Improving the Photovoltaic Model in PowerFactory

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Abstract

This master thesis project is carried out to improve the grid connected PV models in DigSilent (PowerFactory).

A generic model in PowerFactory is already available in the form of a PV template in the library. This model gives the basic understanding of the operation of PV system and has some basic control systems in it. But there are many deficiencies of this model that need to be addressed. This model has PV panel model with many assumptions and approximations. Also it does not have any MPPT control to ensure PV system always operate on maximum power. There is only one type of reactive power control is available based upon voltage deviation. And there is no AC voltage and active power regulation is available. Under these circumstances, there arises a need of an extensive model with all the essential control system to have detailed grid studies.

In this project a new model named KTH model, in PowerFactory is developed which is equipped with many controls systems. Like generic model, this model also uses static generator to represent the PV generator. The model has nominal rated power of 0.5 MVA and designed power factor is 0.9. This model uses the same DC bus bar and capacitor model as of generic model.

A detailed literature study is carried out to have information about the recent research in this area. A new PV panel model is developed which demonstrated better output results as compared to generic model. The main difference with the generic model is that this KTH model has a more realistic PV panel model. Due to difference in modeling of PV panels, the output current and power are different for two models.

Maximum Power Point Tracking (MPPT) control is developed with two different types of methods Incremental Conductance and Perturb and Observe. The main objective of this control is to calculate the DC reference voltage for the controller. Hence, by doing so, MPPT control enables PV system to always operate on maximum power point. Comparison of these methods shows that Incremental Conductance gives better results; therefore it is used in this project.

Setup A presents a detailed comparison between KTH model and generic model keeping the same reactive power control in both models. This comparison indicates the validity of this developed model. Then in Setup B, various additional control systems are implemented in developed KTH model. These controls include active power control, four different types of reactive power control and MPPT control. In the end extensive case studies are performed with developed KTH model with all the essential controls implemented. Three different disturbances are applied Irradiation change, External grid voltage change and three phase short circuit for the both setups. Results of these case studies are compiled in the form of simulation plots and are briefly explained. In the end, results are concluded and some future research tasks are suggested.

List of Abbreviations

PV	Photovoltaic
R & D	Research and Development
EPIA	European Photovoltaic Industry Association
EU	European Union
GW	Gigawatt
MW	Megawatt
MPPT	Maximum Power Point Tracking
IncCond	Incremental Conductance
P&O	Perturb and Observe
MPP	Maximum Power Point
STC	Standard Test Conditions
VSI	Voltage Source Inverter
CSI	Current Source Inverter
THD	Total Harmonic Distortion
LVRT	Low Voltage Ride Through
DSL	DIgSILENT Simulation Language
VSC	Voltage Souce Converter
PLL	Phase Locked Loop
RMS	Root Mean Square
EMT	Electromegnectic Transients
Impp	Current at maximum power point
Vmpp	Voltage at maximum power point
Isc	Short ciruit current of module
Voc	Open circuit voltage of module
AM	Air Mass
η_{EURO}	Euro Efficeincy

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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 energy, 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. R&D in each of these areas is being carried out and is continuing in all parts of the world. Out of which the solar energy is one of the cleanest and the less expensive one. A few years ago the penetration of solar energy into the electricity market was considerably negligible. But the recent statistics shows a drastic change in this situation. As per EPIA forecast 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 provides subsidies for the installation of Photovoltaic (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 increases the market share of the solar energy to notable numbers. During 2011 in 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 is 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 was 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.

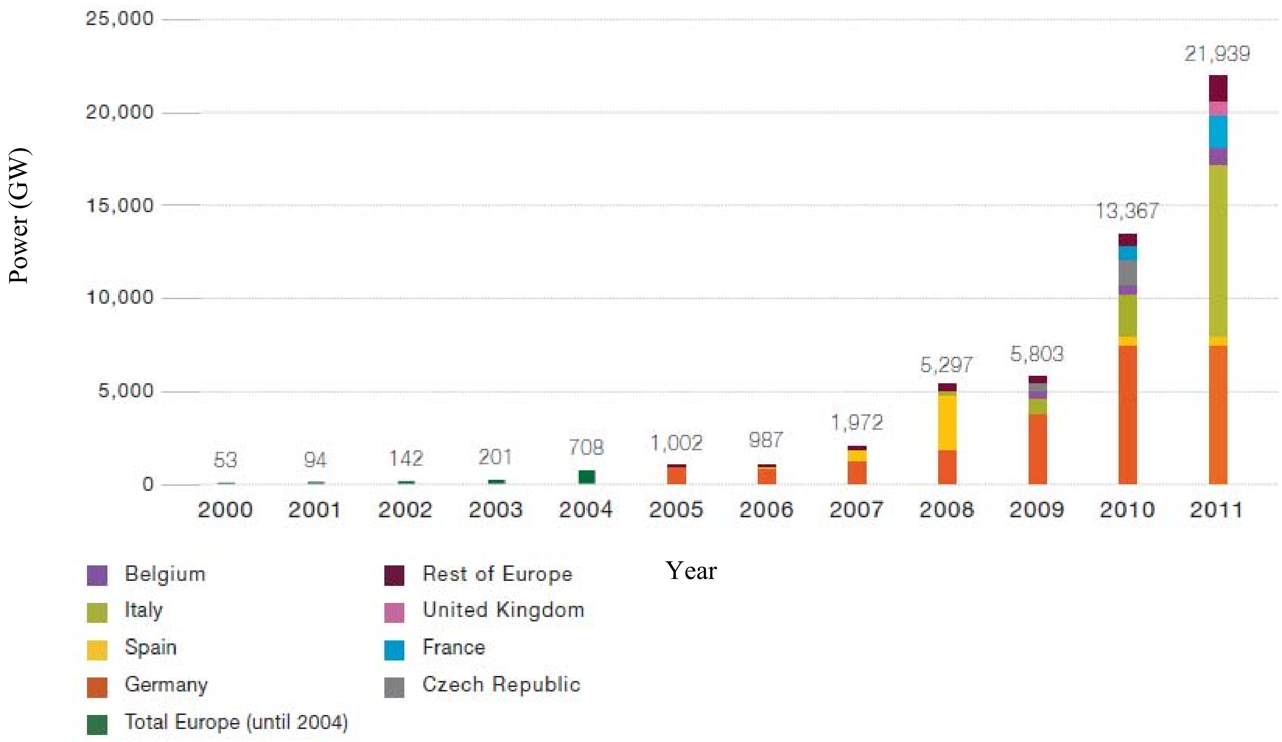

Fig. 1.2 Evolution of new grid connected PV systems in Europe (MW) [2]

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 comes to several megawatts 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.

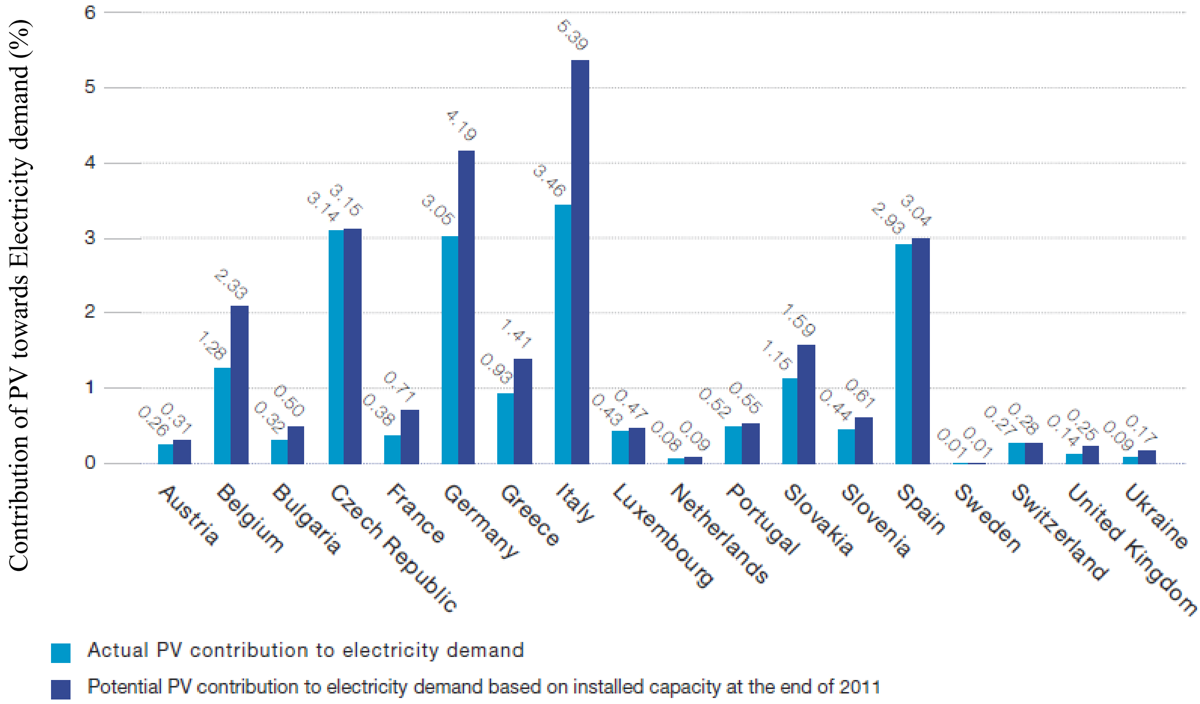

Fig. 1.3 Actual vs. potential PV contribution to electricity demand in 2011(%) [2]

Fig. 1.3 shows that Italy and Germany leads the PV race, whereas Belgium, Czech and Spain also show quite impressive numbers. The possible amount of PV contribution towards the electricity demand is higher than the current contribution and has not achieved by most of the countries except Czech Republic. Also Spain is very close to achieve their potential PV contribution. For Czech Republic the possible % of contribution from PV towards the electricity demand, based upon the installed capacity is 3.15 % whereas 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 European Photovoltaic Energy Association. The cumulative installed capacity of PV systems in Sweden by the end of 2011 is 15MW and for the year 2011, the annual installed PV power is 3MW.

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%, but 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 the voltage fluctuations. Another issue is the interaction 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 accurate PV system model is required that can give more realistic results. In PowerFactory (power industry software), a PV system model is already available. The PowerFactory model complies with the German Grid code and is simple in terms of design. Another model is also available in PSCAD which is a very detailed model and the simulation using the same is a time consuming process. So a much more detailed model complying with the standards in terms of design in PowerFactory is the expected outcome of the project. The developed model is used for utility grid connection studies. The results of this model are then compared with the results of existing model available in PowerFactory.

When the term PV is mentioned, it consists of two main conversion systems. One is the conversion of solar energy into DC power and the other is the DC to AC power conversion. It is required to design PV panel model and Maximum Power Point Tracking (MPPT) control for DC side design. It is also the objective of this project, to implement control systems of converter such as DC voltage regulation, AC voltage regulation, Reactive power control and Active power control etc.

1.2 Project outline

- **Chapter 2** is used to give a brief overview about the general Photo-voltaic 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.

- **Chapter 3** is dedicated to explain the modeling details of PV module inside the Power Factory and also the details of modeling of Maximum Power Point Tracking (MPPT) control. First, the PV panel model and its modeling methodology are explained in the form of equivalent circuit, solar cell equations and modeling assumptions etc. Second part of this chapter discusses about the MPPT control and two different methods used in this project. In this respect, starting from introduction, background and types of MPPT algorithms commonly used are presented.

Finally two MPPT algorithms used in this project, Perturb and Observe (P & O) and Incremental Conductance (IncCond) are explained and results are compared in the end.

- **Chapter 4** gives the brief inside into the modeling details of generic PV model available in PowerFactory and newly developed PV model in PowerFactory. The main idea of the project is to create a better PV system model than the existing generic model, so it is necessary to be familiarized with the both models.

  Chapter 5 is assigned for the analysis and results comparison between the existing generic PV model in PowerFactory and the newly created PV model in Power Factory. First, a comparison between two models is presented and after that some case studies are presented for newly developed model in PowerFactory. In the end a comparison between KTH model and PWM converter based model is presented.

- **Chapter 6** summarizes the conclusions drawn from this research project and it also outlines the possible future work to refine the newly developed PV model in Power Factory.

1.3 Project contribution

- ✓ A new PV model developed in PowerFactory that can be used for PV system simulations and grid studies.
- ✓ A more realistic PV panel model with one diode model.
- ✓ Two types of Maximum Power Point Tracking (MPPT) control developed Perturb and Observation (P&O) and Incremental Conductance (IncCond).
- ✓ A detailed comparison is performed between the Generic PowerFactory model and the developed KTH model in PowerFactory.
- ✓ Several case studies are performed with DC voltage control, AC voltage control, Reactive power control, Active power control and MPPT control in developed KTH model.
- ✓ A comparison between KTH model having static generator and PWM converter based PV model.

2. Photovoltaic System

Introduction to Photovoltaic System

Photovoltaic cells are made of semiconductor materials which have four valence electrons in the outer shell and 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 employed for generating the current in the PV cells and is depicted in Fig. 2.1.

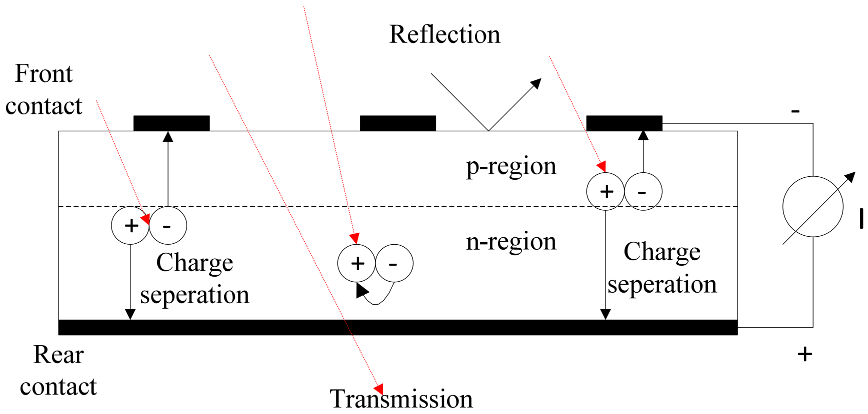

Fig. 2.1 Processes in an irradiated solar cell [3]

2.1 Electrical characteristics of PV system

Equivalent circuit with a single diode is the most popular PV model to describe the characteristics of the photovoltaic system and is shown in Fig. 2.2. A non-irradiated solar cell will behave 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 result 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), inverter sizing and its control.

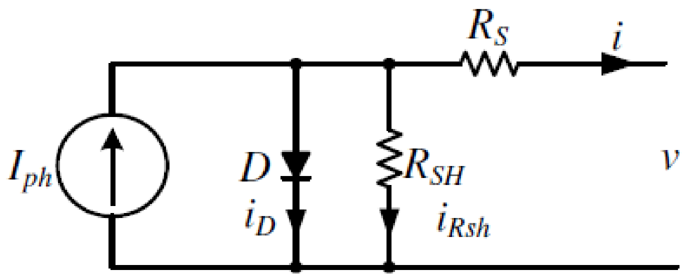

Fig. 2.2 Single diode equivalent circuit of a photovoltaic cell [4]

While describing the V-I characteristics of the PV system there are three main measurement points as well as the obtained values which are important to be mentioned. 1) MPP 2) Short-circuit measurement 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 the short circuit current, I_{sc} and the open circuit measurement with a disconnected load can provide the 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.

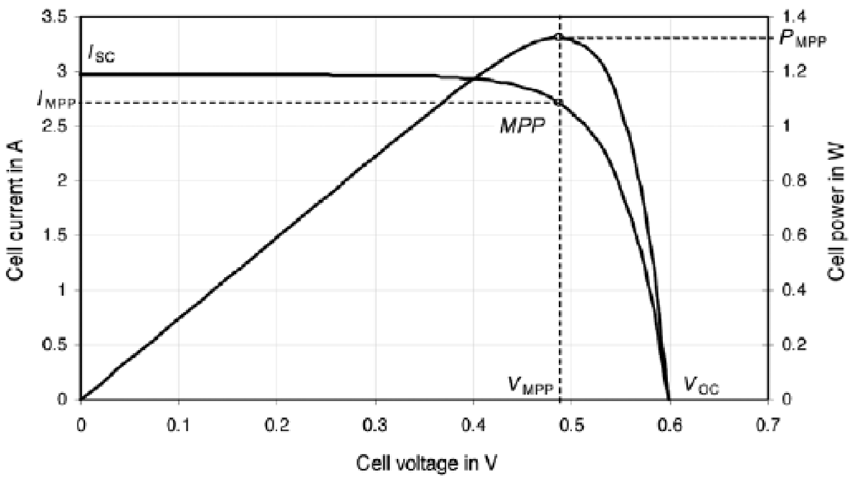

Fig. 2.3 I-V and V-I characteristic of a PV cell with MPP [3]

It can be noticed from the figure that the value of V_{mpp} is lower than V_{oc} and also the I_{mpp} value is lower than the short circuit current I_{sc} . The cell efficiency will be higher if the operating voltage and current are V_{mpp} and I_{mpp} for a particular irradiance and temperature other than any other operating points.

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.

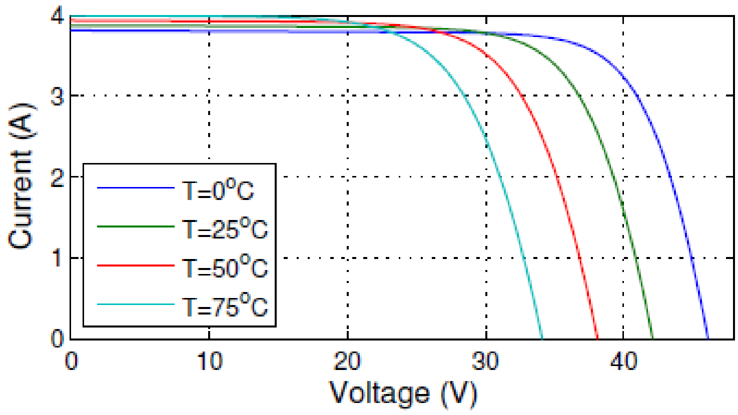

Fig.2.4 Temperature Dependence of Solar Cells [4]

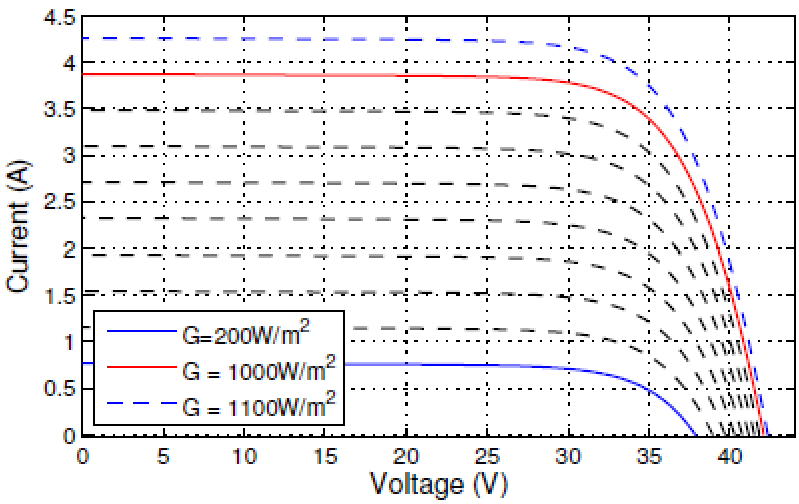

Fig.2.5 Irradiation dependence of Solar cells [4]

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 [3]. 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 the hybrid systems and is implemented in several applications [3].

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 [3]. Centralized systems usually are of higher power rating usually more than 1 MW and normally connect with the medium or low voltage transmission network depending upon 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. DC Power produced by PV Array goes to the DC Bus connected to it. After this a DC-AC inverter, converts the generated DC power to AC power and falls in to the interfacing area of the PV system.

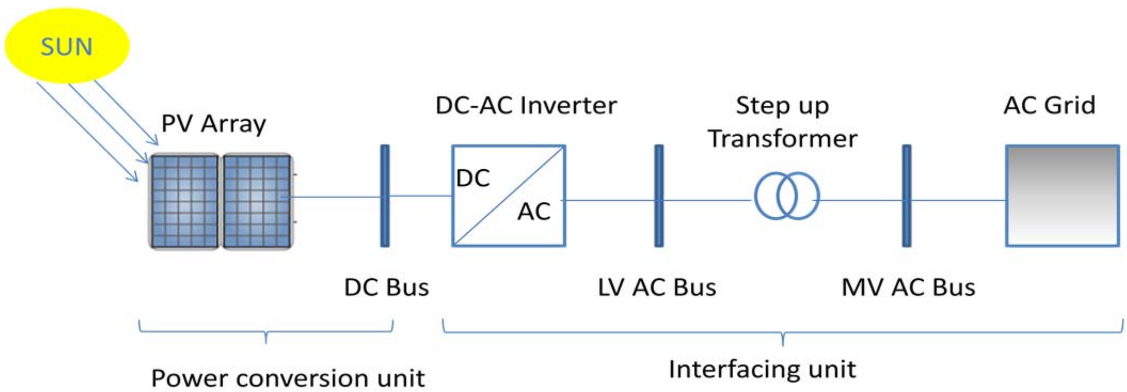

Fig.2.6 Grid connected PV system components

Then with the AC cabling the PV system can be connected to either low or medium voltage transmission grid. Normally, PV system is connected to medium voltage AC grid through a step up transformer as shown in Fig 2.6.

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 such operating point so that it gives maximum power. For this purpose a special MPPT (Maximum Power Point Tracker) control is used with the PV inverters. This MPPT control will be explained in details in chapter 4.

2.3.1 Functions of Inverters

When the focus is on the power electronics function of the PV inverter and all the additional constrains like safety, efficiency etc. are ignored then all PV Inverters can be evaluated with these 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 as 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 the buck characteristics (output voltage is always smaller than input voltage). This is done by using the transformer (inductor). Although there are some transformers less topologies existing, those 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 that can bear these changes and provide smoothness in the system. In this prospective, electrolytic capacitors are used to provide this kind of 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, but there is no isolation in the later method.

a) Conventional Transformer with Galvanic Isolation

Most commonly used method for the galvanic isolation is the conventional transformer operating on grid frequency. This is tried and tested method and is being used right from the start of this 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. 2.7. By controlling AC current the power that is fed into the grid can be controlled.

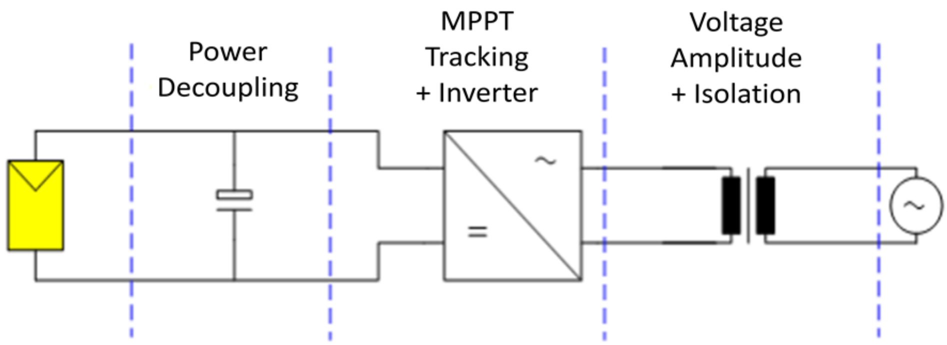

Fig. 2.7 Conventional Transformer Isolation Method [9]

When the power fed into the grid is changed, keeping the DC power constant, DC link capacitor is charged or discharged thus changing the voltage at the terminal of the PV generator.

b) High frequency DC-DC converters without galvanic isolation

Due to various drawbacks of conventional transformer, there arises a need to search for alternative method for this galvanic isolation. As a result high frequency transformer topology arises 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.

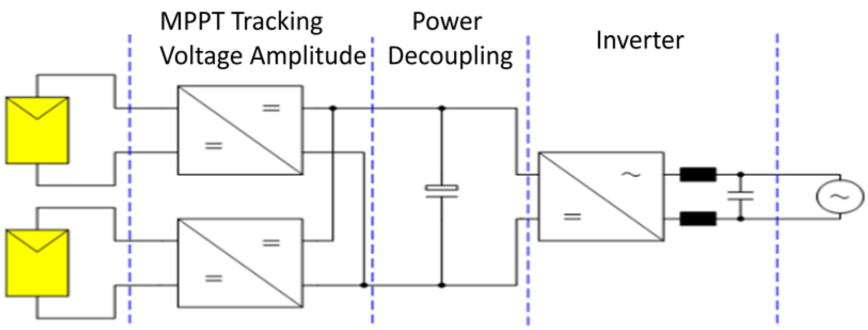

Fig. 2.8 DC-DC Converter Topology without transformer [9]

Transformer less topology as shown in Fig. 2.8 is an upcoming technology, and in development stage. There would 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 developing as it has less overall losses, lighter in weight and cheaper than conventional grid frequency transformer topologies. However there would be some switching losses in these methods. In addition, topologies without transformer increase the control over the system voltage and power because 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 use.

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 currents. 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 have monitoring ground leakage current in this respect [9].

2.4 PV System configurations

Generally types of inverters are classified here in two categories as follows

I. With respect to connection with system
II. With respect to configuration of inverter

2.4.1 With respect to connection with system

According to type of connection to the system, inverters are categorized into the two Types:

a) Single phase inverter

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

b) Three phase inverter

Three phase inverters are usually related to larger systems, and are only used for grid connected PV systems. Three phase converters are practically implemented in a PV system by having three single phase converters connected to each load terminals. This is because for a three wire topology relatively higher DC voltage values (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 configuration of inverter

Depending upon the way in which the inverter and PV array is configured, inverters can be categorized into four general types. They are central inverters, string inverters, multi string inverters and AC module inverters and are shown in Fig. 2.9.

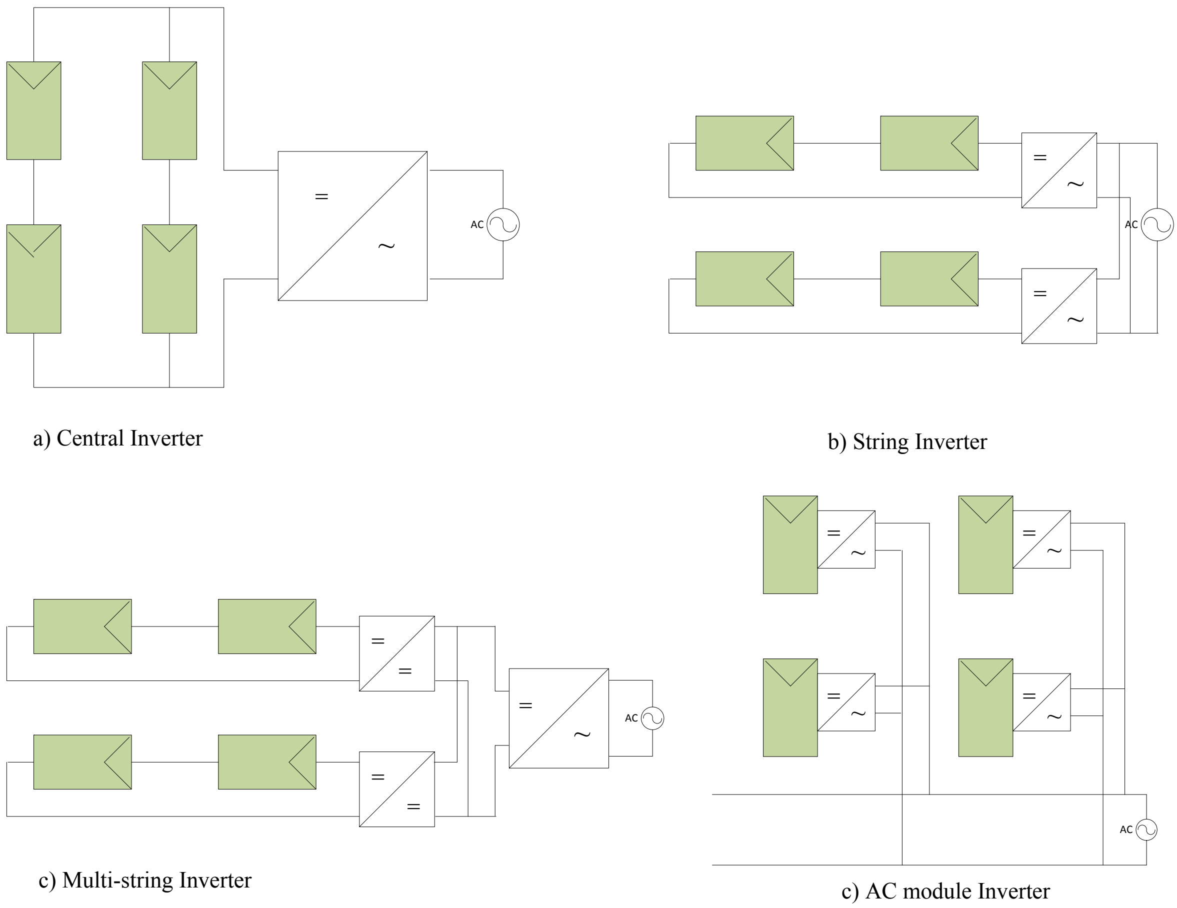

Fig. 2.9 Different configuration of PV-System with inverters [9]

a) Central Inverters:

PV modules are connected in series and parallel to get the higher power level and finally connected to a single converter in the end. Series connection of modules is called a string.

This kind of inverter has enough voltage at its DC side i.e. from 150 V to 1000 V that 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 systems, makes central inverter a better economical choice. Due to a single converter this configuration has low total harmonic distortion (THD) losses in the system. Therefore it is still first choice of medium and large scale PV systems. Central inverters are mainly built with three phase full bridges having IGBTs and low frequency system [9]. The structure of the central inverter can be seen in Fig. 2.8 (a).

This kind of inverter has the disadvantages especially for the small roof top application that it results in mismatching losses between modules of string and missing individual Maximum Power Point Tracking MPPT [9]. Also it has high losses in the DC cables. It has the availability issue as if inverter trips, whole generation is out of the system. Shading effect due to variable irradiance in the system can make it a bad choice as an inverter.

b) String Inverters

For the applications where different panel modules cannot be operated on the same orientation and if the system is subjected to different shading conditions, string inverters are the best choice [9]. As shown in Fig. 2.8 (b), it does not have any parallel connection. Each inverter is responsible for each string having its own MPPT control. When the system has many strings and each string is different from others in configuration then this type of inverter is ideal to use. 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. It is 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 low frequency transformer on the AC side for isolation.

c) Multi String Inverter

This type of inverter is also a type of string inverter with additional DC-DC converter for each string. Basically it is a string inverter 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 more power output of the inverter without having to sacrifice the advantage of string technology [9].

Multi String Inverter has the disadvantages that due to two power conversion level it has more power losses and less efficiency as compared to string inverters. It has the advantage that the user can have a big freedom with respect to the input voltage range of the converter because of an additional DC-DC converter. Also by having a separate MPPT control of each string it is more efficient in that kind of operation. Multi string inverter has the power range of 1 kW to 6 kW [9].

d) Ac Module Inverter

The AC module inverter has the arrangement that 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. This type of inverter is shown in Fig 2.8 (d).

The main advantage of this inverter is that no DC wiring is necessary and risk of electric arc and firing is eliminated in this case. It has 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, as 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. Also PV array operate at the rated power for only a few hours in a year, because the changing solar irradiance so in this condition inverter predominately operate under part load. Generally, increasing the power rating will increase the efficiency of the inverter.

Euro efficiency or European efficiency of PV inverters can be used as an authentic method to compare the efficiencies of different inverters, and can be expressed by the following equation [11].

$$\eta_{EURO} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.1\eta_{30\%} + 0.48\eta_{50\%} + 0.2\eta_{100\%}$$

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 consider the amount of time in percentage that PV inverter is expected to work at partial loads or at different levels of irradiation.

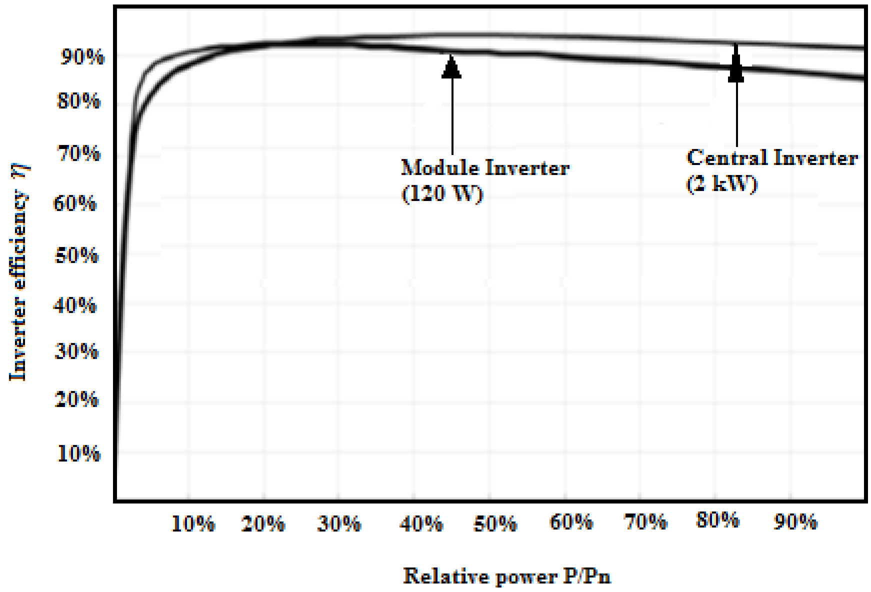

Fig. 2.10 Efficiency over a Range of Relative Photovoltaic Generator Powers [13]

Another aspect of PV inverter is anti-islanding protection. When PV inverter does not disconnect to utility even when it has been shut down, then it causes problems as it continues to supply power to grid even if it is not required. This problem arises as, in grid there are some circuits that may resonate with grid frequency, and in this case this issue can be dangerous for the grid side. So, inverter should be disconnected from the grid after it has been shut down to avoid any kind of accident.

Harmonics in the output power provided by the inverter to the utility should be minimized as much as possible, because these harmonics causes the distortion in the grid voltage and current. It can be said that power quality can be improved by minimizing the THD (Total Harmonic Distortion) 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 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 types 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, the systems which have almost reached its advanced stage of installation and manufacturing exits in Germany, Italy and Spain and all these countries follow their own grid codes. As mentioned most of the countries follows their own grid codes and is 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 does 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. 2.11

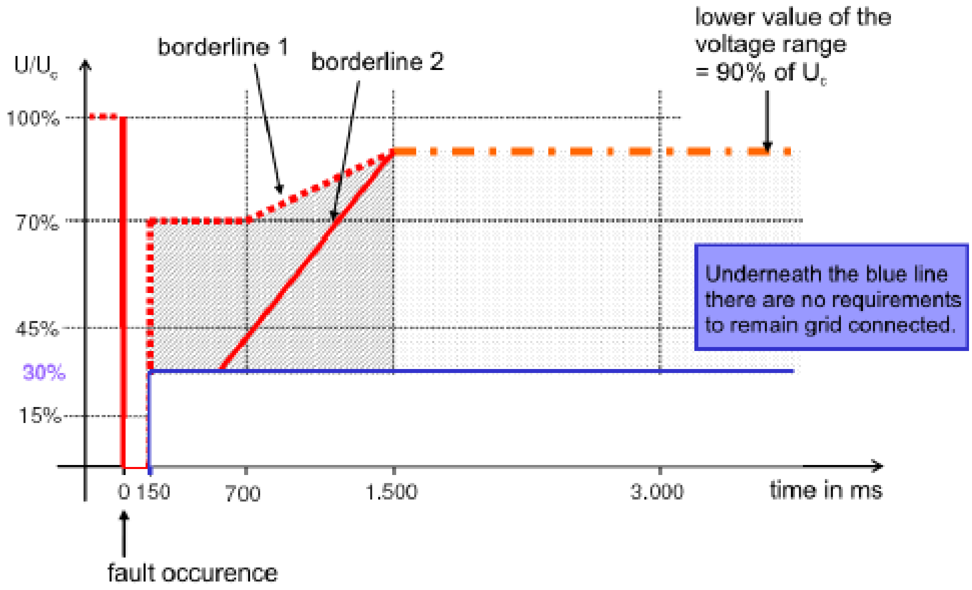

Fig.2.11 Limiting curves of voltage in the event of a network fault [6]

For any voltage drop of ≤ 150 ms, the PV system should not disconnect 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 disconnections as well as 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. 2.12. 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].

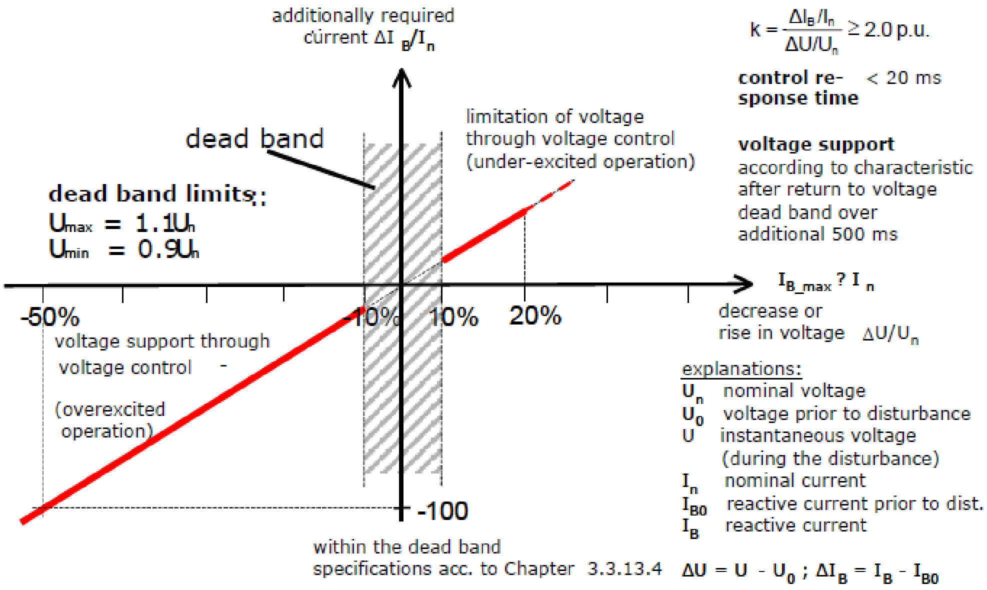

Fig. 2.12 Principle of voltage support at the event of network fault [5]

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, then 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. 2.13 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.

