Solar powered UAV model on MATLAB/Simulink using incremental conductance MPPT technique

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Abstract

Purpose – The aviation industry has started environment friendly and also conventional energy independent alternative energy dependent designs to reduce negative impacts on the nature and to maintain its future activities in a clear, renewable and sustainable way. One possible solution proposed is solar energy. Solar-powered aerial vehicles are seen as key solutions to reduce global warming effects. This study aims to simulate a mathematical model of a solar powered DC motor of an UAV on MATLAB/Simulink environment.

Design/methodology/approach – Maximum power point tracking (MPPT) is a critical term in photovoltaic (PV) array systems to provide the maximum power output to the related systems under certain conditions. In this paper, one of the popular MPPT techniques, "Incremental Conductance", is simulated with solar-powered DC motor for an UAV design on MATLAB/Simulink.

Findings – The cascade structure (PV cell, MPPT, buck converter and DC motor models) is simulated and tested under various irradiance values, and results are compared to the DC motor technical data. As a result of that, mathematical model simulation results are overlapped with motor technical reference values in spite of irradiance changes.

Practical implications – It is suggested to be used in real time applications for future developments.

Originality/value – Different from other solar-powered DC motor literature works, a solar-powered DC motor mathematical model of an UAV is designed and simulated on MATLAB/Simulink environment. To adjust the maximum power output at the solar cell, incremental conductance MPPT technique is preferred and a buck converter structure is connected between MPPT and DC motor mathematical model. It is suggested to be used in solar-powered UAV designs for future developments.

Keywords Buck Converter, Unmanned Aerial Vehicle, MPPT, DC Motor, Incremental Conductance, Maximum Power Point Trackers, Solar Power

Paper type Research paper

Introduction

Solar energy applications in aviation have been a highly subject since as early as the 1970's. It's clear, unlimited, renewable and sustainable form make a prospective substitute for aerial vehicle fuel sources. Noth *et al.* (2007), Turk *et al.* (2018) and Zhu *et al.* (2014) reviewed solar energy oriented aerial vehicles in their studies. Solar-powered flights have started with model aerial vehicles. "Sunrise 1" is the first solar-powered model aircraft. It had 4096 solar cells with a power output of 450 W (Boucher, 1984). During a flight, due to a sand storm, Sunrise 1 was seriously damaged. An advanced version of it, Sunrise 2, was constructed and tested in 1975. The number of solar cells were increased to 4480 to deliver 600 W. Despite all, due to a failure in the command and control system, this version was also damaged again. In 1976, another model aircraft "Solaris" achieved three flights of 150 seconds at the altitude of 50 m (Bruss, 1991). Dave Beck, the designer of "Solar Solitude", from Wisconsin USA, had two records in solar model aircraft competitions. On the other hand, the solar model aircraft, "Solar Excel", collected all the solar model aircraft records between 1990 and 1999 in Germany. MikroSol, PicoSol and NanoSol were the miniature solar model aircrafts that were constructed by Dr Sieghard Dienlin (Stinton, 2011).

After the initiation of solar model aircrafts, next generation aircraft design attempts were defined as manned solar power oriented aerial vehicles. "Solar One" performed its first flight at Lasham Airfield in Hampshire, England. It was initially designed as manned but, it was converted to solar-powered one due to weight problems (Boucher, 1984; Stinton, 2011). The power in "Solar One" was only produced via the weak winter illumination from solar panels and the panels were integrated

