjust the controller parameters. Due to the difference in solvers, although the controller design is almost the same in both Power factory and PSCAD models, the controller parameters may be required to be adjusted in Power factory model to get a better response.
- For the new model, non-zero parameter values of the in-built current controller of the PWM converter in the Power factory generate convergence problem during simulation

of short circuit studies. In the PSCAD model, the current controller does not cause any simulation problem for the same short circuit studies.

- DC voltage regulation implemented using simple PI controller is observed to reduce the dynamic oscillations in the new PV model. It is also observed that during AC side disturbance, the way in which the DC voltage regulation is implemented has got considerable effect on the dynamic response of the PV system.
- Active power control is introduced in the new model in Power factory in order to vary (reduce and then bring back) the active power output of the PV system as per the operator requirements. This power control is implemented to reduce the PV output while the PV system is operating around its rated maximum power and it is a useful control.

6.1 Future work prospect

- The new Power factory model can be used to perform grid studies with two or more PV system models at different voltage levels.
- Active power control is implemented in the new model by varying the reference DC voltage value. Instead of varying the reference DC voltage, it is possible to control the active power by varying the PV array current by adjusting the number of series and parallel modules of the PV array. This type of active power control can be implemented in the new model.
- Model can be modified in order to comply with various grid codes introduced by various organizations and countries.

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8. Appendix

8.1 Parameters used for the new PV model

PV system components	Value
DC current source, Current	0.0214 kA
DC link capacitor, C	10000 µF
Rectifier, Nominal power	0.0112 MVA
Rectifier, DC side voltage	0.4718 kV
Rectifier, AC side voltage	0.18 kV
Rectifier, Series reactor resistance	0.003 Ω
Rectifier, Series reactor inductance	0.004 H
Grid Components	Value
LV transformer, Nominal Power	0.015 MVA
LV transformer, Voltage Ratio	0.18/0.38 kV,Δ/Y
LV transformer, Leakage Inductance	0.05 pu
Line 1, Resistance per km	0.006 Ω
Line 1, Inductance per km	0.000024 H
Fixed load, Active power	0.0006 MW
Fixed load, Reactive power	0.0003 MVaR
Line 2, Resistance per km	0.0155 Ω
Line 2, Inductance per km	10.95e-6 H
MV Transformer, Nominal Power	0.25 MVA
MV transformer, Voltage Ratio	0.38/20 kV, Y/Δ
MV transformer, Leakage Inductance	0.04 pu
Line 3, Resistance per km	178.88 Ω
Line 3, Inductance per km	0.949 H

Table 8.1

PV module parameters	Value
Short circuit current per module, Isc1	3.87
Open circuit voltage per module, Voc1	42.1
Impp0	3.56
Vmpp0	33.7
Tref	25
KI	0.065
KV	-0.16
E_{STC}, Irradiance at STC	1000
nSerialModules Number	14
nParallelModules Number	6
Vb	1000
Ibase	0.04672

Note: Vb is to convert voltage from kV to V and ibase is to convert nominal current to pu

Table 8.2

Track (MPPT module)- Block parameters	Value
Tdelay1	0.049

Vbase	1000
Tdelay	0.05
Vmpp0_array	471.8
Step	70
Epsilon	0.001

Note: Vbase is to convert voltage in V to kV

Table 8.3

Active Power Redn- Block parameters	Value
fUp	50.2
fLow	50.05
Gradient	40
Pbase	0.0101
Tfilter	0.01

Table 8.4

Active power control – Block parameters	Value
Act 0=MPPT;1=InputPref;2=Constant VDCref	0/1/2
TfDC	0.001
Flow	47.5
Fup	50.2
Vconst	0.4718
Kp	0.1
Tp	0.03

Table 8.5

Controller- Block parameters	Value
Tfac	0.002
Tqfac1	0.001
Ibase	0.0507
Tqfac	0.001
KDC	-12976
Kqac	-0.226755
Tqac	-0.002205
Kac	-0.5
Tac	-0.001
TfDC	0
TDC	300
Tlg	0.0011
Tld	0.02323
G	1
Flag 0=Reactivepower:1=Vac;2=Direct_iqref	0/1/2
i_min	0
iq_min	-0.02218
i_max	0.0507
iq_max	0.02218

Table 8.6

Qref – Block parameters	Value
PFlim	0.9
Ubase	0.38

Pbase	0.0101
PF_select:0=const_pf;1=dynamic pf;2=Q(U)	0/1/2
Db	0.03

Table 8.7

8.2 DSL codes inside the PV system blocks

```
Vt=2.8238
Vt1=(2*Vmpp0-Voc1)*(Isc1-Impp0)/(Impp0+(Isc1-Impp0)*ln((Isc1-Impp0)/Isc1))
Rs=0.3571
Rs1=(Vt1*ln((Isc1-Impp0)/Isc1)+Voc1-Vmpp0)/Impp0
Pmpp0=Impp0*Vmpp0
  Isc2=Isc1*(1+(KI/100)*(thetaout-Tref))
  Isc=Isc2*Eout/Estc
    Iph=Isc;
Voc=Voc1+(KV*(thetaout-Tref))
! Voc=log(Iph/I0)*Vt
 Voc2=Voc*(log(Eout)/log(Estc))

  I0=(Isc2/exp(Voc/Vt))

!  I=Iph-I0*exp(V/Vt);

FI0=Istart-Iph+I0*(exp((V+Istart*Rs)/Vt)-1);
FpI0=1+I0*(exp((V+Istart*Rs)/Vt))*Rs/Vt;
I1=Istart-FI0/FpI0;

FI1=I1-Iph+I0*(exp((V+I1*Rs)/Vt)-1);
FpI1=1+I0*(exp((V+I1*Rs)/Vt))*Rs/Vt;
I2=I1-FI1/FpI1;

FI2=I2-Iph+I0*(exp((V+I2*Rs)/Vt)-1);
FpI2=1+I0*(exp((V+I2*Rs)/Vt))*Rs/Vt;
I3=I2-FI2/FpI2;

FI3=I3-Iph+I0*(exp((V+I3*Rs)/Vt)-1);
FpI3=1+I0*(exp((V+I3*Rs)/Vt))*Rs/Vt;
I4=I3-FI3/FpI3;
I=lim(I4,0,3.87)

 V1=lim(V,0,42.1)
 P=V1*I
Parray=Varray*Iarray
```

