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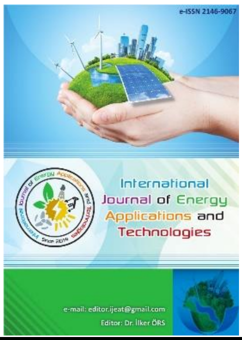

Original Research Article

Modeling and simulation of a grid-connected PV system under varying environmental conditions

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ABSTRACT

With the rapid increase of the requirement of electricity demand throughout the world, renewable energy resources (RERs) particularly solar photovoltaic (PV) is a viable alternative to mitigate the global energy crisis. With the advantages of being inexhaustible, abundant, and clean, PV is considered as one of the most useful RER. Besides, the power efficiency of Solar PV is highly affected by variations of solar irradiance and temperature of the solar cells. Hence, the Maximum Power Point Tracking (MPPT) controller is used to control the switching duty cycle of the power converters which ultimately maximize the output power of the PV array. In this paper, a case study of 240-kW solar PV array is performed in MATLAB/Simulink environment. Simulation is performed on 'SunPower SPR-400E-WHT-D' PV array which is comprised of 88 parallel strings and 7 series connected modules per string. The impact of variable weather conditions (irradiance and temperature) is analysed. Moreover, the 240-kW PV array is connected to 20 kV grid using boost converter and Voltage Source Converter (VSC). In this way, the inverted AC output power is coupled with the AC grid. This bidirectional output power with unity power factor can be utilized by industrial/commercial consumers to fulfil their energy demands. In this study, the results are presented to prove that the maximum power fluctuations during rapid weather changing conditions can be reduced and a collaboration in the installation of PV system can be provided.

Keywords: Renewable energy, Solar PV system, MPPT, DC-DC boost converter, and Voltage source converter

1. Introduction

The increase in energy needs and environmental concerns direct the attention towards Renewable Energy Resources (RERs). The integration of the RERs particularly solar photovoltaic (PV) into the power system network is growing rapidly to become a leading source with a large number of applications. Solar PV, as an important source to harness solar energy, is a clean and viable alternate energy resource with flexible off-grid and on-grid applications that are either in stand-alone or grid-connected configuration [1]. Besides having so many advantages, solar PV system has few limitations like its installation cost and power conversion losses in its electronic circuitry. Nevertheless, in the last 20 years, the demand for solar energy is still increasing from 20 % – 25% annually [2]. Besides, the solar PV system is easy to install, economical operation, noiseless, and environmentally friendly energy resource that has the capability to be deployed for large-scale grid-connected applications [3].

For the utility-interactive solar PV system, the key components used are; PV module, mounting system, DC-DC converter, battery bank, DC-AC converter, transformers, and grid. The factors disturbing the power efficiency of PV plant are; (a) the efficiency of PV panel is low that is 8-15 %, (b) the power conversion losses are high, and (c) one-time higher installation cost of PV plant. The PV panel output power is highly affected by variable weather conditions (irradiance and temperature). However, the maximum power efficiency of PV plant can be achieved by means of an adequate Maximum Power Point Tracking (MPPT) controller and power conversion topology that can track the maximum power for available solar irradiance and temperature [4].

Çetinkaya conducted a research on the performance analysis of 1 MW grid-connected PV power plant in Konya [5]. Although very close values between actual and forecasted values have been obtained, it was shown that some difference was observed especially due to the sudden changes in the weather conditions. The author suggested very useful recommendations for the researchers, investors, operators, the power system management and the legislators. The focus was on the economic feasibility. Karafil et al. simulated the equivalent circuit of the PV panel based on PSIM and MATLAB using the catalogue data for variations in temperature and the solar radiation [6]. The results indicated that low temperature and high solar radiation level conditions are more appropriate for the obtained power values. The study focused only on the PV panels and did not deal with the analysis of necessary components required for a residential PV system. Solar radiation and temperature effects were researched by Palta et al. for a photovoltaic pump system [7]. The authors carried out analysis on the change of solar radiation, temperature, electrical efficiency and pump water flow. An off-grid PV system was considered in the study.

