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A Novel Auto-Scaling Variable Step-Size Maximum Power Point Tracking (MPPT) Method for Photovoltaic System Under Changing Environmental Conditions

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ABSTRACT

This paper proposes a novel auto-scaling variable step-size maximum power point tracking (MPPT) method. The novel method solves the problems associated with conventional variable step-size method. Firstly, the conventional variable step-size method use individual scaling factor N adjusted in order to modify the step-size to balance between the precision of tracking and its divergence rate during the design stage. However, this individual scaling factor N causes the dynamic response of the PV system to be slow in the extremely irradiation change condition. To address this issue, the proposed method combines the dual scaling factors N, which are (N1) with a high value and (N2) with a low value. The N1 is used for a faster response at the beginning of the execution. In the meantime, the second N2 value is used to help stabilize the power oscillation. The proposed method can automatically adjust the algorithm's step-size to obtain a fast dynamic response that adapts to weather variations, resulting in reliable steady-state output power. Secondly, the conventional variable step-size, which is based on division of the PV module power change by the PV voltage change, endures from steady-state power oscillations and dynamic problems, particularly when subjected to sudden environmental changes. In this paper, an improvement to the conventional variable step-size method is introduced, in which the step-size of the proposed method is based solely on the change in PV power in order to completely eliminate the division calculations involved in its structure. As a result, the complexity of algorithm implementation is reduced, allowing for the use of low-cost microcontrollers to reduce system costs. Simulation results are provided through MATLAB-SIMULINK to verify the performance of the novel auto-scaling variable step-size maximum power point tracking (MPPT) method.

1. Introduction:

Renewable energies have numerous economic and environmental benefits, which has increased researchers' interest in the study these types of energies. Researchers in the field of renewable energy concentrate on choosing the type, size, and location of each source from the available renewable energy sources (RESs), as well as investigating the potential of increasing RESs capacities and penetration into traditional electrical power network to minimize both electricity production costs and pollution issues while also improving system reliability and stability. There are numerous types of renewable energy sources (RESs), such as solar PV, wind, fuel cell, and others, that have been employed extensively in electricity generation for on-grid and off-grid applications [1–3].

Due to the crisis in electricity and environmental degradation, Power supply using the PV system has become more popular in recent decades. The capability of the PV power generating system varies due to its insolation, temperature and load; Thus, the maximum power point tracking (MPPT) techniques are essential for a PV system to maximize its power. Since of nonlinearity characteristics of PV output power, the linear control principle cannot be suitable for MPPT. Several MPPT approaches have been introduced. These include, perturb and observe (P&O) algorithm and hill-climbing (HC) algorithm, which are simple to apply and, are normally utilized to transfer the maximum power point (MPP) to the PV panels of such methods [4].

P&O incorporates interference with the PV panel's working voltage, while hill-climbing uses interference with the power converter duty ratio, which implies a simplified control structure [5]. The main drawback in both methods is the MPP fluctuation leading to loss of power and insufficiency under varying weather conditions.

The adjusted P&O method, where the perturbation step-size is continually altered in compliance with the PV array's working point, will provide an excellent dynamic response and steady characteristics. The above-mentioned findings are checked by experimental results [6]. The variable perturbation control is possible

with a neutral-network control (ANN) or fuzzy logic controller (FLC) that is added to the P&O algorithm. The fluctuation around MPP is dramatically diminished and due to the variable perturbation step, the PV system can respond suddenly to the irradiation changes. But the abovementioned approach is too complicated to apply in practice and raises the price of the PV system [6],[7]. The ability of the MPPT to monitor the MPP depends on the step-size of the algorithm. Based on the analysis, there are two forms of perturbation step sizes: large steps and small steps. The use of large steps helps to easily increase the tracking speed, but it can rise the fluctuations at steady-state condition. On the other hand, the oscillations are diminished by using small steps, but the tracking speed becomes slow. The variable step-size (VSS) method is then developed to sustain between the steady-state response and the dynamic response [8]. Nevertheless, in the conventional VSS algorithm and during the steps size measurement, a scaling factor with a constant value is used [9]. Fast and simple ways to attain maximum PV output power are the fractional open-circuit voltage (FOCV) [10], [11] and fractional short-circuit current (FSCC) methods [12],[13]. However, frequent disconnection is needed to compute the short-circuit current I_{sc}, or open-circuit voltage V_{OC} and

