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IMPROVED VARIABLE STEP SIZE INCREMENTAL CONDUCTANCE MPPT METHOD WITH HIGH CONVERGENCE SPEED FOR PV SYSTEMS

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Abstract

Maximum power point tracking (MPPT) algorithms are employed in photovoltaic (PV) systems to provide full utilization of PV array output power. Among all the MPPT algorithms, the Incremental Conductance (INC) algorithm is widely used in PV systems due to the high tracking speed and accuracy. In this paper an improved variable step size algorithm which is based on incremental conductance algorithm is proposed that adjusts the step size according to PV output current. The result of this adaption is to make the algorithm suitable for practical operating conditions due to a wider operating range of irradiation changes. Simulation results confirm that the proposed algorithm increases convergence speed and efficiency in comparison with conventional fixed and variable step size INC algorithms.

Keywords: Photovoltaic, MPPT, Cuk converter, Incremental conductance, Variable step size.

1. Introduction

Solar energy is an attractive source of energy due to its advantages such as cleanness, absence of fuel cost, and low maintenance requirements. However, there are two main problems when solar PV is used: the conversion efficiency is very low and the amount of electric power generated by solar cells varies with weather conditions such as irradiance and temperature [1, 2]. Moreover, a PV array that functions under uniform radiation and temperature conditions presents a nonlinear P-V characteristic. This point on the graph is called the maximum power point (MPP) where the array provides the greatest possible

Abbreviations

INC	Incremental Conductance
MPPT	Maximum Power Point Tracking
P&O	Perturbation and Observe
PV	Photovoltaic
VSS	Variable Step Size

power output under certain environment conditions [3].

To overcome these problems a MPP Tracking (MPPT) method has been used to convey the operation point of PV system on MPP regardless the load, irradiance and temperature [1-3]. The location of the MPP on the V-I curve of the PV array is not known therefore, all of the methods are used from a MPPT algorithm which locates MPP using either mathematical calculations over a valid model, or some search algorithms [1-4]. In recent years, a large number of MPPT algorithms have been proposed and implemented [1-8]. These algorithms vary in complexity, sensor requirements, speed of convergence, costs, range of operation, popularity, the ability to detect multiple local maxima and their applications [5, 6]. Fractional open-circuit voltage and short-circuit current strategies provide a simple and effective way to acquire the maximum power. However, they require periodical disconnection or short-circuit of the PV modules to measure the open-circuit voltage or short-circuit current for reference, resulting in more power loss and low efficiency [7, 8]. On the other hand, fuzzy logic (FL) and neural network (NN) methods that focus on the non-linear characteristics of PV array provide a good alternative for the MPPT control. MPPT systems with FL controllers have been shown to perform well under varying atmospheric conditions. Nevertheless, their effectiveness relies much on the knowledge or experience of the user or engineer in choosing the right error computation and the rule base table. Since most PV arrays have different characteristics, a NN algorithm has to be specifically trained for the PV array with which it will be used. The characteristics of a PV array also change with time, implying that the neural network has to be periodically trained to guarantee accurate MPPT [5, 6, 9, 10].

Among all of the MPPT algorithms, the Hill Climbing and Perturbation and Observe (P&O) algorithms are the most commonly used algorithms in practice by the majority of authors due to their simplicity and easy implementation [5, 6]. Hill climbing and P&O methods are different ways to envision the same fundamental method. Hill climbing involves a perturbation in the duty ratio of the power converter, and P&O is a perturbation in the operating voltage of the PV array. The process is repeated periodically until it reaches the MPP. The system then oscillates about the MPP. The oscillation can be minimized by reducing the perturbation step size, but it also should be mentioned that a smaller step size slows down the MPPT. The main advantages of this method is its simple implementation that can be used from analog circuit [1], However, the main disadvantage of Hill climbing and P&O methods is to fail under rapidly changing atmospheric conditions.

