Modeling and Simulation of PV System with Three Phase Inverter along PV, IV Curves using MATLAB/Simulink

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Abstract-The modeling and simulation research of a solar grid-connected system with an inverter, as well as the experimental verification of the new methodology, are presented in this paper. The simulation of a grid-connected PV system with a 12 KW rated power, made up of a solar generator and a three-phase grid-connected inverter, used this technique. By conducting IV characteristic measurements, results for the PV module characteristics have been simulated. The observed AC output power vs DC input power is fitted to a second-order efficiency model to derive its unique parameters, which account for the power conversion efficiency. The Matlab/Simulink environment was used to produce the simulation results. Whether looking at I-V characteristics or the entire operating system, the results have demonstrated good consistency. A PV array block is needed to produce 12kW power so that we can feed it to the grid. Also, there are some inputs to the PV array i.e. Irradiance and Temperature. These two parameters can change the output power considerably, for example, if the temperature rises, the output power decreases.

Keywords- PV; Three phase inverter; THD; Power system; MPPT.

Nomenclature

Ts	Solar cell temperature at hour t
Sr	Solar cell radiations
At	Ambient temperature
No	Nominal operating temperature
Is	Short current
Sr	Solar cell radiations
Isc	Short circuit current of PV module
I_L	Light generated current
I_D	Diode saturation current
Rsh	Shunt resistance
Rs	Series resistance
Tc	Temperature coefficient
Ki	Current temp. Coefficient of PV module
Voc	Open circuit voltage
Kv	Voltage temp. Coefficient of PV module
FF	Fill factor
Vmpp	Voltage at maximum power point
Impp	Current at maximum power point
Npv	Number of PV modules
G	Amount of sun light
η	Efficiency of the system
PSH	Peak Sun Hours

1. Introduction

PV systems generate electricity by converting sunlight into energy without consuming finite resources like fossil fuels. This makes them an essential part of a sustainable energy future. Solar energy produces minimal greenhouse gas emissions compared to traditional energy sources. Using PV systems helps mitigate climate change by reducing carbon footprints. Relying on solar power decreases dependence on fossil fuels, reducing vulnerability to fuel price fluctuations and geopolitical instability related to energy sourcing. While the initial setup costs for PV systems can be significant, they offer long-term savings. As technology advances and costs decrease, solar power becomes more economically competitive with conventional energy sources. Continuous research and development in PV technology have led to improvements in efficiency and cost-effectiveness, making solar power increasingly viable as an energy solution.

In order to provide low output voltage distortion, fast dynamic response, high reliability, and continuous power supply systems—especially for sensitive and critical loads that cannot afford to suffer an unplanned power outage—the use of uninterruptible power supplies, or UPSs, has grown dramatically in recent years. Hospitals, airline reservation systems, and computer systems are among the essential loads for which UPS is necessary. Three-phase inverter systems, for example, are ideal power applications that often require low total harmonic distortion (THD) and high efficiency. Nonlinear loads and the absence of sinusoidal currents can result in imbalanced conditions, which can raise the voltage drops on the supply network impedance. They also result in resonances and electromagnetic interference (EMI). The adverse effects of harmonics on other electrical loads, such as control and automatic equipment protection systems, lead to decreased reliability and availability. [1].

Development of intensive use of solar systems has been influenced by a number of variables. The most important factors are the rising energy consumption on a global scale as well as the limited availability and high cost of fossil fuels. Two more critical challenges are the impact energy technologies have on the environment and the maturation of photovoltaic technology [15]. The PV module characteristics parameters, which are typically provided by the manufacturer, never exactly match in real-world operating environments. To properly model and precisely simulate PV systems, these properties must be evaluated under actual working conditions. On the other hand, the power conditioning apparatus, which consists of a DC/AC converter and an MPP tracker, modifies the generated DC energy [2]. Large grid-connected photovoltaic (PV) power systems have successfully replaced small independent ones. Utility connectivity gives the renewable power economy a new dimension by merging the temporal excess or the shortfall in renewable electricity with the connected grid that generates base-load power using conventional fuel. [5]. I present a simulation analysis of a solar power system that is connected to the grid and an inverter with a 12 KW rated power in this research.

2. Simulation for Proposed Model

First of all, a PV array block is needed to produce 12kW power so that we can then fed it to the grid. Also there are some inputs to the PV array i.e. Irradiance and Temperature. There is a proposed simulation model of the system given below in Fig. 1.

