Vietnam Journal of Science and Technology ***57*** *(1) (2019) 82-91*

doi:10.15625/2525-2518/57/1/10979

STUDY ON FAST CHARGER FOR 5V/1500F SUPERCAPACITOR MODULE FROM PHOTOVOLTAIC PANEL

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Received: 13 December 2017; Accepted for publication: 17 November 2018

Abstract. Supercapacitor can be used for energy storage and peak power control in order to increase the efficiency and the life cycle of the system. Energy storage systems or energy buffers using supercapacitor for solar energy systems have been presented in many recent studies. However, fast-charging process for supercapacitor from photovoltaic (PV) is mentioned very little. In this paper, the fast-charging system is designed with two power stages and limited current control algorithms. This charger can protect 5V/1500F supercapacitor module and 100 W PV panel safely. The experiment results under various solar irradiance intensity conditions are described by the characteristics of voltage and current.

Keywords: buck DC – DC converter, current limit control, supercapacitor (SC), photovoltaic (PV), solar energy.

Classification numbers: 4.1.1; 3.4.1.

1. INTRODUCTION

Worldwide growth of photovoltaics (PV) has been an exponential curve in period_2007-2017. The green energy or renewable energy helps to reduce environmental pollution and depletion of fuel. Investments in solar PV capacities are now rapidly growing in both connected grid and off - grid mode. Solar generation has been a reliable source for supplying electricity in regions without access to the grid for long term. The biggest solar energy plants reached over 1000 MW. In addition, electrical energy storage devices also evolved from traditional lead acid batteries to lithium ion batteries and especially supercapacitors (SC). Supercapacitor has considerable advantages, such as small bulk, high energy storage density, no electrochemical reaction, high charge/discharge current, less maintenance, long life and so on. Thereby, many researchers and scientists are interested in studying supercapacitor and developing it for practical applications [1].

The voltage and current of solar panels depend on the intensity of the solar irradiation, the panel temperature and the load characteristics. It is a nonlinear system with unstable voltage and current [2]. The use of supercapacitors in the solar cell system to improve the performance is mentioned in many articles such as hybrid energy management systems, renewable energy, harvesting energy and energy buffer [3-6]. When supercapacitors work as an energy buffer, it should be powered up as quickly as possible. On a sunny day, we only have a few hours to reach high solar radiation and on the cloudy day, fast-charging system is very necessary.

In this paper, a solar system is designed for fast charging a supercapacitor module 5V/1500F with two power stages from the 100 W photovoltaic panel. The first stage is a solar controller board. And the second stage is the traditional DC-DC buck converter designed to rapidly charge the 5V/1500F supercapacitor module. The buck converter modulates the charging voltage with IC XL4016 and limits the charging current of the supercapacitor module. The experiment results show that we had decrease of charging time, stability and safety under various condition of solar irradiation.

2. MATLAB MODEL AND CHARACTERISTIC CURVES OF PHOTOVOLTAIC

The simplest equivalent circuit of a solar cell is a current source in parallel with a diode (Figure 1) [7]. The output of the current source is directly proportional to the solar energy (photons) that hits on the solar cell (photocurrent I_{ph}). During darkness, the solar cell is not an active device; it works as a diode. It produces neither a current nor a voltage. However, if it is allowed to connect to an external source (large voltage) it generates a current I_d, called diode (D) current or dark current. Series resistance R_S in a solar cell has three causes: the movement of current through the emitter and base of the solar cell; the contact resistance between the metal contact and the silicon; and the resistance of the top and rear metal contacts. Shunt resistance R_{sh}, in parallel with the diode, this corresponds to the leakage current to the ground.

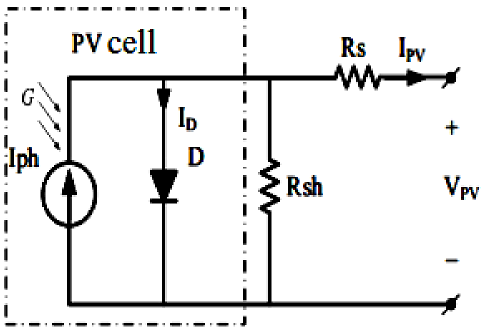

Figure 1. Equivalent electrical circuit of a photovoltaic module.

