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Simulation and performance analysis grid interfaced solar photovoltaic system

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Abstract: Solar photovoltaic (SPV) system offers an alternative to the conventional system of electricity generation. It helps to meet out the increasing energy demand nonetheless it limits the pollution as it is clean, green and emission free. It has been finding more attention of industries and academia in recent year. This paper presents a simulation study of the grid-connected solar PV system to evaluate the performance of the system in the different insolation. In this paper, the components of the SPV grid connected system are described. The study shows the behavior of the SPV system for different insolation and the bi-directional power flow capability through the grid as well. The performance analysis may be helpful for researcher of this field.
Keywords: Solar PV (SPV) system, Grid connected, Bi-directional, DC-DC converter, InC MPPT.

I. INTRODUCTION

There are many Renewable Energy Sources (RES): wind, solar, geo-thermal, ocean-thermal, bio-mass, tidal and hydro, but in India majorly solar, wind, bio-power and small hydro are contributing for the total power generation as RES. Among all RES, solar power systems and wind power systems are the affable key for electrification. Solar energy is the energy that received from the sun and very important to maintain life on earth. From several decades solar energy has been considered as an enormous source of energy and also an inexpensive source of energy, because it is freely offered by nature. As the solar energy is unlimited in nature, they turn out to be most encouraging renewable power sources. Solar power in India is a fast developing industry (India was ranked 5th in solar power). India's solar installed capacity reached 20 GW in February 2018. The 20 GW capacities were initially targeted for 2022, but the India reached the goal four years ahead of plan [1]-[2]. Wind energy is also a prime source of energy in India (India was ranked 4th in wind power), but due to ease in installation (it is very fast growing) solar is more popular.

All-pervading and plentiful accessibility of solar energy has a terrific potential to make a momentous role to the world's energy needs. Two ways to extort the solar energy are solar thermal plants and solar cells i.e. photovoltaic (PV) cells. In existing renewable energy projects the PV cell is on the foremost edge as the capable future energy technology alternative [3]. The direct conversion of solar radiation into electrical energy by PV cells has several important advantages. On the other hand its proficient extraction demands exploit of some momentous confronts such as energy instability, massive investment low energy conversion efficiency of module, and energy price [4]-[8]. Reducing energy cost of PV structure is an immense concern since maintenance necessity is very low and the only real cost savings to be made is in efficiency development. The latest literature reveals that research efforts goal to boost the power output of the module in provisions of Maximum Power Point Tracking (MPPT) technique.

II. TOPOLOGIES FOR SPV GRID INTERFACE

The grid connected topologies may be single stage, two stage or multi stage conversion as shown in figure 1. In single power stage grid connected topology figure 1 (a) only one DC-AC converter is there, in this case optimum use of PV generated power is not done as the MPPT is not present. In two stages topology there is intermediate stage between PV and DC-AC converter that is DC-DC converter stage along with the MPPT. Two stage grid connected configuration figure 1 (b) is more realistic as the optimum use of produced power is possible. In multistage configuration figure 1 (c) there is one more stage between DC-DC converter and DC-AC converter known as DC-DC conversion stage with galvanic isolation job of this DC-DC cont. The multistage configuration has drawbacks such as higher component count, higher cost and large size.

