Abstract— Photovoltaic systems are becoming part of our daily life experience. One of the main issues is their low efficiency. In order to optimize their performance and enhance their efficiency, a complete understanding of their operation is a must. In this paper a complete model for a stand-alone PV system is presented. The system consists of a PV module, DC/DC Buck converter, Maximum Power Tracker, and a load. The mathematical models of these components are implemented in Matlab/Simulink. The system is tested under different temperature and radiation conditions. The parameters that affect the performance of the system are investigated. Increasing the frequency of the MPPT controller enhances the speed of the system which is needed in fast changing weather conditions. With the PI controller the performance of the system is improved. The models used in the paper can be used for educational or research purposes.

Keywords—PV system; maximum power point; stand-alone;

I. INTRODUCTION

Humanity has relied on fossil fuel in the last few hundred years. The conventional energy sources such as oil, gas, coal and uranium have some shortcomings; they are depleted and they have many energy-related environmental problems. The emission of carbon dioxide led to the rise of the earth temperature, the phenomena which is called the Global Warming. These reasons along with the ever growing energy demand forces the governments around the world to adopt plans for increasing the renewable energy share in the energy global market. Among these renewable energy sources, solar energy is the most elegant and fascinating renewable technology. Solar energy is free and does not harm the environment. Photovoltaic System (PV) is one of the exciting new technology to convert sunlight directly into electricity. According to the learning curve we are entering a new era where the price of PV cells has dropped near to $ 1/Wp [1]. Photovoltaic energy systems are becoming part of our daily life in many developing countries. Nowadays millions of Photovoltaic (PV) modules are installed on rooftops and building facades [1].

PV system can be classified in two main categories; grid-connected and stand-alone PV systems. In the grid-connected PV system the power is directly fed into the grid. In stand-alone systems the loads are usually located at remote areas where there is no access to the grid. Stand-alone PV systems are becoming used widely in many applications and they have great potential especially in remote areas where there is no excess to grid and installing utilities lines is uneconomical. It is estimated that the cost of a mile of a 230-kV is 1 million dollar [2].

Libya is one of the countries blessed with plenty of the solar energy resource. The average solar radiation in Libya is around 7.5 kWh/m²/day with about 3000 to 3500 sunshine hours per year [3]. There are a number stand-alone PV systems installed in Libya. The applications of PV in Libya begun in 1970s where small-scale and medium-scale stand-alone PV systems are used for communications, cathodic protection, rural electrification and water pumping. However is blessed with such a huge renewable energy resources, their share in electricity production is still negligible.

The main issue in PV systems is the fluctuation caused by the variations in weather conditions. These fluctuations cause variations in the temperature and the radiation on hourly and daily basis. When the PV module or array is directly connected to the load a specific current flows through the load and a voltage is built across the load terminals. As the weather changes the temperature and the radiation change, and of course the maximum power point moves away. In order to maximize the power all the time a variable load should be connected. This could be achieved by inserting a power conditioning circuit between the PV module and the load. These circuits are the switching power converters. The most widely used converter is the Buck DC/DC converter equipped with an MPPT (Maximum Power Point Tracker) controller. There are many maximum power tracking algorithms reported in the literature. The system under consideration in this paper is shown in Figure. 1. There are a lot of publications in the area of modeling PV systems. In our work we focus on the effect of the controller parameters on the system performance.

Figure 1. A Stand-alone PV system
Modeling and control of PV systems are very important in the area of education, research and development. The paper focuses on the modeling of the PV system and the effect of the MPPT parameters on the system dynamics. The system consists of a PV module, DC-DC Buck converter and MPPT controller. The models of these components are built using Matlab/Simulink. The implemented models can be used for educational or research purposes. Many different simulation scenarios are carried out to investigate the role of the controller parameters. The MPPT is improved using PI controller where the duty cycle direct control is used. The paper starts with the modeling of the main components which are the PV module, the DC/DC converter and the MPPT controller. Then the effect of the temperature and the radiation on the maximum power point is investigated. The controller is tested under different weather conditions.

II. THE MATHEMATICAL MODEL OF THE PV MODULE

PV solar cells are made from semiconductor material and rely on the photoelectric effect to generate electricity. The most widely used semiconductor for terrestrial applications is the silicon. The basic PV cell is the p-n junction shown in Figure 2.

In the dark the characteristics of the PV cell is similar to the normal diode. When sunlight with energy greater than the semiconductor energy gap hits the cell electrons becomes free and a considerable current flows in the external circuit. As PV cells are fragile and have low voltage they grouped into modules encapsulated from front and supported by metallic panel for protection. The modules are then connected in series and parallel to form an array as shown in Figure 3. Many studies focus on modeling the PV cell instead of the PV module [4,5]. This is not practical because the manufacturer provides the module data not the cell data. In order to obtain the IV and PV curves a mathematical model must be derived. There are many methods for modeling PV modules in the literature [6]. The model derived in this paper is based on the single-diode model [7] and extracting some of the parameters from the manufacturer data sheet [8]. The electrical circuit model is shown in Figure 4. The model used in the paper is with middle complexity where the temperature dependence of $I_0$, $I_{ph}$, and $V_{oc}$ are included. Also the parasitic resistances $R_s$ and $R_{sh}$ and their temperature dependence are considered. The ideality factor is used as a variable to match the simulated data with the manufacturing data.

