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Adaptive voltage control for MPPT-firefly algorithm output in PV system

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Abstract. In general, Photovoltaic (PV) array is not able to generate maximum power automatically, because some partial shading caused by trees, clouds, or buildings. Irradiation imperfections received by the PV array are overcome by applying Maximum Power Point Tracking (MPPT) to the output of the PV array. In order to overcome these partial shading problems, this system is employing Firefly Algorithm (FA) as MPPT method. It optimizes the output power of the solar PV array by Zeta Converter. Output voltage of MPPT has high rate such that it needs stepdown device to regulate certain voltage. Constant voltage will be the input voltage of Buck Converter and controlled using Adaptive PID. Adaptive control based on MRAC has design that almost same as the conventional PID structure and it has better performance in several conditions. The proposed system is expected to have stable output and able to perfectly emulate the response of the reference model. From the simulation results, it appears that FA have high tracking accuracy and high tracking speed to reach maximum power of PV array. In the output voltage regulation, adaptive control does not have a stable error status and consistently follows the set point value.

1. Introduction

Energy is very necessary in human life, this utilization represents economic and social development. Many countries try to find ways to solve energy problems that include energy resources, environmental pollution, global warming, and energy inefficiency. This is why researchers around the world are interested in studying renewable energy sources, such as Photovoltaic (PV) [1]. PV generally cannot work directly at its maximum power, because the PV operating voltage mostly follow the battery voltage connected to the PV. Therefore, the application of Maximum Power Point Tracking (MPPT) must be used to regulate PV module in order to achieve Maximum Power Point (MPP) [2-4]. Commonly problems in PV that are connected in an array certainly not all receive the same level of irradiation and maybe even some of them are covered in shadows caused by trees, clouds, or other objects. In this condition, the power generated from each PV module becomes unbalanced, such that the total output power will decrease and also cause multi-peak on the PV characteristic curve [5-8].

Many researchers have developed various MPPT methods to track PV's maximum power points and overcome problems caused by partial shadows, and several methods have reached an optimal solution [8-11]. For this reason, a metaheuristic algorithm with an examination concept is used as an optimization problem without defining a definite objective function. Firefly Algorithm (FA) can obtain global peaks by utilizing randomization to avoid trapping algorithms at local peak [12,13].

To keep the voltage value maintained in accordance with the reference value of the maximum power value obtained by MPPT, the right controller is needed. DC-DC converters are a real form of DC voltage regulators both up, down, or both. System dynamics are needed to design controllers that are able to achieve the desired value. PID control is widely applied in the industrial world with a variety of adjustment techniques [14]. One of the adaptive techniques is that MRAC has succeeded in increasing the system response rather than the fixed parameter PID controller [15-18] by providing a reference model followed by the system response. MIT rules are used in this study to determine adaptive PID parameters [19]. Therefore, the main objective of this research is to emphasize how to design an MPPT system that has a constant output voltage.

2. System description

In this system uses two DC-DC converters, a zeta converter and a buck converter that connects the PV array to generate power in load demand. In order to obtain the maximum power of the PV array, this research is using zeta converter. The second DC-DC converter or buck converter is used to control the output voltage at 12V. The system will be simulated according to the original conditions, starting from the PV array, zeta converter, buck converter and load as a given disturbance. The block diagram of the proposed system is illustrated in Figure 1.

