# Modeling of photovoltaic power system in on-grid and performance analysis of the system under variant climates

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**Abstract**

This paper investigates modeling, design and control aspects of a Photovoltaic system (PV) integrated with the Utility grid with the help of bus bar to provide better power quality and to share the load demand of end users using renewable energy resources. The performance analysis of on-grid photovoltaic power systems is carried out under varying solar irradiance and constant temperature and constant electrical loads, since the power generated from a PV mainly depends on the climate conditions such as Solar irradiances and temperature. These irregular climatic condition leads to change in Active power injected to grid, so the Maximum Power Point Tracking (MPPT) technique is applied to PV panels in order to extract the maximum power at its respective irradiance and temperature conditions. In addition, the Voltage oriented control strategy incorporated with the on-grid inverter to maintain the power factor as unity and constant grid voltage irrespective of variations in solar irradiance. The simulations are carried out on 0.1 MW grid connected PV system which is designed and modelled in MATLAB / Simulink software.

Keywords: Drive train; Wind turbine; Power system; MPPT; DFIG

## I. Introduction

At present the demand for electric energy in our planet increases rapidly due to the urbanization and industrialization. The world's net electricity usage is expected to rise 64.1 trillion kilowatt-hours in 2030. At present a large amount of electricity is produced from the fossil fuels, due to its low prices but it causes lot of issues in the environment (Mengelkamp et al. 2018). For this scenario integration of Renewable energy sources like PV, Wind, hydropower etc. with the utility grid can be a better substitute. (Lasseter, Robert H., and Paolo Paigi. 2004) The solar radiation is one of the renewable energy sources and hence the light can be converted to clean electricity. PV system has limitations since it is intermittent in nature and completely dependent on the environmental conditions such as the solar irradiance variations.

Solar irradiance is the measure of power per unit area. It is very small in the morning due to diffused light from the sun and it is very large at zenith (Gregg WW and Carder KL 1990). The intensity of light gradually increases and remains same for certain time then decreases to zero as shown in Fig.1. The area under the parabola (actual irradiance) and the rectangle (assumed irradiance) are same. So, in this research two radiations are taken as 500 W/m$^2$(cloudy day) and 1000 W/m$^2$(bright sunny day) at air mass ratio as 1. The

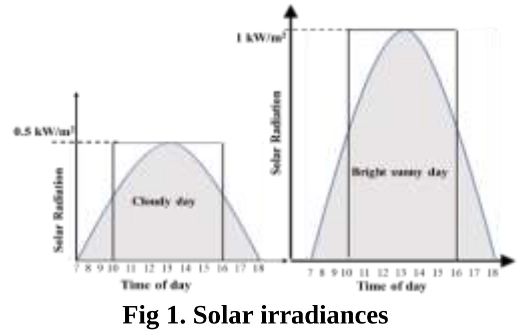


**Fig 1. Solar irradiances**

integration of this renewable PV system in the power grid as more reliable power with higher quality to the electrical grid and it is responsibility of engineers and researchers. (Kazmerski, Lawrence L 1997; Humada, Ali M., et al. 2016) The manufacturing technology of cells, inverters, the weather parameters as global irradiance, ambient temperature and soiling losses, and installation configuration are the various factors affecting the performance of a grid connected PV system.

Many researchers have been investigating in the integration of renewable energy systems like PV, wind, biomass etc. with the power grid and also in dynamic modelling, stability and control strategy in stand-alone and grid connected conditions. Lidula, N. W. A., and A. D. Rajapakse. (2011) has focused on available control schemes in Micro grid and given tabular form data on existing microgrid testing systems. It also helps researchers to find out the possible area to work in microgrid to enhance its performance. Some of the major challenges on reliable operation and control in micro grid has been discussed in Olivares et al. (2018); Rajesh KS, Dash SS, Rajagopal R and Sridhar R (2017). They have encapsulated the overview of some important controllers like model predictive control, droop control in AC microgrid. Khatib T (2010) has proposed the design of stand-alone photovoltaic (PV) system to satisfy the electrical load for a single residential household in rural area in Jordan and he also stated complete design steps for household electric loads by considering irradiation and electrical load data of that local area and it will be a guideline for researchers to design on-grid PV system. Step by step explanation given by Ashok Kumar, L., S. Sumathi, and P. Surekha (2015); Chouder et al. (2012) was very helpful in designing PV parameters and modelling of the PV array in Matlab/Simulink platform. Rezk, Hegazy, and Ali M. Eltamaly (2015); Yadav et al. (2012) has depicted some of important MPPT techniques like as hill climbing, incremental conductance, perturb-and-observe and fuzzy logic controller and the results of all techniques are compared and some of the parameters like voltage, current and power output for each different combination has been simulated using Simulink tools. There are two generalized concepts to solve the electrical load demand from the end users in future. One is sharing of power from non-renewable and renewable energy systems and other is to enhance the power electronics in power generation, transmission/distribution and end-user appliances. Blaabjerg et al. (2006) has discussed about emerging renewable energy sources by means of power electronics. Modern power electronics require high quality, small, lightweight, reliable, and efficient power supplies (Muhammad Rashid 2017), so researchers and engineers are dealing with converters incorporated with power grid to sort out power quality issues. Teodorescu, Remus, Pedro Rodriguez, and Marco Liserre (2010) has divided work into 3 parts such as control, synchronization and anti-islanding techniques for PV converters, which helps to study the problems arising during all circumstances. Modelling of converters, control of grid converters during fault are clearly explained by Teodorescu (2018). To model DC-DC converter and calculation of parameters under the variations of climatic conditions proposed by Erickson, R. W., and D. Maksimovic (2011) was very helpful and the book also elucidates fundamental concepts on modelling of various DC-DC converters, it will be very helpful for researchers to understand. Zhao et al. (2011) has presented grid-connected PV system with a novel PWM control technique and digital PI current control algorithm is applied to maintain the current phase angle and improve performance with changing atmospheric conditions. Inverter control based on mathematical model of photovoltaic inverter and a simulation using Matlab was explained by Cao, Neng, Ya Jun Cao, and Jiao Yu Liu (2013). An improved MPPT with better performance based on voltage-oriented control is proposed irrespective of its irradiation variations verified using PV array emulator, results demonstrate that the proposed method provides effective tracking given by Tsengenes, Georgios, and Georgios Adamidis (2011); Kadri, Riad, Jean-Paul Gaubert, and Gerard Champenois (2010). A brief description on Voltage oriented control scheme was given by Peltoniemi Pasi (2009); Zhao T, Zong Q, Zhang T and Xu Y (2016); Espinoza-Trejo DR (2014) described the controller equations and system equations and then the controllers are simplified and their performances are studied. In addition, the system is validated through experimental results, and closed-loop performance is evaluated under different irradiance and set-point changes.