On-grid PV systems have been widely studied in the literature. Munir et al. explained the implementation of a complete distributed energy resource system [8]. PV modules were controlled by means of an MPPT algorithm employing a DC/DC boost converter. A phase locked loop (PLL) circuit was used to integrate the single phase inverter with the grid. In literature, various MPPT controller techniques have been used to maximize the power efficiency of the solar plant. These are; perturb & observe (P&O) [9], incremental conductance (IC) [10], and artificial intelligence-based control algorithms [11,12] have been proposed. These algorithms have benefits as well as limitations in terms of computational time, complexity, and implementation cost. Celik and Teke developed a hybrid method to operate the system on MPP for mitigating the variations in the output power due to the temperature and radiation fluctuations. The proposed method was compared with P&O, IC and ANN based MPPT methods under both rapidly changing radiation and partially shaded conditions by using PSCAD/EMTDC program. For these conditions, it was also shown that the THD value of the output current is kept less than 5% and the power factor is always kept at higher than 0.98 [13]. AlhajOmar et al. evaluated the performance of MPPT algorithms namely P&O, IC and Fuzzy Logic (FL) [14]. The models of the algorithms were built in Matlab/Simulink and simulation results demonstrated fuzzy logic technique has better tracking achievement. In addition to the available control technique, the objective of the current research is to cope with the fluctuating weather conditions. The authors in [15] explained briefly that the temperature of the solar PV highly affect the voltage while the irradiance of solar PV has a huge impact on the current. Hence, irradiance and temperature particularly disturb the power quality of Solar PV array.

In this study, the necessary elements for the integration of PV plants into the electric power system are designed and tested. First, the mathematical model of PV cell is analysed. Moreover, PWM based MPPT controller is designed which monitor the current and voltage of PV module and control the duty cycle of switch of DC-DC converter. This converter rises the output voltage of low solar voltage to a suitable level corresponding to the optimal PV power. Furthermore, DC-AC VSC is employed to convert boosted DC to AC voltage. This generated energy in AC form in phase with the utility voltage is instantaneously transferred to the grid. In the presented method, it was aimed to obtain a system with lower complexity and high efficiency. The rest of the paper is organized as follows: Section 2 presents the detailed model of solar cell, DC-DC converter modelling and operation, an overview of MPPT, and working mechanism of VSC. The performance evaluation of the proposed model in the form of various simulation results is performed in section 3. Finally, the paper is concluded with the summary of the future work for further improvement of current work.

2. Model Design of Components of Solar PV

The key elements used in Grid-Tied PV system are; solar panel, DC-DC boost converter, MPPT controller, DC-AC inverter, and coupling transformer that connect inverted AC to the grid. System modelling is performed as follows:

A. Solar PV model

The working of PV Cell is like a p-n junction diode. It works only in daytime and at night it only produces 'diode current' which is also called as 'dark current'. PV array is composed of various PV modules, while PV cells are the building blocks for the PV modules. The equivalent model for PV Cell is presented in **Figure 1**.

The equivalent model of PV cell is modelled with I_{ph} the photo current, I_d diode current, I_s shunt current passing through R_{sh} shunt resistance, and total output current (I) flowing through R_s series resistance. R_s is connected in series with parallel combination of R_{sh} and diode [16]. R_{sh} represents the intrinsic behaviour of the semiconductors while R_s shows the resistance between neighbour PV cells as explained by the authors in [17]. However, the net current equation obtained using Kirchhoff Current Law;

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_d} - \mathrm{I_{sh}} \quad (1)$$

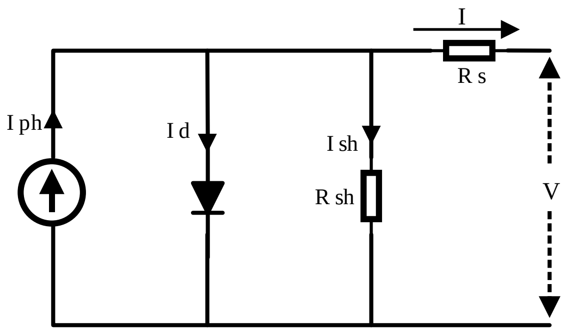

Figure 1. Equivalent model of PV cell

After substituting the values of the diode and shunt current, we obtained,

$$I = \mathrm{I_{ph}} - \mathrm{I_0}\left\{\exp\left[\frac{q(V+IR_s)}{AKT}\right] - 1\right\} - \left\{\frac{(V+IR_s)}{R_{sh}}\right\} \quad (2)$$