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with a small set of Ni-Cad batteries. In "Solar Riser", the power of the solar panel (350 W) was not enough to drive the motor in a direct way thus solar panel was used as a solar battery charger and the motor was driven using solar panel charged Ni-Cd packs. Its first flight was in 1979 at Flabob, CA (Boucher, 1984). In the design of "Gossamer Penguin", the motor and the solar cells that were removed from the two damaged versions of Sunrise 1 and 2 were used. It realized its first flight as the world's first manned and solar-powered flight on May 18, 1980. However, it had safety problems for a pilot considering higher altitudes. The "Solar Challenger", was a result of "Gossamer Penguin" success and it was developed aiming a new solar manned aerial vehicle. It had 16128 solar cells providing 2500 W at sea level. Solar energy was the only energy source of it and there was not energy storage system onboard during its flight in 1981. "Solair I" was designed and built by Günter Rochelt. It was composed of 2499 solar cells to provide 1800 W. However, its energy was not sufficient to climb and it was integrated with a 22.7 kg Ni-Cd battery. In 1983, its flight took place mostly via solar energy powered (not all powered) in 5 hours 41 minutes. "Sunseeker" was a manned solar-powered aircraft designed by Eric Raymond. It performed 21 successful solar-powered flights across the USA with 121 hours in the air. "Icaré 2", "O Sole Mio" and "Solair II" were solar manned aircraft competitors of an aeronautical competition at Germany in 1996. The winner was "Icaré 2" (Voit-Nitschmann, 2001) and the other two projects were evaluated as unairworthy in the competition. However, they had demonstrations after some development stages as well.

"Pathfinder" was a high altitude long endurance solar-powered aircraft. It performed its first flight in 1993 at Dryden. It broke the "Solar Challenger"s altitude record in 1995. After many achievements, Pathfinder was improved entirely including systems, wingspan and its name was updated as "Pathfinder Plus". Another high altitude long endurance solar-powered aircraft prototype design was "Centurion". It had similarities with Pathfinder. By means of double wingspan, it had capability to carry high scientific research loads. "Helios" was another prototype project of solar-powered series high altitude long endurance aircrafts. It performed a sustained flight at an approximate altitude of 29,524 m (96,863 ft) and a 40-min flight above 29,261 m (96,000 ft) and it broke an unofficial World record in 2001, near Hawaii. Thus, it realized the first goal of NASA. Due to structural failures, it fell into the Pacific Ocean in 2003. "Solitair" was designed for year-around operations in northern Europe latitude between 1994 and 1998 at the DLR Institute of Flight Systems. A proof-of-concept model was constructed and its total on board power was provided by adjustable solar panels to absorb optimum solar radiation (Tozer *et al.*, 2000; Keidel, 2000; Solitair at DLR, 2019). "Heliplat" was a solar-powered high altitude aircraft design project which was financially supported under European Program. The aim of its design was to research the construction feasibilty of broadband communications and Earth observations on a solar-powered aerial vehicle (Tozer *et al.*, 2000; Romeo and Frulla, 2004). "Solong" solar-powered aircraft performed its flight in the air for 48 h and 16 min over California's Colorado Desert with a wingspan was 4.75 m and weight 11.5 kg. "Sky-Sailor" was a solar-powered aircraft for the exploration of Mars. It performed a successful an autonomous flight more than 27 h in 2008. Solar Impulse 1 and 2 were manned HALE projects. Solar Impulse 1 performed an all-night flight by flying for 26 h in 2010 (Pınar, 2013). Solar Impulse 2 had more than 17,000 solar cells and it achieved a valuable success without using fossil fuel flying more than 23 days in the air. Zephyr series were manufactured in two different versions: Zephyr S and Zephyr T. It could fly through the stratosphere and were not affected from meteorological conditions. They could carry heavy loads and they had various design characteristics (Makaracı, 2018). A new member of Zephyr family, Zephyr S HAPS (High Altitude Pseudo-Satellite), broke a world record by flying in the stratosphere nearly an average altitude of 70.000 feet in 2018.

Existing solar-powered UAV mathematical model studies from literature generally focus on mission oriented conceptual designs or mass, performance and aerodynamic analyses (Klockner *et al.*, 2013; Kingry *et al.*, 2018; Palpandi and Prasanna Moorthy, 2019; Rajendran and Smith, 2018; Alsahlani and Rahulan, 2017). In this study, differ from other solar-powered DC motor literature studies (Atallah *et al.*, 2014; Deepa and Pawar, 2014; Singh *et al.*, 2015; Kashyap *et al.*, 2013; Vishnu Murthy *et al.*, 2017), the aim is a solar-powered DC motor mathematical model design for an UAV considering the weight of the designed UAV and its selected DC motor. In our previous work (Turk *et al.*, 2018), a mathematical model of a solar-powered dc motor design for an UAV was simulated on MATLAB/Simulink software environment without using any maximum power point tracking (MPPT) algorithm. In this work, using the same solar cell and DC motor technical data, an incremental conductance MPPT algorithm and a buck converter structures were integrated to the MATLAB/Simulink model to transfer the maximum power from solar cells considering various irradiance (altitude) values. Simulations were performed and results compared to the DC motor technical data. As a consequence, simulation results are obtained as compatible with the DC motor technical data.