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as result of the intermittent disconnection of the PV panel, an increased power loss occurs. In addition, FLC and ANN [14]-[18] approaches are also well-suited to non-linearity control. It has been shown that MPPT fuzzy logic controllers work fine at various weather conditions. Nevertheless, their reliability be contingent heavily on the user's expertise in selecting the correct error measurement, membership function shape and their boundaries, and rule-based table. While PV arrays are not similarly characterized, neural-network techniques must be instructed for any PV array uniquely. The features of the PV array often vary over time to so that the neural network requires intermittent training in order to ensure accurate MPPT. A new flexible fuzzy logic controller (FLC) based on a variable step-size hill-climbing MPPT method is proposed in [19]. The proposed method's main advantages are the MPP's accurate and adaptive tracking performance and the elimination of power variations around the MPP in transient and steady-state conditions. In [20], an adaptive calculation block for determining the MPPT reference voltage point (using λ and T measurements) and an FLC block for modifying the duty cycle of a pulse width machine (PWM) were introduced, this method being faster than the standard P&O and INC algorithms, respectively, and had a high accuracy and low oscillation. However, the expense and complexity of implementation have been noted as disadvantages. Many studies have recently undertaken on a new topology known as cuckoo search optimization (CS), [21]. This method has several advantages over both conventional and other methods [21]. Cuckoo search optimization is developed in [22] for PV system and is compared to two methods: artificial neural network (ANN) and incremental conductance methods (IC). The ant colony optimization (ACO) algorithm [23] was noticed to have a better performance in finding global maximum power point (GMPP) than the P&O and constant voltage tracking (CVT) algorithms, as well as being simpler than the PSO algorithm on the basis of iterations and independence from the initial conditions. Furthermore, the bee colony optimization (BCO) algorithm [24], bat optimization (BO) algorithm [25], and salp swarm optimization (SSO) algorithm [26] (all biologically inspired algorithms) were used in solar MPPT units, primarily for their ability to detect and identify the GMPP under PSC. On the other hand, their efficiency, implementation complexity, and applicability in large-scale solar system, require further investigation. Reinforcement learning (RL) was used among artificial intelligence (AI) and machine learning algorithms to reduce set-up time and monitor the MPP for various PV sources (various PV characteristics) under various operating conditions. [27]. Numerous variable step-size methods were introduced for use in P&O [28],[29], HC [30],[31], incremental-conductance (INC) [32] and incremental-resistance (INR) [33]. While they can minimize constant state oscillations close to MPP, their dynamic response becomes slow under fast changing of the atmospheric conditions which can also reduce the efficiency of the algorithm.

This paper proposes a new MPPT method to overcome the abovementioned issues. The step-size can be automatically specified in the proposed method to guarantee good balance between the tracking speed and stable-state conditions. In the sections below, the design theory of the proposed method is presented.

This paper contains five sections. The introduction is presented in Section I. Section II defines the conventional hill-climbing based-MPPT method concept. Section III provides a brief overview of the latest developed VSS based-MPPT method. Section IV explains the proposed MPPT method and its implementation. Simulation results and the system model parameters used in this work are addressed in Section V. The conclusions from this work are presented in Section VI.

2. Conventional hill-climbing based-MPPT method

The P-D relationship curve in hill is shown in in figure (1), where the PV power is depicted by *P* and the duty cycle of the power converter is denoted by *D*. Numerically, when the *dP/dD* is reduced by control, the maximum power points can be traced. This method is named the hill-climbing (HC) method, rendering the system control mechanism simpler to one control loop.

The curve slope is zero when the MPP is reached by the operating point. Since the solar cell's P-V curve is different as the weather conditions varies, the HC method should track the difference of the MPP under changing weather conditions. The conventional HC or INC based MPPT method, however, in order for this algorithm to approach the MPP, it utilized a fixed step-size, which leads to the above-mentioned issue.

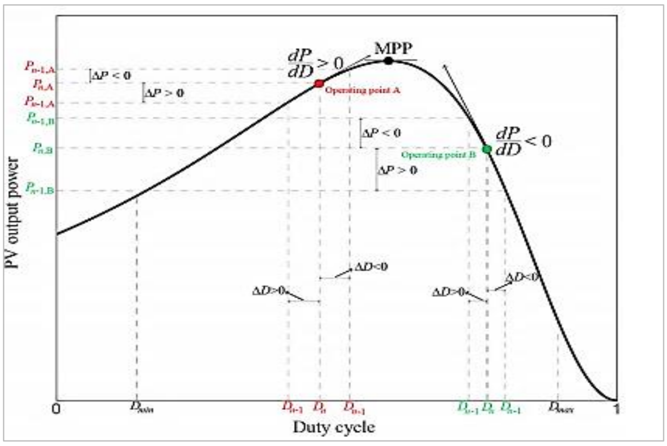

Figure 1: P-D relationship curve when the power converter is interconnected between the load and PV source [34].

Figure (2) displays the hill-climbing (HC) algorithm flowchart. "*Flag*" is a variable that has a value of "0" or "1", which indicates the path to be taken on the curve shown in figure (2) to rise the PV power. "*a*" denotes the duty cycle step-size, and its value between 0 and 1. The PV power is represented by "P_{pv}" and the duty cycle value is donated by "*D*". The value in the prior calculation of PV power $P_{pv}(k-1)$ is compared with the actual PV power $P_{pv}(k)$. The "Flag" symbol is either supplemented or remains unchanged, as seen in the results of the comparison. Then the *D(k)* is modified until the algorithm reaches the MPP. The benefit of the MPPT climbing method is its ease of implementation. The disadvantages of this method are discussed in the following paragraphs.