Incremental conductance (INC) algorithm, which is based on the fact that the slope of the power versus voltage curve corresponding to PV array is zero at the MPP, has been proposed to improve the tracking accuracy and dynamic performance under rapidly varying conditions [5, 6, 9-14]. Although the INC method is a little more complicated compared to the P&O/hill climbing strategies, it can be easily implemented due to the advancements of digital signal processors or microcontrollers. The INC MPPT algorithm usually has a fixed iteration step size [9], determined by the requirements of the accuracy at steady state and the response speed of the MPPT. Thus, the trade-off between the dynamics and steady state accuracy has to be addressed by the corresponding design. To solve these problems, some algorithms with variable step size are proposed in literatures [10-14]. The step size is automatically tuned according to the inherent PV array characteristics. If the operating point is farther from MPP, it increases the step size which enables a fast tracking ability. On the other hand, if the operating point is close to the MPP, the step size becomes very small that the oscillation becomes well reduced contributing to a higher efficiency.

In this paper an improved variable step size algorithm which is based on the incremental conductance algorithm is proposed to adjust the step size using the slope of power versus voltage curves of PV array and also to adapt step size according to sun irradiation levels using PV output current. Proposed method can increase convergence speed of MPPT for a wide operation range without degrading steady state response.

2. PV Array and MPPT

The PV cell is usually represented by the single or double exponential model [13]. Figure 1 shows the single exponential circuit model. The output current of a solar array is given by [4]:

$$I = I_g - I_d - V_d / R_{sh} \tag{1}$$

where I_g is the light-generated photocurrent, R_{sh} is the parallel resistance; And I_d and V_d are the current and voltage of the p–n junction diode respectively. The relationship with which I_d and V_d of the p–n junction diode are given by:

$$V_d = V + IR_s \tag{2}$$

and:

$$I_d = I_{sat}\left\{\exp(\frac{qV_d}{nKT}) - 1\right\} \tag{3}$$

where R_s, I_{sat}, n, q, k and T respectively represent the series resistance, reverse saturation current, ideality factor of the diode, electron charge, Boltzmann's constant and temperature.

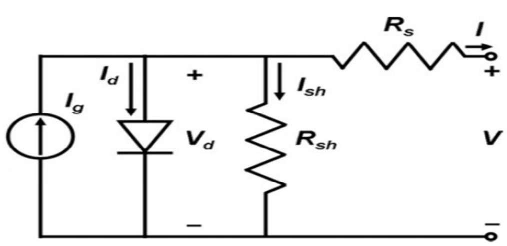

Fig. 1. Electrical model of solar cell.

The terms related to the R_{sh} in Eq. (1) can be generally ignored, because the value of it in PV arrays is relatively high in the majority of practical cases; therefore (1) can be simplified into:

$$I_{pv} = I_g - I_{sat}\left\{\exp(\frac{q(V_{pv} + I_{pv}R_s)}{nKT}) - 1\right\} \tag{4}$$

A single solar cell can only produce a small amount of power. To increase the output power of a system, solar cells are generally connected in series or parallel to form PV modules [9]. The main equation for the output current of a module is:

$$I_{pv} = N_p I_g - N_p I_{sat}\left\{\exp(\frac{q(V_{pv} + I_{pv}R_s)}{N_s nKT}) - 1\right\} \tag{5}$$

where N_S represents the number of PV cells connected in series, and N_P represents the number of such strings connected in parallel.

In this paper we use BP350 PV module [17]. The electrical characteristics of this module are listed in Table 1. Figures 2 and 3 show the BP350 output V-I and V-P characteristics respectively that simulated in MATLAB based on electrical model of solar cell. It is clear that MPP location of PV module is not fixed and moves with environmental conditions such as sun irradiation level and temperature.

Table 1. BP350 PV module specifications.