Theoretical background

Maximum power point tracking

The output power of a solar cell changes with temperature, solar insulation level, loads and direction of the sun. The maximum power point (MPP) is single in the photovoltaic (PV) characteristics of the solar cell for particular operating conditions. It is required to operate closely to this point. In this point, output of a solar cell approaches near to its MPP. This operation is called MPPT (Kachhiya *et al.*, 2011). It is necessary to track the MPP to improve system efficiency.

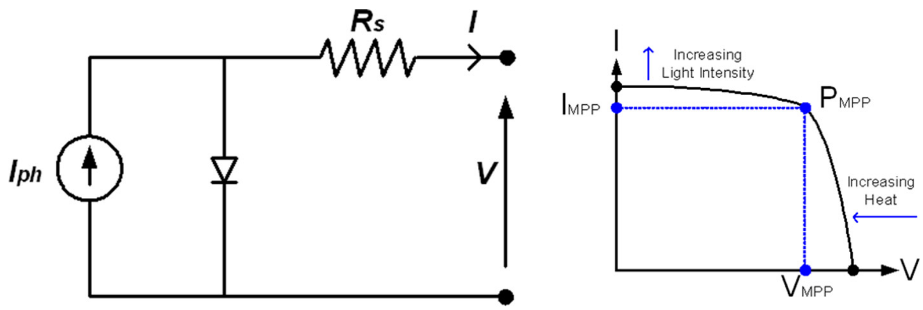
PV arrays contain a series of solar cells. Each battery can be modeled with a diode and a parallel current source (I_{PH}) as shown in Figure 1. The resulting Current-Voltage graph varies according to light and temperature. This change also affects open circuit voltage (V_{OC}) and short circuit current (I_{OC}).

The relation of V voltage and I current of the PV battery shown in Figure 1 can be modeled by using the following equation:

$$I = I_{PH} - I_{SAT}\left(e^{q(V+IRS)}/_{nkT} - 1\right) \quad (1)$$

The I_{PH} light production current shown in the formula (1) is the diode saturation current depending on the type of the I_{SAT}

Figure 1 PV battery I–V relation



solar cell, the charge on the electron q, the serial resistance of the R_S array, the ideal factor of the diode n, the Boltzmann constant k and the temperature of the PV cell in T (in Kelvin).

MPPT is a necessary optimization process to determine the relationship between the current and the maximum power operating point. Voltage is controlled to move close to the MPP, until obtaining the peak power. If the voltage keeps increasing, the power will reduce, and by adjusting the reverse direction, the voltage is controlled at the maximum power. There are many methods used for MPPT and generally, they can be classified in two categories. One of them is direct and the other one is indirect (Chafle and Vaidya, 2013). Commonly used indirect methods are fractional open circuit voltage (FOCV) and fractional short circuit current. However, the low efficiency of the indirect methods is a major drawback. Both methods work similar. For this reason, basic principle will be explained through FOCV.

The FOCV, which is the one of the indirect methods, based on a method that a fraction of V_{OC}, which is between 0.71 and 0.78 of the V_{OC}, is able to harvest a power from a point close to MPP (2):

$$V_{mpp} \approx k \times V_{OC} \tag{2}$$

Since the fixed constant k is generally assumed as 0.75 (Kobayashi *et al.*, 2004), it can be quickly approached to *Vmpp* if *k* is assumed 0, 75. When 75 per cent of the open circuit voltage is requested from the panel, system is able to work closely at *Vmpp*. Despite the advantages of the quick and simple operation of the technique, its efficiency is low due to its inability to reach the actual MPP and to obtain low power in changing light and temperature conditions. Due to the low efficiency of the indirect methods, our study is focused on direct methods.

