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Impact of Photovoltaic Microgrid System on Renewable Energy Building

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ABSTRACT

This paper analyzes the supportive function of the photovoltaic PV system in integrating the microgrid role to deliver the necessarily clean electricity to the individual dwellings. The study focuses on the merit of the flexibility in designing a renewable energy PV system in terms of power quality and quantity, in addition to reducing the air pollution by reducing the dependency on the conventional power generation station. A comparison between a direct current DC microgrid and an alternating current AC microgrid is shown in terms of system's components and requirements. The process of an algorithm for the Maximum Power Point Tracking MPPT to guarantee a higher level of harvested energy is also shown. A PV system design is introduced in this study for a desired power level generating to satisfy the electricity requirements of a small scale dwelling with a maximum power delivering capability of 9 kW. MATLAB/Simulink is adopted to investigate and evaluate the PV system performance in guaranteeing the MPPT functioning.

Keywords: Renewable Energy Sources, Microgrid System, Traditional Power Station, Photovoltaic PV Panel, MPPT Algorithm, MATLAB/Simulink
JEL Classifications: C3689, D4, Q24

NOMENCLATURE

THD Total Harmonic Distortion
V_{rms} Root Mean Square of load voltage
$V_{1,rms}$ Root Mean Square of 1st fundamental voltage
I_{PV} PV cell output current (A)
I_d Diode current (A)
I_{sh} Shunt current (A)
V_d Diode Voltage (V)
V_T Temperature voltage (V)
I_o Diode saturation current (A)
V_{PV} PV cell output voltage (V)
R_s PV cell series resistor (Ω)
R_{sh} PV cell shunt resistor (Ω)
N_s No. of PV cells in series
N_P No. of PV cells in parallel
V_{Tot} Total output voltage from a PV module
I_{Tot} Total output current from a PV module
V_{DC} *DC link voltage*
V_{MPP} Voltage at Maximum Power Point
INP Integer number of PV panels in series
SV_INP PV string voltage
SP_INP PV string power
SN_INP PV string number
P_{Tot} System total power
D Duty cycle of DC-DC boost converter

1. INTRODUCTION

Since decades ago, fossil fuel represents a main source of energy to be used in the conventional power generation stations. The massive dependency on fossil fuel in electricity generation increases noticeably the level of air pollution, and consequently causes exacerbation the global warming problem according to Hussain et al., (2014); Bierwirth, (2020); Richard and Lucy, (2014). The study in (Grainger and Stevenson, 2008) showed the installation and the performance of a conventional power station, and how the centralized station consuming extra energy as transmission and distribution lines losses, in addition to the losses in the transformers of generator side and end user side. These losses are also increases the consuming to the fossil fuels, and consequently increases the emissions of CO_2, and it increases the rate of air pollution.

The conventional electricity generation station depends on a centralized process in generating and delivering the electrical power to the end users as mentioned from Ali, (2020); Hussain, (2020); Hussain, (2017). The level of the losses due to the transmission lines and the transformers is proportional with the drawn currents. In addition, many studies (Anyaka and Olawoore, 2014; Chapman, 2003; Blaabjerg et al., 2006) explained that the alternating generator as a first part in the electricity generation in power station works through the principle of rotating a magnet inside a stator coil. Many turbines that rotate the rotor are working by an external mechanical effect that can be done using steam energy which is obtained by fossil fuels.

The unidirectional electrical power generation, and transmission from power a conventional power station to the end users have disadvantages which are representing by, firstly, the instability in the electricity pricing which is based on the electrical power demand, units operations and maintenance operations, and the daily fossil fuels price. The second disadvantage of the only reliance on the conventional power station is the lack of control and treatment to the case of unbalance load currents of the three phase electrical network. The third disadvantage is the energy losses due to the consumed power in the resistance of transmission and distribution lines. as well as the limited capability for any required increase in the size of the network due to the limitation in the infrastructure of the conventional power station and network (Abdullah et al, 2020; Farhad et al., 2016; Hosham et al., 2018).

