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An improved incremental conductance based MPPT approach for PV modules

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Abstract: This paper presents a new maximum power point tracking (MPPT) method based on an incremental conductance (IC) algorithm, constant voltage, and look-up table approach. Convergence time, one of the indicators of MPPT quality, is considered for improving MPPT performance of photovoltaic (PV) modules. In this context, a novel hybrid MPPT approach has been proposed. This proposed method consists of three stages. In the first stage, the value of load resistance is calculated. Then the initial operation point of the PV module is determined by using the constant voltage method or look-up table approach. An IC algorithm is used in order to increase MPPT accuracy in the last stage. One of the novelties of this proposed approach is the determination criterion related to sample numbers of PV module current or solar irradiance. With the help of this approach, the initial operation point of the PV module is optimized before MPPT starts. Thus, convergence time is reduced. In this paper, a DC–DC boost converter has been designed to show the performance of the proposed approach. Then the proposed approach is compared with an IC algorithm. Experimental results show that the performance of the proposed approach is better than that of the IC algorithm in terms of convergence time. On the other hand, since the proposed approach is convenient for reducing convergence time, it can be used instead of variable step size algorithms. Furthermore, there are no topological constraints in the proposed approach. Therefore, this method can be easily applied to other converter topologies for low power or microconverter (module-based converter)-based applications.

Key words: Incremental conductance (IC) algorithm, maximum power point tracking, photovoltaic module, convergence time

1. Introduction

Photovoltaic (PV) modules are used to convert sunlight energy into electrical energy and they are defined as a nonlinear DC power source. The dependency of environmental factors and p–n junction structure makes PV modules an unreliable power source for electricity continuity. Furthermore, there is one unique point on the voltage–current (V–I) curve, which is defined as maximum power point (MPP). PV modules should be operated under MPP condition for the purpose of obtaining high efficiency. Therefore, MPPT controlled DC–DC converters are used to increase the energy conversion efficiency of PV modules. In this context, there are many algorithms and methods presented in the literature [1–18].

Many algorithms and methods have been proposed to conduct MPPT operations in PV applications. The basic aim of these algorithms and methods is to maximize the available power of PV modules. Perturbation and observation (P&O) and IC are very common algorithms in terms of easy adaptation to PV systems and they are always considered as cost effective methods. When the success of MPPT operation is evaluated, the P&O

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algorithm is unsuccessful for sudden changes in solar irradiance. However, the IC algorithm performs better than P&O for this condition [1–3].

There are more conventional methods based on the characteristic value of PV modules. Maximum power current and maximum power voltage of PV modules have linear relationships between short circuit current and open circuit voltage, respectively, in these methods. In order to measure these variables, an additional component is required. This additional component is usually a static switch (MOSFET, IGBT etc.). Switches are connected in series to the PV module while open circuit voltage is measured and they are connected in parallel to the PV module while short circuit current is measured. During these measurements, power loss increases with the value of sample time. This additional measurement increases the cost and complexity of hardware. Furthermore, accuracy of these methods is low compared with hill-climbing based methods [4–6]. When it comes to look-up table-based methods [7], such as fuzzy logic and neural network techniques [8–10], they have relatively quick response under sudden changes in environmental factors. However, unexpected disturbances, such as shades on the PV modules, which are not assumed, detrimentally affect the MPPT performance [1,11].

Convergence time is an important issue for quality of MPPT operation. Since conventional methods do not take into account this parameter and paradigm of response time and fluctuation at MPP are important problems for conventional algorithms such as P&O and IC, adaptive and variable step size algorithms have been developed [11–14]. In these algorithms, due to the variable step size approach, duty ratio is optimized and convergence time can be reduced. However, this algorithm requires a developed microcontroller and includes complex mathematical functions [1,2]. On the other hand, even if short circuit current or open circuit voltage measurement-based algorithms come up with a convergence time problem, energy loss and hardware complexity increase. Furthermore, MPPT accuracy is very low in these approaches due to variable coefficients based on environmental factors [4–6,15–18].

This paper proposes a new approach in order to manage MPPT operation in an efficient way to reduce convergence time. This approach consists of three stages. The first stage is the calculation of load resistance value. Then the voltage and current of the PV module are measured twice in a small time interval. The result of measurements determines the initial operation condition of the PV module. If PV module voltage is higher than maximum power voltage, the initial duty cycle value of the switch gate signal is determined by the constant voltage method. Maximum power voltage of the PV module is assumed constant under different values of solar irradiance in this method. On the other hand, if PV module voltage is lower than maximum power voltage, the initial duty cycle value is determined by the value of PV module current. This determination is based on the look-up table approach. These two stages are designed to decrease the convergence time. Then the accuracy of the MPPT operation is increased in the last stage. For this purpose, the IC algorithm is used. In order to verify the proposed method, a DC–DC boost converter is designed to adjust equivalent resistance of the PV module, which is an important parameter for the MPPT operation. Features of this approach can be summarized as follows:

- This approach does not require any additional component. There are no additional sensors to realize the MPPT operation.