Direct methods are based on current and voltage measurements of the system. Their common feature is sharing an individual algorithm based on their methodology. Hill climbing perturb & observe (P & O) are the most common algorithms used for MPPT. In the P & O and Hill Climbing algorithm, system continuously measures the power drawn by the current and voltage sensors and tries to stop the find duty cycle closest to the MPP (Chafle and Vaidya, 2013). Both algorithms are based on same idea. Only difference is a Proportional-Integral (PI) controller is utilized at P & O algorithm. Those algorithms are both simple and fast. However, the absolute MPP cannot be obtained. Found MPP is always close to the real MPP. However, the difference between the found one and the real one causes duty cycle to change continuously. This causes oscillations at output power. There are many methods to obtain MPP at PV systems (Chafle and Vaidya, 2013) but when considering both simplicity and efficiency, incremental conductance is used in the proposed system.

In our study, incremental conductance (IC) method is used for MPPT with a buck converter. In this method, processor measures incremental current and voltage changes drawn from PV array to forecast the effect of a voltage change. IC method requires digital circuit to accomplish the tracking (Esram and Chapman, 2007). The speed of obtaining the MPP depends on the power of the processor. Today's technology enables basic IC and modified IC methods to obtain the MPP very quickly with affordable processors (De Brito *et al.*, 2012). In addition, the structure of IC algorithm prevents oscillations on MPP when the MPP is reached (Onat, 2010). This stability increases the efficiency by preventing power ripples. In case of the changing MPP, derivative operation will quickly detect the direction of new MPP and obtain it. In brief, this method requires more computational power compared to the commonly used P&O but can track changes of the MPP very fast compared to the P&O and Hill Climbing algorithms (Chafle and Vaidya, 2013). In addition, IC algorithm causes small oscillations at the output power until it reaches to the MPP. After the MPP obtained, algorithm stops and no oscillations occur. If the MPP of solar cell changes, algorithm starts to work again until it finds the new MPP.

The IC method is developed to reduce the drawbacks of the P&O method (Kordestani *et al.*, 2018). The method reduces the tracking time and enhances the power in varying environments (Putri *et al.*, 2015). The MPP can be calculated by means of the relation between dI/dV and $-I/V$. If dP/dV is negative, then MPP is lies on the right side of the recent position and if the dP/dV is positive, the MPP is on left side (Balamurugan and Manoharan, 2012). *Vp* represents the value predicted by the algorithm. The IC method can be defined as the following:

$$\frac{dP}{dV} = \frac{d(V \times I)}{dV} = I\frac{dV}{dV} + \frac{dI}{dV} \tag{3}$$

$$= I + V\frac{dI}{dV} \tag{4}$$

MPP is obtained at $dP/dV = 0$ and:

$$\frac{dI}{dV} = -\frac{1}{V} \tag{5}$$

$$\frac{dP}{dV} > 0 \text{ then } V_p < V_{mpp} \tag{6}$$

$$\frac{dP}{dV} = 0 \text{ then } V_p < V_{mpp} \tag{7}$$

$$\frac{dP}{dV} < 0 \text{ then } V_p > V_{mpp} \tag{8}$$

Buck converter

A buck converter can be named as a voltage regulator as also called a step down regulator since the output voltage is lower than the input voltage. Generally, a diode is connected in parallel with the input voltage source, a capacitor, and the load that means output voltage. An inductor is between the diode and the capacitor, and switch is connected between the input voltage source and the diode.

Buck converter is presented in Figure 2 is used in switching power supply circuits where the desired output must be lower than the input. The transistor switching between input and output continuously switches at high frequency. To ensure continuity at the output, the circuit inductor (L) uses the stored energy when the switch is switched off. This circuit operation can also be called the flywheel circuit. This naming is because it continues to conduct the current, such as a mechanical flywheel, despite the discrete signal.