This research work focuses on performance on-grid PV power system to extract the maximum power from the solar panels during the variation of solar irradiance. In this paper Section I brief out the PV system configuration and various techniques applied to enhance the performance and efficiency of the system. Section II focuses on novel modelling of PV array using current source, diode, shunt and series resistance. It explains about the electrical characteristics, V-I and P-V characteristics of PV system under varying solar irradiation. Section III explains on study of Incremental conductance MPPT technique, variation of duty cycle with respect to irradiance and simulation using Matlab. The detailed modelling and working of DC-DC converter in on and off states and its parameter calculations are explained under Section IV. Voltage oriented control strategy applied to DC/AC inverter is explained in Section V and its various stages of operation like Phase Locked Loop (PLL), abc-dq transformation, Current control technique and DC link voltage control are explained. Simulation results of all sections are discussed under Section VI. The simulation results have proven the effectiveness of the MPPT technique in extraction the maximum power from power system during variation of the environmental conditions. Finally, in Section VII, the conclusions of research work are discussed.

## II. System Configuration

The system configuration of the studied PV power system is depicted in Fig. 2. The power system consisting of PV station of 100kW rating integrated through main point of common coupling (PCC) bus bar to inject the generated power and enhance the system performance. In this research work SunPower SPR305E NHTP 305W solar panel was taken for analysis and simulation results were compared with the data sheet. The PV station consists of many PV panels electrically connected in parallel-series combinations to achieve the desired power capacity. Number of series, parallel strings connected are 5 and 66 respectively to form 250V PV array. The incremental conductance MPPT technique is implemented to extract maximum power from PV station under variation of the solar irradiance and temperature. In order to step up the voltage from 250V to 575V the PV station is equipped with the DC/DC boost converter. Then the DC power is fed into 3 phase Voltage source inverters coupled with voltage-oriented control technique to convert DC into AC. Then inverter is interconnected with the PCC-bus through 575 V/100 KV Δ/Y transformer. The power system is controlled to operate at unity power factor, and the injected active power is transmitted to the electrical grid. And on other side electrical utility grid of 120kV is step down to 100 kV and connected to bus bar through 30km transmission line.

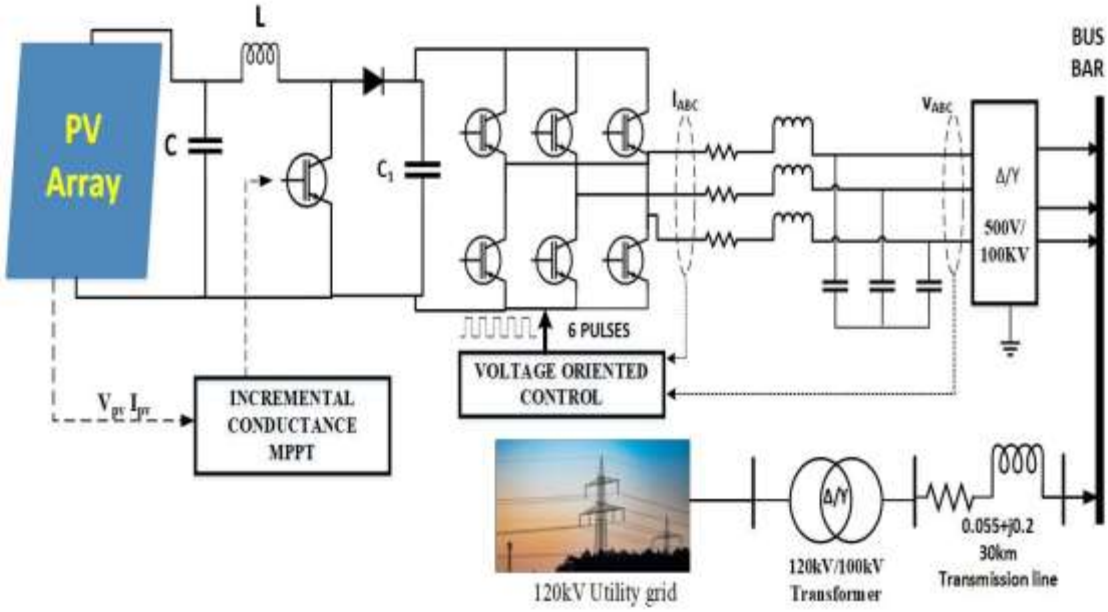


**Fig. 2 System configuration of PV power system**

## III. Photovoltaic conversion system model

In this section, the electrical modeling of PV system and its characteristics are explained briefly. The PV station consists of 66 parallel strings and 5 series strings interconnected to obtain 250V. The electrical modelling of PV array has been introduced based on the Shockley diode as shown in Fig. 3.