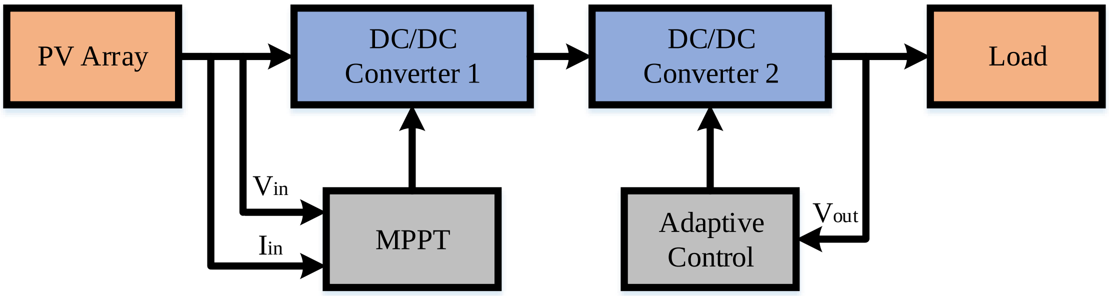

Figure 1. Block diagram of proposed system.

2.1. MPPT-firefly algorithm in PV array

PV array is a combination of several PV modules that are expected to produce high voltage or current or even power than a PV module. The power generated has a higher voltage value so that it can be used for more loads. In this research using a PV array with 3 PV modules that are connected in series and have a partial shadow issues or failure of the PV module. The voltage at MPP, current at MPP, and MPP from PV module are successively represented by V_{mp}, I_{mp}, and P_{mp} as shown in Figure 2. Thus, the voltage on the MPP of the PV array connected in series is $3 \times V_{mp}$, the current at MPP is I_{mp}, and the maximum power is $3 \times P_{mp}$.

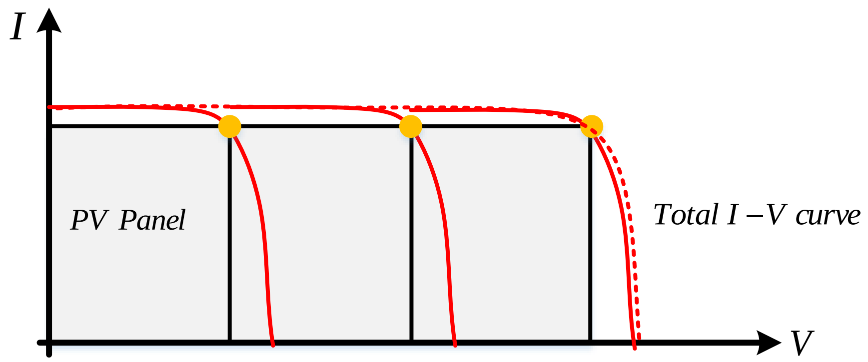

Figure 2. I-V curve of PV modules connected in series.

PV arrays using the FA algorithm applied to MPPT are expected to be able to achieve global MPP values with non-uniform irradiation conditions. This algorithm is applied to DC converters namely Zeta Converter as shown in Figure 3. This converter has buck capability and boost capability but has non-inverting output voltage values. The FA algorithm has two basic functions of flickering, namely for communication between fireflies (aim to attract other fireflies) and to attract their prey. The attractiveness of fireflies is determined by the brightness of the fireflies associated with the value of the objective function. The inputs of FA are the output voltage and current of PV array.