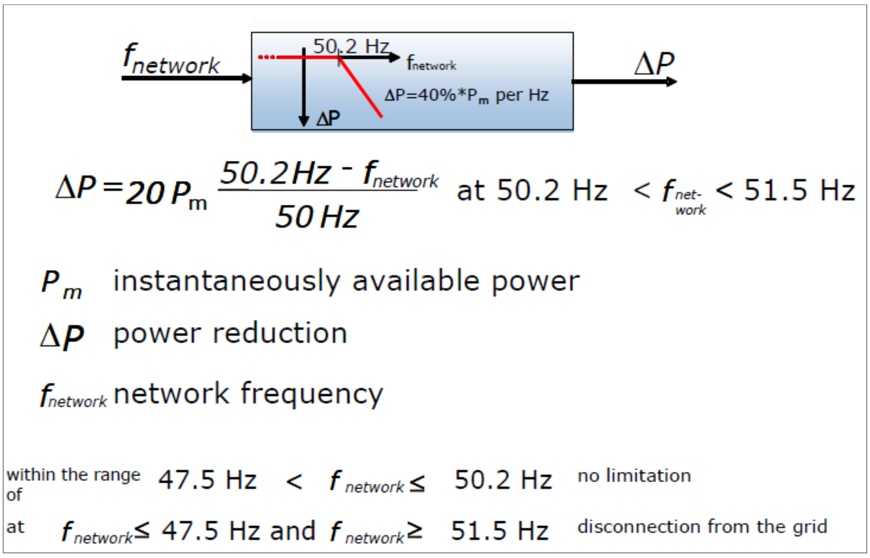

Fig. 2.13 Active power reduction in case of over frequency [5]

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. 2.14 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 0.9 under-excited and 0.9 over-exited states [5].

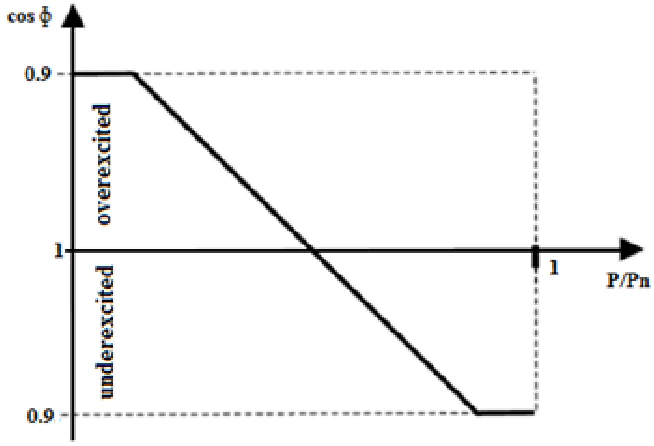

Fig. 2.14 Dynamic power factor operation characteristic [6]

3. PV Modeling & Maximum Power Point Tracking

In this chapter firstly the Photovoltaic system modeling is discussed. In this respect some derivations and solar cell basic model will be presented. Secondly, assumptions and approximation, on which the model is built, are presented. The other part of this chapter contains the Maximum Power Point Tracking (MPPT). In this respect, different methods of MPPT will be first discussed and then modeling procedure on which it is modeled is described. In the end comparison between two MPPT methods is presented.

3.1 PV Module

Inside the PV module, basic solar cell equations are used to calculate current on the basis of input voltage at any instant. Some derivations of basic solar cell equations are carried out to calculate the unknown parameters using the method as indicated in [4]. The equivalent circuit of solar cell with a series resistance is used for derivation of the PV equations as shown in Fig 3.1. This series resistance R_s refers to losses due to poor conductivity in the solar cell.

In this model one diode model is used for modeling of PV module as shown in Fig 3.1. One diode model is used for the sake of avoiding complexity in the system.

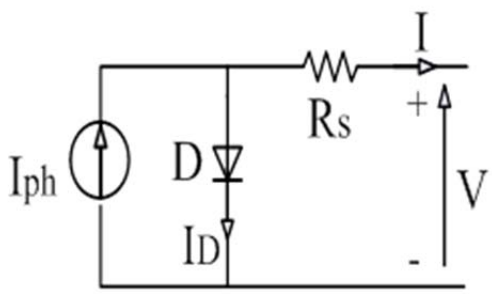

Fig 3.1 The equivalent circuit of a solar cell with a series resistance

From Fig 3.1, the output current of the PV module can be calculated using (3.1) and (3.2). The total output current of this model is the difference between photo electric current and diode current I_D as shown in (3.1). This diode current is itself equal to a quantity having multiplication of I_0 (dark current) and an exponential term as shown in (3.2).

$$I = I_{ph} - I_D \tag{3.1}$$

$$I = I_{ph} - I_0 exp(\frac{V+IRs}{V_t}) \tag{3.2}$$

In case of short circuit conditions, using (3.2), the photo electric current is equal to the short circuit current of the PV module as shown in (3.3).

$$I_{ph} = I_{sc} \tag{3.3}$$

In an ideal solar cell the saturation current (dark current) can be calculated by using the open circuit conditions in the method used in [4]. It can be worth noticing that this current only depends upon the temperature of the module and is independent from the irradiance variations. The expression for the dark current is given by

$$I_0 = \frac{I_{sct}}{\exp(\frac{V_{oct}}{V_t})} \tag{3.4}$$

Where V_{oct} is the open circuit voltage with just temperature dependence and I_{sct} is the short circuit current with just temperature dependence.

The unknown parameters in (3.2) i.e. R_s and V_t are derived using the method explained in Appendix 8.4.

PV Array does not operate on Standard Test Conditions (STC) at all the time. Whereas all the parameters inside the PV module data sheet, are given on Standard Test Conditions (STC), so corrections should be made to convert all the voltages and currents in the calculation accordingly. Also any changes in temperature and irradiance of the system should be incorporated in the calculations, so that PV system could modify its voltage and current based upon any change in the irradiance and temperature. So these issues are included in these calculations using (3.5) - (3.8) as described in [4] and [14].

Short circuit current, which is almost linear function of irradiance and temperature, so accordingly expression for short circuit current is approximated as follows.

$$I_{sct} = I_{sc1}(1 + \frac{K_I}{100}(T - Tref)) \tag{3.5}$$

$$I_{sc} = I_{sct}(\frac{E}{E_{STC}}) \tag{3.6}$$

Where I_{sct} is the short circuit current with just temperature dependence, K_I is the temperature correction factor for current and is defined in the data sheet of the PV module. I_{sc} is the short circuit current with both temperature and irradiance.

Open circuit voltage can be expressed as linear function of temperature and irradiance.

$$V_{oct} = V_{oc1} + [K_V(T_{user} - Tref)] \quad (3.7)$$

$$V_{oc} = V_{oct}\left(\frac{\ln E}{\ln E_{stc}}\right) \quad (3.8)$$

Where V_{oct} is the open circuit voltage with just temperature dependence and K_V is the temperature correction factor for the voltage which is defined in the data sheet of PV Module. Also V_{oc} is the open circuit voltage with both temperature and irradiance dependence.

Where

T_{ref} = Temperature at the STC considered as 25 C.
I_{sc1}= Short circuit current at STC (defined in the data sheet of the module)
V_{oc1}= Open circuit voltage at STC (defined in the data sheet the module)
E = Irradiance at the output
T =Temperature at the output
E_{STC} = Irradiance at STC

These above derived (3.1) - (3.8) are used in the DSL code of the PV module inside the PV array model for calculations. But (3.2) cannot be solved numerically, as current is the function of voltage and current i.e. I=f (I,V). So Newton-Raphson method is employed in order to calculate the current.

The general expression for Newton-Raphson is described by (3.9) in which current for the next iteration can be estimated.

$$I_1 = I_{ini} - \frac{F(I_0)}{F'(I_0)} \quad (3.9)$$

Where

I_1=Calculated current for the next iteration
I_{ini}=Initial value of current
$F(I_0)$=Function to be solved
$F'(I_0)$= Derivative of the function

Equation (3.2) is taken as a function to be solved as given by

$$FI_0 = I_{ini} - I_{ph} + I_0(\exp(\frac{V+I_{ini}R_s}{V_t}) - 1) \qquad (3.10)$$

The derivative of this equation is calculated and is shown below

$$FI_0 = 1 + I_0 \exp\left(\frac{V+I_{ini}R_s}{V_t}\right)(R_s/V_t) \qquad (3.11)$$

In the first iteration, the current value for the next iteration is calculated from (3.9). In this respect 4 iterations are used to estimate the value of the current precisely. In MATLAB for loop is used to run 4 iterations, but in PowerFactory loop cannot be applied so (3.9)-(3.11) are used as it four times to estimate the final value of the current.

3.2 Maximum Power Point Tracking (MPPT)

3.2.1 Background

The output of a photovoltaic system depends very much upon the weather conditions i.e. solar irradiation, temperature and shading effects due to clouds. These parameters in a PV system never remain constant, instead kept on changing at each instant. Also mostly solar cells in the market can achieve a maximum of 15-20% energy conversion. But after a lot human effort and research, Atla electronics (USA) reached to an efficiency of 23.5 % as verified by National Renewable Energy Laboratory (NREL) in 2012[15] [16]. So it the power electronic converters that provide the controllability over this energy conversion issue from sun light to electricity. Under these circumstances it is very important to for power electronic converter to have such a control that can ensure to have a maximum possible output power from PV array with changing weather conditions.

MPPT function is to regulate the DC output voltage or current in such a way that the maximum possible power can be obtained, with respect to any changes in weather conditions. The maximum power point (MPP) is the point at which system has the highest possible efficiency. For one weather condition there can only be one operating point in the system that can give the optimal maximum efficiency. Therefore to track this point in the system is very important in order to increase the system efficiency. Particularly, the system having any kind of converter needs Maximum Power Point Tracking (MPPT) in order to make sure that it deliver maximum power to other side.

PV array characteristics are nonlinear and greatly depend upon weather condition as shown in Fig 3.2. Due to this weather dependence there is one single operation point in each characteristics that will give us the maximum point out of array. Particularly with grid connected PV system, it is very important for a converter to track the maximum power point with every change in the solar irradiation and temperature. Therefore MPPT control in a PV system became very essential for an efficient system.

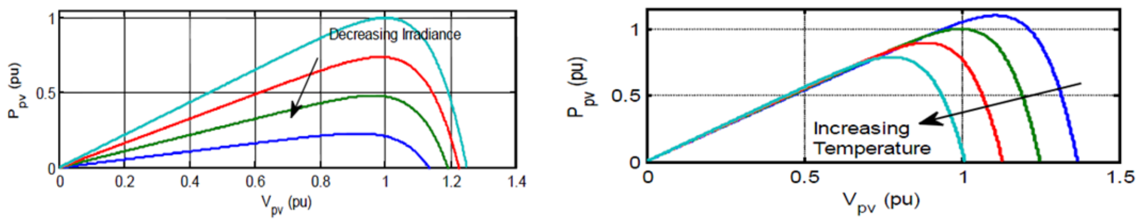

Fig 3.2 Irradiation and Temperature Impact on power-voltage characteristics of PV array [14]

3.2.2 MPPT Scheme

The power generated by a PV system is nonlinear, but static function of PV generator terminal voltage i.e. V_{dc}. For each irradiation and temperature value it exhibits a global peak in power corresponding to an optimum voltage. Maximum power can be obtained from the PV system, if its dc voltage is regulated at an optimum value. Therefore function of MPPT control in a PV system is to find the value of optimum dc voltage and issue the dc voltage reference command i.e. $V_{dcref.}$ This reference dc voltage is then further given to the main controller that will regulate dc voltage accordingly.

3.3 Types of MPPT Control

There are many MPPT techniques proposed and implemented in PV system e.g. Perturb and Observe (P & O)/ Hill Climbing, Incremental Conductance (IncCond), Fractional Open Circuit Voltage / Constant Voltage (CV) and Fractional Short Circuit Current as explained in the literature [14], [17] and [18]. The methods vary in complexity, sensors required, convergence speed, cost, range of effectiveness, implementation hardware, popularity, and in other respects.

After many comparative studies and surveys, P&O and IncCond techniques can be said as two most widely used MPPT method as indicated in [14], [17] and [19]. These two methods are implemented in this project and are explained below in details.

3.3.1 Perturb and Observe (P & O)

P & O method is one of the most widely used MPPT methods because of its simplicity and ease to implement. It works by creating a perturbation in terminal dc voltage of PV array and observes its consequences on output power of PV array. If power increases with incremental perturbation, it continues to make perturbation in the same direction otherwise it is reversed. In case of power increase with incremental perturbation, the operating point would be on the left hand side of the maximum power point.

If incremental perturbation causes power to decrease, it indicate that MPP has crossed and operating point is somewhere on the right hand side of MPP. In this case, it reverses its perturbation and start making detrimental perturbation in the voltage of PV array in order to track the maximum power point. Once the MPP is achieved, the operating point would be at maximum power point as shown in Fig 3.3.

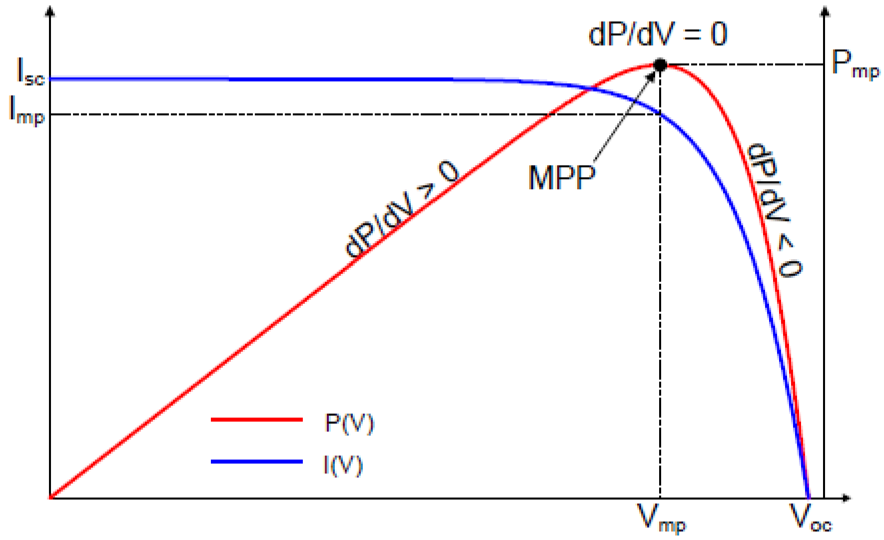

Fig 3.3 Perturb and Observe (P & O) [20]

It has three conditions

I. dP/dV>0 (Left hand side of MPP)

II. dP/dV<0 (Right hand side of MPP)

III. dP/dV=0 (At MPP) (3.12)

It can also be seen from Fig 3.3 that voltage corresponding to MPP called V_{mp} and current I called I_{mp}. These values at STC are available in the data sheet of every PV module.

Fig 3.4 illustrates a flowchart of the algorithm used to implement this MPPT technique in this project as explained in [17]. Like most of the other techniques, P &O also needs measurement of V_{pv} and I_{pv} as input to its algorithm.

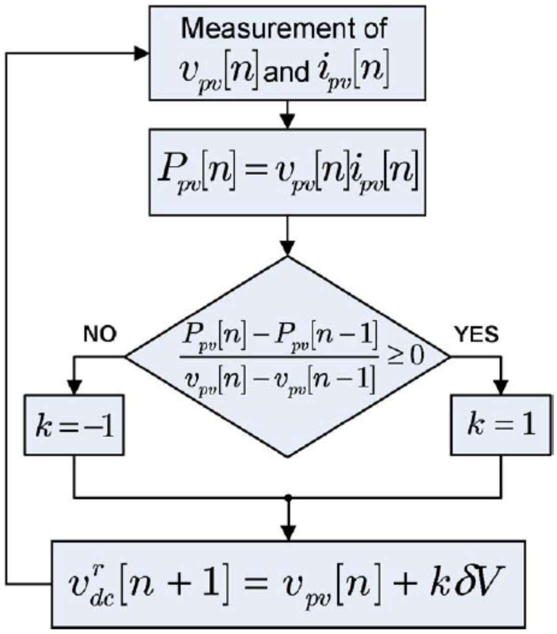

Fig 3.4 Flowchart of P & O Algorithm [7]

The algorithm calculates the power P_{pv} by multiplying V_{pv} and $I_{pv.}$ After that it checks the value of dP/dV, according to (3.12). If dP/dV is greater than zero, it set the value of k=1 making an incremental perturbation in the voltage. The quantity δV is actually a voltage increment step and is a design parameter. This parameter depends upon the tracking speed and accuracy of algorithm [17] and is calculated by

$$\delta V = \frac{(Vmp0)(Tdelay)}{step} = \frac{Vmp0}{(freq)(step)} \qquad (3.13)$$

Where

V_{mp0}= Voltage of PV array at maximum power point at STC
T_{delay}= Time delay value between two measurements in seconds
freq= Frequency of MPPT algorithm in Hz (which is inverse of Tdelay)
step= Design Parameter

The parameter δV is very important in deciding the speed of the algorithm as well as accuracy. While designing the MPPT control it should be kept in mind that δV should be carefully selected, as bad choice of this parameters can lead to wrong operation of MPPT. Generally, too large value of δV would cause ripples in the output voltage, whereas too small value of δV can result in a slow response of MPPT at the output. It is a tradeoff between fast tracking speed and accuracy of the output. Typical MPPT frequency used in the MPPT is 10-20 Hz, but higher frequencies can be used in order to reduce the ripples in the output of PV array.

Fig 3.5 shows the model of P&O MPPT technique implemented in PowerFactory for the PV system. This model is based upon the algorithm shown in Fig 3.4. In this model V_{array} and I_{array} are two inputs taken from the output of the PV array. In the start, delay blocks are used in front of voltage and current inputs, in order to take measurement values of V_{array} and I_{array} after specified interval. Due to first main voltage delay block, a delayed value of voltage obtained i.e. V123, which is further passed through another "voltage delay" block to get the value of Udelay. Hence Change in voltage is calculated as follows

$$DeltaU = V123 - UDelay \tag{3.14}$$

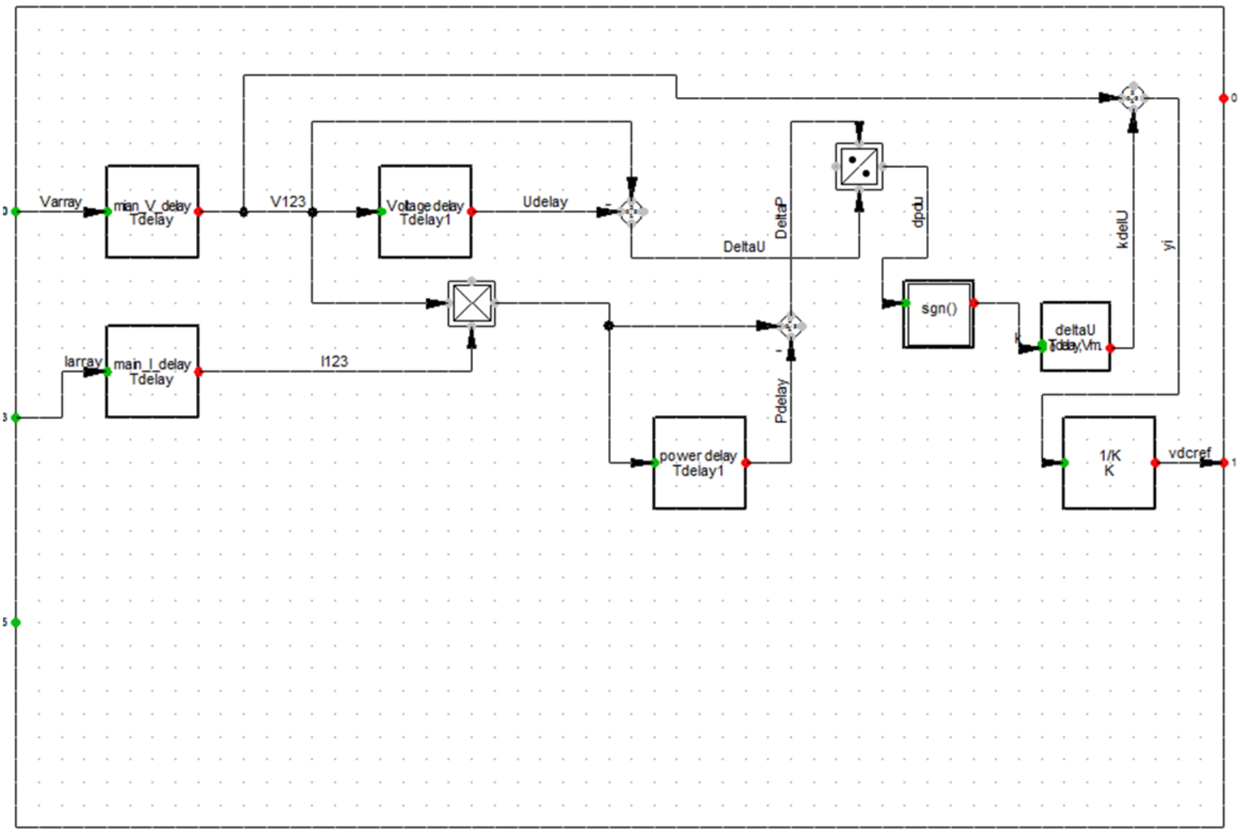

Fig 3.5 Model of P & O MPPT technique implemented in Power Factory

To get delayed value of power, first delayed values of voltage and current i.e. V123 and I123 are multiplied to get delayed power. Similar to voltage, this power then passed through a "power delay" block to get the value of change in power described as

$$DeltaP = P123 - PDelay \tag{3.15}$$

By analyzing the DeltaP/DeltaV according to conditions presented in (3.12), the voltage value for the next cycle can be calculated as

$$Vdc[n+1] = Vpv[n] + k\delta V \tag{3.16}$$

At the right hand side of the above equation, Vpv[n] is the voltage value of PV array for current cycle whereas quantity kδV is actually deciding factor in voltage increment or decrement for the next cycle. More specifically, δV is the constant value once calculated, but magnitude and sign of "k" decides the increment or decrement in the value of voltage for the next cycle.

P & O MPPT technique has one major drawback that once it tracks down MPP, it starts oscillating around that maximum point. Exact MPP can never be reached with this method. Also, these oscillations cause a power loss which depends upon the size of single perturbation step. A solution to this conflicting situation is to have a variable perturbation size that gets smaller towards the MPP as indicated in [14], [18] and [21]. This phenomenon of oscillation around MPP creates severe problem in case of fast changes in environmental conditions. Under fast changing of environmental conditions, P & O may fail to track the correct maximum power point and can be diverged from actual point. Some techniques like three point weight comparison or optimizing sampling rate have been introduced to overcome this drawback [22].

3.3.2 Incremental Conductance (IncCond)

In order to avoid the drawbacks caused by P&O method, Incremental Conductance (IncCond) MPPT techniques is developed. This method provides better results in tracking the MPP without having many oscillations around maximum power point. This method based on the fact that the slope of power curve is zero at MPP. Calculating the slope of power curve as shown in Fig 3.6 as follows

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0 \qquad (3.17)$$

$$\frac{I}{V} + \frac{dI}{dV} = 0 \qquad (3.18)$$

Using (3.17) and (3.18), IncCond algorithm works. Particularly (3.18) is evaluated such that if this equation holds it means MPP is achieved. In (3.18), instantaneous conductance (I/V) and incremental conductance (dI/dV) are compared; when both of the conductances are equal MPP is met.

From (3.17) and (3.18) it can be concluded that

I. dI/dV>-I/V (Left of MPP)
II. dI/dV<-I/V (Right of MPP)
III. dI/dV=-I/V (At MPP) (3.19)

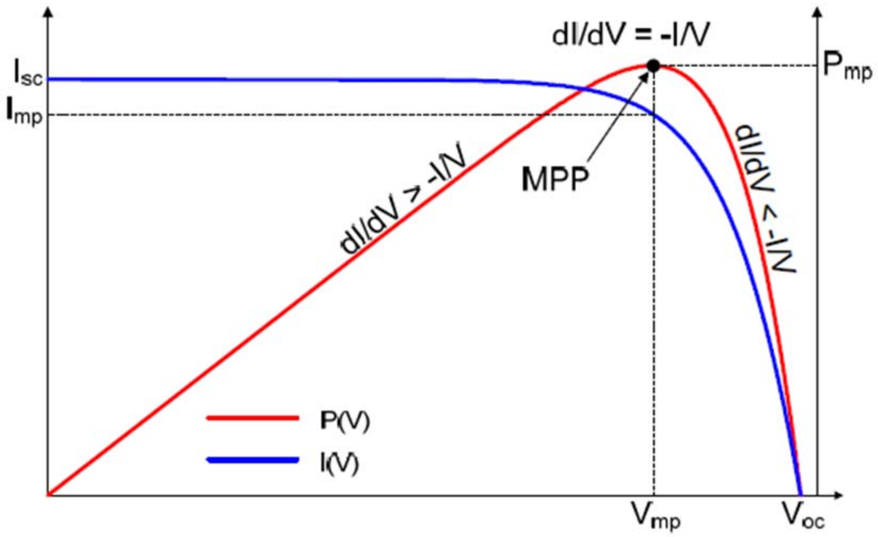

Fig 3.6 Incremental Conductance (IncCond) [20]

From Fig 3.6, it is clear that if $dI/dV>-I/V$ holds, operating point is at the left of the MPP and voltage needs to be increased to track towards MPP. Similarly if $dI/dV<-I/V$ holds then voltage should be decrease in order to find MPP. But if $dI/dV=-I/V$ holds, there is no need to change the terminal dc voltage as in this case it is already at MPP.

This can be achieved by applying an intelligent algorithm as described by the flowchart of Fig 3.7. It starts by taking the measurement values of voltage v_{pv} and current i_{pv}. If there is no change in v_{pv} and i_{pv} as compared to last cycle, it goes back and takes new measurements. As soon as it observes some changes in v_{pv} or i_{pv}, it starts operating. From Fig 3.7 it can be noticed that if $(di_{pv}/dv_{pv}+i_{pv}/v_{pv})$ is positive and larger than an small value, ϵ, then operating point is at the left hand side of the MPP, and voltage is increased by one incremental step; if $(di_{pv}/dv_{pv}+i_{pv}/v_{pv})$ is negative and larger than small value ϵ, then voltage is decreased by one step. Once $(di_{pv}/dv_{pv}+i_{pv}/v_{pv})$ becomes an absolute value smaller than ϵ, MPP considered to have been reached and voltage is kept unchanged, as soon as a new change is observed in i_{pv}.

The magnitude of voltage incremental step δV is calculated from (3.13). As already explained, this step value determines the speed of the algorithm, so it should be carefully selected.

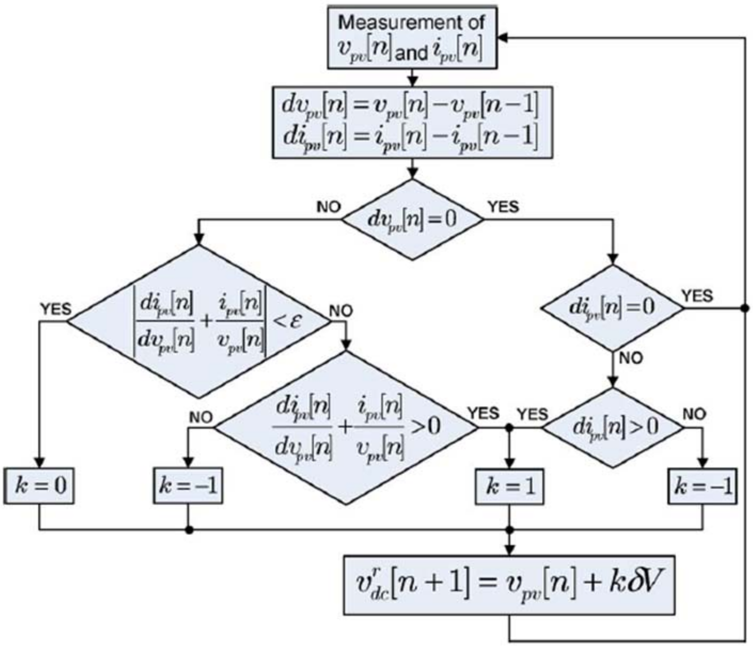

Fig 3.7 Flowchart of IncCond Algorithm [7]

In IncCond method, small value ϵ, is very important in perturbation step calculation, as according to (3.16) the voltage value for the next step is dependent on the value of *k*, which is indirectly dependent on epsilon. This small value ϵ, is selected by considering a tradeoff between the problem of not operating exactly at MPP and possibility of oscillating around it [13]. If too high value is selected, it would cause operating point of PV system to move away from MPP. On the other hand, if too low value is selected, it can cause more oscillations around MPP. Therefore by hit and trail method a suitable value for each case should be selected.

Fig 3.8 shows a model of IncCond which is implemented in PowerFactory for this project. This model is based upon the algorithm shown in Fig 3.7. Similar to P & O method, in this model here V_{array} and I_{array} are two inputs taken from the output of the PV array. In the start, delay blocks are used in front of voltage and current inputs, in order to take measurement values of V_{array} and I_{array} after specified interval. From main voltage and current delay blocks, the delayed values of voltage and current are obtained i.e. V123 and I123. Then, in order to get the values of change in voltage "dv" and change in current "di" for each cycle, these values are passed through "voltage delay" and "current delay" blocks.

There are four inputs to the input selector i.e. delayed voltage, delayed currents, di and dv. According to the algorithm shown in Fig. 3.7, input selector decides the value of k. After calculating the value of k, using (3.13) it calculates the value of δV in the next block named as deltaU. This block also takes value of k as input, multiplies it with the δV value and finally gives the value "kδV". In the end, the value for the V_{dcref} i.e. reference dc voltage, is calculated using (3.16).

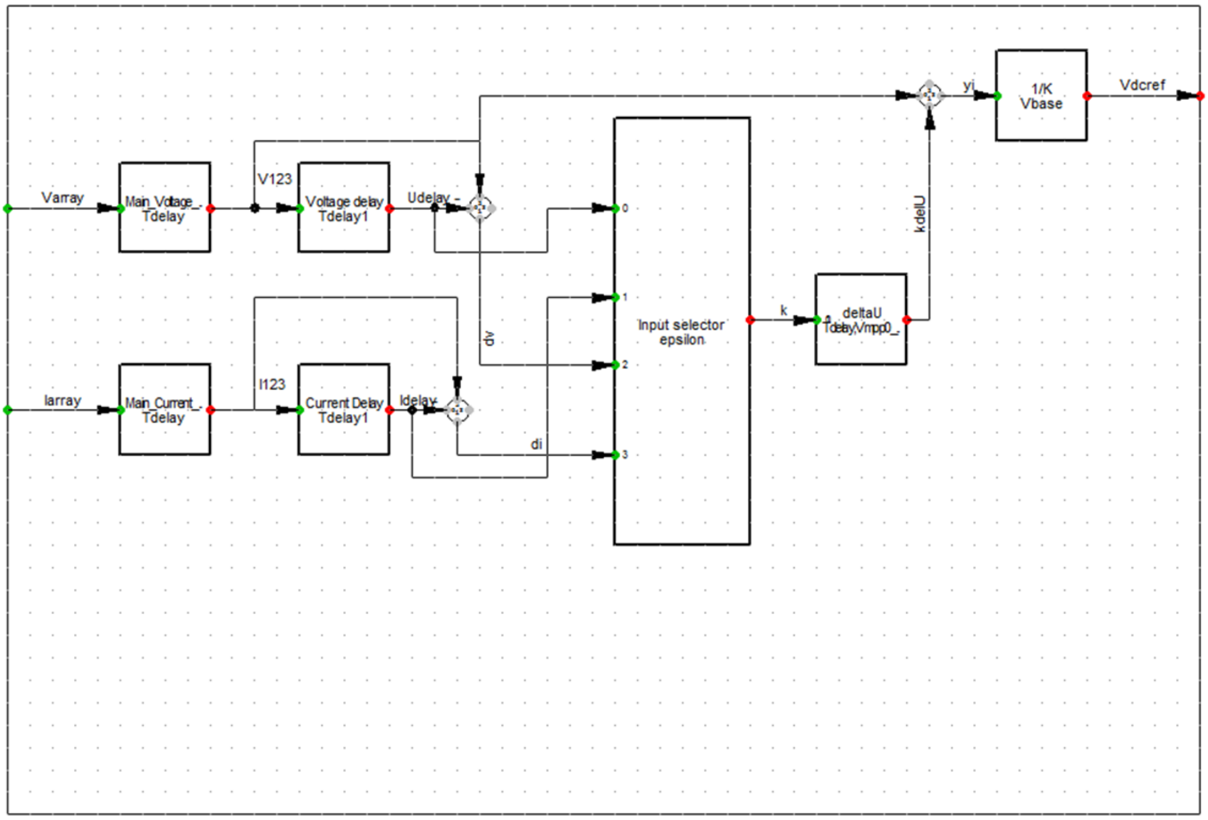

Fig 3.8 Model of IncCond MPPT technique implemented in Power Factory

3.4 Comparison between P & O and IncCond

Incremental Conductance (IncCond) shows better performance in fast changing environmental conditions. First advantage of IncCond is that it does not oscillate around MPP as it was the case for P & O method. This is due to the check of condition di=0, which made it possible to maintain a constant voltage across dc link once MPP is found. Furthermore, using the conditions (3.20) and (3.21) helps in determining the relative location of MPP [23].

$$\frac{di_{pv}}{dv_{pv}} + \frac{i_{pv}}{v_{pv}} > 0 \qquad (3.20)$$

$$di_{pv} > 0 \qquad (3.21)$$

It can be observed from Fig 3.9 and Fig 3.10 that in case of P&O MPPT method, continous oscillations around MPPT can be observed. But in case of IncCond these oscillations are removed, by using some additional conditons i.e. di=0.This condition made it possible to maintain a constant voltage across dc link once MPP is achieved.

These oscillations are also present in P&O method even when there is no disturbance in the system as shown in Fig 3.10. But IncCond exhibits better results than P&O method as there are no such oscillations present in this method. These oscillations causes power losses in the system and are not desirable to have efficient power system.

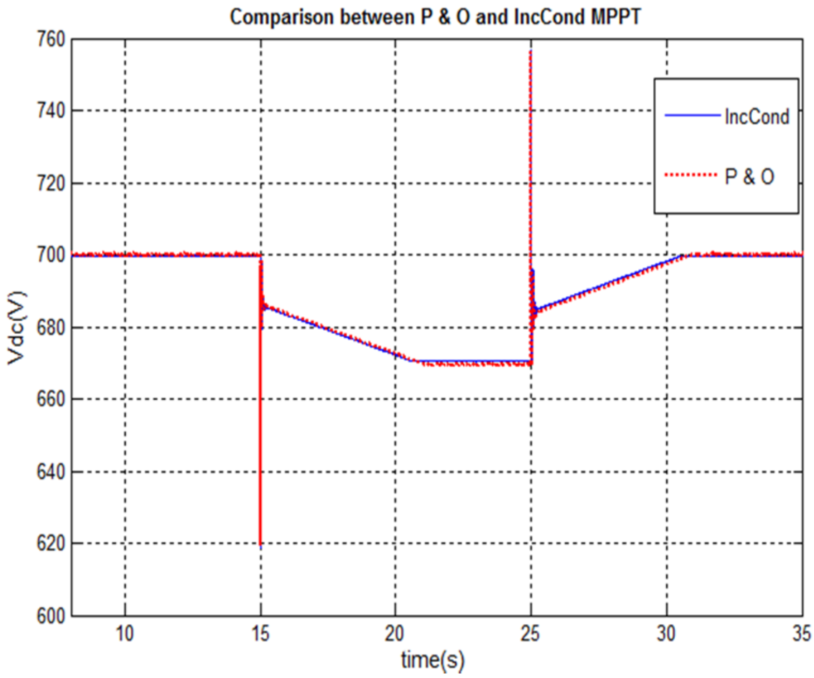

Fig 3.9Comparison of P & O and IncCond MPPT

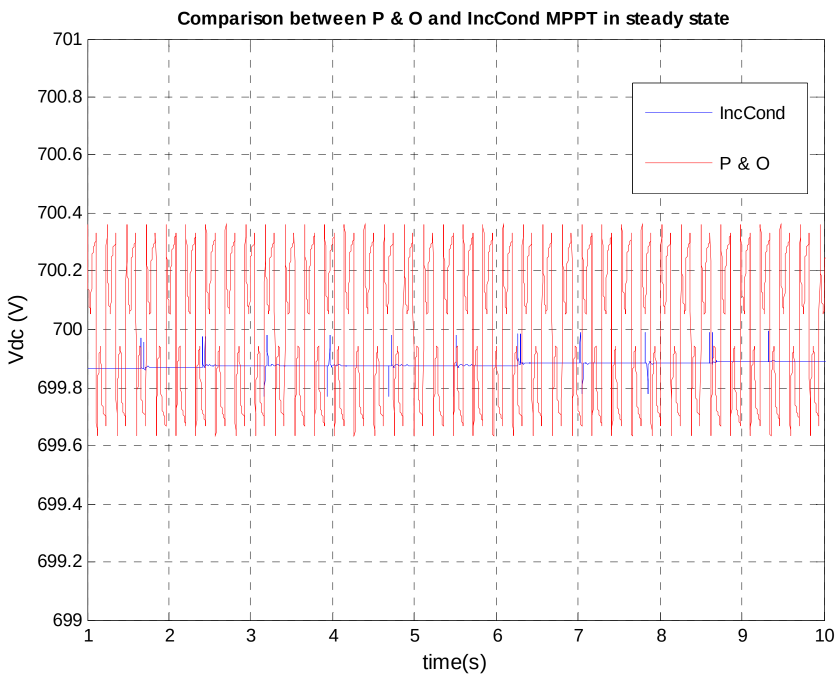

Fig 3.10 Comparison of P & O and IncCond MPPT in steady state

4. PV Models in PowerFactory

This chapter provides the basic overview of the PV models in PowerFactory. Modeling details of generic PV model available in PowerFactory and newly developed KTH model in PowerFactory are presented. The content of this chapter validate that newly developed KTH model is much improved one as compared to the generic model available in PowerFactory.

4.1 General PV modeling in PowerFactory

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. 4.1.

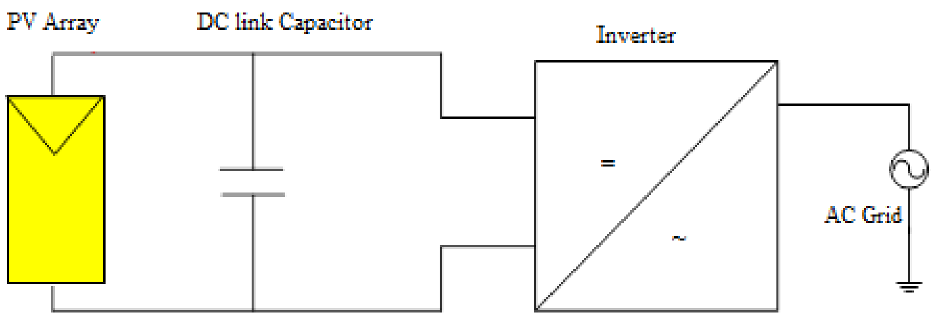

Fig. 4.1 Grid connected PV system model

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 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. 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.

2. **Interfacing converter**

In PowerFactory the interfacing converter can be represented by either a static generator or a PWM converter. In PowerFactory when PV system is represented by the static generator, then there is no need to physically represent interfacing converter. In this case static generator or includes the PV array and interfacing converter in it.

But in case of a PWM converter, PV array needs to be physically represented with a current source connected to a DC bus bar along with a DC link capacitor. PWM converter is also separately represented. The two different possible ways of PV system modeling in Power Factory are shown in Fig. 4.2.