The MPPT control system has been shown to frequently diverge from the maximum operating point during a continuously changing environment conditions [35].

In the event of fast-changing insolation conditions, the MPPT hill-climbing controller will often cause the system operating point to be away from the optimum point. If an abrupt rise or decrease occurs in insolation, the controller may be misled and led to the wrong direction according to the HC algorithm. This continues until the abrupt insolation transition reduces or stops. Another downside this easy tracking approach has a problem offering effective results between tracking speed and steady-state condition because a constant step-size is used as control parameter. When the step-size "a" is a small-step, it takes time to arrive at MPP and the system dynamic response is poor. When the step-size "a" is a large-step, the PV power oscillations around MPP are high and the average PV power is slightly lower than the optimum, contributing to energy loss [35]. These control issues can be minimized by modifying this method. A new MPPT algorithm is developed in section IV to enhance the HC tracking algorithm.

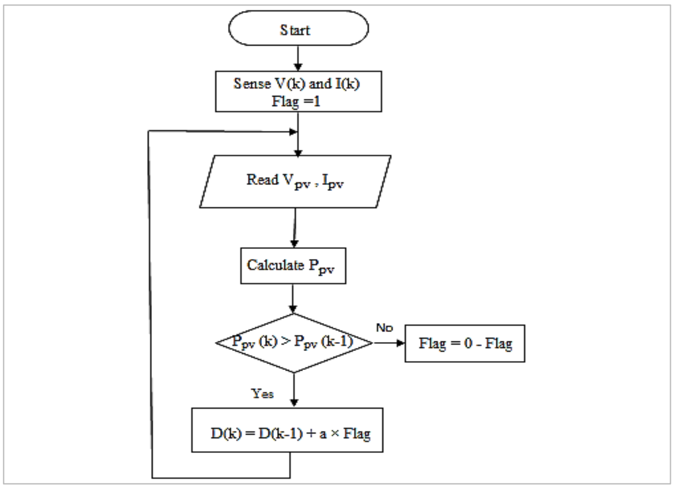

Figure 2: The flowchart of hill-climbing based-MPPT method

3. Variable step-size methods

The MPPT algorithm can respond quickly if the duty cycle modification uses a large step-size, but it can increase constant oscillations around MPP which makes it hard to track MPP accurately and thus reduces the efficiency of energy production. Alternatively, the steady state response can be enhanced when a small step-size is employed, but the tracking speed becomes slow. Variable step-size methods were proposed to enhance MPPT methods efficiency [36-38]. The derivative (*dP/dV*) is used in [36] to substitute a fixed step-size in the traditional INC method. This derivative or slope (*dP/dV*) declines as long as the operating point of the algorithm is moving toward the MPP; and the slope will be zero, when the MPP is attained. This slope changes, however, as the weather conditions change Normally, the scale factor N is multiplying by this derivative to reflect the convergence of the algorithm. *D* represents the converter's duty cycle:

$$D_k = D_{k-1} + N \times \left|\frac{dP}{dV}\right| \tag{1}$$

The derivative (*dP/dD*) is utilized in [25] to indicate the variable step-size.

$$D_k = D_{k-1} + N \times \left|\frac{dP}{dD}\right| \tag{2}$$

The *N* value in Eq (1) and Eq (2) should be selected carefully in order to ensure acceptable result of the VSS in the MPPT algorithm. The selection of the *N* may be specified in accordance with Eq. (3) and Eq (4)[35]. If the system reaches the steady state, it will attain the constant number *N* using the derived (*dP/dV*) and D_{max}, where D_{max} is allowed the maximum step-size.

$$N \times \left|\frac{dP}{dV}\right| < \Delta D_{max} \tag{3}$$

$$N < \Delta D_{max} / \left|\frac{dP}{dV}\right| \tag{4}$$

In an attempt to address these issues, the INC MPPT algorithm is developed in [33]. However, current *I* and variation of the current ΔI are used in this algorithm, which needs great precision current sensor and thus, the hardware costs can be increased.

4. Proposed MPPT method

The key distinction with this method compared to the other methods is that the step-size of hill-climbing (HC) based-MPPT can be modified by the function threshold levels (*T*) – which can be determined based on the exponential power multiplication of the PV power (*P*) and the derivative slope (|*dP/dV*|) as shown below:

$$T = P_{PV}^{n} \times \left|\frac{dP}{dV}\right| \tag{5}$$

Where n is an index. The product of the PV power (*P*) and the derivative slope (|*dP/dV*|) is being used to monitor the hill-climbing (HC) based-MPPT step-size as shown in Figure (3). The method proposed should guarantee that in two variable size step modes, the system must work, even if the irradiation is changed quickly.

A related methodology of the conventional VSS MPPT method in [32] is retained with the developed method here. The discrepancy between conventional and new methods is focused on that; firstly, a variable step-size of the proposed method, relying only on the change of the PV power (ΔP), while conventional method developed in [35] based on the alter in the PV power with regard to the alter in PV voltage ($\Delta P/\Delta V$).