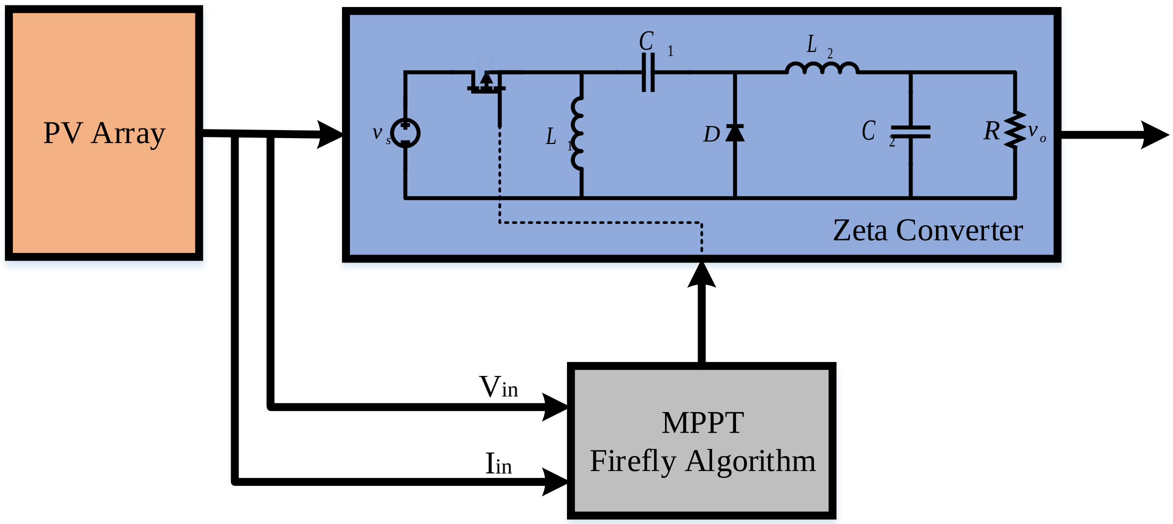

Figure 3. Block diagram of MPPT-FA using Zeta converter.

The relative attraction value β depends on the evaluation of other fireflies. Thus, the attraction will vary according to the distance r_{ij} between fireflies i and fireflies j. The attraction of β can be determined by

$$\beta = \beta_0 e^{-\gamma r^2} \tag{1}$$

r is the distance between two fireflies. β_0 is the attraction at $r = 0$ or the initial attraction. γ usually varies between 0.1 to 10 [4].

The distance between the two fireflies i and j at the positions $\boldsymbol{x_i}$ and $\boldsymbol{x_j}$ can be defined as Cartesian distance

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \tag{2}$$

where $x_{i,k}$ and $x_{j,k}$are the k-component in the spatial coordinates of the firefly i and firefly j, and d is the dimension number. For the MPPT case, which is a 1-dimensional case, the value d = 1 is used.

Movement of fireflies that are attracted to fireflies that are brighter is determined by

$$x_i = x_i + \beta \cdot (x_j - x_i) + \alpha \cdot \left(rand - \frac{1}{2}\right) \tag{3}$$

The second part of equation (2-9) shows the movement of fireflies based on their appeal to lighter fireflies. The third part of equation (2-9) shows the movement based on random values where α is a random parameter with α∈ [0,1] and rand is a random perturbation value between 0 to 1 [4]. Randomization provides a good way to avoid local search and to move to search on a global MPP. In general, small α values tend to lead to local search, while large α leads to global search [8].

On the MPPT system, x_i or the position of the fireflies is V_{ref} and it is compared the brightness of the fireflies or the output power of PV (P) in that position. Other variables of FA that are converted to PV systems can be seen in Table 1.

Table 1. Conversion of PV *systems* to FA *variables.*

FA	PV System
Position of fireflies ($\boldsymbol{x_i}$)	Input voltage (V_{ref})
Distance between fireflies ($\boldsymbol{r_{ij}}$)	Voltage Deviation (ΔV_{ref})
Attraction ($\boldsymbol{\beta}$)	Exponential function of ΔV_{ref}
Brightness	MPP (P)
Brightness of the brightest fireflies	Global MPP (P_{Gbest})

Because the converter can only respond to one command at a time, the fireflies are initialized and then treated in the same manner in succession. The flow diagram of the FA control behavior for MPPT is shown in Figure 4.