- The proposed method can be applied to other DC–DC converter topologies. There are no topological constraints. This method is applied to single PV module applications, which are called microconverter-based MPPT in the literature.

- The proposed approach is cost effective and it can be easily conducted by using a basic microcontroller.

- Convergence time is remarkably reduced compared with the classical IC algorithm.

The rest of this paper is organized as follows. In Section 2, the IC algorithm is explained by illustrations.

The proposed approach is presented in Section 3. Experimental studies were conducted to verify the effective performance of the proposed approach in terms of convergence time. These experimental results are shown in Section 4.

2. Incremental conductance algorithm

The voltage–current (V–I) characteristic of PV modules is nonlinear. Therefore, there is one unique MPP under a certain environmental condition. This situation can be defined as a drawback for a power generation system. In order to eliminate this disadvantageous condition, MPPT systems are used. A typical MPPT system consists of current and voltage sensors, which are generally a Hall-effect current sensor and voltage divider circuit, respectively, a DC–DC converter, and a MPPT algorithm as presented in Figure 1.

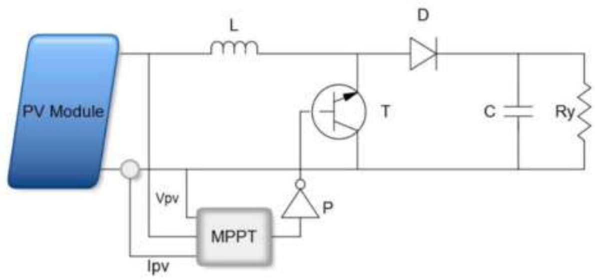

Figure 1. A typical MPPT system.

IC is a hill-climbing–based MPPT algorithm. An important feature of this algorithm is its high tracking accuracy under sudden changes in solar irradiance [1,2]. In this algorithm, first of all, the current and voltage of the PV module are measured. Incremental conductance and instantaneous conductance are calculated. Then some comparisons are made in order to determine the direction of duty ratio of the switch gate signal as presented in Figure 2. The mathematical basis of this algorithm is derivative of power with respect to voltage. As given in (1-3), there are three possible conditions for the initial operation point of the PV module.

$$\frac{dP}{dV} = 0 \rightarrow \frac{\Delta I}{\Delta V} = -\frac{I}{V} \rightarrow MPP \tag{1}$$

$$\frac{dP}{dV} > 0 \rightarrow \frac{\Delta I}{\Delta V} > -\frac{I}{V} \tag{2}$$

$$\frac{dP}{dV} < 0 \rightarrow \frac{\Delta I}{\Delta V} < -\frac{I}{V} \tag{3}$$

In order to explain this algorithm, the derivative of power with respect to voltage can be used as a control index. Figure 3a shows a typical V–P (voltage–power) characteristic of the PV module. If the value of this index is negative, reference voltage has to be increased. On the other hand, if this is positive, reference voltage has to be decreased. Since the operation point of the PV module depends on the value of load resistance and dynamic environmental conditions, this index is rarely equal to zero. Contrary to the P&O algorithm, MPPT accuracy is perfect under quick changes in solar irradiance for this algorithm as given in Table 1.