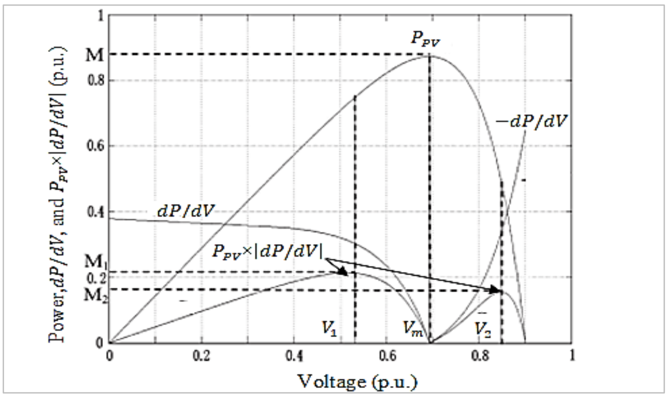

Figure 3: Normalized power, power slope against voltage, and the power product and its slopes [33].

During the abrupt irradiance changes, the step-size of the method provided in [32],[39] depends on the derivate $\Delta P/\Delta V$, this could cause a dynamical degradation in performance during the quick variation in irradiation. In addition, at the steady-state condition, constant power oscillation may arise all across the MPP [40]. To resolve the latter issue, a VSS is developed in this paper, relying just on the change of the PV power, as shown in Eq (6). The VSS MPPT algorithm can be used to monitor the power converter duty cycle directly.

Under normal weather conditions, the condition that the ΔP is exactly equal zero will never be fulfilled due to various inevitable variables such as measuring error, ripples and noise. Therefore, the operating point fluctuates across the MPP. It is evident from figure (4) that PV voltage change is slight in the area close and right to MPP which could result in big $\Delta P/\Delta V$ steps. While these big steps improve the speed of tracking at the beginning of the PV process, they will rise the constant power fluctuations around MPP, impacting the accuracy of the MPPT algorithm, which in turn reduces the effectiveness of the algorithm.

During abrupt irradiance changes, the conventional variable step-size will give a low transient efficiency. As illustrated in figure (4) if the irradiance varies from G_1 to G_2, the power changes (ΔP) are significant, whereas the voltage changes (ΔV) are comparatively slight. As the steps rely on $\Delta P/\Delta$V, this would lead to a high adjusted duty ratio (ΔD), thus the operational point in the P-V curve is driven to the wrong side and far from the new MPP location.

As result, the PV power decreases significantly, and it requires more time to attain the MPP.

In addition, the efficiency of tracking will be decreased.

The new MPPT method is proposed to resolve the abovementioned issues – which only relies on an alter of PV power (ΔP). The VSS MPPT method can be used in order to explicitly regulate the converter switch so that the converter duty cycle can be modified as seen in (6);

$$S_t = N \times |dP| \tag{6}$$

Where S_t(t = 0, 1,…) indicates the step-size of the variable at period *t* ; *N* is the factor adjusted in order to modify the step-size to balance between the precision of tracking and its divergence rate during the design stage. More details about the scaling factor are discussed later.

To confirm that the step-size converged., the *N* value in Eq (6) should be chosen carefully.

$$N \times |dP| < \Delta D_{max} \tag{7}$$

$$N < \Delta D_{max} / |dP| \tag{8}$$

It can be noticeable that in figure (4), the alteration of PV power (ΔP) is vital away from the MPP and slightly small around the MPP. Therefore, the step size dependent on ΔP is large when the operational point is a way from the MPP and is reduced when the point of operation is heading to MPP. The proposed VSS is based only on ΔP, unlike the conventional variable-step that is completely dependent on two variables (ΔP and ΔV). With the elimination of a division ΔV, it is possible to simplify the algorithm by further removing significant step size changes that happen at minor change of PV voltage.

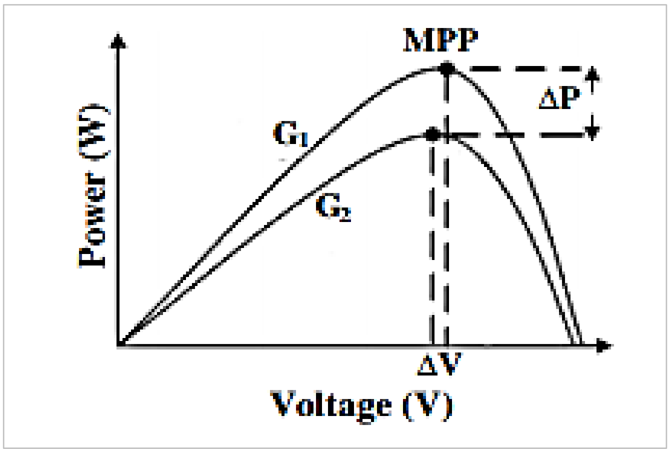

Figure 4: Change in irradiance on the P-V curve [40].

