Modeling and Implementation of Photovoltaic Modules for a DC-DC Boost Converter

(Model Fotovolta dan Pelaksanaannya bagi Penukar Galakan DC-DC)

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ABSTRACT

A photovoltaic (PV) system is a renewable energy system intended to convert sunlight into the usable electricity. Due to the rapid world infrastructure development, the demand for electricity is increasing drastically. One of the promising energy resources is the PV. The required energy demand can be provided by the increase of PV system deployment. Thus, as part of the design, development and implementation of a new PV system, a system design simulation is essential. This is to ensure that the designed system works properly according to design specifications. For this reason, a PV mathematical model is necessary in the development process of the PV system especially in the MATLAB/Simulink software environment. With the developed PV model, the PV system design and simulation is made handy, thus escalates the future energy demand. This work describes the development of the PV mathematical model in the MATLAB/Simulink software environment based on the PV related equations. The equations are formed by the consideration of the equivalent circuit of PV cell. The developed PV model characteristics such as the Power-Voltage (P-V) and Current-Voltage (I-V) curves are obtained as the simulation output in MATLAB/Simulink. The obtained characteristics are compared to the actual PV model A 100W RNG-50D Renogy, as to verify the effectiveness and closeness of the developed PV model to the real PV module. In addition, in the simulation, a dc-dc boost converter is also designed and integrated with the PV model as to verify the PV module and capability as a PV power source. The simulation results with the dc-dc boost converter DC-DC integration have shown that the developed PV model is very effective to be used for the PV system simulation.

Keywords: Photovoltaic system; DC-DC converter; P-V characteristics; I-V characteristics; MATLAB /SIMULINK

ABSTRAK

Sistem fotovolta (PV) adalah sistem tenaga boleh diperbaharui yang bertujuan untuk menukar cahaya matahari menjadi elektrik yang boleh digunakan. Oleh kerana pembangunan infrastruktur dunia yang pesat, permintaan elektrik meningkat secara drastik. Salah satu sumber tenaga yang menjanjikan ialah PV. Permintaan tenaga yang diperlukan boleh disediakan oleh peningkatan penggunaan sistem PV. Oleh itu, sebagai sebahagian daripada reka bentuk, pembangunan dan pelaksanaan sistem PV baru, simulasi reka bentuk sistem adalah penting. Ini adalah untuk memastikan sistem yang direka bentuk berfungsi dengan baik mengikut spesifikasi reka bentuk. Atas sebab ini, model matematik PV diperlukan dalam proses pembangunan sistem PV terutamanya dalam persekitaran perisian MATLAB/Simulink. Dengan model PV yang dibangunkan, reka bentuk dan simulasi sistem PV dibuat berguna, dengan itu meningkatkan permintaan tenaga masa depan. Kerja ini menerangkan pembangunan model matematik PV dalam persekitaran perisian MATLAB/Simulink berdasarkan persamaan berkaitan PV. Persamaan dibentuk oleh pertimbangan litar setara sel PV. Model PV yang dibangunkan mempunyai ciri-ciri seperti lengkung Power-Voltage (P-V) dan Current-Voltage (I-V) diperolehi sebagai output simulasi dalam MATLAB/

Simulink. Ciri-ciri yang diperolehi dibandingkan dengan model PV sebenar A 100W RNG-50D Renogy, untuk melihat keberkesanan dan kedekatan model PV yang dibangunkan dengan modul PV sebenar. Di samping itu, dalam simulasi, penukar rangsangan dc-dc juga direka dan disatukan dengan model PV untuk mengesahkan modul dan keupayaan PV sebagai bekalan kuasa PV. Hasil simulasi dengan penukar rangsangan dc-dc integrasi DC-DC telah menunjukkan bahawa model PV yang dibangunkan sangat berkesan untuk digunakan untuk simulasi sistem PV.

Kata kunci: Sistem fotovolta; penukar DC-DC; ciri-ciri P-V; ciri-ciri I-V; MATLAB/SIMULINK

INTRODUCTION

A photovoltaic (PV) system is a renewable energy system which intended to convert sunlight into the usable electricity. Due to the rapid infrastructure and technology development, the demand for electricity has increased drastically. One of the promising energy resources is the PV. It is one of the alternative energy resources available for current and future energy demand. The energy demand can be fulfilled by increasing of PV system deployment. Thus, as part of the design, development, implementation and deployment of more PV systems, the system design and simulation process are essential. This is to ensure that the designed system works properly according to design specifications prior to the system installation. In addition, the performance of PV is affected by the weather conditions (Noor Adilah 2021). For this reason, a PV mathematical model is necessary in the development process of the PV system, thus increasing the supply of the future energy. The implementation of the PV model in the simulation is essential in achieving PV maximum power (Hasan 2018). With the PV model, the PV system design and simulation are made handy and efficient, thus increases the supply of the future energy demand.