The current I_D and I_{ph} are calculated by the formula below [8]:

$$I_D = I_S\left(e^{\frac{qV_D}{nkT}} - 1\right) \tag{1}$$

$$I_{ph} = \mu_{sc}\ \ T_c - T_{ref}\ \ + I_{sc}\ \ G \tag{2}$$

$$I_S = \frac{I_{SC} + K_I \Delta T}{\exp\left(q\frac{V_{OC} + K_V.\Delta T}{nkT}\right) - 1} \tag{3}$$

where:

I_S: saturation current of diode; q = 1.60217646×10^{-19} C (the electron charge); k = 1.3806503×10^{-23} $J.K^{-1}$ (the Boltzmann constant); T: the temperature of the p-n junction (in K); n is the diode ideality factor (n = 1.2 with Si-Mono and n = 1.3 with Si-Poly); V_D: diode voltage.

$\Delta T = T_c - T_{ref}$; T_c: working temperature of solar cell; T_{ref} = 25 °C; G: solar irradiation (W/m^2); K_V: the open-circuit voltage/temperature coefficient of V_{OC}; K_I: the short-circuit current/temperature coefficient of I_{SC}.

Following the Kirchhoff law, we have:

$$I_{ph} - I_D - \frac{V_D}{R_{sh}} - I_{PV} = 0 \quad (4)$$

$$V_{PV} = V_D - R_S I_{PV} \quad (5)$$

According to (1) - (5), we build the simulation model of PV in Matlab Simulink as in Figure 2.

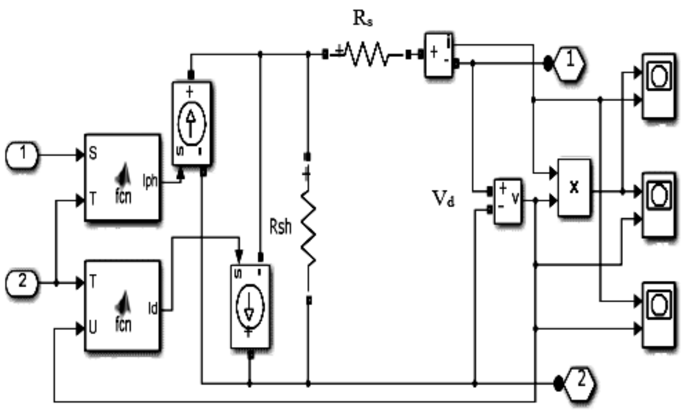

Figure 2. Simulation model of PV in Matlab Simulink software.

In this paper, the PV panel has been made by NingBo Reneled New Energy Co., Ltd with parameters as follows: Typical peak power: 100 W; Number of Cells: 36 Cells; V_{oc}: 22.64 V; I_{sc}: 5.7 A; Voltage at peak power V_{mp}: 18.78 V; Current at peak power I_{mp}: 5.32 A; K_V: -0.38 %/°C; K_I: 0.04 %/°C.

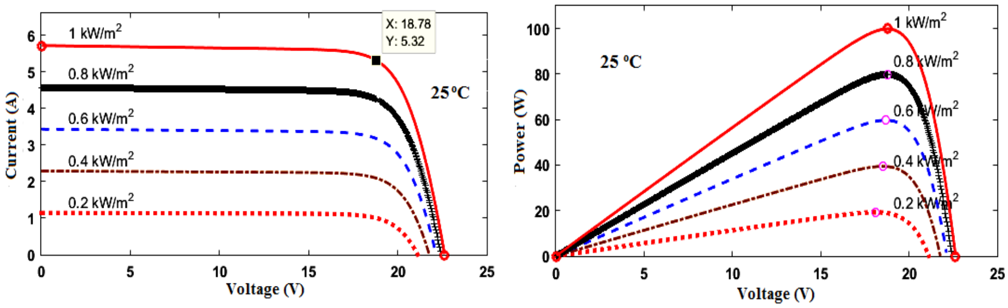

Figure 3. V-A and V-P curve of PV at 25 °C temperature.