The dependency on the fossil fuels leads to dwindling these fossil fuels, and at the same time it gives a great impetus to search for effective alternatives that could reduce the negative impacts of fossil fuels on energy users and the population in general.

In addition to the above explained demerits of the conventional power station and grid, regarding the individual dwellings, which may be in places far from the boundaries of the electrical network, a microgrid of a photovoltaic system represents an efficient alternative that meets the electrical demands of far individual dwellings.

This paper discusses the above points in details, and proposes a certain general steps to design a suitable PV system for any power delivering capacity. The paper remaining is arranged as follows; the motivation of transferring to the decentralized distributed microgrid, and the comparison between the direct current and the alternating current microgrids are shown in Section 2. The positive effect of inserting a Maximum Power Point MPP tracker to the PV system of the microgrid is explained in Section 3. Section 4 shows the design steps of a 9 kW PV system. Section 5 analyzes the collected simulation results, whereas the concluded points are discussed in Section 6.

2. MICROGRID SYSTEMS BASED ON RENEWABLE SOLAR ENERGY

The photovoltaic microgrid system is a power generation system, it can be a grid connected or a standalone system. The microgrid offers the capability of harvesting solar energy and converting it to an electrical power to be delivered to the electrical appliances and/or export the extra power to the connected grid, so it can be represented by a bi-directional grid (Hussain, 2020; Hussain, 2019; Michael et al., 2017). In other words, the microgrid boosts the conventional grid by satisfying the power requirements of the local load, and at the same time reducing the power demands from the grid. Moreover, microgrid based on the clean renewable energy sources such as solar photovoltaic is noticeably contributing in reducing the air pollution. Consequently, PV based microgrid mitigating the global warming problem through its role as an effective alternative to fossil fuel energy. Many researchers have explained the positive impact of using clean renewable energy on the general population through its use as an energy source for operating electric vehicles and other moving machines such as tractors, conveyers, cranes, and trains (Arellano et al., 2013; Galus et al., 2010; Guille and Gross, 2009).

Renewable solar photovoltaic cell/panel is effectively converting the solar energy into a direct current electrical power with a certain level positively proportional with the incident light intensity and negatively proportional with the level of ambient temperature (Hussain, 2018; Hussain and Fernando, 2019; Hussain and Khaled, 2020), whereas the level of the desired power can be obtained by connecting a number of PV panels in a suitable arrangement of parallel and serial connection among the included panels.

There are three types of microgrids; alternating current microgrid, and direct current microgrid, and hybrid microgrid which includes mixing of microgrids of alternating current AC and direct current DC (Guille and Gross, 2009).

2.1. Alternating Current Microgrid

The AC microgrid based on PV solar energy is supplied by the DC voltage of the PV array, then based on the system design, the microgrid produces a suitable alternative voltage to the AC appliances. In addition to the PV matrix and the DC-DC converter, the AC microgrid includes single phase or three phase DC to AC inverter, low pass power filter, and step up or step down insulation transformer. Total Harmonics Distortion THD as explained by Attia et al., (2013); Attia et al., (2016); M. A. Razzak et al., (2016), represents an important parameter considered to evaluate the quality of the produced alternating voltage waveform 50 Hz, or 60 Hz, especially when decide to connect the AC microgrid to the conventional grid, the level of THD should be less than 5%:

$$THD = \frac{\sqrt{V_{rms}^2 - V_{1,rms}^2}}{V_{rms}^2} \quad (1)$$

Where V_{rms} represents the root mean square value of the AC load voltage, and $V_{1,rms}$ represents the root mean square value of the first fundamental component.

2.2. Direct Current Microgrid

The direct current DC microgrid based on PV solar energy is supplied by the DC voltage of the PV array, then based on the system design, the microgrid produces a suitable direct voltage to the DC appliances. This microgrid can be used to supply the direct current appliances such as a standalone dwellings which are contenting direct current electrical appliances. In addition to the PV matrix, the main part in this type of microgrid is the DC-DC converter and the Maximum Power Point Tracking algorithm MPPT which inserted to control the width of the converter driving pulses that to guarantee harvesting maximum level of electrical power after converting from the received solar energy (Abdourraziq and Maaroufi, 2017; N. Kalaiarasi et al., 2014; Tilak and Kuldeep, 2011).