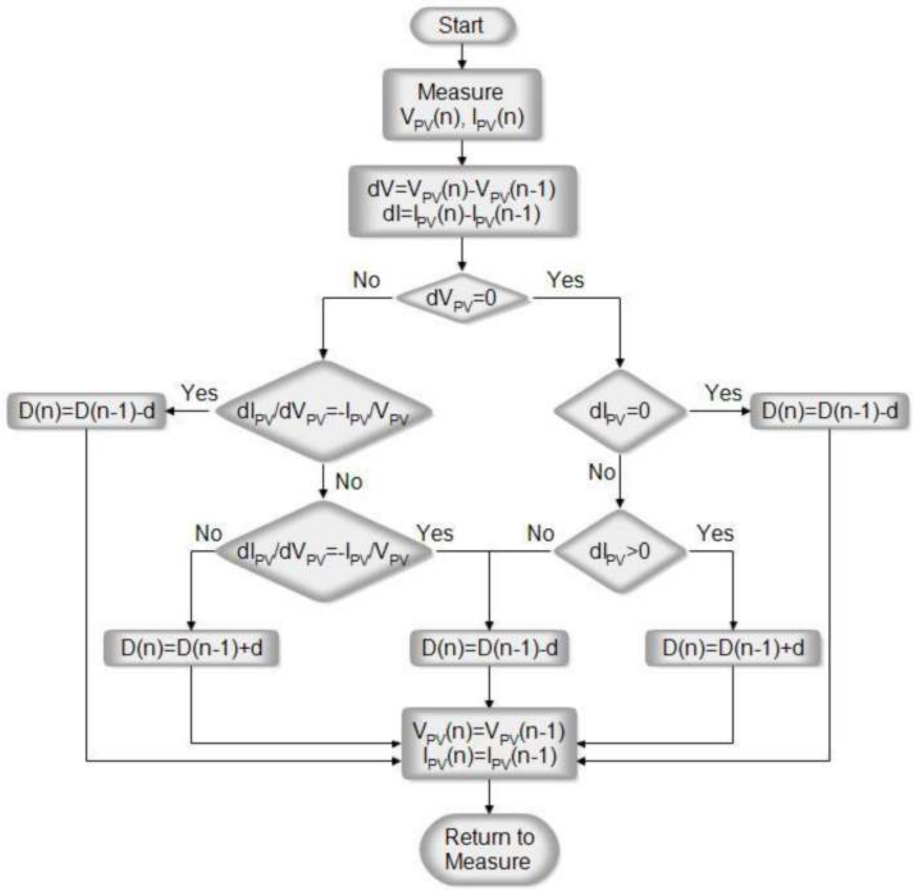

Figure 2. Flowchart of IC algorithm.

Table 1. All possible scenarios of the IC algorithm.

General condition	First point	Change in condition	Happened	Duty cycle	Next point	MPPT success
Fixed solar irradiance ($2Q_{amb}$)	MPP-1	R_{Load} ++	A (P↓V↓)	D ++	B	Perfect
	B	R_{Load} ++	A (P↓V↓)	D ++	G	
	MPP-1	R_{Load} –	D (P↓V↑)	D –	C	
	C	R_{Load} –	D (P↓V↓)	D –	Below C	
Variable solar irradiance	MPP-2	$2Q_{amb}$	B (P↑V↓)	D –	G	
	MPP-2	$2Q_{amb}$	C (P↑V↑)	D ++	MPP-1	
	MPP-1	Q_{amb}	E (P↓V↓)	D ++	H	
	MPP-1	Q_{amb}	F (P↓V↑)	D –	Below F	

The operation principle of this algorithm can be summarized as follows. If the PV module operates under MPP condition, this operation condition continues by the time change of solar irradiance and/or temperature occurs. In other words, change of duty cycle (d = 0) equals zero, if environmental conditions are the same. However, the value of load resistance may change at any moment. For example, if the new operation point of the PV module changes from MPP-1 to A, which means a decrement of power as shown in Figure 3b, point A is an inefficient point ($2Q_{amb}$) and PV module voltage has to be increased in the next cycle. It is possible to experience the same situation in the right side of MPP-1 ($2Q_{amb}$), if the operation point changes from MPP-1 to D. PV module voltage has to be decreased from point D to C for this condition. Table 1 summarizes all possible conditions for MPPT operation.

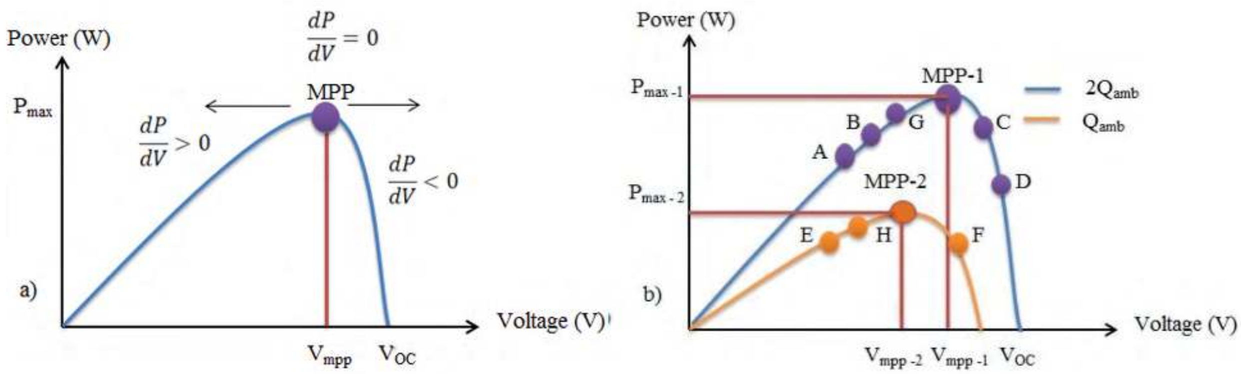

Figure 3. a) V-P curve of PV module b) Explanation of IC algorithm.