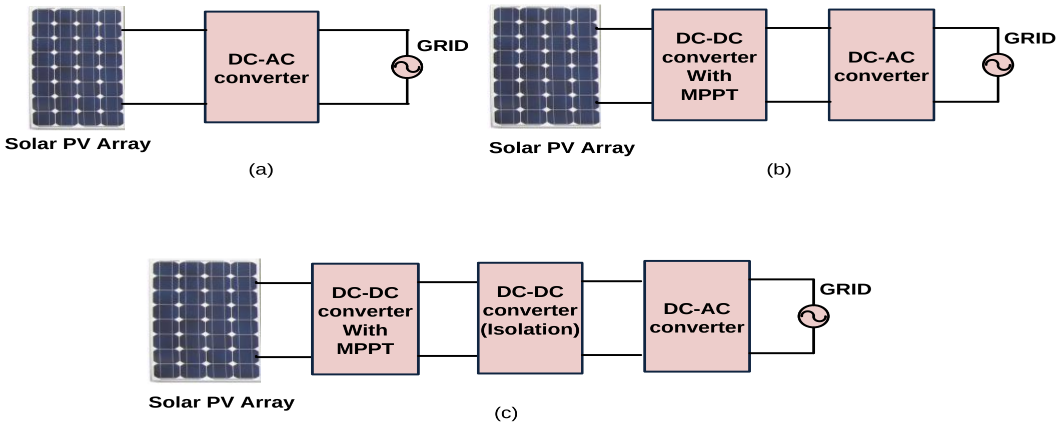

Figure 1 *Block diagram representation of grid interfaced PV system*

In this paper two stages configuration is analyzed. A SPV power generation system consists of numerous components like cells, electrical connections and BOS to regulating and/or changing the electrical outputs [9]-[12]. The BOS consist of a DC- DC (Boost) converter with Incremental Conductance (InC) MPPT, DC-AC (3-phase VSI) converter and an LC (passive) filter. The SPV system is rated in peak watts (Wp) which is an amount of electrical power that a SPV system can deliver at Standard Test Conditions (STC).

III. PROPOSED WORK

The aim of this work is to analyses the behavior of grid when solar is interfaced with it. As studied, that grid interfaced system is used with or without battery storage. As we know the storage of large power is very costly due to cost of batteries its maintenance and control. Hence when SPV generation is feeding the local load, and interfaced with grid then in the absence of solar radiance there is grid to feed the required power to local load. Here in this paper grid interfaced SPV generation is analyzed with the bi-directional behavior of grid. When there is surplus power in SPV generation it feed to grid and in absence of solar power grid feeds the SPV's local load. The block diagram of proposed system is shown in the figure 2.

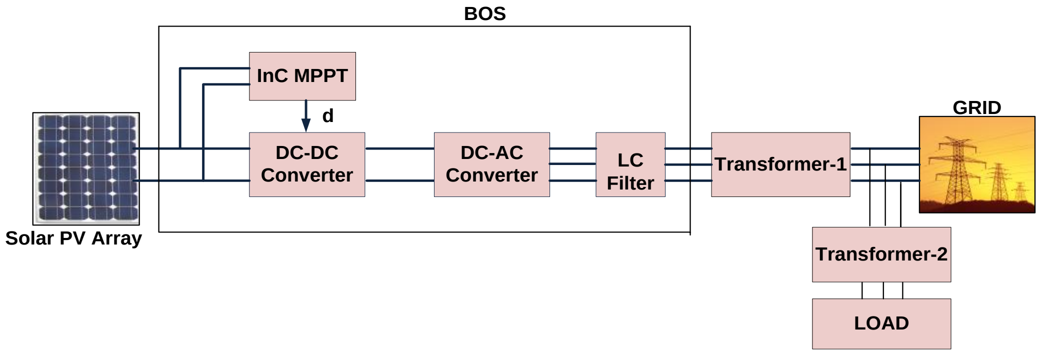

Figure 2 *Block diagram of proposed system*

IV. MODELLING OF SOLAR PV GENERATION SYSTEM

The **solar PV system** cell/module/array, manufacturing process and material used is discussed [6]. Solar PV V-I and P-V characteristics are explained [7]-[8]. The photovoltaic (PV) cell is on the leading edge as the promising future energy technology option. The direct conversion of solar radiation to electrical energy by PV cells has a number of significant advantages and has some significant challenges such as energy fluctuation, huge investment low energy conversion efficiency of module, and energy cost. A solar PV system required several components other than PV generation unit or PV array, these components are referred as *Power Condition Unit (BOS)* / *Balance of System (BOS)* [9]-[12] that includes DC-DC converters, maximum power point tracker (MPPT), DC-AC converters or inverters, peripheries / mountings and different control and protection circuits.

Figure 3 gives the modelling of solar cell with single diode model [7]-[8]; equation (1) governs the characteristics of a solar PV cell which behaves more like a current source.