3. PROPOSED TWO VOLTAGE STEPS P AND O ALGORITHM

The solar energy represented by the incident solar can be converted to direct current DC electrical power through the photovoltaic PV cell. The DC electricity produced by the PV cell is affected by the weather conditions, such as, the ambient temperature and the light intensity. The instantaneous quantity of the delivered power which represented by the instantaneous output voltage and current from the PV cell, a high power quantity can be harvested at a high incident light and a low ambient temperature, whereas, a low power quantity will be harvested at a low light intensity and a high ambient temperature as explained in (2) – (6) with respect to the PV cell equivalent circuit of Figure 1.

$$I_d = I_0\left[e^{\frac{V_d}{V_T}} - 1\right] \quad (2)$$

$$I_{ph} = qAG_r\left[I_n + I_p\right] \quad (3)$$

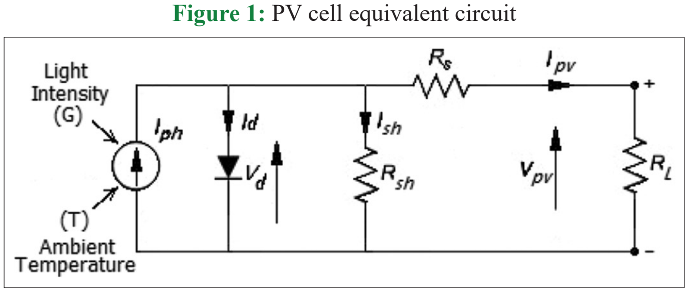
$$I_{sh} = \frac{V_d}{R_{sh}} \quad (4)$$

$$I_{PV} = I_{ph} - I_d - I_{sh} \quad (5)$$

$$V_{PV} = V_d - R_S I_{PV} \quad (6)$$

Where V_{PV} is the PV cell output voltage in volt, I_{PV} is the PV cell output current in Amp, I_{ph} is the incident light current in Amp, I_o is the diode reverse saturation current in Amp, R_S is the serial resistor in Ohm, R_{sh} is the parallel resistor in Ohm, L_n and L_p are the electron and hole diffusion length respectively, G_r is a generation rate, A is a cell area, whereas $V_T = kT_c/q$ which represents the thermal voltage in volt, T_c is the cell temperature, q is the charge of an electron, and k is Boltzmann's constant (Abdourraziq and Maaroufi, 2017; N. Kalaiarasi et al., 2014; Tilak and Kuldeep, 2011).

Figure 1: PV cell equivalent circuit



The selected photovoltaic module APOS Energy AS140 of specifications shown in the Table 1 below is considered for further steps in this study.

Figure 2 shows the PV module characteristics in terms of the output current and output power at constant ambient temperature of 25°C and different light intensity levels (Red: 100 W/m^2, Blue: 500 W/m^2, and Green: 1000 W/m^2). Figure 3 shows the characteristics at constant light intensity 1000 W/m^2 and different values of ambient temperature (Green: 0°C, Blue: 25°C, and Red: 50°C).

Connecting the PV panels in series of N_S panels and in parallel N_P panels is leading to have higher total voltage ($V_{Tot} = N_S \times V_{PV}$) and current ($I_{Tot} = N_P \times I_{PV}$) respectively from the photovoltaic matrix.

Based on the fact of that the level of produced power from the PV panel is affected by the instantaneous levels of light intensity and the ambient temperature, and for each weather condition there is a maximum power point. Different algorithms have proposed from the researcher to guarantee working the PV panel within the MPP location to harvest maximum power during the variation in the weather conditions. Many conventional algorithms have proposed to track the reference value of the voltage at the MPP, such as Perturb and Observe P and O algorithm, and Incremental Conductance IC algorithm. Modern algorithms and controller have also proposed to predict the reference voltage or to facilitate the way of reference voltage tracking, such as, Artificial Neural Networks ANN algorithm, and Fuzzy Logic Control FLC controller (Abdourraziq and Maaroufi, 2017; N. Kalaiarasi et al., 2014; Tilak and Kuldeep, 2011).