As shown in the above diagram, the buck converter works with the flywheel circuit consisting of the switching transistor (S), diode (D_{in}), inductor (L) and capacitor (C). When the transistor switches to the ON position, the current from the source passes through the switch and begins to charge the inductor. At the same time, the current passes through the output capacitor and the load. The diode is reversed during this operation and is in the closed position. When the switch is OFF, the inductor is reversed and discharges through the load and the capacitor. This process continues until the next state. The on time that the switch is open is named as duty cycle. And it is symbolized as D. Also input voltage is shown as V_{IN} and output voltage is represented as $V_{O.}$

Buck converters calculations are;

For calculating voltage gain:

Figure 2 Buck converter

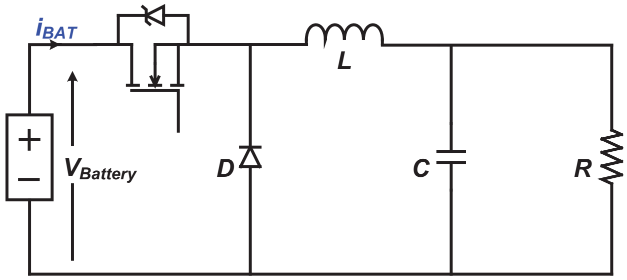


Figure 3 General view of solar-powered DC motor using incremental conductance MPPT technique and buck converter

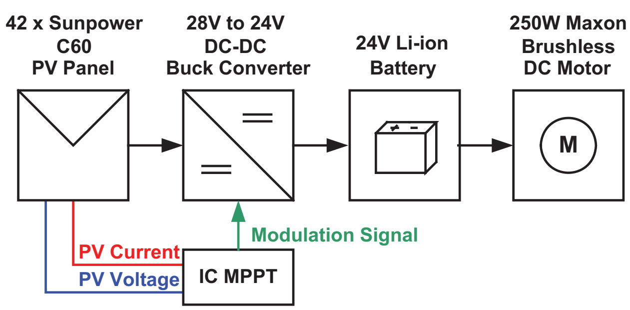


Table I Sunpower C60 PV panel specifications

Parameter	Value
Mass of solar cell	8 g
Length and width	0.125 m x 0.125 m
Area of single solar panel	0.0150 m^2
Efficiency of solar cell	22%
Rated voltage and current	0.57 V – 5.37 A
Typical peak power (P_{mpp})	3.34 W
Voltage at peak power (V_{mpp})	0.574 V
Current at peak power (I_{mpp}*)	0.682 A
Short circuit current (I_{sc})	6.24 A
Open circuit voltage (V_{oc})	0.68 V

Source: Eshop Terms Website (2019)

Figure 4 Detailed reconfiguration structure

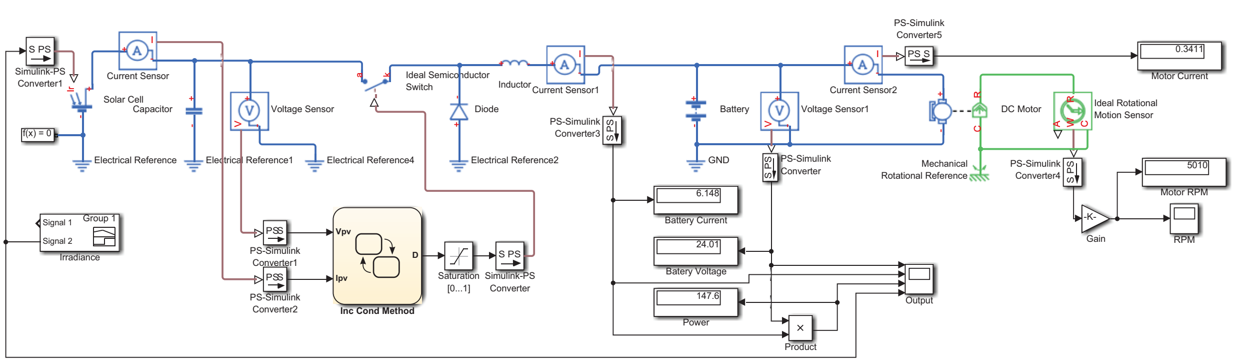


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Table II Weight estimation of mUAV