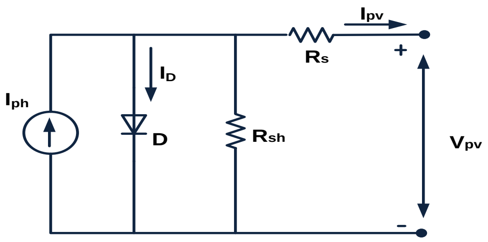

Figure 3 *Electrical equivalent circuit of a solar PV cell*

$$I_{pv} = I_{ph} - I_s \left[\exp\left\{\frac{V_{pv} + I_{pv}\ R_s}{N \times V_T}\right\} - 1\right] - \frac{V_{pv} + I_{pv}\ R_s}{R_{sh}} \quad (1)$$

I_{ph} is the solar induced or photon generated current and is proportional to the light input: $I_{ph} = I_{ph0}\frac{I_r}{I_{r0}}$

I_r is the irradiance (light intensity or insolation) in W/m^2 falling on the cell.
I_{ph0} is the measured solar-generated current for the standard irradiance I_{r0}.
I_s is the saturation current of the diode.
V_T is the thermal voltage,
V_T =kT/q where:
k is the Boltzmann constant.
T is the solar cell operating temperature.
q is the elementary charge on an electron.
N is the quality factor (diode emission coefficient) of the diode.
V_{PV} is the voltage across the solar cell's electrical ports.
R_S is series and R_{SH} is shunt resstance.

Figure 4 gives general I-V and P-V characteristics of a solar cell corresponding to the equation (1). A single PV cell generates DC potential in the range of 0.5 to 1 volts with small power output less than 2 W at STC (*STC: 1000 W/m2, 25 °C*).

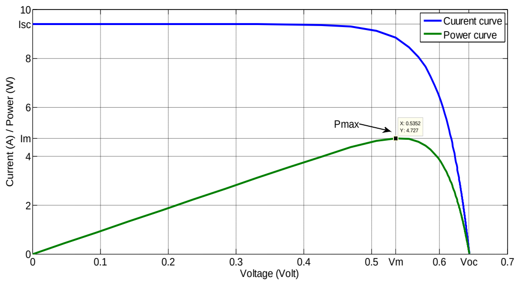

Figure 4 *Solar cell I-V and P-V characteristics*

The general nonlinear I-V characteristic and P-V characteristic of a PV module is observed in figure 4, where I_{sc} is the short circuit current of the solar module, V_{oc} is the open circuit voltage of the solar module, I_m is the current at which module delivers maximum power and V_m is the terminal voltage of solar module at which module deliver maximum power. Solar cell PV & VI characteristics are rely upon the weather condition so that a circuitry called MPPT is required to get maximum output from solar module. Some of the key aspects of the MPPT are:

- Maximum power can be transferred only at a specific terminal voltage for a given environmental condition known as maximum power point (MPP).
- MPP also changes with change in environmental conditions such as insolation temperature.
- MPP occurs normally at 70-80% of the open circuit voltage.
- Rate of change of power with respect to voltage (dP/dV) or current (dP/dI) becomes zero at MPP.

The **InC method** is preferred in this paper, as choice of the MPPT algorithm due to complexity of time taken by the algorithm to track the MPP, the implementation cost, ease of implementation and oscillation around the MPP [13]-[14]. InC method is based on the fact that slop of the PV array power curve is zero at the MPP (P_{max}), This can be expressed as follows:

$$Power: \quad P = V \times I$$

$$\frac{dP}{dV} = I + V\frac{dI}{dV}$$

At true MPPT $\frac{dP}{dV} = 0$

$$I + V\frac{dI}{dV} = 0$$

$$\frac{dI}{dV} = -\frac{I}{V} \quad (2)$$

Where dI/dV : Incremental conductance,
I/V : Instantaneous conductance.

Equation no. 2 indicates that MPP can be found by comparing instantaneous to the incremental conductance. The operation of this method can be divided in three zones as shown in table 1. The flow chart of the method is given in figure 5.

Table 1 Methodology of InC Method

Before MPP	After MPP	At MPP
$\frac{dP}{dV} > 0 \;\; or \;\; \frac{dI}{dV} + \frac{I}{V} > 0$	$\frac{dP}{dV} < 0 \;\; or \;\; \frac{dI}{dV} + \frac{I}{V} < 0$	$\frac{dP}{dV} = 0 \;\; or \;\; \frac{dI}{dV} + \frac{I}{V} = 0$