4. DESIGN STEPS OF A MID-SCALE 9 KW MICROGRID PV SYSTEM

The desired PV system is able to produce 9 kW, and based on the daily five hours period of harvesting solar energy by a solar photovoltaic system (Hussain and Khaled, 2020), the maximum kW hours energy which daily harvested is shown in (7).

$$\text{Harvested Energy} = P \times t \text{ (W.h} \quad (7)$$

Table 1: Specifications of the selected PV panel module APOS Energy AS140

Module parameter	Parameter value
Power (W) at maximum power point MPP	139.2 W
Output voltage at MPP	17.76 V
Output current at MPP	7.84 A
Open circuit voltage (V_{oc})	22.33 V
Short circuit current (I_{sc})	8.51 A
No. of cells Ncell	36
Parallel resistor Rsh	65.8898 Ω
Serial resistor RS	0.26294 Ω

So, 9 kW × 5 h = 45 kW Hours can be harvested from the desired PV system. This energy can be delivered to the connected AC or DC appliances, or it can be sold to the electrical grid after connecting the suitable rated power inverter, and power filter with/without insulation transformer. The avoidable cost due to the use of renewable energy can be calculated by (8):

$$\text{Avoidable cost}=\text{No.of kW.h} \times \text{cost of 1 kW.h} \quad (8)$$

Regardless the type of the connected electrical appliances, the designed photovoltaic system should deliver the required rated power and DC voltage that to either connect to DC loads or to connect to DC/AC inverter, this paper explains the design steps of a PV system to be able to produce 9 kW, or 45 kW hours daily with guaranteeing the MPPT working condition during the day hours.

Figure 4 mentions the common measures to design a photovoltaic system for any desired level of a rated power:

Figure 2: Characteristics of the PV module APOS Energy AS140 during constant ambient temperature 25°C and three different levels of light intensity (Red: 100 W/m2, Blue: 500 W/m2, and Green: 1000 W/m2); (a) Output current curves, (b) Output power curves

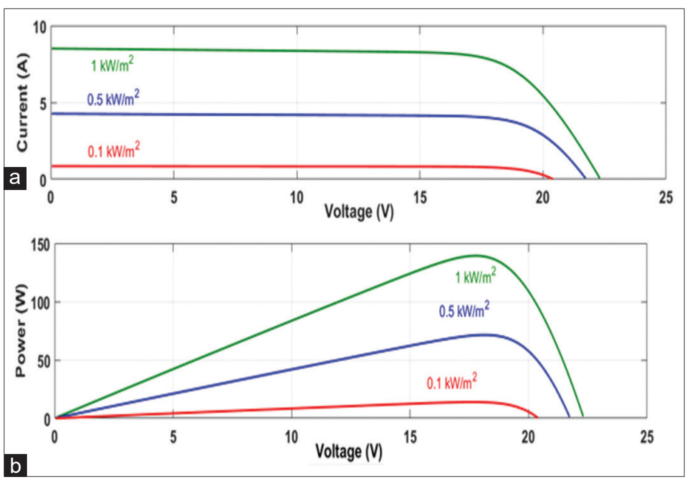
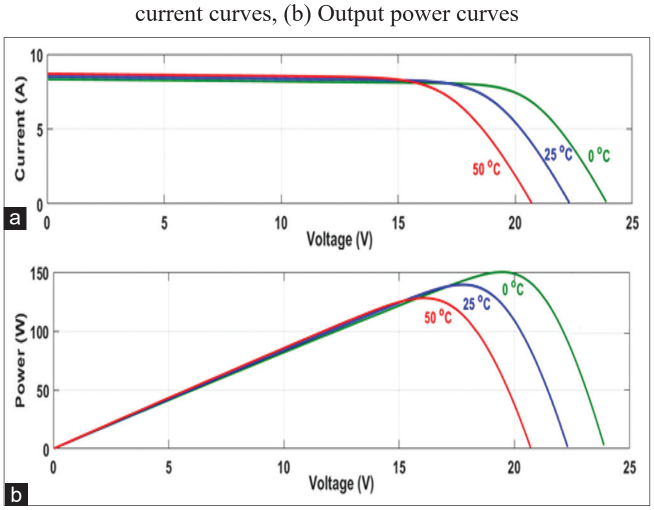