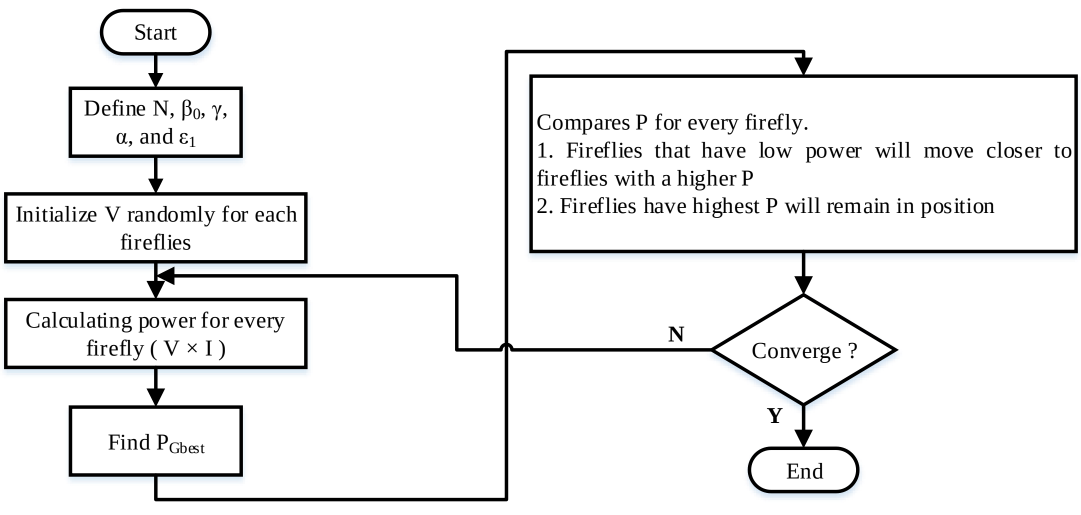

Figure 4. Flowchart of MPPT-*firefly algorithm.*

IOP Conf. Series: Materials Science and Engineering **732** (2020) 012048 doi:10.1088/1757-899X/732/1/012048

2.2. *Adaptive control in buck converter*

Adaptive controller is applied to second DC converters namely buck converter. The configuration of buck converter is shown in Figure 5. The desired output voltage is a step down voltage which is generated by the Pulse Width Modulation (PWM). PWM sets the ignition on the buck converter switch based on the duty cycle value. In this study, buck converter operates in CCM (Continuous Conduction Mode) so that the inductor current is always greater than zero. The advantages of buck configuration are high efficiency, simple circuit, no need for transformers, low stress level on switch components, and small ripple at the output voltage, furthermore, the filter needed is relatively small. The buck converter circuit does not have an isolation component to maintain the system between input and output.

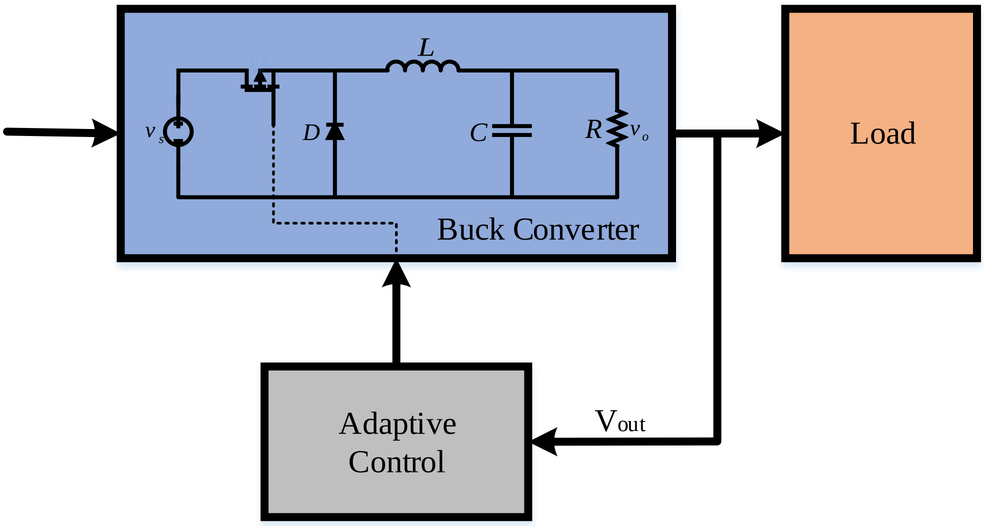

Figure 5. Block diagram of adaptive control using Buck converter

The state space averaged model is obtained by combining the ON and OFF condition, the mathematical expression for buck converter is shown in (4).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} V_{in} \tag{4}$$

Designing an adaptive control according to reference model (MRAC) is one type of adaptive control structure by developing adaptation parameters for PID control using certain rules.

