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Design and Analysis of Grid-Tied Photovoltaic (PV) Systems under Uncertain Weather Conditions

U. YOUNAS[1], B. AKDEMIR[1] and A. A. KULAKSIZ[1]

[1] Konya Technical University / Turkey, umair.ciitatd@gmail.com
[1]Konya Technical University / Turkey, bayakdemir@selcuk.edu.tr
[1]Konya Technical University / Turkey, afsin@selcuk.edu.tr

***Abstract* – Considering the rapid growth in global energy demand, renewable energy resources (RERs) particularly solar PV is the prominent need of modern power systems to mitigate the global energy crisis. PV is considered as one of the most useful RER, since it is inexhaustible, abundant, and clean. Besides, the power efficiency of Solar PV is highly affected by variations of solar irradiance and temperature of the solar cells. Hence, 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, 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 AC grid. This bidirectional output power with unity factor can be utilized by industrial / commercial consumers to fulfil their energy demands.**

***Keywords* - Renewable Energy, Solar PV system, MPPT, DC-DC Boost Converter, and Voltage Source Converter.**

I. INTRODUCTION

THIS rising energy demand and environmental footprints divert the attention of the modern researchers towards Renewable Energy Resources (RERs). Therefore, the deployment of RERs particularly; the integration of solar photovoltaic (PV) is growing rapidly due to its flexible applications. Solar PV is clean and viable alternate energy resource with flexible off-grid and on-grid applications that are either in stand-alone (water pumping, electric vehicle charging or battery charging, and home energy supply system) or grid-connected configuration (power can be fed to the grid) [1]. Although, 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 of solar energy is still increasing from $20\,\% - 25\%$ annually [2]. Besides, solar PV system is easy to install, less operational cost, noiseless, and environmental friendly energy resource that have capability to be deployed for large-scale grid-connected applications [3].

The key elements used in solar PV system are; PV module, DC-DC converter, battery bank, DC-AC converter, 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 with 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 of the solar cells [4]. Although, the major contribution of the article is to analyse the impact of variable weather conditions on performance of PV array. Hence, it is important to be familiar with basic knowledge of PV array.

A single PV array is composed of various PV modules. While, each PV module have different IV characteristics. A single MPPT controller can be used if all the PV modules have the same characteristics. Due to partial shading, variable temperature, and irradiance, the behaviour of PV modules may vary. Hence, separate MPPT controller is required for each PV module to operate under the maximum power conditions. In literature, various MPPT controller techniques have been used to maximize the power efficiency of solar plant. These are; perturb & observe [5], incremental conductance [6], and artificial intelligence-based control algorithms [7], [8] have been proposed. These algorithms have benefits as well as limitations in terms of computational time, complexity, and implementation cost. In addition to available control technique, the objective of the research is to cope with the fluctuating weather conditions. The authors in [9] explained briefly that the temperature of the solar PV highly affect the voltage while, Irradiance of solar PV have huge impact on current. Hence, Irradiance and temperature particularly disturb the power quality of Soar PV array.

In this paper, the key elements of grid-connected solar PV plant are discussed. First, the mathematical model of PV cell is designed and 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 boosts the output voltage of the solar PV module. Furthermore, DC-AC VSC is employed to convert boosted DC to AC voltage. This inverted AC is further coupled with the grid. The rest of the paper is organized as follows:

Section 2 presents the detailed model of solar cell, DC-DC converter modelling and operation, 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.

II. 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. The 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 day time 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.

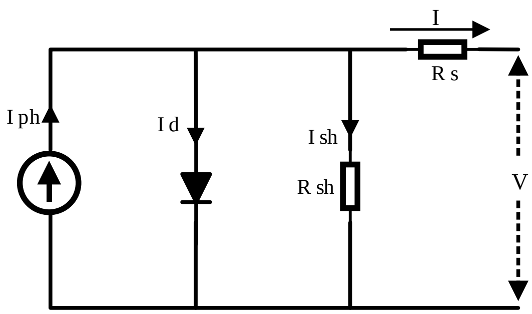

Figure 1: Equivalent model of PV cell

The equivalent model of PV cell is modelled with $\mathrm{I_{ph}}$the photo current, $\mathrm{I_d}$ diode current, $\mathrm{I_s}$ shunt current passing through $\mathrm{R_{sh}}$ shunt resistance, and total output current (I) flowing through $\mathrm{R_s}$ series resistance. $\mathrm{R_s}$ is connected in series with parallel combination of $\mathrm{R_{sh}}$ and diode [10]. $\mathrm{R_{sh}}$ represents the intrinsic behaviour of the semiconductors while, $\mathrm{R_s}$ shows the resistance between neighbour PV cells as explained by the authors in [11]. However, net current equation obtained using Kirchhoff Current Law;

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

After substituting the values of 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 proposed model not disturbing 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,

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

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*.