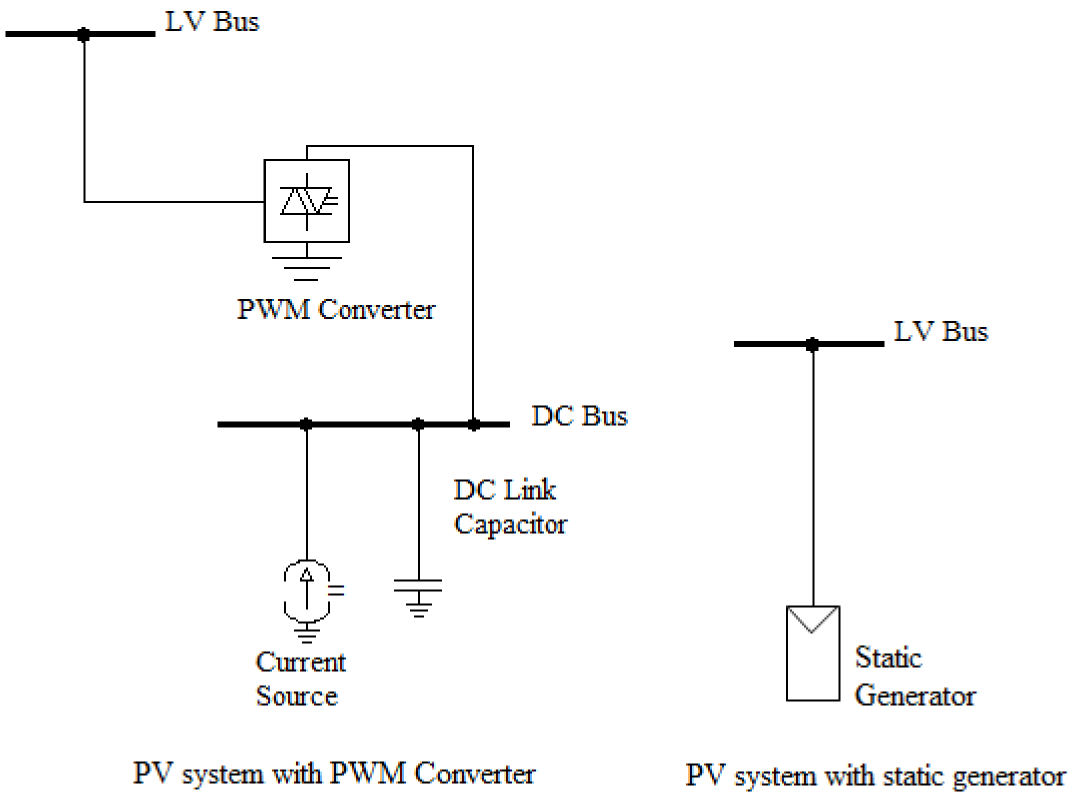

Fig. 4.2 Different PV system modeling in Power factory

In the PowerFactory there is a PV system component 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. But in this project static generator is used to model PV generator and will be explained in details in coming section.

4.2 Static generator

Static generator is an easy to use model of any kind of static (no rotating) generator in Power Factory. It can be used for following [24].

- Photovoltaic Generators
- Fuel Cells
- Storage devices
- HVDC Terminals
- Reactive Power Compensators
- Wind Generators

4.2.1 Basic data

As in this project, static generator is used as photovoltaic generator, so it is selected from category list as "Photovoltaic". Any number of parallel machines can be used according to system rating requirements. In this respect, the total rating of generator would be equal to the rating of a single generator multiplied by the number of parallel machines used. Also under the ratings tab, it is required to specify the rating for one generator in MVA and the power factor at which machine is designed as shown in Fig 4.3.

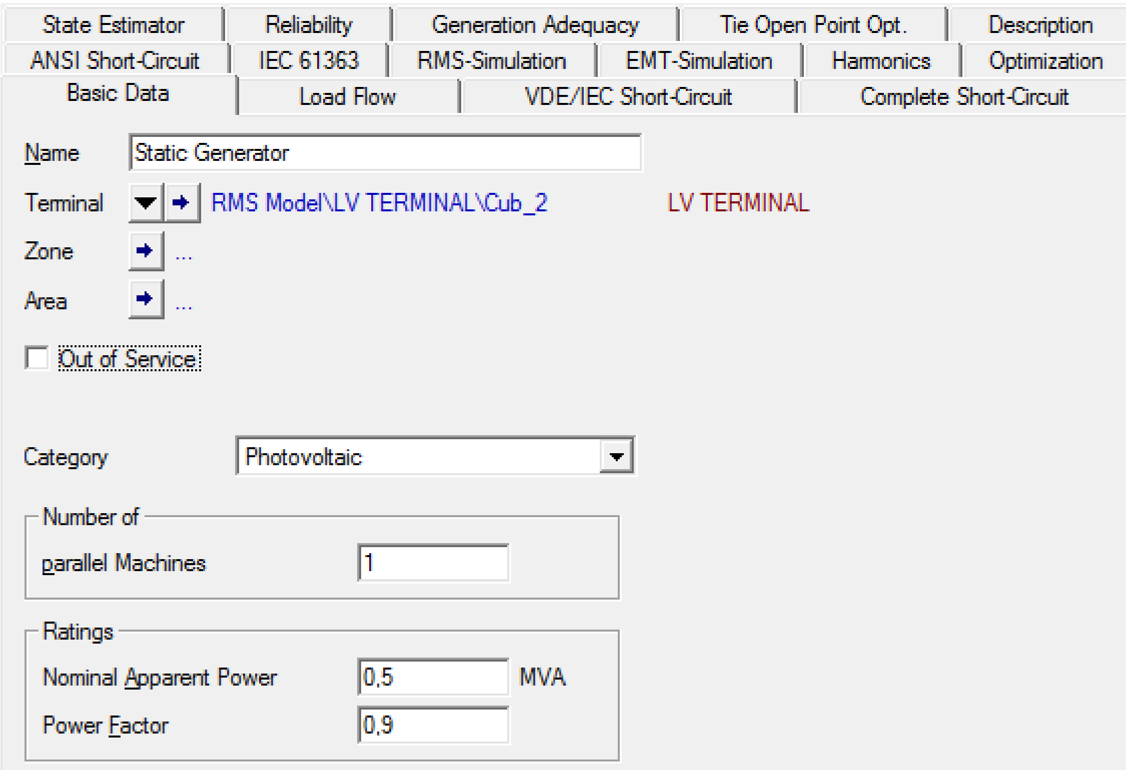

Fig. 4.3 Basic Data for Static Generator

4.2.2 Load Flow Analysis

A typical interface window of the static generator in load flow is shown in Fig. 4.4. 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. For the load flow, the variables need to be defined initially to calculate the load flow analysis; can be set using static generator. In Fig 4.4 it can be seen that active power and reactive power are defined in the start to calculate the load flow of the system. These variables can be changed according to the requirement of the system.

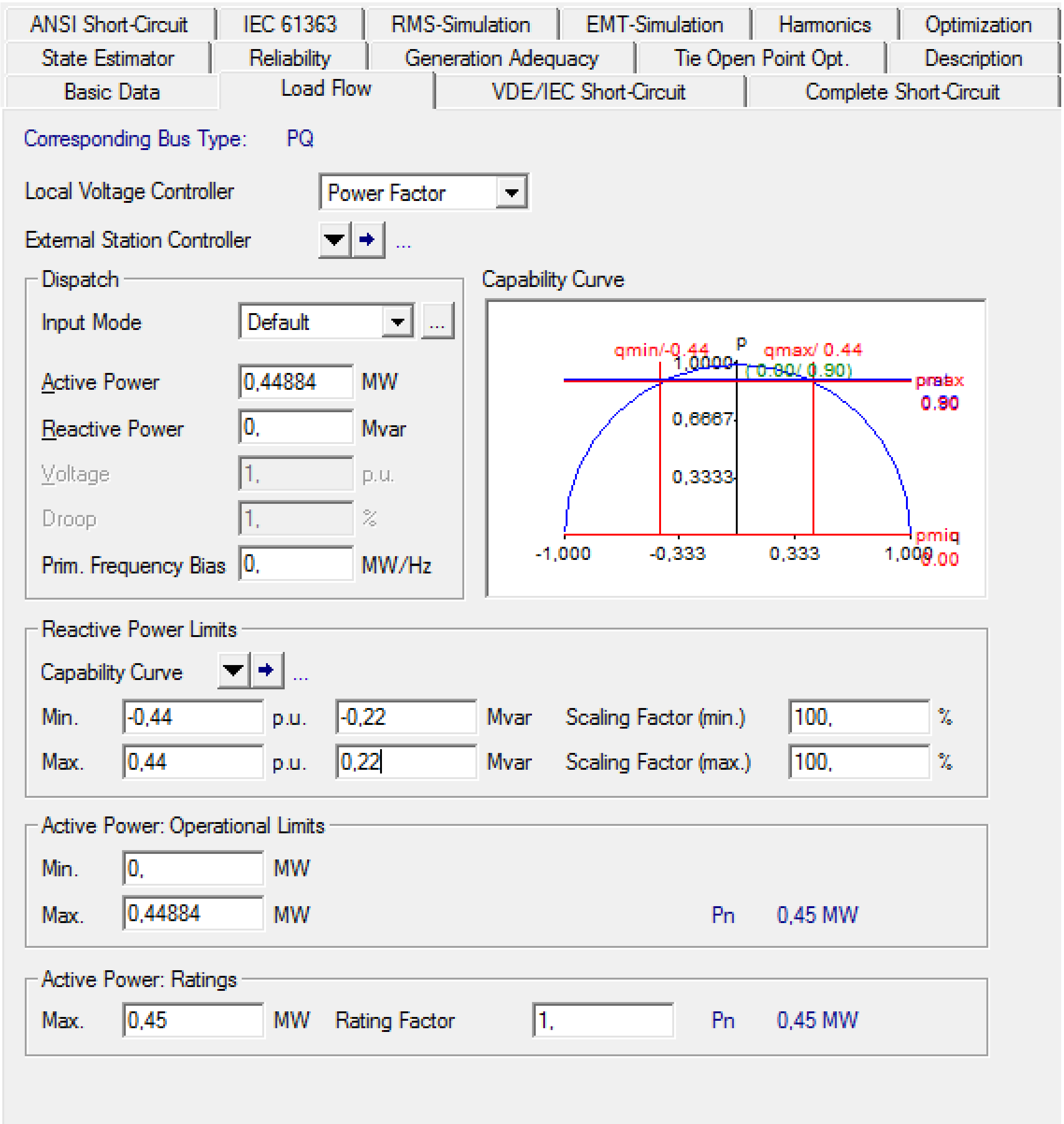

Fig 4.4 Static generator power flow under steady state conditions

The reactive power limits of the PV system are based upon either capability curve of the static generator shown in Fig. 4.5 or can be manually defined.

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. Assume that the PV system is expected to work at 0.9 power factor. In capability curve of the PV system shown in Fig. 4.5, the upper red line is the limit of the active power that can be transferred at 0.9 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 Fig 4.5. 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.

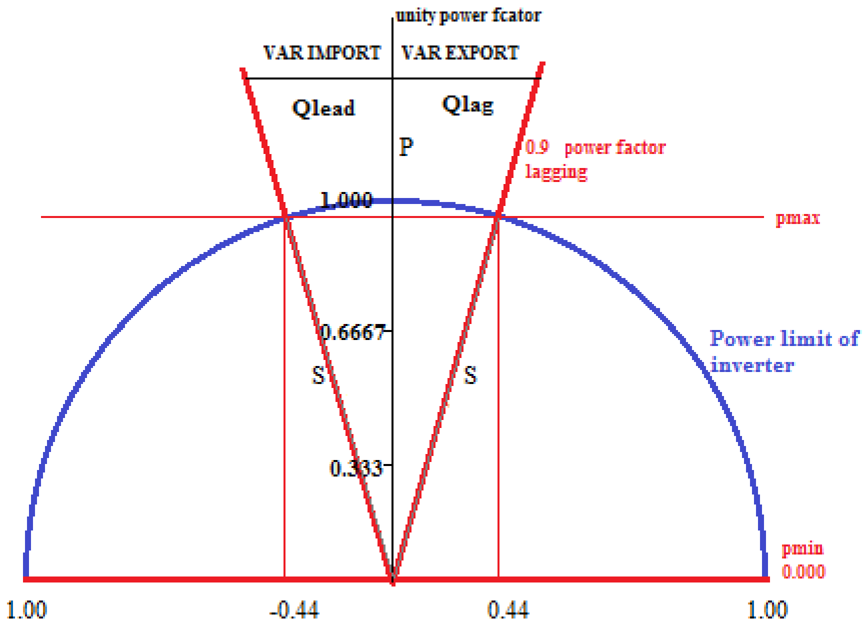

Fig 4.5 Capability curve of the inverter

4.3 Generic PV model in PowerFactory

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 PowerFactory tool in the form of a template. This 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, type of control etc.

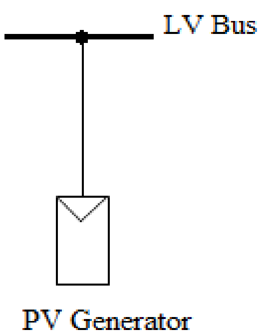

Fig 4.6 Photovoltaic template

4.3.1 Frame of Generic PV Model

The control frame of the PV System in generic model is shown in Fig 4.7. 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.

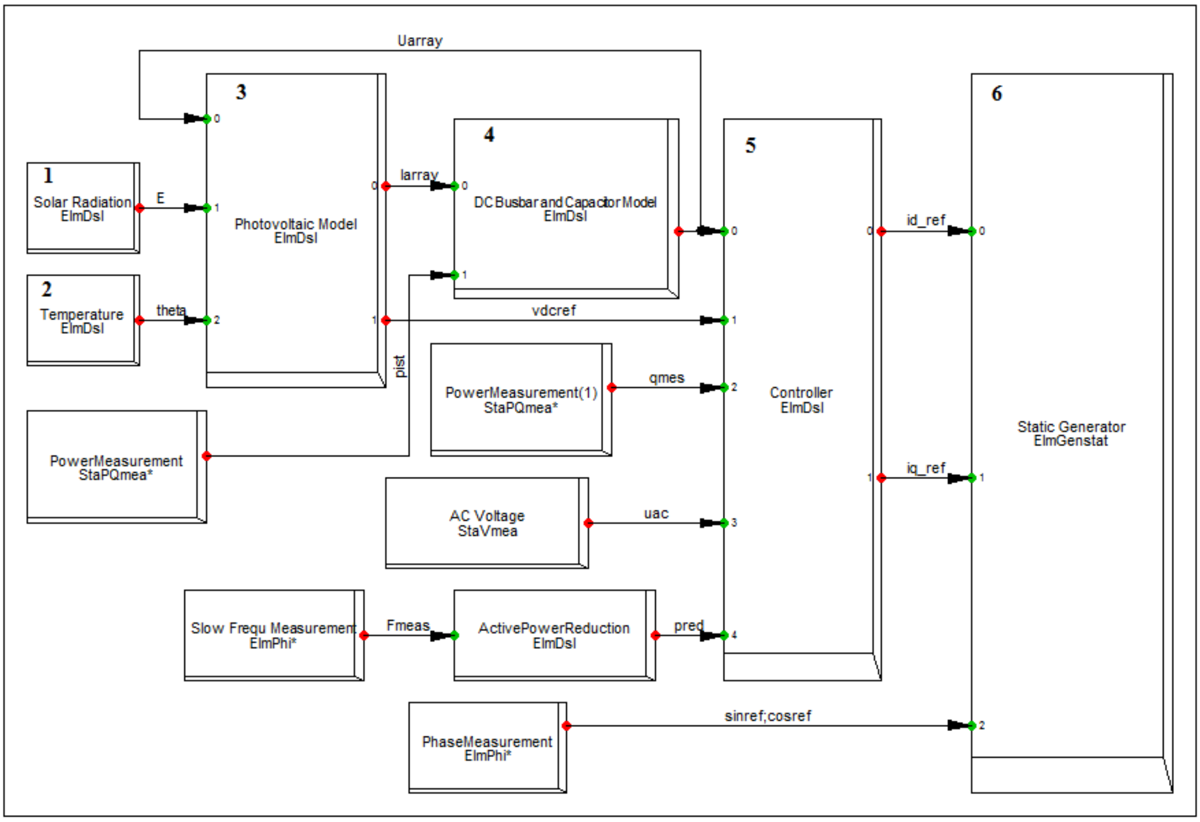

Fig 4.7 Frame of Generic PV Model

Slot 1 & 2: Solar radiation and temperature

Solar radiation and temperature both are modeled as limited time integrators. The purpose of these slots is to accumulate change of irradiance per second or 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. It can be noticed that in this PV model there is no maximum power point tracker (MPPT) control available. The output voltage of this model is assumed to operate on maximum power point and is taken as equal to the reference dc voltage "vdcref" for the controller. There are many unknown approximations used to calculate the final module current. Inside the PV panel model variables and parameters used for calculation are unknown and undefined. So it is very difficult to identify any scientific reference of these equations.

Slot 4: DC bus bar and capacitor model

This slot represents the mode 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 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. 4.8. It is 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. This 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 i_d (for active power) and i_q (for reactive power) are the outputs of this controller. These currents values are given as input to the static generator, which is the interfacing converter.

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. 2.12.

The equations represented in this block use a deadband of 10% of the nominal voltage and determine the i_q (q-axis component of the current). A deadband of 10% means, that it will not provide or absorb the reactive power as long as voltage deviation would be within 10 % of nominal voltage. This deadband value can be changed according to the requirement of the system.

The q-axis component of the current is calculated as follows

$$i_q = \mathrm{K}(\mathrm{duac}) \qquad (4.1)$$

Where

K= parameters named as "droop"
du_{ac}=Difference in actual voltage and steady state voltage

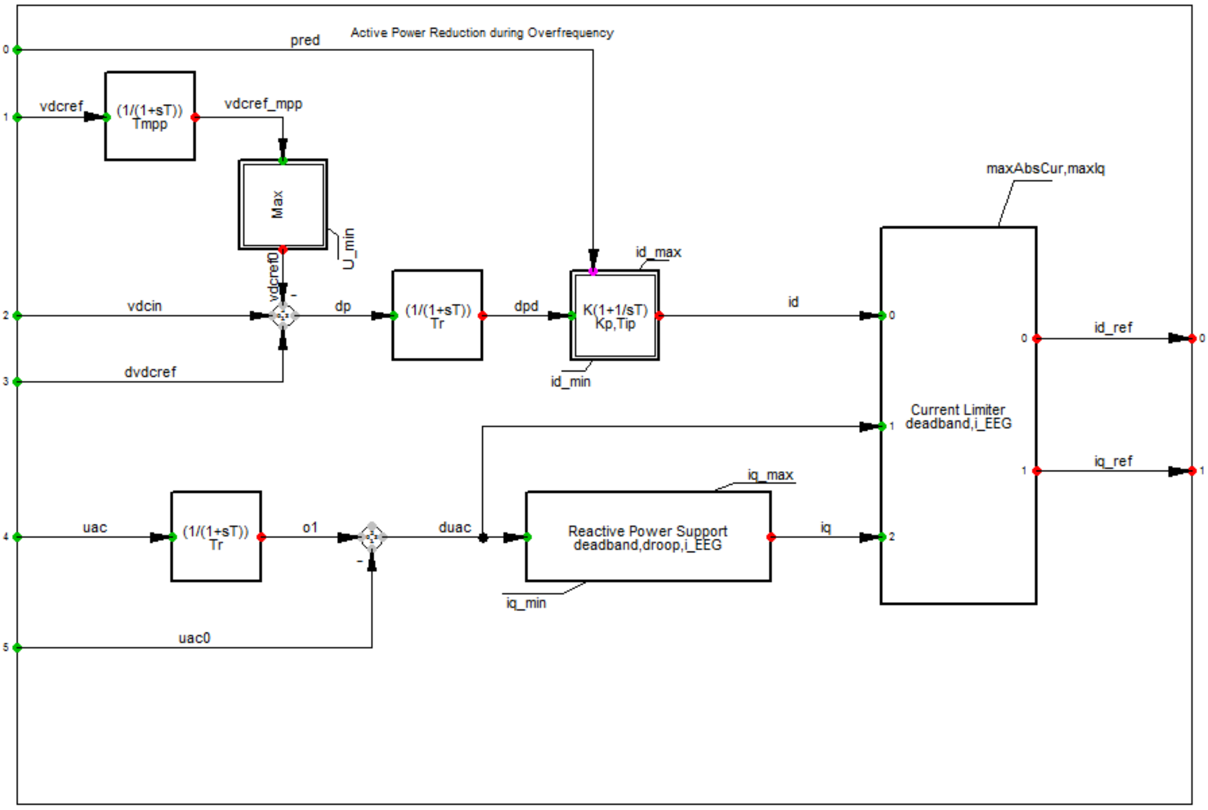

Fig 4.8 Control frame of Generic Model

In (4.1) the value of K is calculated on the basis of droop control and is denoted as droop in the parameters. The definition of iq is written according to Transmission Code 2007 [5] and System Service Ordinance SDLWindV.

In the end the values of i_d , i_q and the voltage deviation du_{ac} enters the current limiter that gives the final reference values of i_d and i_q as i_{d_ref} and i_{q_ref}. Current limiter, limits the current in the d axis in case of fault which is based upon the value of the current in q-axis. This limiter also controls the value of i_{d_ref}, in case of short circuit fault, such that there would not be any active power during the short circuit. Also current in q-axis is limited between maximum and minimum absolute possible current. This upper and lower current limit values are used as parameters and can be changed accordingly.

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-axis 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.

4.4 KTH Model in PowerFactory

4.4.1 Background

It has already been discussed that a generic model of PV system is available in PowerFactory as a template. This PV model gives the basic understanding about the working principle of a PV system and is explained under section 4.3 in details. But this generic model has following issues:

- PV array model with lot of undefined assumptions and internal variables.
- No MPPT control
- Only one type of reactive power control available
- No active power curtailment

So under these circumstances, there arises a need of a model which could explain the PV system in more details and can exhibit PV system with more controls in it.

4.4.2 Features of KTH Model in PowerFactory

This KTH model is equipped with following additional features as compared to generic model:

1. A more realistic PV Array Model
   - Based upon the equations with authentic scientific references.
   - Incorporates the environmental impacts (Irradiation & Temperature)
   - One diode model is used to model PV module

2. Two types of MPPT control:
   - Perturb and Observation (P & O)
   - Incremental Conductance (IncCond)

3. Four types of Q control
   - Unity Power Factor (Q Control 1)
   - Dynamic Power Factor (Q Control 2)
   - Droop based Control (Q Control 3)
   - AC Voltage Control (Q Control 4)

4. Active Power Control
   - Active power curtailment based on given Pref
   - Based upon frequency

4.4.3 Frame of KTH Model

General overview of the KTH model is shown in Fig 4.9. This is the complete frame of the new KTH model in which solar irradiation model, temperature model, PV array model, different control systems, measurement devices and static generator are shown. This will be elaborated in details in coming section.

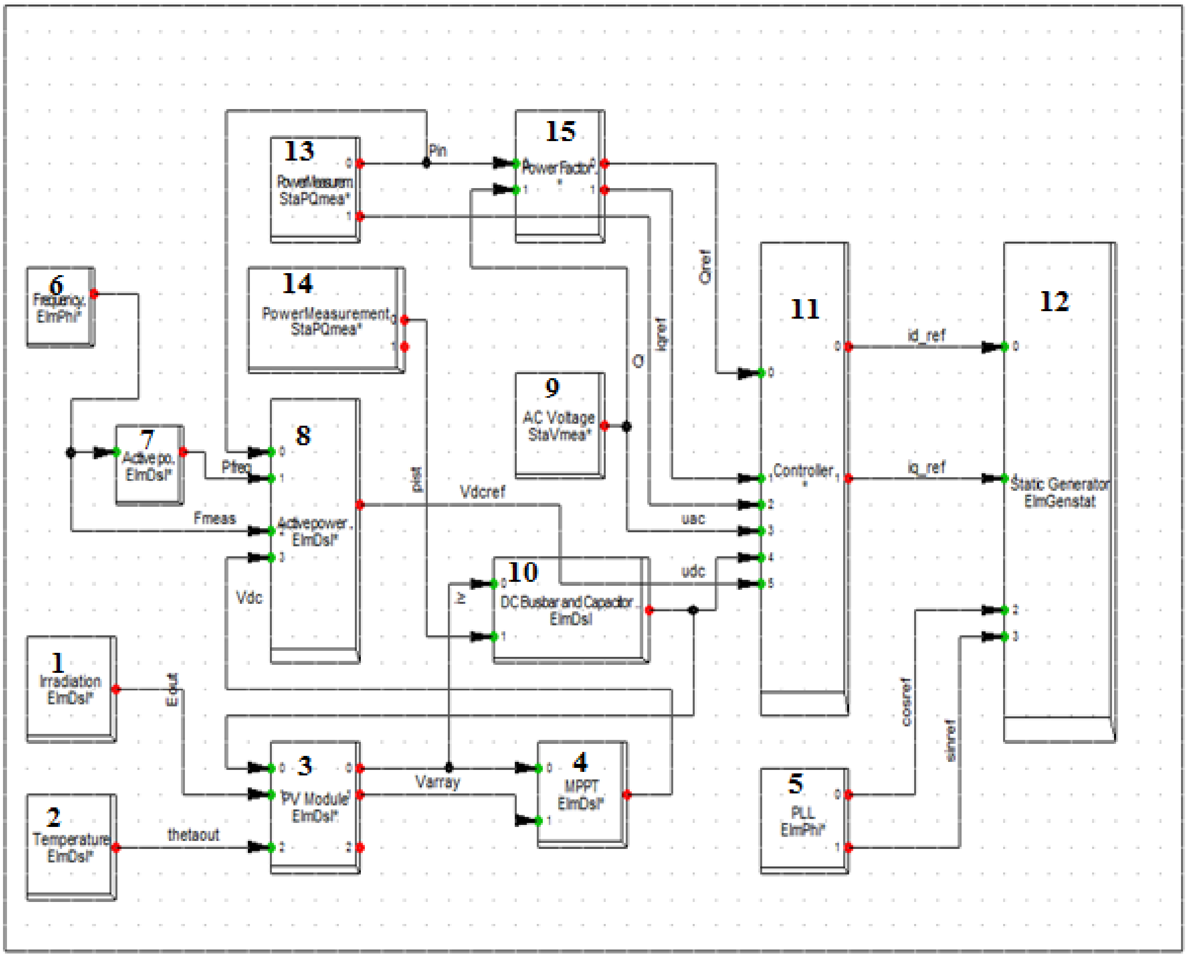

Fig 4.9 Frame of a KTH Model

Solar Irradiation (Slot1)

Solar irradiation is modeled in the form of an integrator that will sum all the potential change of solar irradiation per second "dE" and integrate over time. The variable "dE" is given as input to this integrator.

The value of irradiation "E" along with another input "Ein" is then given to a summation point that performs summation and finally gives the value of "Eout" which is the final value of solar irradiation given to the PV array model .The solar irradiation model is shown in Fig 4.10. This model can be used to see the effects of changing solar irradiation in the form of step on the output voltage, current and power of the PV array.

Temperature (Slot 2)

Similar to solar irradiation, temperature slot is modeled in the form of an integrator that will sum all the potential change of temperature per second "dtheta" and integrate over time. The variable "dtheta" is given as input to this integrator and it gives the temperature at the output. This model is shown in Fig 4.11.

This value of temperature "theta" along with another input "thetain" is then given to a summation point that performs summation and finally gives the value of "thetaout" which is the final value of temperature given to the PV array model. Temperature slot is modeled like this in order to have a step change of temperature.

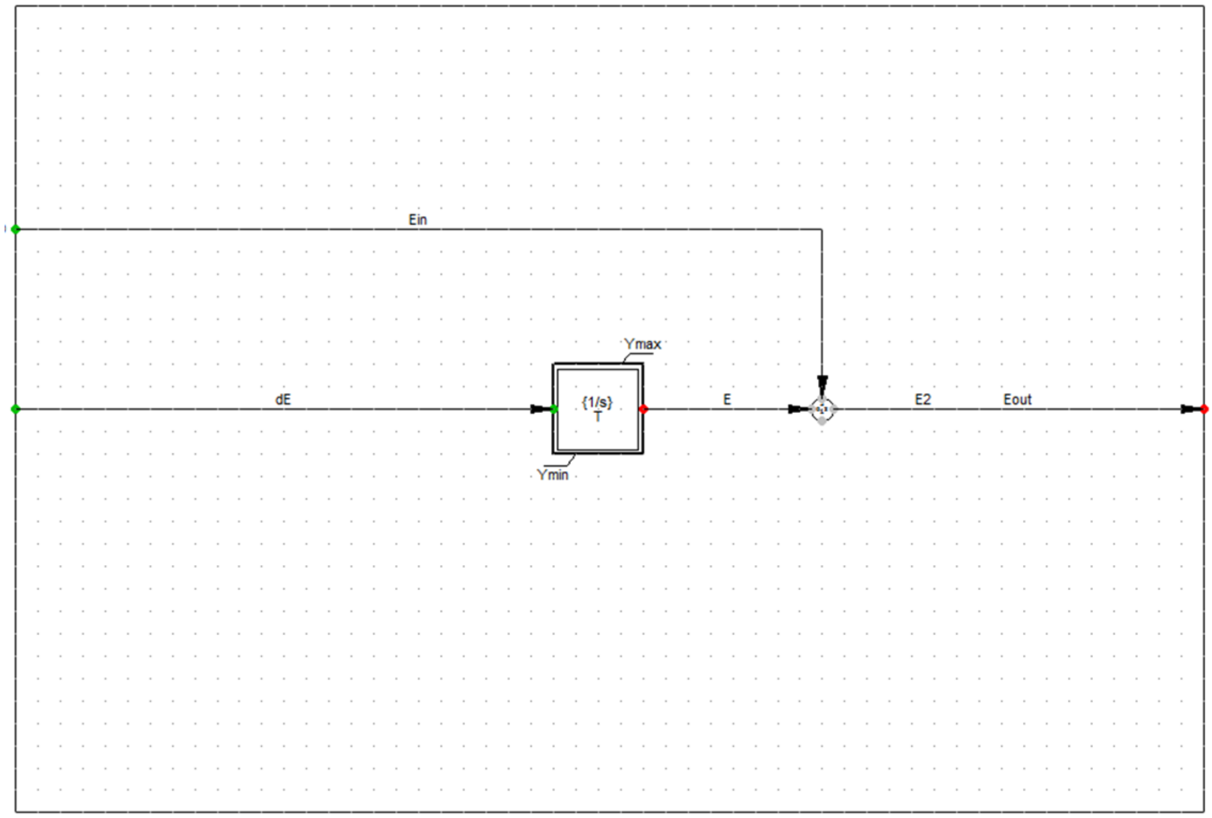

Fig 4.10 Solar Irradiation Slot of a KTH Model

PV Module (Slot 3)

PV module is indicated as slot 3 in the frame of KTH model in Fig 4.9. The detailed PV array model is shown in Fig 4.12.

This new PV array model is modeled in a more accurate way using the equations with authentic scientific references. It also incorporates the environmental impacts (irradiation and temperature) variation and output current has dependency on these environmental variables.

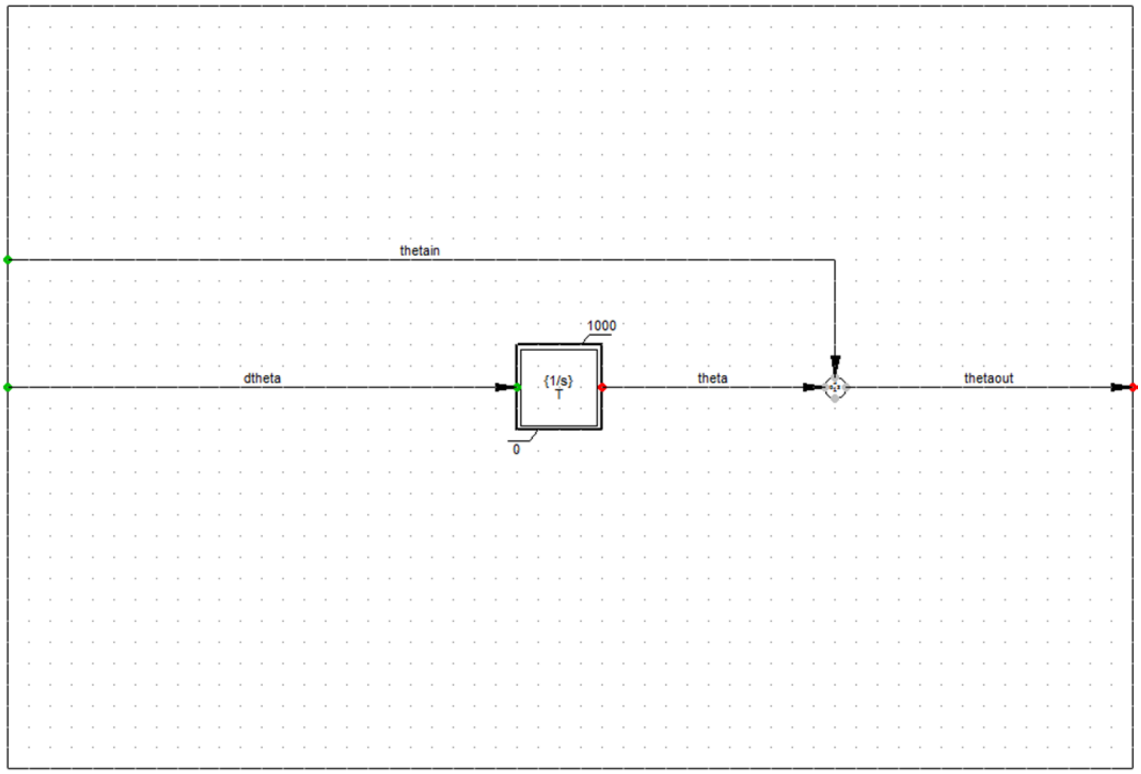

Fig 4.11 Temperature Slot of a KTH Model

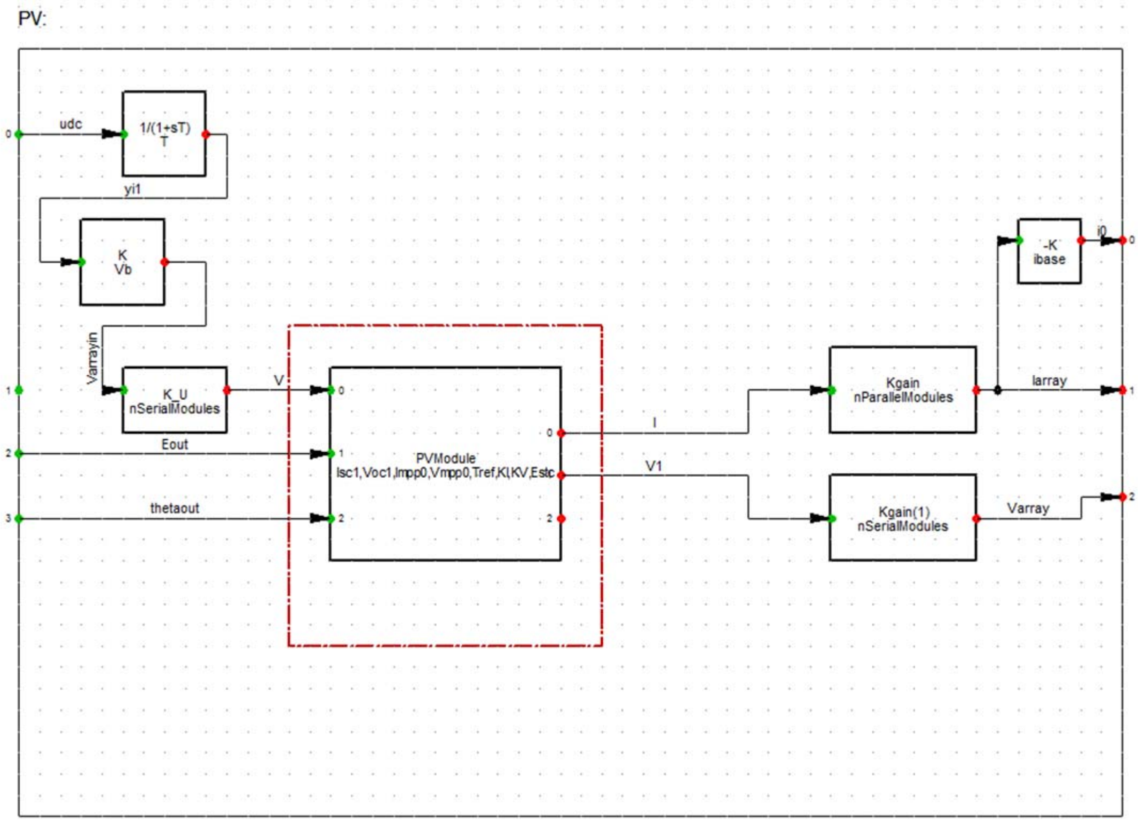

Fig 4.12 PV module slot of KTH Model

Photovoltaic system is modeled by considering the basic equations of solar cell. This PV array model is shown in Fig 4.12.

This model consists of several blocks in it. Input to this PV array model is dc voltage, solar irradiation and temperature. At the output, it gives PV array current and PV array voltage. This PV model has one main block (Photovoltaic Module), which has red colored box around it. All the main equations are placed inside this PV module box. On the basis of these calculations it gives voltage and current of PV array at the output. Inside the PV module all calculations are performed for one PV module, but this PV array consists of a number of series and parallel modules that on a whole makes this PV array.

Input dc voltage "udc" is in per unit and is passed through a low pass filter to attenuate the high frequency under abnormal conditions and in normal conditions this block is deactivated. After this the voltage is multiplied with its base value to get the actual value of the voltage. This filtered voltage is divided by the "number of series modules (ns)" to make it input dc voltage for one module, and is given to PV module for the calculations.

The other two inputs to the PV module are the solar irradiation "Eout" and temperature "thetaout", which are the values coming out from a solar irradiation block and temperature block.

MPPT (Slot 4)

The slot 4 in the frame of KTH PV model represents MPPT control and has already been explained in details under the section 3.2-3.4. The output of this slot gives the reference dc voltage i.e Vdcref, which can be given to controller (slot 11) in the frame of new model via an active power control block (slot 8). The details of these blocks will be explained in coming sections.

PLL (Slot 5)

This slot contains a Phase Locked Loop (PLL) device that generates an output signal whose phase is related to the phase of an input reference signal. PLL contains an internal oscillator that is synchronized by being phase locked with some grid power signal. For this case, it is locked to voltage in the system. In new model, this PLL is connected to LV bus bar.

The basic structure of a PLL is shown in Fig. 4.13. Phase detector produces a signal proportional to the phase difference between V (input reference signal) and V' (output signal). Loop Filter is a low pass filter to cut off higher frequency signals. Finally, voltage controlled oscillator adjust its frequency such that phase of input signal and output signal are matched. PLL slot in this KTH model is same as of generic model.