Figure 3: Characteristics of the PV module APOS Energy AS140 during constant light intensity 1000 W/m2, and three different ambient temperature (Green: 0°C, Blue: 25°C, and Red: 50 °C); (a) Output current curves, (b) Output power curves



The total number of photovoltaic panels in series connection of one string equals the number of serially connected PV panels NM in a one string, as discussed by Ali, (2020); Hussain, (2019), which equals the value of DC link voltage V_{DC} divided by the MPP voltage V_{MPP}:

$$No.of\ PV\ panels\ in\ one\ string = N\_PV\ Panels = \frac{V_{DC}}{V_{MPP}} \quad (9)$$

The Integer Number of PV Panels (INP) in one string is the higher integer number which is greater than the measured number of (12):

$$\text{INP} = \text{Integer number } (\geq \text{N\_PV Panels}) \quad (10)$$

The string voltage of the integer number of PV panels SV_INP equals to:

$$\text{SV\_INP}=\text{INP} \times \text{V}_{\text{MPP}} \quad (11)$$

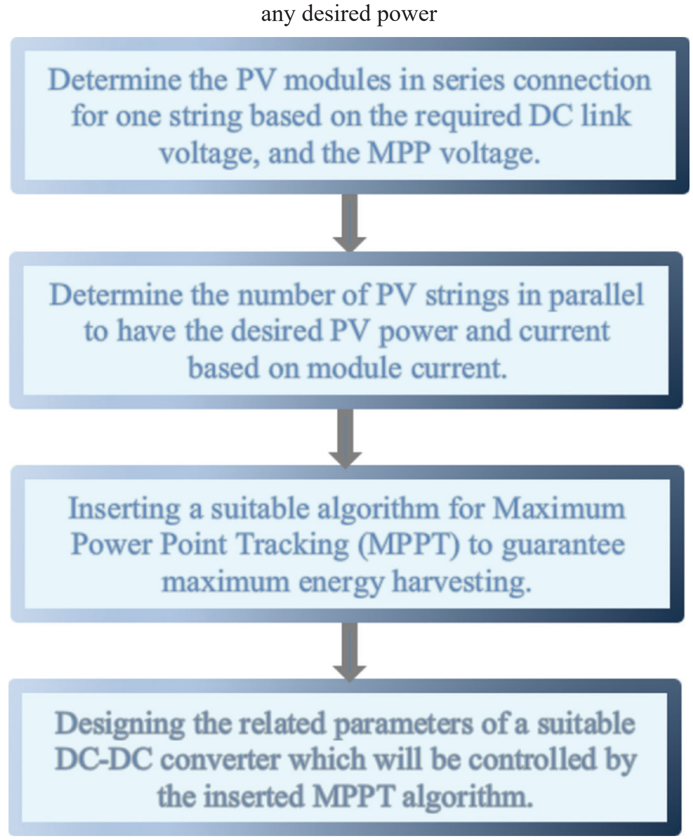
The quantity of the delivered power from a string of INP panels is SP_INP which can be determined by considering the total number of PV panels in one string INP and the panel power at maximum power point P_{MPP} condition (12):

$$\text{SV\_INP}=\text{INP} \times \text{P}_{\text{MPP}} \quad (12)$$

The rated power of one string SP_INP can be considered to determine the total number of PV strings SN_INP for the whole PV array of the desired PV system in any system rated power P_{Tot}:

$$SN\_INP = \frac{P_{Tot}}{SP\_INP} \quad (13)$$

Figure 4: The common measures to design a photovoltaic system for any desired power



Considering the required rated power 9 kW of the desired mid-scale PV system, and considering the total required 35 kW·hours for each daily five hours PV panels power harvesting (Hussain and Khaled, 2020).

For AC electrical appliances of 220 V to 230 V or for DC appliances, DC link voltage 380 V is suitable to be produced from the DC-DC converter.