The mathematical model of a solar cell based on the single diode model is given as [8]:

$$I(T,G,V) = I_{ph} - I_0(e^{(V+IR_s)/nV_kT} - 1) - (V + I \cdot R_s)/R_{sh}$$

where the variables in (1) are given as:

$$I_{ph} = I_{ph} \cdot G/G_{nom}$$

$$I_{ph}(T) = I_{ph} + K_c(T-T_{aux})$$

$$K_s = (I_{ph}(T_1) - I_{ph}(T_2))/(T_2 - T_1)$$

$$I_0 = I_{oc}(T_1)(T/T_1)\beta \cdot e^{(qE_{g}/kT) - 1}$$

$$I_s(T) = I_{ac}(T)(e^{(qE_{g}/kT) - 1})$$

$$R(T) = -dV/dI_{ph} - 1/(I_{ph} \cdot q/nkT \cdot e^{(qE_{g}/kT)})$$

$$R_{sh} = V_{oc}/(I_{ph} - e^{(qE_{g}/kT) - 1})$$

$$R_s(T) = R_s \cdot (T/T_{aux})^\gamma$$

The parameters in the model are explained briefly. $I_{ph}$ is the photo generated current in Amperes. $I_{ph}$ is the photo generated current at the nominal radiation. $I_0$ is the diode dark saturation current. $I_d$ is the diode dark current. $I_{sh}$ is the shunt current. $R_s$ is the series resistance. $R_{sh}$ is the shunt resistance. $G$ is the solar radiation in $W/m^2$. The $G_{nom}$ is the radiation the PV module is calibrated at. $n$ is the ideality factor. $e$ is the electron charge. $k$ is Boltzmann’s constant. $V_g$ is the semiconductor energy gap. $K_0$ is the short-circuit current temperature coefficient. $V_{th}$ is the thermal voltage and given by $V_{th} = nkT/e$. The manufacturer provides the following: $N_0$: the number of cells in series, $N_p$: the number of series per module.
number of cells in parallel, $I_{sc}$: the short-circuit current, $V_{oc}$: the open-circuit voltage, $K_c$: the short-circuit current temperature coefficient. The Solarex MSX60 60W module is used in the simulation. The equations from (1) to (9) are implemented in Matlab/Simulink and shown in Figure 5.

After extracting the parameters the masked PV module is shown in Figure 6 along with the mask. The PV module can be used as circuit element in SimPowerSystem/Matlab toolbox and does not need extra interface as the solar cell in Simscape/Matlab toolbox [5].

When the PV module is connected to a load a specific current will flow through the load and a voltage will be built across the load terminals. The IV characteristics are shown in Figure 7. The radiation is set to 1000 $W/m^2$ and the cell temperature is 25°C. When the terminal of the module is short circuited a maximum current flows, this current is known as the short-circuit current. As the load resistance increases the operating point moves to the right and the power increases. At a point called the maximum power point (MPP) the power reaches to its maximum. Increasing the point to the right of the MPP, the load is decreased and the power is reduced. At a very high load resistance the current is zero, the voltage at this point is the open-circuit voltage. In order to harvest maximum power the load should equal $R_{mpp}$ and this is impractical because the weather is keep changing and as a result the radiation and the temperature change.

In order to understand the behavior of the PV module simulations are carried out. The effect of the temperature on the IV and PV characteristics are shown in Figure 8 and Figure 9. The effect of the radiation on the IV and PV characteristics are shown in Figure 10 and Figure 11.
It is clear that as the temperature increases the short-circuit current increases slightly while the open-circuit is reduced. The resultant effect is a reduction in the PV module power as the temperature of the cell rises. The radiation has a stronger effect on the characteristics of the PV module. As the radiation is increased the current increases linearly with the radiation and the voltage increases logarithmically. The generated power increases as the radiation increases.

III. THE MAXIMUM POWER POINT

The MPP changes with the temperature and the radiation. Figure 12 shows the variation of the MPP with both the temperature and the radiation. The MPP increases with the radiation and decreases with the temperature increase. For desert climate such as the weather in Libya the radiation is very high and the temperature of the cell will be also very high like the situation the Sahara Desert. From Figure 12, areas with lower radiation as the coastal line on the Mediterranean may have higher potential for PV because the average temperature is lower than the center and the far south of Libya. Additionally, some studies reported performance degradation of PV modules in the desert because of the very high temperature and sand accumulation due to the sand storms [9].