Electrical Characteristics	Value for T=25, Ir=1 kW/m^2
Maximum power (P_{max})	50 (w)
Voltage at P_{max} (V_{mpp})	17.9 (v)
Current at P_{max} (I_{mpp})	2.9 (A)
Open-circuit voltage (V_{oc})	21.8 (v)
Short-circuit current (I_{sc})	3.2 (A)

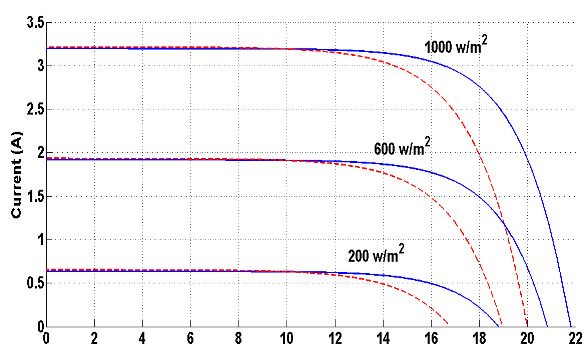

Fig. 2. PV module V-I curves, with changing irradiation level and temperature, T=25℃ (blue-line) and T=50℃ (red-dash line).

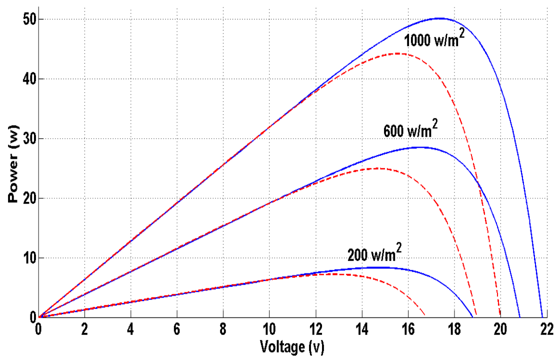

Fig. 3. PV module V-P curves, with changing irradiation level and temperature, *T*=25℃ (blue-line) and *T*=50℃ (red-dash line).

A MPPT system can be used to maintain the PV module operating point at the MPP. The block diagram of the MPPT controller is shown in Fig. 4 [16]. Usually, a MPPT controller uses a DC-DC converter, which is widely used in PV power systems as a matching interface between the PV panel and the load. Hence the main function of a MPPT controller is to adjust the panel output voltage to a value in which the panel transfers maximum energy to the load by controlling the on-off times of the converter's power switch transistor. The power delivered to the load is at maximum when the source internal impedance matches the load impedance.

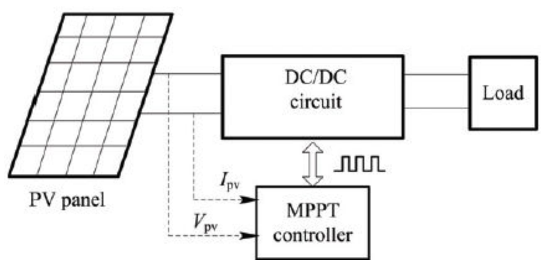

Fig. 4. The block diagram of the MPPT controller.

3. Incremental Conductance MPPT Algorithm

The INC MPPT algorithm is based on the fact that the slope of the PV array power curve is zero at the MPP, positive on the left-hand-side of the MPP, and negative on the right-hand-side of it [5-14]. Therefore we can search for the location of MPP calculating the slope of this curve:

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V} \tag{6}$$

At MPP:

$$\frac{dP}{dV} = 0 \longrightarrow \frac{\Delta I}{\Delta V} = -\frac{I}{V} \tag{7}$$

According to the Eq. (7), MPP can be tracked by comparing instantaneous conductance (I/V) and the incremental conductance ($\Delta I/\Delta V$).

$$\left\{\begin{array}{ll} \dfrac{\Delta I}{\Delta V} > -\dfrac{I}{V} & \text{Left of MPP} \\ \dfrac{\Delta I}{\Delta V} = -\dfrac{I}{V} & \text{at MPP} \\ \dfrac{\Delta I}{\Delta V} < -\dfrac{I}{V} & \text{Right of MPP} \end{array}\right\} \tag{8}$$

The INC MPPT algorithm usually uses a fixed iteration step size to change the duty cycle of DC/DC converter. The step size for the INC MPPT determines how fast the MPP is tracked. Fast tracking can be achieved with bigger increments, but the system might not run exactly at the MPP and oscillate around it; thus, there is to be a comparatively low efficiency. This situation is inverted when the MPPT is operating with a smaller increment. Therefore, a trade-off between the dynamics and oscillations has to be made for the fixed step-size MPPT.