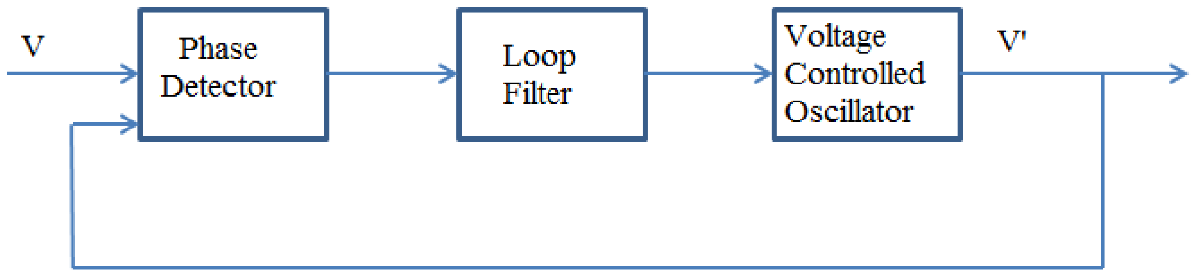

Fig 4.13 The basic structure of a PLL

The explanation of Slot 6, 7, 8.9,12,13 and 14 will be presented under the section 4.5.

DC Bus bar and Capacitor (Slot 10)

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 as shown in Fig 4.14. The output of this block is the dc voltage across the capacitor, which is used as the feedback to the PV module and as well as the input to the controller.

In this model, a current is first calculated by dividing the measured active power by actual dc voltage. This current is compared with input array current, which gives the actual current in the capacitor. Finally, integrating this current gives the actual dc voltage across the capacitor. The dynamics of the capacitor is given by

$$i(t) = C\frac{dU_{dc}(t)}{dt} \tag{4.2}$$

$$i_{ph}(t) - \frac{P_{ac}(t)}{U_{dc}(t)} = C\frac{dU_{dc}(t)}{dt} \tag{4.3}$$

P_{ac} is measured from active power measurement block, i_{ph} is the current output of PV array and u_{dc} is actual dc voltage across capacitor. The capacitance value C is used as a parameter and can be changed accordingly.

The description about other blocks of KTH model frame will be explained under the section 4.5 as those slots are related to control of PV system.

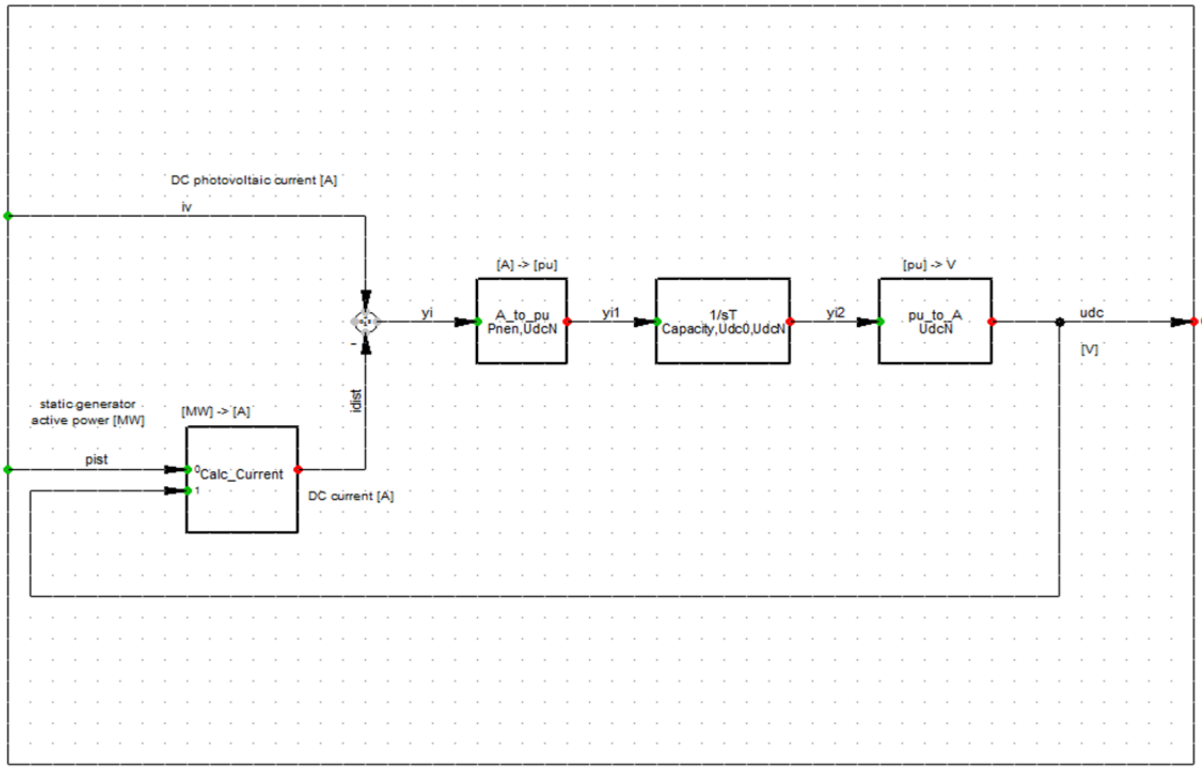

Fig 4.14 Dc Bus bar and Capacitor Slot

Basic structure of d-axis and q-axis current control

In the stability model of static generator shown in Appendix 8.5, the inputs: id_ref, iq_ref, cosref, sinref are used to determine the modulation index in the dq-reference frame. An inbuilt current controller is available within the PWM converter of static generator as shown in Appendix 8.6. The use of the built-in current controller is optional.

From the output definition of the stability 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. This outside controller will be explained in the section 4.5.2.

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 that in turns provide gate signal to VSC valves. Furthermore, to obtain the values of cosref and sinref, a phase measurement unit is employed along with the PWM converter. Based upon these reference angles, the d-axis and q-axis components of the modulation index are transformed back to the global (abc) reference frame.

Finally, the active power can be regulated by controlling id which is based on dc voltage regulation of PV system. And reactive power can be regulated by controlling iq which is either based upon AC voltage regulation or reactive power control strategies.

4.5 Control system in KTH Model

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. The main idea of the additional control is to provide an extra control over the output components. For the current PV system several control are implemented in PowerFactory for the regulation of DC voltage, AC voltage, reactive power output and active power output.

As explained previously the current generic PowerFactory 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 KTH model with options to choose depending upon the requirement. 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.

In Fig 4.9, slots 6, 7, 8 and 13 belongs to the active power curtailment of the PV system.

Frequency measurement (Slot 6)
Slot 6 is the frequency measurement unit. It measures the frequency of the system and gives its output to active power reduction block (slot 7).

Frequency measurement (Slot 7 and Slot 8)
Slot 7 is the active power reduction block. Slot 8 is active power curtailment block. Slot7 and Slot 8 will be explained under the section 4.5.1.

AC voltage measurement (Slot 9)
Slot 9 is AC voltage measurement device, which measures the AC voltage in per unit and gives it to controller for AC voltage regulation.

Main controller (Slot 11)
Slot 11 is the main controller. The output out of the controller (slot 11) is given to static generator. Slot 11 will be explained under the section 4.5.2.

Static generator (Slot 12)
Slot 12 represents the static generator which is directly associated with VSC in the system. It has already been explained under section 4.2.

Power measurement (Slot 13 & Slot 14)
Slot 13 and 14 are the power measurement unit which will provide the measured AC power from the AC side of the PV system. It should be kept in mind that slot 13 measures the active power and reactive power and gives the corresponding measured value to controller, Qref block and active power control block. In contrast, slot 14 is also a measurement device, but it only measures the active power in MW and serves as the input to the DC bus bar and capacitor slot. Both active power as well as reactive power are measured and are given to various slots for further controller design.

Qref block (Slot 15)
Slot 15 is the Qref block which is designed to provide the 'Q_{ref}' value to the controller (slot 11). The obtained 'Q_{ref}' value out of the Qref slot is used inside the controller for reactive power regulation.

The explanation about slots related to control system of KTH model frame is summarized in Table1.

Table 1: Details of control system slots in KTH Model Frame

Slot Number	*Slot Title*
6	*Frequency measurement*
7	*Active power reduction based upon frequency*
8	*Active power curtailment*
9	*AC Voltage measurement*
11	*Main controller*
12	*Static generator*
13 &14	*Power measurement*
15	*Power factor control*

4.5.1 Active power curtailment (slot 7 & Slot 8)

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. 4.15 shows the active power control technique employed within the system.

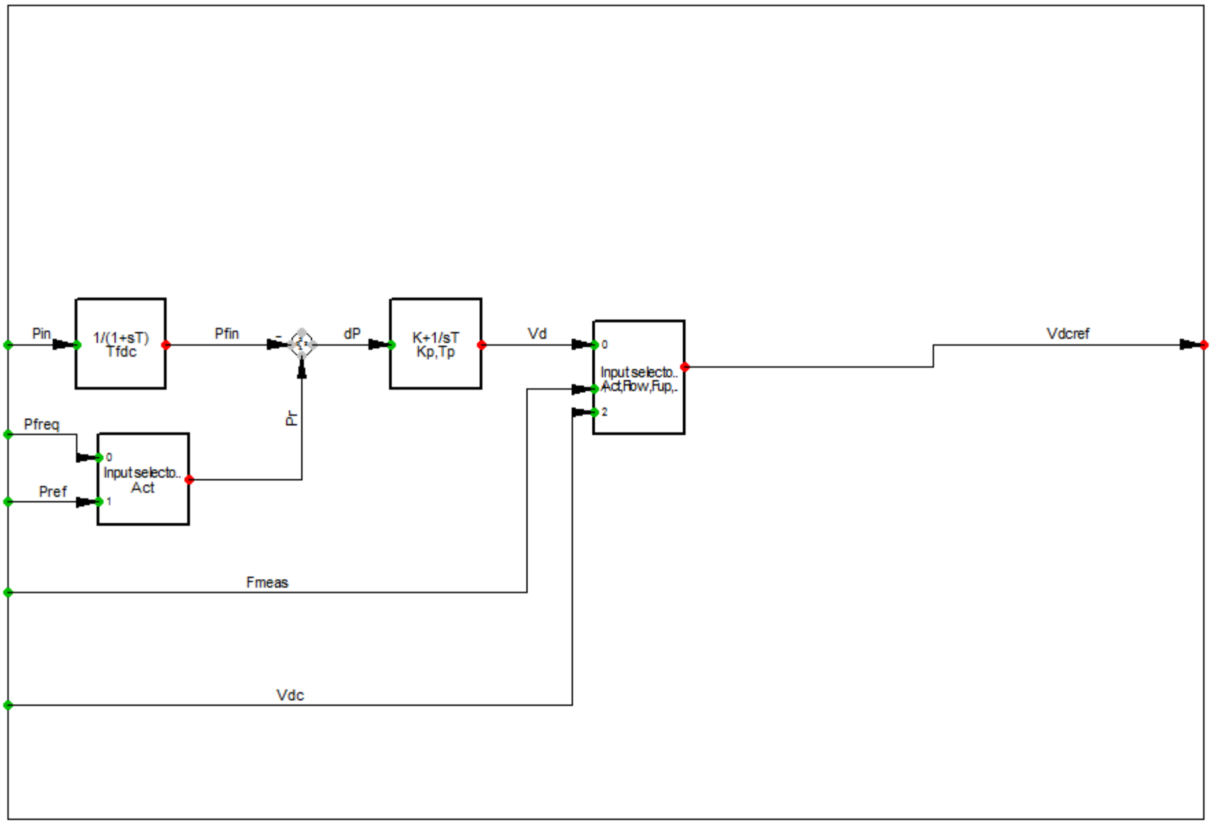

Fig. 4.15 Active Power Curtailment

As seen in the 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. 4.15.

In the grid code there is a recommendation to reduce the active power in case of over frequency as explained in Fig. 2.13. 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 Vdcref. For any 'Act' parameter value (here it is set to 0) other than 1, 'Pfreq' option is enabled and is the usual choice during the normal operating condition.

Vdcref is the output of the active power control block which goes into the main controller. 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'.

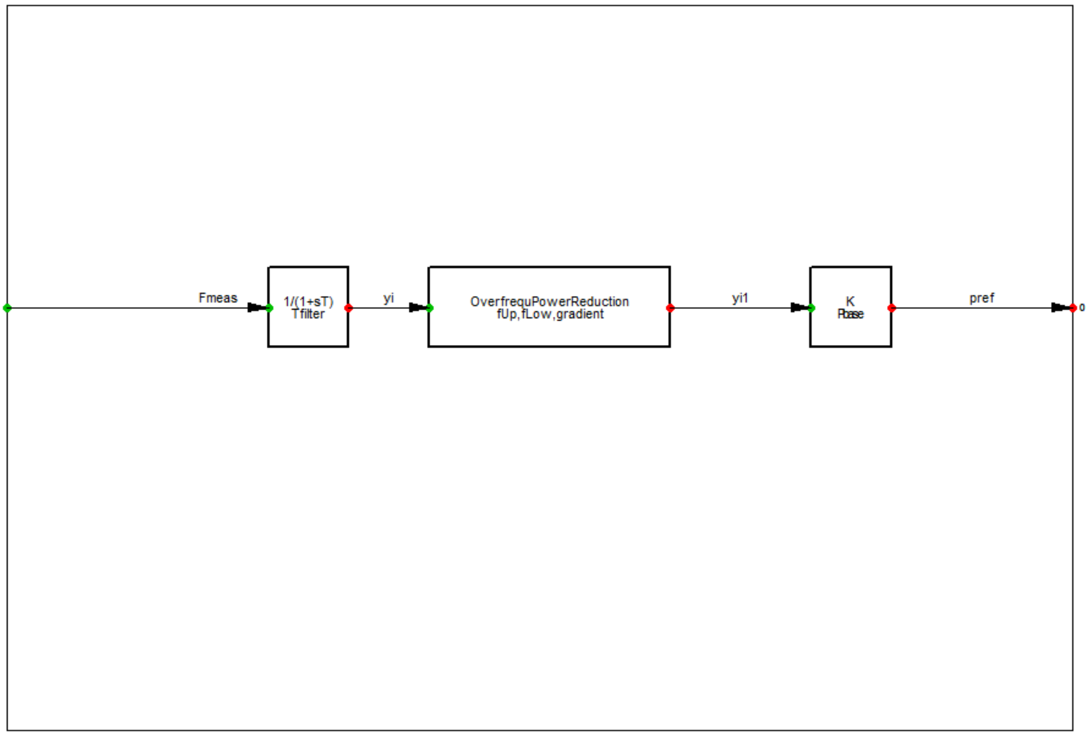

Fig. 4.16 Active power reduction block

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. 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. Three following options can be selected.

- 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:

$$F_p(s) = K_p + \frac{1}{T_p s} \tag{4.4}$$

Where

- K_p is the gain of the active power controller
- T_p is the time constant of the active power controller in seconds

4.5.2 Main Controller (slot 11)

The block diagram of the main controller implemented to obtain the values of 'iq_ref' and 'id_ref' is shown in Fig. 4.17.

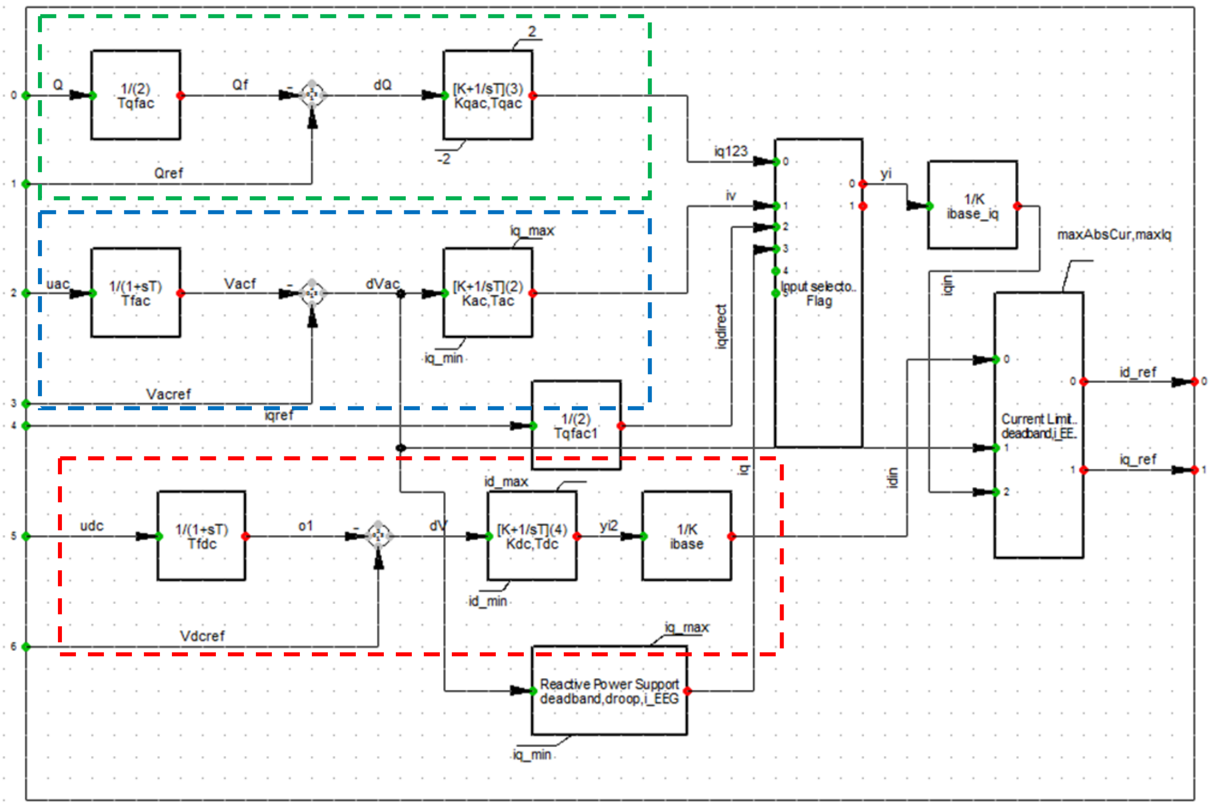

Fig. 4.17 Controller block diagram

The topmost part is the reactive power control with 'Q' and 'Qref' as input and 'iq' as output as represented in green color box in figure. Down to reactive power control is the AC voltage regulation with 'uac' and 'Vacref' as inputs and 'iv' as output as shown in blue color box. Next is ' iqref' which is a directly calculated 'iq_ref' value and is an output of the power factor (Qref block). 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 (4.5) as follows:

$$ibase = \frac{2S_{base}}{3V_{sd}} \qquad (4.5)$$

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 as shown in blue box. The output ‘yi4’ is further converter to pu using ‘ibase’ to obtain the desired value of ‘id_ref’ in pu.

In this controller block, reactive power control used in generic model is also used as it as an additional option to control reactive power. This type of control exists in ‘Reactive Power Support’ block in Fig 4.17.

a) DC voltage regulation

DC voltage regulation is realized with the help of a PI controller which is the most widely used method as shown in Fig. 4.18. In this case the inputs ‘Vdcref’ and ‘udc’ are used to determine the error between them. Then the error is passed through the PI controller to obtain the value of ‘id_ref’ which is the input to the static generator to control the active power. 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 uses following equation.

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

Where

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

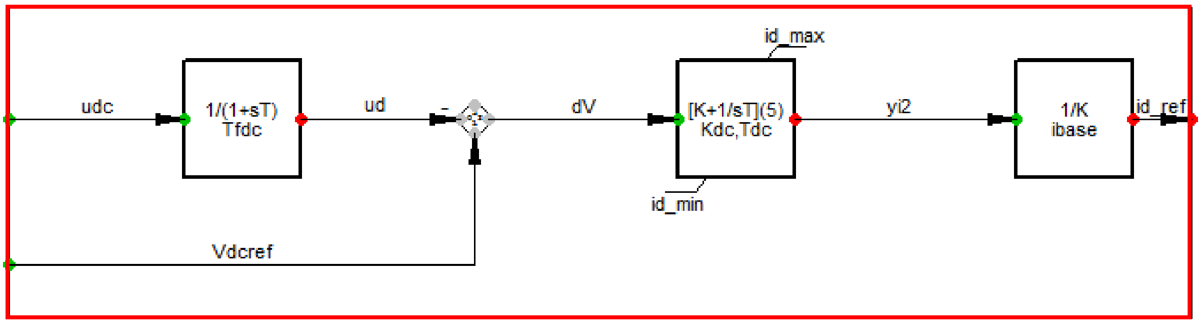

Fig. 4.18 DC voltage regulation

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

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}. This 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. 4.19 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, $F_{ac}(s)$ using (4.6) to obtain the iq_ref. This iq_ref is used as input to static generator to regulate reactive power and hence AC voltage at the regulation bus.

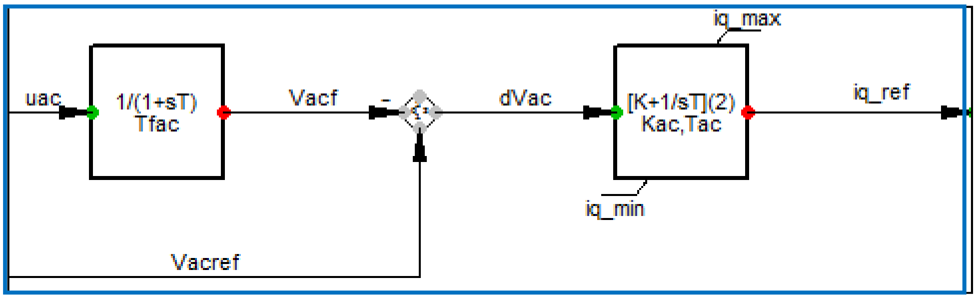

Fig. 4.19 AC voltage regulation

The limits of i_q are determined using (4.7). First V_{sd} is calculated as the peak value of the line-ground inverter AC side voltage. Then Q_s is already known as it is the maximum reactive power of the PV system in MVaR (reactive power corresponding to 0.9 power factor in this model). Since as all other quantities are known, i_q can be easily calculated from below equation.

$$Q_s = -\frac{3}{2} V_{sd} i_q \tag{4.7}$$

This value of i_q is used as maximum (positive value) and minimum (negative value) limits as the parameters of the main controller.

c) Reactive power control

The actual reactive power termed here as 'Q' in Fig. 4.20 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 next 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) using (4.6) to obtain the value of iq_ref which is the input to the static generator for reactive power control.

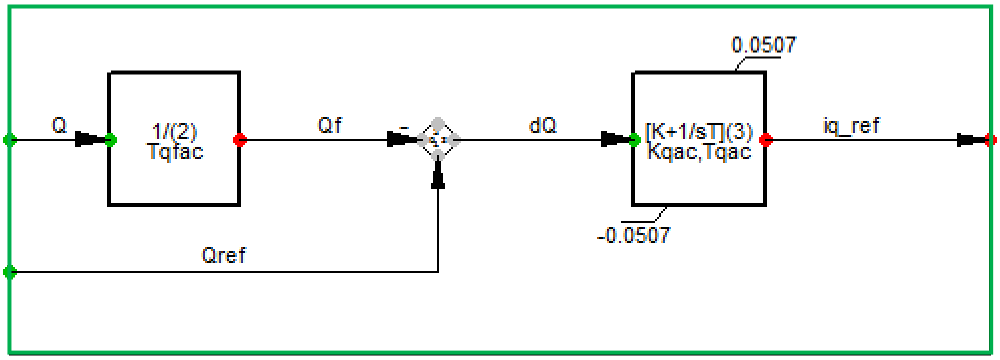

Fig. 4.20 Reactive power control

4.5.3 Qref block (slot 15)

The 'Qref' input shown in Fig. 4.20 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. 4.21.

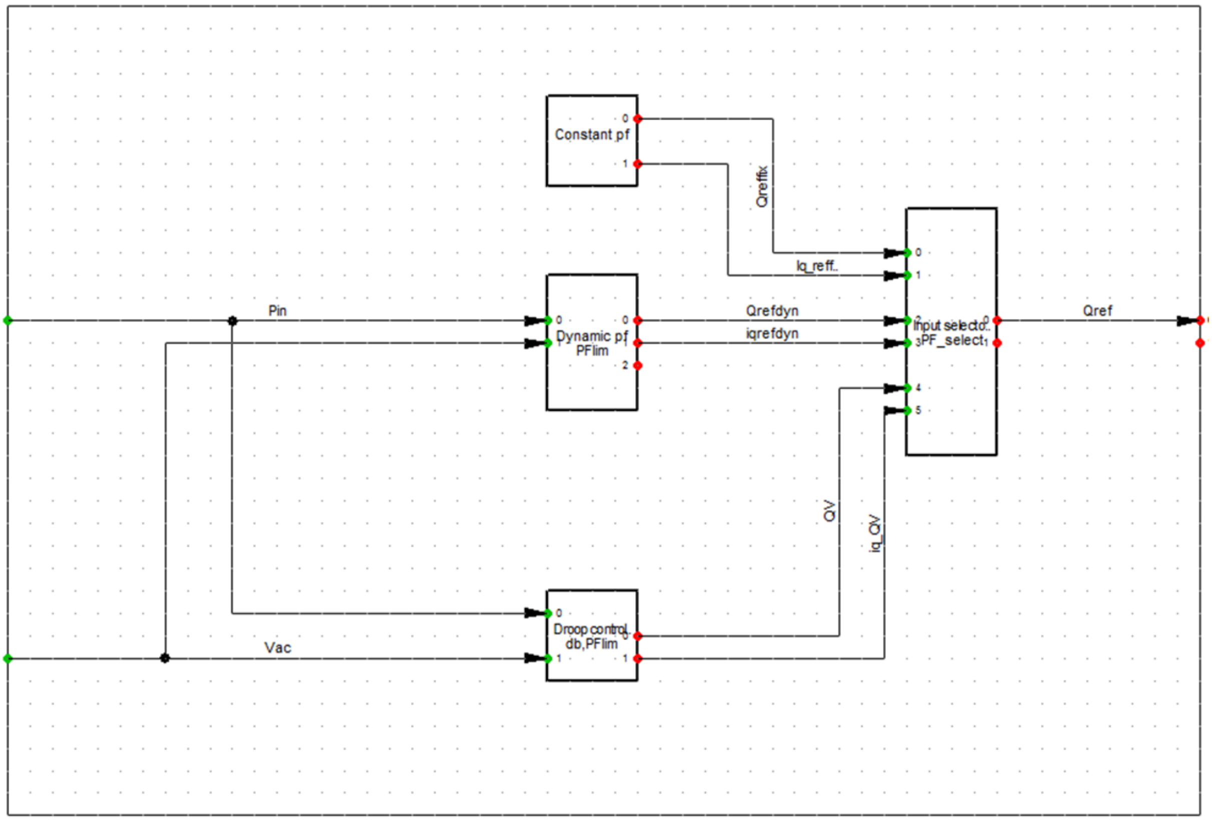

Fig. 4.21 Qref block

The Qref block outputs the 'Q_{ref}' value based upon the choice selected from three options.

1. unity power factor
2. dynamic power factor
3. Q(U) operation

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. 2.14 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. 4.22.

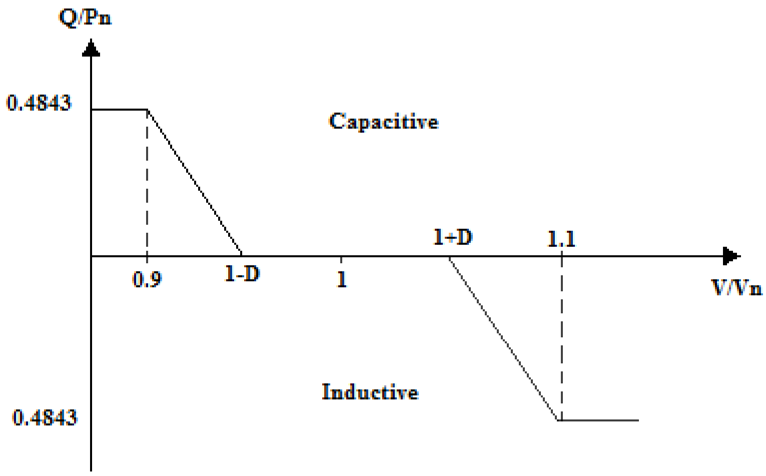

Fig. 4.22 Q(U) curve

The obtained Qref' is given to the main controller block and is used to get the desired value of 'iq_ref'.

4.6 Comparison of two models in terms of control systems

In the end, the control systems present in both models are summarized in the form of a table and is shown as Table 2.

It can be observed from Table 2 that there are some new control systems implemented in the KTH model which were not present in generic model. Active power control, AC voltage control, reactive power control (based on active power) and MPPT control are the newly implemented control in KTH model. These additional controls make this new KTH model more advanced and more reliable as compared to generic model.

Table 2: Comparison of two models in terms of control system

Control Technique	*Generic Model*	*KTH Model*
DC Voltage Regulation	*Y*	*Y*
MPPT (Maximum Power Point Tracking)	*N*	*Y*
Unity Power Factor- Control Strategy 1	*Y*	*Y*
Dynamic Power Factor- Control Strategy 2	*N*	*Y*
Droop Control based on Voltage- Control Strategy 3	*Y*	*Y*
AC Voltage Regulation- Control Strategy 4	*N*	*Y*
Active Power Curtailment	*N*	*Y*
Frequency based Active Power Control	*Y*	*Y*

5. Model Analysis and Case Studies

In this chapter, three setups will be discussed. In Setup A, a comparison between the results of generic model and newly developed KTH model will be presented. Second part of this chapter describes Setup B, in which several case studies are presented with different control systems in new KTH model. In Setup C a comparison between KTH model based on static generator and PWM converter based model is presented. The simulations will be presented and results will be explained in details.

5.1 Single line diagram of the system

The single line diagram of the power system used in the analysis of both generic model and new KTH model in PowerFactory is shown in Fig 5.1.

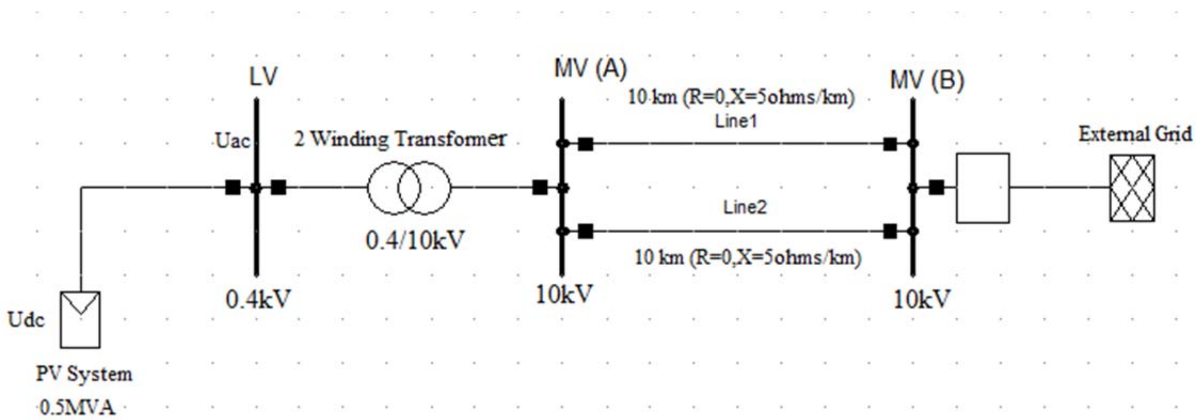

Fig 5.1 Single line diagram of the system

The system includes a PV model of 0.5 MVA and is connected to LV bus of 0.4 kV. The PV system includes the inverter and gives the AC quantities at the output. The measurement point of AC power and AC voltage is at LV bus. After the LV bus, a 2 winding transformer is placed to step up the voltage up to 10kV at the MV (A) bus. This is followed by two parallel short transmission lines each of 10 km. The system is lossless, so all the components in this system have no resistance. After the transmission line, it is connected to external grid via another MV (B) bus of 10 kV. The detailed system specifications of above system are summarized in the table and are given in Appendix 8.1.

5.2 Comparison and Analysis of PowerFactory Models (Setup A)

This comparison is based on following facts:

- Generic model and developed KTH model have the same reactive power control.
- There is no MPPT control in both models at this time.
- This comparison is without any additional controls developed in new model.

It is noticeable that PV array model in both models are different, which can be main difference in two model at this stage. Reactive power control based upon voltage deviation is used for both the models.
These models are compared by having different case studies. Three types of disturbances are used to see its impact on the output of the models.

- Case 1: Irradiance change in PV system
- Case 2: Decrease in external grid voltage
- Case 3: Three phase short circuit at MV (A) Bus

5.2.1 Case 1: Irradiance change in PV system

Irradiance in the system is decreased from 1000 W/m^2 to 500 W/m^2 at t=1 and brought back to 1000 W/m^2 at t=1.1. This is shown in Fig 5.2 below.

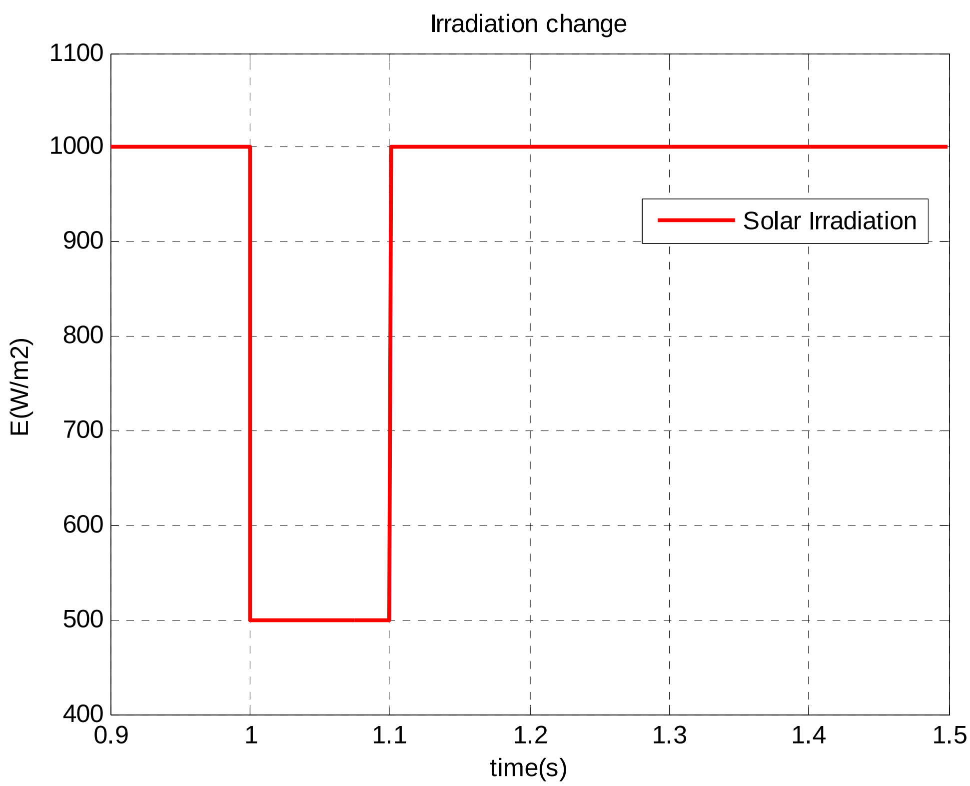

Fig 5.2 Solar irradiation change

DC voltage of the both models with the irradiance change is shown in Fig 5.3. It can be seen from the below Fig 5.3, that general response of DC voltage is same for both models. As in this case a constant dc voltage reference is used for the DC voltage control so very quickly after the irradiation change, voltage comes to its initial value. The change in the voltage due to irradiation variation is less in case of KTH model as compared to generic model.

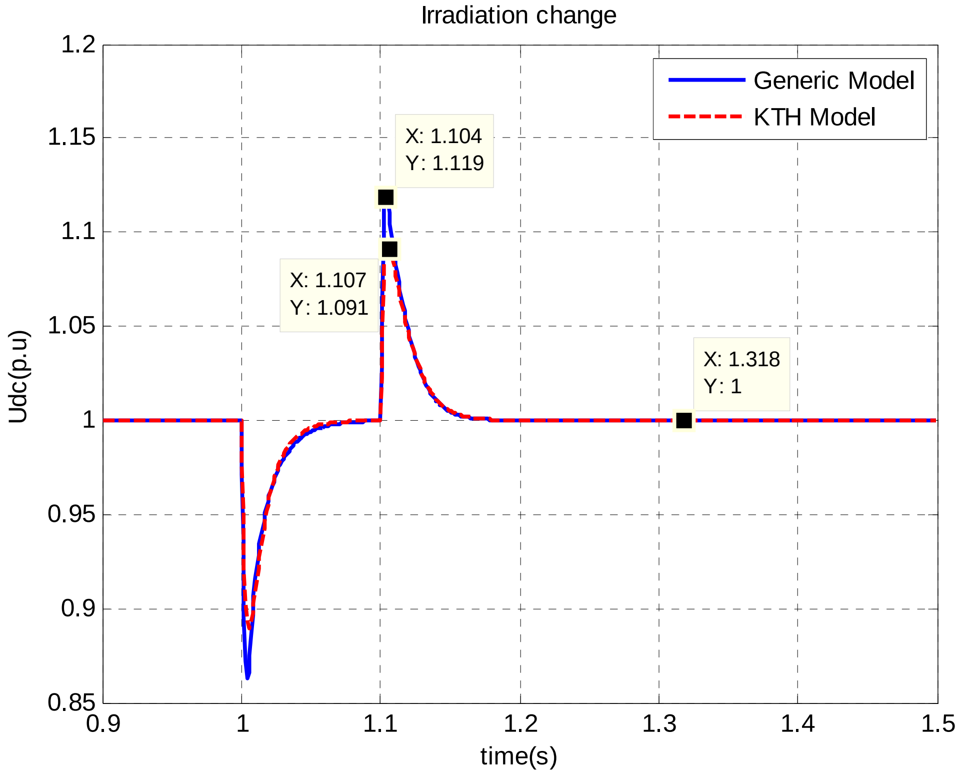

Fig 5.3 DC voltage of PV system

Fig 5.4 shows the DC current of two models which is the main difference in the two models at this time. It can be seen that current decrease is less in case of KTH model with the irradiation decrease. This current difference is due to the different nature of the modeling method of the PV array model. For KTH model, basic solar cell equations are used from authentic scientific references and every variable and parameter is defined, whereas in case of generic model a lot of assumptions are used in the modeling procedure. Also many undefined internal variable and parameters are used.