In Eq. (2), the values of the constants are written as follows; $\mathrm{I_0}$ is diffusion current of diode junction, q is the electronic charge which is $1.602 * 10^{-23}C$, K is Boltzmann constant that is $1.38 * 10^{-23}J/K$, T is the temperature of p-n junction, and A is the ideality factor which is considered as 1 in the proposed model not disturbing the maximum power point of PV cell. Eq (2) can be further simplified by neglecting the value of R_{sh}.

$$I = \mathrm{I_{ph}} - \mathrm{I_0}\left\{\exp\left[\frac{q(V+IR_s)}{AKT}\right] - 1\right\} \quad (3)$$

The maximum power equation of PV cell becomes,

$$P_{max} = V_{max}I_{max} = V_{max}\left[\mathrm{I_{ph}} - \mathrm{I_0}\left\{\exp\left(\frac{qV_{max}}{AKT}\right) - 1\right\}\right] \quad (4)$$

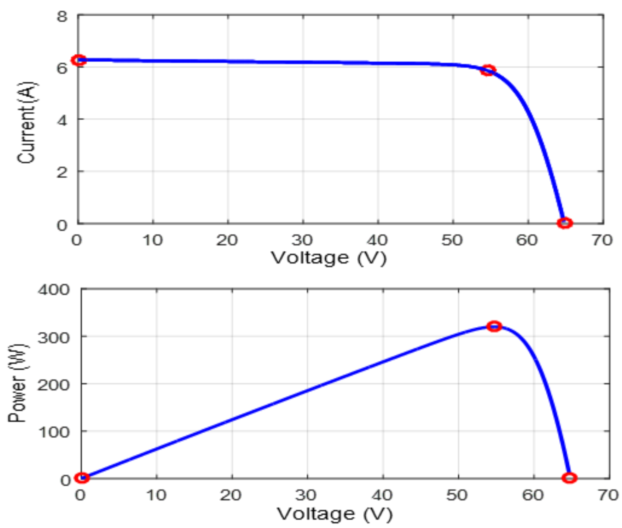

Figure 2. IV and PV characteristics of the proposed PV model

The Eq. (4) is the desired equation to achieve the maximum power point. The main objective of this paper is to analyse the impact of unpredictable weather conditions (variable solar irradiance and flexible temperature) on the maximum power performance of the PV system. The PV characteristics of the proposed PV model are demonstrated in **Figure 2**.

In **Figure 2**, the IV and PV characteristics are performed for the proposed model. These non-linear characteristics show that the variations with temperature of the PV array are comparatively less but are highly sensitive to the variations of solar irradiance for net power of PV array.

B. Boost converter model

In the proposed model, the boost converter is configured to boost up the level of PV voltage and the circuit model is presented in **Figure 3**. Although, the PV generator voltage is not so high due to variable solar irradiance. Therefore, the boost converter is employed to boost the voltage level up. The boosted voltage level is totally dependent on the switching duty cycle of the power switch (IGBT). The total time duration T of the switch is comprised of;

$$T = T_{on} + T_{off} \quad (5)$$

The duty cycle (D) is the ratio of the ON-Time of the power switch. With respect to total time. This can be modelled as,

$$Duty\ Cycle, D = \left({}^{T_{on}}/_{T}\right) \quad (6)$$

The final equation of output voltage of boost converter can be written as [18]:

$$V_o = \left(\frac{1}{1-D}\right)V_{pv} \quad (7)$$

As the value of D fluctuates between (0 &1). Therefore, it is obvious from Eq. (7) that the minimum boosted output will be equal to V_{pv} when D=0. By increasing the value of D, the output voltage will increase by scalar multiple of V_{pv}.