DSL code 1: PV module

```
!Reactive Power Calculation
P=yi1/Pb
```

```
t=sqr(((PFlim-1)*(P-0.5)/(0-0.5))+1)
t1=sqr(((1-PFlim)*(P-0.5)/(0.5-1))+1)
k= abs((1-t)/t)
k1=abs((1-t1)/t1)
d=sqrt(k)
d1=sqrt(k1)
yo1=select(P<=0.5,yi1*d,select(P>0.5,-yi1*d1,0))
!Iqref calculation

vdref=Ub*(sqrt(2/3))
vd=yi2*vdref
vs=select((vd-vdref)>(0.5*vdref),vdref,vd)
iq=-(1/1.5/vs)*yo1
yo2=select(P<=0.5,iq,select(P>0.5,iq,0))
```

DSL code 2: Qref Block- dynamic pf block

```
! Qref calculation
vdref1=Ub1*(sqrt(2/3))
vd1=yi2*sqrt(2/3)
vs1=select(abs(vd1-vdref1)>(0.5*vdref1),vdref1,vd1)
V=vs1/vdref1
Qmax=yi1*tan(acos(PFlim))
Q1=Qmax/(db-0.1)*(V-1+db)
Q2=Qmax/(db-0.1)*(V-1-db)
a=1-db
b=1+db
yo1=select(V<0.9,Qmax,select(V>=0.9.and.V<=a,Q1,select(V>=b
.and.V<=1.1,Q2,select(V>1.1,-Qmax,0))))

!Iqref calculation

iq1=-(1/1.5/yi2)*yo1
yo2=select(V<0.9,iq1,select(V>=0.9.and.V<=a,iq1,select(V>=b.and.
V<=1.1,iq1,select(V>1.1,iq1,0))))
```

DSL code 3: Qref block- Droop control block

```
inc(yneu)=1
inc(yalt)=1
yneu=select(yi<=fUp,1,1-gradient/100*(yi-fUp))
yalt=delay(min(yo,yneu),0.01)
yo=select(yi<fLow,yneu,yalt)
```

DSL code 4: Active power reduction block

8.3 Block diagram of the PV system model components

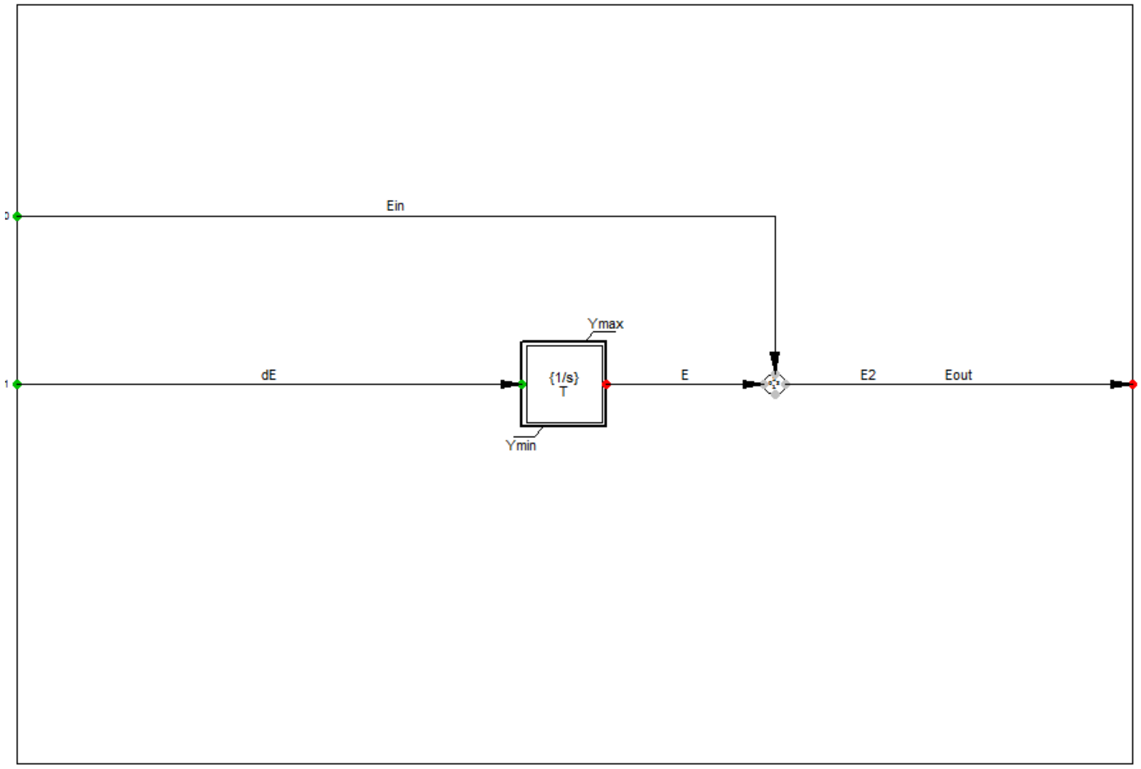

Fig. 8.1 Irradiance block (slot 11)