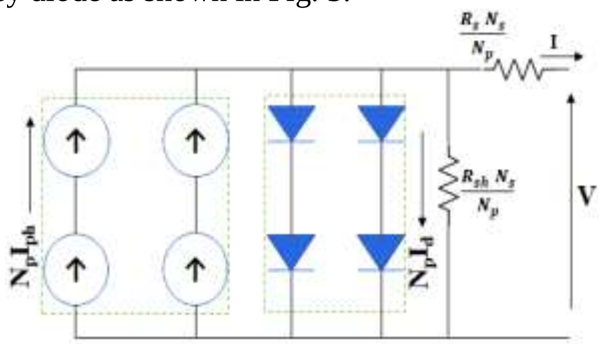


**Fig. 3 Diode model of PV array**

Mathematical equation of PV cell given in equation (1) to determine its P-V and I-V characteristics and its variations with irradiance and temperature are shown in Fig 4a and 4b respectively.

$$I = N_p I_{ph} - N_p I_s \left( e^{\frac{q\left(\frac{V}{N_s} + \frac{R_s I}{N_p}\right)}{KTA}} - 1 \right) - \left[ \frac{\frac{N_p V}{N_s} + R_s I}{R_{sh}} \right] \quad (1)$$

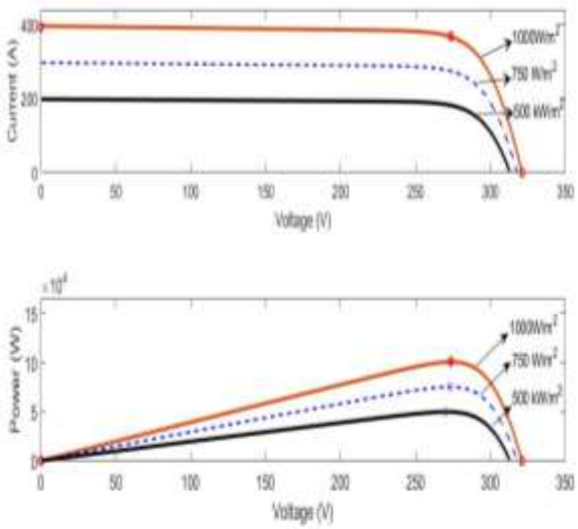

**Fig 4a. Current and Power characteristics with dependence on irradiance**

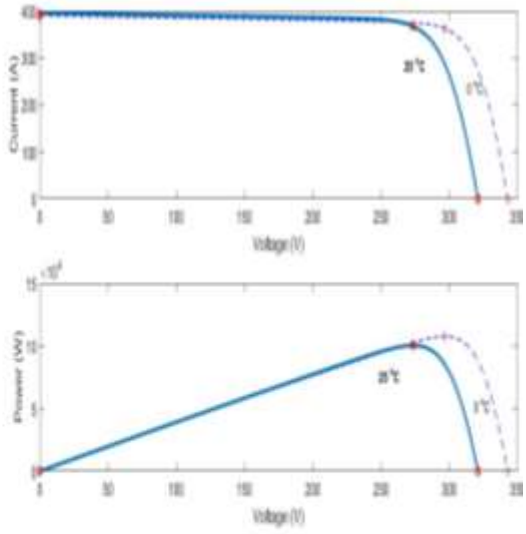

**Fig 4b. Current and Power characteristics with dependence on temperature**

The current-voltage (I-V) relationship of PV array is given in equation (2), Photocurrent $I_{ph}$ is the electric current through photodiode, as the result of exposure to radiant power is given in equation (3) and current $I_s$ passing through the shunt resistance is given in equation (4). The current flowing through the diode is explained using Schottky diode equation given in equation (5).

$$I = N_p I_{ph} - N_p I_s \left( e^{\frac{q\left(\frac{V}{N_s}+\frac{R_s I}{N_p}\right)}{KTA}} - 1 \right) - \left[ \frac{\frac{N_p V}{N_s} + R_s I}{R_{sh}} \right] \quad (2)$$

$$I = I_{ph} = \frac{G}{1000}[I_{sc} + K_i(T\text{-}T_{ref})] \quad (3)$$

$$I_S = I_{rs} \left( \frac{T}{T_{ref}} \right)^3 e^{\frac{qE_g}{KA}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}. \quad (4)$$

$$I_{diode} = I_o - [\exp\left[\frac{qV}{\propto kT}\right] - 1] \quad (5)$$

A Matlab based simulation study on PV array is carried out. The simulation model makes use of above circuit equation of PV solar cell based on its diode behaviour, effect of irradiance and temperature and taking into consideration of I-V and P-V characteristics. In this paper SunPower SPR305E NHTP 305W solar panel was taken for analysis and simulation results were compared with the data sheet. Simulated P-V and I-V characteristics are coinciding with the manufactures data sheet. Some of the electrical data's taken from sheet are tabulated in Table 1

**Table 1 PV array specifications**

| | | |
|---|---|---|
| Peak power | $P_{max}$ | 305 W |
| Rated voltage | $V_{mpp}$ | 54.7 V |
| Rated current | $I_{mpp}$ | 5.58 A |
| Open circuit voltage | $V_{oc}$ | 64.2 V |
| Short circuit current | $I_{sc}$ | 5.96 A |
| Maximum system voltage | $V_{max}$ | 600 V |

## IV. MPPT for photovoltaic system

As the intensity of the solar radiation varies with time, MPPT is essential to extract the maximum output power from PV array. The MPPT is to regulate the boost converter controller, in order to operate the PV array works at the maximum power point.