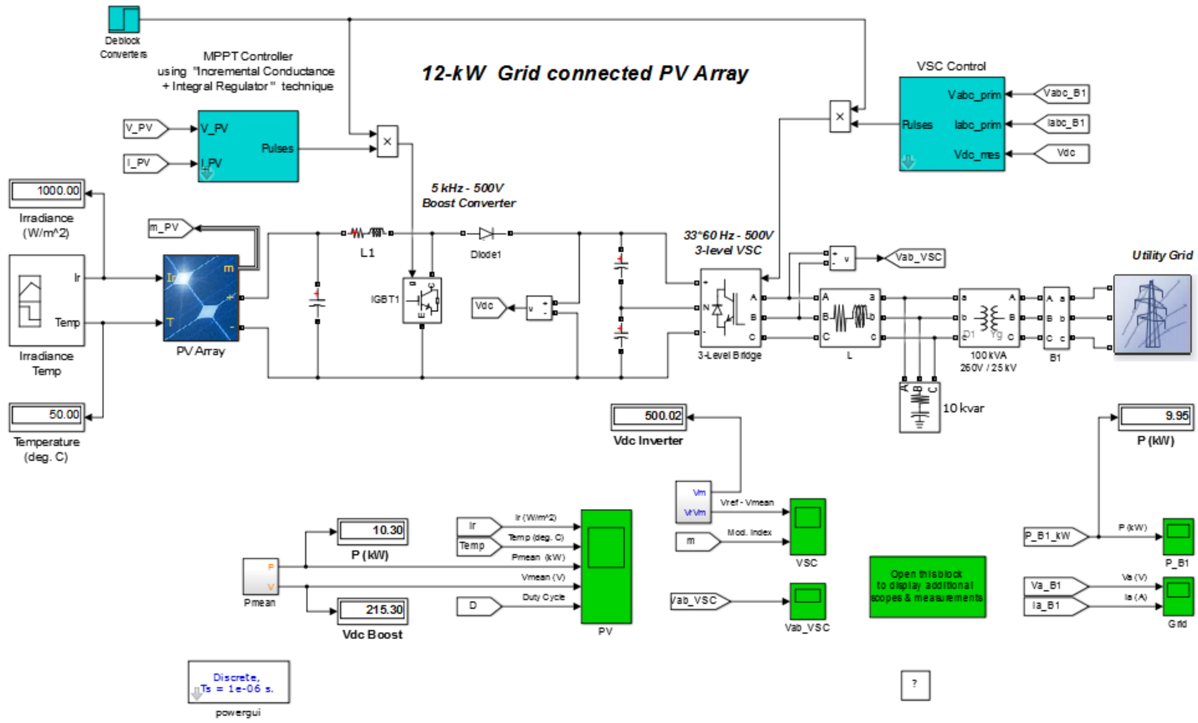

Fig. 1: Simulation of proposed model

I also set some parameters and calculations for this system and for solar irradiance, it shows in the next part of calculations and results. Devices that use photovoltaic energy are nonlinear. Temperature and sunlight are factors that affect their characteristics. By using photovoltaic cells, sunlight is transformed into electricity. Parallel and series PV modules make up photovoltaic arrays. Cells are gathered into groups to form panels or modules. The voltage and current generated at a PV's terminals can be used to supply not just a DC load, but they can also be linked to an inverter to generate alternating current. For a very long period, academics and professionals have utilized photovoltaic cell models to describe the behavior of solar cells.

Table 1: PV and irradiance parameters of solar power system

Parameter	Typical Value/Range
PV Module Efficiency	15% - 22%
Solar Irradiance	~1000 W/m² (under optimal conditions)

Peak Sun Hours	Varies by location and season
Temperature Coefficients	Varies by panel type and manufacturer
Capacity Factor	15% - 25% (varies based on system design)
Tilt Angle	Latitude-dependent for optimal efficiency
Orientation	Towards the sun's path for maximum exposure
System Losses	Varies based on system components and setup
Energy Yield	Dependent on panel efficiency and location

Table 1 refers to the percentage of sunlight that a solar panel can convert into usable electricity. Typical efficiencies for commercially available panels range from 15% to 22%, with some advanced panels reaching even higher efficiencies. The amount of solar power striking a given area at a given time. The standard unit is watts per square meter (W/m²). Average solar irradiance values vary greatly based on location, time of day, season, and weather conditions. For example, it can range from around 1000 W/m² for optimal conditions to much lower during cloudy or overcast days. This represents the number of hours per day when the solar irradiance averages 1000 W/m². It's a crucial factor for estimating the energy output of a PV system in a particular location so all other values are given in table 2.

There is a Boost converter which is used to maintain DC voltages at 500V to track maximum power point. Also, there is inverter which gets DC input and convert it into AC so that it could be fed into grid. Notice that the VSC Control gives pulse to the inverter but there is another block Deblock which is used here to off the controllers for 0.05s which shows in results section and Fig. 2 given below. After inverter, there is a filter or capacitor bank which is making the output (VI) sinusoids smooth. Then it further fed to transformer which is delivering power to grid which shows in the Fig. 3 and results section