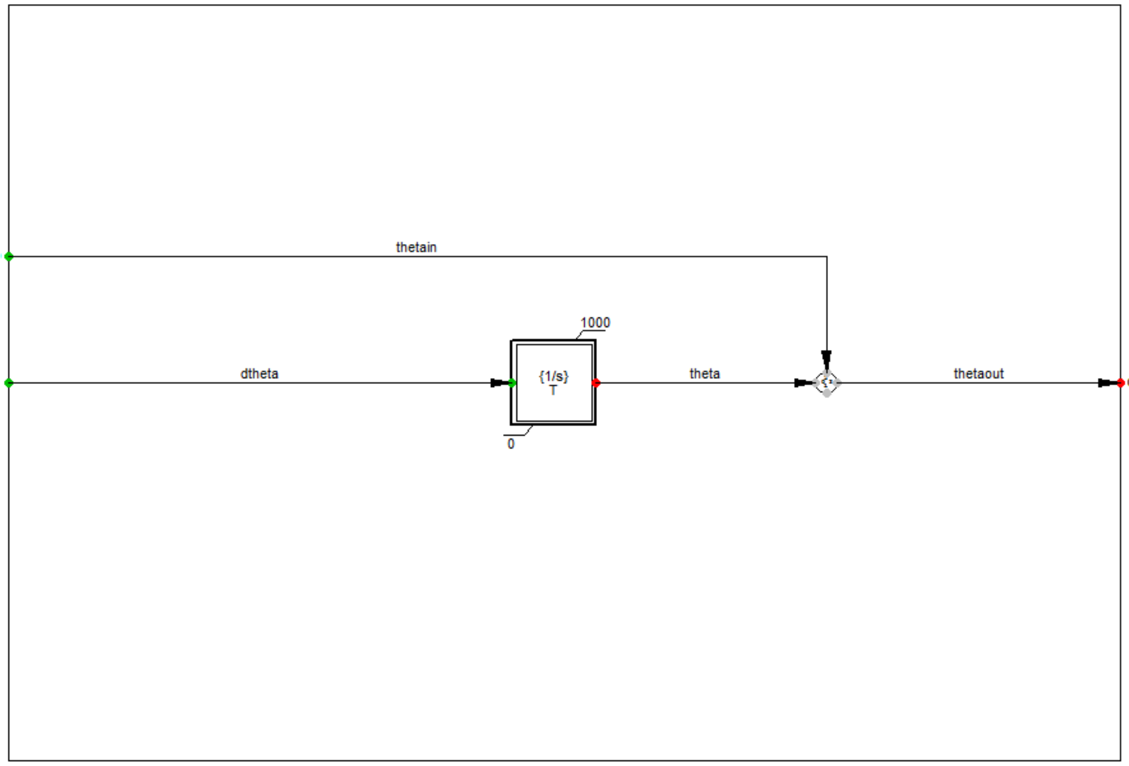

Fig. 8.2 Temperature block (slot 12)

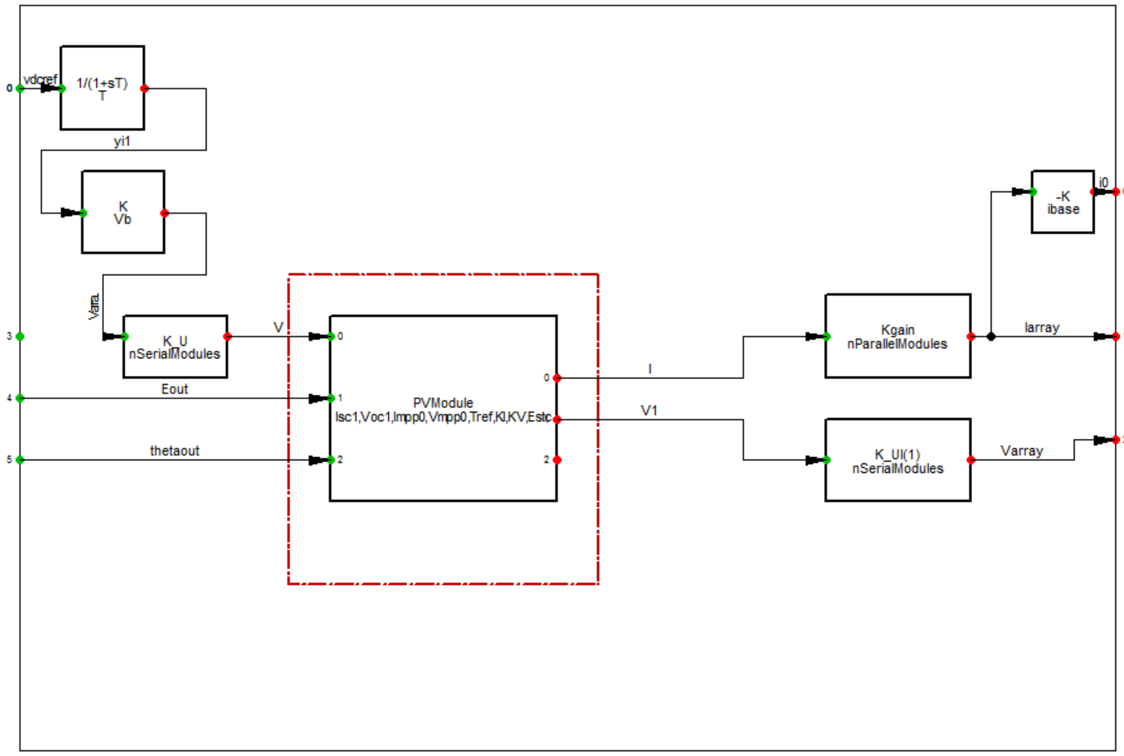

Fig. 8.3 PV module (slot 13)