The amount of solar irradiance and temperature may change at any moment. It may cause a change in the operation point of the PV module. For example, if the amount of solar irradiance increases from Q_{amb} (orange curve) to $2Q_{amb}$ (blue curve) as shown in Figure 3b, the new operation point of the PV module changes from point MPP-2 to B. According to Eq. (2), PV module voltage decreases and the new operation point is close to G. Therefore, the success of the algorithm is perfect for this condition. On the other hand, the operation point may change from point MPP-2 to C. According to Eq. (2), PV module voltage increases for this condition. Consequently, when the IC algorithm is used, MPPT operation is easily achieved perfectly. However, convergence time still needs to be improved in order to reduce energy loss.

3. Proposed MPPT approach

MPPT is rather a complex process. Many parameters need to be optimized in this process. In this study, a simple, high speed, and cost effective method is proposed in order to achieve MPPT operation with low convergence time. In this context, the proposed approach consists of three stages. The value of load resistance is calculated by using Ohm's law in the first stage. Then the initial operation point is determined by using one of two approaches. One of the approaches is based on the constant voltage method. When the initial operation point is lower than maximum power voltage, this method is used. The other approach is estimation of the amount of solar irradiance. When PV module voltage is higher than maximum power voltage, this approach is used. These two substages are designed to determine the initial value of the duty cycle of the switch gate signal. In the last stage, the IC algorithm is used to increase the accuracy of MPPT.

3.1. Analysis of the proposed MPPT approach

The software side of the MPPT system is an algorithm or method, which is the main focus of this study. The MPPT process consists of three stages. The value of load resistance is calculated in the first stage. This calculation is realized before MPPT starts. Therefore, PV module current equals output current of the boost converter. This stage is easily implemented by measuring the output voltage of the boost converter and the current of the PV module. Thus, the value of load resistance is calculated as given in Eq. (4):

$$R_{Load} = \frac{V_O}{I_{PV}} \quad , \tag{4}$$

where R_{Load} is the value of load resistance, V_O is the output voltage of the boost converter, and I_{PV} is the PV module current. The second stage is the determination of the initial operation point. Therefore, PV module current and voltage are measured twice for different values of duty cycle. During these measurements, duty ratio values have to be chosen close each other. Then PV module power is calculated for two operation conditions. By defining an index as given in Eq. (5), the initial operation point of PV module is determined.

$$k = \frac{dP}{dV} = \frac{P(n+1) - P(n)}{V(n+1) - V(n)} \quad (5)$$

If value of k is negative, PV module voltage is higher than maximum power voltage. The operation point of the PV module is on the right side of the MPP. In this circumstance, there is rather a limited change in voltage of the PV module on the right side of the MPP and maximum power voltage can be accepted as constant for this condition. The initial duty cycle is calculated as given in Eq. (6) in this stage. V_{mpp}(STC) and I_{mpp}(STC) are the PV module voltage and PV module current under standard test conditions, respectively. η is the efficiency of the DC–DC converter.

$$D = 1 - \sqrt{\frac{V_{mpp}(STC)}{I_{mpp}(STC) \times R_{Load} \times \eta}} \quad (6)$$

If the value of k is positive, PV module voltage is lower than maximum power voltage. The operation point of the PV module is on the left side of the MPP. The voltage range of the PV module is very large on the left side of the MPP with respect to the right side. Therefore, PV module current is the reference parameter for this condition. PV module current is measured under different solar irradiance levels and these measurement results are tabulated. According to the tabulated data, equivalent resistance of the PV module, which is voltage divided by current, is set as the reference parameter and the initial value of duty cycle is calculated as given in Eq. (7):