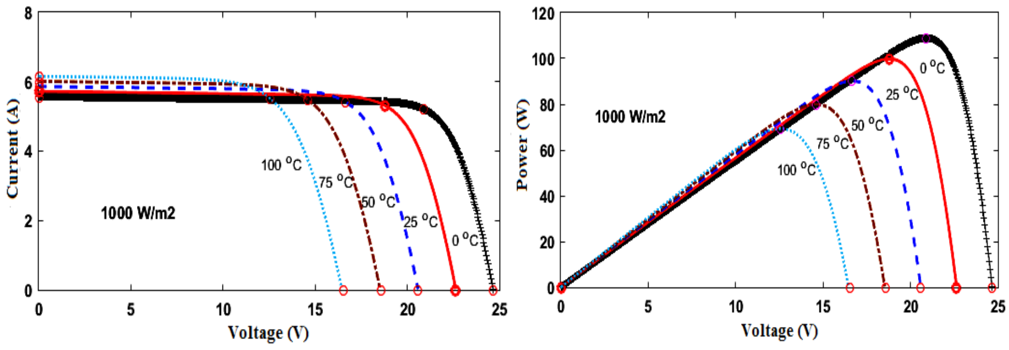

Figure 4. V-A and V-P curve of PV at 1000 W/m^2 solar irradiation.

The result of simulation is shown in Figure 3 and Figure 4. The values of PV voltage and current depend on the intensity of the solar radiation and the PV panel temperature. PV panels have non-linear characteristic curves. Besides, for each type of load, PV has different working points. This is a challenge for fast-charging supercapacitor from solar panels.

3. EXPERIMENT SYSTEM

3.1. Design of solar – supercapacitor system

Figure 5 shows diagram of experiment system including 5V/1500F supercapacitor module (two serial 2.7V/3000F Maxwell supercapacitors), 100W PV panel, solar power stage, SC power stage, I-V sensors and Oscilloscope LeCroy Wave Surfer 424.

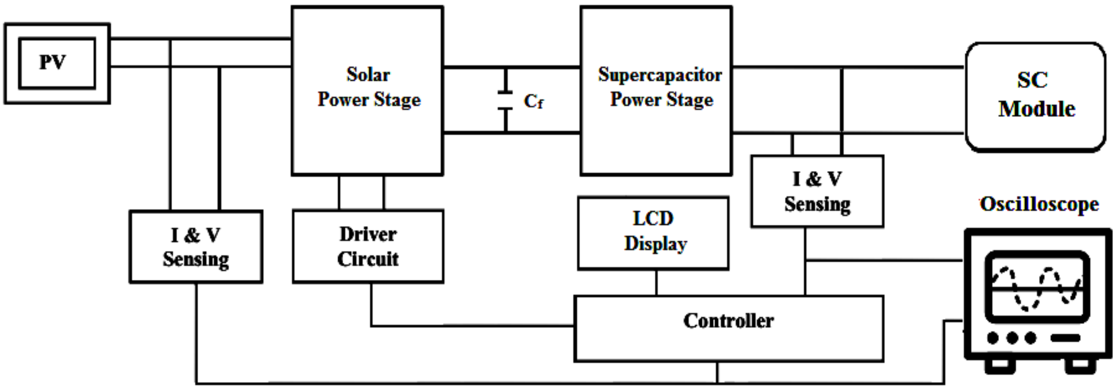

Figure 5. Structure of experiment system.

3.1.1. Supercapacitor power stage

The supercapacitor power stage is a traditional buck converter controlled by IC XL4016. IC XL4016 has a built-in MOSFET, 180 kHz PWM fix frequency, maximum current at 8 A and high efficiency up to 96%. The structure of the entire buck circuit is shown in Figure 6.