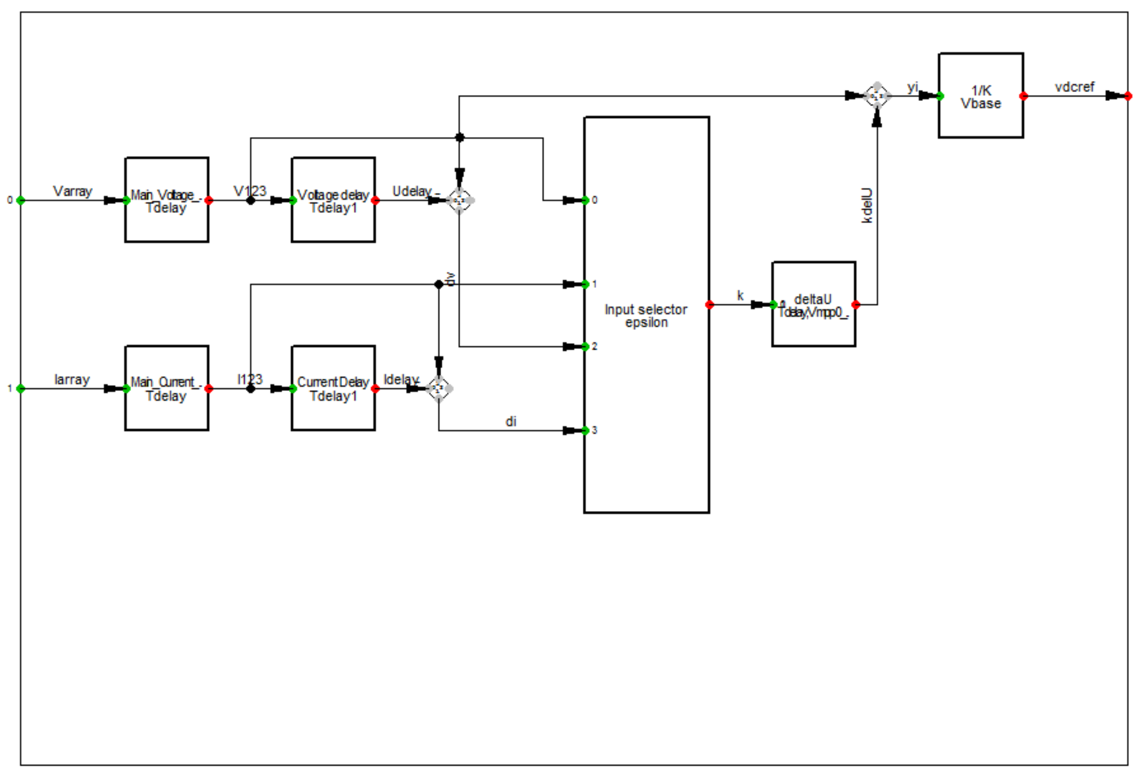

Fig. 8.4 MPPT block (slot 14)

8.4 MATLAB code to determine the controller parameters

```
clc;
close all

f=50;
phase=0
W=2*pi*f;
%system date

%%%%%%based on the ... paper
Vmpp=0.4718;        %************ Give Total Value
Impp=0.0214;        %************ Give Total Value
%PV output rating power
PpouPV=Vmpp*Impp%*1e6%MW   %############## PV output power

Ubase=0.18; %************ Give AC side rated line-line voltage
Vs=Ubase*sqrt(2/3)
pf=0.90;      %********** Give Power factor
ReactPower=PpouPV*tan(acos(pf))
Sbase=sqrt((PpouPV^2)+(ReactPower^2))   %%%%%%%%%%%%%%%%Inverter power
rating
Ppu=PpouPV/Sbase;
Zbase=(Ubase^2)/Sbase;

%Vs= 0.147%e3
L=4e-3;         %*********   Inductance of the Series Recator connected
with the inverter
Xl=2*pi*50*L;
Lpu=Xl/Zbase;
R=3e-3;% was 1e-3    %******** Resistance of the Series Recator connected
with the inverter+Switching losses
Rpu=R/Zbase;
toi=.5e-3
%Dc Bus capacitor
C=10000e-6 %*********** DC side capacitor
Xc=(1/(W*C));
Cpu=Xc/Zbase;
%filter
Cf=10e-6;     %*********** Filter Capacitor if required




%line
Lg=12e-5*2*(.18/.38)^2;     %********* Line inductance note here the
transformer rating
Rg=3e-2*2*(.18/.38)^2 ;     %********** Line Reactance note here the
transformer rating


% Current controller (PI controller) data
Kp=Lpu/toi/W         %########### Gain to be given for the Inverter IN-
BUILT controller
Ki=Rpu/toi/W          %########### Timeconstant=1/Ki to be given for the
Inverter IN-BUILT controller
```

```
% Closed loof function of current controller loop
s=tf('s')
Gcl_current=1/(toi*s+1);
% figure, margin(Gcl_current)

% DC-bus Voltage regulation

WcV=200; %cross over frequancy of Dc_bus voltage loop
Gv=(-2/C)/s;
Gp=Gcl_current; %power controller dynamic
Kv=C/3/s;
Tdc=3/C   %#######Tdc#######initial controller transfer function(
Gol=-Kv*Gp*Gv; % Open loop transfer function
K0=1/abs(freqresp(Gol, WcV));
Gol_uncomp=K0*Gol;
[Gm,Pm,Wg,Wp] = margin(Gol_uncomp);
PM=60-Pm;
Beta=(1-sin(PM*pi/180))/(1+sin(PM*pi/180));
tolead=1/WcV/sqrt(Beta);
Tld=tolead
Tlg=Beta*tolead
Flead=(tolead*s+1)/(Beta*tolead*s+1);
%#######Tld=tolead,Tlg=Beta*Tolead##########
Kvlead=1/abs(freqresp(Flead*Gol_uncomp,WcV));
Gol_comp=Kvlead*Flead*Gol_uncomp;
GAINtot=K0*Kvlead;  %#######Kdc##########
Kdc=-GAINtot



%%%%%%%%%%%%%%%%%%
% AC Voltage regulation
Gain_Q2iq=-2/3/Vs;% the relstionship between reacitve power and q-axis
current
G_ACsystem=-Lg*W;% Ac system is approximated to only a gain based on the
some simplification by igonring the dynamic of PLL

Gc=Gcl_current; %Current controller dynamic
to_Vac=1/100; % VAC control loop time constant 1/Hz
Kp_Vac=-to_Vac^-1/toi^-1/Lg/W; %######Kac######
Kac=Kp_Vac
Kq_Vac=-to_Vac^-1/Lg/W;   %#####Tac=1/Kq_Vac######
Tac=1/Kq_Vac


%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%
% Reactive power controller design loop
tauq=100;
kpQ=tauq*toi*-2/3/Vs;%########Kqac########
Kqac=kpQ
kiQ=tauq*-2/3/Vs;         %#######Tqac=1/kiQ#######
Tqac=1/kiQ
```