To solve this problem, different INC MPPT algorithms with variable step size are proposed in literature [10-14]. A modified variable step size algorithm is proposed in [10] that suggest using the PV output power to directly control the power converter duty cycle to reduce well the complexity of the system. The variable step size adopted to diminish this problem is shown as follows:

$$D(n) = D(n-1) \pm N\left|\frac{dP}{dV}\right| = D(n-1) \pm N\left|\frac{P(n) - P(n-1)}{V(n) - V(n-1)}\right| \tag{9}$$

where P, V and D respectively represent the PV array output voltage, power and duty cycle. N is the scaling factor which is tuned at the design stage to adjust the step size.

The performance of the MPPT system is essentially decided by the scaling factor (N) for the variable step-size MPPT algorithm. To guarantee the convergence of the MPPT update rule, the variable step rule must meet the following inequality:

$$N \times \left|\frac{dP}{dV}\right| < \Delta D_{\max} \tag{10}$$

where ΔD_{max} is the largest step size for fixed step-size MPPT operation and is chosen as the upper limit for the variable step size INC MPPT method. Therefore, the scaling factor can be obtained as:

$$N < \Delta D_{\max} / \left|\frac{dP}{dV}\right| \tag{11}$$

If Eq. (11) cannot be satisfied, the variable step size INC MPPT will be working with a fixed step size of the previously set upper limiter ΔD_{max}.

However this method may increase convergence speed and also reduce oscillation in steady state, but it brings forth a major problem for wider operation range in practice [11]. This problem occurs because the slopes of V-P curves of

PV module for different irradiation levels at a fix operation point will not be the same. So the step sizes are calculated for different sun irradiation levels with different values in result of a constant N and variable slopes of P-V curves. We can rewrite Eq. (11) as:

$$\left|\frac{dP}{dV}\right| > \frac{\Delta D_{\max}}{N} \tag{12}$$

where we know that the result of $\Delta D_{max}/N$ is constant, because both parameters are constant coefficients. Therefore we can say that the result of dP/dV is compared with a constant at all time.

Figure 5 shows the values of $\Delta D_{max}/N$ and dP/dV [11]. As shown, power at P_1 is much larger than power at P_2 ($P_1 >> P_2$). The scaling factor (N) that obtained from Eq. (11) almost cannot make the system realize the variable step size MPPT algorithm for P_1, because $\Delta D_{max}/N$ ($>|dP/dV|$) is so small that the fixed step size ΔD_{max} is too large to make the following step size within the variable step-size range. Furthermore, for P_2, the same scaling factor N always lets the system work with the variable step size, which reduces the system response speed greatly. Thus, there is a "dead band" for the fixed N from Eq. (11), and it is impossible for the variable step size INC MPPT to find an optimal scaling factor to be suitable for both power curves (P_1 and P_2) in the dead band at the same time.

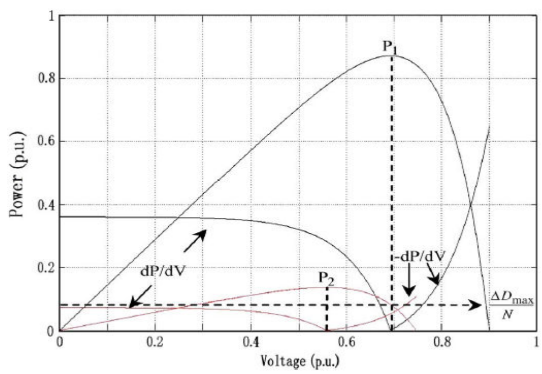

Fig. 5. Normalized power and slope of power versus voltage under different irradiation conditions.

For solving mentioned problem, in this paper a new method for obtaining variable step size is proposed. Proposed method adjusts variable step size using slope of V-P curve and also can adapt step sizes according to sun irradiation level.