Parameter	Value
C60 Solar Cell	8 g (each) x 42 pieces = 336 g
Connection Cable	100 g
MPPT	200
UAV	600 g
Motor	1,100 g
ESC	80 g
Battery	300 g
Total Weight	2,716 g
For Safety Flight	3,000 g

Source: Turk *et al.* (2018)

Table III Specifications of 250 W maxon DC motor

Parameter	Value
Nominal Voltage	24 V
No Load Speed	5000 rpm
No Load Current	341 mA
Nominal Speed	4300 rpm
Nominal Current	7.51 A
Terminal Resistance	0.43 ʻΩ
Terminal Inductance	0.17 mH
Stall Torque	2,540 mNm
Stall Current	55.8 A

Source: Maxon motor website (2019)

$$V_O = D \times V_{IN} \tag{9}$$

To calculate the inductor for ripple requirements:

$$L = \frac{(V_{IN} - V_O)}{\Delta L} DT \tag{10}$$

Simulation and results

In the simulation, a mathematical model of 42 × C60 serial connected solar cell structure is integrated with 250 Watts Maxon DC motor mathematical model. IC MPPT model and Buck Converter model are located into the mathematical model between solar cell structure and DC motor. It is assumed that the mathematical model simulates a daily operation. Quality factor is taken as 1 and device simulation and measurement temperatures are selected as *25°C* (Pukhrem, 2013). Operation of solar cell structure is assumed as ideal. Thus, loss coefficients Rs and Rp are ignored during simulations (González-Longatt, 2005). Solar irradiance ratio is taken as variable to simulate different levels of flight. General view of the designed mathematical model is shown in Figure 3.

MATLAB/Simulink 2016 configuration of the designed mathematical model is represented in Figure 4. System is powered by a 42 × C60 Sunpower PV array. Panel specifications are defined in Table I. The generated power is harvested using a DC-DC Buck converter. MPPT is done by using Incremental Conductance algorithm. After the maximized power is obtained, it is used for feeding the output battery. The power obtained through the battery is used for no load simulations of the solar-powered DC motor of UAV. Simulation results are compared to the no load information of Maxon DC motor. DC motor technical data is presented in Table II. Weight Estimation of designed mUAV is shown in Table II. The technical data of selected DC motor of the mUAV can be seen from Table III.

PV and IV curves of 42xC60 Sunpower PV array are shown in Figure 5. Power, voltage and current values are calculated through various irradiance ratios to simulate the different altitudes of designed UAV flight at PV output. In Figure 6, DC motor no load simulation results are seen. Considering Table III information, especially no load technical data, it can be said that result approximation of simulation is successful. In case of altitude changes (irradiance change), the proposed model refreshes MPPT and maintains RPM (revolution per minute), voltage and current values as defined in technical spec. The error values belong to voltage, RPM and current are approximately smaller than 1 per cent.

Due to the changes of irradiance during the simulation, harvested current changes due to the principles of PV cell behavior presented in Figure 1. 1,000 W/m^2, 800 W/m^2 and 600 W/m^2 irradiance is given for 3 s each as irradiance input to PV panel. Power and current changes are shown in Figure 6.

The output voltage of the buck converter shows very small changes during the simulation. So, it can be assumed as 24 V DC output fixed. Current and power changes with the input irradiance of the system.

Figure 5 PV and IV curves of 42 × C60 Sunpower PV array

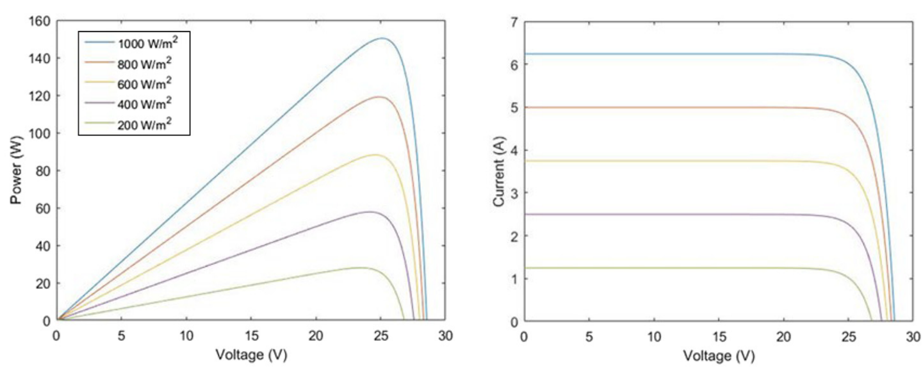


Figure 6 Solar-powered buck converter Voltage, current, power output values according to changing irradiance