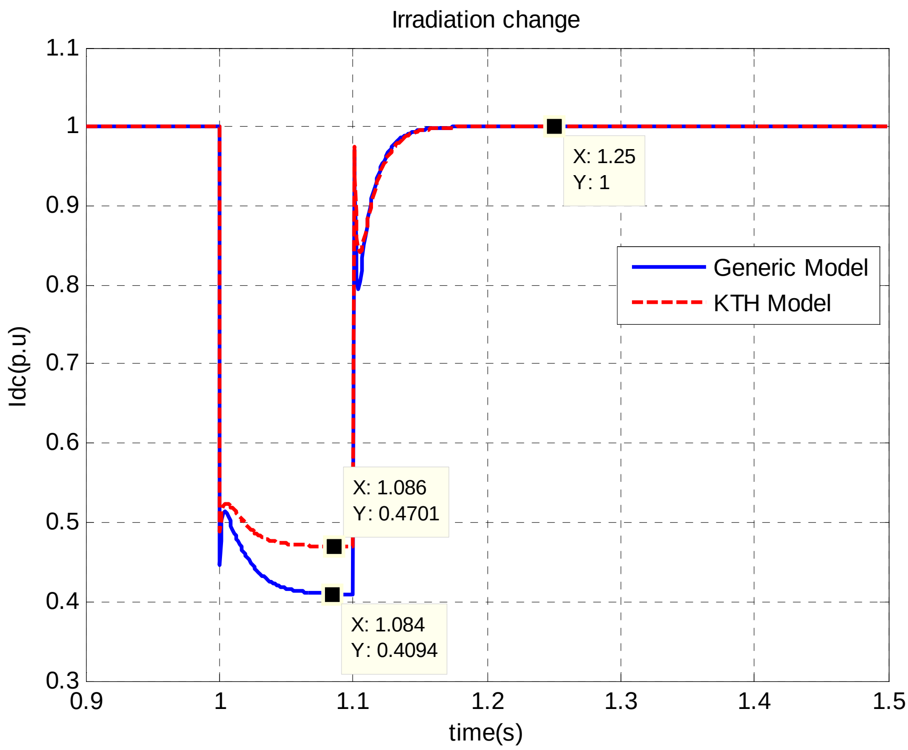

Fig 5.4 DC current of PV system

Also value of current obtained at E=500 W/m^2 is very close to expected value in case of KTH model, whereas in generic model value of current is somehow lower than expected. In other words, with new KTH model we are getting more current and hence more power at a given irradiation value.

Fig 5.5 depicts the active power of the PV system for both models. The green curve representing expected result (curve from MATLAB equations). It is noticeable that red curve representing the KTH model has power output which is closer to expected result as compared to generic model.

AC voltage of the both model is shown in Fig 5.6 and is quite close to each other. Fig 5.7 represents the reactive power of the PV system in case of irradiation change. This reactive power control is based on deadband, and in this case voltage variation is within deadband. Therefore there is no reactive power regulation expected. Also in figure reactive power shown is negligible. First of all reactive power is plotted in Mvar, secondly scale of y-axis is so small, therefore difference between the reactive powers of two models is very minute. This difference can be due to numerical calculation difference in two models.

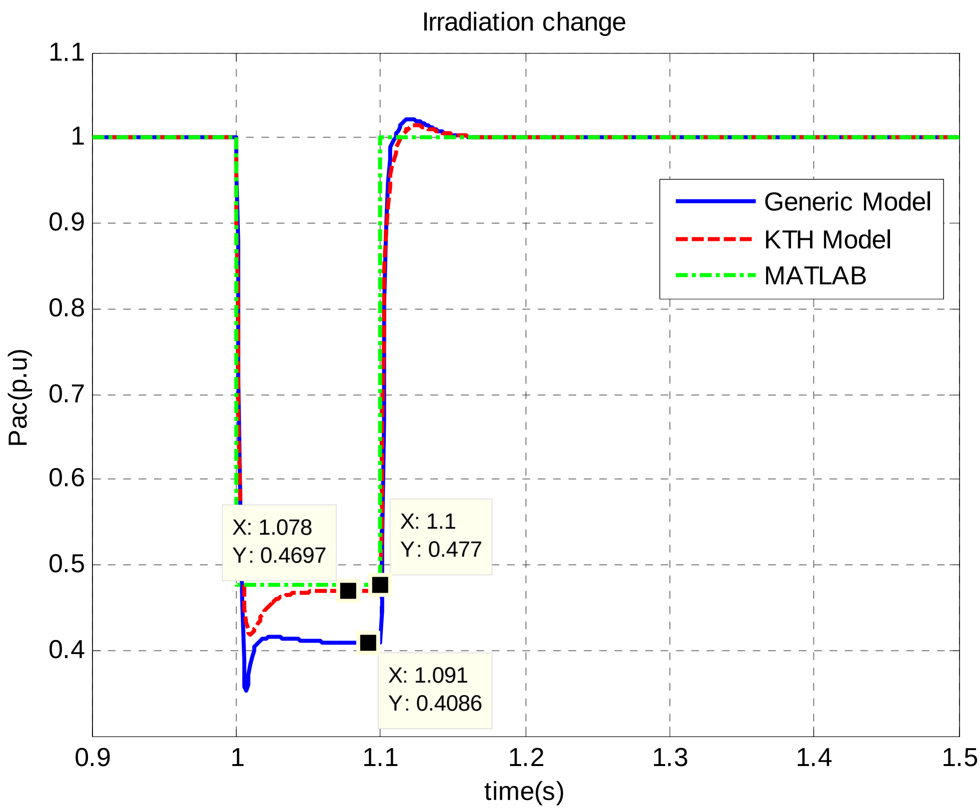

Fig 5.5 Active Power of PV system

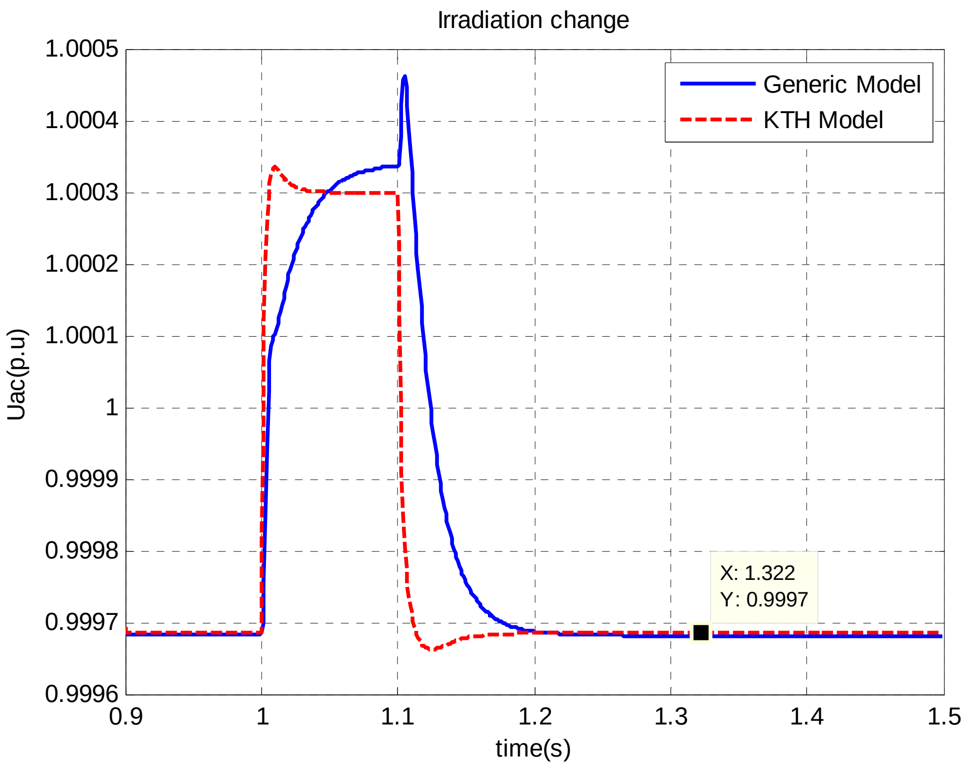

Fig 5.6 AC voltage at LV terminal

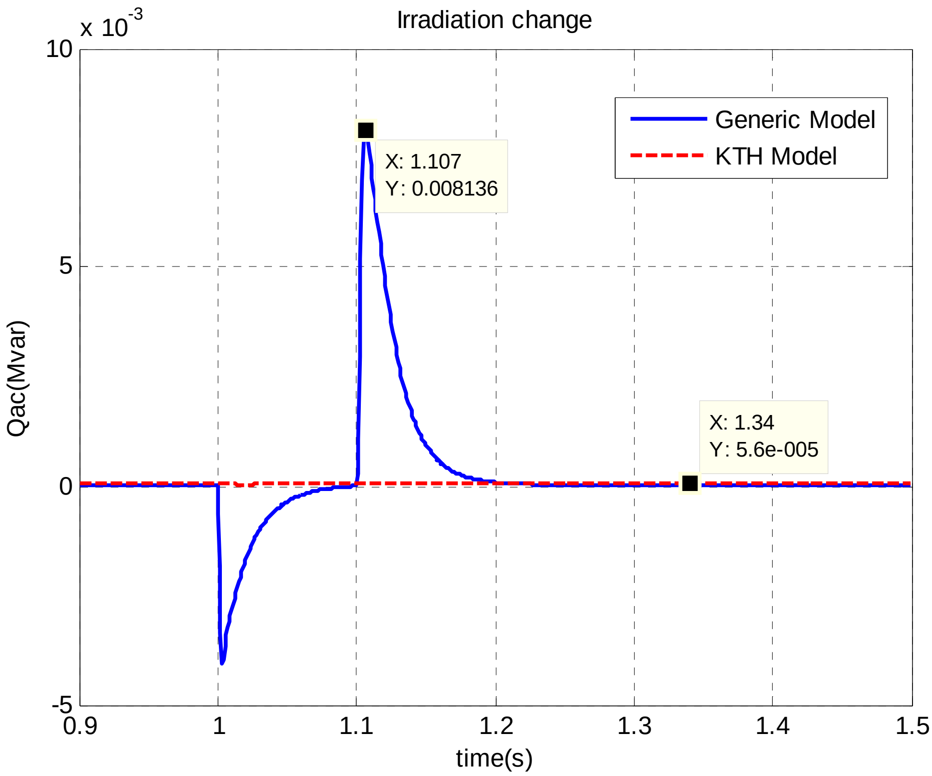

Fig 5.7 Reactive Power of PV system

5.2.2 Case 2: Decrease in external grid voltage by 1%

This section illustrates the response of two models in case of external grid voltage decrease by 1 %. It should be noted that this disturbance is permanent i.e. at t=1 external grid voltage is decreased by 1 % permanently. As both models have same reactive power control at this stage so it is very interesting to see whether both models show same behavior or not in case of grid voltage change.

The DC voltage increases a bit in both models with external grid voltage decrease at t=1 and comes back to original value due to constant dc voltage reference setting. DC voltage is shown in Fig 5.8.

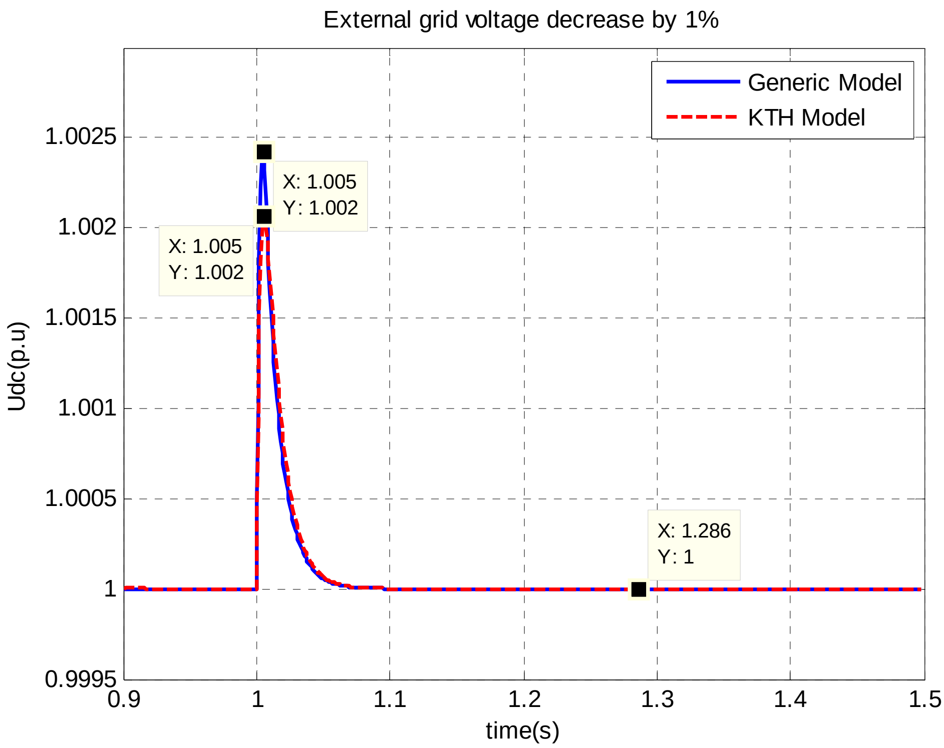

Fig 5.8 DC voltage of PV system

Fig 5.9 and 5.10 shows the DC current and active power of the two models respectively. It is clear from Fig 5.9 that response of the DC current of PV system is close to each other in case of external grid voltage decrease. Similarly active power for both models as shown in Fig 5.10 exhibits the same response and small difference is due to the different modeling of PV panel.

The important thing to be mentioned here is in case of external grid voltage change, variation in DC voltage and active power is very small. This is justified as in case of voltage decrease of external grid, PV system should not change its active power instead reactive power and AC voltage should regulate in this case.

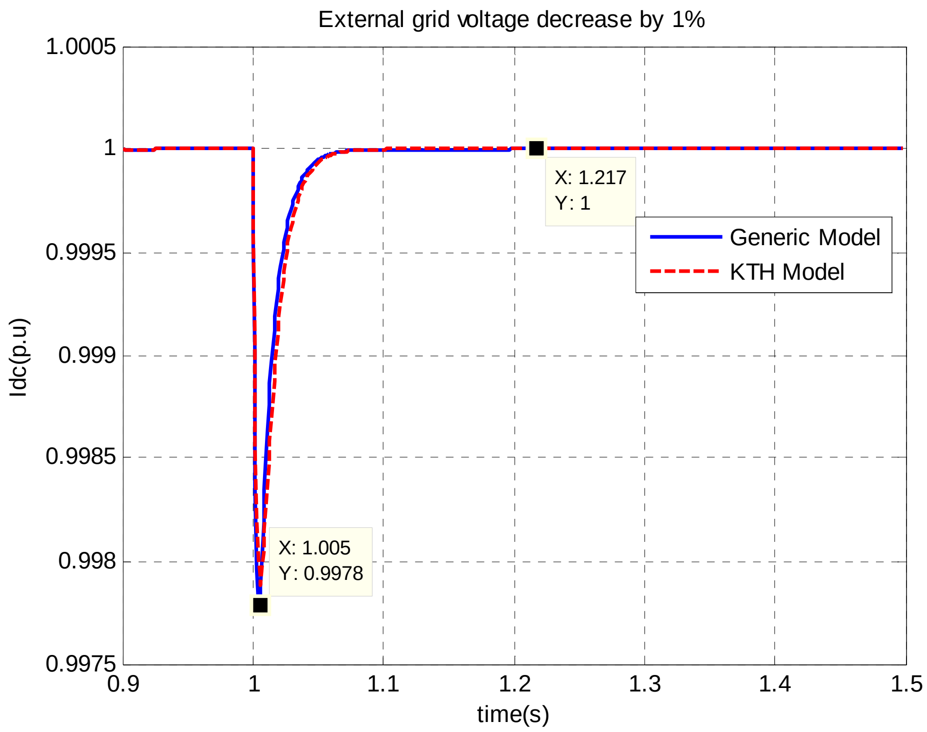

Fig 5.9 DC current of PV system

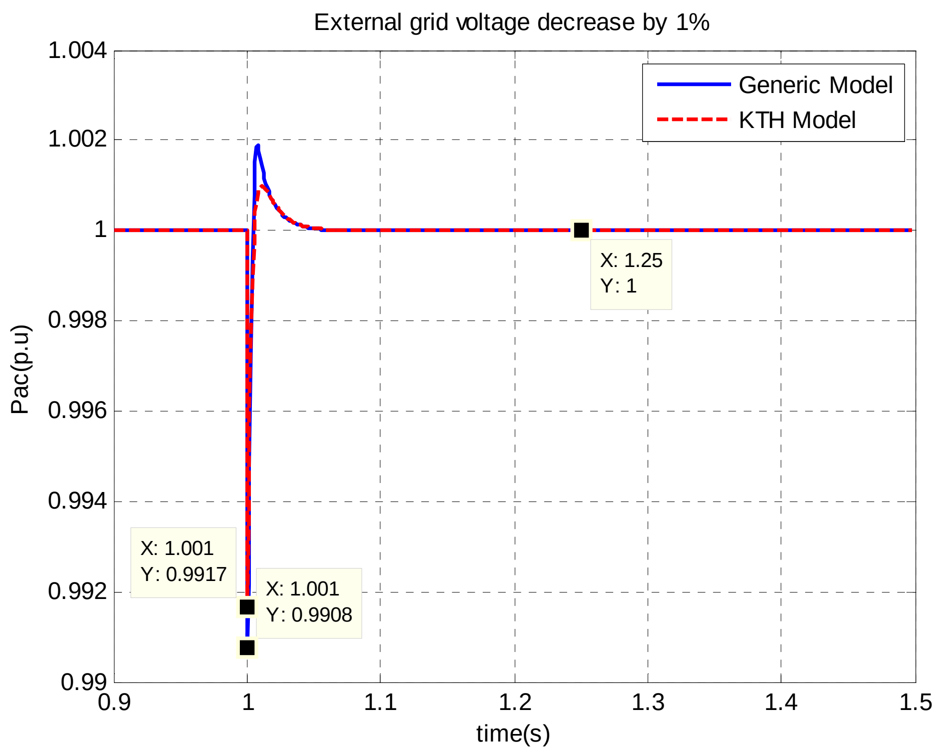

Fig 5.10 Active power of PV system

The response of AC voltage and reactive power in this case is shown in Fig 5.11 and 5.12 respectively. As both models have same reactive power control, the response of the AC voltage is almost the same. AC voltage is decreased by same percentage as external grid voltage is decreased. It should also be noticed that there is no AC voltage control applied, therefore AC voltage at LV terminal is decreased.

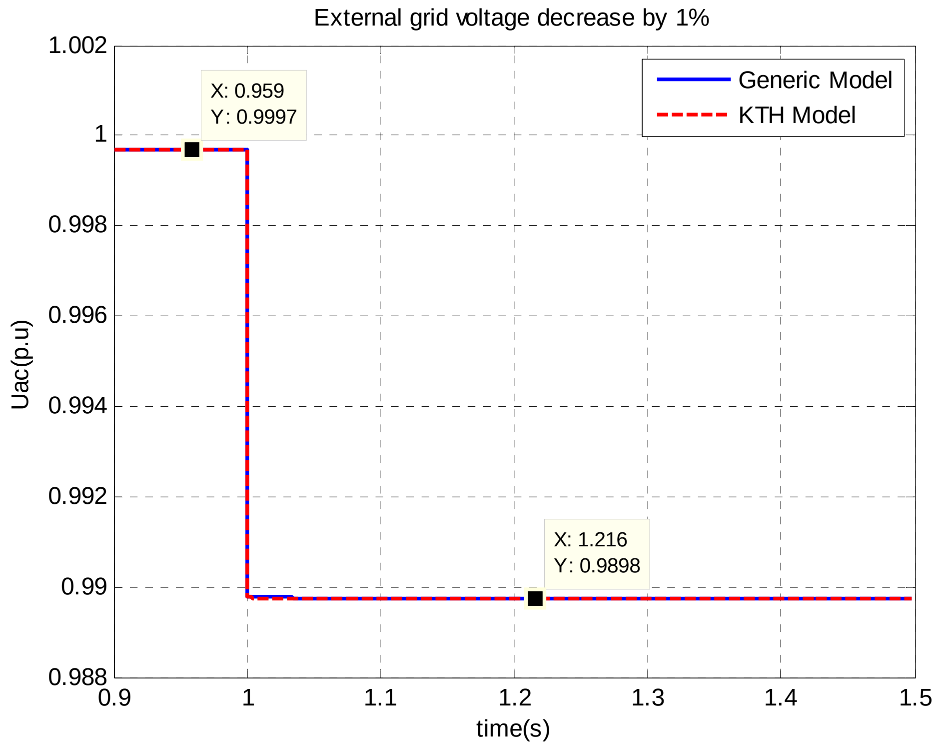

Fig 5.11 AC Voltage at LV terminal

Reactive power for both models shown in Fig 5.12 is also close to each other. The voltage variation is within deadband so there would be no reactive power regulation expected in this case. In figure reactive power is almost negligible. Also scale at y-axis is so small and reactive power shown is in Mvar therefore difference between the reactive power values is also very small. This difference can be due to numerical calculation difference in two models.

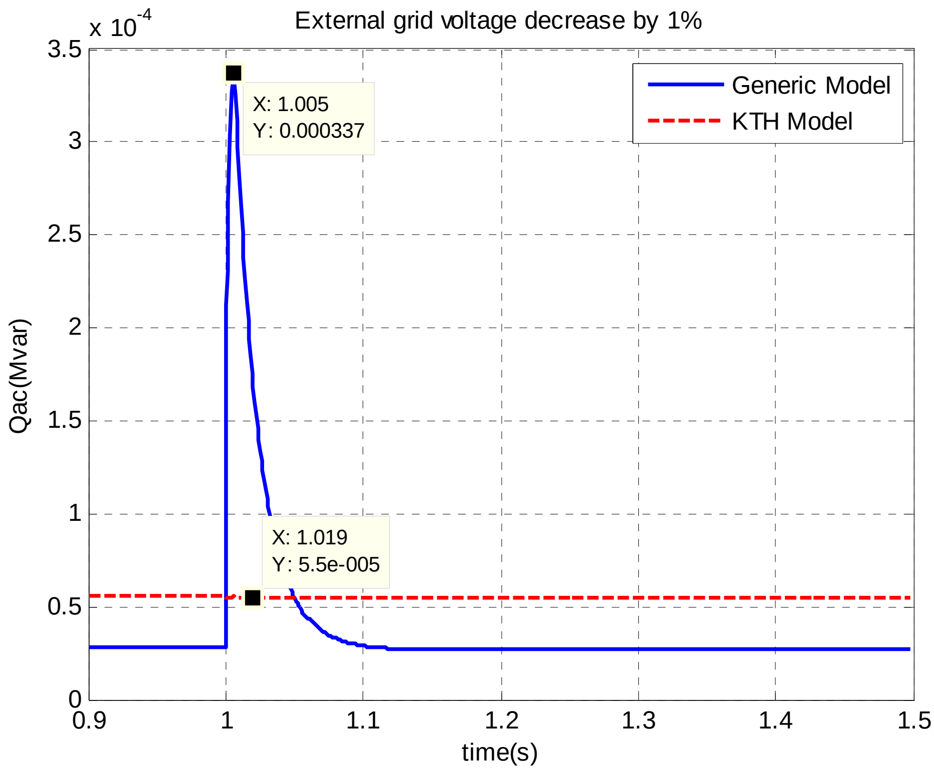

Fig 5.12 Reactive power of PV system

5.2.3 Case 3: Three phase short circuit

In this section, a three phase short circuit is used as disturbance to check its impact on the model output. As short circuit fault is the most severe disturbance in power system therefore if model works well in this severe condition it will increase the validity of the model. Short circuit event is created at t=1 and is removed at t=1.1 at MV (A) bus bar as shown in Fig 5.1.

Both models behave very similar to each other in case of short circuit fault in the system. DC voltage of PV system is shown in Fig 5.13. At t=1 when short circuit happens, DC voltage for the both models increases to open circuit voltage of PV system. When short circuit is removed DC voltage comes back to its initial value.

Fig 5.14 and 5.15 shows the DC current and active power of the PV system during short circuit, respectively. It can be noticed that during the short circuit fault duration i.e. 100ms current and power of the PV system becomes zero and comes back to its initial value as soon as the fault is removed. This response is very similar for the both generic and KTH model. The small difference can be explained on the basis of the modeling difference of two PV models.

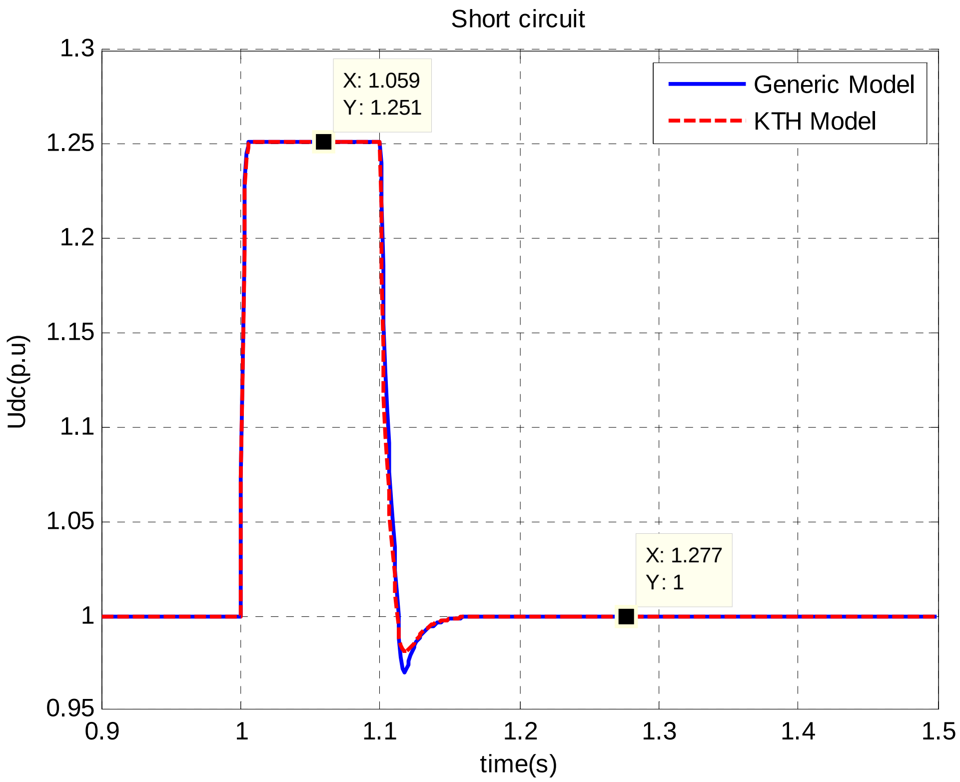

Fig 5.13 DC voltage of PV system

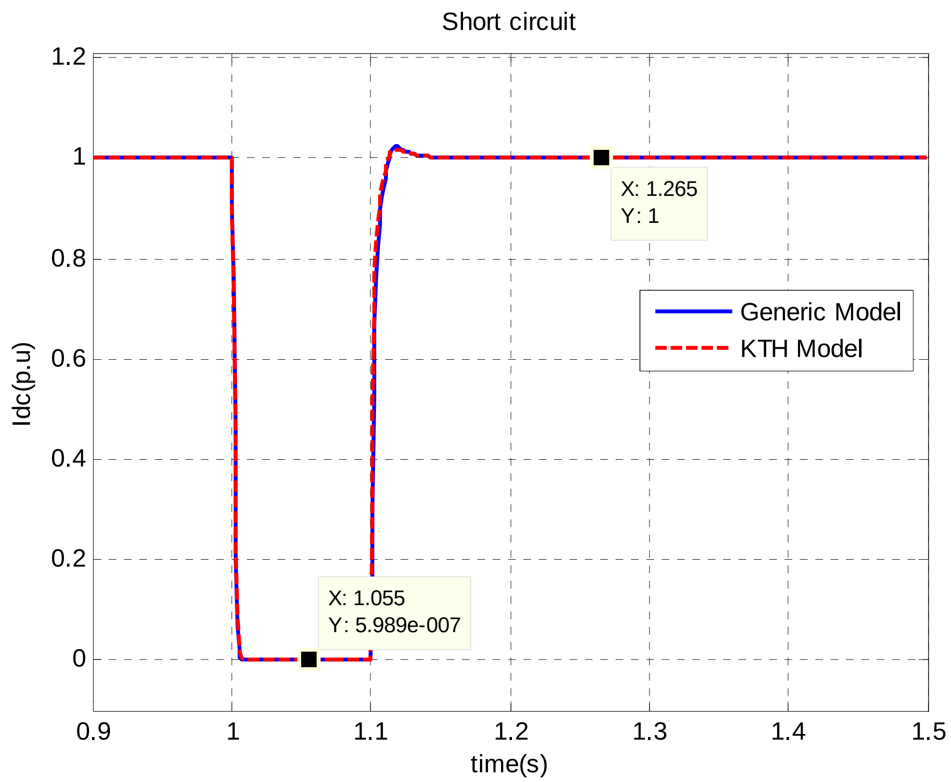

Fig 5.14 DC current of PV system

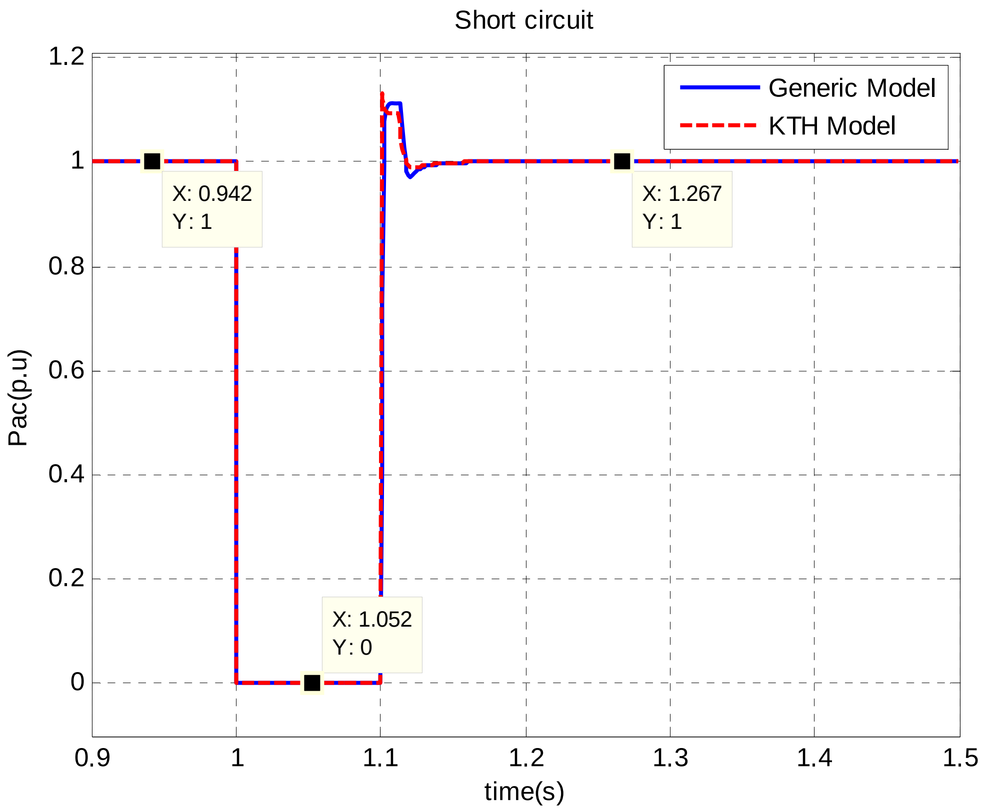

Fig 5.15 Active power of PV system

Fig 5.16 and Fig 5.17 describes the AC voltage and reactive power of PV system for the both models in case of short circuit fault. As expected, during short circuit i.e. from t=1 to t=1.1, AC voltage at the LV terminal becomes zero for the both models. This AC voltage quickly comes back to original value after the removal of this fault. As both models have the same reactive power control so response of reactive power and AC voltage is expected to be quite similar to each other.

This can also be confirmed from Fig 5.16 in which reactive power of PV system is shown in case of short circuit in the system. The response of reactive power is very close for the both models. As soon as the short circuit is removed, a reactive power is supplied by PV system in order to maintain voltage at the LV terminal of PV system. It should be noted that in Fig 5.17, the reactive power limits of the inverter are intentionally increased to see whether this model is capable of regulating reactive power for voltage support. In this case reactive power limits are increased up to 0.5 Mvar.

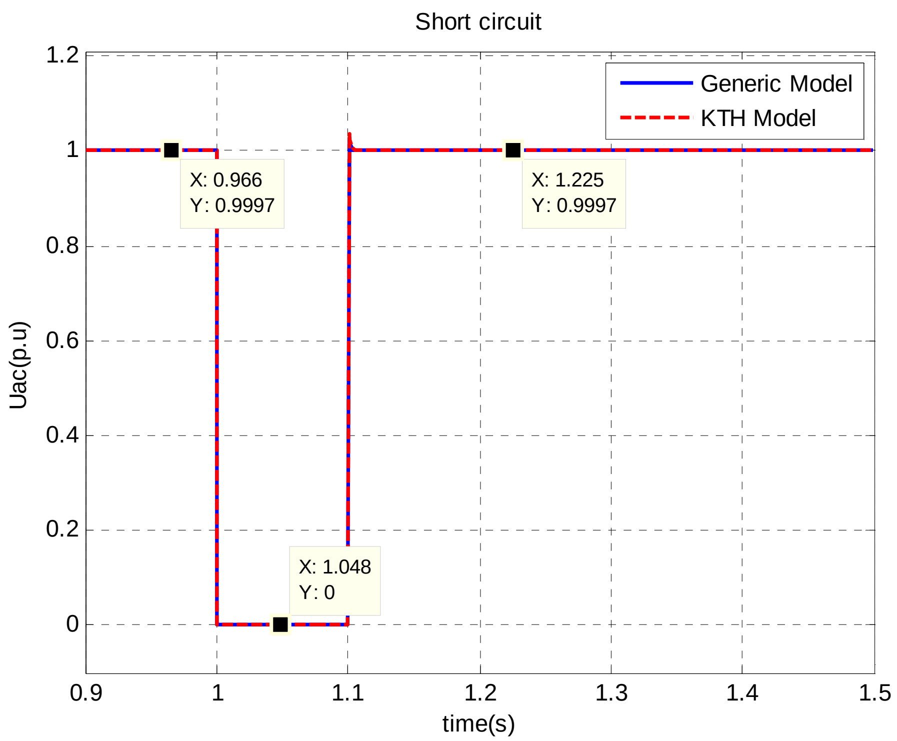

Fig 5.16 AC Voltage at LV terminal

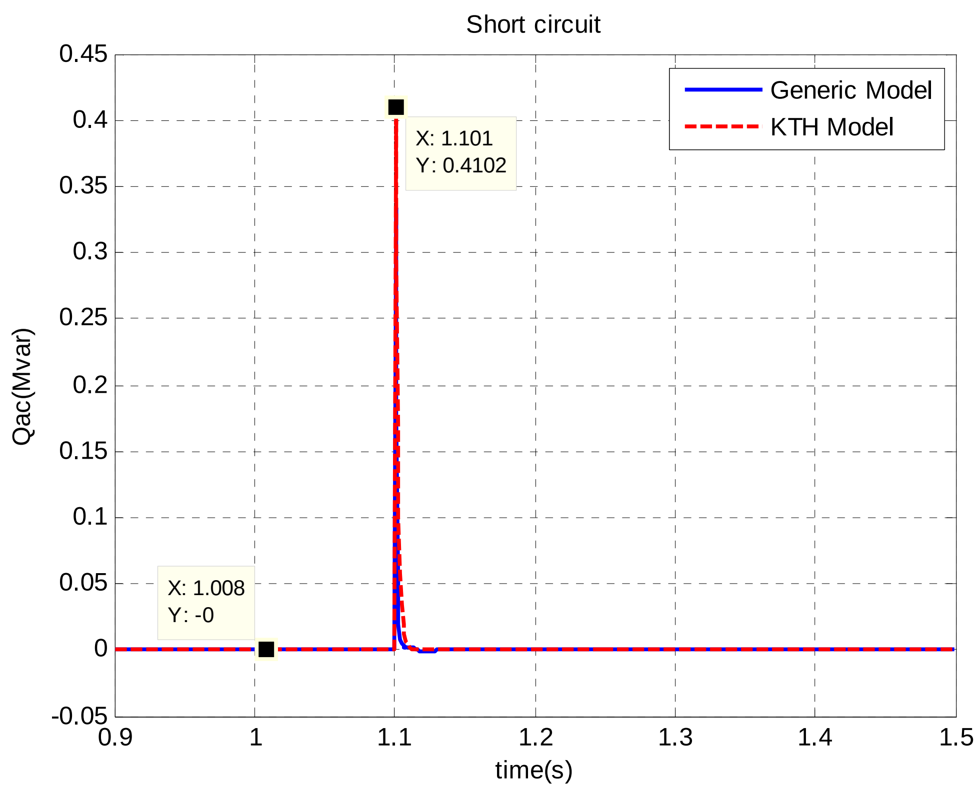

Fig 5.17 Reactive power of PV system

Summary:

On the basis of above comparison results between the generic model and newly developed KTH model, it can be concluded that overall response of the both models is quite similar. The only difference is the different nature of modeling the PV array model. In this respect, PV current and hence power is different. As both models are behaving in the same way with similar reactive power control therefore this newly developed KTH model is validated by this comparison.

5.3 Results Analysis of newly developed KTH model (Setup B)

After the validation of this developed model, detail results analysis of this model will be presented. This KTH model is now equipped with following additional control systems in it.

- MPPT control
- Four types of reactive power controls
- Active power control

The detailed features of this model have already been presented under the section 4.4.

Following simulations are based upon three different case studies:

Case 1: Decrease in irradiance of PV system from 1000 W/m^2 to 500 W/m^2 (Permanent Disturbance)
Case 2: 10 % decrease in external grid voltage (Permanent Disturbance)
Case 3: Three phase short circuit at MV (A) Bus (for 100 ms)

These cases are analyzed and presented in the coming sections with different control strategies. Note that now MPPT control is included in the system, so a time delay in the PV array model is used in order to filter the unnecessary oscillations in the output. This delay value is selected by considering a tradeoff between the oscillations in the output and to ensure that model works for each case for this value. A delay value of T=0.05 second is selected for this model and can be changed accordingly.

5.3.1 Case1: Irradiation change

For first case, solar irradiation is decreased from 1000 W/m^2 to 500 W/m^2. This decrease can be realized as suddenly clouds appear and intensity of sunlight decreases. This disturbance is made in order to check how this model behaves with sudden decrement in irradiation.

Fig 5.18 shows the change in irradiation in the form of a step decrease from 1000 W/m^2 to 500 W/m^2. The starting time of irradiation decrease is 15 sec and is a permanent disturbance.