The second major difference between the method proposed here and conventional method in [32] is dependent on the operational value of *N*. The conventional MPPT method uses individual scaling factor *N*; however, the proposed method uses a dual scaling factor *N*. As the slope is decreased, the new algorithm adheres to the combination of the dual scaling factor which is: (N_1) with high value and (N_2) with low value. The N_1 is used for quicker response at the start of the execution. The second N_2 value is used in the meantime to regulate the system's power oscillation. The goal of this proposed method is to attain accelerated tracking time and high accuracy by reducing the power oscillation around the MPP. With dual scaling factor *N* values, the increment step-size is more strategic because the time response can be easily controlled to reach the MPP quickly.

The product curve is based on the two values/points (M_1 and M_2) which corresponds to (V_1 and V_2) at both sides of the MPP. Determination of the *N* selection in step perturbation can be done depends on both the increment of the threshold function $\Delta T/\Delta V$ and the normalized PV power curve. Whenever the PV output voltage is outside the range of V_1 and V_2, the HC MPPT operates with the high value of N_1. Otherwise, the low value of N_2 is applied (as shown in figure. (3)). The abovementioned concept can be expressed by:

$$\begin{cases} \Delta T/\Delta V \geq 0, & \text{High value N (left of MPP)} \\ \Delta T/\Delta V < 0, & \text{Low value N (left of MPP)} \\ \Delta T/\Delta V > 0, & \text{Low value N (right of MPP)} \\ \Delta T/\Delta V \leq 0, & \text{High value N (right of MPP)} \end{cases} \quad (9)$$

There is therefore an expression in Eq (9) to decide whether to select low or high *N* value that reflects on the tracking response of the new method. The selection of the N_1 and N_2 value may be specified in accordance with Eq (7) and Eq (8).

The two ends of the threshold become closer to the maximum power whenever the *n* (index) is increased, as illustrated in figure (5). Therefore, the greater the *n* value, the quicker the system's response and vice versa.

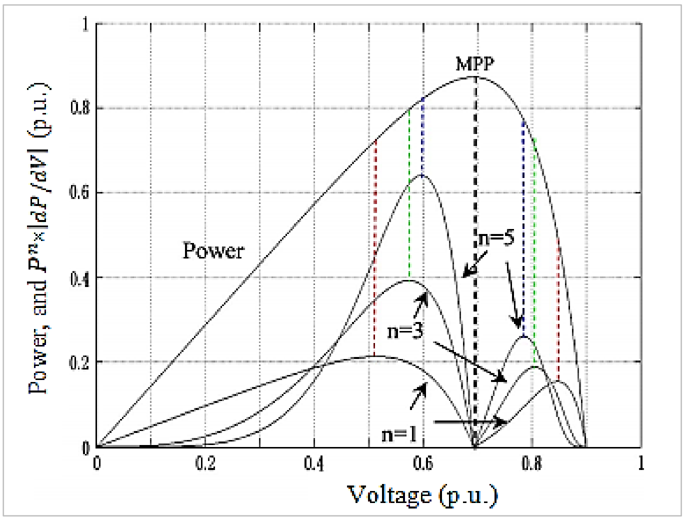

Figure 5: Normalized power and $P_{PV}^n \times \left|\frac{dP}{dV}\right|$ with different index *n* value [33].

$$\begin{cases} dP = 0, & \text{at MPP} \\ dP < 0, & \text{left of MPP} \\ dP > 0, & \text{right of MPP} \end{cases}$$

Figure (6) displays the flowchart of the proposed algorithm. At the MPP left-side, if $\Delta T/\Delta V \geq 0$, the proposed MPPT algorithm will function with the high N_1 value; alternatively, the proposed MPPT algorithm will function with the low N_2 value. At the MPP right-side, if $\Delta T/\Delta V \leq 0$, the MPPT algorithm will function with the high N_1 value; alternatively, the MPPT algorithm will function with the low N_2 value.

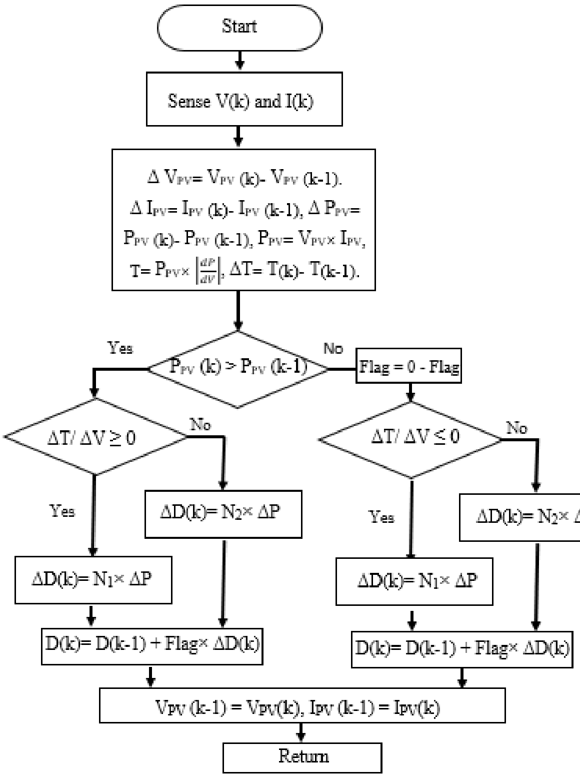

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Figure 6: The flowchart of proposed MPPT algorithm

5. Simulation results and analysis

The schematic representation of the PV system seen in the figure (7) is built in MATLAB-SIMULINK. to verify functionality of the proposed MPPT algorithm. The PV system's specifications are specified in Table 1.