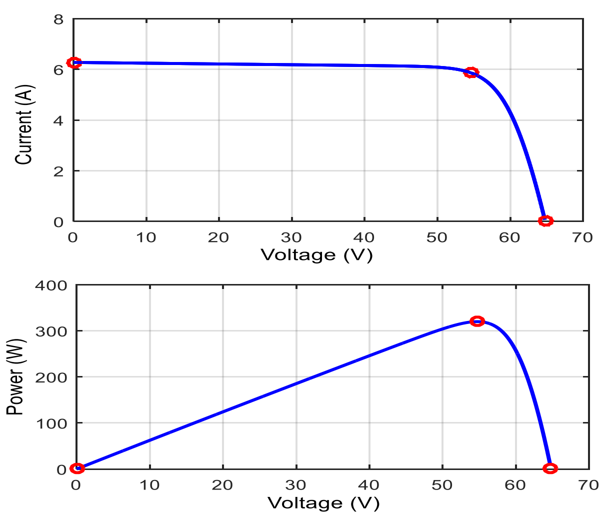

Figure 2: IV and PV characteristics of the proposed PV model

In Figure *2*, the IV and PV characteristics are performed for the proposed model. These non-linear characteristics shows 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, 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;

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

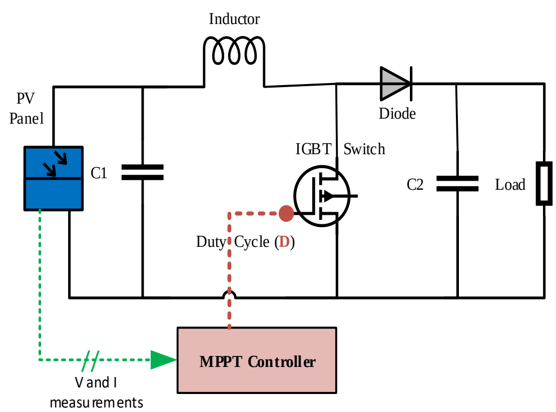

Figure 3: Model design of Boost Converter

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 [12]:

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

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

C. Proposed PV Array Model Design

The proposed model comprised of all the necessary components required for PV panel as presented in Figure *4*. The objective of the case study is for the residential level. This PV array provide maximum of 240 kw that is applicable to fulfil the normal residential load. The model use *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. While, in each module total 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 provide 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. 5 k-Hz boost converter is implemented which 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 measure 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 simulation model, the built-in inverter control block is used that have two main control loops; external control loop and internal control loop. As, total input to the VSC is 500 V DC hence, external control loop regulates the DC voltage between positive and negative 500 V and internal loop deals with grid currents.

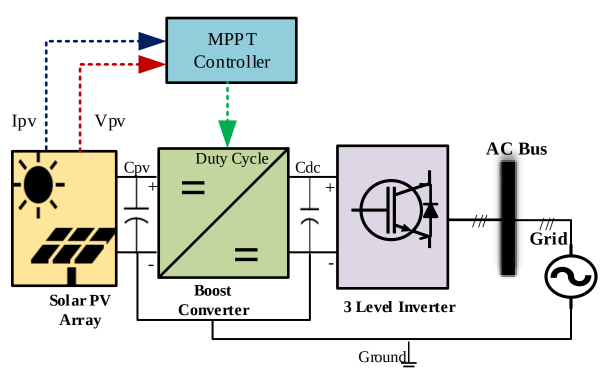

Figure 4: Proposed model design of Grid-Connected PV

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

III. 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 have less effect on power of PV array. While, PV power is highly sensitive to change in irradiance due to change in current of PV array.