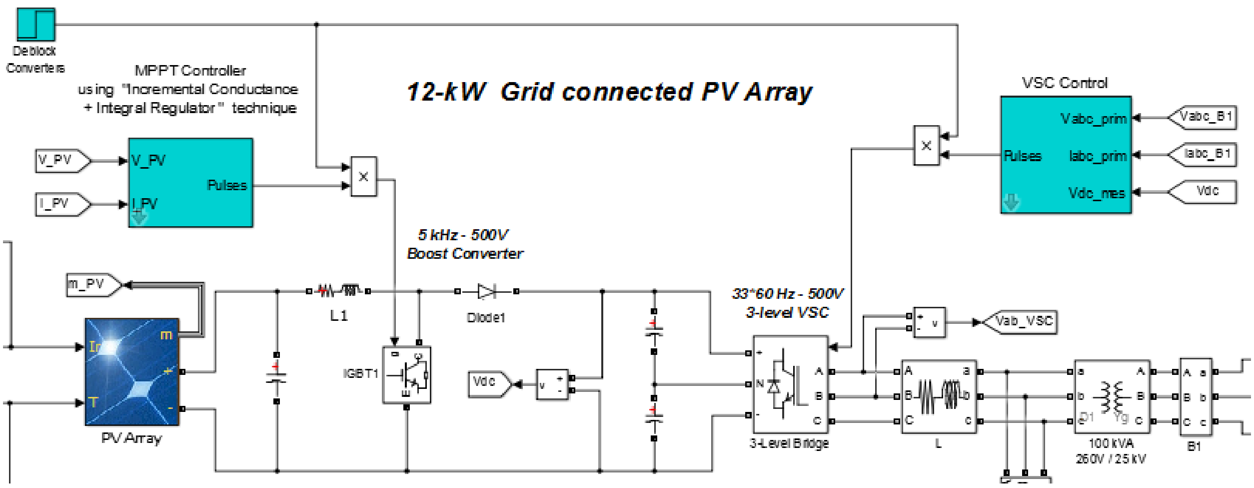

Fig. 2: VSC control of for the inverter

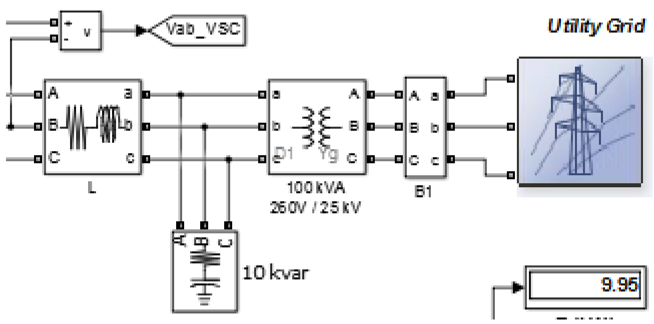

Fig. 3: Filter and capacitor bank for smooth curves

3. Calculations

When designing a photovoltaic (PV) system, several parameters and equations need to be considered. These include are solar irradiance which is amount of solar power per unit area received on the Earth's surface. It is typically measured in watts per square meter (W/m²). The solar irradiance depends on factors like location, time of year, and time of day. Panel Efficiency (η) the efficiency of the PV panels in converting incident solar energy into electrical energy. It is usually expressed as a percentage. System Capacity is total capacity or power rating of the PV system, which is the maximum power it can generate. It is measured in watts (W) or kilowatts (kW). Daily Energy Demand is amount of electrical energy required by the load or the building over a 24-hour period. It is typically measured in watt-hours (Wh) or kilowatt-hours (kWh) [9].

Peak Sun Hours is equivalent number of hours per day when the solar irradiance is equal to 1,000 W/m². PSH takes into account variations in solar irradiance throughout the day. Array Tilt Angle (θ) is an angle at which the PV panels are tilted with respect to the horizontal plane. The tilt angle affects the amount of solar energy captured by the panels, depending on the geographical location. Array Azimuth Angle is the angle between the south direction and the orientation of the PV panels. The azimuth angle determines the orientation of the panels for optimal sunlight capture. Energy Yield is amount of energy produced by the PV system, calculated by multiplying the solar irradiance, panel efficiency, and the number of hours the system operates by using equation 1 to 5.

$$Daily\ Energy\ Production = G \times \eta \times A \times PSH \quad (1)$$

$$Number\ of\ panels = \frac{C}{Panel\ capacity \times Panel\ efficiency} \quad (2)$$

$$Area\ required = Number\ of\ panels \times Panel\ area \quad (3)$$

Load demand is daily energy consumption of the load in kilowatt-hours (kWh). Peak sun hours is the average number of hours of sunlight per day at the installation location. System efficiency is overall efficiency of the PV system, accounting for losses due to factors like module efficiency, inverter efficiency, shading, soiling, and temperature [6].

$$PV\ Array\ Capacity\ (kWp) = \frac{Load\ Demand\ (kWh/day}{Peak\ Sun\ Hours \times System\ Efficiency} \quad (4)$$

Once the PV array capacity is determined, you can calculate the number of PV modules required based on the specifications of the chosen PV module.

$$Number\ of\ Modules = \frac{PV\ Array\ Capacity\ (kWp)}{Individual\ Module\ Capacity\ (kWp)} \quad (5)$$

The inverter converts the DC power generated by the PV array into AC power that can be fed into the grid. The inverter size should be chosen based on the maximum power output of the PV array. Consider the inverter efficiency in the equation is given below from equation 6 to 11.

$$Inverter\ Capacity\ (kW) = \frac{PV\ Array\ Capacity\ (kWp) \times Inverter\ Oversizing\ Factor}{Inverter\ Efficiency} \quad (6)$$

$$Annual\ energy\ yield\ (kWh) = PV\ Array\ Capacity\ (kWp) \times Annual\ Performance\ Ratio\ (APR) \times Annual\ Solar\ Radiation\ (kWh/m^2) \quad (7)$$

$$Ts = At + \frac{Sr \times (No - 20)}{0.8} \quad (8)$$

$$Is = Sr\ [Isc + ki \times (Ts - 25)] \quad (9)$$

$$FF = \frac{Vmmp \times Immp}{Voc \times Isc} \quad (10)$$

$$Ppv = Npv \times FF \times Vs \times Is \quad (11)$$

These are the specific equation which is used to implement our PV system and which is taken from this reference [13] and all values are given in detail in table 2.

Annual performance ratio (APR) is the ratio of actual energy output to the theoretical energy output, accounting for system losses due to shading, soiling, module degradation, temperature, etc. Annual solar Radiation is the average annual solar radiation at the installation location, typically provided by solar resource data [17].

These equations provide a basic framework for designing a PV system and inverter. However, it's important to note that the actual design process can be more complex and may involve additional factors such as shading analysis [10], temperature effects, inverter efficiency, and electrical losses. Professional software tools or consultation with a solar energy expert can help in optimizing the design based on specific requirements and constraints. See the Table 2 for reference calculations.