From Figure 12 the MPP changes with the weather and in order for the DC/DC converter to match the MPP the range of the weather change need to be identified. For each radiation level and temperature degree there is a load that achieves the MPP. Every MPP in Figure 12 corresponds to an optimum load value. The load is plotted as a function of the radiation and the temperature and is shown in Figure 13. The optimum resistance changes slightly with the temperature. The radiation has a strong effect of the optimum resistance where the relation is nonlinear.

For radiation levels larger than 500 $W/m^2$ the optimum resistance decreases linearly. At low radiation levels below (500 $W/m^2$) the relation is nonlinear. When the radiation is very low the optimum resistance becomes very large and this is because the maximum power is reduced at these levels. In stand-alone PV systems design it is important to find the range of the variation in the optimum resistance associated with a given weather data.

![Figure 11. The effect of the radiation on the PV characteristics](image1)

![Figure 12. The MPP as function of the radiation and the temperature](image2)

![Figure 13. The optimum resistance as function of the radiation and the temperature](image3)

![Figure 14. The Perturb and Observe Algorithm](image4)

There are many techniques for maximum power tracking [10]. The most widely used method in practice is the perturb and observe method (P&O) [11]. The basic concept of P&O is shown in Figure 14. Suppose that the load forces the PV curve to operate at point A in Figure 7 which is too far from the MPP. The voltage is perturbed by small increment to the right, then the power will change, $AP$. If $AP$ is positive then the MPP is to the right and if $AP$ is negative then the MPP is to the left. The perturbation continues along the PV curve until the MPP is reached. The Matlab/Simulink implementation of the P&O algorithm is shown in Figure 15.
The main advantage of this algorithm is its simplicity, however, it has shortcomings. At low irradiance conditions the PV curve is flatten which makes it difficult to find the MPP. Another disadvantage is the oscillation around the MPP. At very rapidly changing weather P&O may show erratic behavior which is called the fake MPP [10].

IV. DC/DC BUCK CONVERTER

DC/DC converters are used as matching circuits between renewable energy sources and the loads. The DC/DC converter works as a variable load in order to achieve power maximization. The Buck converter simulated using SimPowerSystems Matlab/toolbox is shown in Figure 16. The input is directly connected to the PV Module. The gate of the MOSFET is fired through the PWM which is derived by the MPPT controller.

The parameters of the Buck converter are shown in Figure 16. The Buck converter works as a variable resistor controlled by the duty cycle of the PWM generator. For the ideal DC/DC Buck converter the following equations hold:

\[ \frac{V_{out}}{V_{in}} = \frac{I_{out}}{I_{in}} = D \]  

\[ R_{eq} = \frac{R_{in}}{D^2} \]  

V. STAND-ALONE PV SYSTEM

The system in Figure 1 is modeled from control viewpoint in Figure 17. As the temperature or the radiation changes a new maximum power point is created. The system needs to move to this new set point. The MPPT achieves the tracking task along with the PI controller. The required duty ration value is then fed to the PWM that triggers the gate of the MOSFET in the Buck converter. The Matlab/Simulink implementation of the whole system is shown in Figure 18.

In order to test the performance of the system a number of scenarios have been simulated. Scenario I: (200 W/m² and 25 C), (600 W/m² and 40 C), (800 W/m² and 50 C) and (1000 W/m² and 60 C). It can be seen from Figure 20 that the system tracks the maximum power even at these low levels. Scenario II: (500 W/m² and 25 C), (600 W/m² and 40 C), (1200 W/m² and 50 C) and (1000 W/m² and 60 C) to emulate the weather in the Sahara Desert in Libya. Figure 21 shows the corresponding output power. The effect of the PI gain on the system performance is tested. Increasing the PI controller gain increases the rise time of the system and hence improves the response of the system against the change in the temperature and the radiation, this is shown in Figure 22. Figure 23 shows the effect of the MPPT frequency on the system response. At 200 Hz the response is slow at 1 kHz the response becomes
faster. Increasing the frequency of the MPPT beyond 1 kHz does not improve the system response because the dynamic of the whole system is controlled by the dynamics of the converter.

V. Conclusion

In this paper the modeling of stand-alone PV system is reported. The system components are the PV module, the DC/DC Buck converter, the maximum power point tracker and the load. These models are implemented in Matlab/Simulink. With the implemented models analysis to the MPP is done. Different simulation scenarios are carried out to test the performance of the system. With the PI controller the performance of the system is improved. The presented models in this paper can be used for educational and research purposes. Because of the ever increasing focus on PV system in the last decades, this paper could be used as an introductory tutorial to modeling and simulation of PV systems components. Additional components such as lead-acid battery, fuel cell and electrolyzer are under development by authors. More complex controllers based on artificial intelligence techniques such as neural networks, fuzzy logic and genetic algorithms may be combined with the models presented in the paper.

REFERENCES