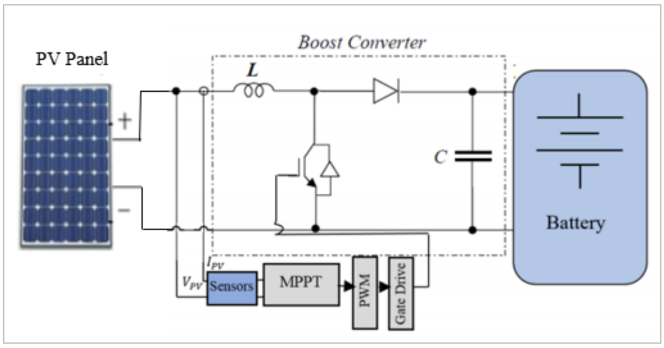

Figure 7: PV system block diagram

Table 1: Specification of PV system used in MATLAB simulation

Item	Value
Maximum Power (P_{max})	180 W
Open Circuit Voltage (V_{oc})	44.8 V
Maximum Power Voltage (V_{mpp})	35.86 V
Short Circuit Current (I_{sc})	5.6 A
Maximum Power Current (I_{mpp})	5.02 A
Battery	48V ,33 Ah
Switching Frequency	25 kHz
Inductor	400 uH
Capacitor	1 mF
Battery	48V ,33 Ah

Case 1: The PV system is tested under rapid decrease of irradiation:

The simulation setups are basically the same to have fair evaluation between the proposed MPPT method with other MPPT methods. The sampling time is selected as a 0.02 for the MPPT algorithm. The PV system is tested with varied irradiation and fixed temperature (T) = 25°C. Figure (8.a) shows the HC based-MPPT method performance with step-size of 0.01. The irradiation was suddenly decreased from 1000 W/m^2 to 400 W/m^2 at 0.5 s, and the system takes around 0.22 s to reach the MPP. Under the same condition, the HC based-MPPT method performance with step-size of 0.05 was tested, as shown in figure (8.b). It is found that the and the system takes around 0.06 s to reach the MPP.

In comparison with the above method, the MPPT method with a step-size of 0.05 has a better tracking speed but static fluctuations are more intense around the MPP. Under the same conditions, the response time when using step-size of 0.05 just takes few MPPT sampling times, and with a larger step-size, it can be decreased further. Nevertheless, increased the step-size can increase the oscillation at steady-state condition and, therefore, reduces the PV system efficiency. The method based-MPPT proposed in [32] is included in this simulation. The PV output power of the method introduced in [32] under same conditions above can be shown in figure (8.c). This method uses a fixed scaling factor *N* equal 0.06. It requires only 0.05 s to reach the MPP. However, the method response was slightly slowed when the irradiation suddenly decreased. This is due to the fact that this method has only an individual scaling factor. The proposed MPPT method performance under the same condition is displayed in figure (8.d). Compared with the previous MPPT method, this method only needs 0.03 s to reach the MPP with a zero oscillation around the MPP, and it offers rapid response under abrupt irradiation variations. The reason behind this is the use of a dual scaling factor; if the operational point is not close to MPP, and based on the principle of the proposed method, the high *N* value is selected. This selection will boost the tracking speed of the MPPT algorithm. Otherwise, the low *N* value is selected. This selection can help diminish the oscillation around the MPP, thus increasing the PV system efficiency.

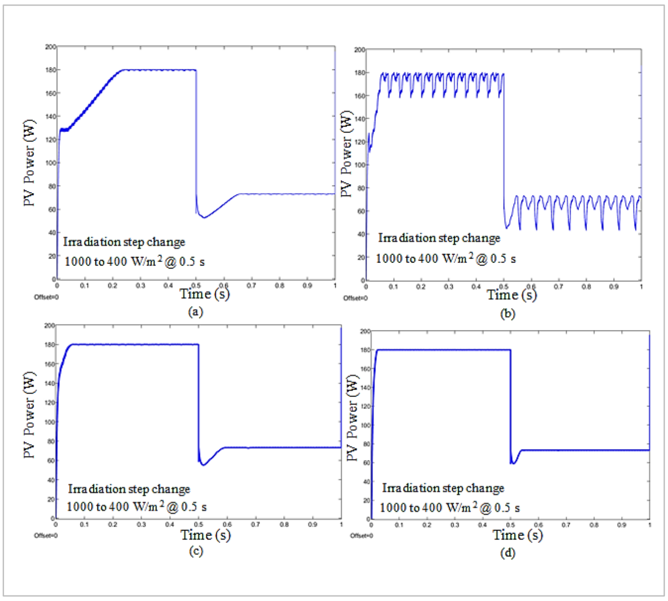

Figure 8: Simulation waveforms of (a) MPPT method with step-size (ΔD=0.01), (b) MPPT method with fixed step-size (ΔD=0.05), (c)method proposed in [32],and (d) proposed MPPT method under the conditions of sudden decrease of irradiation and constant T=25°C.