PHOTOVOLTAIC MODELING

The overall block diagram of the PV modeling system work carried out is shown in Figure 1.
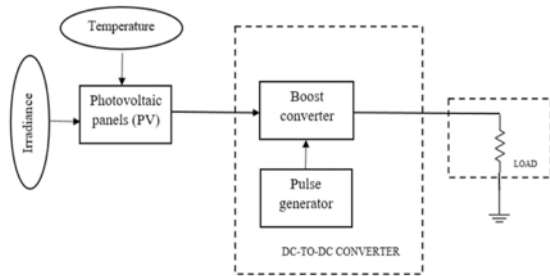

FIGURE 1. Block diagram of the PV modelling system

The photovoltaic panels block represents the PV model which generates the DC power. The model is capable of supplying enough power required by the load. The power generation depends on the two parameters which are surrounding temperature and the Sun irradiance. Based on these conditions, the DC-DC boost converter steps up the PV dc voltage to suit the load voltage requirement. In other words, the PV model is used as an input power source to a

dc-dc boost converter. A pulse generator is integrated into the system to provide a switching signal to adjust the gain of the dc-dc boost converter. The resistor is connected to the system as a load.

The basic model of the photovoltaic cell is represented by the equivalent circuit shown in Figure 2 (Yadaf 2008). It consists of a photocurrent or light-generated current, diode, shunt resistor and series resistor.
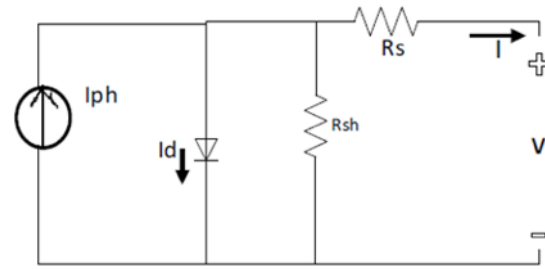

FIGURE 2. PV cell electrical equivalent circuit

The current supply I_{ph} represents the photocurrent. The parameter I represents the saturation current of PV. The intrinsic series and shunt resistances are represented by R_s and R_{sh}, respectively. R_{sh} is usually very large while R_s is small. The series resistance represents the restriction in the current path, while the shunt resistance represents the leakage current (Yadaf 2008).

Applying Kirchhoff's law around the circuit, the photovoltaic current is obtained as in (1) (Yadaf 2008. Amrani, 2007).

$$I_{pv} = I_{ph} - I_d - I_{sh} \tag{1}$$

where I_{ph} is the photocurrent, I_d is the diode current and I_{sh} is the shunt current.

Due to the large value of R_{sh}, the I_{sh} can be ignored, thus equation (1) can be simplified as equation (2):

$$I_{pv} = I_{ph} - I_d \tag{2}$$

The photocurrent can be represented as (Natarajan 2012. Ramos 2010):

$$I_{ph}[I_{sc} + k_i(T - T_r)]G \tag{3}$$

where I_{sc} is the short circuit current, k_i is the temperature coefficient of the short circuit current, T is the cell operating temperature (K), T_r is the reference temperature (K), G is the solar irradiance per 1000W/m^2

I_d is the cell diode current as in equation (4)

$$I_d = I_s \left[\left(\frac{qV_d}{nKN_s T} + I_{pv}R_s \right) - 1 \right] \qquad (4)$$

where I_s is the diode saturation current, q is the electron charge, V_d is diode voltage, n is the ideality factor of the diode, K is Boltzman's constant, N_s is the number of PV cell in series, R_s is the series resistor and I_s is the diode saturation current as in equation (5) (Xuan 2015. Nurul 2016).

$$I_s = I_{rs} * \left(\frac{T}{T_n} \right)^3 * exp \left[\frac{q * Eg0 * (\frac{1}{T_n} - \frac{1}{T})}{n * K} \right] \qquad (5)$$

where I_{rs} is the reverse saturation current, $Eg0$ is the band energy of the semiconductor gap (eV), I_{rs} is the cell reverse saturation current as in equation (6).

$$I_{rs} = \frac{I_{sc}}{expexp \left(\frac{qV_{oc}}{nN_s KT} \right) - 1} \qquad (6)$$

where V_{oc} is the short circuit voltage.