The DC link voltage of 380 V, and the MPP voltage 17.76 V of the system PV panel module (APOS Energy AS140) used in (9), and (10) to determine the number of PV panels serially connected in one string:

$$N\_PV\ Panels = \frac{V_{DC}}{V_{MPP}} = \frac{380V}{17.76V} = 21.4$$

So, the nearest higher integer is *INP* = 22 PV Panels.
The actual string voltage based on the 22 PV panels will equal to:

$SV\_INP = INP \times V_{MPP} = 22 \times 17.76\ V = 390.7\ V$

The total power can be delivered from 22 PV string based on (12) will be

$SP\_INT = INP \times P_{MPP} = 22 \times 139.2\ W = 3062.4\ W$

For realizing 9 kW rated power, the number of required PV string can be obtained from (13)

$$SN\_INP = \frac{P_{Tot}}{SP\_INP} = \frac{9kW}{3.06kW} = 2.94$$

So, the total number of required PV strings is 3. For the case of using step-up DC-DC boost converter of the below relationship in which input DC link voltage V_{dc}, output load voltage V_o, and duty cycle ratio *D*, it can work around *D* = 0.5 (Danial, 2011).

$$V_o = \frac{V_{in}}{1-D} \qquad (14)$$

In other words, dc link voltage of 190 V can be adopted to be boosted to 380 V. In this case, 11 PV panels serially connected in one string will be used instead of 22 panels, and to have 9 kW rated PV system, and the number of string will be 6 instead of 3.

The suitable design and connection of the PV array is shown in Figure 5, the array of PV modules of APOS Energy AS140, at Maximum Power Point Tracking condition guarantees harvesting 9 kW.

5. SIMULATION RESULTS AND ANALYSIS

The design of this study is evaluated through MATLAB/Simulink, firstly, the proposed PV array of 6 string and 11 PV modules in each string is tested and the behavior is demonstrated in Figure 6 below in which, at the MPP working condition, the total output current equals to 7.84 A × 6 = 47 A, the total output voltage

Figure 5: The PV array arrangement using 66 PV panels of module APOS Energy AS140 for 9 kW PV system

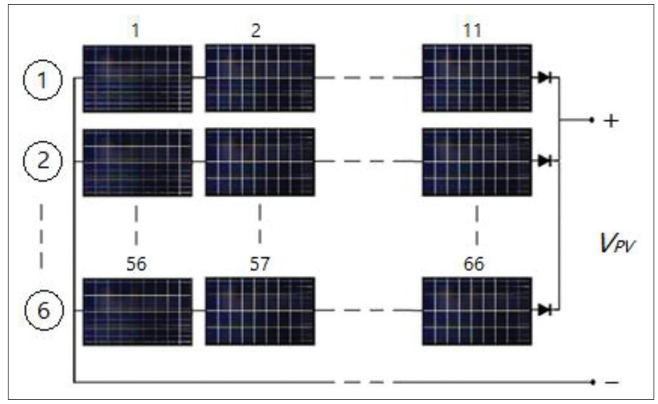


Figure 6: The behavior of 9 kW PV array 6 strings × 11 panels using PV module APOS Energy AS140 in terms of output current and output power at different light intensity and 25°C ambient temperature

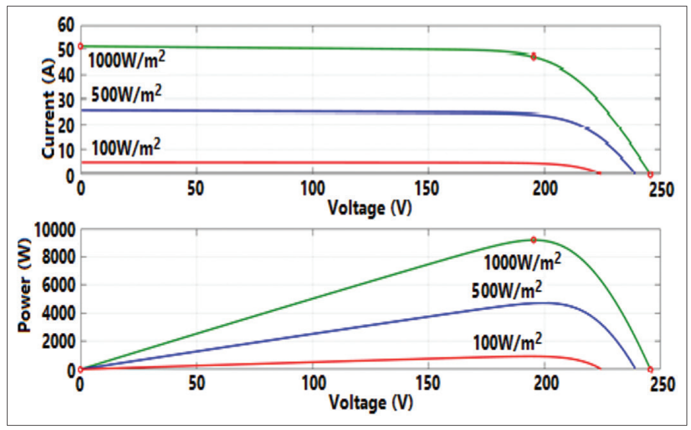


Figure 7: Simulation results of 9 kW PV system at different light intensity and different load; from up to down: light intensity irradiance level, load resistance, Duty cycle, load voltage, and load power