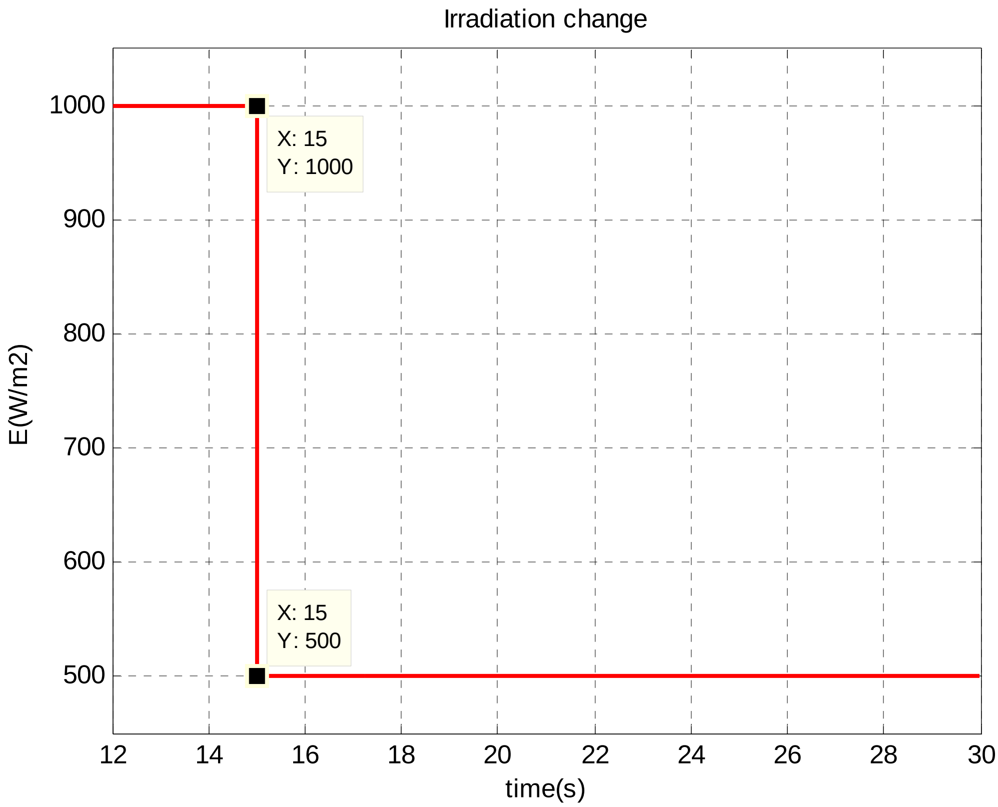

Fig 5.18 Irradiance decrease from 1000W/m^2 to 500 w/m^2

DC voltage of the PV system responds to this irradiation change as shown in Fig 5.19. MPPT is now in the system also a delay has been added to filter the high frequency oscillations. Under these conditions, DC voltage decreases with decrease in irradiation and takes some seconds to find its maximum power point and become steady. It can be seen from Fig 5.19 that DC voltage first give an overshoot in the start and quickly after that MPPT function start working which causes the voltage to become steady value as determined by MPPT algorithm. The value of DC voltage at 500 W/m^2 irradiance is quite same as expected value, which proves the validity of MPPT function.

Fig 5.20 shows the active power of the PV system with the sudden decrease in irradiation. It is clear from Fig 5.20 that in steady state active power was 1 p.u. As disturbance applies in the system at t=15, active power decrease and a small ripple is observed. Then very quickly MPPT function works in order to find the point at which maximum possible power at 500 W/m^2 irradiation can be obtained. This function track down MPP and a power of 0.477 p.u is obtained which is the maximum power at this irradiation. Hence new model works well with MPPT and regulate the DC voltage and active power with the change in irradiation of the PV system.

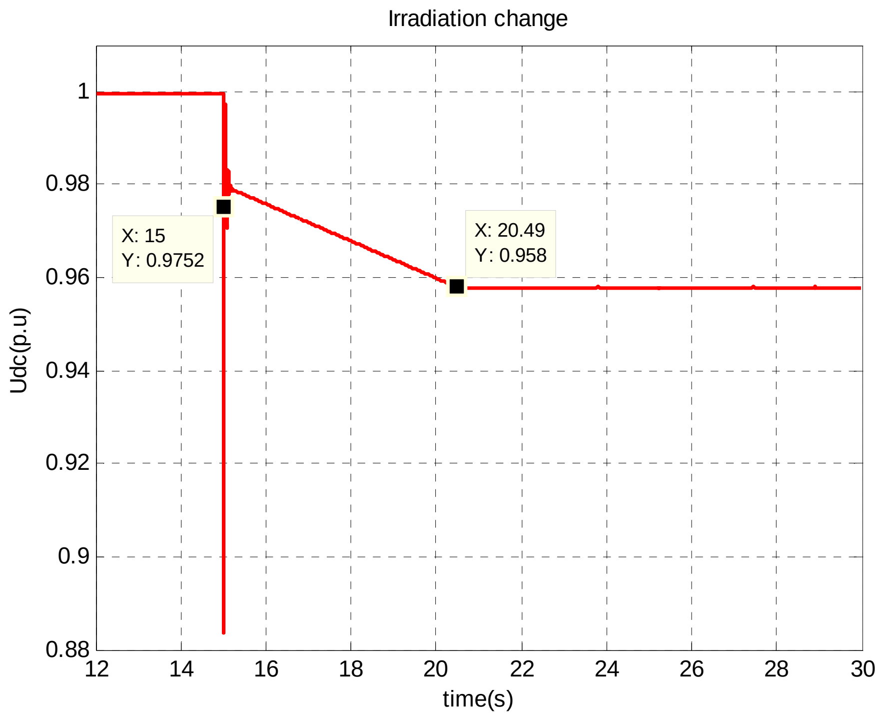

Fig 5.19 DC voltage of PV system

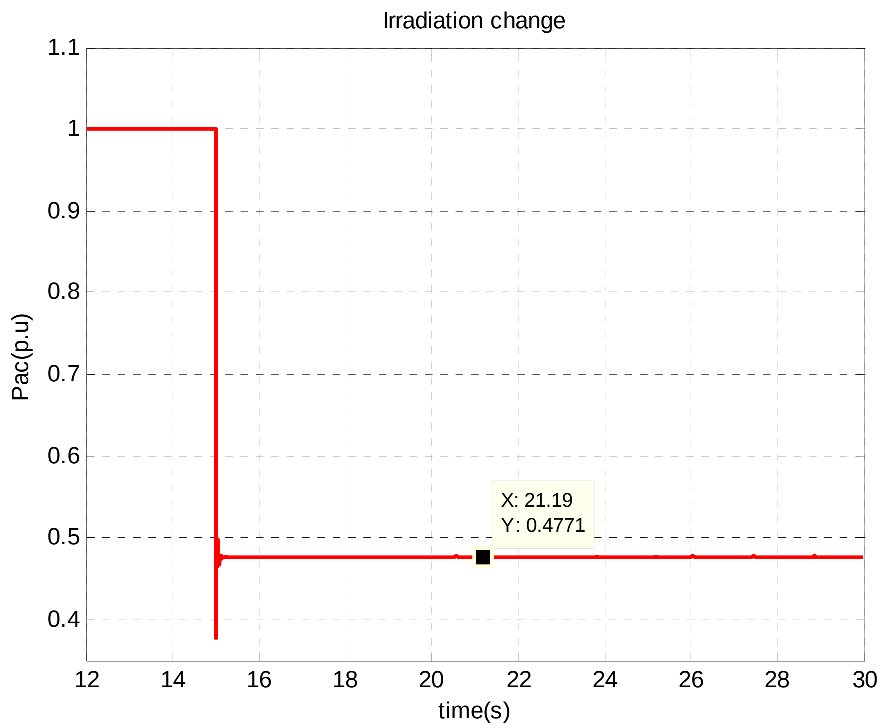

Fig 5.20 Active Power of PV system

In order to see how this new KTH model behaves with different reactive power controls, following simulation are presented and results are discussed.

a. Unity power factor (Q Control 1)

In this control, PV system always operates at unity power factor. This works by initializing reference value of reactive power 'Qref' equal to zero. Based on this Qref, reactive power can be controlled by using PI controller as already shown in Fig 4.20. Hence in this control strategy, reactive power is controlled such that no reactive power is supplied to make it possible to maintain unity power factor of the PV system.

Fig 5.21 shows that in case of irradiation decrease at t=15, reactive power is controlled to be zero. As y-axis scale is very small and plot showing reactive power in Mvar, so reactive power is almost zero in the below figure.

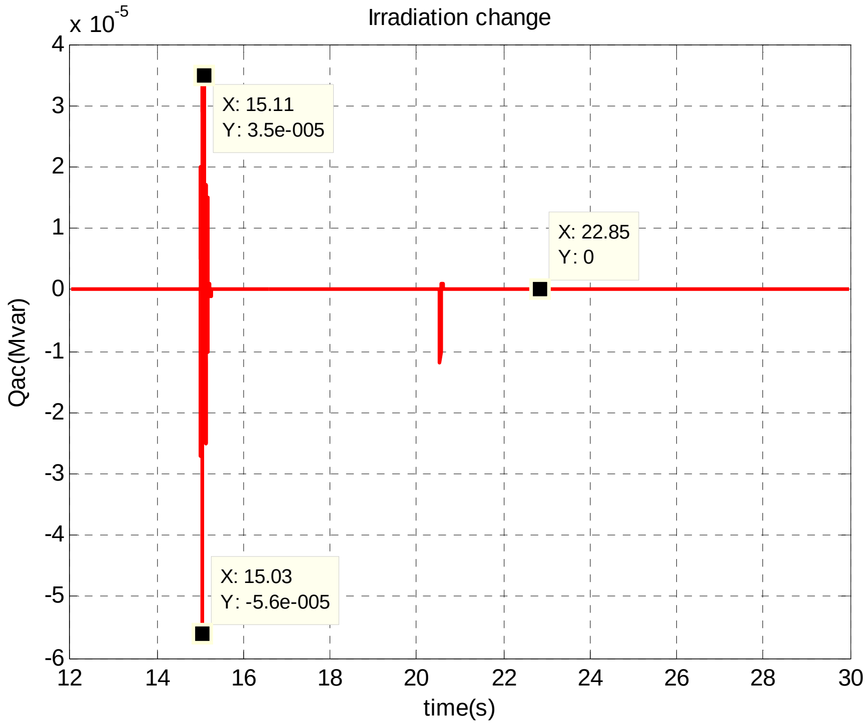

Fig 5.21 Reactive Power of PV system

In this type of reactive power control, AC voltage changes a bit which can be seen in Fig 5.22. Therefore voltage is slightly changed with the change in irradiation of the system.

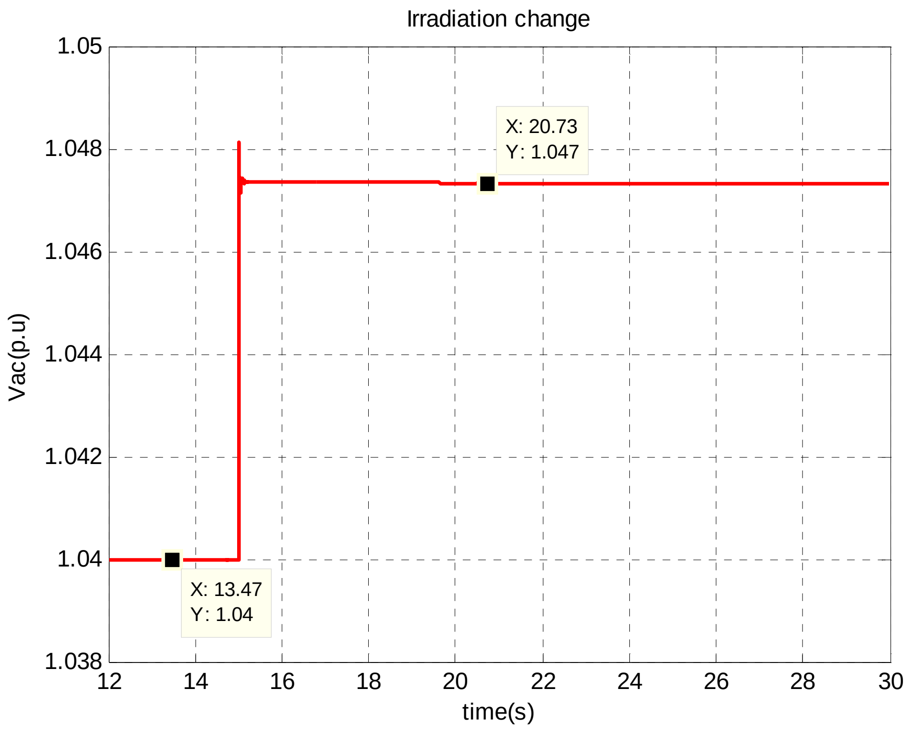

Fig 5.22 AC voltage at LV terminal

b. Dynamic PF operation Q(P) (Q Control 2)

In dynamic PF operation, reactive power is regulated based on instantaneous value of active power. Based on curve presented in Fig 2.14, reactive power varies depending upon active power to keep the power factor within 0.9 inductive and capacitive.

Initially, according to PV system design it operates at 0.9 inductive power factor. Due to decrease in active power, power factor from Fig 2.14 corresponding to this active power is calculated i.e. 0.9954. Hence reactive power is regulated in order to maintain this power factor in the PV system. Hence, reactive power is controlled on the basis of active power.

Fig 5.23 demonstrates the reactive power change on the basis of dynamic power factor control. It can be seen in the figure that initially PV system was operating at 0.9 PF, it was absorbing 0.2174 Mvar reactive power. When irradiation decreases, PV system reduces its absorption of reactive power to 0.0205 Mvar in order to maintain a PF of 0.9954. Power factor keep on changing with the change in the irradiation. That is why; this is called dynamic power factor operation.

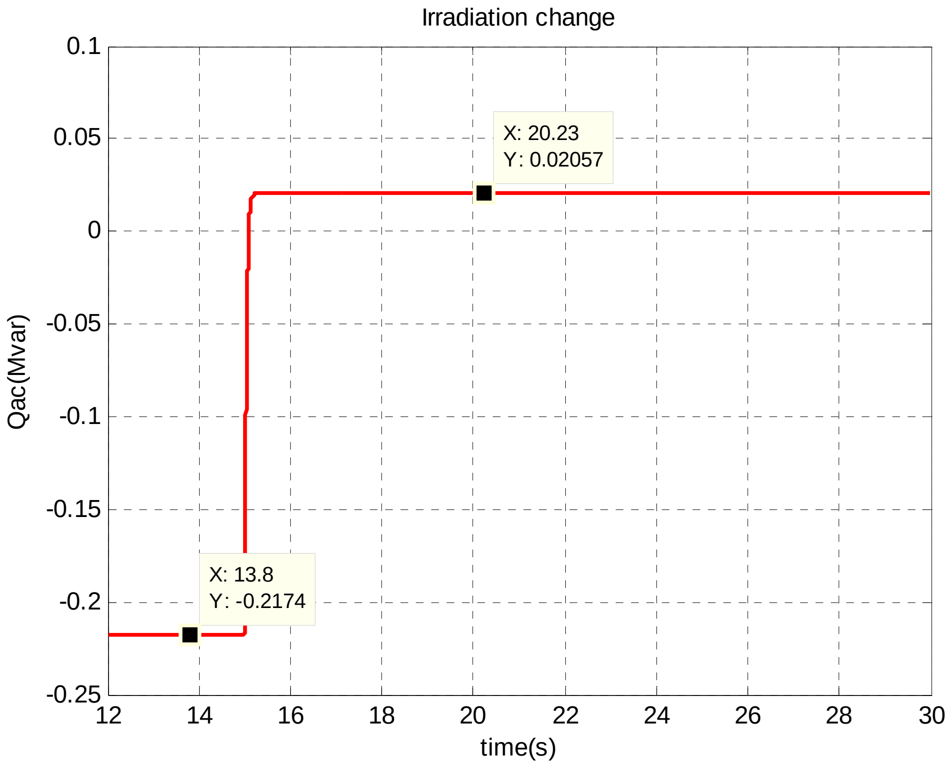

Fig 5.23 Reactive Power of PV system

In this case, AC voltage changes a bit with change in irradiation as shown in Fig 5.24. Power factor variation can be seen from Fig 5.25 which is evident that PF initially was 0.9 and becomes 0.9954 as irradiation and active power decreases.

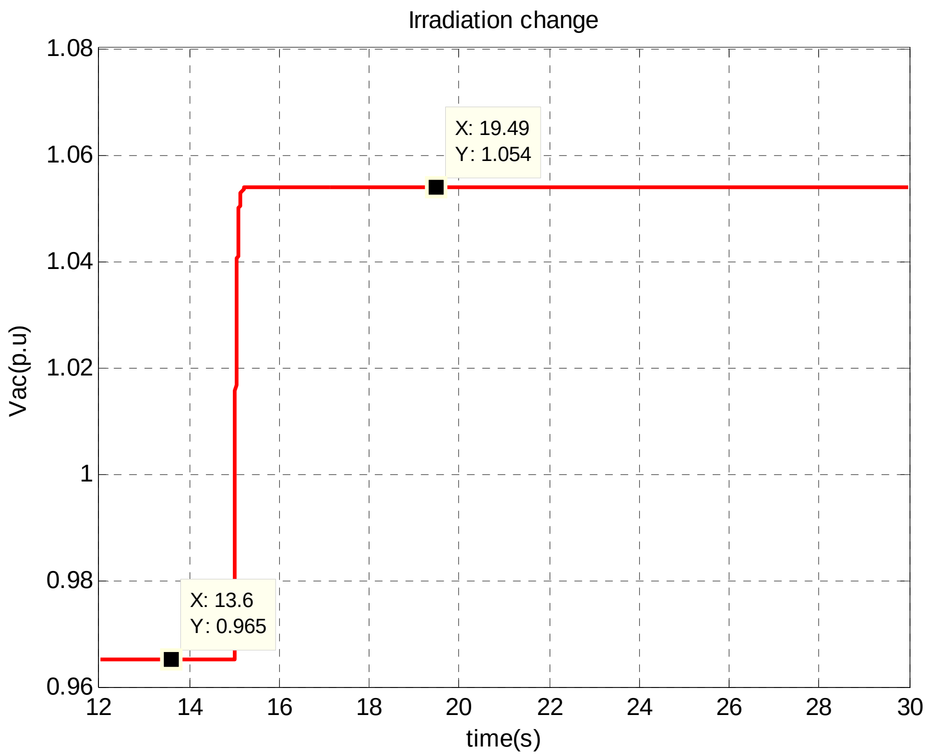

Fig 5.24 AC voltage at LV terminal

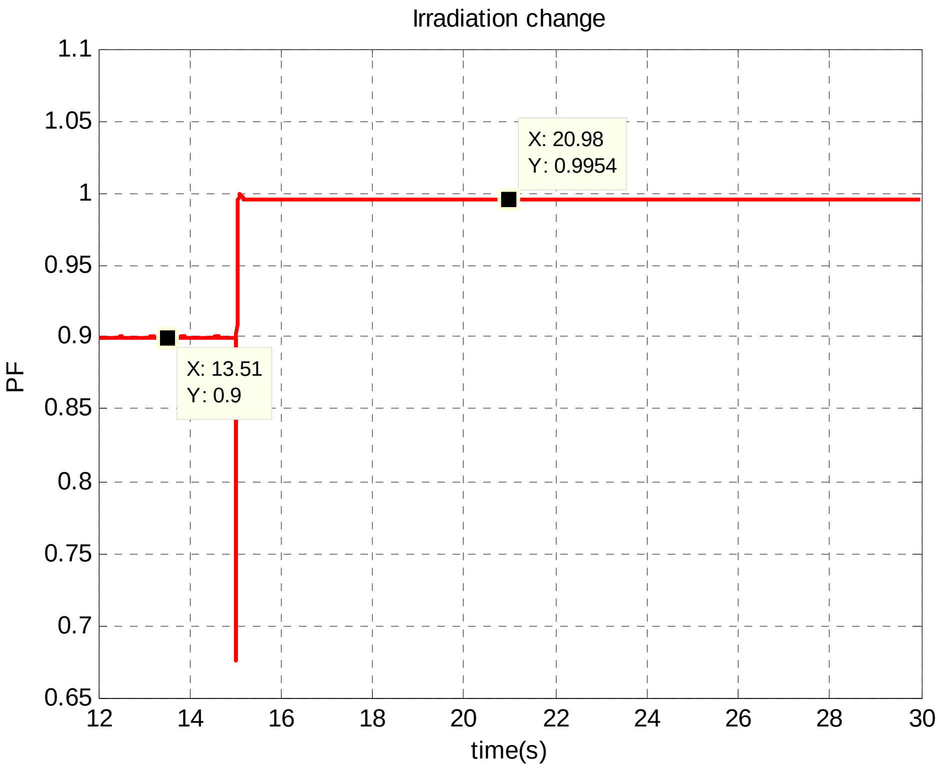

Fig 5.25 Power Factor

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

Droop based reactive power is designed to regulate reactive power based upon voltage deviation at the regulating point.

Also this control is used to avoid unwanted injection of reactive power when the voltage variation of the grid is within the dead band. This type of control is designed based on the curve as shown in Fig 4.22. For the current system, dead band is defined as 0.05, which means if the voltage variation would be within 5 % of the grid voltage, no reactive power will be regulated. It is shown in Fig 5.26 that as irradiation changes, reactive power is almost negligible and can be considered as zero.

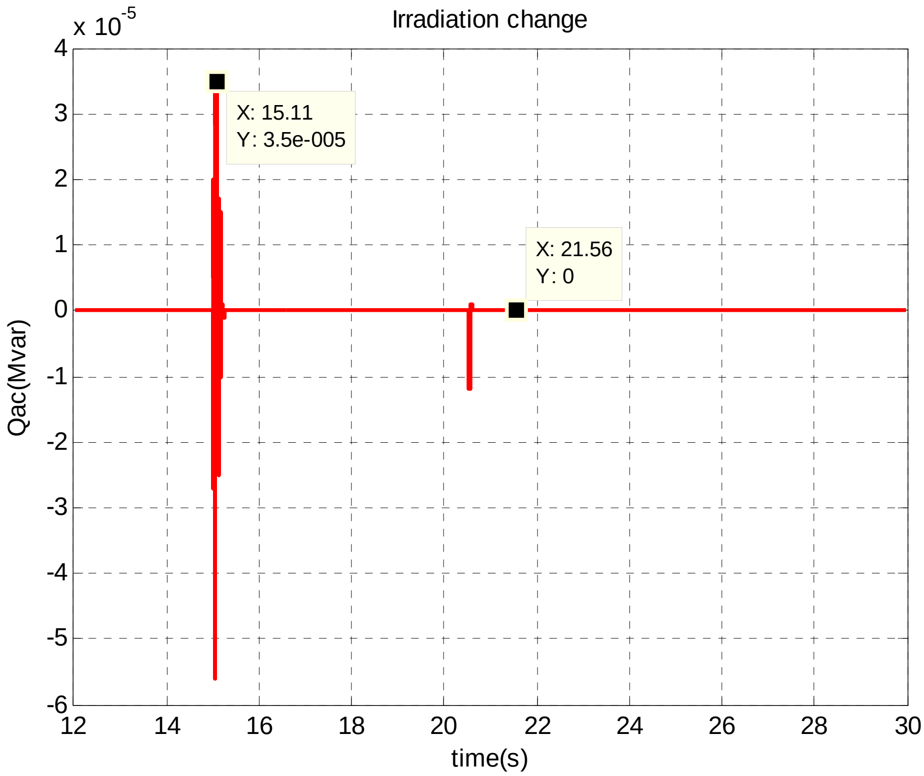

Fig 5.26 Reactive Power of PV system

AC voltage variation can be seen in Fig 5.27, which proves that PV system should not inject reactive power as the voltage variations in this figure is not more than dead band. This voltage variation is not sufficient to initiate any reactive power regulation.

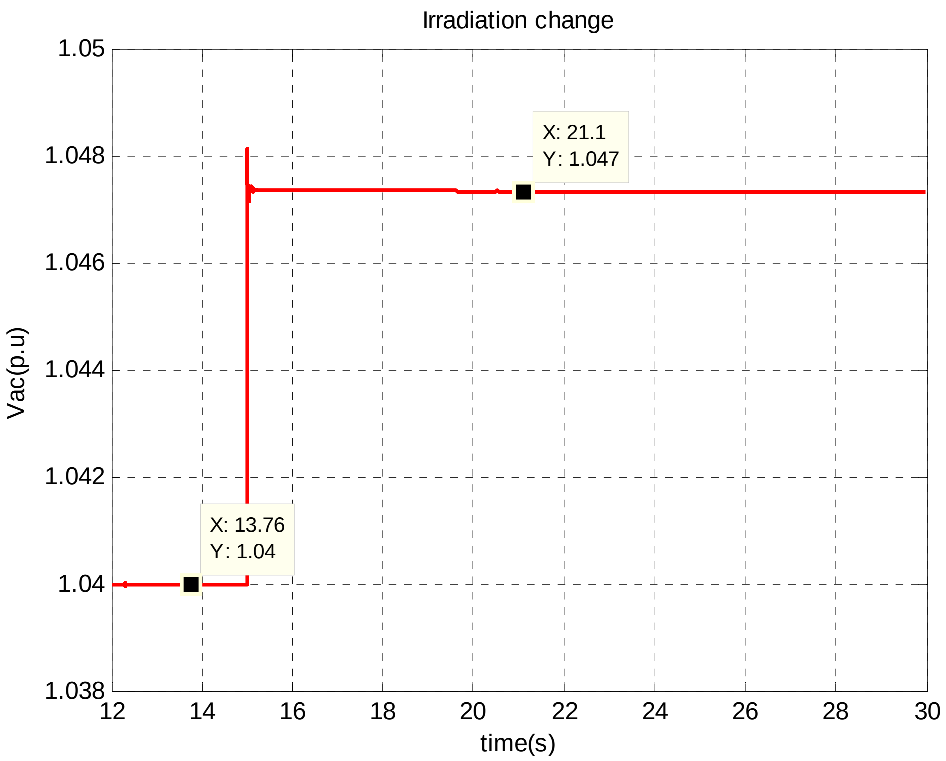

Fig 5.27 AC voltage at LV terminal

d. AC voltage control (Q Control 4)

When reactive power control is based upon AC voltage regulation, the response of the AC voltage and reactive power of the system is shown in Fig 5.28 and Fig 5.29 respectively. In this case at steady state, system was operating at unity power factor and no reactive power was supplied. As soon as irradiation in the system decreases AC voltage of the system starts varying. Reactive power is regulated such that voltage of the system comes back to its initial value.

Fig 5.28 shows AC voltage of the system with change in irradiation. It is clear from below figure that as soon as irradiation decreases in the system, AC voltage control made it possible to bring AC voltage back quickly to its initial value.

From Fig 5.29 it is clear that as the ac voltage tries to increase in the start with decrease in irradiation, reactive power is absorbed from the grid in order to maintain a constant AC voltage at LV terminal of PV system.

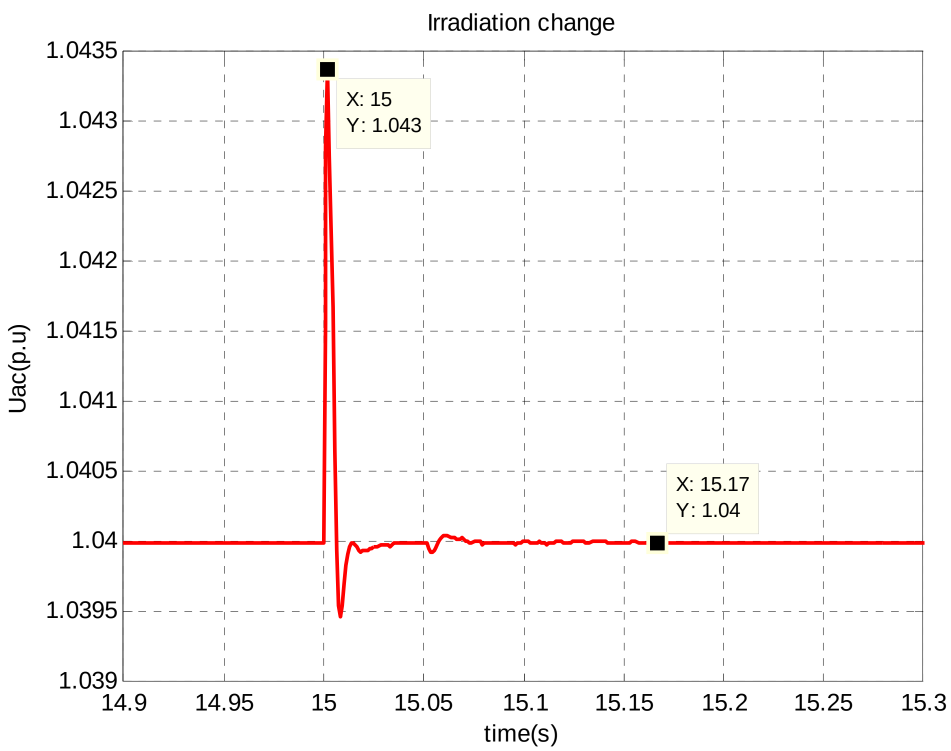

Fig 5.28 AC voltage at LV terminal

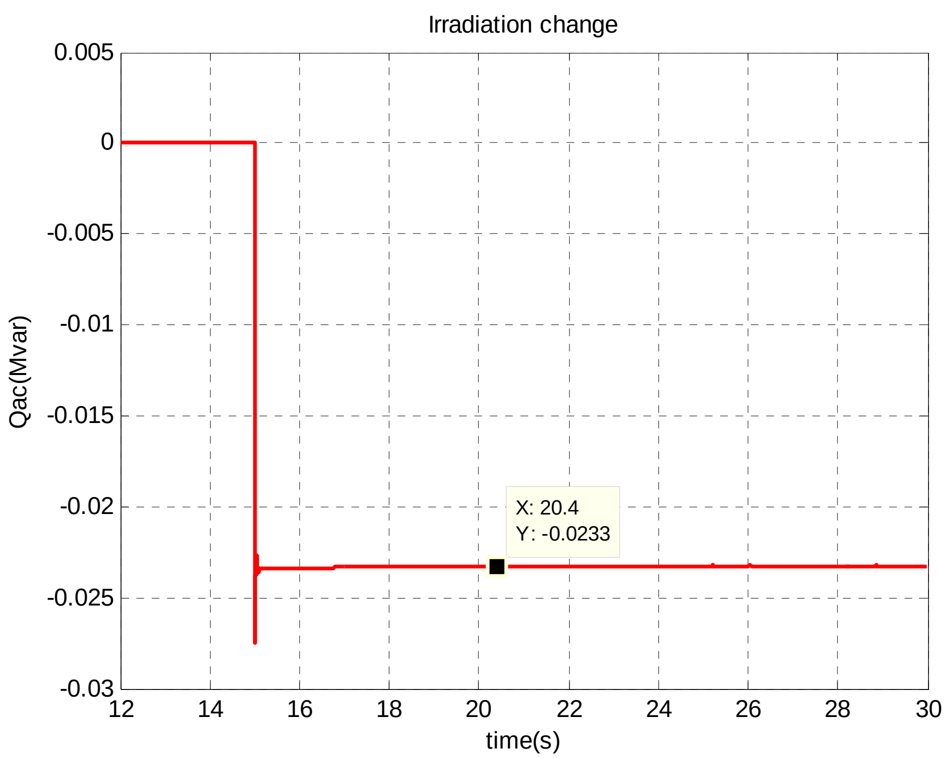

Fig 5.29Reactive power of PV system

In Fig 5.30 different reactive power control strategies with the change in irradiation are compared. Reactive power for these different control strategies is plotted in the figure. The Qcontrol 1 and Q control3 shows similar behavior as in both cases there is no regulation of reactive power. The QControl1 is for unity power factor so there is no reactive power supplied or absorbed. The Qcontrol 3 is based upon voltage variation at regulation point, as voltage variation is within deadband so no reactive power is regulated. For Qcontrol 2, absorption of reactive power is reduced on the basis of active power change in the system. In Qcontrol 4, reactive power is absorbed from the grid in order to make AC voltage constant at the regulation point.

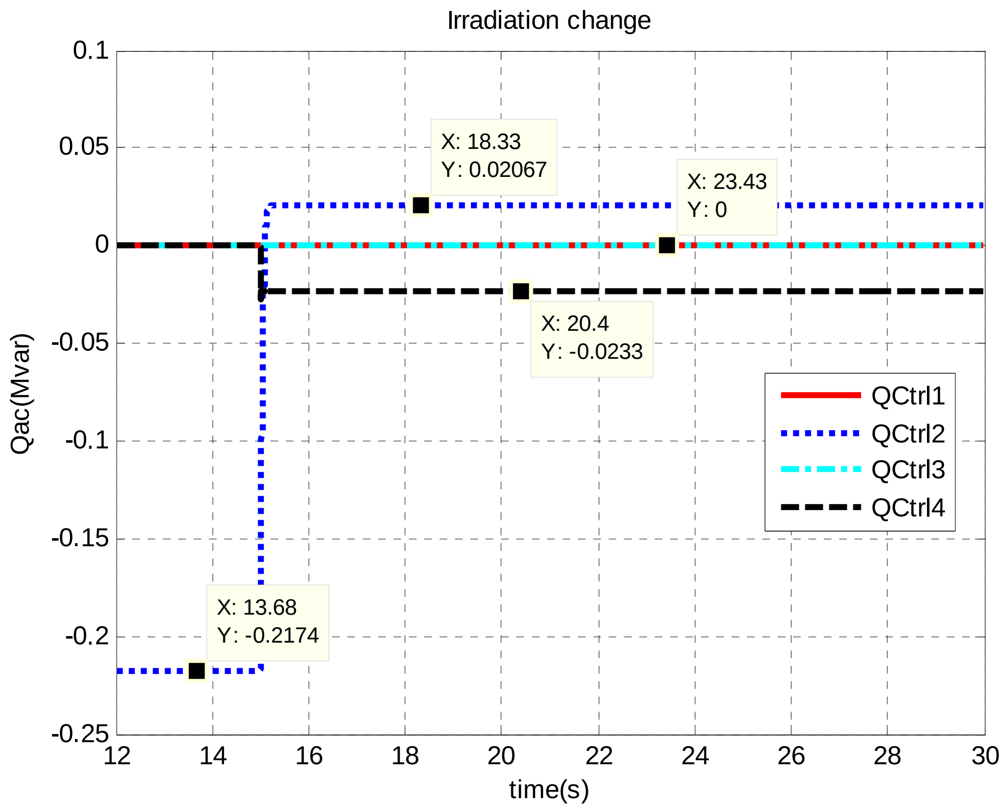

Fig 5.30Reactive power with different Q Control Strategies

5.3.2 Case 2: Decrease in external grid voltage by 10%

Next case is to check how KTH model works in case of external grid voltage decrease by 10%. Obviously this is a big voltage drop in the system, so a lot of reactive power needs to be regulated in order to maintain the voltage at LV terminal of PV system. This case is to check the capability of newly developed KTH model in case of such a huge disturbance in the system. Fig 5.31 shows the external grid voltage decrease by 10%, which is used a disturbance in this case.

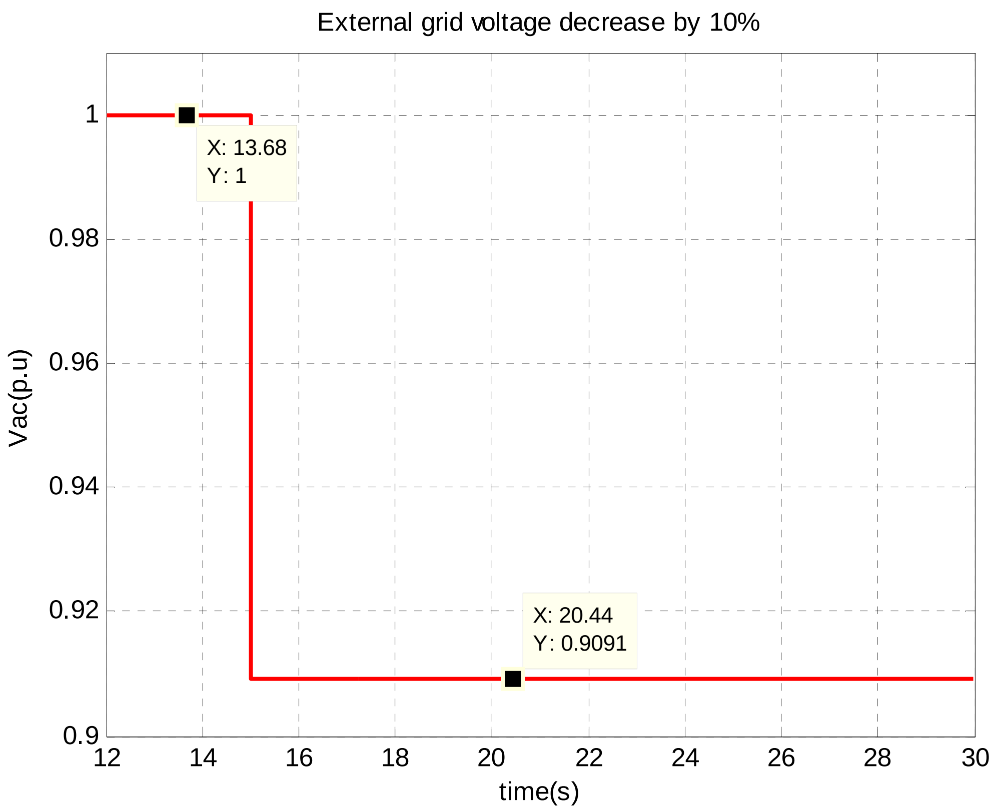

Fig 5.31 External grid voltage decrease

Under normal conditions, reactive power operational limits are defined and PV system cannot supply reactive power more than its limits. But for this case reactive power limits are increased as much as to supply enough reactive power to compensate such a big voltage drop. AC voltage regulation (Q Control 4) is used in this case to show, how this model act with this disturbance. External grid voltage is decreased by 10% at t=15.

DC voltage of the PV system is shown in Fig 5.32, in which it can be observed that at t=15 second when grid voltage is decreased, its DC voltage increases in start but within a second it is maintained at its nominal value.

Active power decreases to 0.94 p.u. when disturbance is applied in the system and very quickly like DC voltage it comes back to its steady state value. Hence model works perfect with respect to active power with change in grid voltage. Active power of PV system is shown in Fig 5.33.