Thus, the output current of the photovoltaic module is represented by equation (7) (Amrani 2007. Zainal, 2016).

$$: N_p * I_{ph} - N_p * I_s \left(exp \left(\frac{qV_d}{nKN_s T} + I_{pv}R_s \right) - 1 \right) \qquad (7)$$

where N_p is the number of PV cell in parallel.

Table 1 presents the constant value of parameters related to the equation of the equivalent circuit of a solar panel (Hamdi 2017).

TABLE 1. Constant parameters

Parameters	Value
Series resistor, R_s	0.221 Ω
Electron charge, q	1.602×10^{-19} C
Boltzmann constant, K	1.3805×10^{-23} J/K
Temperature coefficient of short circuit current, K_i	0.04 %/°C
Bandgap for silicon, E_g	1.1 E_v
Ideality factor for Si-mono, n	1.2

The value of the temperature coefficient of short circuit current, K_i is based on the type of solar panel itself. In this work, the 100 W PV panel Renogy RNG-100D is used as a reference. The constant value of K_i is based on the datasheet which is 0.04 %/°C. Since the 100W RNG-100D *Renogy* is monocrystalline, the ideality factor is 1.2. The specification of the reference model is shown in Table 2.

TABLE 2. Specification of 100W RNG-100D

Parameters	Specifications
Material	Monocrystalline
Maximum power at Standard Test Condition (STC)	100 W
Optimum operating voltage (Vmp)	18.9 V
Optimum operating current (Imp)	5.29 A
Open circuit voltage (Voc)	22.5 V
Short circuit current (Isc)	5.75 A
Temperature coefficient of Isc	0.04 %/°C
Number of PV in series (Ns)	36

PHOTOVOLTAIC IMPLEMENTATION

The PV modeling is implemented mathematically in the MATLAB/Simulink software environment. Figure 3 illustrates the developed modeling system in MATLAB/Simulink with temperature and irradiance setting parameters. The actual solar panels are tested to the same Standard Test Condition (STC) with a temperature of 25 °C and irradiance of 1000 W/m^2. The PV model is made up of five subsystems or blocks that represent different functions based on the equations obtained from the equivalent circuit. The output of the are the I_{pv} and V_{pv}
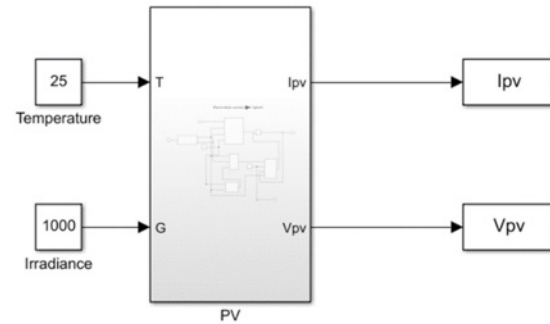

FIGURE 3. PV model with temperature and irradiation

The five subsystems or blocks inside the model are shown in Figure 4. Each block represents equation which has been explained previously. All the subsystems are integrated to represent the equation of photovoltaic output current, I_{pv}
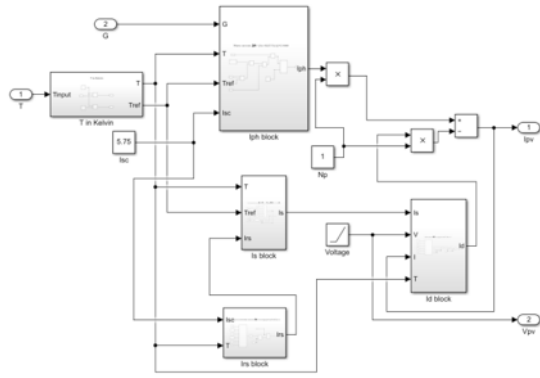
FIGURE 4. Model of PV current, I_{pv}