$$D = 1 - \sqrt{\frac{R_{mpp}(Q)}{R_{Load} \times \eta}} \quad (7)$$

3.2. Tabulation of current and equivalent resistance values of the PV module

The look-up table consists of two variables, namely PV module current and equivalent resistance of the PV module. The input variable of the look-up table is PV module current, which is used to estimate the amount of solar irradiance. Then PV module current is used to calculate the equivalent resistance of the PV module, R_{mpp}(Q), which is the output variable of the look-up table. Determination of how to tabulate these variables is as follows. PV module current is obtained by simulations or experiments under different solar irradiance conditions. Then V–I characteristic curves of the PV module are obtained under certain conditions. As presented in Figure 4, five different V–I curves are obtained by simulation studies. With the help of these characteristic curves, MPP voltage and current are obtained. Finally, R_{mpp}(Q) is calculated as given in Eq. (8):

$$R_{mpp}(Q) = \frac{V_{mpp}(Q)}{I_{mpp}(Q)} \quad , \quad (8)$$

where V_{mpp}(Q) and I_{mpp}(Q) are the maximum power voltage and maximum power current under certain conditions, respectively. After tabulation, the value of R_{mpp}(Q) is determined by the value of PV module

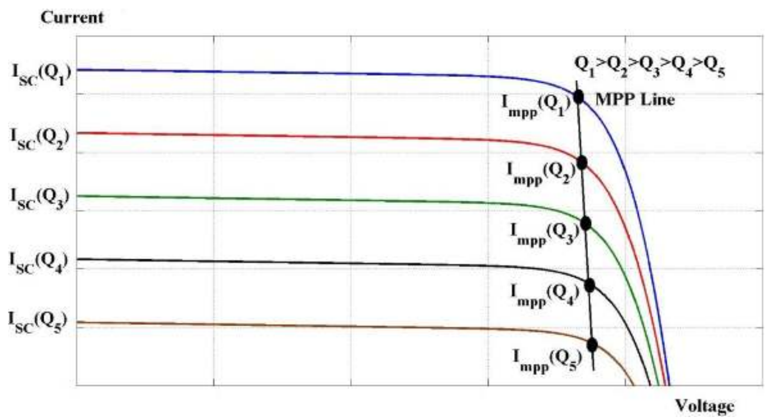

Figure 4. V–I curve of PV module under different solar irradiance.

current. Then the duty cycle of the switch gate signal is calculated by Eq. (6) or Eq. (7). Thus, the initial value of the duty cycle is close to its optimum. Convergence time decreases obviously through our proposed approach. Number of $R_{mpp}(Q)$ is a critical parameter that determines MPPT success. For this parameter, Eq. (9) can be defined:

$$I_{SC}(Q_n) > I_{PV}(n) > I_{mpp}(Q_n) \Rightarrow R_{mpp}(Q_n) = \left.\frac{V_{mpp}(Q_n)}{I_{mpp}(Q_n)}\right|_{n=1,2,3,4,5.....} \tag{9}$$

Even if several V–I curves of the PV module can be obtained under different solar irradiance conditions, there is a correlation between the number of V–I curves and the success of the proposed approach. This correlation has to be confirmed in order to ensure the success of our proposed approach. The success of MPPT depends on the mathematical formula given in Eq. (10). Figure 5 outlines this mathematical equation.

$$\Delta I_n = I_{SC}(Q_n) - I_{mpp}(Q_n) < \Delta I_{SC}(Q_n - Q_{n-1}) \tag{10}$$

The third stage of the proposed approach is included for the purpose of increasing MPPT accuracy. Therefore, the IC algorithm is used and MPPT accuracy is increased. Figure 6 presents a general schematic of the proposed approach.

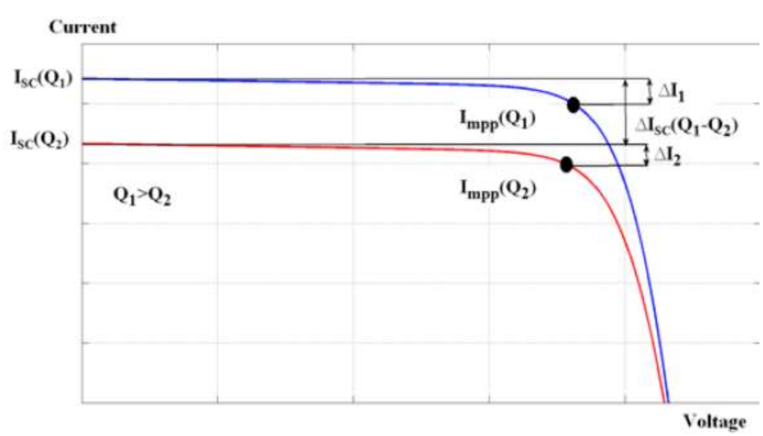

Figure 5. Illustration of Eq. (10).