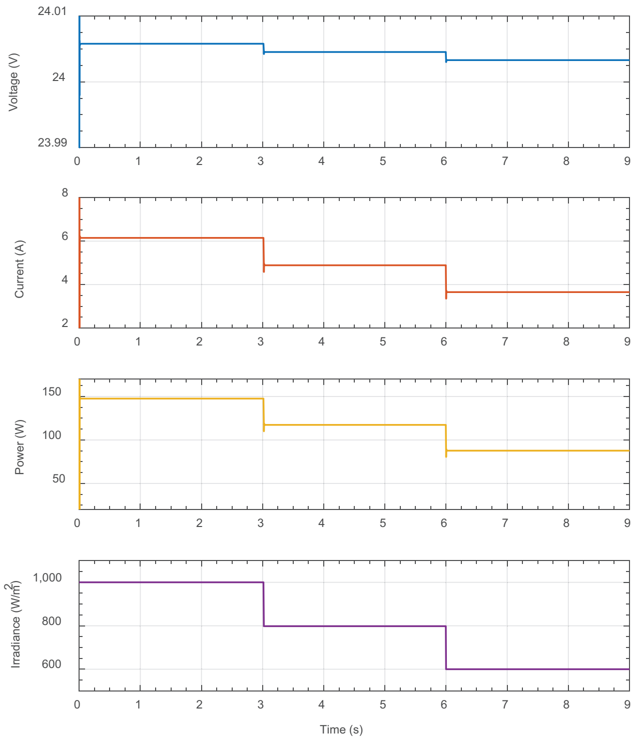
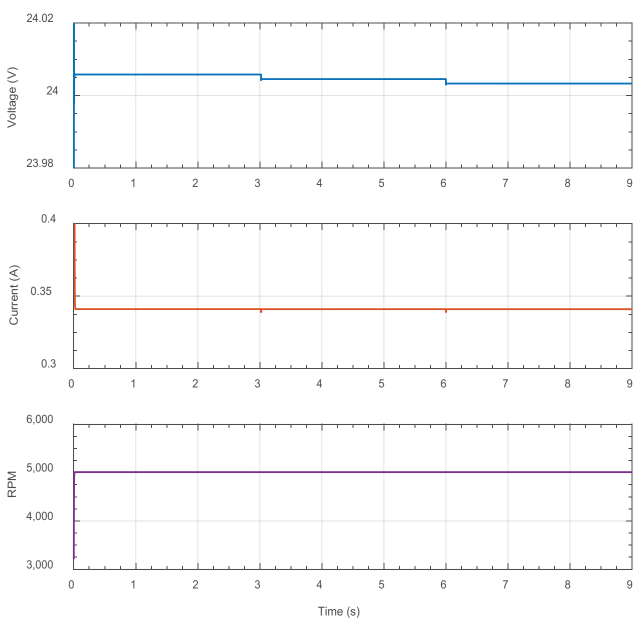


Figure 7 Solar-powered DC motor current-voltage –RPM simulation results



Values of motor RPM and No-Load current are shown in the Figure 7. It can be observed that under the constant voltage and No-Load conditions, technical values for RPM and No-Load current values are obtained correctly.

Conclusion

In this study, a solar-powered UAV mathematical model is simulated on MATLAB/Simulink environment by means of incremental conductance MPPT technique. Simulations are conducted under various irradiance values and results are compared to the DC motor technical data. As a result of that, mathematical model simulation results are overlapped with motor technical reference values in spite of irradiance changes. In the upcoming work, it is planning to add a propeller mathematical model into the current mathematical model to achieve the completed mathematical model of solar-powered UAV propulsion system.

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