The algorithm is developed to as per the flow chart as shown in Fig. 5, that is the incremental conductance MPPT technique. The corresponding simulation block diagram is developed and its corresponding MATLAB / Simulink model is shown in Fig. 6.This strategy of incremental conductance is to find the slope of the power $P_{pv}$ vs $V_{pv}$ of the solar array is equal to zero that is $\frac{dP_{pv}}{dV_{pv}}=0$. The $\frac{dP_{pv}}{dV_{pv}}$ is positive and negative at the left side and the right side of the MPPT of the IV characteristics of the solar cell respectively. The mathematical model of incremental conductance MPPT technique can be expressed as below: The output power from PV array: $P_{pv}=V_{pv}I_{pv}$ the derivative of $P_{pv}$ is written as

$$\frac{dP_{pv}}{dV_{pv}}=\frac{d}{dV_{pv}}[V_{pv}I_{pv}]=I_{pv}+V_{pv}\frac{dI_{pv}}{dV_{pv}}$$

if $\frac{dP_{pv}}{dV_{pv}}=0$, then equation becomes $\frac{dI_{pv}}{dV_{pv}}=-\frac{I_{pv}}{V_{pv}}$ at MPP and $\Delta V_n=0$.

$\frac{dI_{pv}}{dV_{pv}}>-\frac{I_{pv}}{V_{pv}}$ at the left of $V_{pv}$,

$\frac{dI_{pv}}{dV_{pv}}<-\frac{I_{pv}}{V_{pv}}$ at the right of $V_{pv}$.

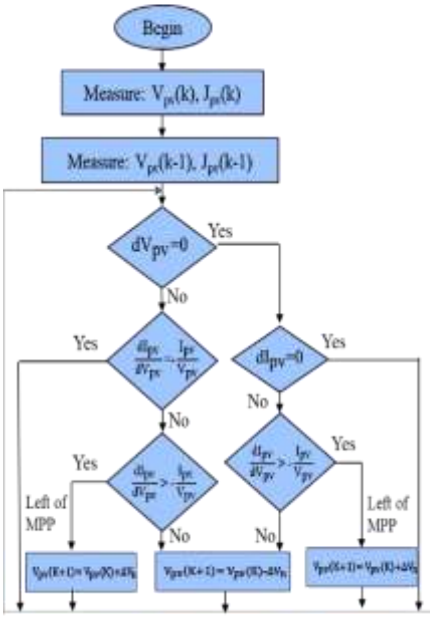


**Fig 5. Flow chart of INC-MPPT**

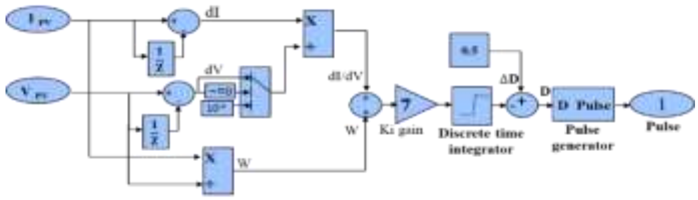


**Fig 6. Simulink Block diagram of INC-MPPT**

## V. Modelling of DC-DC converter

In this paper boost converter is used in reducing the output voltage ripples from the panel, step up the voltage and maintain the power rating for the load. The boost converter is shown in Fig 7 in which it has IGBT switch coupled with MPPT tracker for voltage control in the circuit by varying duty cycle ratio.

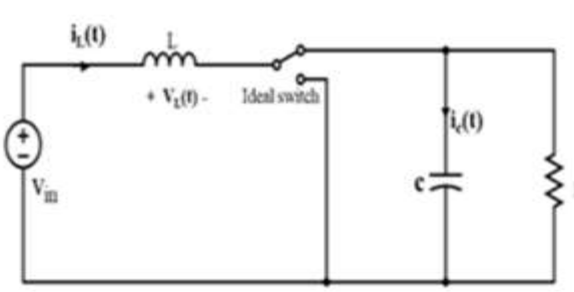


**Fig 7 DC-DC Boost converter**

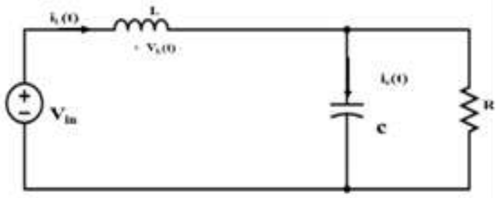


**Fig. 8a. Switch at Position1**

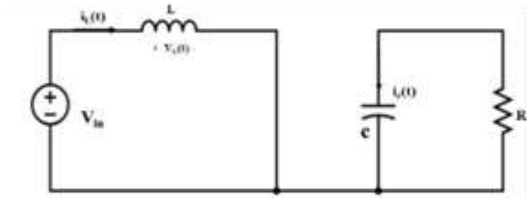


**Fig. 8b. Switch at Position 2**

When switch is at position 1, the right side of inductor is ground, results in Fig 8a. The inductor voltage and capacitor current are given at equation 6 and 7 respectively.

$$V_L = V_R \qquad (6)$$

$$i_C = -{}^{V}/_{R} \qquad (7)$$

When the switch is at position 2, inductor is connected to output leads to Fig 8b. The inductor voltage and capacitance current are equation 8 and 9 respectively.

$$V{=}V_R{+}V_L \qquad (8)$$

$$i_C = -{}^{V}/_{R} \qquad (9)$$

The voltage conversion ratio is ratio of output voltage to input voltage of boost converter is given in equation (10).