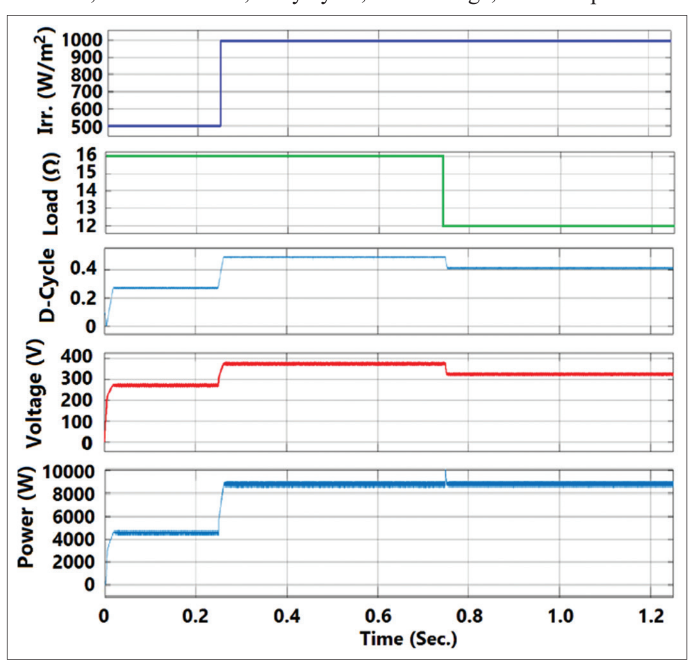


Table 2: Designed parameters of the inserted boost DC-DC converter

Converter parameter	Parameter value
Inductor	0.25 mH
Capacitor	220 μF
Load resistor	16 Ω
Load rated power	9 kW
Switching frequency	10 kHz

equals to 17.76 V × 11 = 195.36 V, and the total output power approximately equals to 9180 W.

A boost DC-DC converter is designed and inserted in the PV system to guarantee the working conditions of maximum power point tracking, the converter design is done based on the steps of Danial, (2011). Table 2 shows the designed parameters of the converter. An algorithm of Perturb and Observe (Hussain, 2018) is selected and inserted to control the boost converter to guarantee the MPPT working condition, the simulation results are recorded for 1.25 s divider to five equal subdivision of 0.25 s.

Full simulation results are shown in Figure 7 below, in which light intensity of 500 W/m^2 is selected for the first time division, then set to be 1000 W/m^2, whereas the connected load is 16 Ω for the first three divisions, then at time of 0.75 s, the load reduced to be 12 Ω. The duty cycle is controlled by the inserted MPPT algorithm; it is noticeable that the duty cycle is varied from 0.25 to 0.5 that to have maximum load power. Figure 7 shows load voltage and how it is affected by the weather and load conditions to guarantee the maximum load power at any level of light intensity.

6. CONCLUSION

This study focused on demonstrating the consequences of a full dependency on the traditional power grid and what the kind of benefits by partially or totally using the renewable energy sources to reduce the traditional grid dependency step by step. This study mentioned the difference between the DC appliances photovoltaic system and AC appliances PV system from the points of system components, and process. A generalized procedure to design any desired PV system for any rated power and shown and discussed, and relationships written. A design of a practical sample of 9 kW PV system for mid-scale building rated power, with all the relation relations have shown. A boost DC-DC converter with a controlled algorithm of Perturb and Observe for MPPT functioning are also inserted in the PV system design. The proposed PV system design and simulation have simulated and evaluated using MATLAB/Simulink, the simulation results and the results analysis reflects the effectiveness and the success of this study proposal in terms of PV array arrangement, the system rated power with respect to the inserted MPPT algorithm, duty cycle control for different weather condition and different load level.

7. ACKNOWLEDGMENT

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