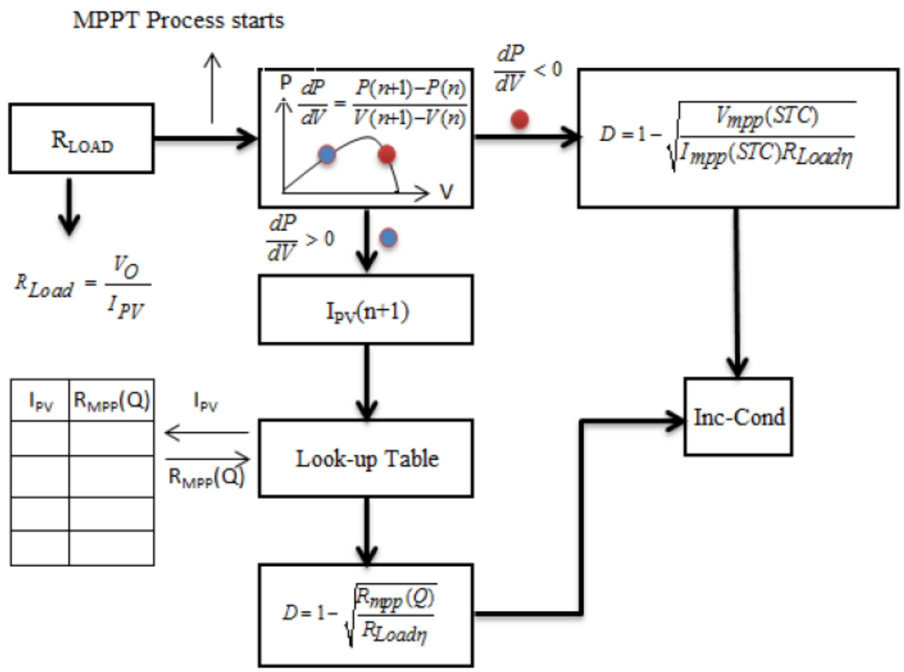

Figure 6. General schematic of proposed approach.

3.3. Power converter circuit

MPPT systems require a power converter circuit, which is a boost converter in this study. The design of the boost converter with MPPT operation is slightly different from the conventional one. The difference is related to how to determine the peak inductor current. While inductor current is calculated by using minimum input voltage in the design of the conventional boost converter, inductor current has to be calculated by using the maximum power voltage of the PV module as given in Eq. (11):

$$L = V_{mpp} \frac{\Delta t}{I_{mpp}} = \frac{D \times T_p}{\Delta I_{mpp}}, \tag{11}$$

where D is the duty cycle, T_P is the switching period, and ΔI_{mpp} is the ripple of inductor current. The other design process can be summarized as follows. The output capacitor of the boost converter should be chosen as large as possible to reduce the ripple of the capacitor voltage. PIC18F452 has been used to generate the PWM signal for the power switch. This microcontroller is also used as an analogue digital converter and analogue data are converted to digital data by PIC18F452. Table 2 summarizes the specification of the designed system. Figure 7 shows the designed circuits.

Table 2. Specification of designed circuit.

Input voltage range	10.8–21.6 V	Switch	IRFP450
Maximum input current	5.42 A	Diode	MUR860
Switching frequency	20 kHz	Microprocessor	PIC18F452
Ripple of inductor current	30%xI_{mpp}	Current transducer	LTS 25 N-P
Ripple of output voltage	1%xV_{out}	Sense of voltage	Voltage divider
Inductor	1 mH	Capacitor	100 uF

Figure 7. Photo of MPPT system.

4. Experimental results

A boost converter has been designed to perform MPPT operation with the proposed approach. The designed boost converter has been performed with the IC algorithm to compare with the performance of the proposed approach. It is noted that since experimental studies are realized in a few minutes, environmental conditions are approximately the same.

Load resistance is 33 Ω and the step size of the duty cycle is set as 2% in the first case. The power converter is performed with the IC algorithm and convergence time takes approximately 30 ms in this case. Figure 8a shows changes in voltage and current for the first case. Then the boost converter is performed with the proposed approach. Convergence time is obviously reduced, because the initial value of the duty cycle is determined by the look-up table approach and convergence time is approximately 10 ms. Figure 8b presents changes in voltage and current for the proposed approach.