The Buck converter uses one inductor and one capacitor, which means this system is a 2nd order system. The system model is described as:

$$\frac{Y_p(s)}{U(s)} = \frac{b}{s^2 + a_1 s + a_2} \tag{5}$$

The second-order reference model given by:

$$\frac{Y_m(s)}{U(s)} = \frac{bm_1 s^2 + bm_2 s + bm_3}{s^3 + am_1 s^2 + am_2 s + am_3} \tag{6}$$

The adaptation error:

$$\varepsilon = Y_p - Y_m \tag{7}$$

The cost function is denoted as:

$$J(\theta)=\frac{\varepsilon^2(\theta)}{2} \quad (8)$$

Where ε is the difference between the output system and the output model reference or error. MIT rule is employed in this adaptive control design, the change in error respects to the parameter θ and the change in parameter θ respects to time can determine the value of the cost function to be close to zero so that it obtains the same value as the reference value. γ is a definite positive value that indicates the adaptability of the controller.

$$\begin{aligned}\frac{d\theta}{dt}&=-\gamma\frac{\partial J}{\partial\theta}=-\gamma\varepsilon\frac{\partial\varepsilon}{\partial\theta}\\ \frac{dK_p}{dt}&=-\gamma_p\frac{\partial J}{\partial K_p}=-\gamma\frac{\partial J}{\partial\varepsilon}\frac{\partial\varepsilon}{\partial Y_p}\frac{\partial Y_p}{\partial K_p}\end{aligned} \quad (9)$$

Where; $\frac{\partial J}{\partial\varepsilon}=\varepsilon$, $\frac{\partial\varepsilon}{\partial Y_p}=1$

The adaptive PID controller parameters K_p, K_i, and K_d are shown in (10).

$$\begin{aligned}\frac{dK_p}{dt}&=-\gamma_p\frac{\partial J}{\partial K_p}=-\gamma_p\varepsilon\frac{bs}{\left(s^3+(a_1+bK_d)s^2+(a_2+bK_p)s+bK_i\right)}\left(R(s)-Y_p(s)\right)\\ \frac{dK_i}{dt}&=-\gamma_i\frac{\partial J}{\partial K_i}=-\gamma_i\varepsilon\frac{b}{\left(s^3+(a_1+bK_d)s^2+(a_2+bK_p)s+bK_i\right)}\left(R(s)-Y_p(s)\right)\\ \frac{dK_d}{dt}&=-\gamma_d\frac{\partial J}{\partial K_d}=-\gamma_d\varepsilon\frac{bs^2}{\left(s^3+(a_1+bK_d)s^2+(a_2+bK_p)s+bK_i\right)}\left(R(s)-Y_p(s)\right)\end{aligned} \quad (10)$$

By stating that $am_1=a_1+bK_d$; $am_2=a_2+bK_p$; $am_3=bK_i$

3. Results and analysis

In this study, using 3 PV modules installed in series as PV array. The use of PV array aims to get a graph that has a maximum of 3 peaks, two local peaks and one global peak. The SP-100-P36 is chosen for PV array modelling. The module has maximum power 60W and 36 series connected polycrystalline cells. The parameters of SP-100-P36 are provided in Table 2. In this research using the FA method to explore the maximum power value at the output of the PV array. Some parameter for FA are summarized in Table 3.

Table 2. SP-100-P36 solar module parameters.

Parameters	Value
Maximum Power (P_{max})	100 W
Voltage at Maximum Power (V_{mp})	17,6 V
Current at Maximum Power (I_{mp})	5,69 A
Open Circuit Voltage (V_{oc})	22,6 V
Short Circuit Current (I_{sc})	6,09 A

Table 3. FA parameters.