$$D' = \frac{1}{1-D} \qquad (10)$$

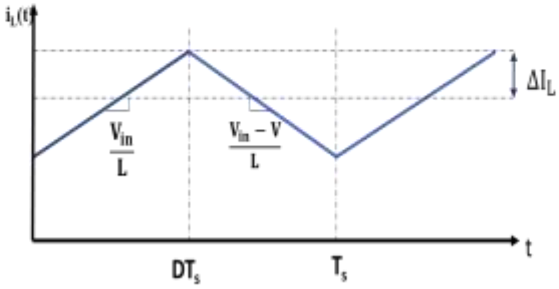


**Fig 9 Inductor current waveform**

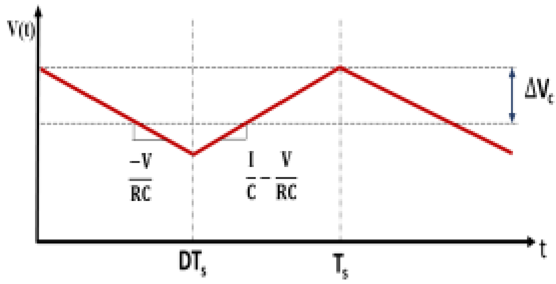


**Fig 10 Capacitor voltage waveform**

As shown in Fig 9 during the first sub interval, with switch at position 1, the slope of inductor current is given by

$$\frac{dI_L}{dt} = \frac{v_L(t)}{L} = \frac{v_{in}}{L}.$$

When switch is in down, the slope of inductor current waveform is

$$\frac{dI_L}{dt} = \frac{V_{in}-V}{L}.$$

And finally, expression (11) can be used to select the inductor value L.

$$\Delta i_L = \frac{V_{in}}{2L} DT_s \qquad (11)$$

With expression of $\Delta V$ the capacitor voltage can be determined. During the first interval and second interval slope of capacitor voltage waveform shown in Fig 10 is

$$\frac{dV_c}{dt} = \frac{-V}{RC}$$

and it becomes

$$\frac{dV_c}{dt} = \frac{I}{C} - \frac{V}{RC}.$$

Then finally voltage ripple is calculated using equation (12). This expression can be used to select the capacitor value to obtain given output voltage ripple peak magnitude $\Delta V$.

$$\Delta V = \frac{V}{RC} DT_s \quad (12)$$

## VI. DC/AC Inverter Controller

A 3-level, 3-phase DC/AC inverter is used to integrate the PV with the electrical grid. Fig. 11 describes the control scheme for DC/AC inverter. Voltage oriented control strategy (VOC) is incorporated to regulate the $V_{dc1}$, control injected active power is fed to the electrical grid, and achieve the demanded reactive power. This strategy can give a constant DC-Link voltage between RSC and GSC, it is fast dynamics and decoupled control ability in the PV system. The mathematical equations are written as below.

$$V_{abc} = V_{abc\_inv} - R_f I_{abc\_inc} - L_f \frac{dI_{abc\_inv}}{dt},$$

$$V_{d\_inv} = V_d + R_f I_d + L_f \frac{dI_d}{dt} - \omega L_f I_q, \text{ and}$$

$$V_{q\_inv} = V_q + R_f I_q + L_f \frac{dI_q}{dt} - \omega L_f I_d$$

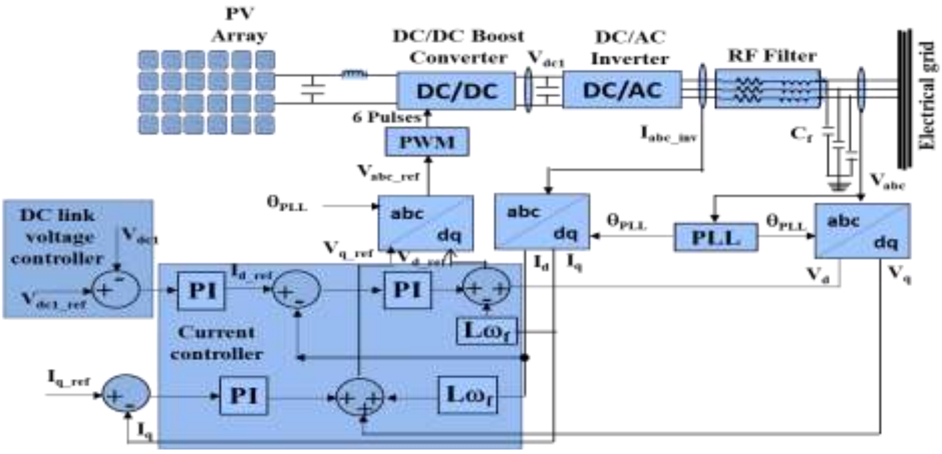


**Fig 11. Block diagram of Voltage control scheme**

### a) Phase Locked Loop

A closed loop frequency control technique for phase locked loop in PV system is employed to estimate the grid voltage angle ($\theta_{PLL}$) for abc to dq transformation and synchronize output voltage from the inverter with the grid current and voltage. The block diagram of PLL is as shown in figure 12. The grid voltage is converted into the synchronous voltages $V_d$, and $V_q$. The difference between the $V_{q^*}$ and $V_q$ as error (ε) is passed through PI-controller. Then the output of the PI controller is compared with nominal frequency (ω) and the output is integrated to obtain the $\theta_{PLL}$.

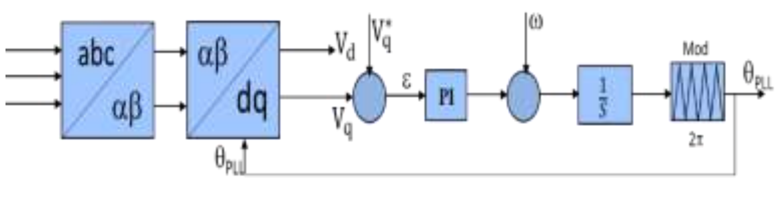


**Fig 12 Block diagram of PLL**

### b) DC-Link Voltage Controller

The $V_{dc1}$ (DC link voltage controller) is responsible for voltage regulation at constant specified value. The reference DC-link voltage ($V_{dc1\text{-}ref}$) is compared with an actual value ($V_{dc1}$) and the error (ε) is applied to PI-controller to regulate the DC-link voltage at 250 V / 500 V. The output of this controller is used as direct axis of reference current ($I_d^*$ or $I_{d\text{-}ref}$) for the inner current controller. The DC-link voltage can be written as follows:

$$V_{dc\,1}=2\sqrt{\frac{2}{3}}V_{abc;\,LL,\,rms}=2V_{peak,\,ph}$$

### c) Current Controller

This current controller is to control $I_d$ independently to regulate the $V_{dc\,1}$, and the $I_q$ is to control the injected reactive power (Q). The current controller employs independently the $I_{d\text{-}ref}$ which is generated from DC-link voltage controller to regulate DC-link voltage, and the $I_{q\text{-}ref}$ is imposed to zero for keeping the power of PCC-bus at unity power factor. Since the $V_d$ is aligned with grid voltage vector, thus the $V_q = 0$. Therefore, the active power (P) and reactive power (Q) can be controlled independently by $I_d$ and $I_q$ respectively. Then,

$$P=\frac{3}{2}\left(V_q I_q+V_d I_d\right)=\frac{3}{2}V_d I_d$$

$$Q=\frac{3}{2}\left(V_q I_d\text{-}V_d I_q\right)=\frac{3}{2}V_d I_q$$

## VII. Simulation results and discussion

The performance of grid connected PV power system under varying solar irradiance and constant temperature are analysed and simulated using Matlab software as follows. The temperature of PV array surface is considered to be at 25°C during the complete simulation time and the solar irradiances given are 500 W/m$^2$ and 1000 W/m$^2$ and, this is due to the change of solar irradiation during a cloudy day and the bright sunny day as shown in Fig 13 and 14. During gradual change of irradiance from 500 to 800 W/m$^2$ the PV panel voltage output also remains constant, when there is a sudden change of irradiation from 800 to 1000 W/m$^2$ there forms small voltage sag as shown in Fig 15. Unlike PV voltage, the PV current changes according to the irradiance. PV panel produces the maximum current when its irradiance is 1000 W/m$^2$ as shown in Fig 16. When the irradiance changes from 500 to 1000 W/m$^2$, the MPPT controller increases the array output voltage from 254.8 V to 273.5 V in order to detect the maximum power from the PV array. Similarly, the output current of the PV array increases from 200 A to 367.7 A. The derivative of power with respect to the voltage produced ($\frac{dP_{pv}}{dV_{pv}}=0$) in the PV array is zero. Hence the maximum power point during variation of the solar irradiance is exactly tracking and duty cycle ratio is given in Fig 17. Voltage across the DC link capacitor is obtained from the simulation results of PV system modelled as shown in Fig.18. In this DC link voltage is attained 500 V within 0.1 s, it experiences a small voltage swell during sudden irradiance change and hence it remains constant throughout the operation. Fig 19 shows the reference and actual d-axis current are superimpose with each other, whereas q axis remains are maintained at zero level. In the Fig 20 it is evident that that the active power reaches the maximum value (100 kW) when the irradiance reaches 1000 W/m$^2$ till it is nearly 50 kW and increases gradually with increase in irradiance. The injected voltage ($V_a$) and injected current ($I_a$) are in phase with each other as shown in Fig.21. At starting the power factor of the inverter becomes leading and after few seconds it becomes unity, then it is maintained throughout the simulation as shown in Fig.22. Since the output quality of VSC control is good it is injected into the bus bar. At the point of common coupling, voltage and current from the PV station and power station are synchronized it is shown in Fig 23. This well-regulated power is supplied to the end users.

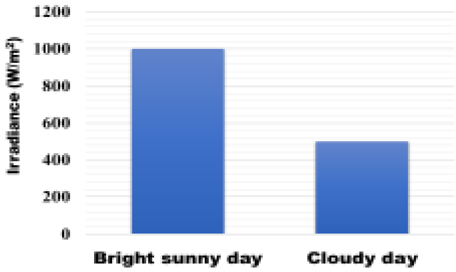


Fig 13. Solar irradiance (W/m$^2$)