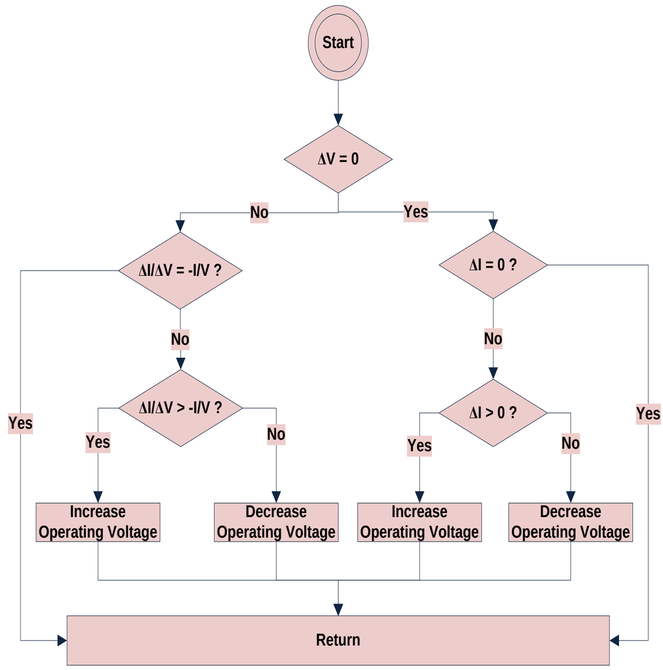

Figure 5 *Flowchart of InC method*

The **Boost Converter** output voltage is greater than applied input voltage and conversely the output current is lower than the value of input current. The circuit diagram of boost converter shown in figure 6.

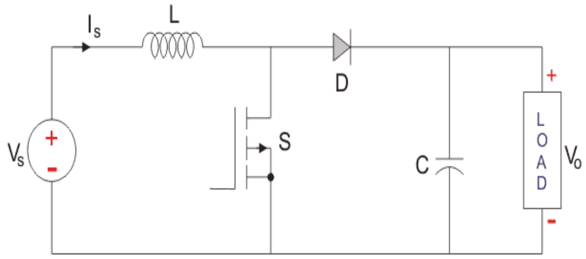

Figure 6 *Boost Converter*

Expression of the equations relating input and output voltage and current values of boost converters are given below:

$$V_o = \frac{V_S}{(1-d)} \quad (3)$$

Where d = duty cycle. Assuming lossless converter:

$$P_o = P_S \quad (4)$$

$$V_o I_o = V_S I_S \quad (5)$$

$$\frac{V_o}{V_S} = \frac{I_S}{I_o} = \frac{1}{(1-d)} \quad (6)$$

By knowing the values of V_S in and I_S, we can find out the value of input resistance of the converter:

$$R_S = \frac{V_S}{I_S} = \frac{[V_o\ (1-d)]}{[I_o\ (1-d)]} = \frac{R_o}{(1-d)^2} \quad (7)$$

From above expression of R_S, it is concluded that the Boost converter cannot be used for the values of input impedance greater than the value of load impedance.

A **VSI** is a power electronics device consists of a DC source and power electronic switches. It converts DC voltage into an AC voltage and can be two or multi level. In this system a 3-phase, 3-level neutral point clamped (NPC) multilevel inverter is employed. Generally, pulse-width modulation (PWM) is used for pulse generation in VSI. The VSI control method compensates for the active and reactive power and harmonic currents of linear and nonlinear loads by setting an appropriate reference of control loop. The control strategy for the integration of renewable energy sources to the utility grid has been proposed in [15]-[17]. A three-level NPC MLI is implemented in this paper as the interfacing system between Solar PV (SPV) generation system and AC grid. The NPC MLI converts the DC link voltage to AC and keeps unity power factor. The system is modeled in synchronous rotating d-q frame with a decoupled control strategy for reducing the control complexity. This control strategy control achieves faster tracking. The VSI control system as shown in figure 7 uses two control loops: DC voltage control (external) loop and current control (internal) loop. The PLL detects the amplitude and the position of the grid voltage vector [15]-[21]. This plays an important role in making inverter output and grid angles equal [19]-[21].