8.5 Comparison results

8.5.1 Active power control

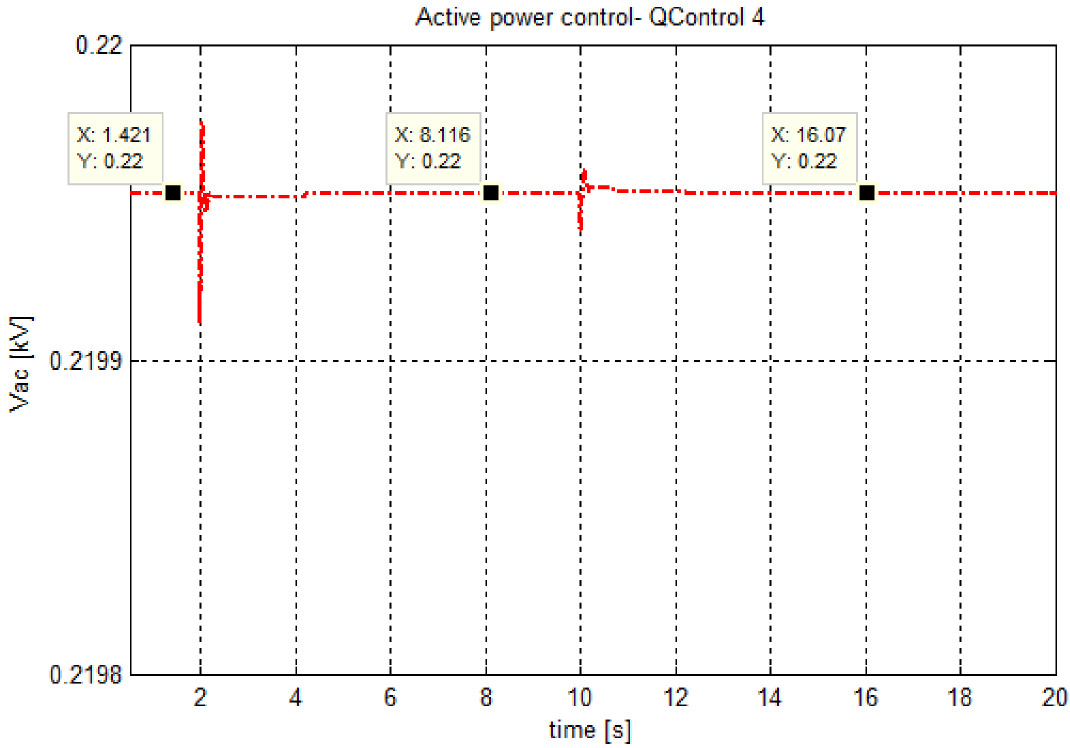

Fig. 8.5 AC voltage at terminal L2

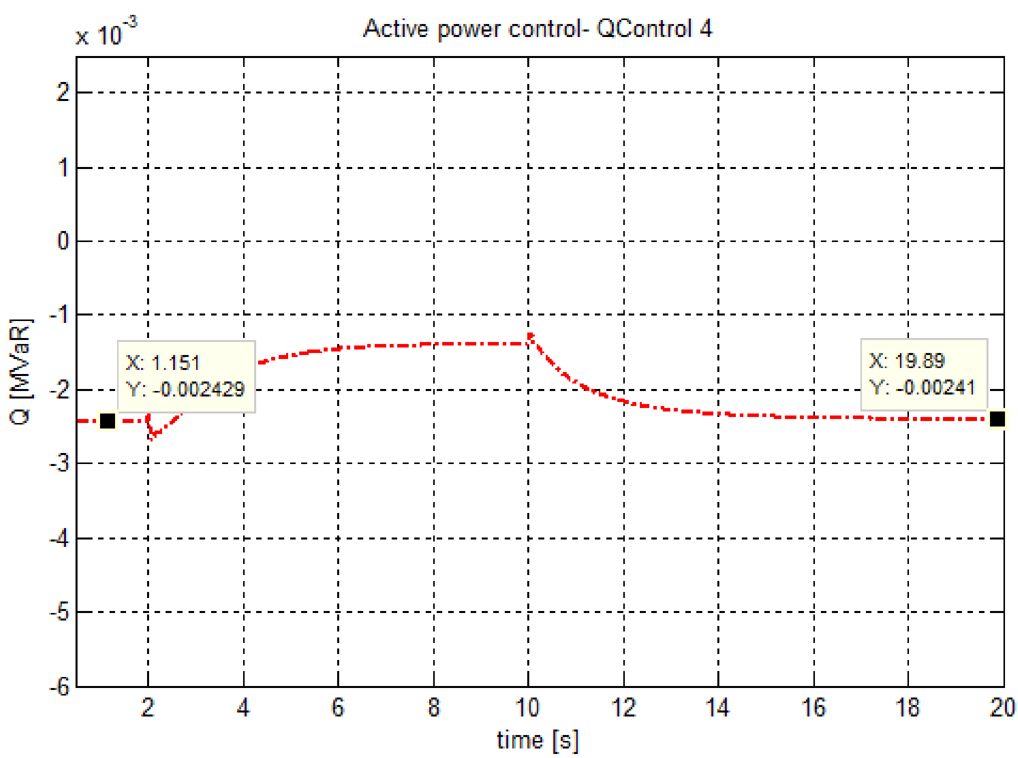

Fig. 8.6 Reactive power of the PV system

8.5.2 Scenario 2: Decrease in external grid voltage