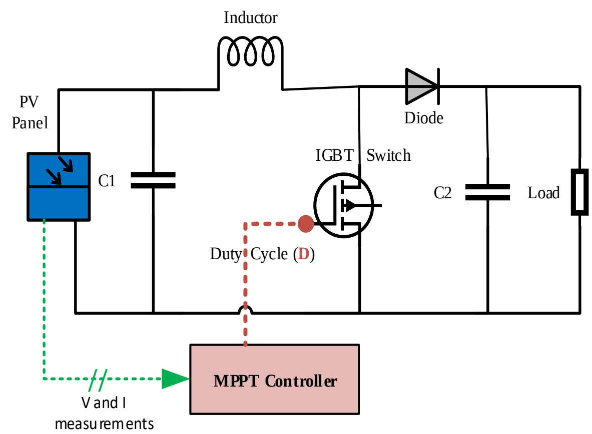

Figure 3. Model design of Boost Converter

C. Proposed PV array model design

The proposed model comprised of all the necessary components required for a residential PV system is presented in **Figure 4**. This PV array provides a maximum of 240 kW that is applicable to fulfil the normal residential load. The model uses *SunPower SPR 400E-WHT-D* PV array. This PV array comprised of 88 parallel strings and 7 PV modules are series-connected in each string. In each module a total of 128 cells are present. The other important components used in the system are; boost converter, MPPT controller, voltage source inverter, transformer, and the grid.

The PV array is operated under different conditions of temperature and irradiance. The comparative analysis is performed in performance evaluation section with temperature ranges from $25 - 45\ C^0$ and irradiance vary slowly from $1000 - 200\ w/m^2$ and the respective impact on PV array output power is evaluated.

The PV array provides maximum of 240 kW at $1000\ w/m^2$ solar irradiance with temperature $45\ C^0$. The output capacitor is used to smooth the output of PV array. Boost converter with 5 kHz switching frequency is implemented to convert normal 273 V DC to 500 V DC voltage. Built in incremental conductance MPPT controller is used to control the power switch used in boost converter. MPPT measures the values of current and voltage from PV array and adjust the width of the pulses to generate desired maximum power from the PV array.

The VSC (3 level bridge DC-AC inverter) is incorporated which convert 500 V DC to AC voltage. In the simulation model, the built-in inverter control block is used that have two main control loops; external control loop and internal control loop. As the total input to the VSC is 500 V DC, external control loop regulates the DC voltage between positive and negative 500 V and internal loop deals with grid currents.

To keep the unity power factor, the reactive current is kept zero. Moreover, the active and reactive voltages which are the signals from the current controller are converted to three modulating signals. MPPT PWM generator uses these modulating signals as reference and generates the desired output voltage.

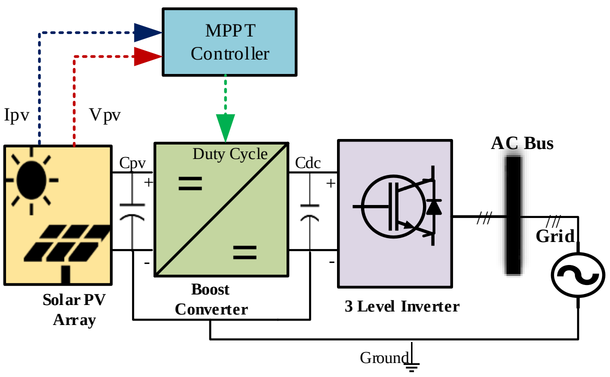

Figure 4. Proposed model design of Grid-Connected PV

3. Performance Evaluation

In the proposed research, the simulation analysis is performed on *SunPower SPR 400E-WHT-D* PV array having 400 kW of maximum power generation capacity. In this section, the analysis of current, voltage, solar power, solar irradiance/isolation and temperature of the solar PV cells will be performed.