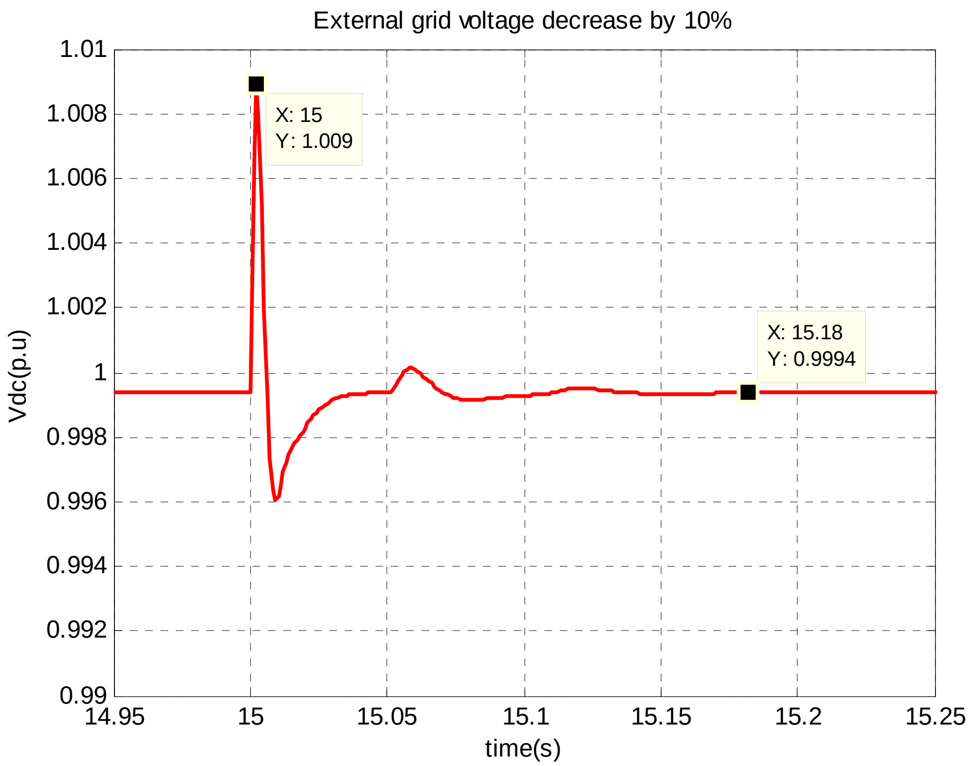

Fig 5.32 DC voltage of PV system

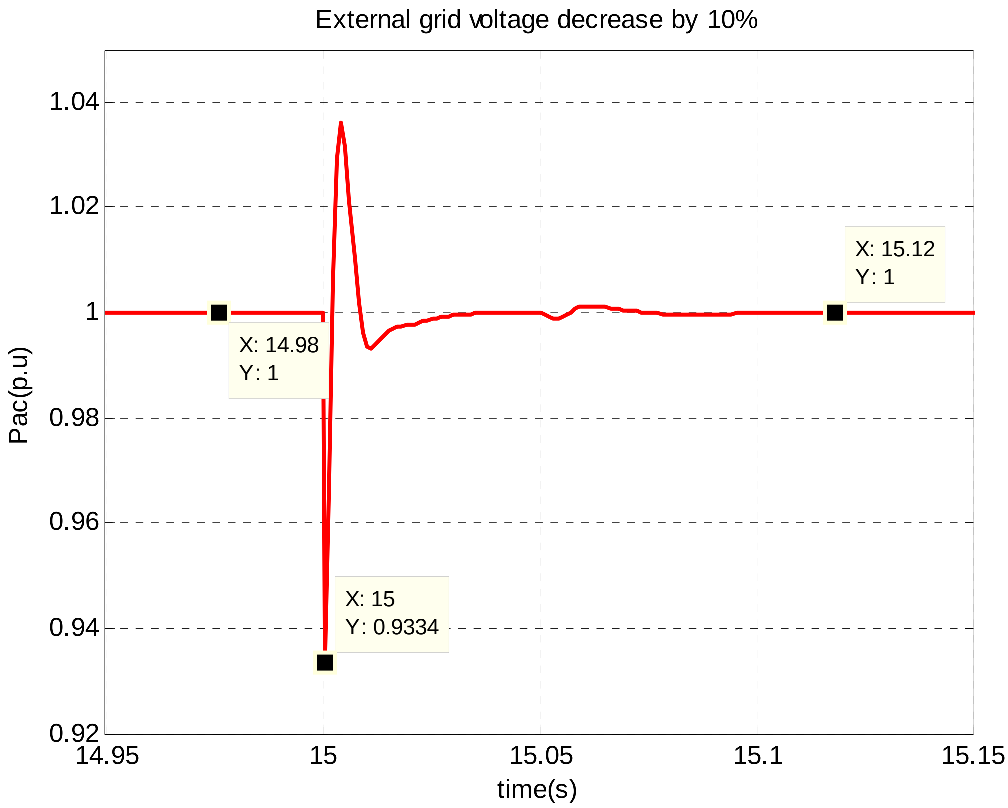

Fig 5.33 Active power of PV system

When external voltage decreases by 10% AC voltage at LV terminal of PV system also decreases without any AC voltage control. But when AC voltage control (Q control4) is there in the system, it helps to maintain a constant AC voltage at the terminal of PV system.

Fig 5.34 shows voltage decreases due to external grid voltage decrease, but due to AC voltage control it quickly comes back to its original value in less than a second. It is very fast control that helps to maintain a constant voltage at regulation point even with 10% grid voltage decrease.

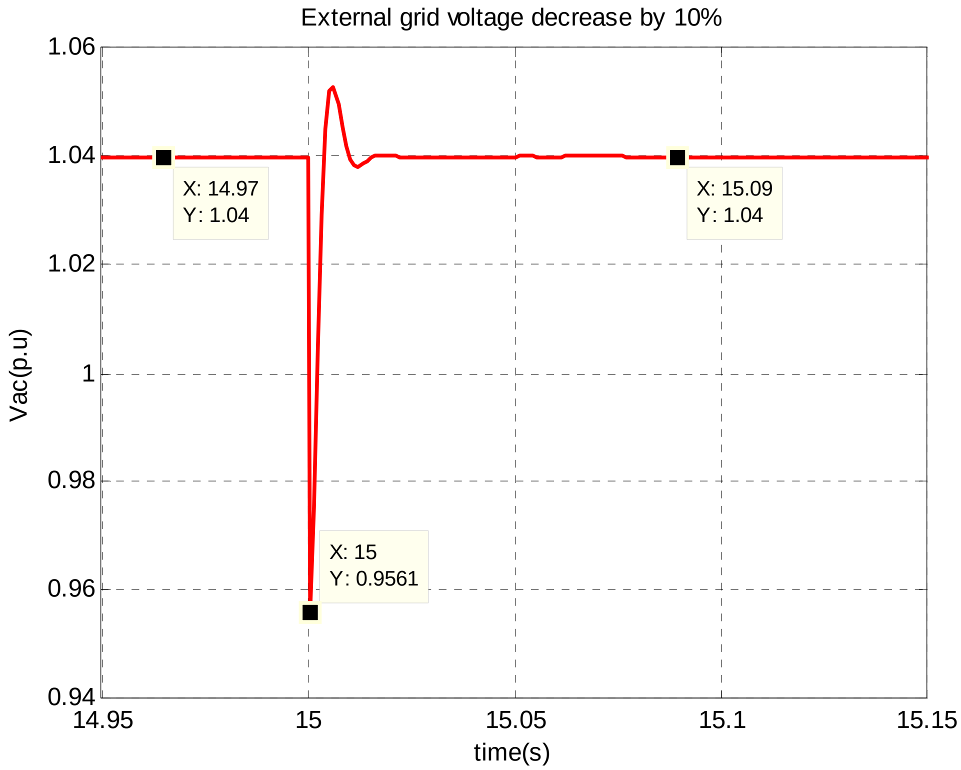

Fig 5.34 AC voltage at LV terminal

It is obvious from Fig 5.35 that PV system injects a lot of reactive power to external grid, in order to bring the voltage at LV terminal back to desired value. It injects a reactive power of about 0.3 Mvar to compensate decrease of external grid voltage. It shows that KTH model is capable of providing reactive power in order to maintain a constant voltage at LV terminal of PV system and to ensure it works in any disturbance of voltage.

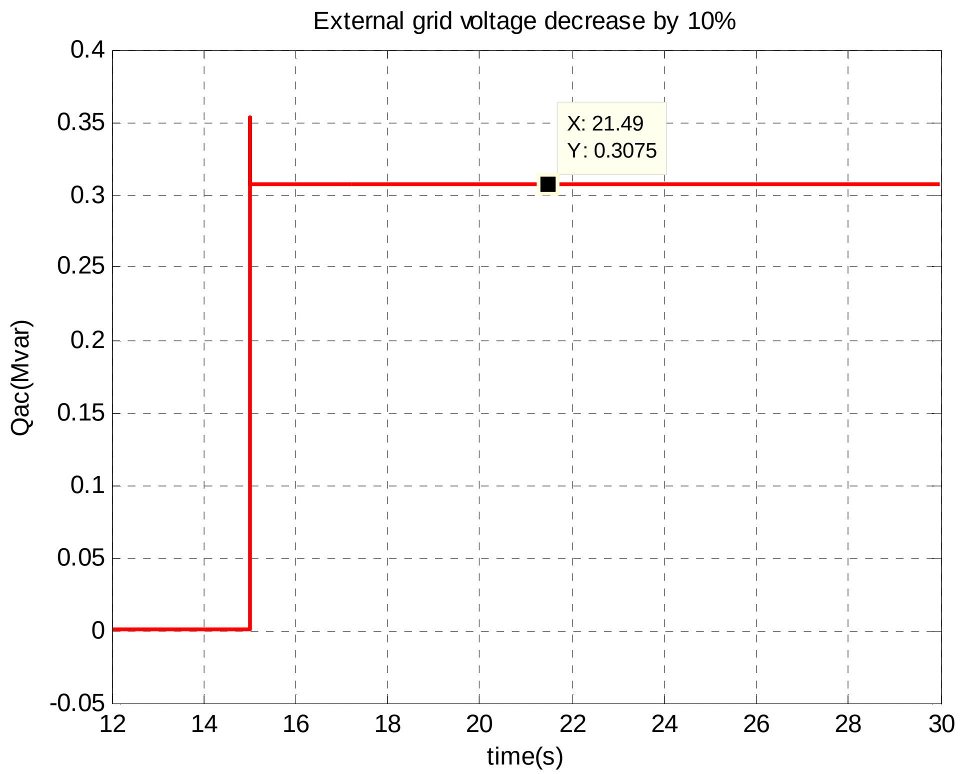

Fig 5.35 Reactive power of PV system

5.3.3 Case 3: Short circuit fault at MV (A) bus bar

A three phase short circuit at MV (A) bus bar is created at t=15 and is removed at t=15.1. The system response in this disturbance is very important to analyze. As MPPT control is also activated, so its interaction with the severe disturbance can also be a point of interest in this analysis. AC voltage regulation (Q Control 4) is used in this case to show, how this model act with this disturbance.

Fig 5.36 shows the DC voltage response of the PV system with the short circuit at bus MV(A). When short circuit is applied and quickly removed, DC voltage first increases to open circuit voltage of the system and then starts decreasing. But in this case, due to MPPT control a time delay in the system of T=0.05 was used to filter high frequency oscillations in the output. This causes the system to take some time to reach the DC voltage, active power and reactive power after the removal of short circuit fault. This can be seen in Fig 5.36 in case of DC voltage of the PV system. It takes some time to attain a steady state value after the disturbance is removed.

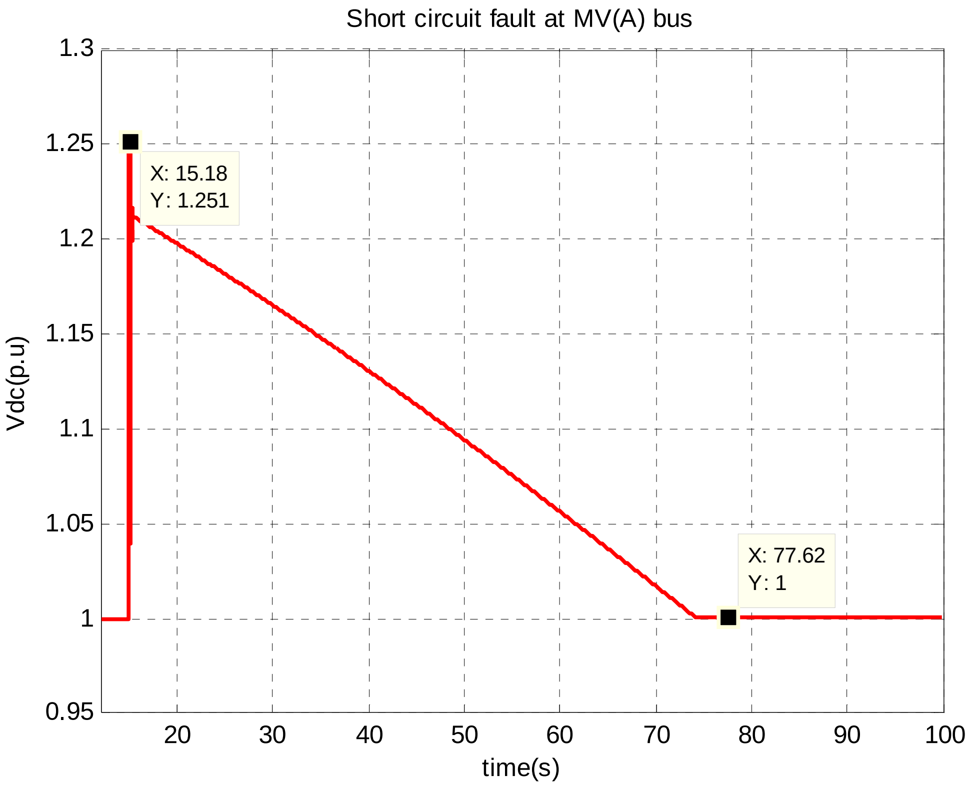

Fig 5.36 DC voltage of PV system

Active power of the system as can be observed in Fig 5.37 reduces to zero in case of short circuit fault duration. When fault is removed, it also takes some time to achieve the steady state value of active power.

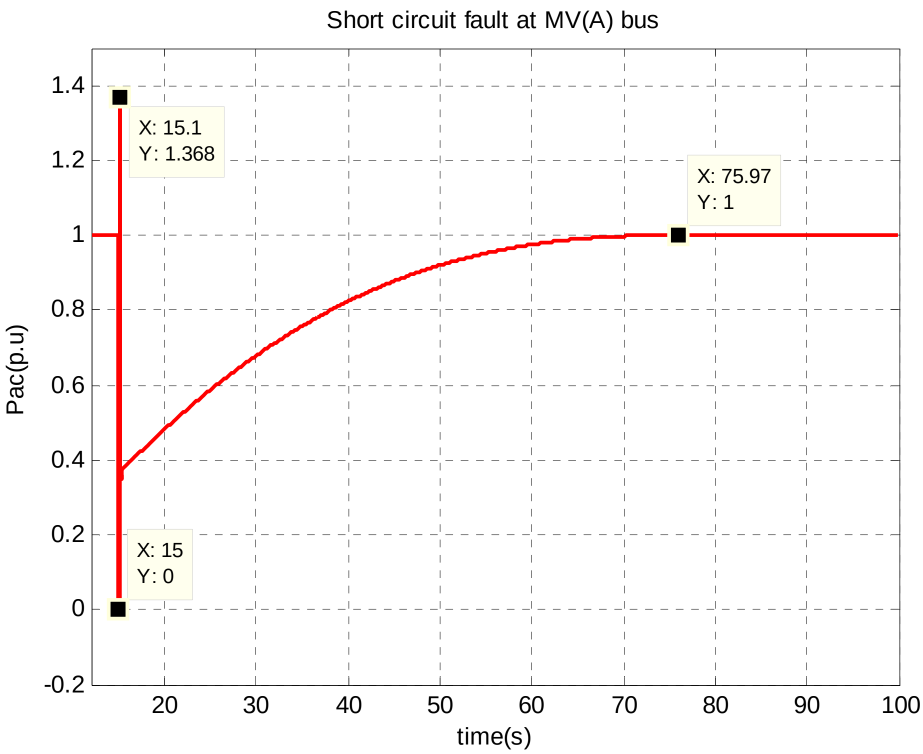

Fig 5.37 Active power of PV system

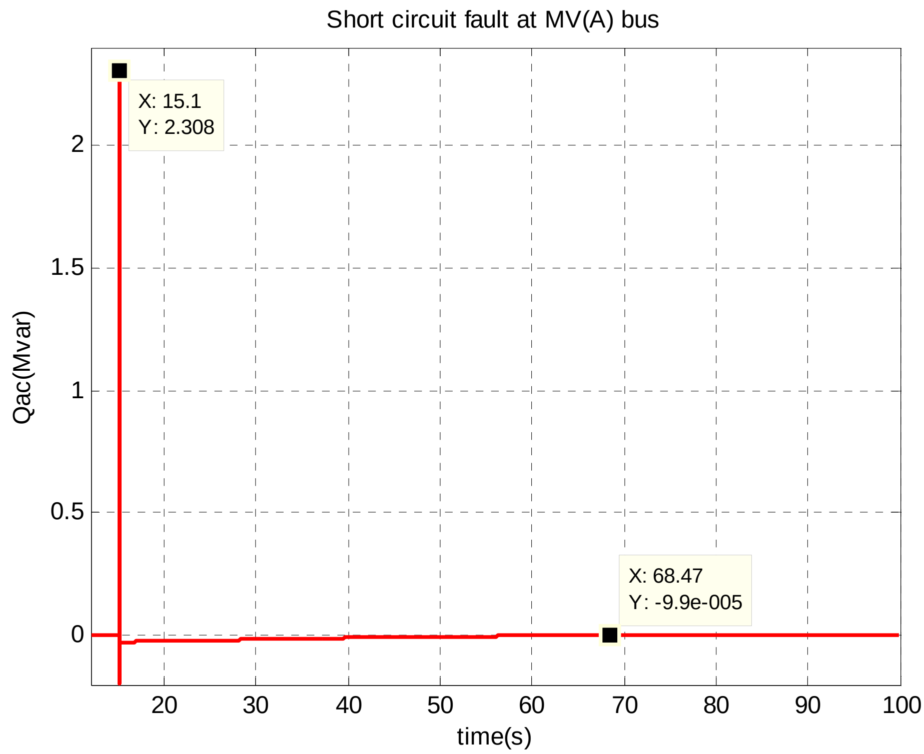

Fig 5.38 Reactive power of PV system

PV system injects the reactive power to the grid after the fault is removed, in order to bring AC voltage at LV terminal back to its original steady state value. Reactive power is shown in Fig 5.38 whereas AC voltage at LV terminal is presented in Fig 5.39.

AC voltage becomes zero during the short circuit fault, and as soon as fault is removed it return back to its initial steady state value. Due to AC voltage regulation control, PV system made it possible to very quickly regulate its AC voltage as shown in Fig 5.39.

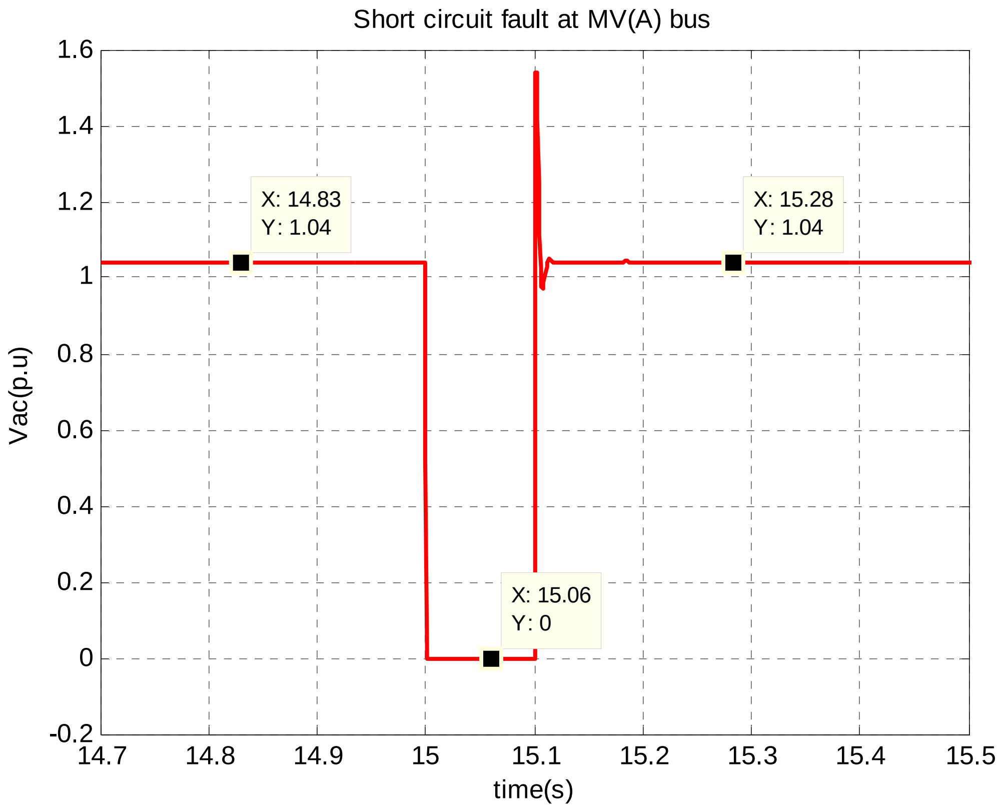

Fig 5.39 AC voltage at LV terminal

5.3.4 Active power Curtailment

Active power control is another type of unique control which is new addition in the control system of a KTH model. This control can be realized, when PV system is operating on its maximum power point and there arises a need to reduce the active power coming out of the PV system. This can be due to need of AC grid if for some reason; 100% active power is not required. But active power produced by PV array remains constant at a particular weather condition (irradiation, temperature and shading). Under these circumstances, active power control is developed and is implemented in this new model.

This control is implemented by providing a reference active power 'Pref' value as a parameter and a PI controller is used to calculate the corresponding V_{dcref} for the main controller. For this case parameter event 'Act' at t=15 is created which set Act=1 and give the Pref value. Hence at t=15 active power control starts operating.

Fig 5.40 shows the DC voltage decrease when active power of PV system is decreased by setting the value of Pref= 85% P i.e. it mean value of Pref equals to 15 % decrease of nominal value of active power.

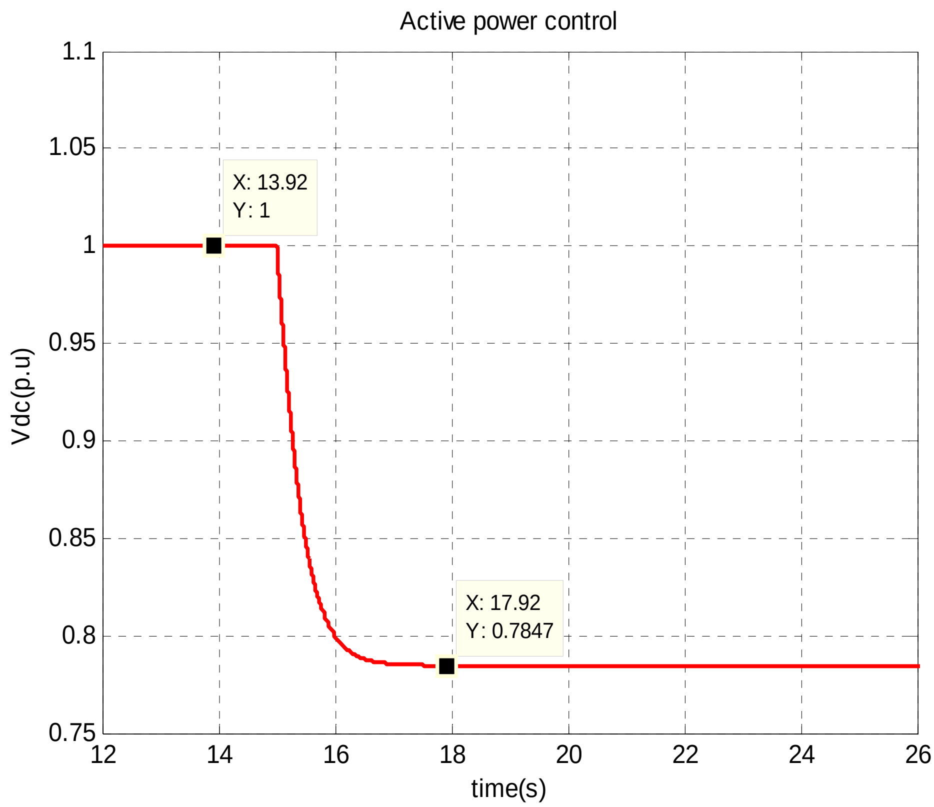

Fig 5.40 DC voltage of PV System with 15% Pref decrease

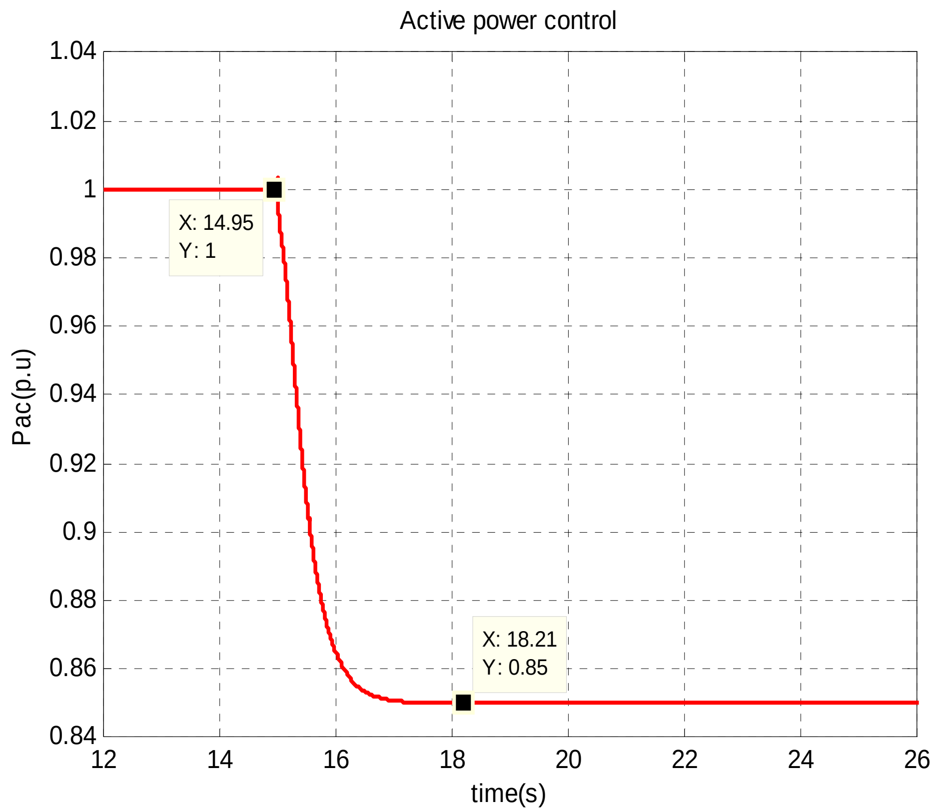

Fig 5.41 Active power of PV System with 15% Pref decrease

Fig 5.41 demonstrates the active power of PV system when active power control is enabled. It is clear that when Pref is reduced 15% of the nominal power, active power of PV system starts following its reference value which results in a decrease of active power of the system by 15 %.

In the end function of active power control with different percentage reduction of Pref value is presented. Fig 5.42 to Fig 5.44 shows active power control operation with 5%, 10% and 15 % decrease in 'Pref' value respectively. PI controller used in this control is tuned so that active power quickly follows the reference value of active power.

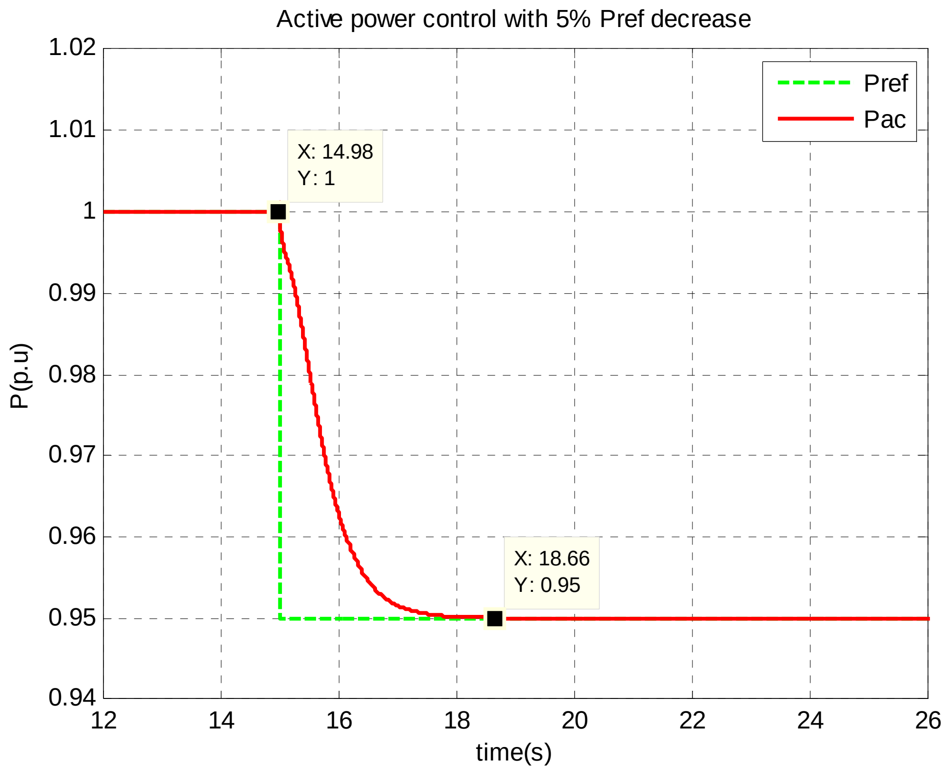

Fig 5.42 Active power control with 5% Pref decrease

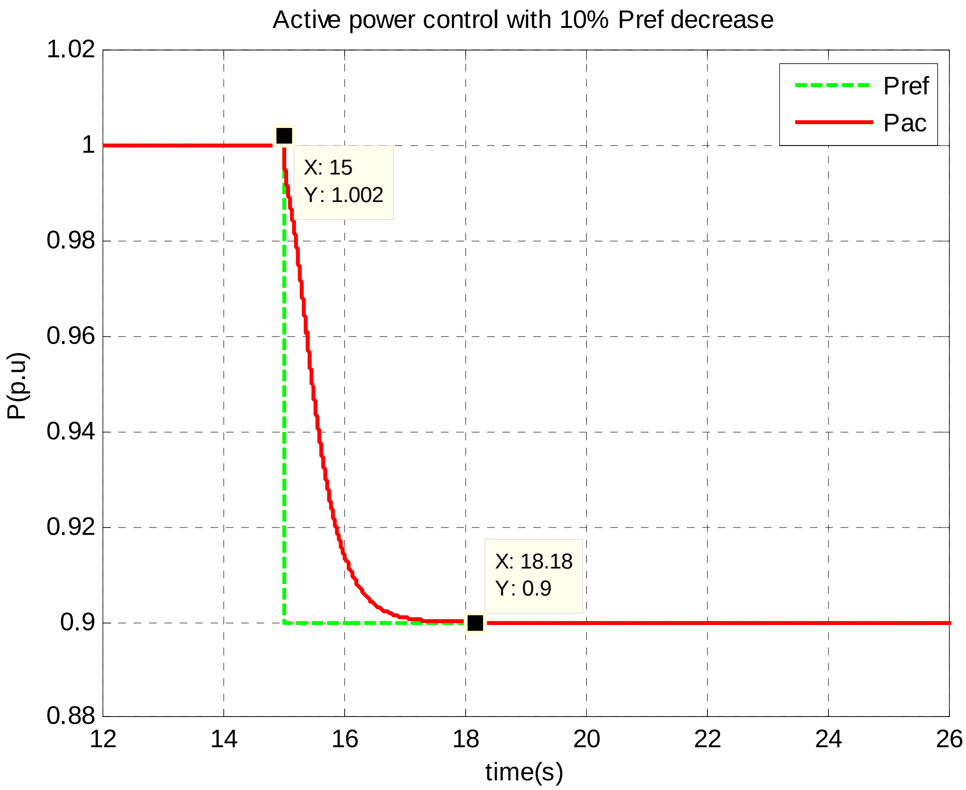

Fig 5.43 Active power control with 10% Pref decrease

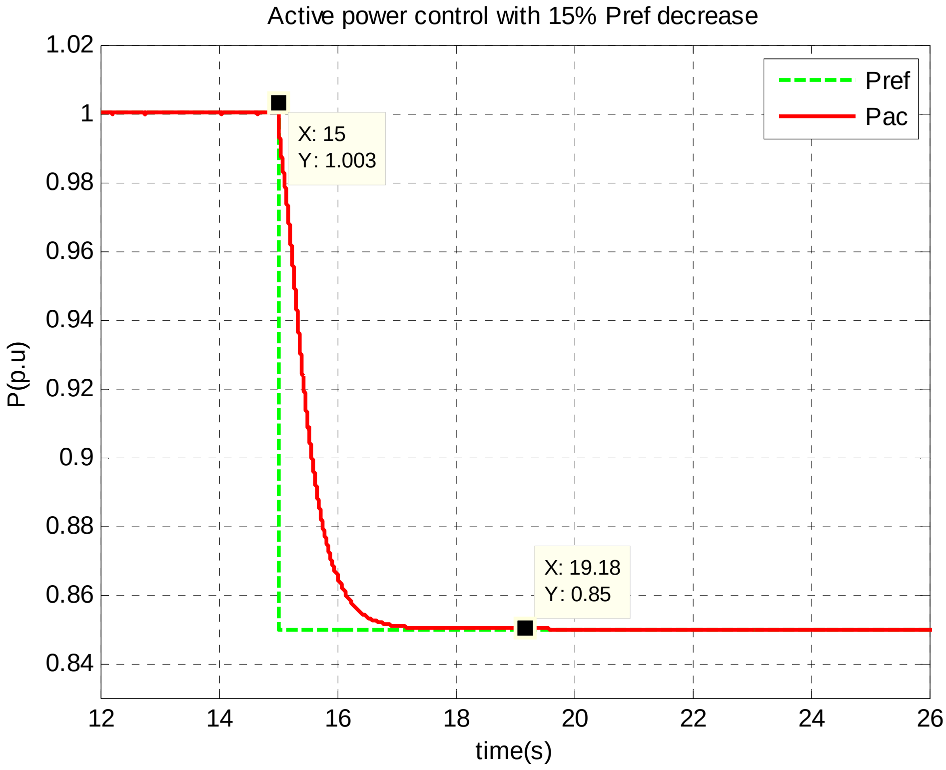

Fig 5.44 Active power control with 15% Pref decrease

5.3.5 Active power control with system frequency

This active power control is implemented by manually changing the system frequency and analyzing its impact on active power of the system. System frequency is manually increased from 50 Hz to 51 Hz by creating a parameter event at t=15 and is changed back to its original value at t=150. Frequency change of the system is shown in Fig 5.45.

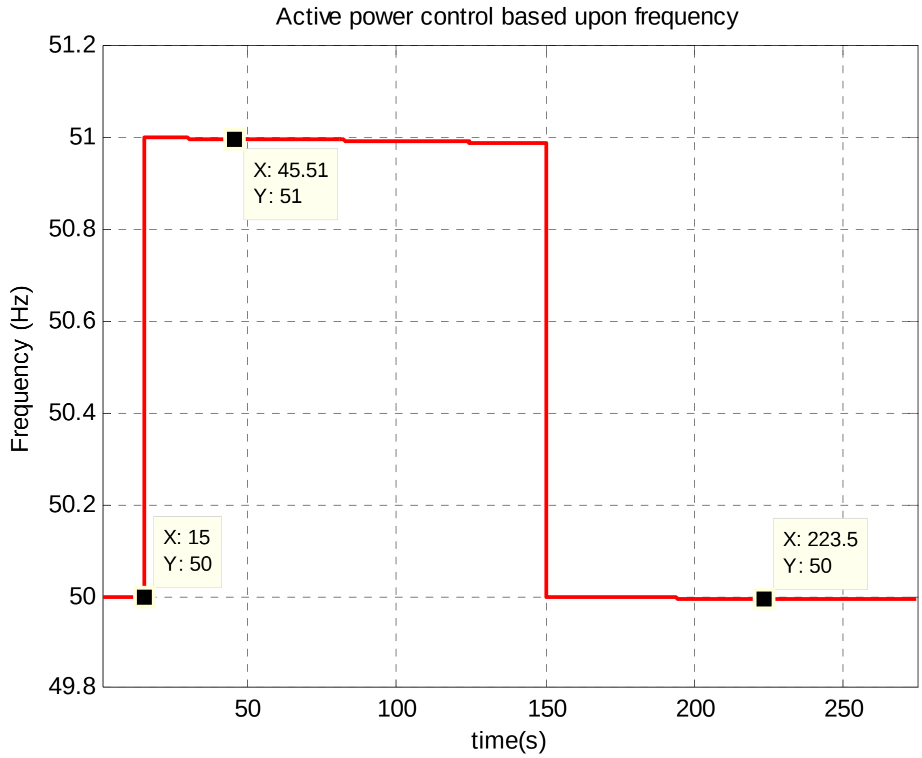

Fig 5.45 System frequency

According to the regulation presented in Fig 2.13, change in power with 1 Hz change in frequency is calculated as 0.143 MW and can be seen in Fig 5.46. Active power decrease to the value 0.143 MW and as soon as frequency comes back to 50 Hz, it starts increasing and comes back to its steady state value at t=260.

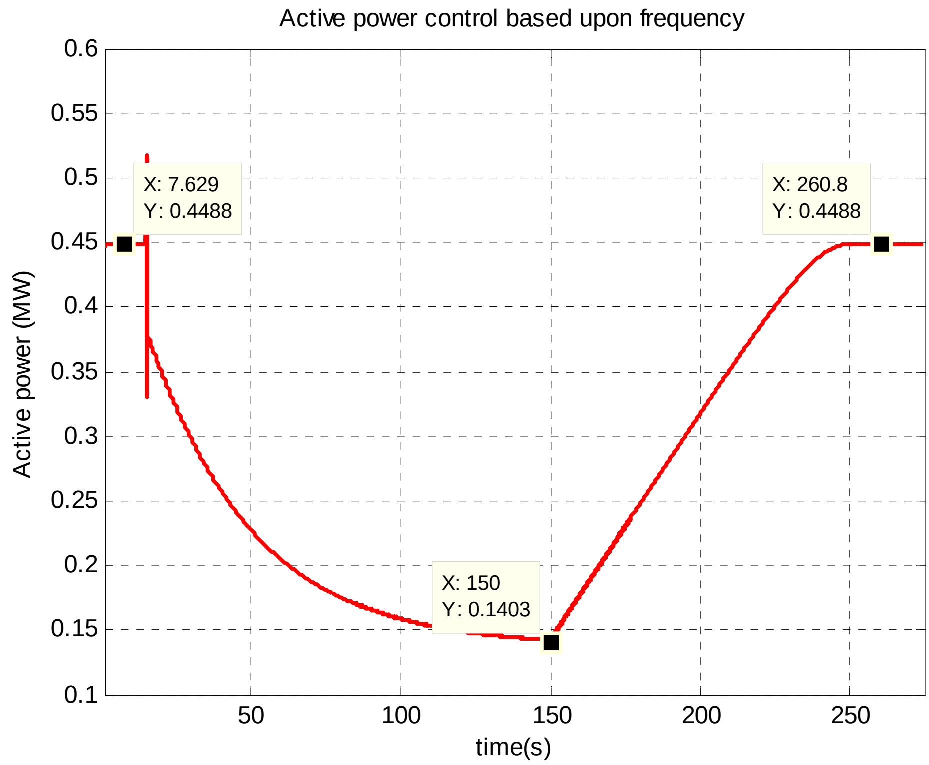

Fig 5.46 System frequency

This type of control takes some time to reach to steady state value after the disturbances. This can be explained on the fact that first of all MPPT is there in the system also due to active power PI controller time constant it takes some time to reach steady state. This time constant value has already been set after many tradeoffs and that is why same value is used.

5.3.6 Validation of MPPT control

First solar cell equations are written in MATLAB and a plot with changing irradiation is plotted and is shown in Fig 5.47. As it can be seen in this figure that for each curve there is a point at which power is maximum and is called MPP of the curve as indicated by data dips. MPP gives approximately 700 V for 1000 W/m^2 and 691V for 800 W/m^2.