The main idea of the proposed method is that the fixed line ($\Delta D_{max}/N$) in Fig.5 must move up and down when sun irradiation level changes between P_1 and P_2. We can use PV module output current to estimate the sun irradiation level, because there is a direct relation between sun irradiation level and PV module output current. Therefore proposed method can be implemented without needing for climatic sensor or other extra measurements. For adapting the variable step size with output current, we can use from Eq. (13) rather than Eq. (9):

$$D(n) = D(n-1) \pm \frac{N}{I} \times \left| \frac{dP}{dV} \right| \quad (13)$$

When variable step size INC algorithm uses from Eq. (13), the inequality in Eq. (12) changes into:

$$\left| \frac{dP}{dV} \right| > \frac{\Delta D_{max}}{N} \times I \quad (14)$$

Therefore now, the slope of V-P curves is being compared with a variable coefficient that changes by output current of PV module. Figure 6 shows the flowchart of the proposed method for obtaining new step size by each step.

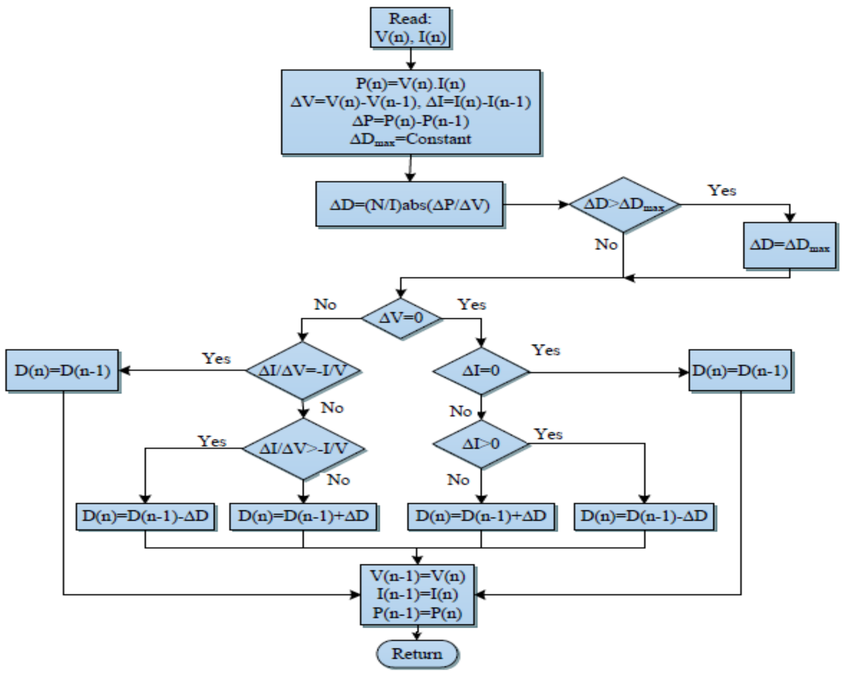

Fig. 6. Flowchart of the proposed variable step size INC MPPT algorithm.

4. DC/DC Converter

Most current designs for MPPT consist of three basic components: a switch-mode DC/DC converter, a control circuit, and tracking algorithm. The heart of the MPPT hardware is a switch-mode DC/DC converter [15]. The bad choice of the converter makes the MPPT less useful and also the bad converter design affects significantly the system efficiency.

Among all the topologies available the Buck, Boost, Buck-Boost and Cuk converters are the most popular converters in PV systems and each of them can be useful for a special application. Both Cuk and buck–boost converters provide the opportunity to have either higher or lower output voltage considering the input voltage and also just these two converters- regardless of cell temperature, solar global irradiation and connected load- are able to follow the MPP of PV panel at all times [9, 15]. Although the buck–boost configuration is cheaper than the Cuk's one, some disadvantages, such as discontinuous input current, high peak currents in power components, and poor transient response, make it less efficient. On the other hand, the Cuk converter has low switching losses and the highest efficiency among non-isolated dc–dc converters. It can also provide a better output-current characteristic due to the inductor on the output stage [9]. However Cuk converter has the highest values of reactive components, which is the main drawback for this type. Because of mentioned advantages, we decide to design a Cuk converter for MPPT system in this study.