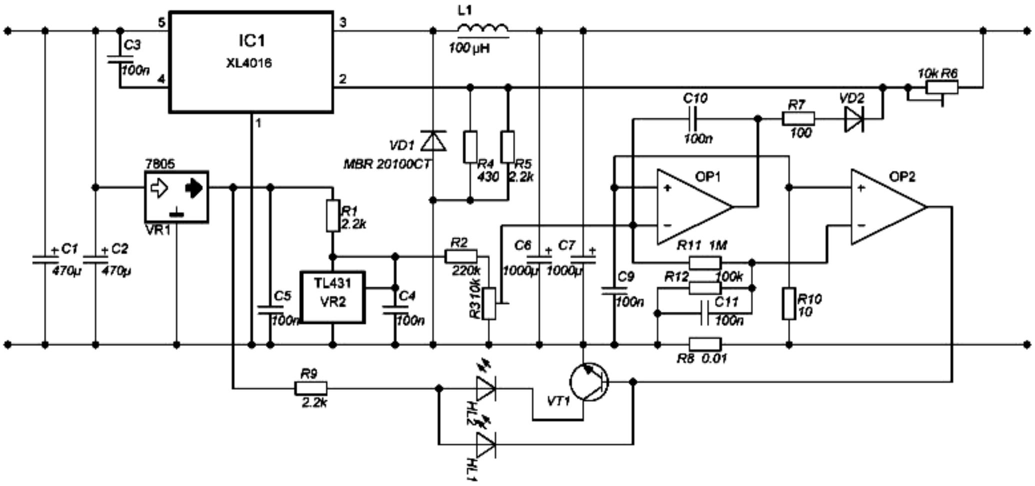

Figure 6. Diagram of buck converter with IC XL 4016 and PI controller.

Figure 7. Buck charging converter.

Two Op-amps OP1 and OP2 of IC LM358 are used to implement current limiting algorithm and turn on/off notification LED. The charging current is measured by a shunt resistance of 0.01 Ω (R8), then feedback to the first Op-amp OP1. IC TL431 will generate 2.5 V standard voltage from 5 V of IC 7805, through 220 kΩ (R_2) resistor and 10 kΩ (R_3) rheostat to create comparable reference voltage. If charging current equates to limited current, output voltage of OP1 is 5 V. The voltage goes to Feedback pin of XL4016 (pin 2). TTL shutdown mode is active when voltage of pin 2 is greater than 3.3 V, so the charging current cannot exceed the set value. The output voltage is measured through 10 kΩ rheostat (R_6) and returned to feedback pin. XL 4016 keeps the output voltage equability.

The charge capacities of the supercapacitors are influenced by the various rate of voltage and current. It means that dU/dt and dI/dt are as small as possible. The relationship between the ripple of charge voltage, charge current, PWM frequency, filter capacitor C_{out}, inductor L and duty-cycle can be expressed as in the following equations:

$$\Delta U_C = \frac{D.I_{load}}{C_{out}.f_s} \tag{6}$$

$$\Delta I = \frac{1}{2}.\frac{V_{in} - V_o}{L}.\frac{V_o}{V_{in}}.T_s \tag{7}$$

In order to decrease ΔU_c and ΔI, we used high PWM frequency (f_s of XL4018 is 180 kHz), output capacitor of buck converter with 1000 µF and 100 µH inductor. The buck converter is presented in Fig. 7.

3.1.2. Solar power stage

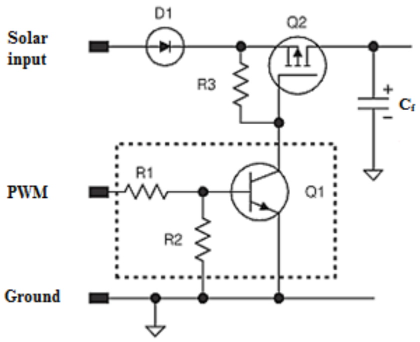

Figure 8. Circuit of the solar power stage.

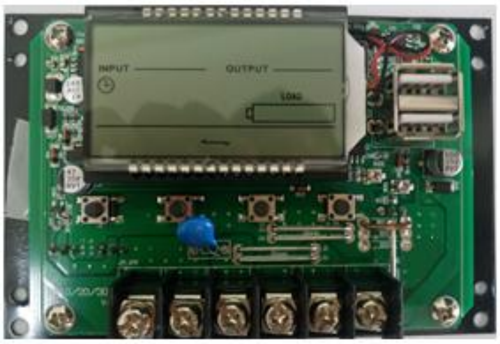

Figure 9. Solar controller board.