Table 2: Reference calculations for PV array

Parameters	Values
Parallel strings	10
Series connected modules per strings	4
Module	Sun power SPR-30SE-WHT-D
Maximum power (W)	305.226
Cells per module (Ncell)	96
Open circuit voltage (V)	64.2
Short circuit voltage (V)	5.96
Voltage at MPPT (V)	54.7
Current at MPPT (A)	5.58
Tc of Voc	0.27269
Tc of Isc	0.061745

I_L (A)	6.0092
I_D (A)	6.3014e^{-12}
Diode identity factor	0.94504
Rsh (ohms)	269.5934
Rs (ohms)	0.37152
P_{array} (KW)	12.2
Total current of PV array (A)	55.8
Total voltage of PV array (V)	218.8
Irradiance (W/m^2)	1000
Temperature (^{o}c)	25-50

The AC output power of the inverter should match the electrical requirements of the load and grid connection standards. The equation for calculating the AC output power is

$$AC\ Output\ Power\ (Pac) = \frac{Load\ Demand\ (W)}{Inverter\ Efficiency} \quad (14)$$

Load Demand is power demand of the load in watts (W). Inverter Efficiency is the efficiency of the inverter, which represents the ratio of AC output power to DC input power. Sizing the Inverter is to select an appropriate inverter, you need to consider the AC output power and the inverter's power rating. The inverter's power rating should be equal to or greater than the calculated AC output power [7]. It's important to consider any potential future expansions or changes in the PV system when selecting the inverter's size. Over-sizing Factor is to account for potential variations in PV array performance over time, it's common to include an over-sizing factor when selecting the inverter size. This factor is typically between 1.1 and 1.25, depending on the desired level of oversizing [12].

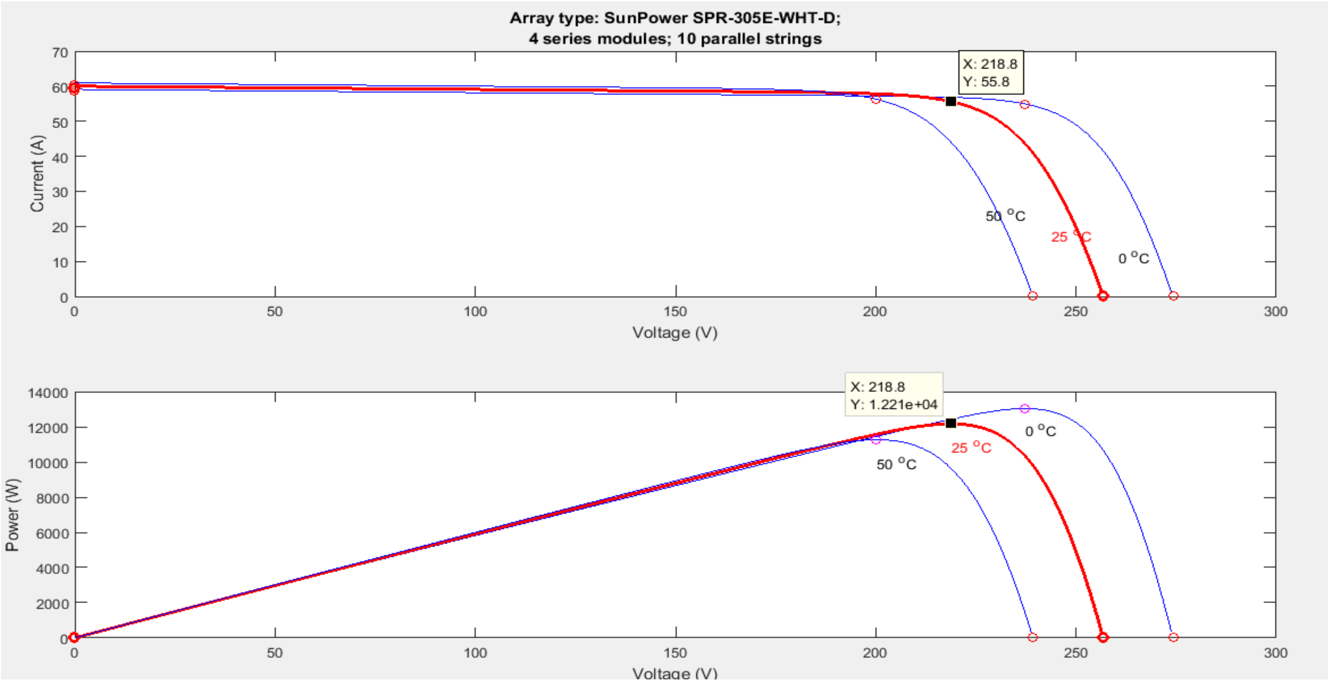

Fig. 4 PV and IV curves of the PV system

Designing an inverter for a photovoltaic (PV) system involves considering various factors such as the PV array specifications, grid requirements, and system efficiency. DC input voltage of the inverter should be compatible with the PV array's specifications. Generally, the inverter should be designed to accommodate the maximum DC voltage of the PV array under standard test conditions (STC). The equation 12 to 13 for determining the required DC input voltage and current is

$$DC\ Input\ Voltage\ (Vdc) = Maximum\ PV\ Array\ Open\ Circuit\ Voltage\ (Voc) \quad (12)$$

The DC input current of the inverter is determined by the power output of the PV array and the DC input voltage. The equation for calculating the DC input current is

$$DC\ Input\ Current\ (Idc) = \frac{PV\ Array\ Power\ Output\ (W)}{DC\ Input\ Voltage\ (Vdc)} \quad (13)$$

These equations provide a basic understanding of the design considerations for an inverter in a PV system. However, the actual design process may involve additional factors such as inverter efficiency curves, maximum power point tracking (MPPT), harmonics analysis, and compliance with relevant standards and regulations. It's recommended to consult inverter manufacturer specifications, local guidelines, and the support of a professional to ensure a proper and efficient inverter design for your specific PV system.