Figure 7 shows the Cuk converter configuration designed for load matching in MPPT system between PV array and load. The relations between output and input currents and voltages are given in the following:

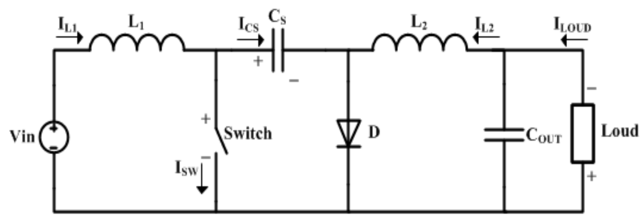

Fig. 7. Cuk converter configuration.

$$\frac{V_o}{V_{in}} = -\frac{D}{1-D} \tag{15}$$

$$\frac{I_o}{I_{in}} = -\frac{1-D}{D} \tag{16}$$

Then input impedance of converter can be computed using:

$$R_{in} = \frac{(1-D)^2}{D^2} * R_L \tag{17}$$

Also optimum value for load that PV system can work on MPP is computed by:

$$R_{opt} = \frac{V_{MPP}}{I_{MPP}} \tag{18}$$

Therefore operation point of PV system can be adjusted on MPP by changing the duty cycle of switching of Cuk converter and the role of MPPT algorithm here would be searching for an appropriate value for duty cycle.

5. Simulation Results

A stand-alone PV system with MPPT has been designed and simulated in MATLAB-Simulink software for assessing the proposed MPPT method. Designed system consists of PV array (BP350), MPPT algorithm (improved variable step size INC), a Cuk converter and also a resistive load as is shown in Fig. 8.

The components used in Cuk converter in simulation are as follows:

1) Inductors: L_1= 3 mH , L_2= 4 mH

2) Capacitors: C_S=47 µF, C_{OUT}=2.2 µF

3) Switching frequency = 25 kHz

4) Resistive loud R_L=10 Ω

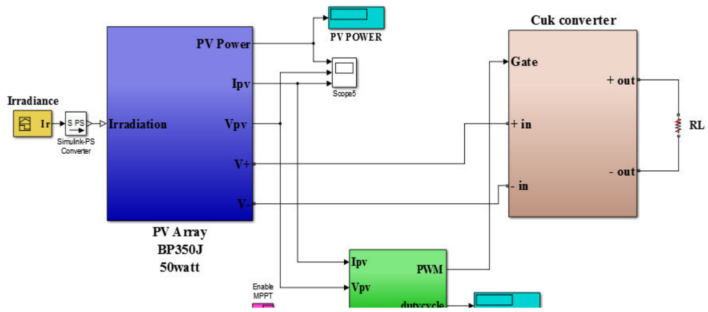

Fig. 8. Simulated Stand-alone PV system with MPPT.

To test the system operation and comparing the proposed variable step size INC algorithm with fixed step size and conventional variable step size INC, we set temperature constant at 25℃ and assume that sun irradiation level varies between 200W/m^2 and 1000W/m^2 in order to model a wide range operation point. Irradiation level is 200W/m^2 and it suddenly changes at t=0.05s to 1000W/m^2 and then comes back to 200W/m^2 at t=0.1s. All conditions used for simulations are the same and MPPT system updates the duty cycle of Cuk converter every 1ms.

Figure 9 shows clearly whenever INC used a larger fixed step size, convergence speed and steady state oscillation around MPP both have increased which as a result reduced the efficiency of the system.

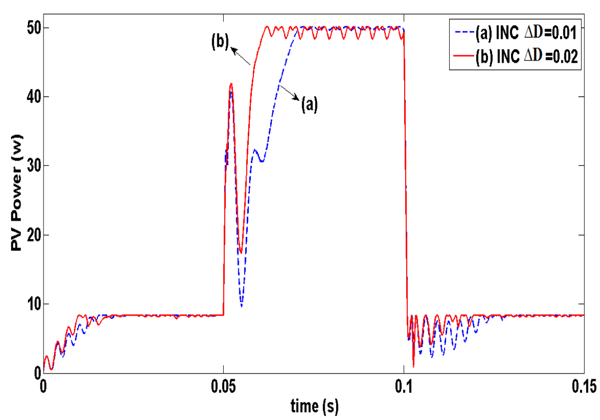

Fig. 9. PV array output power, fixed step size INC.