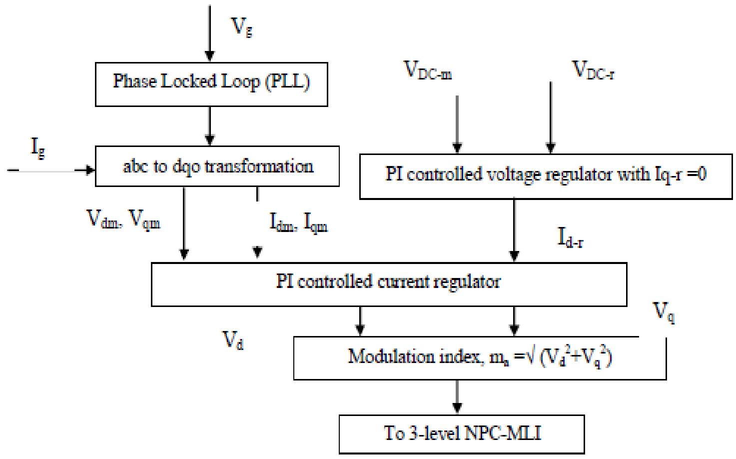

Figure 7 *Inverter control strategy of grid connected system*

V. SIMULATION RESULTS AND DISCUSSION

In this proposed system has a solar PV generation system of 97 kW and voltage output is 375V DC, this fed to the boost converter (operated with 5 kHz switching frequency). The duty cycle of boost converter is controlled by InC MPPT technique. Boost converter output is fed to the 3-phase, 3-level VSI, and the switching pulses for inverter is controlled by PI controller. The output voltage of VSI is 500V which is filtered through a passive filter to reduce its harmonic contents. The AC output then stepped up into 11kV using transformer and fed to grid. Modeling of solar PV array is done by adopting following parameters shown in Table 2.

In this paper grid interfaced solar PV generation system with domestic/commercial load is analyzed in two parts:

- Unidirectional power flow
- Bidirectional power flow

Table 2 Specifications of Solar PV Generation System

S. No.	System Parameter	Rating/Values
1	No. of parallel string	40
2	No. of series connected modules per string	10

3	Module specification under STC [Voc, Isc, V_M, I_M]	37.5V, 8.56A, 30.5V, 7.97A
4	Model parameter for module [Rsh, Rs, Is, Iph, N]	184.8015Ω, 0.30721Ω, 1.8459e-10A, 8.5742A, 0.99139
5	Maximum power of array P_{Max}	97 kW

.

- **Unidirectional Power Flow**

In grid interactive solar PV generation system, power is supplied to the 3-pahse resistive-inductive (R-L) load at 400kV and surplus power is feed to the grid at 11kV via step down/up transformer respectively. As already SPV system performance with varying insolation is studied in various literatures and the tracking of MPP by system is observed, here with constant insolation is taken to evaluate the performance with grid as well as load. Irradiance is shown in figure 8. The resultant change in duty cycle is observed in figure 9; it is adjusted by the InC MPPT. The output results of the boost converter V_{dc} and power fed by SPV are shown in the figure 10 and 11 respectively.