4. Results and Discussion

4.1 PV and VI curve:

A solar photovoltaic system's PV (photovoltaic) and IV (current-voltage) curves are crucial components. These graphs show how the system's current, voltage, and power output relate to one another under various operating scenarios. The relationship between a solar system's output powers (P) and voltage (V) under constant irradiance (sunlight intensity) and temperature conditions is represented by the PV curve, as shown in Fig. 4. The curve usually has a distinctive form and a maximum power point (MPP) that represents the system's optimal operating efficiency. By adjusting the voltage and calculating the related power output, the PV curve is produced.

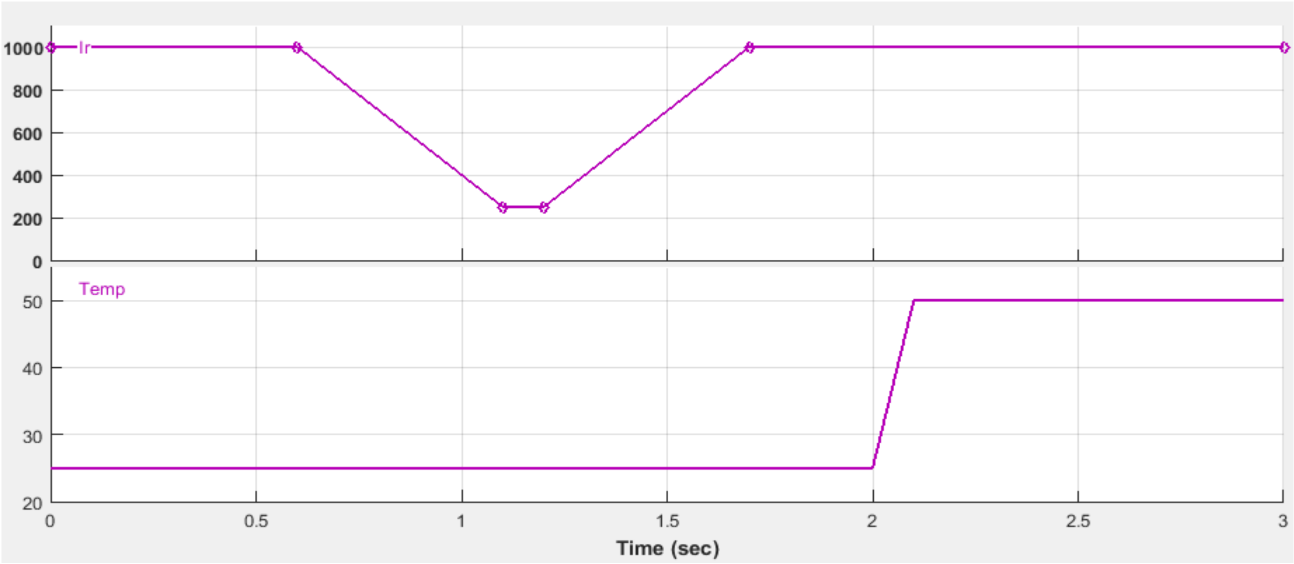

Fig. 5: Irradiance and temperature of the PV system

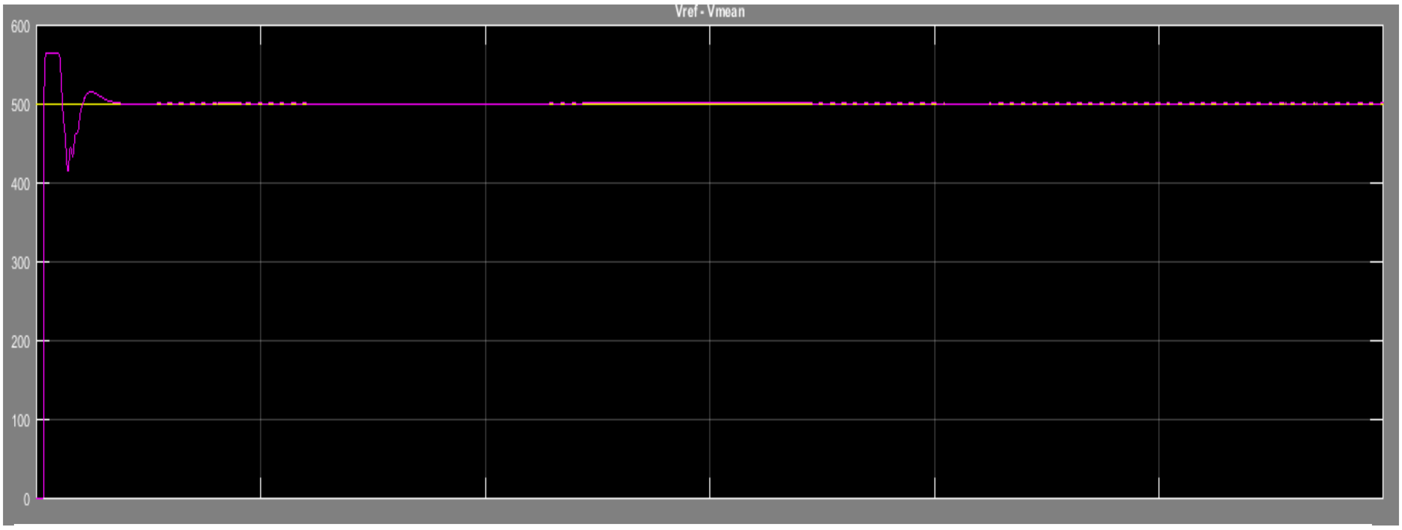

Fig. 6: V_{dc} in Boost Converter

The relationship between a solar system's output of current (I) and voltage (V) at constant temperature and irradiance is depicted by the IV curve. It illustrates how changing voltage affects the system's current output [11]. Measuring the current at various voltage levels yields the IV curve. The calculations state that at a temperature of 25, the maximum power is 12.21 kW. Moreover, note that power drops as voltage drops as temperature fluctuates between 0 and 50.

4.2 Irradiance and Temperature:

Irradiance and temperature are two key environmental factors that affect the performance of a photovoltaic (PV) system. As given below Fig. 7 shows the irradiance refers to the amount of solar energy (sunlight) that reaches the surface of the PV modules per unit area. It is typically measured in units of watts per square meter (W/m²). The irradiance level has a direct impact on the power output of the PV system. Higher irradiance levels result in greater power generation, while lower levels reduce the system's output. The relationship between irradiance and power output is not linear. It follows a non-linear response, often described by the International Electro technical Commission (IEC) standard as the "I-V curve." As the irradiance increases, the current output of the PV system increases, resulting in higher power output [8]. However, the voltage output tends to remain relatively constant. The maximum power point (MPP) on the I-V curve represents the operating point where the system generates the highest power for a given irradiance level.

The performance of PV systems is also significantly influenced by temperature. The PV modules' efficiency drops with increasing temperature. This can be attributed to the modules' temperature coefficient, which establishes the relationship between temperature and output voltage and current [9]. Generally speaking, when the temperature rises, the PV system's voltage output falls and its current output rises. As a result, the total power output is decreased. A module's temperature coefficient, which shows the percentage change in module output for every degree Celsius (°C) that the temperature changes, is provided in the datasheet. In PV

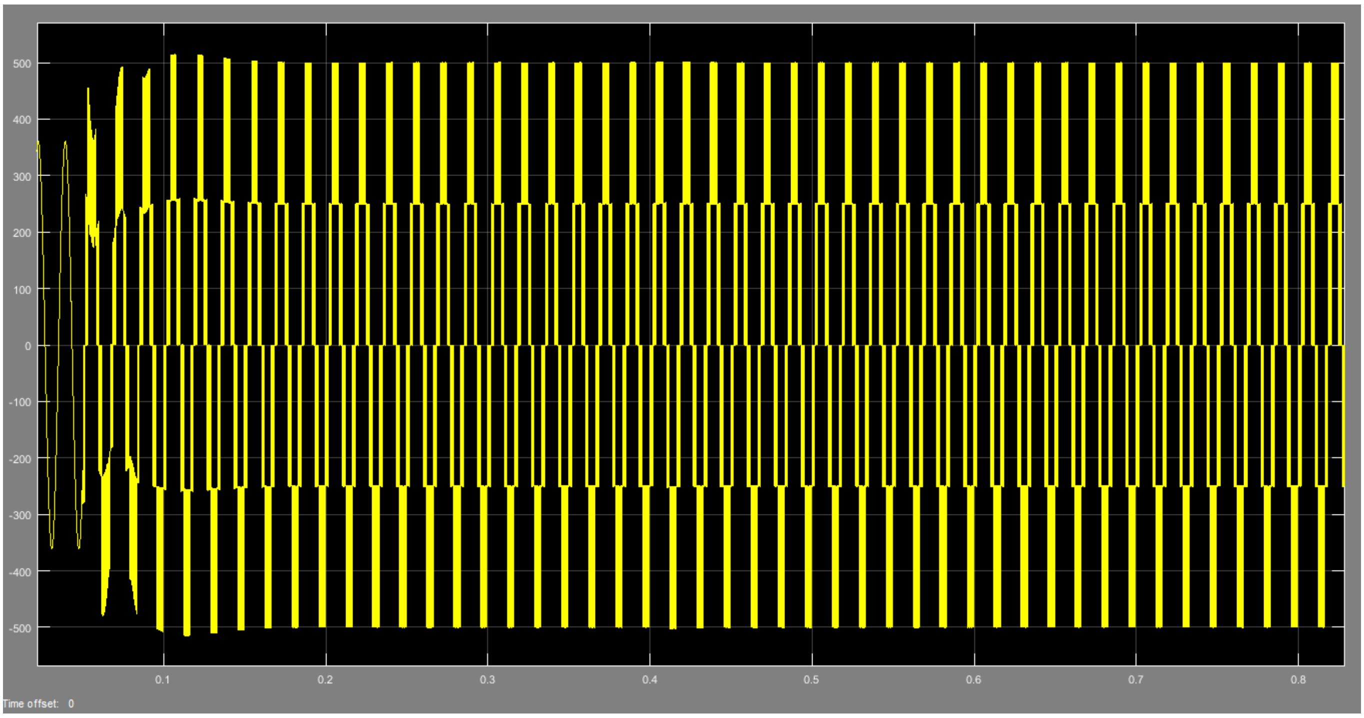

Fig. 7: Curve of voltages just after inverter.