Parameter	Value
Number of Fireflies (N)	5
Firefly attractiveness(β_0)	1
Light absorption coefficient (γ)	1
Random Parameter (α)	0,1
Tolerance Value(ε_1)	1

IOP Conf. Series: Materials Science and Engineering **732** (2020) 012048 doi:10.1088/1757-899X/732/1/012048

The output of the zeta converter is unstable at a certain value, so controller is required to make the output voltage stable. Constant voltage will be controlled using adaptive PID controller and the output voltage will be constant in set point. The second DC converter used in this research is buck converter. Buck converters have the following parameters, $L = 1mH$, $C = 470\mu F$, $R = 100\Omega$ and input voltage of $52V$. In this system will have two scenarios, namely the first case is a situation where the PV array is affected by the shadow or not; and the second case is the input voltage of the buck converter changes. Table 4 shows MPP of each case.

Table 4. MPP in several case.

Case	Irradiation (W/m^2)			MPP (W)
	M1	M2	M3	
1	1000	1000	1000	300.432
2	900	800	700	246.253

In Figure 6 and Figure 7 show the MPPT signal (proposed method and P&O) from the zeta converter to output voltage of buck converter at $1000\ \mathrm{W/m^2}$ irradiation uniformly and experiences different partial shadows on each module. Figure 6 shows the output power of MPPT accordance with the maximum power of PV is 300,238 W. There is a little error that occurs due to the determination of the parameters of the PSO that is not optimal yet. The voltage generated by the buck converter matches the desired voltage which is 12V. The same results are shown in Figure 7, when the PV array gets unequal irradiation, the maximum power value obtained is 245,873. Clearly, MMPT systems are able to achieve maximum power with tracking accuracy up to 98.76% and tracking time is less than 0.3 seconds. This shows that the designed MPPT and controller are work properly.

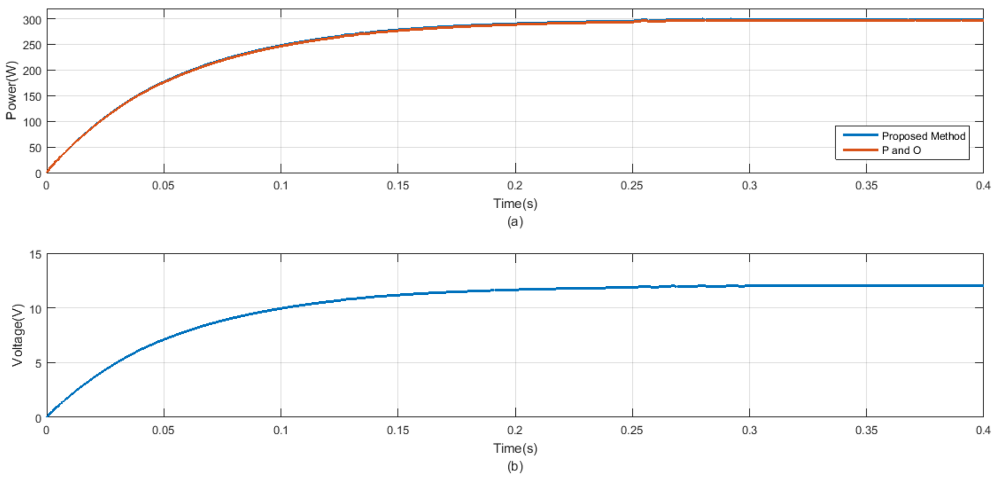

Figure 6. (a) Output power of MPPT and (b) output voltage of buck converter in case 1.