A. Analysis of PV and IV characteristics

In this research, we considered only 240 kW of the maximum power generation. The PV and IV characteristics of the proposed array are demonstrated in **Figure 5**. This is the exact response of the proposed PV array. The PV and IV characteristics are analysed based on variation in temperature. Normally, the temperature varies between $25C^0$ to $45C^0$. In this simulation environment, the simulation performed on $25C^0$ to $45C^0$ respectively. It is clear from the **Figure 5** that huge variation in temperature has less effect on the power of PV array. Besides, PV power is highly sensitive to change in irradiance due to the change in current of PV array.

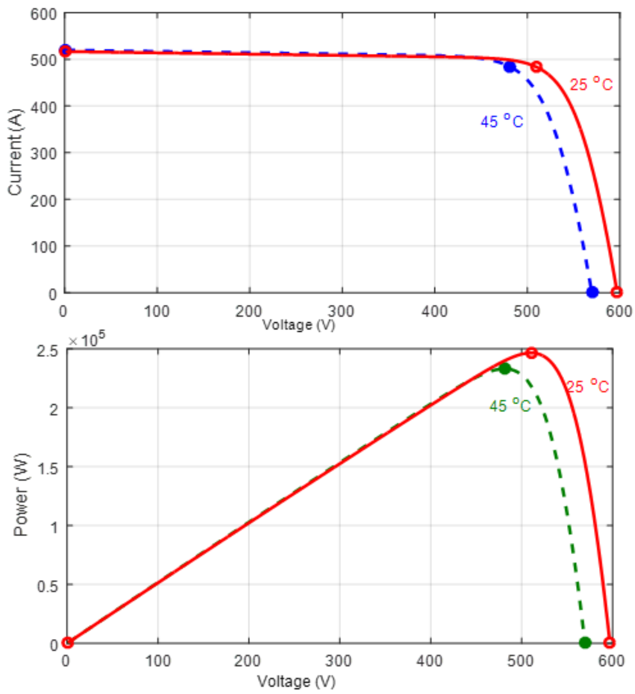

Figure 5. PV and IV characteristics of the PV array

B. Analysis of voltage and current of PV array

The proposed PV array is executed to accomplish 240 kW of power. However, the simulation results presented in **Figure 6** shows the (490 v) voltage and (485 A) current capacity of PV array. This product of voltage and current gave rise to 238 kW which is quite close to the desired 240 kW of power that is extracted from the PV array.

The key factors under consideration are temperature and irradiance. As it is obvious from the results of Figure 7 that the change in irradiance highly disturbs the current that in turns change the power generation of PV array. Therefore, simulation results are mostly based on the impact of irradiance on PV performance.

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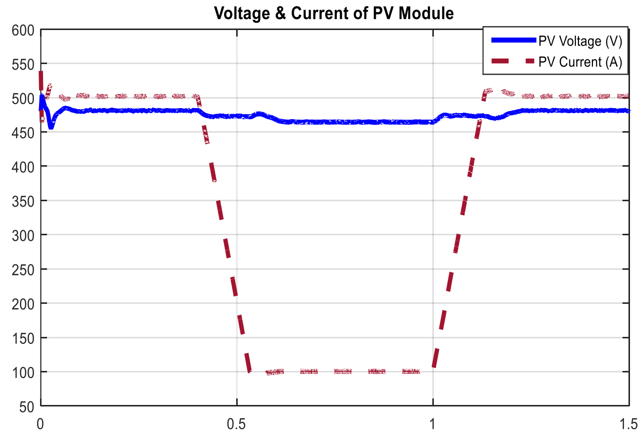

Figure 6. Voltage and Current of the PV array

C. PV analysis of array with respect to irradiance

In MATLAB / Simulink directory, initially, the behaviour of PV voltage and PV power is analysed at 1000 w/m^2 and the temperature is kept constant that is 40 C^0. In this case, we achieve almost stable PV voltage and achieved 240 kW which is the desired maximum power of the proposed PV array. Later, irradiance is slightly decreased, and a huge reduction in PV power is noticed respectively. Again, the increase in output power is examined when irradiance actor is increased. Finally, the maximum power (240 kW) appeared when irradiance value approaches to 1000 w/m^2. The simulation results related to the voltage and power of the PV array under irradiance fluctuations are depicted in **Figure 7.**