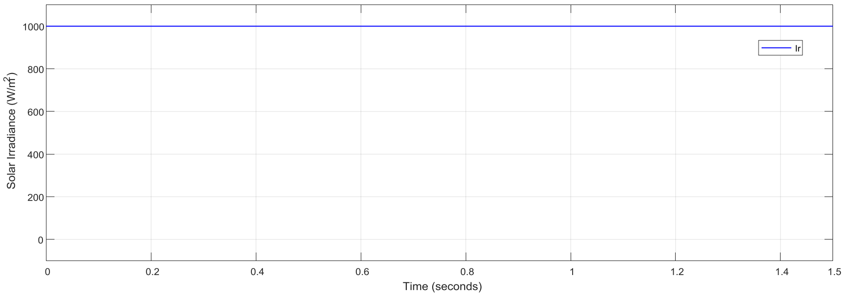

Figure 8 *Irradiance*

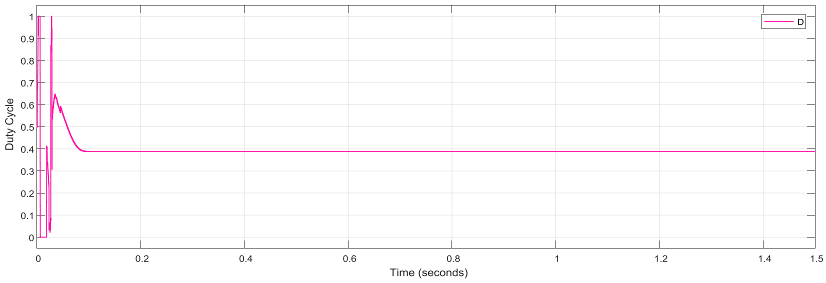

Figure 9 *Duty cycle*

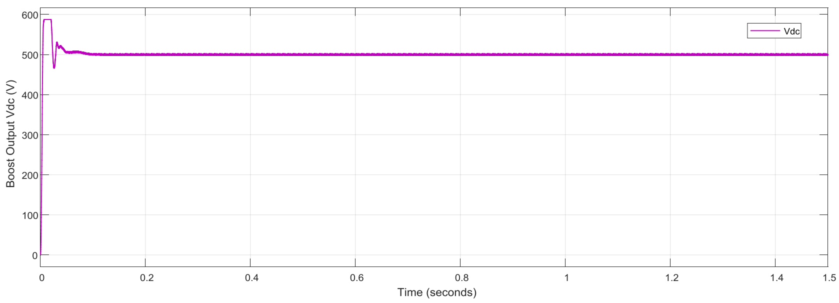

Figure 10 *Boost Output V_{DC}*

Power distribution by SPV system at PCC is 96.40 kW, to the grid 69.92 kW and to the load 26.37 kW during normal insolation at 1 kW/m^2 shown in figure 11. The load and grid voltage per phase are shown in figure 12 and 13 respectively. The voltages are measured as phase to ground (maximum value). Whereas line to line (RMS value) considered for load is 400V and for grid is 11kV. The phase to ground (maximum voltage) is showing in the simulation results. The value of load and grid voltage is 324V and 8.98kV.

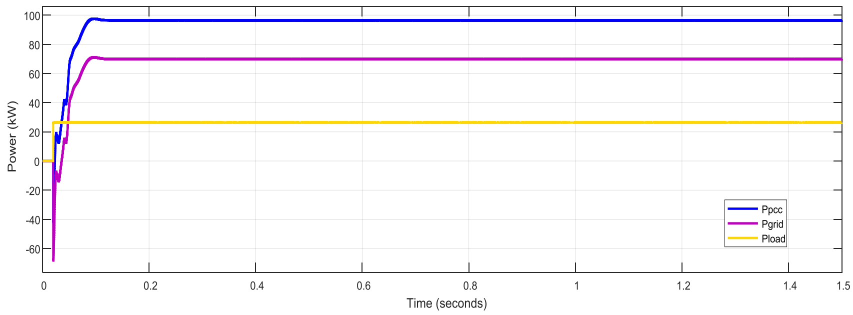

Figure 10 *Solar PV power to grid and load*

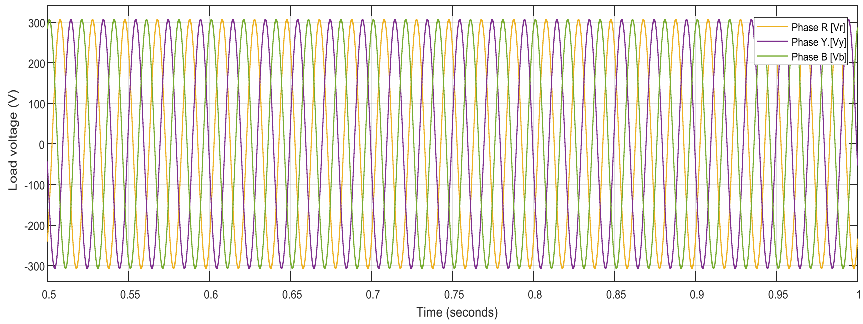

Figure 11 *Load Voltage*

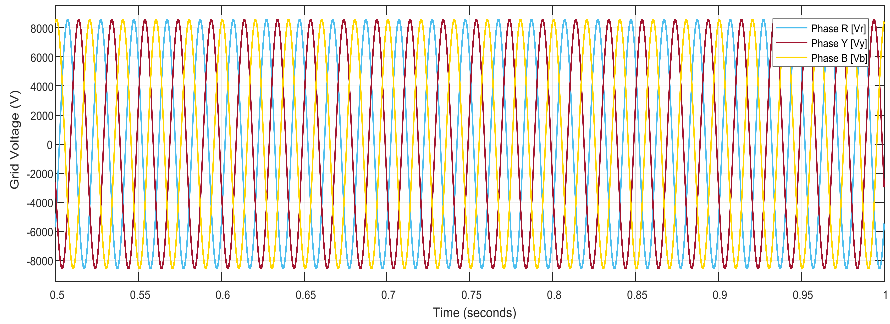

Figure 12 *Grid Voltage*

- **Bidirectional Power Flow**

During insolation/irradiance, the grid and the domestic/commercial AC load both are fed by the solar array at different voltage level 11kV and 400V respectively. For showing the bi-directional behavior of grid system, the insolation given to the solar PV is as shown in figure 13. For the duration 0.6 to 1 sec. there is almost negligible insolation, and corresponding change in duty cycle can be seen in figure 14.