The model of temperature in Figure 5 is developed to converts the temperature from degree Celsius to Kelvin (K). The T_{input} block refers the operating temperature in degree Celsius. The reference temperature (Ref Temp) block is set to be 25 °C for the STC compliance. In general, the value of unit Kelvin is 273 K. This model has two outputs in unit Kelvin which are the Temperature, T and the reference temperature, T_{ref}.
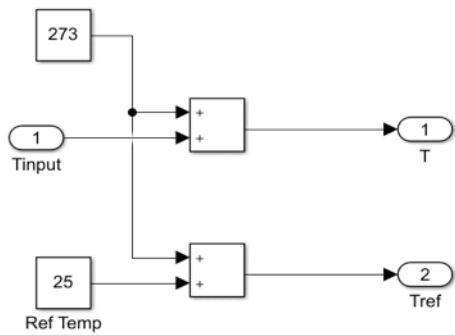

FIGURE 5. Temperature Model

The photocurrent, I_{ph} model is depicted in Figure 6. The inputs are the solar irradiance, G in W/m^2, short circuit current, I_{sc}, temperature, T and reference temperature, T_{ref}. The input refers to the temperature coefficient for 100W RNG-100D *Renogy* type which is 0.04 %/°C.
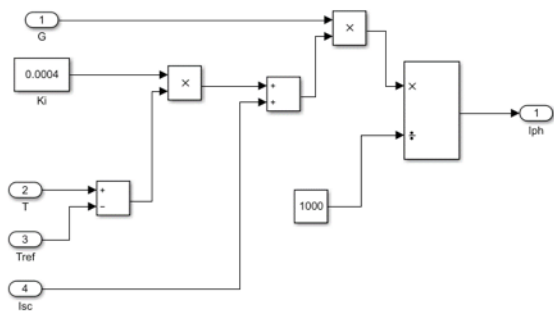

FIGURE 6. Model of the photocurrent, I_{ph}

Figure 7 describes the model of diode current, I_d. Some of the inputs are the number of PV cells connected in series, N_s, q, and R_s. The value of K depends on the specification of the PV model. The value of the series resistor connected in the equivalent circuit is a small value which is 0.221Ω.
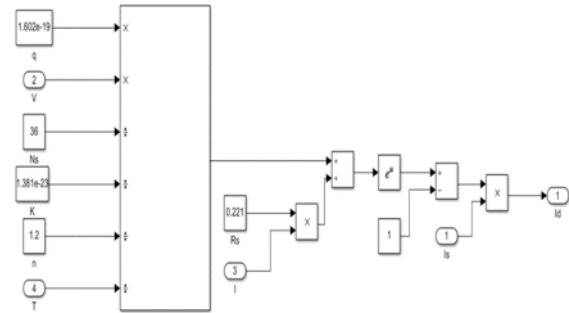

FIGURE 7. Model of diode current, I_d

The subsystem for the saturation current model, I_s in Figure 8 includes the input of reverse saturation current, which is obtained from another subsystem. Some parameters constants are required in these models such as the bandgap for silicon, Boltzmann constant, K, electron charge, q and ideality factor, n. The subsystem is used for the system power determination.
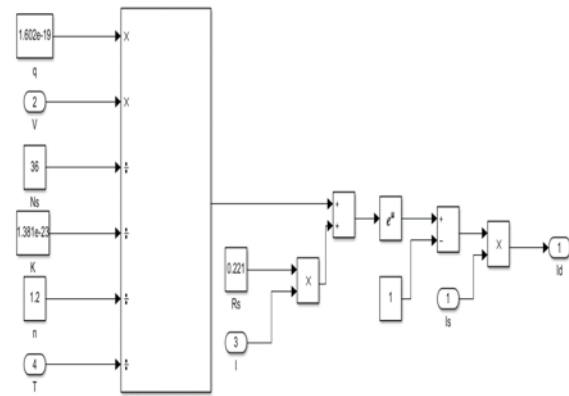

FIGURE 8. Model of saturation current, I_s

Figure 9 shows the model for the reverse saturation current, I_{rs} which consists of several input values such as I_{sc}, K, N_s and T.
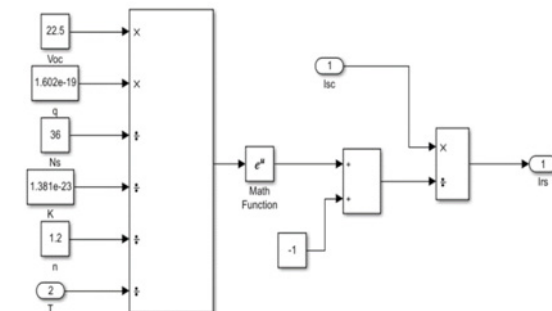