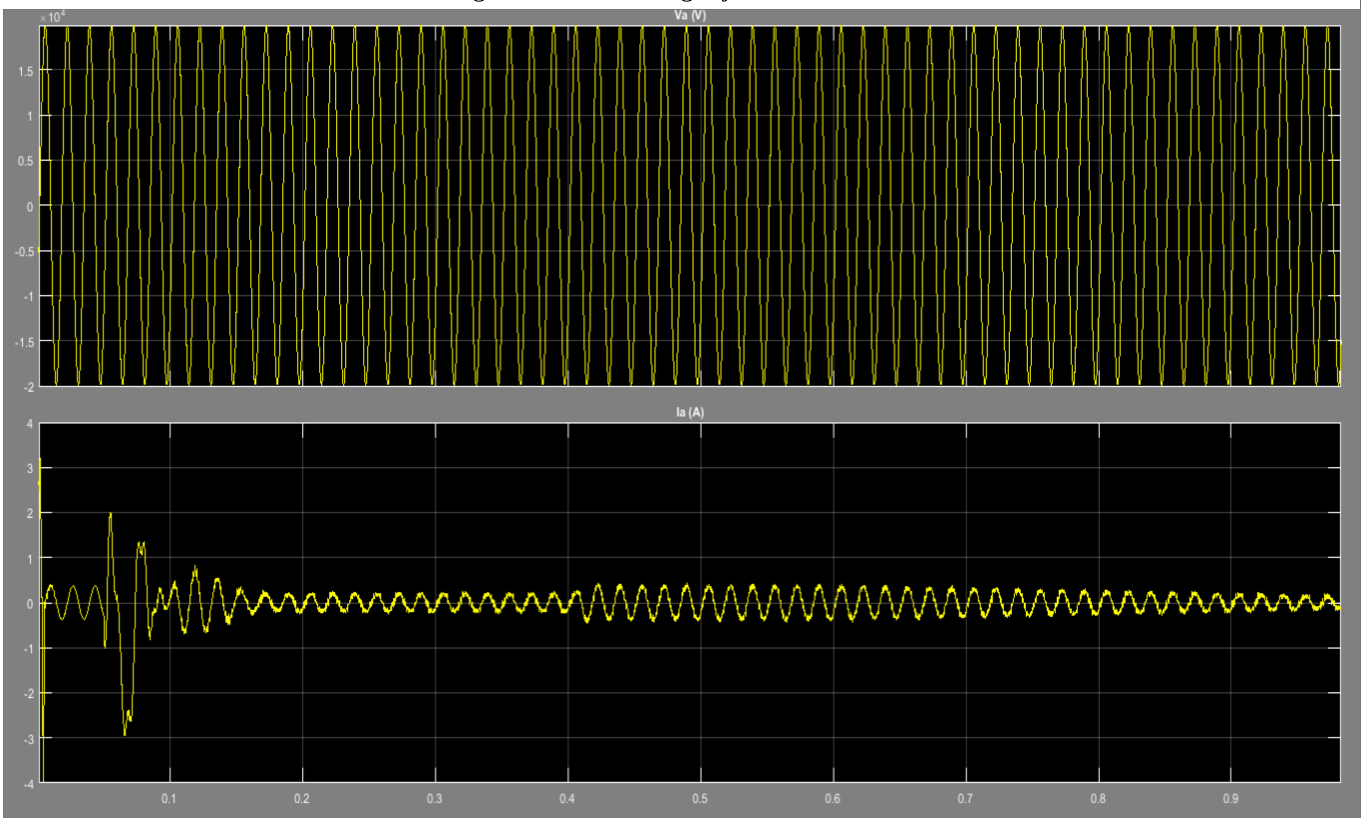

Fig. 8: Curve of voltage and current of Grid

systems, the maximum power point tracking (MPPT) technique is frequently used to account for temperature effects. While taking into account the fluctuating irradiance and temperature circumstances, MPPT algorithms [14] continuously modify the system's operating point to optimum power output. The irradiance value is shifting from 1000 to 250 and back again, as you can see. In addition, the temperature increases from 25 to 50 [18].

The switch's duty cycle, or D, measures how much of the overall switching period the switch is closed for. The boost converter can modify the output voltage level by adjusting the duty cycle [4][16]. The boost converter can step up the input voltage to a specified output voltage level by altering the duty cycle. After some time of settling, the DC voltage stays at 500V as anticipated.

4.4 V_{ab_sc}:

Voltage waveforms just after inverter are given in Fig. 7.