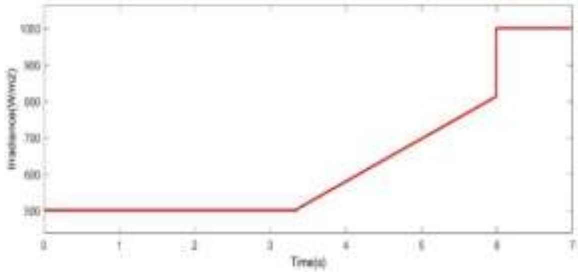

Fig 14. Irradiance input to PV system

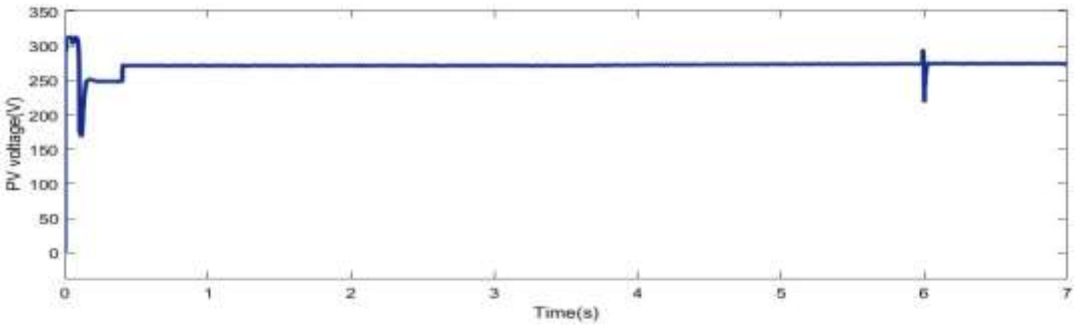


Fig 15. PV system voltage

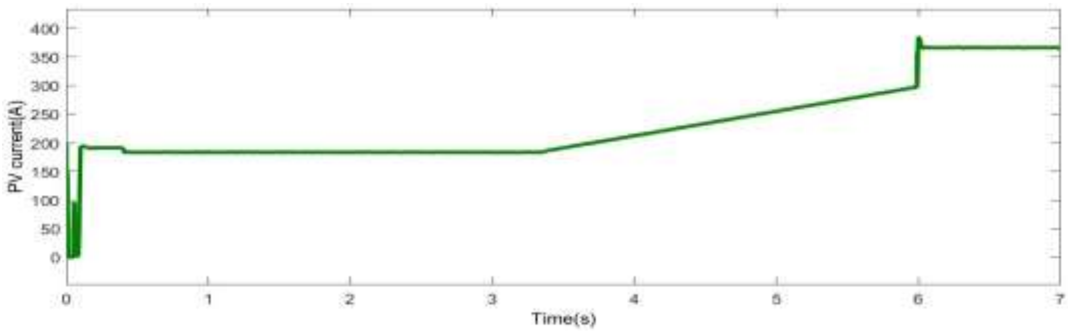


Fig 16. PV system current

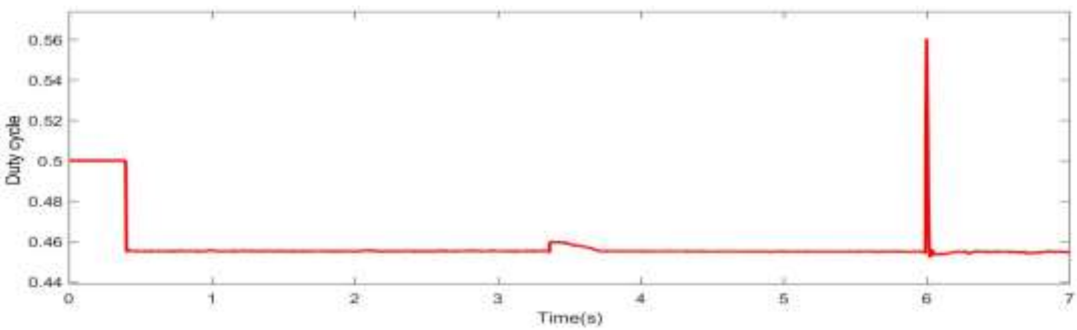


Fig 17. Duty cycle

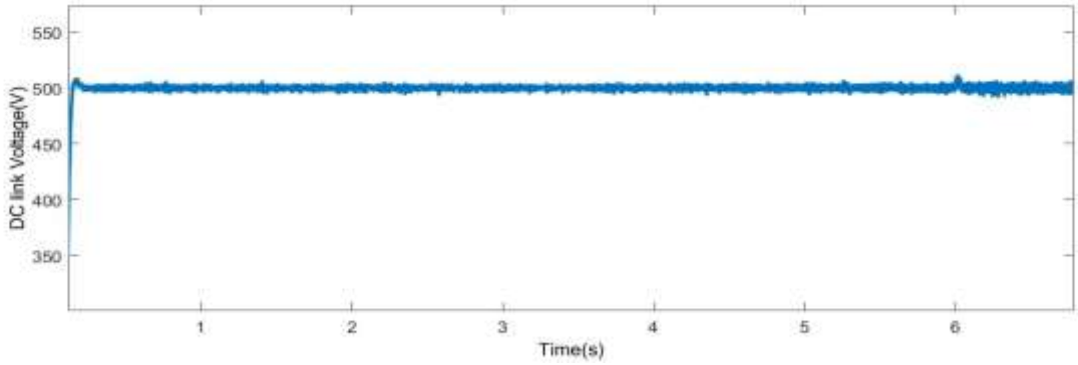


Fig 18. DC link voltage

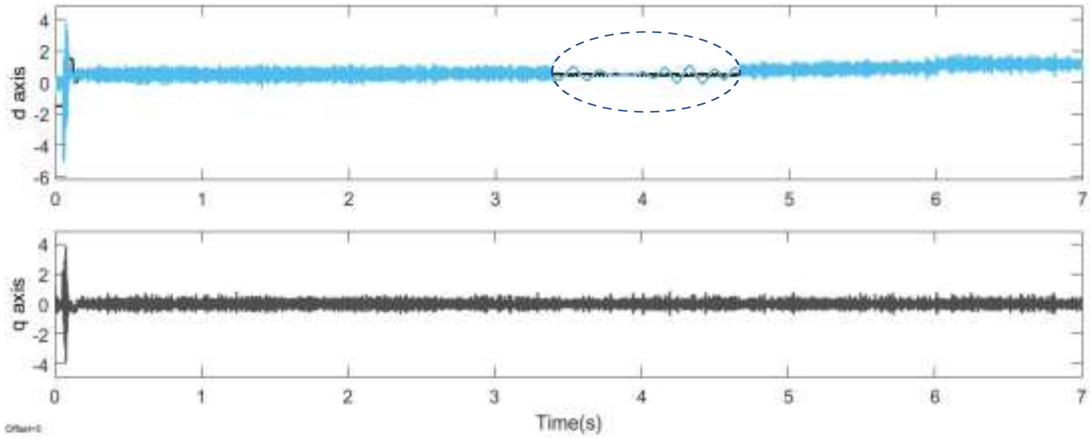


Fig 19. d-q axis components of PV current

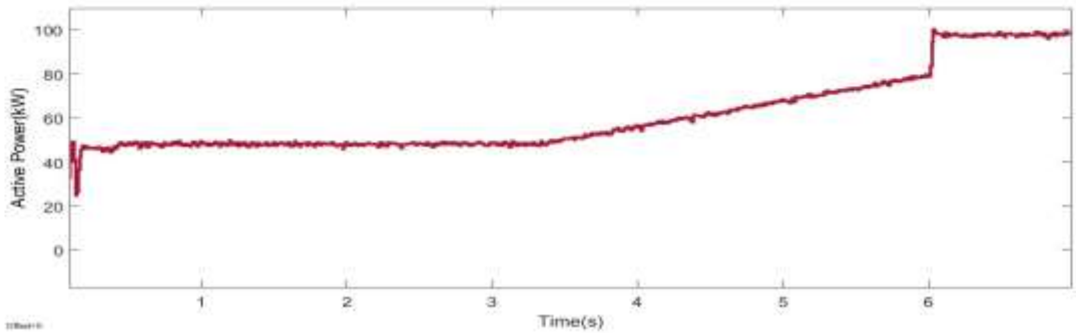


Fig 20. Injected Active Power

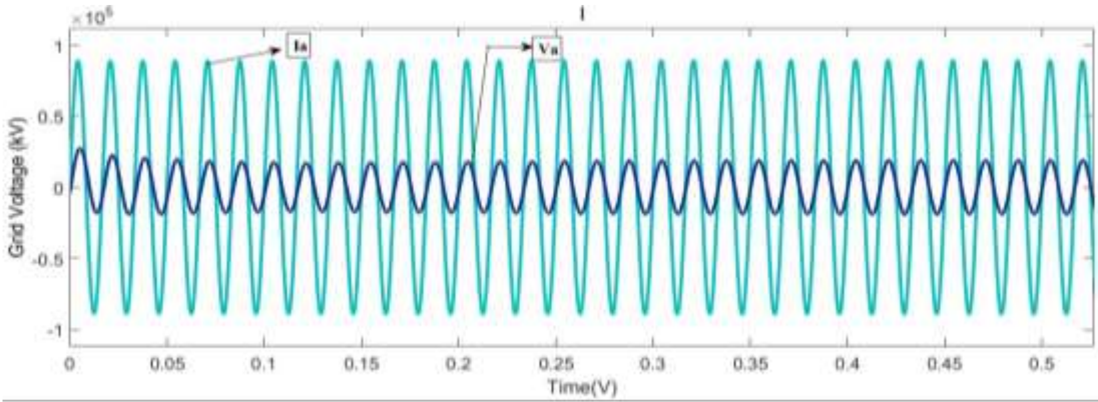


Fig 21 Grid voltage and current from PV system

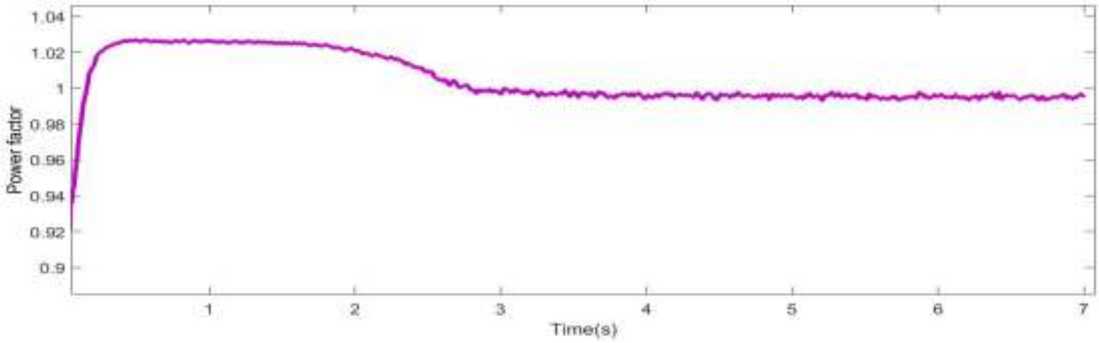


**Fig 22. Power factor of inverter**

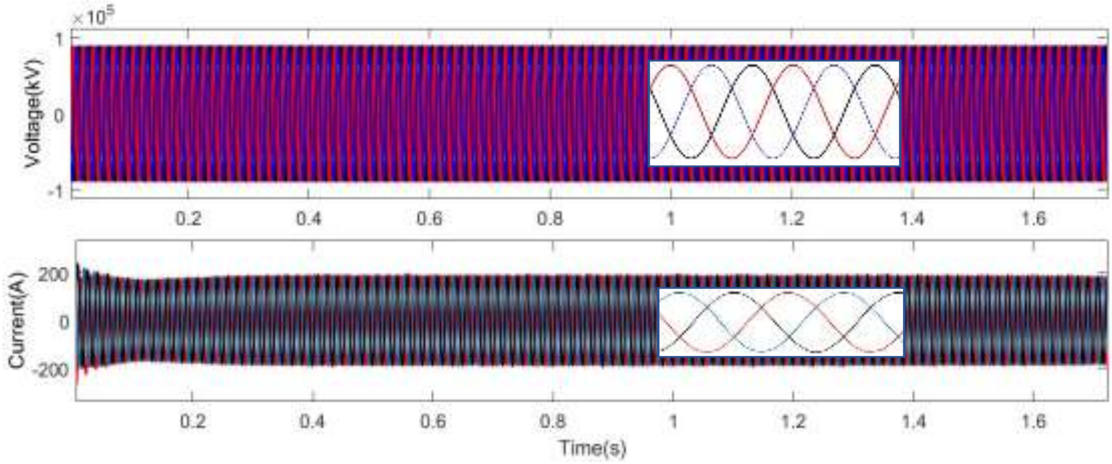


**Fig 23. Voltage and current at PCC**

## VIII. Conclusion

In this paper a detailed investigation is made on dynamic modelling, design and control strategy of a grid connected PV power system. The PV station is of 0.1 MW rating integrated with the 120 kV utility grid through point of common coupling and active power and other electrical ratings are measured at the bus bar. Modelling of PV array is used to analyses VI and PV characteristics of PV array, which helps in designing the parameter values of DC-DC converter. And further mathematical model of PV array and converter are completely studied and designed. The simulation results have proven the validity of the INC MPPT technique in extraction of maximum power from PV and properly maintains its duty cycle ratio fed to converter array during variation of irradiance. Furthermore, the control strategy successfully maintains distortion less grid voltage and maintains unity power factor irrespective of variations in environmental condition.

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