Figure 8 presents a circuit of the solar power stage and Figure 9 demonstrates a solar controller board, which were used in our research. The charging process of the supercapacitor is different from the battery. When SC is empty, its voltage is very low ($V_{SC} \approx 0$ V). And when SC is full, it will not get any more energy ($I_{charge} \approx 0$ A). At the beginning of the charging process, the set voltage is 5 V, while the feedback voltage is 0 V, the buck converter will work with maximum duty cycle. This could damage IC XL4016. Therefore, we use one more power stage for this charging system. The solar power stage performs the following tasks:

- Measure the voltage/current of the PV panel (V_{PV} and I_{PV}), the charge voltage/current of the SC module (V_{SC} and I_{SC}).
- If $I_{SC} \geq 8$A or $I_{SC} \leq 0$A then Q_2 (see Fig. 8) is OFF. When $I_{SC} = 0$A for 15 minutes, the solar panel board (see Fig. 9) will display that the supercapacitor module is FULL.
- When V_{PV} or/and I_{PV} are very low, Q_2 is turn OFF.
- Overload, Short Circuit Protection.
- Adjustable charge time in 24 hours.

The entire experiment system is show in Fig. 10.

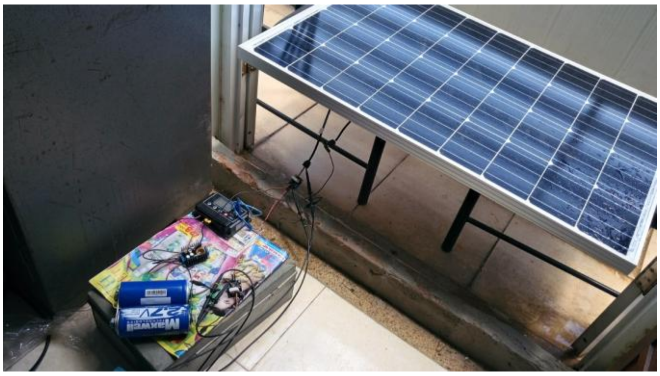

Figure 10. Experiment charge system.

3.2. Experiment result

3.2.1. Experiment in sunny day

During under clear sky, the solar irradiation varies from 800 to 900 W/m^2. However, the outdoor temperature is high and it raises the temperature of the PV panel. The temperature of PV can reach up to 75 ^{o}C. With 4.8 V output charge voltage and 6 A limited current, result of charging process is showed in Figs. 11-14. Compared to the simulation results, we can see the similarity between them. PV voltage drops to 4 V, and then increases slowly. 5V/1500F supercapacitor module is charged in 3000 seconds. When SC voltage is increasing, charging current decreases gradually to zero and PV voltage is up to peak voltage at currently temperature and radiation.

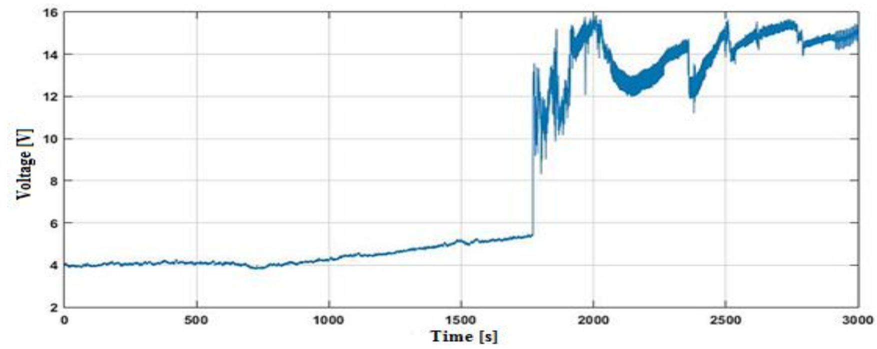

Figure 11. Voltage of PV panel in sunny day.

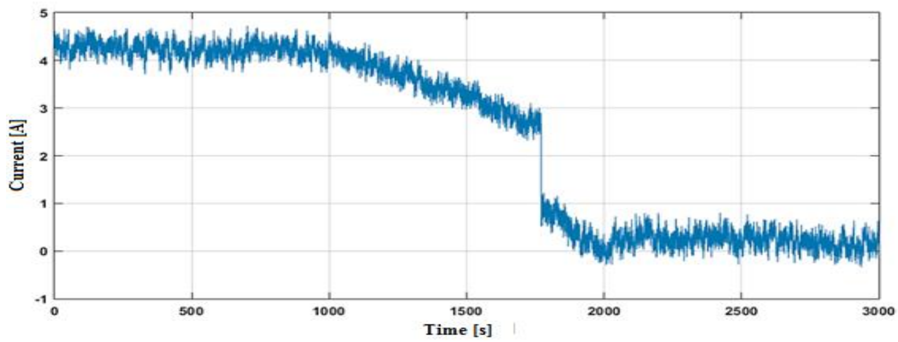

Figure 12. Current of PV pane in sunny dayl.