Figure 10 shows the results of variable step size INC proposed in [10]. Results confirm that convergence speed and efficiency of MPPT system increased effectively in comparison with fixed step size INC. It also indicates when using N=0.02, the system could not converge at 1000W/m^2 because of the large value of ΔD and if we use N=0.01, the system works at 1000W/m^2 with no oscillation and reduction of convergence speed at t=0.1s (200W/m^2) in result of small ΔD.

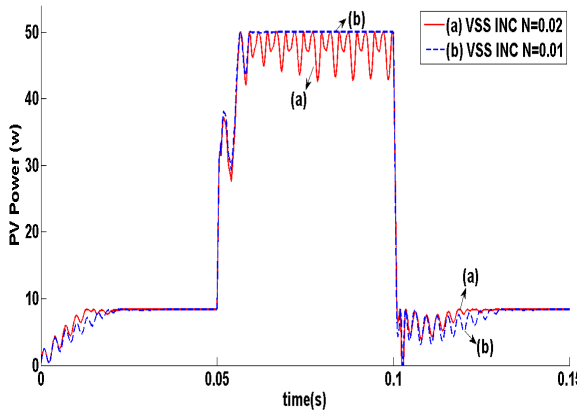

Fig. 10. PV array output power, variable step size INC.

For comparing proposed method with algorithm suggested in [10] we used from N values for them. According to the obtained results, two algorithms reached the same steady state response and then we compared their convergence speed. It is good to mention that for both algorithms, maximum allowable change for duty cycle (ΔD_{max}) is set at 0.05 for all simulations. Figure 11 indicates the results of this comparison. It is clear that proposed method can achieve the same steady state response with a larger value N because of adapting with sun irradiance level. The result of this adaption is the more convergence speed when PV module works on small irradiation level (200W/m^2). In other words normalizing the N by output current of PV module allows the MPPT system to select a bigger N for algorithm which results in increasing the convergence speed without increasing steady state oscillation.

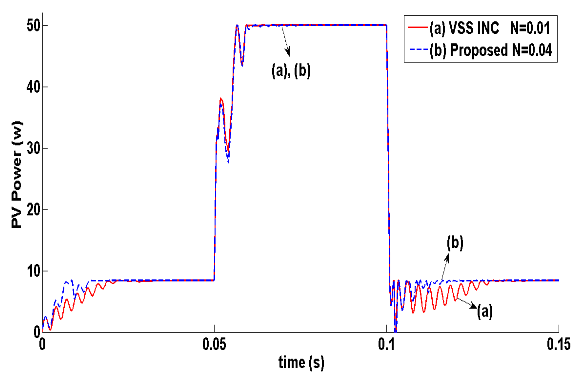

Fig. 11. PV array output power, Proposed and Variable step size INC [10].

Simulation results based on efficiency (η) of each algorithm are summarized in Table 2.

Table 2. Performance of simulated algorithms.

Algorithm	ΔD	N	η(%)
Fixed Step-Size INC	0.005	-	86.68
	0.01	-	92.21
	0.02	-	76.41
Variable Step-Size INC [10]	Max=0.05	0.005	90.74
	Max=0.05	0.01	93.27
	Max=0.05	0.02	91.16
Proposed variable step size INC	Max=0.05	0.02	94.56
	Max=0.05	0.04	95.11

6. Conclusion

In this paper an improved variable step size INC algorithm has been proposed. This method can increase convergence speed as well as steady state response of MPPT for a wide range of operation as a result of adjusting step sizes according to sun irradiation level using PV output current. The proposed algorithm simulated in MATLAB-Simulink software and compared with conventional fixed and variable step size INC algorithms. Simulation results confirm that the proposed method increases the efficiency of MPPT system effectively. We will use an experimental setup based on digital microcontrollers for verifying proposed method in future works.

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