Case 2: The PV system is tested under rapid increase of irradiation:

In this condition, the irradiation was abruptly increased from 500 W/m^2 to 1000 W/m^2 at 0.5 s The PV output power of the following MPPT methods: HC based-MPPT method with a small step-size , HC based-MPPT method with a large step-size , MPPT method introduced in [32], and the proposed method is shown in figure (9).

Th average PV power with a large step-size is 175 W which is decreased by 4 %, in comparison with a small step-size which has average PV power of 179 W, as shown in figure (9.a) and figure (9.b), correspondingly. The waveforms clearly appear in figure (9.c), and figure (9.d) indicates that they can overcome the issues of fixed step-size. In these two figures, the oscillations around the MPP are almost zero, and the average PV power of the method introduced in [32] and the proposed method is 179.4 W and 179.8 W, respectively. Furthermore, the dynamic response is evidently quicker than the HC MPPT method with a small step-size.

The proposed MPPT method can work under nearly all irradiation conditions. The proposed method is therefore more adequate for existing environmental conditions in PV systems.

Table 2: Performance of the comparison MPPT methods

Method	Parameters	Average power at 1000W/m^2	Tracking speed with fixed irradiation	Tracking speed with irradiation step change	
			500 W/m^2	1000 to 400 W/m^2	500 to 1000 W/m^2
Fixed step size	ΔD = 0.01	179 W	0.35 s	0.2 s	0.15s
Fixed step size	ΔD = 0.05	175 W	0.09 s	0.06 s	0.09s
Ref [32]	N =0.06	179.4 W	0.15 s	0.09 s	0.03s
Proposed	N_1 =0.13, N_2 =0.04	179.8 W	0.06 s	0.04 s	0.01s

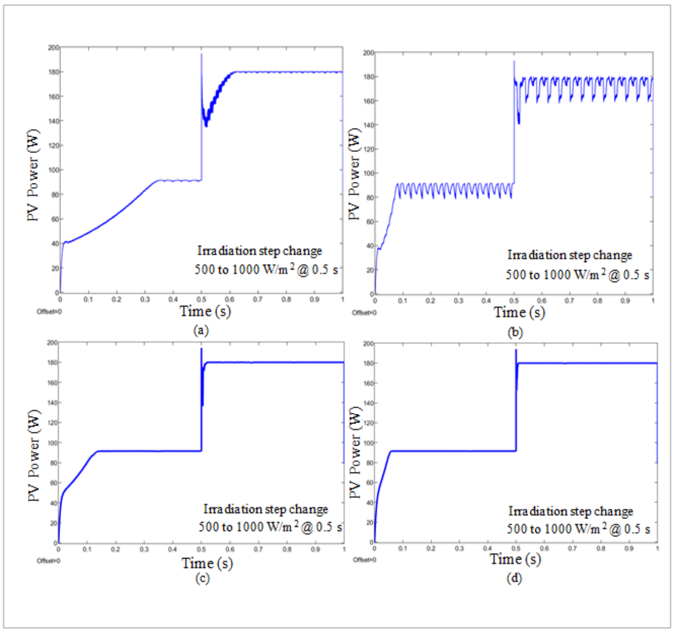

Figure 9: Simulation waveforms of (a) MPPT method with step size (ΔD=0.01), (b) MPPT method with fixed step-size (ΔD=0.05), (c)method proposed in [32],and (d) proposed MPPT method under the conditions of sudden increase of irradiation and constant T=25°C.

Case 3: The PV system is tested under slow ramp irradiation:

In this condition, for additional verification, the proposed method tested also under slow irradiation change. The irradiation changed under the ramp rate of 60W/1s.

Figure (10.a) shows the MPPT method with a step-size of 0.01, the MPPT method with a step-size of 0.05 (figure(10.b)), the MPPT method developed in [32] (figure (10.c)), and the proposed MPPT method (figure (10.d)) when irradiation slowly changes from 700 W/m^{2}to 760 W/m^2. It can be clearly stated that all the compared MPPT methods succeeded in keeping track of the new MPP under the slowed change of irradiation.

The figures above indicate that the proposed MPPT method provides an overall better performance than other MPPT methods.