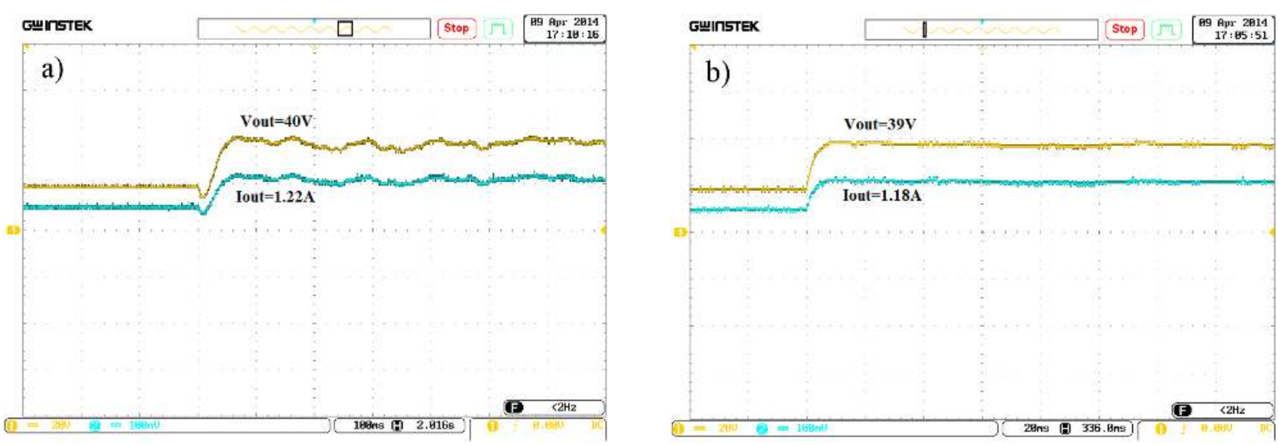

Figure 8. a) Case 1: IC b) Case 2: Proposed approach.

The step size of the duty cycle is set as 1% for the purpose of comparing with the first two cases. As shown in Figure 9a, convergence time increases as expected and is approximately 50 ms. When our boost converter is performed with the proposed MPPT approach, convergence time decreases, and is approximately 10 ms. Thus, it is verified that since the initial operation point is determined as close as possible to its optimum due to the proposed approach, convergence time is not affected by the changes in the step size of the duty cycle as presented in Figure 9b.

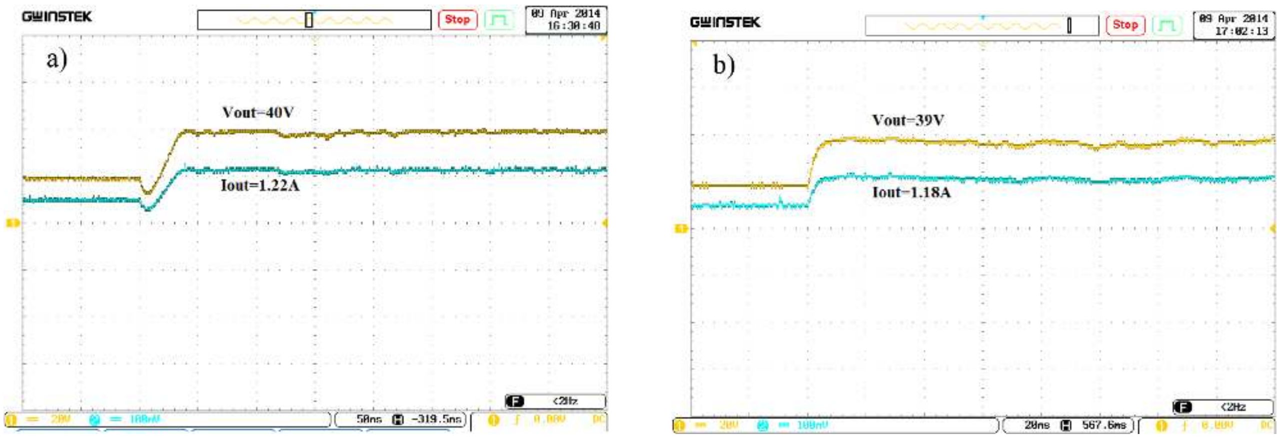

Figure 9. a) Case 3: IC b) Case 4: Proposed approach.

5. Conclusion

MPPT is an important issue in PV systems. One of the important topics to be developed is to decrease convergence time. The main difference of this study is decreasing the convergence time to MPP by not affecting the amount of fluctuations in voltage and current of the PV module at the MPP. Although convergence time and fluctuations of voltage and current are a dilemma in the variable step size algorithm, there is no methodology constraint in the case of the proposed approach. Therefore, convergence time is considered independently in this study.