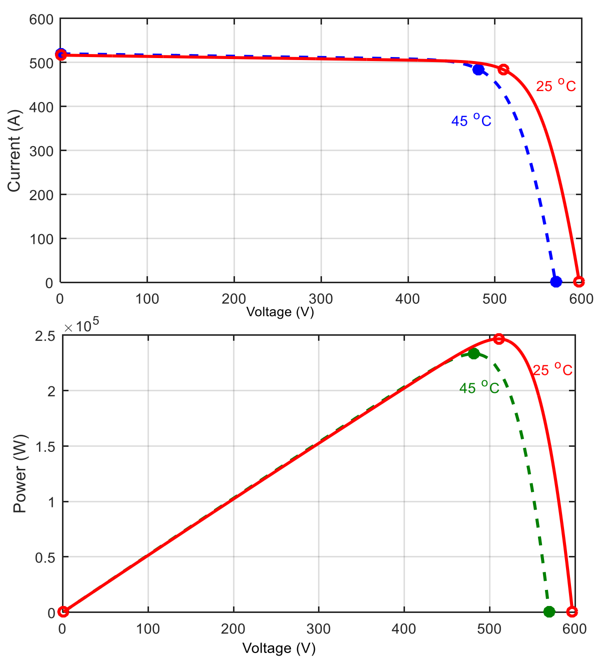

Figure 5: PV and IV characteristics of the PV array

B. Analysis of Voltage and Current of PV Array

The proposed PV array is executed to accomplish 240 kW of the 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 desired 240 kw of power that is extracted from the PV array.

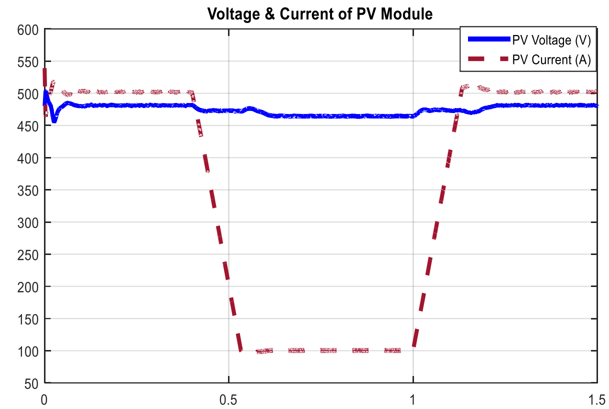

Figure 6: Voltage and Current of the PV array

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 disturb 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.

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 proposed PV array. Later, irradiance is slightly decreased, and huge reduction in PV power is noticed respectively. Again, 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 voltage and power of the PV array under irradiance fluctuations are depicted in Figure *7*.

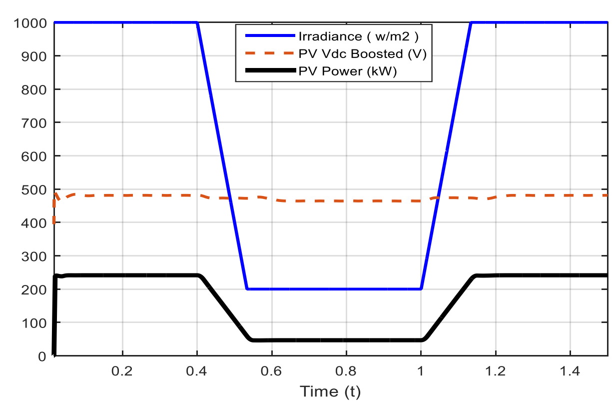

Figure 7: Impact of irradiance on PV characteristics of solar array

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 [13]. In grid-connected PV system, consumer have 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 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.

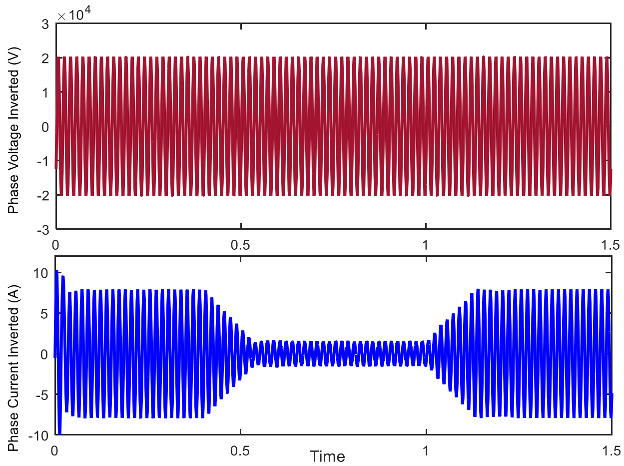

Figure 8: Single phase AC voltage and respective current

The inverted voltage is connected to three-phase 20 KV grid. Like boost converter, the power switching device of DC-AC inverter plays 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.