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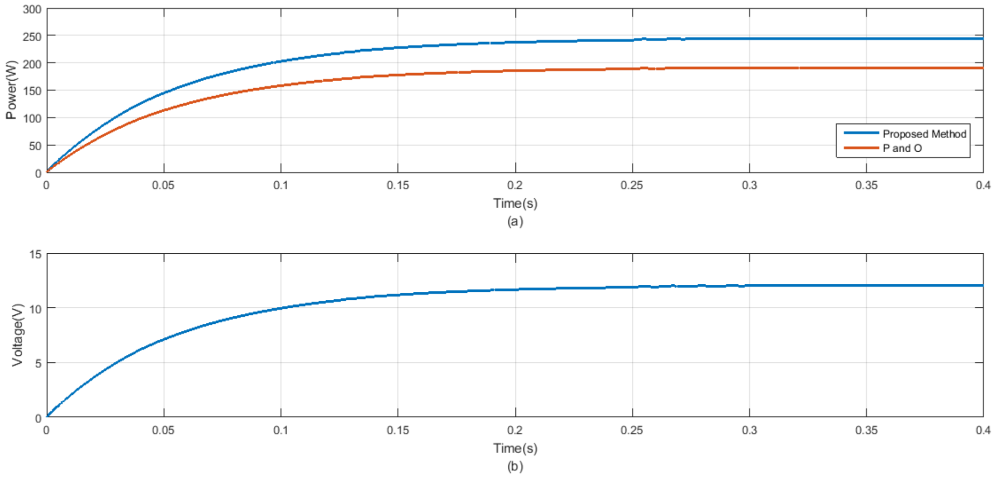

Figure 7. (a) Output power of MPPT and (b) output voltage of buck converter in case 2.

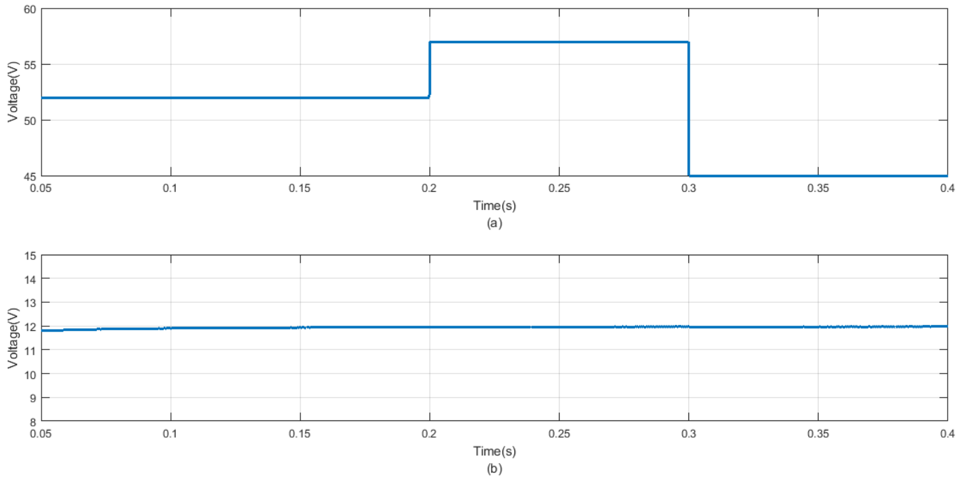

Figure 8. (a) Input voltage variations and (b) output voltage when the input voltage changes.

In order to find out the controller is working well, then in this study carried out changes in the input voltage of the buck converter as shown in Figure 8. The input voltage starts at 53V and then rises to 58 V at t = 0.2, the response of output voltage in accordance with the desired value of 12 V. The same thing happens when the input voltage drops to 45V at t = 0.3, the output voltage is fixed and does not change at set point value.

4. Conclusion
The FA method finds maximum power point accurately after that adaptive controller generate the stable output voltage. From the simulation results, it appears that FA have high tracking accuracy and high tracking speed to reach maximum power of PV array. Furthermore, the output voltage regulation, adaptive control does not have error steady state and consistently follows the set point value.

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