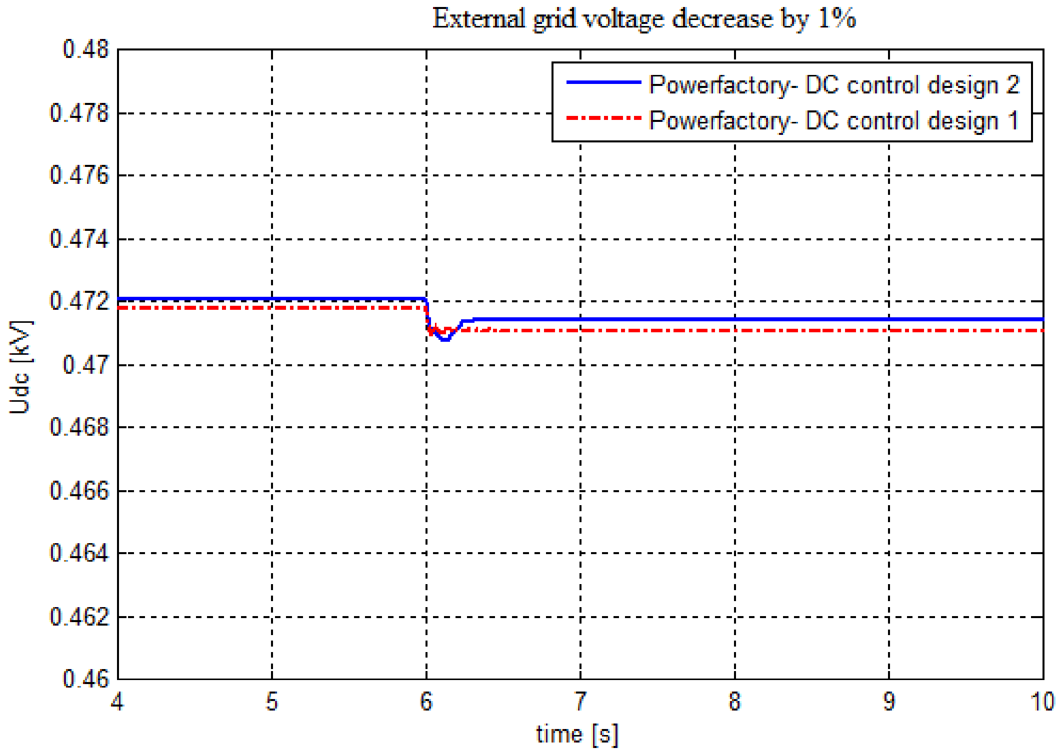

Fig. 8.7 DC voltage of PV system

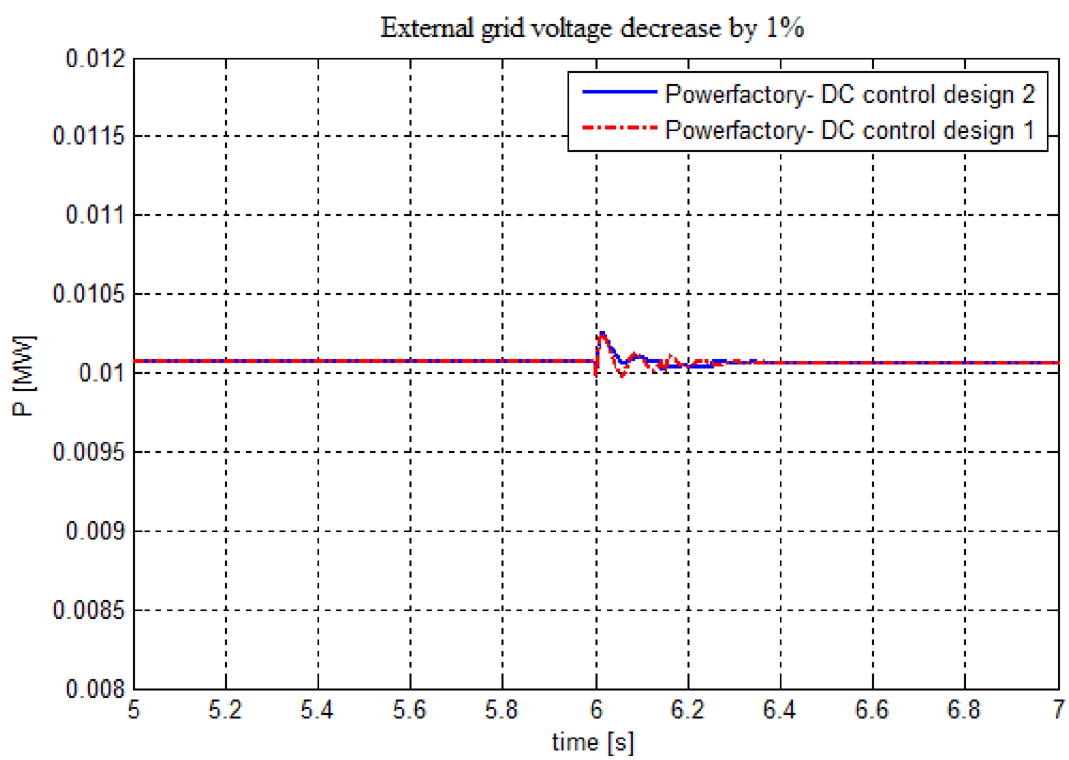

Fig. 8.8 Active power of the PV system

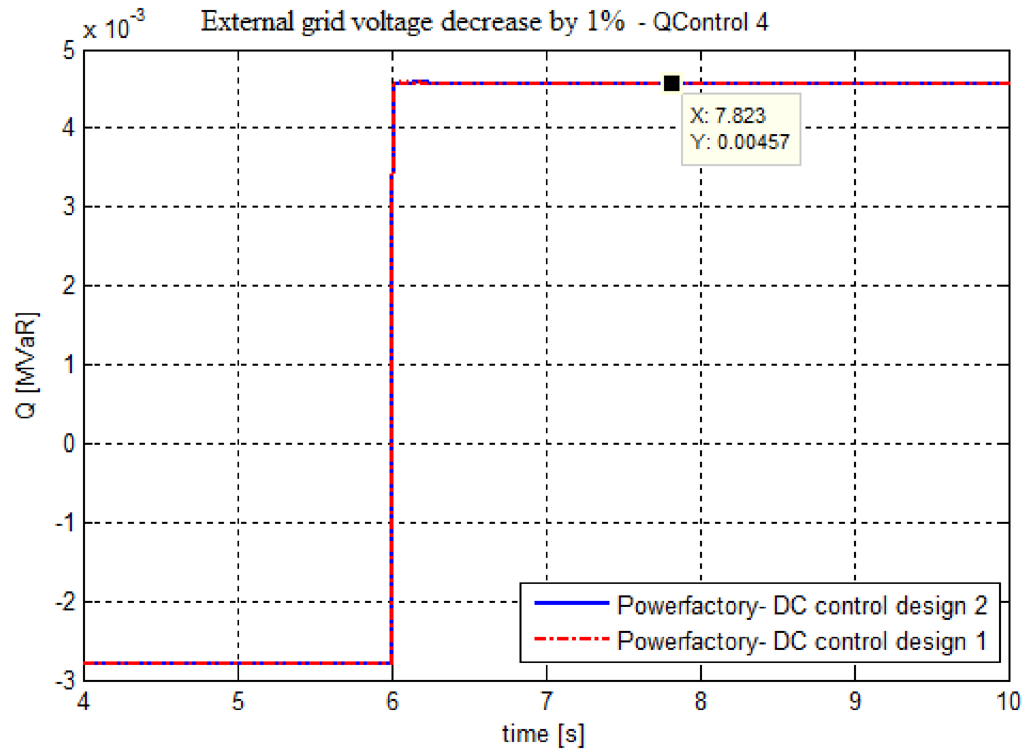