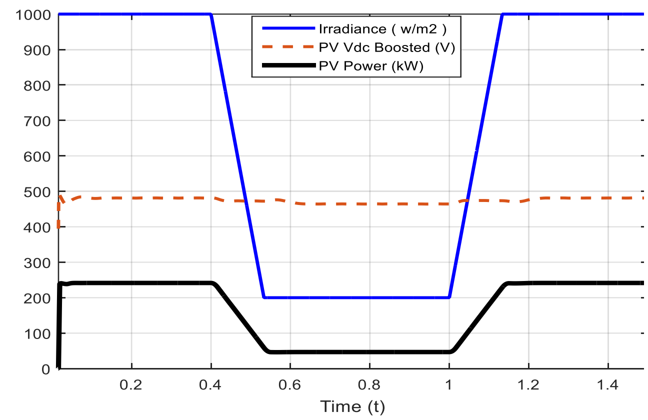

Figure 7. Impact of irradiance on PV characteristics of solar array

D. Three level DC-AC inverter analysis

The DC-AC converter is the most important electronic element which converts boosted DC voltage to AC voltage [19]. In grid-connected PV system, consumer has the right to use grid power to satisfy load demand and can sell power to grid at the time of peak load demand. However, it is important to sustain the quality of the inverted signals in PV system. In the proposed model, the single-phase grid voltage and inverted AC voltage and current are analyzed that are demonstrated in **Figure 8** and **Figure 9** respectively.

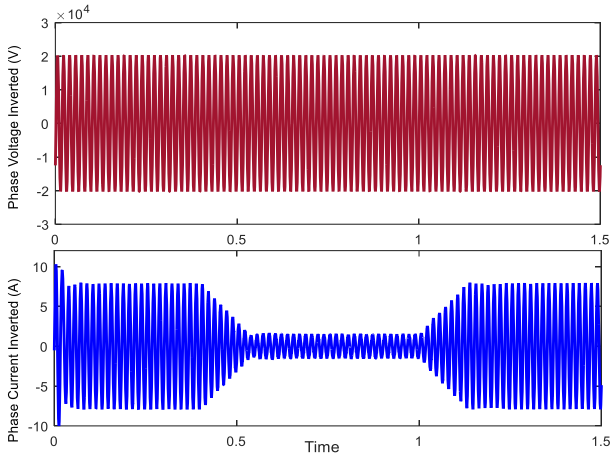

Figure 8. Single phase AC voltage and respective current

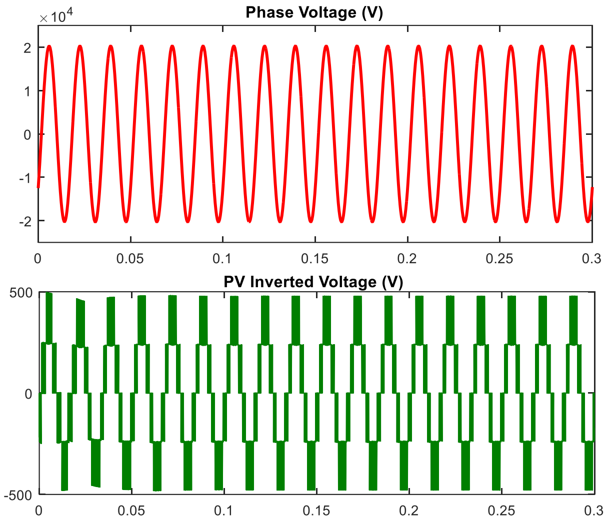

Figure 9. Grid and Inverted AC Voltage

The inverted voltage is connected to three-phase 20 kV grid. Like boost converter, the power switching device of DC-AC inverter plays a crucial role to reduce the power losses. In this model, 3 level inverter and IGBT is used as a power switch. The switching frequency is set high (3.7 kHz) to minimize the output power losses.

The output of 3 level inverter converts boosted DC voltage to desired AC voltage. As stated earlier, in this case study, the built-in model of inverter is used. However, the AC voltage is recovered but still have ripples as plotted in **Figure 10**. By increasing the levels of inverter (multi-level inverters) the ripples and harmonics in the output signal can be minimized to a significant level. As the major focus of this research is on the analysis side, to improve grid synchronization of grid-tied PV systems, the levels of inverter must be improved to achieve more quality results [20].