FIGURE 9. Model of reverse saturation current, I_{rs}

In order to verify the functionality of the PV model, a dc-dc boost converter is integrated into the modeling system. Figure 10 shows the dc-dc boost converter with DC voltage supply as a power supply source. Initially, a dc voltage source is used to verify the boost converter operation. Next, the PV model is used to supply power to the load through the boost converter. The boost converter consists of an inductor, L, diode, D, capacitor, C, load resistor, R_L and the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) as the switching device. The switching signals for the MOSFET are generated by pulse generator which varies the converter dc output voltage. The input voltage, V_i is set to 22.5 V and the desired output voltage, V_0 is 50 V. The simulation was carried out in the MATLAB/Simulink software environment to obtain the PV characteristic.
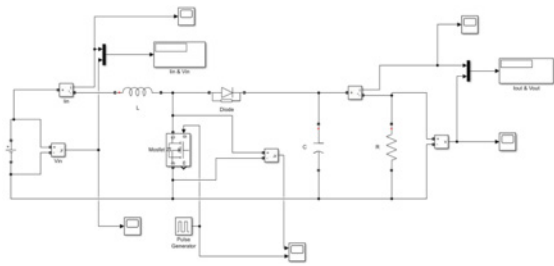

FIGURE 10. DC-DC boost converter with DC voltage supply

The gain of the converter is described by Equation (8).

$$\frac{V_o}{V_i} = \frac{1}{(1-D)} \tag{8}$$

where V_i, V_o and D is the dc input voltage, dc output voltage and duty cycle respectively.

Based on the input and output voltage and power of 100W requirement, the value of the resistor, R is calculated to be 25Ω. The values of inductor and capacitor are calculated to be 24 µH and 24 µF respectively.

Figure 11 shows the integration of the PV model with the dc-dc boost converter. This simulation circuit is intended to verify the functionality of modeling PV. The output current of the PV model is connected to a controlled current source (CCS) as it represents an ideal current source that is powerful to maintain the specified flow through it regardless of the voltage across the source. The significance parameters are input voltage (V_i), input current (I_i), output voltage (V_o) and output current (I_o).

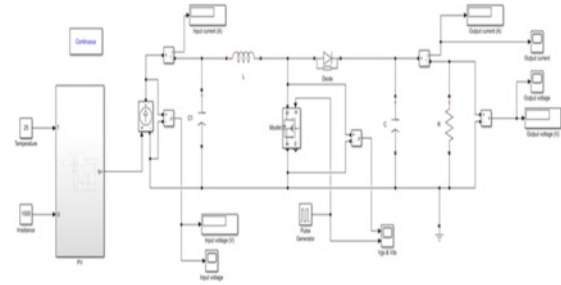FIGURE 11. PV model as an input to boost converter

RESULTS AND DISCUSSION

PHOTOVOLTAIC MODEL CHARACTERISTIC

In the simulation, the value of temperature and irradiance are set to 25°C and 1000W/ m^2 respectively as specified in the STC. The parameters obtained are used to plot the current-voltage (I-V) and power-voltage (P-V) characteristic curves for comparison with the actual reference PV panel. Figure 12 depicts the obtained simulation result of the I-V curve of the developed PV model.
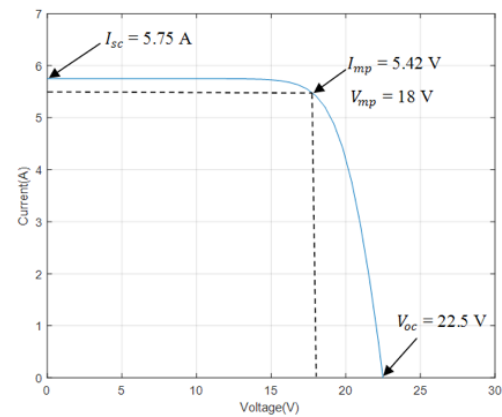

FIGURE 12. I-V curve of the PV model at STC

From the figure, it shows that that short circuit current, I_{sc} is 5.75 A and the open circuit voltage, V_{oc} is 22.5 V. The maximum operating current, I_{mp} and maximum operating voltage, V_{mp} are 5.42 and 18V respectively.