Fig. 8.9 Reactive power of the PV system

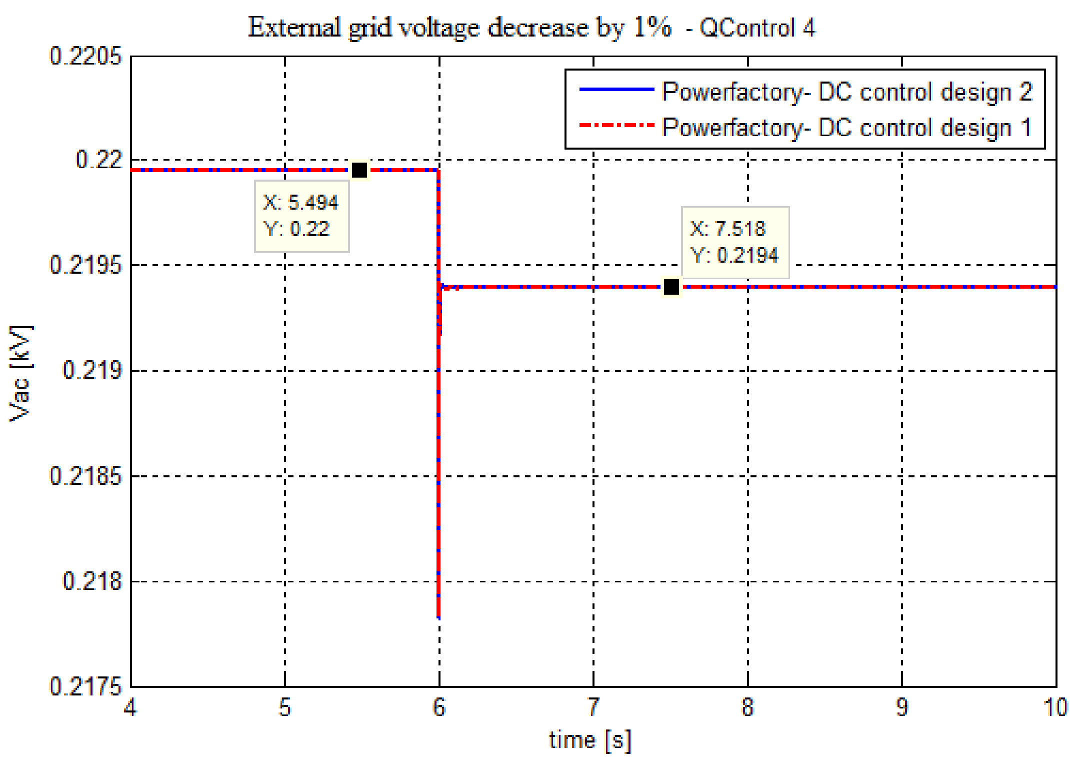

Fig. 8.10 AC voltage at terminal L2

8.5.3 Scenario 3: Three phase short circuit fault at CCP

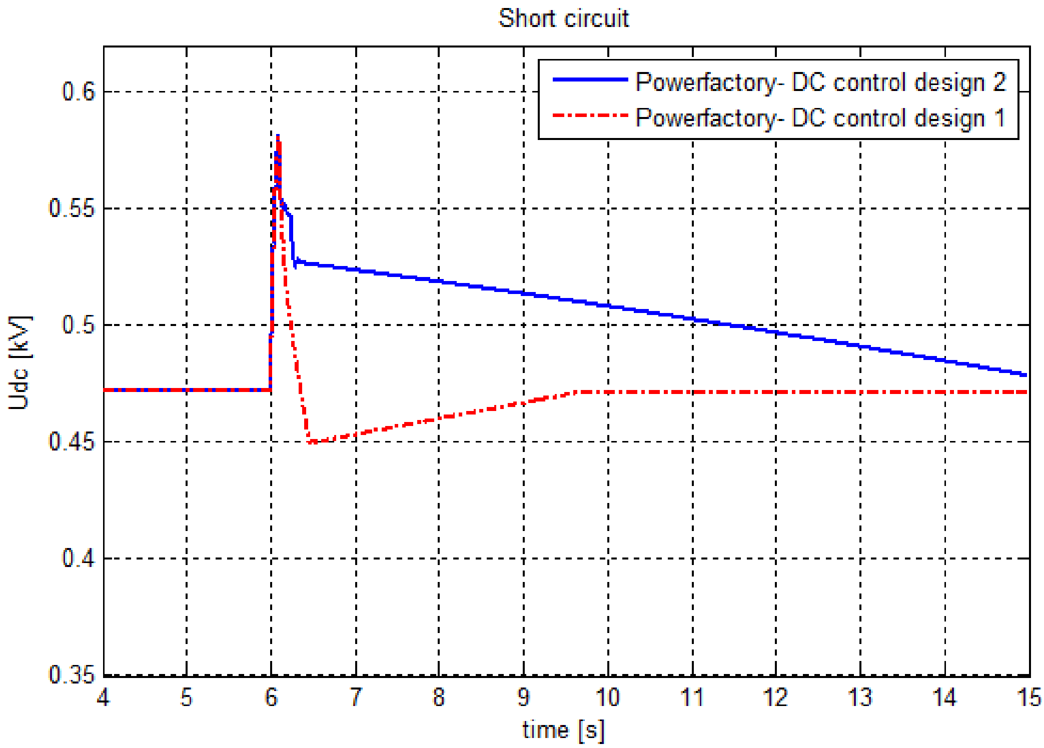

Fig. 8.11 DC voltage of the PV system