In this paper, a new approach has been presented to reduce convergence time by not affecting the amount of fluctuations at the MPP. The proposed approach consists of three stages. The value of load resistance is calculated in the first stage. Then the initial operation point of the PV module is determined by the look-up table or constant voltage method in the second stage. If the initial operation point of the PV module is on the left side of the MPP, the tabulation (look-up table) method is used. On the other hand, if the initial operation point is on the right side of the MPP, the constant voltage method is used. In the last stage, the IC algorithm is used to ensure the correctness of MPPT.

Experimental studies have been carried out with the conventional IC algorithm and the proposed approach. It is shown that convergence time is remarkably reduced when the proposed method is applied. Moreover, there is no remarkable difference in convergence time for different step sizes of the duty cycle. However, it is shown that the step size of the duty cycle affects this time when the IC algorithm is applied. Consequently, it is verified that the proposed approach performs better than the IC algorithm and it can be applied to other DC–DC converter topologies to reduce the convergence time, especially for low power or microconverter-based applications. In addition, this method can be chosen as an alternative to the variable step size IC algorithm presented before.

In further research, in addition to convergence time, the partial shading problem will be studied under sudden changes in solar irradiance and load resistance.

References

[1] Esram T, Chapman P. Comparison of photovoltaic array maximum power point tracking techniques. IEEE T Energy Conver 2007; 22: 439–449.

[2] Femia N, Petrone G, Spagnuolo G, Vitelli M. Optimization of perturb and observe maximum power point tracking method. IEEE T Power Electr 2005; 20: 963–973.

[3] Reisi AR, Moradi MH, Jamasb S. Classification and comparison of maximum power point tracking techniques for photovoltaic system: a review. Renew Sust Energ Rev 2013; 19: 43–443.

[4] Toshihiko N, Shigenori T, Ryo N. Short current pulse based maximum power point tracking method for multiple photovoltaic and converter module system. IEEE T Ind Electron 2002; 49: 217–223.

[5] Taftich T, Agbossou K, Doumbia ML, Chériti A. An improved maximum power point tracking method for photovoltaic systems. Renew Energ 2008; 33: 1508–1516.

[6] Moradi MH, Reisi AR. A hybrid maximum power point tracking method for photovoltaic systems. Sol Energ 2011; 85: 2965–2976.

[7] Duru HT. A maximum power tracking algorithm based on $I_{mpp}=f(P_{max})$ function for matching passive and active loads to a photovoltaic generator. Sol Energ 2006; 80: 812–822.

[8] Ramaprabha R, Balaji M, Mathur BL. Maximum power point tracking of partially shaded solar PV system using modified Fibonacci search method with fuzzy controller. Electr Pow Compo Sys 2012; 43: 754–765.

[9] Punitha K, Devaraj D, Sakthivel S. Artificial neural network based modified incremental conductance algorithm for maximum power point tracking in photovoltaic system under partial shading conditions. Energ 2013; 62: 330–340.

[10] Liu Y, Liu C, Huang J, Chen J. Neural network based maximum power point tracking methods for photovoltaic systems operating under fast changing environments. Sol Energ 2013; 89: 42–53.

[11] Fangrui L, Shanxu D, Fei L, Bangyin L, Yong K. A variable step size INC MPPT method for PV systems. IEEE T Ind Electron 2008; 55: 2622–2628.

[12] Lee K, Kim R. An adaptive maximum power point tracking scheme based on a variable scaling factor for photovoltaic systems. IEEE T Energy Convers 2012; 27: 1002–1008.

[13] Chen Y, Lai Z, Liang R. A novel auto scaling variable step size MPPT method for a PV system. Sol Energ 2014; 102: 247–256.

[14] Mei Q, Shan M, Liu L, Guerrero JM. A novel improved variable step size incremental resistance MPPT method for PV systems. IEEE T Ind Electron 2011; 58: 2427–2434.

[15] Enrique JM, Andújar JM, Bohorquez MA. A reliable, fast and low cost maximum power point tracker for photovoltaic applications. Sol Energ 2010; 84: 79–89.

[16] Petreuş D, Pătărău T, Dărăban S, Morel C, Morley B. A novel maximum power point tracker based on analog and digital control loops. Sol Energ 2011; 85: 588–600.

[17] Scarpa VVR, Buso S, Spiazzi G. Low complexity MPPT technique exploiting the PV module MPP locus characterization. IEEE T Ind Electron 2009; 56: 1531–1538.

[18] Lin CH, Huang CH, Du Y, Chen J. Maximum photovoltaic power tracking for the PV array using the fractional-order incremental conductance method. Appl Energ 2011; 88: 4840–4847.