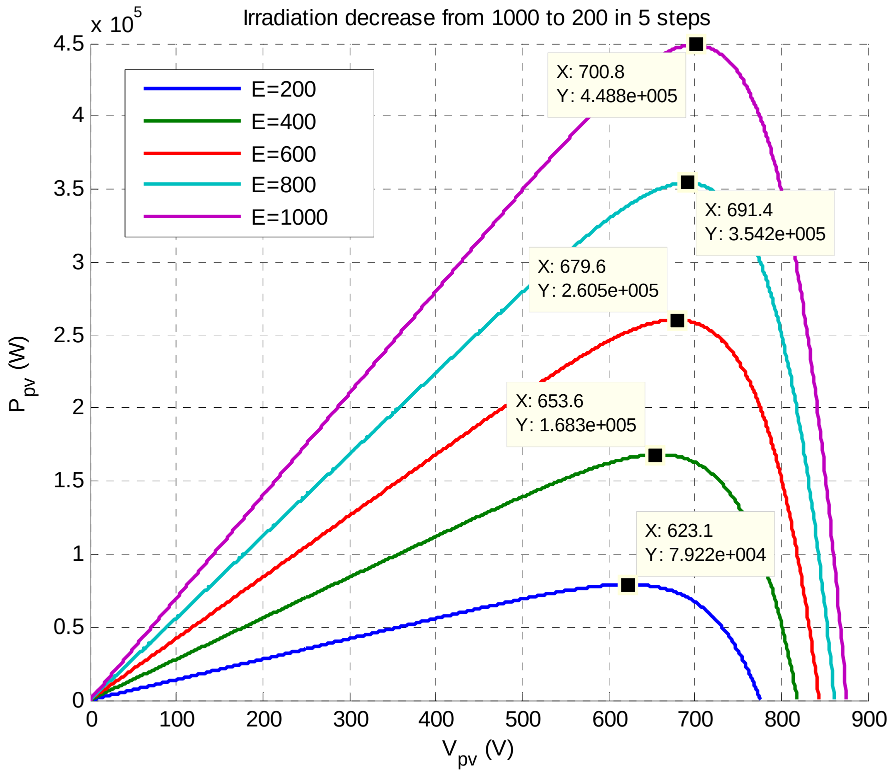

Fig 5.47 PV characteristics

In order to validate the MPPT control, this plot from MATLAB based upon static equations is compared with the dynamic behavior of MPPT control in PowerFactory. Fig 5.48(a) shows how the PV characteristics changes when irradiation changes from 1000 W/m^2 to 800 W/m^2 in dynamics. In this figure a dynamic response from PowerFactory is plotted with these two static curves. Here, green and blue are two static PV characteristics obtained from MATLAB equations for 1000 W/m^2 and 800 W/m^2 irradiation respectively. The red curve shows how PV characteristics changes in power factory when irradiation changes from 1000 W/m^2 to 800 W/m^2.

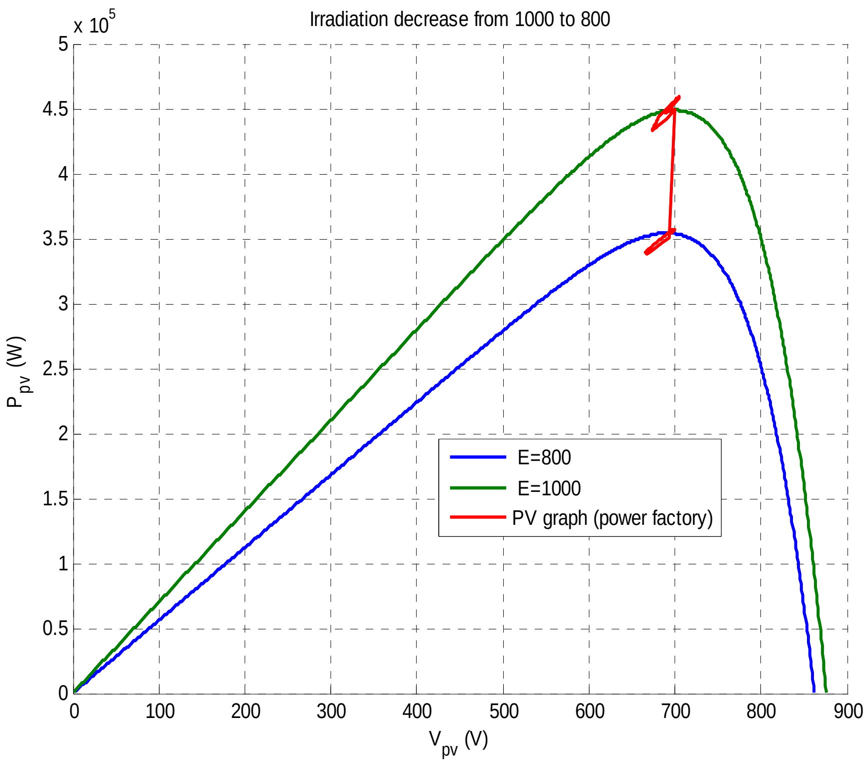

Fig 5.48(a) PV characteristics with power factory

In order to analyze it in more details the Fig 5.48(b) shows the same response by having a closer look of Fig 5.48(a).

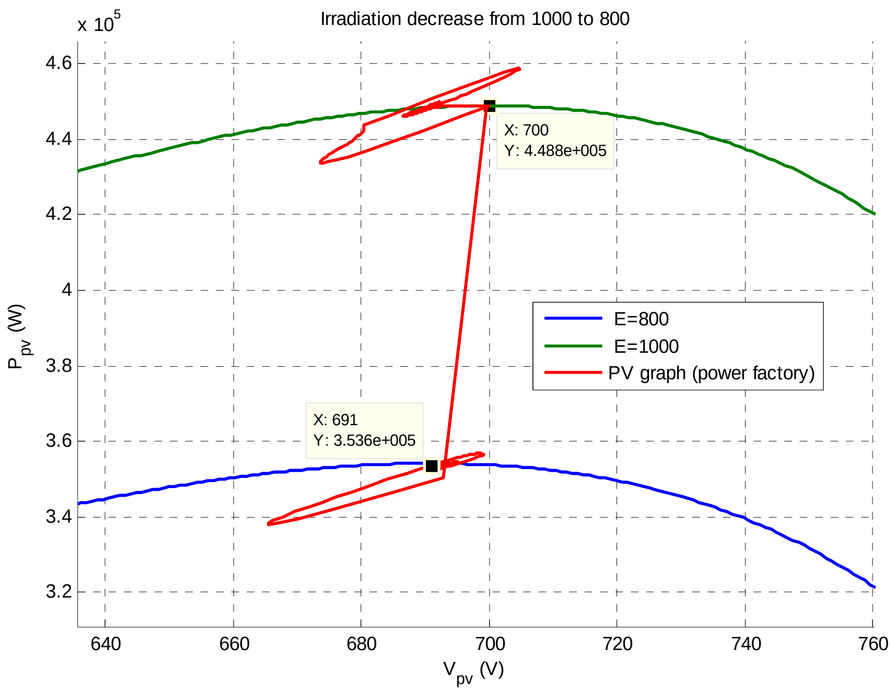

Fig 5.48(b) PV characteristics with power factory (closer look)

Fig 5.48 (b) shows that PV characteristics start from 1000 W/m^2 and as MPPT is there in the system, it takes a little while to track to its maximum power point for this irradiation (green curve). This is why there are some oscillations in the start. As soon as irradiation decreases to 800 W/m^2, active power decreases and now characteristics come to (blue curve). Now MPPT again tracks for this curve and after some minor oscillations, it finds the MPP for 800 W/m^2 irradiation.

The main purpose of showing this comparison between PowerFactory and MATLAB equations is to show that MPPT control works fine. It is also clear that this control works perfect even in case of dynamic behavior of MPPT, as red curve exactly starts with and ends to the same point as was expected.

5.4 Comparison between KTH model (static generator) and PWM converter model (Setup C)

In this section a comparison is presented between KTH model having the static generator and a PWM converter based PV system model.

For this comparison following conditions are brought into consideration

- There is no MPPT control in the system
- Both models have same reactive power control (based on AC voltage-Q Control 4)

In this comparison only Case 1 is investigated:

Case 1: Irradiance change in PV system (Irradiation is decreased to 500W/m^2 at t=0.3 and increased back to 1000w/m^2 at t=0.7)

In Fig 4.2 the basic structure of both models has already been shown. The brief description of two models is presented as

1. KTH Model based on static generator having DC bus bar model

In this model the PV system is represented by a static generator. The DC bus bar model used in this PV model calculates the DC voltage instead of directly measuring it.

2. Model based on PWM converter having no DC bus bar model

In this model a current source is used to represent the PV system with a DC bus bar connecting to it as shown in Fig 4.2. The DC voltage is measured from the voltage measuring device at the DC bus bar. This model is presented and explained in details in a master thesis project named “Comparison of a three phase single stage PV system in PSCAD and PowerFactory”.

The DC voltage of the two models is almost similar to each other in case of irradiation change in the system. In PWM converter, there is a bit more oscillations as compared to static generator. But overall response is quite similar. The DC voltage for the both models is shown as follows

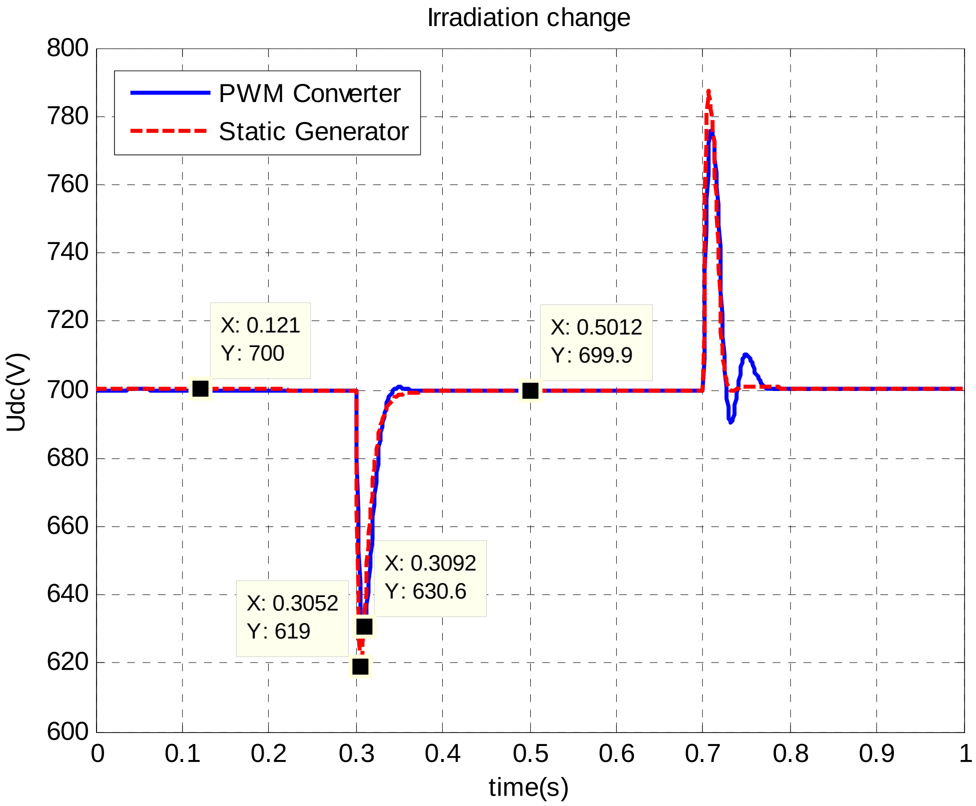

Fig.5.49 DC voltage of PV system

The active power of the two models is shown in Fig.5.50. It is clear from the figure that both models exhibit the similar response. There is only a minute difference in the form of a small overshoot, but this can be ignored as overall behavior is almost the same.

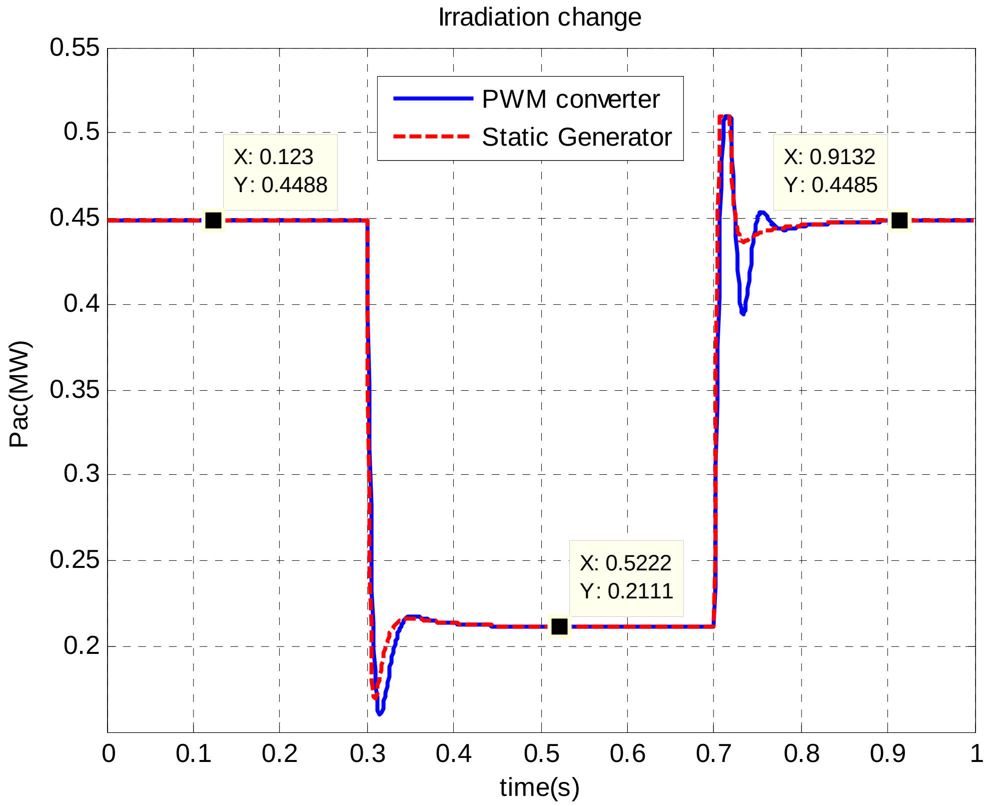

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Fig.5.50 Active power of PV system

The AC voltage of the two models is shown in Fig 5.51. It is clear from the data dip values in the figure that AC voltage at the LV terminal in case of irradiation change is almost identical. This response is based on Q control 4 in which AC voltage is controlled to a constant value. It can be seen from Fig 5.51 that the irradiation decreases and then increases; AC voltage comes back very fast to its controlled value for these two changes in both models. In case of PWM converter there is bit more oscillations in the AC voltage as compared to static generator.

In Fig 5.52, a zoomed in view of Fig 5.51 is presented. In Fig 5.52-(a) a zoomed in view of left peak in Fig 5.51 (peak due to first decrease in the irradiation of the system) is shown. It can be seen that in case of static generator, voltage comes back very quickly to its controlled value. Whereas in case of PWM converter it takes a bit longer time to reach to steady state value. Similarly in the Fig 5.52(b) a zoomed in view of second peak of Fig 5.51 is presented. This figure shows that AC voltage reaches its steady state value earlier for static generator than PWM converter. There are also some oscillations in the AC voltage in case of PWM converter, but static generator does not give much oscillations.

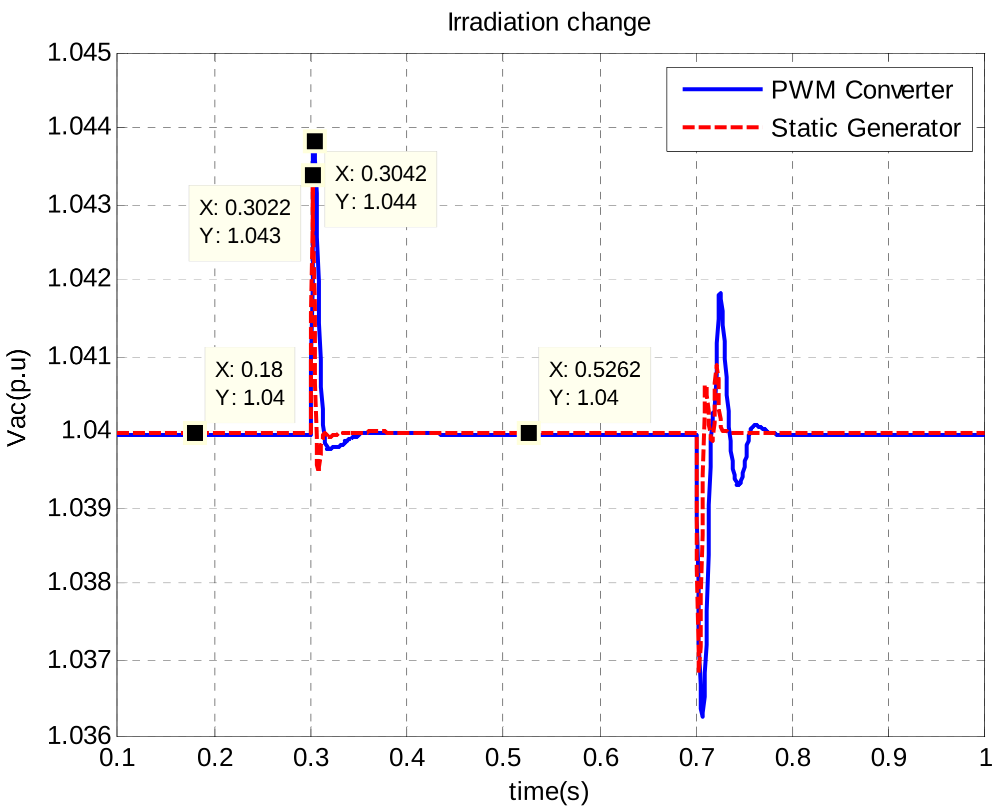

Fig.5.51 AC voltage at LV terminal

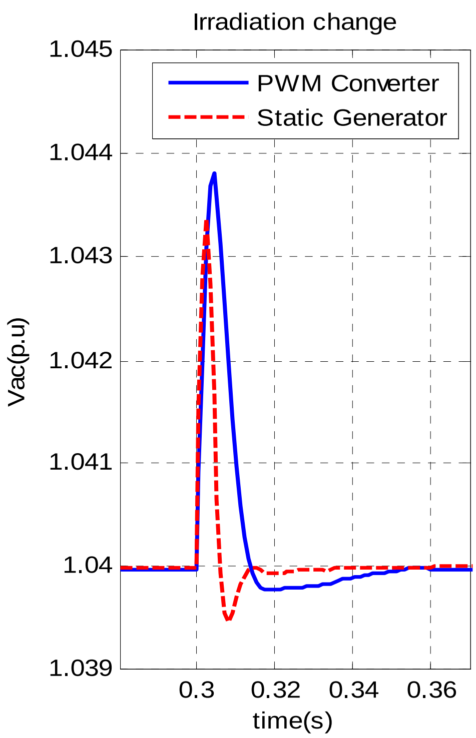

Fig.5.52 (a) Zoomed in view of left peak of Fig 5.51

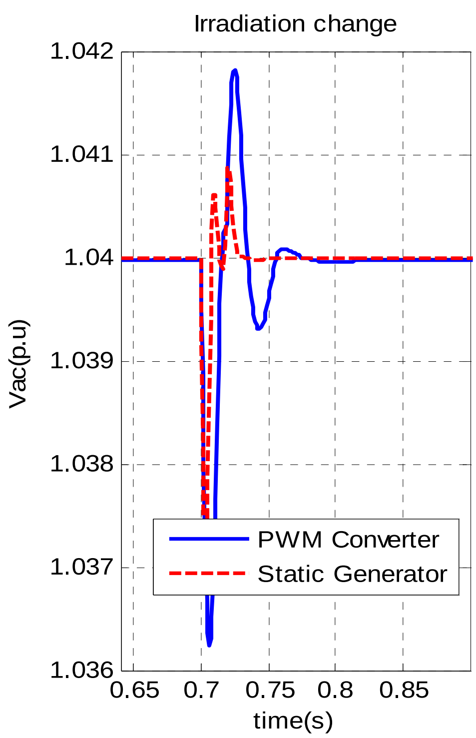

Fig.5.52 (b) Zoomed in view of right peak of Fig 5.51

Fig 5.53 shows the reactive power response of the two models with irradiation change in the system. It should be noted that at t=0.3 when irradiation decreases, reactive power is absorbed from the grid in order to stabilize the AC voltage to a constant value. In this case response of the both models is quite similar. But at t=0.7 when the irradiation increases again both models shows a bit different behavior. Reactive power from the PV system is released to the grid. In case of static generator reactive power reaches to a steady state value without oscillations. On the other hand, with PWM converter model, some oscillations can be observed in the reactive power but finally it reaches to its steady state value.

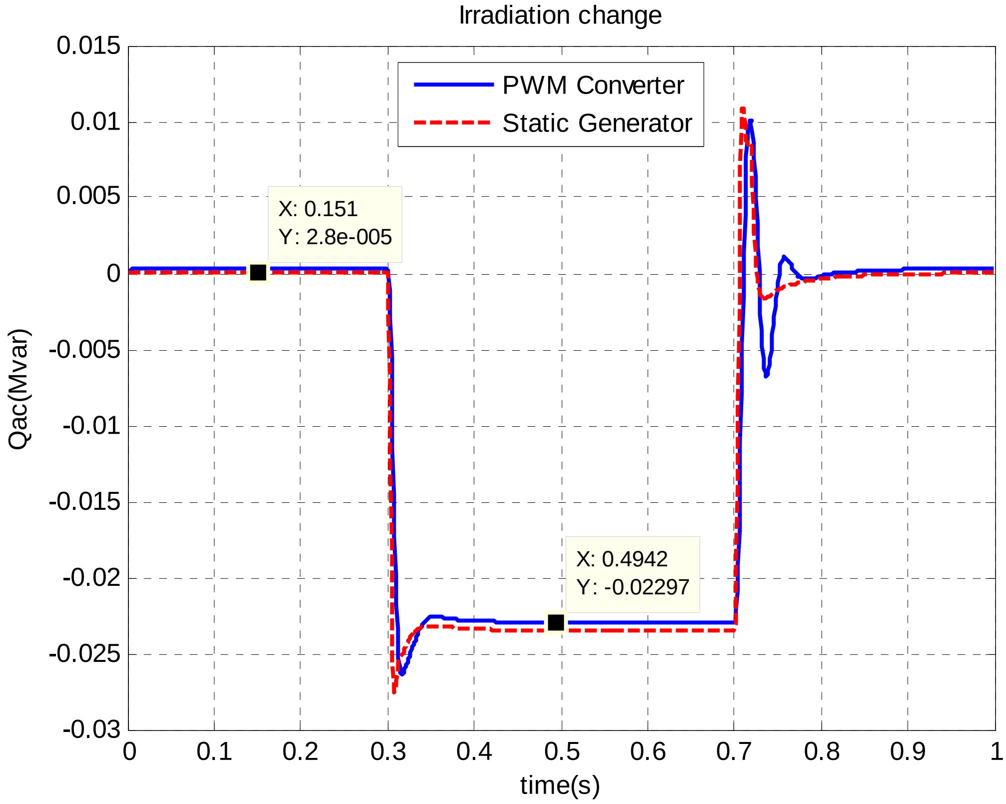

Fig.5.53 Reactive power of the PV system

6. Conclusions and Future Work

This project focuses on the improvement of PV model in PowerFactory. In this respect, a new model named KTH model in PowerFactory is developed which is equipped with many controls system. The following conclusions are drawn from this project.

The developed KTH model in PowerFactory is compared in details with already available generic model in PowerFactory using the same reactive power control for the both models. For all types of disturbances, both models behave in a similar way, which validate the developed KTH model in PowerFactory.

In generic model, PV panel is modeled with unknown approximations and parameters. Therefore, in KTH model, a more realistic PV panel model is developed which is based on the solar cell equations. This panel model gives power output which is more close to expected one as compared to that of generic model.

As far as control systems are concerned, there were some basic controls available in generic model, but still there is a need of many other controls. Therefore in KTH model, the following new control systems are implemented as compared to generic model i.e. active power curtailment, MPPT control and four different types of reactive power controls. These control systems in a PV model are very essential in order to perform the effective grid studies, making power system more reliable and efficient.

There was no MPPT control in the generic model; therefore in KTH model MPPT control is implemented to increase the efficiency of the system. Because MPPT ensures the PV panel to always operates on maximum power point in case of any change in irradiation. This MPPT control causes some high frequency oscillations in the system. But at the same time it gives more power at the output which increases the system's efficiency. A time delay in the PV panel model is used to filter these high frequency oscillations. Two methods of MPPT control are implemented in this project Perturb and Observe and Incremental Conductance. The comparison of these two methods shows that Incremental Conductance provides better results than Perturb and Observe. This is because Incremental Conductance does not give oscillations around MPP.

Reactive power support is very important for a PV system according to the grid codes. In generic model there is only one type of reactive power control present. But in KTH model four different types of reactive power controls i.e. unity power factor, dynamic power factor, droop control and AC voltage regulation are implemented. It provides flexibility in the KTH model to use any one of the available reactive power control strategies, depending upon the requirement of the system.

Active power curtailment implemented in the KTH model provides a facility to reduce the active power coming out of PV generator according to grid demand. This control was not present in generic model.

In Setup B, various transient grid studies are performed in KTH model having all the implemented controls. In this respect, it is concluded that KTH model in PowerFactory works perfect in case of severe short circuit fault with any kind of control for reactive power. Hence it provides a facility to perform short circuit analysis by creating fault anywhere in the system. In case of external grid voltage change, KTH model is capable of providing reactive power to the grid or absorbing reactive power from the grid. Hence, it increases the voltage stability in the system. Also this model behaves well in case of any solar irradiation change in the system. Especially with MPPT control we can have maximum possible power for any value of the irradiation in system.

In Setup C, a comparison is carried out between KTH model with static generator and PWM converter based PV model. It is concluded that both models behave in a similar way for the change in irradiation in the system. In case of PWM converter based model, more oscillations are observed as compared to KTH model based on static generator.

Future work

After the development of KTH model there can be many analyses which could be performed using this model in PowerFactory. And still there can be many more additions or improvement in this model possible.

Suggested possible future works in this respect can be as

- This KTH PowerFactory model can be used to perform grid studies with two or more PV system connected in parallel with each other. It would be interesting to analyze the interaction between these parallel PV systems.

- A more detailed solar irradiation model can be developed by taking into consideration the following advanced aspects i.e. cloud modeling, different shading effects and angle of incidence of sun light.

- This PV model can be further investigated in order to comply with different grid codes introduced by various countries.

- Further grid studies can be performed from this developed model by having AC generators and different loads in the system instead of Infinite bus.

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8. Appendix

8.1 Parameters used for the new PV model

Table 8.1: System Parameters

PV system components	*Value*
Static Generator	***0.5 MVA***
DC side voltage of PV	***0.7 kV***
LV terminal AC voltage	***0.4 kV***
MV(A) terminal AC voltage	***10 kV***
MV(B)terminal AC voltage	***10 kV***
Transformer	
Transformer, Nominal Power	***0.63 MVA***
Transformer, Voltage Ratio	***0.4kV/10kV***
Transformer, Vector Group	***Dyn11***
Transformer, Impedance	***4%***
Transmission Lines	
Line 1, Total length	***10km***
Line 1, Resistance per km	***0 Ω***
Line 1, Reactance per km	***5 Ω***
Line 1, Impedance per km	***5 Ω***
Line 2, Total length	***10km***
Line 2, Resistance per km	***0 Ω***
Line 2, Reactance per km	***5 Ω***
Line 2, Impedance per km	***5 Ω***

Table 8.2: PV module Parameters

Parameters	Value
Time constant, T	***0.05 sec***
Short circuit current per module, Isc1	***5 A***
Open circuit voltage per module, Voc1	***43.8 V***
Current at MPP , I_{mpp0}	***4.58 A***
Voltage at MPP, V_{mpp0}	***35 V***
T_{ref}	***25 C***
K_I	***0.0004***
K_V	***-0.0039***
E_{STC}***, Irradiance at STC***	***1000 W/m²***
nSerialModules Number	***20***
nParallelModules Number	***140***

Table 8.3: DC Bus bar and Capacitor

DC Bus bar and Capacitor parameters	Value
Capacitance	***0.0172***
Initial DC voltage	***700 V***
Nominal DC voltage	***1 p.u***
Rated Power	***0.5 MVA***

Table 8.4: MPPT Parameters

Track (MPPT module)- Block parameters	Value
Tdelay1	0.045 s
Vbase	1
Tdelay	0.05 s
Vmpp0_array	700 V
Step	125
Epsilon	0.01

Table 8.5: Active Power Reduction Parameters

Active Power Redn- Block parameters	Value
fUp	50.2Hz
fLow	50.05Hz
Gradient	0.05
Pbase	0.44884 MW
Tfilter	0.01 s

Table 8.7: Qref Block Parameters

Qref – Block parameters	Value
PFlim	0.9
Ubase	0.4 kV
Pbase	0.44884 MW
PF_select:0=const_pf;1=dynamic pf;2=Q(U)	0/1/2
db	0.05

Table 8.8: Controller Parameters

Controller- Block parameters	Value
Tfac	0.002
Tqfac1	0.001
ibase	1.02
ibase_iq	1
Tfqac	0
Kdc	-0.005
Kqac	0
Tqac	-0.041
Kac	-0.5
Tac	-0.0002131
Tfdc	0
Tdc	0.015
Flag 0=Reactivepower:1=Vac;2=Direct_iqref	0/1/2
id_min	0
iq_min	-3
id_max	1
iq_max	3

Table 8.9: Active Power Control Parameters

Active power control – Block parameters	***Value***
Act 0=MPPT;1=InputPref;2=Constant VDCref	***0/1/2***
Pfreq_fun ; 0=off ; on=1	***0/1***
Tfdc	***0.001 s***
Flow	***47.5 Hz***
Fup	***50.2 Hz***
Vconst	***700 V***
Kp	***0***
Tp	***0.0005***

8.2 DSL codes inside the PV system blocks

```
Vt1=(2*Vmpp0-Voc1)*(Isc1-Impp0)/(Impp0+(Isc1-Impp0)*ln((Isc1-Impp0)/Isc1))
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)*Vt1
 Voc2=Voc*(log(Eout)/log(Estc))

  I0=(Isc2/exp(Voc/Vt1))

!  I=Iph-I0*exp(V/Vt1);

FI0=Istart-Iph+I0*(exp((V+Istart*Rs1)/Vt1)-1);
FpI0=1+I0*(exp((V+Istart*Rs1)/Vt1))*Rs1/Vt1;
I1=Istart-FI0/FpI0;

FI1=I1-Iph+I0*(exp((V+I1*Rs1)/Vt1)-1);
```

```
FpI1=1+I0*(exp((V+I1*Rs1)/Vt1))*Rs1/Vt1;
I2=I1-FI1/FpI1;

FI2=I2-Iph+I0*(exp((V+I2*Rs1)/Vt1)-1);
FpI2=1+I0*(exp((V+I2*Rs1)/Vt1))*Rs1/Vt1;
I3=I2-FI2/FpI2;

FI3=I3-Iph+I0*(exp((V+I3*Rs1)/Vt1)-1);
FpI3=1+I0*(exp((V+I3*Rs1)/Vt1))*Rs1/Vt1;
I4=I3-FI3/FpI3;
! I=I4;
!  V1=V  ;
I=lim(I4,0,5)
V1=lim(V,0,43.8)
 P=V1*I
Parray=Varray*Iarray
```

8.3 MATLAB code to determine the controller parameters

```
clc;
clear all
close all

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

%%%%%%based on the ... paper
Vmpp=0.700;       %************ Give Total Value
Impp=0.6412;       %************ Give Total Value
%PV output rating power
PpouPV=Vmpp*Impp%*1e6%MW   %############## PV output power

Ubase=0.4; %************ 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;
Udc=Vmpp;       %%%%%%%%%%%%%%% DC voltage
Zbasedc=(Udc^2/Sbase)
Ibase=Sbase/(sqrt(3)*Ubase);
Rbase=Udc/Impp;
Uphase=Ubase/sqrt(3);   %Vsd
Vspu=Vs/Uphase;
%Vs= 0.147%e3
L=0.1e-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
toipu=.5e-3*W
%Dc Bus capacitor
C=17200e-6 %*********** DC side capacitor
Xc=(1/(W*C));
Cpu=Xc/Zbasedc;
%filter
Cf=10e-6;     %*********** Filter Capacitor if required
Xcf=-(1/(2*pi*50*Cf));
Cfpu=Xcf/Zbase;

%Refrtence
Iqref=0;
Idref=0;
Pref=PpouPV/2 %MW
Qref=0
%line
Lg=0.0424*(.4/10)^2     %********* Line inductance note here the
transformer rating
Xlg=2*pi*50*Lg
Lgpu=Xlg/Zbase;

Rg=0.06275*(.4/10)^2      %********** Line Reactance note here the
transformer rating
Rgpu=Rg/Zbase;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%limits
DcBus_UpperLimit=Pref;
DcBus_LowerLimit=-Pref;

AcBus_UpperLimit=Pref;
AcBus_LowerLimit=-Pref;
% PI controller data
Kp=Lpu/toipu          %########### Gain to be given for the Inverter IN-
BUILT controller
Ki=Rpu/toipu          %########### Timeconstant=1/Ki to be given for the
Inverter IN-BUILT controller


% how to calculate Vdc DC bus voltage
Vsd=Vs;
DeltaP=1*Pref/2;
Idref1=2/3*Pref/Vsd
DeltaQ=0;
Qs0=0;
Ps0=0;
Vtd= Vsd+(2*L*W/3/Vsd)*Qs0+(2*L/3/Vsd/toi)*DeltaP
Vtq= (2*L*W/3/Vsd)*Ps0-(2*L/3/Vsd/toi)*DeltaQ
Vt=sqrt(Vtd^2+Vtq^2)
Vdc=2*Vt
% Closed loof function of current controller loop
s=tf('s')
Gcl_current=1/(toi*s+1);
% figure, margin(Gcl_current)
```

```
%How to design controller for DC-bus Voltage regulation

WcV=25 %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;
%figure, margin(Gol_uncomp)

[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)
Tlgg=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##########

%figure, margin(Gol_comp)
%figure, step(feedback(Gol_comp,1))
zpk(Gol_comp);
```

8.4 Derivation for Rs and Vt

The unknown variables Vt and Rs are calculated by the method described as follows.

At MPPT dP/dV=0 gives the below expression

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0 \qquad (8.1)$$

Solving for dV/dI in (8.1) gives

$$\frac{dV}{dI} = -\frac{V}{I} \qquad (8.2)$$

Also from (3.2), following expression can be derived for V.

$$V = V_t \ln\left(\frac{I_{ph} - I}{I_0}\right) - R_s I \tag{8.3}$$

From (3.4), putting the value of I_0 in (8.3) at MPP gives

$$V_{mp} = V_t \ln\left(\frac{I_{ph} - I_{mp}}{I_{ph}}\right)\left(e^{\frac{V_{oc}}{V_t}}\right) - R_s I_{mp} \tag{8.4}$$

From (3.3) it is also known that I_{ph}=I_{sc}, putting above and solving for R_s yield the expression as shown in (8.5).

$$R_s = \frac{V_t \frac{ln(I_{sc} - I_{mp})}{I_{sc}} + V_{oc} - V_{mp}}{I_{mp}} \tag{8.5}$$

From (8.3), taking derivate with respect to I gives

$$\frac{dV}{dI} = -\frac{Vt}{I_{ph} - I} - R_s \tag{8.6}$$

By comparing (8.2) and (8.6) the final derive expression for V_t is shown in (8.7).

$$V_t = \frac{(2V_{mp} - V_{oc})(I_{sc} - I_{mp})}{I_{mp} + (I_{sc} - I_{mp})\ln\left(\frac{I_{sc} - I_{mp}}{I_{sc}}\right)} \tag{8.7}$$

Hence from (8.5) and (8.7) the values of Rs and Vt can be calculated respectively. It should be noted these parameters are easy to calculate with these expression as all the entities involved in these expressions are known from the data sheet of the PV module.

8.5 Stability Models

There are two possible types of models that are supported by static generator:

- Current source model
- Voltage source model

In this project, current source model for the RMS and EMT simulations are used. It takes the id_ref ,iq_ref,cosref and sinref as input to the model. The output of the model provides frequency and d-axis & q-axis components of current.

Fig 4.6 Input/output Definition of model for Stability Analysis [24]

The input and output definition of the parameters involved in current source model are shown in Table 1 and Table 2 respectively.

Table 3: Input Definition of the Current Source Model

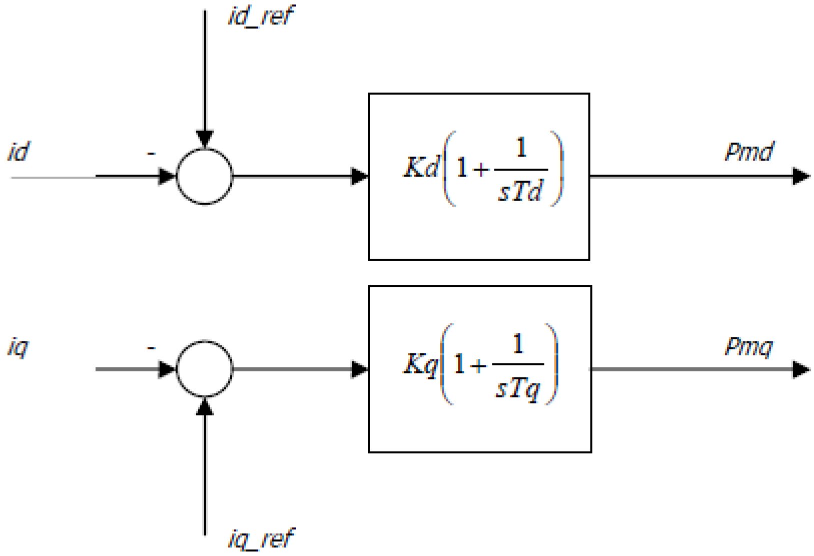
Parameters	***Description***	***Unit***
Id_ref	*d_Axis Current Reference*	*p.u*
Iq_ref	*q_Axis Current Reference*	*p.u*
cosref	*Cos(dq-Reference-Angle)*	
sinref	*Sin(dq-Reference-Angle)*	

Table 4: Output Definition of the Current Source Model

Parameters	***Description***	***Unit***
xspeed	*Frequency*	*p.u*
Id	*Current, d_Axis*	*p.u*
Iq	*Current,q_Axis*	*p.u*

The reader is referred to Technical reference for Static Generator available in the software DigSilent (PowerFactory) [24] to have detailed overview of the stability models of static generator.

8.6 Built-in Current controller



$$Kd\left(1+\frac{1}{sTd}\right)$$

$$Kq\left(1+\frac{1}{sTq}\right)$$

Fig 4.7 Built-in current controller in static generator