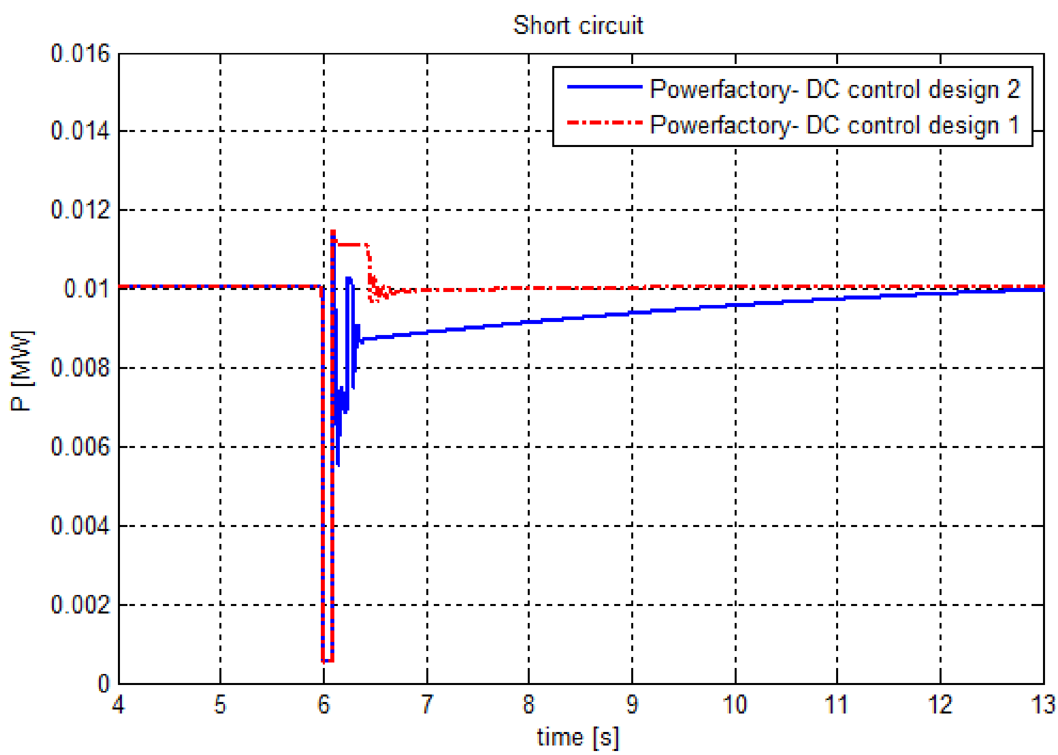

Fig. 8.12 Active power of the PV system

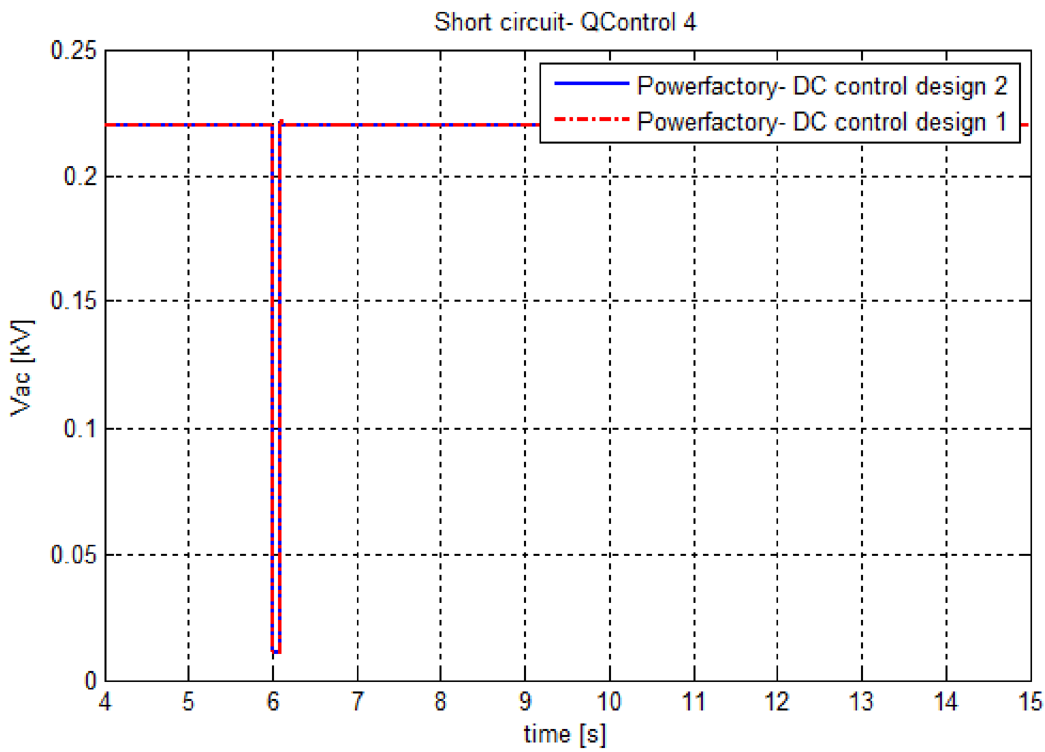

Fig. 8.13 AC voltage at terminal L2

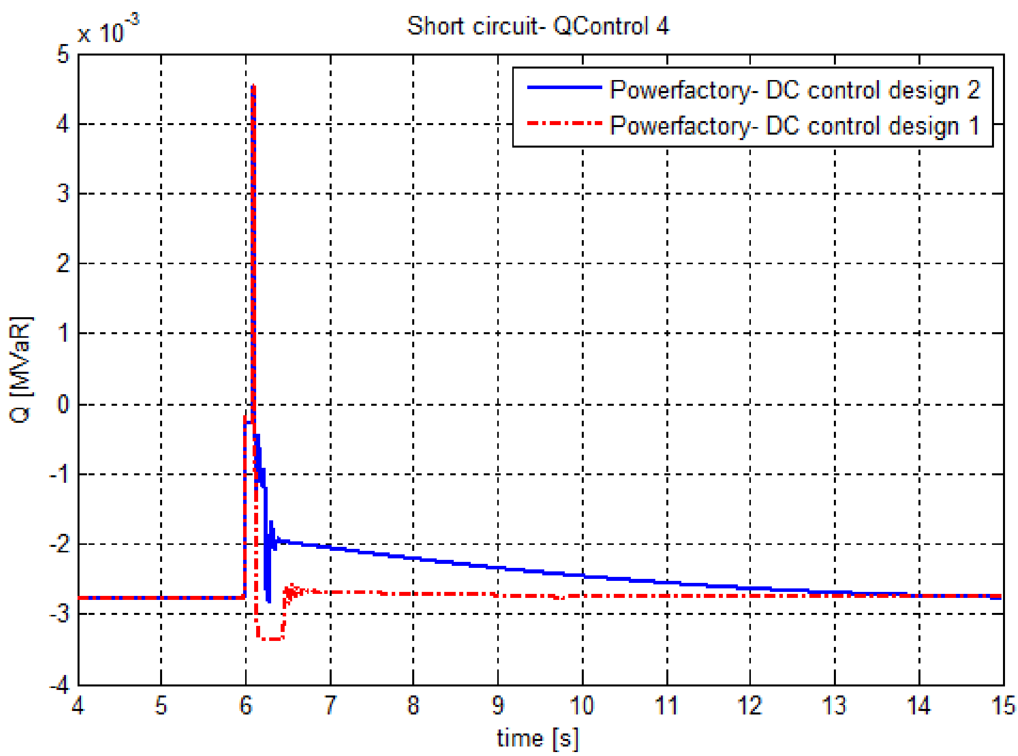

Fig. 8.14 Reactive power of the PV system