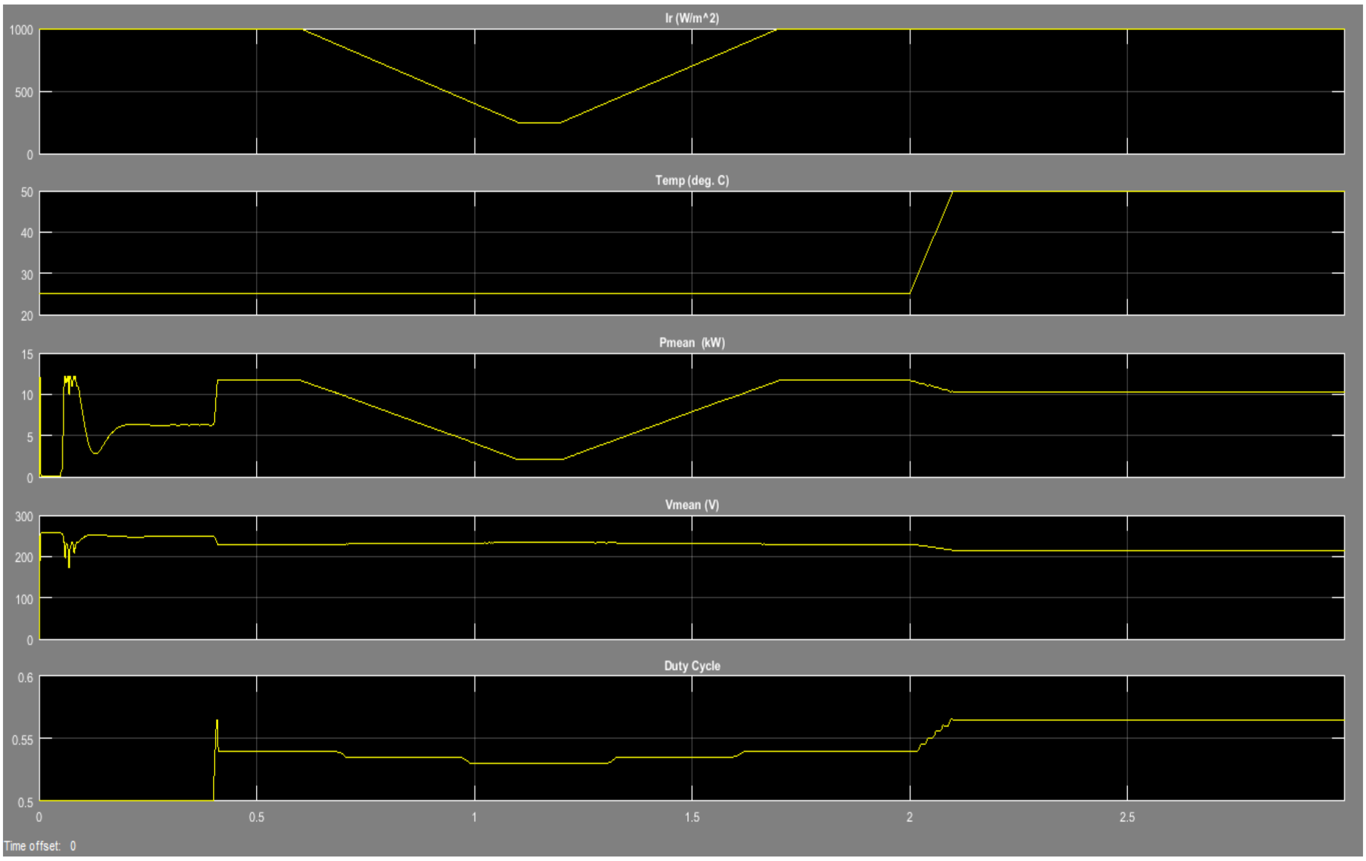

Fig. 9: Curves of different parameters

4.3 V_{dc} in Boost Converter:

V_{dc} is a term used to describe the output voltage of a boost converter. An example of a boost converter is a DC-DC converter, which raises input voltage to raise output voltage. It is frequently used in power electronic systems to effectively step up voltage levels. An inductor, a switch (often a transistor), a diode, and a capacitor make up the boost converter. The switch and the inductor both receive the input voltage Vin. The inductor receives current when the switch is closed, storing energy in its magnetic field. The "on" or "charging" phase is right now. The switch is open during the "off" or "discharging" phase, and the inductor discharges the accumulated energy [3]. The output capacitor and load can both be reached by the current thanks to the diode. The output voltage, Vdc, is consequently greater than the input voltage. The output voltage of a boost converter can be calculated using the following equation, assuming ideal components

$$Vdc = Vin \times \frac{1+D}{1-D} \quad (15)$$

4.5 Grid

Clearly, after passing through filter of capacitor bank, the sinusoid of voltage and current becomes very smooth as compare to the curves after inverter in Fig. 8.

4.6 PV

As shown in Fig. 11 the first graph is of irradiance and it is changing as expected from 1000->250->1000, second graph is of temperature and it is changing from 25->50. Third graph is of Pmean in which till t=0.05s, there is no controller in working due to Deblocking. But after that the power goes up towards 12kW. Then it went down and as duty cycle changes the power again rises up towards 12kW. When irradiance value goes down to 250W/m^2, the Pmean also drops and when Ir rises to 1000W/m^2, Pmean again rises. Fourth graph is of Vmean which changes according to the change in duty cycle graph (fifth graph).

5. Conclusion

The key components of a grid-connected photovoltaic system have been modeled and studied using simulation in this work using Matlab/Simulink. The simulation results achieved using this approach, based on the evaluation of the primary PV module characteristics, have demonstrated that the PV module model described here accurately defines the I-V characteristic. Finally, a viable option to forecast the energy output of the entire plant connected to the utility grid is to simulate the entire system of the PV generator and three phase inverter, including the inverter parameter settings. Then, a Boost converter is used to maintain DC voltages at 500V to track maximum power point. Also, there is an inverter that gets DC input and converts it into AC so that it can be fed into the grid. Notice that the VSC Control gives a pulse to the inverter but there is a block Deblock which is used here to off the controllers for 0.05s.

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