After inverting the voltage, a transformer is used to step the voltage level up. This AC power transmitted through a transmission line to couple with grid voltage through AC bus.

The AC voltage and current graphs are depicted in **Figure 11**. The three-phase grid AC voltage and current are plotted for analysis. The voltage level is kept constant to 20 kV and the current value is varied with respect to the change in solar irradiance.

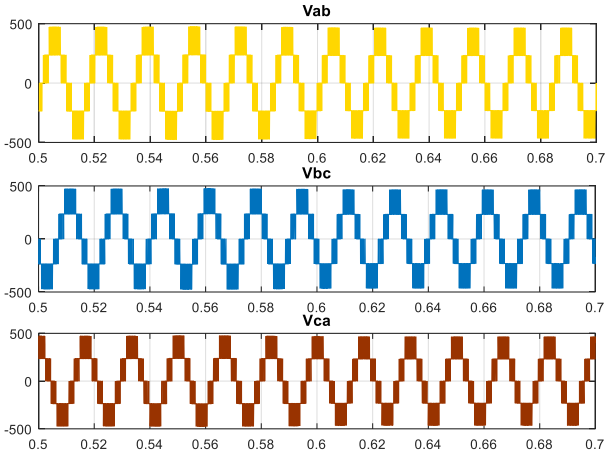

Figure 10. Three phases of inverted voltage

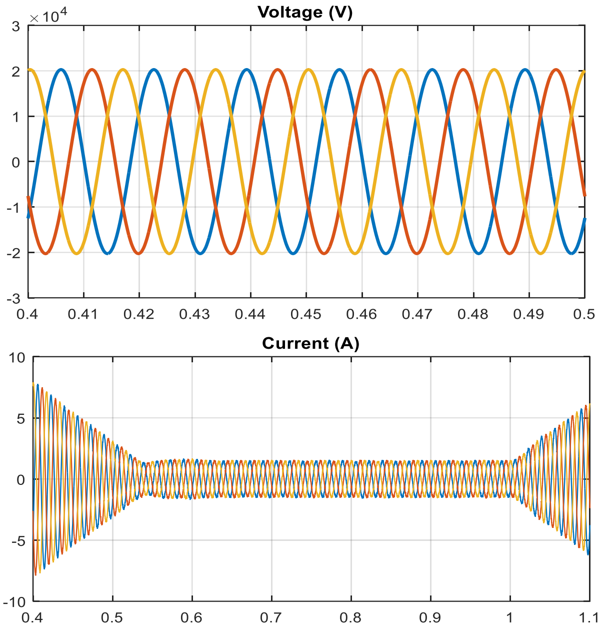

Figure 11. Inverted 3 phase voltage and currents

4. Conclusion

The major objective of this study is to analyze the performance of PV system under the influence of fluctuating environmental conditions. The key components and the operation of grid-connected PV system are first explained and the simulation is performed in MATLAB/Simulink directory on SunPower SPR 400E-WHT-D PV array. The simulation is performed to get 240 kW PV power at 1000 w/m^2 solar irradiance and 45 C^0 temperature of solar array. The analysis on boost converter, MPPT converter, 3 level bridge inverter and role of MPPT is explained. The simulation study might help the installation of PV array with feasible solar irradiance and reduce the maximum power fluctuations during rapid weather changing conditions. Moreover, the inverted voltage and current results are not considered too efficient for large scale practical applications of PV installations. Another recommendation resulting from the analysis of results is to improve grid synchronization of grid-tied PV system, the levels of inverter must be increased to improve power quality as well as reducing the switching losses. Therefore, by incorporating the suggestions of future work, the performance of PV array can be further improved. In future work, the objective is to extend this work by incorporating a hybrid power system with solar PV, wind energy, and battery banks. Moreover, adaptive/intelligent MPPT controller will be designed to improve maximum power tracking of PV, and PLL will be employed to enhance grid synchronization.

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