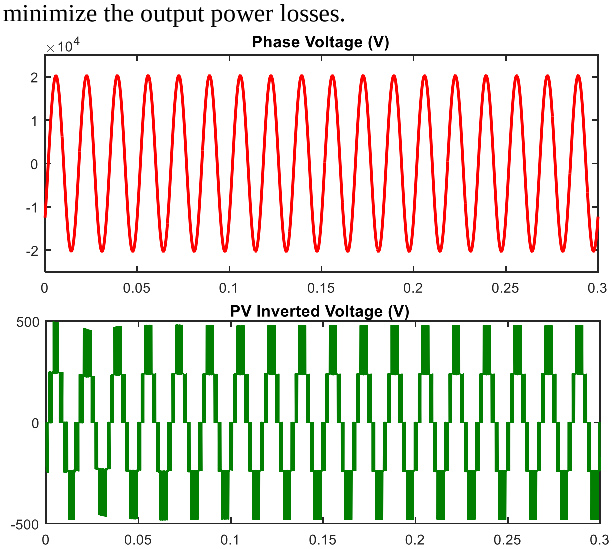

Figure 9: Grid and Inverted AC Voltage

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. Although, 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. Although, the major focus of the research is on the analysis hence, to improve grid synchronization of grid-tied PV systems the levels of inverter must be improved to achieve more quality results [14].

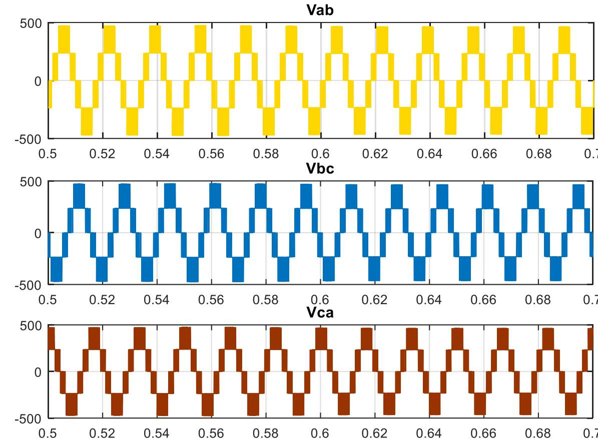

Figure 10: Three phases of inverted voltage

After inverting the voltage, 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 voltage and current at AC are plotted for analysis. The voltage level is kept constant to 20 kV while, the value of current is varied with respect to the change in solar irradiance.

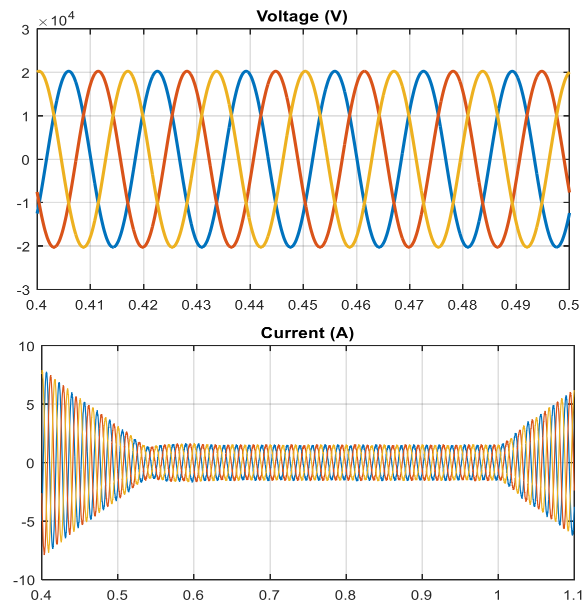

Figure 11: Inverted 3 phase voltage and curents

IV. Conclusion

The main motivation of the paper is to analyze the performance of PV system under the influence of variable weather conditions like temperature and irradiance of solar cells. 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. Therefore, by incorporating the suggestions of future work, performance of PV array can be further improved.

In future work, the objective is to extend this work by introducing hybrid power system with Solar PV, Wind energy, and battery banks will be the active participants. 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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