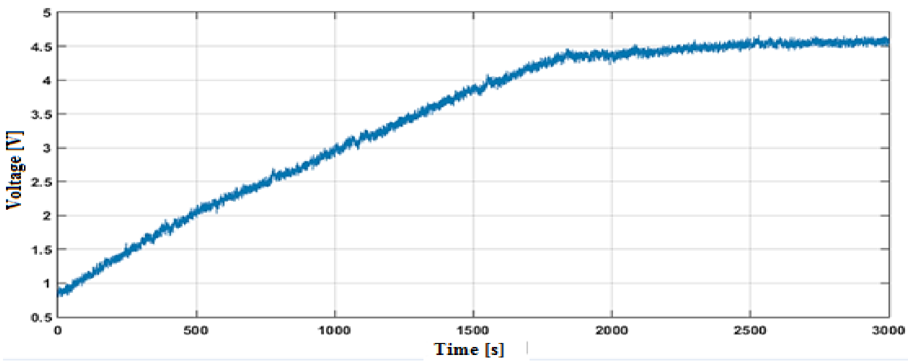

Figure 13. Voltage of supercapacitor in sunny day.

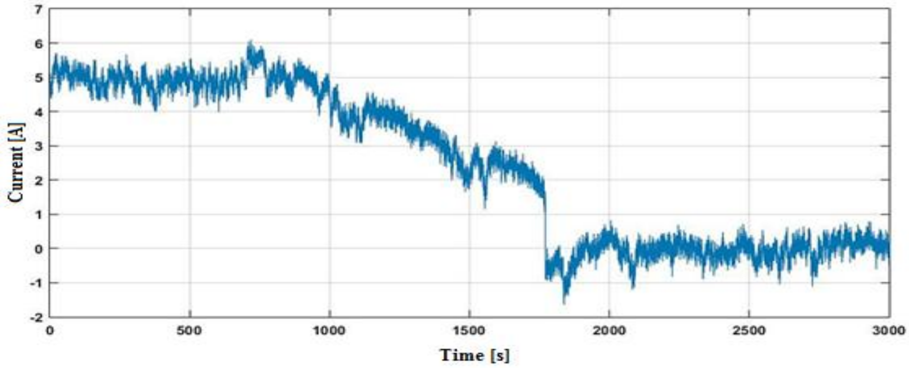

Figure 14. Charging current of supercapacitor in sunny day.

3.2.2. Experiment in cloudy day

When it becomes cloudy, the solar irradiation varies from 600 to 700 W/m^2. The temperature of PV panel can increase to 60^{o}C. The result of charging process is showed in Figs. 15-18. Similar to the above experiment, PV voltage also drops to under 4V. Due to weaker solar radiation, the charging current is smaller. Thus, supercapacitor needs to be charged in approximately 3500 seconds.

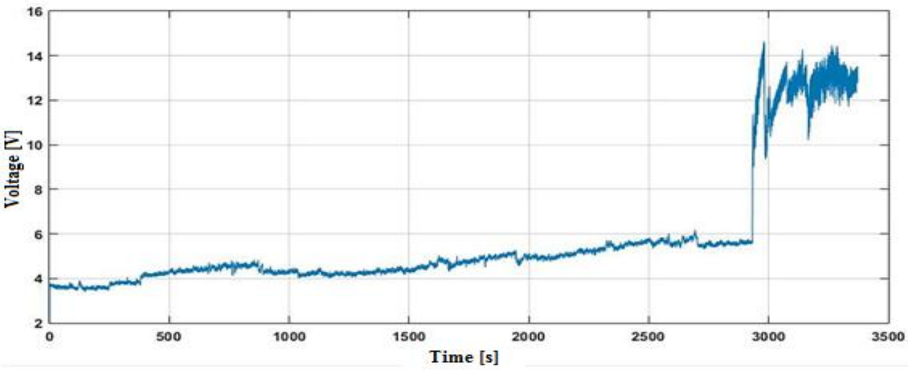

Figure 15. Voltage of PV panel in cloudy day.