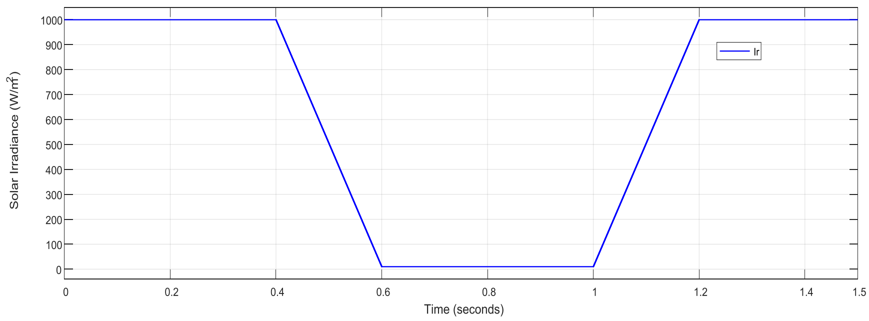

Figure 13 *Irradiance*

Without insolation, solar array is not capable to provide power to the load and at this time grid feeds power to the load and shows its bi-directional power flow capabilities. Figure 15 describe the behavior of the system during negligible irradiance, power distribution by SPV system at PCC is 96.39 kW (blue), to the grid 69.31 kW (pink) and to the load 26.37 kW (yellow) during normal insolation at 1 kW/m^2 shown in figure 15. During 0.6 to 1 sec solar PV system fails to provide power to the load and grid as well, at this time grid feeds the power 26.37 kW, which is shown in figure by its negative direction of flow (pink).

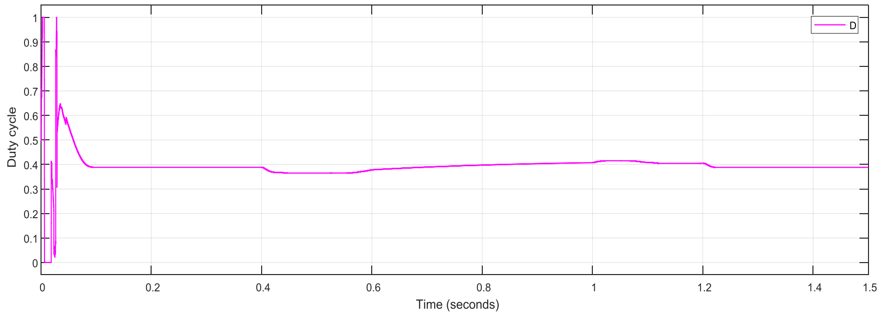

Figure 14 *Duty cycle*

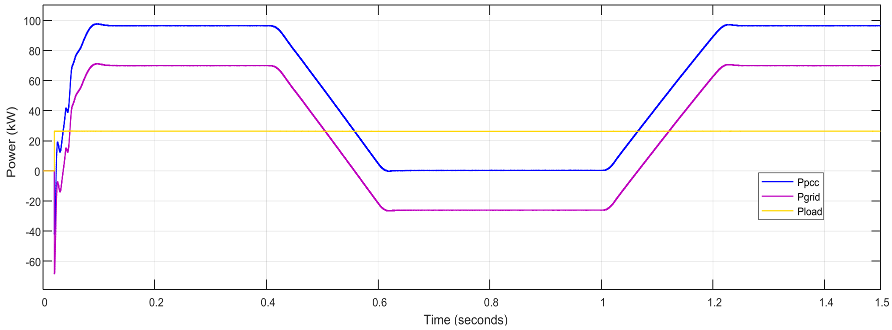

Figure 15 *Power to the load from solar array and grid*

IV. CONCLUSION

This paper presents performance of solar generation system and has been analyzed for grid connected system and with domestic/commercial 3-phase load for varying insolation. It has been seen from simulation results that InC MPPT can efficiently track the change in insolation and maximum power received for the load as well as for grid. Also simulation is carried out to verify the bidirectional power flow from the grid, which is observed when the insolation through the sun was negligible/almost zero then solar PV system, was not capable to provide power at that time grid delivered the power to the load. Solar power generation is the system, which we can install near to the load, but storage of solar power is very costly. The solution of that is to connect the solar power connected load to the grid as well, so that in absence of insolation or at night grid can feed the local load. All the system have been modeled and simulated in MATLAB/SIMULINK.

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