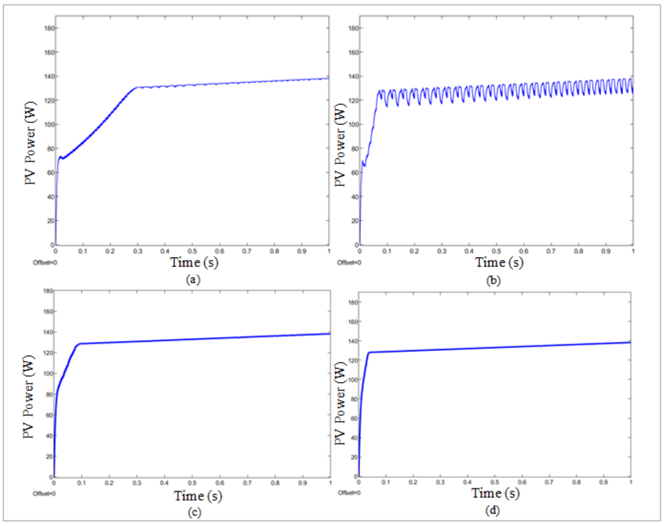

Figure 10 Simulation waveforms of (a) MPPT method with step- size (ΔD=0.01), (b) MPPT method with fixed step-size (ΔD=0.05), (c)method proposed in[32],and (d) proposed MPPT method under the conditions of slow change of irradiation and constant T=25°C.

Case 4: The PV system is verified under rapid change of temperature:

The behavior of the PV system when the temperature altered from 75°C, 25°C, and 50°C can be shown in figure (11).In the case of the small-step size HC based-MPPT method , (figure (11.a)), it requires

around 0.2 s to track MPP, while in case of the large-step size HC based-MPPT method, (figure (11.b)), it requires only 0.05 s to reach MPP. However, serve oscillations are found on the PV output power waveform. It was noted that, the method developed in [32] (figure (11.c)) has same tracking response of HC based-MPPT method with large-step size. On the other hand, it takes 0.03 s to track the MPP using proposed method (figure (11.d)).

The proposed method has nearly same tracking accuracy of the method in [32] but with a better tracking speed-which means it could reduce the PV system losses that usually occur in [32] during the time when the operational point is perturbing toward the MPP.

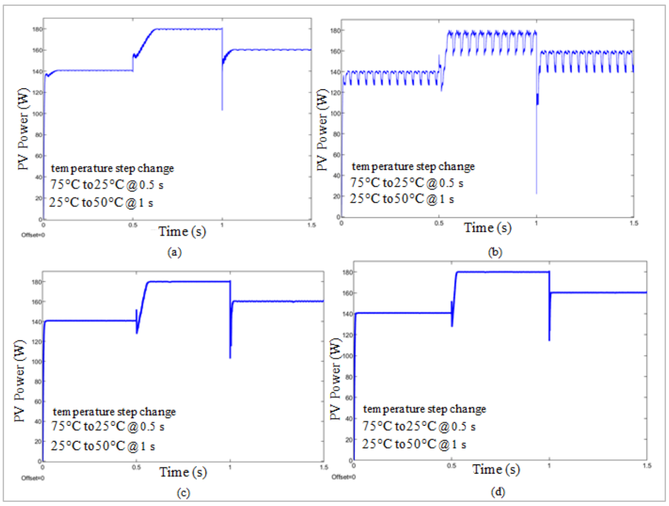

Figure 11: Simulation waveforms of (a) MPPT method with fixed step-size (ΔD=0.01), (b) MPPT method with fixed step-size (ΔD=0.05), (c)method proposed in [32],and (d) proposed method during rapid change of temperature and G = 1000 W/m^2 .

Table 2 summarizes the compared outcomes of various MPPT methods. The tracking speed under fixed irradiation (400W/m2-1000W/m2) for MPPT method with a small step-size (ΔD=0.01) is very slow. Although, the tracking speed for a large step-size (ΔD=0.05) MPPT method is faster, the average PV power is the minimum. For the method developed in [32] with N equal to 0.06, the speed of tracking sometimes is slower than the MPPT method with a large step-size, under fixed and varied irradiation. Since the method developed in [32] used individual N scaling value, it does not respond to the abrupt change in irradiation. As the irradiation varies quickly, proposed variable step-size HC based-MPPT method demonstrates very good performance. The findings demonstrate a rapid tracking speed and with high accuracy of tracking MPP.

6. Conclusions

A new VSS HC based-MPPT method has developed in this paper. This method would enhance stable performance and dynamic performance at the same time. In comparison with the previous MPPT methods, the proposed method uses a dual scaling factor *N*. The findings have shown that by applying a combination of large *N* value at the start and once the operational point is far from the MPP, and of small *N* value when the operational point is closer to the MPP, the tracking time involved to attain the MPP is quicker and with nearly zero PV output power oscillation. This further attribution enhanced the MPPT's efficiency. Moreover, the proposed MPPT design scheme is explored in depth and a basic rule for realization is illustrated. In MATLAB-SIMULINK, the proposed method and other MPPT methods are simulated. Simulated results can confirm the feasibility of the proposed method.

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