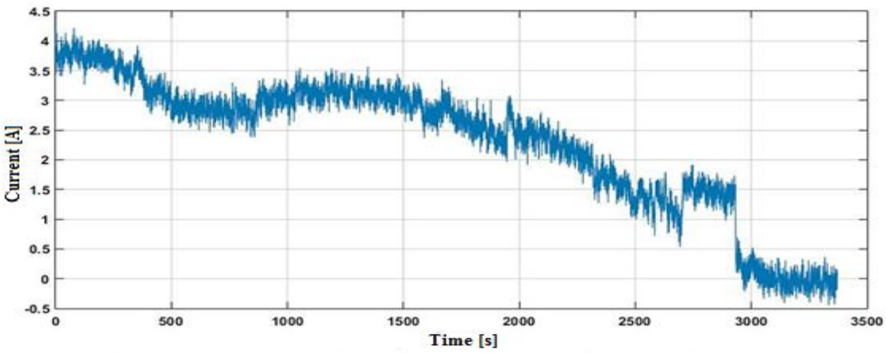

Figure 16. Current of PV panel in cloudy day.

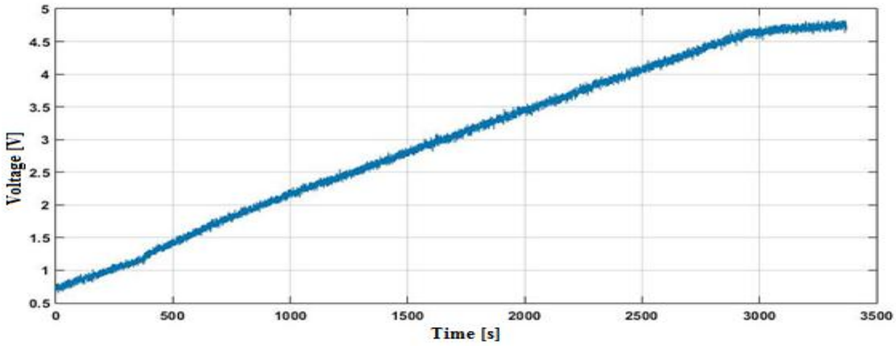

Figure 17. Voltage of supercapacitor in cloudy day.

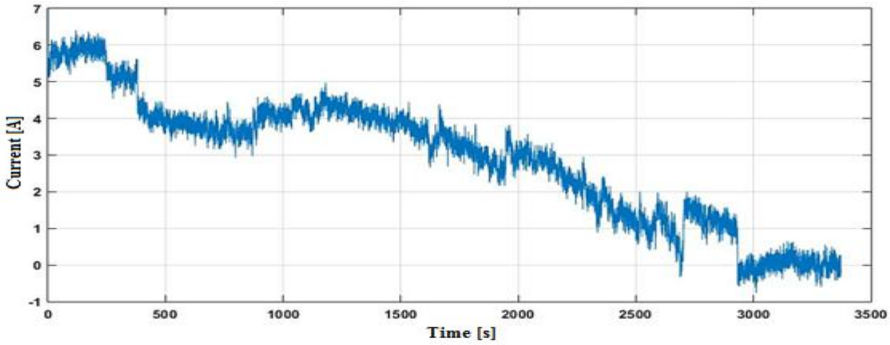

Figure 18. Charging current of supercapacitor in cloudy day.

4. CONCLUSION

In conclusion, we presented a solar system to fast charge the 5V/1500F supercapacitor module for 100 W PV array. The solar systems consist of two power stages: solar power stage and buck charge converter with IC XL4016. Supercapacitor was fully charged for less than one hour. With the fast-charging system, we can enhance performance and efficiency of energy buffers for any hybrid energy store system (HESS).

Acknowledgement. The authors acknowledge financial support from Support the Young Scientists Program of Vietnam Academy of Science and Technology and Institute for Tropical Technology (2018 annual project).

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