Figure 13 shows the Power-Voltage (P-V) characteristic curve of the developed PV model that shows the maximum power generated of 100W. Both curves characteristics are compared to that of the 100W RNG-100D *Renogy* as depicted in Table 2.
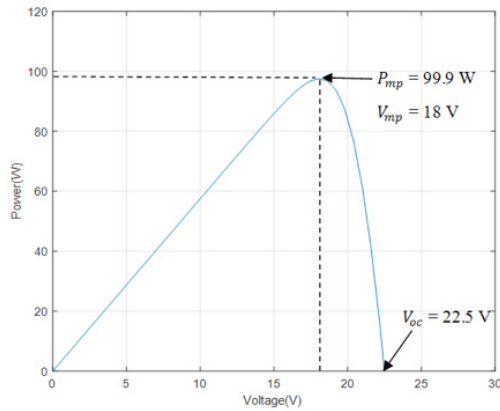
FIGURE 13. P-V curve of the PV model at STC

The values of V_{oc} and V_{mp} from P-V curve of Figure 13 are the same with the values of V_{oc} and V_{mp} in Figure 12. Both curves are compared to the 100W RNG-100D *Renogy* I-V characteristic curves as shown in Figure 14. It proves that the implemented mathematical model in Simulink has a similar characteristic to the reference model.
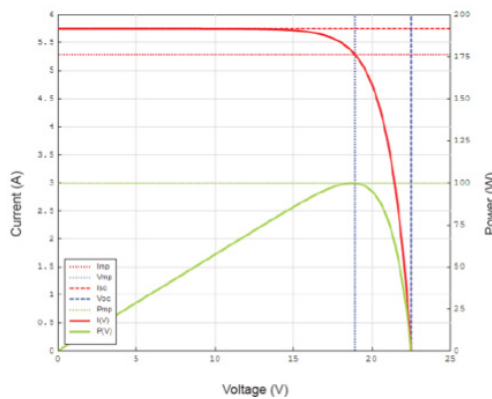

FIGURE 14. I-V and P-V curve of the RNG-100D PV panel characteristic at STC

PV MODEL FOR A DC-DC BOOST CONVERTER

This section shows the outcomes of the PV model as the input to dc-dc boost converter circuit. The process of boosting up the voltage is achieved through the utilization of the pulse generator which turns the MOSFET on and off continuously. The PV model is used to supply the dc input voltage to the boost converter circuit. Figure 15 illustrates the input voltage to the boost converter. From the figure, it can be seen that the input voltage which is supplied by the PV model is approximately 28.5V.
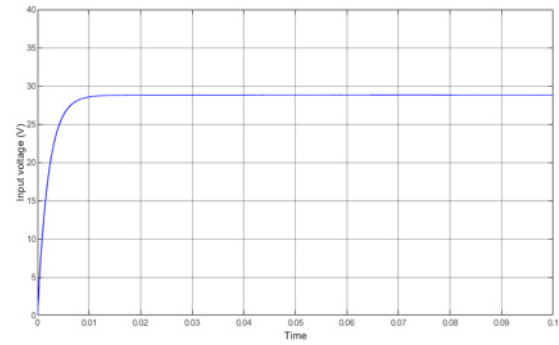

FIGURE 15. Output voltage of PV model connected to the boost converter

Based on the designed gain of the DC-DC boost converter, the input voltage is stepped up to approximately 64.2V and it can be seen in Figure 16. This result proves the efficacy of the PV developed model.
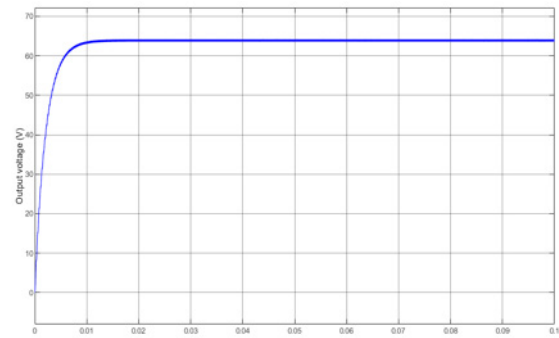

FIGURE 16. Output voltage waveform of the boost converter

CONCLUSION

In conclusion, the mathematical modelling of the PV panel and the integration of dc-dc boost converter were presented in this paper. The system was developed and simulated in the MATLAB/Simulink Professional software environment. In addition, the PV model was used successfully as a power source for the dc-dc boost converter. The obtained I-V and P-V characteristic curves are compared to the actual reference PV panel model RNG-100D from *Renogy* and they showed similar characteristics. Thus, these results have shown the efficacy of the developed PV model in supplying the required power by the load.

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