Indonesian Journal of Electrical Engineering and Computer Science
Vol. 6, No. 2, May 2017, pp. 225 ~ 232
DOI: 10.11591/ijeecs.v6.i2.pp225-232

Distributed Fast Maximum Power Point Tracking Technique for Mismatched Module Application

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Abstract

This paper propose distributed fast maximum power point tracking (DFMPPT) technique to achieve maximum power point tracking (MPPT). This paper implements the algorithm in distributed MPPT (DMPPT) architecture for mismatched condition with single module, and string connection. The MPPT method uses indirect and direct MPPT method by fractional open-circuit voltage (FOCV) with incremental conductance (INC) for high-speed maximum energy harvesting. This method is proven to be fast for tracking maximum power point (MPP) which achieves the peak power less in 1.7ms via for a single module with efficiency of 99.7% compared to the recent MPPT technique to reach MPP in 1.75ms with 95.8% efficiency. While for string configuration, the efficiency of the whole system is rated by 85.583% by taking 8.675ms to reach global MPP.

***Keywords**: photovoltaic (PV) system, maximum power point tracking (MPPT), distributed maximum power point tracking (DMPPT), incremental conductance (INC), distributed fast maximum power point tracking (DFMPPT)*

1. Introduction

For a century, fossil fuel has dominating the power industries. Fossil fuel, coal, and their equivalents are known as one of major contributor to human’s carbon footprint on the environment. Not only that it pollute the air, but also triggers climate change. With the recent initiative taken by Germany to forbid the use of internal combustion engines in their parliamentary amendment by 2030 in [1], the renewable energy industry may flourish rapidly.

Photovoltaic (PV) system require maximum power point tracking (MPPT) system in order to provide efficient energy harvesting in mismatch condition. Mismatch conditions is when the PV system operates in non-uniform condition due to clouds, partial shading, dirt, and others [2, 3]. PV arrays in partial shading will have multiple peaks in the power curve from the effect of bypass diodes used for protection when PV string produces different output. Thus, the performance of the PV system in centralized MPPT (CMPPT) system will degrade due to the presence the multiple peak [4]. To overcome this limitation, the system should employ the implementation of distributed MPPT (DMPPT).

Conventional direct MPPT algorithm such as perturb and observe (P&O) algorithm, and incremental conductance (INC) track maximum power with tracking speed in a factor of tenth of milliseconds, below 100ms according to [5]. However conventional MPPT algorithm methods were defeated by soft-computing methods in terms of efficiency, and stability of tracking MPP. Such methods include fuzzy logic controller, particle swarm optimization (PSO), artificial neural network (ANN), and others. Soft computing methods require complex computation process, and memory. Such requirements are infeasible for low-cost microcontroller to handle; therefore, the MPPT system will become more expensive. In addition, the tracking speed for soft computing methods such as PSO, ANN, genetic algorithm (GA) takes time to complete computational iteration, thus, slower compared to conventional direct MPPT method [5–7]. Method proposed by [5] achieves MPP in 12ms with 99.6% efficiency, while 140ms to reach global MPP for mismatch condition. The highest tracking speed as proposed in [8] reach MPP in 1.78ms with efficiency of 95.8%.

However, this paper aim for a simple, low-cost (using low-cost microcontroller with only single voltage and current sensors), and high-speed MPPT technique for some small to medium

Received February 10, 2017; Revised April 15, 2017; Accepted April 30, 2017

application require extreme transient in solar such as in satellite transponder, solar roof on electric/hybrid vehicle, and others.

2. Research Method

2.1. Proposed Algorithm

This paper proposes the hybrid combination of direct and indirect MPPT method as one MPPT technique for high-speed MPP tracking called as DFMPPT using the Incremental Conductance (INC), and Fractional Open-Circuit Voltage method (FOCV). The algorithm flowchart of the proposed DFMPPT technique can be referred in Figure 1. Typically, INC method is conventional direct MPPT techniques that use perturbation of operating parameter based on direct measurement of PV parameter. The method is having higher tracking speed, and overall MPPT efficiency compared to the Perturb and Observe (P&O) technique [5,6]. INC algorithm tracks for MPP by comparative process of the conductance, and its gradient [9]. The INC algorithm is simplified as shown in equation below;

$$V_{PV(k+1)} = V_{PV(k)} \pm \Delta V = V_{PV(k)} + sign(G + dG) \cdot \Delta V \tag{1}$$

where $V_{PV(k+1)}$ is the next operating reference voltage for PV source, $V_{PV(k)}$ is the measured PV operating voltage, G is the measured conductance (I/V), dG is the difference of conductance to previous value, and ΔV is the perturbation step size.

INC method has its limitation similar to P&O MPPT algorithm where the MPP tracking operating point will oscillate around the MPP. This oscillation can be reduced by using small step size. However, with small step size as proposed in [10], the oscillation is reducing, but the MPP tracking will be slower. This limitation can be improved using FOCV method to as a quick reference of maximum power point voltage, V_{MPP}. The from FOCV estimation, the MPPT operation will be fine-tuned by INC method.

On the other hand, FOCV and its equivalent-the Fractional Short Circuit Current (FSCC) method; are referred as indirect MPPT technique since the method does not measure for the actual power extracted from the PV module [6], [11]. FOCV and FSCC use approximation of MPP parameter by fraction of open-circuit voltage, V_{OC}, and short-circuit current, I_{SC}, as stated in specification of PV module, or either by empirical data analysis. Enslin et al [11] originate this method back in the year 1997, which states that MPP is located at 76% of V_{OC}. Newer study suggest that the MPP located between 70-82% of V_{OC} [12].

Since the DFMPPT hybrid combination of both direct and indirect method, therefore it depends on the type of the DC-DC converter being used. For instance, buck converters are able to disconnect the PV source to the load by switching device; therefore, open-circuit voltage parameter can be tracked. For boost converter, however, switching device is connected in parallel between PV source and the load, therefore, open-circuit voltage cannot be determined using the converter. Nevertheless, short-circuit parameter for FSCC can be obtained by providing 100% duty cycle to the switching device, shorting the circuit.

The DC-DC converter used in this paper is buck converter. Therefore, FOCV parameter can be determine easily by providing duty cycle value of 0% to the switching device. Initially, the DC-DC converter is switched off, while the MPPT algorithm sub-routine searching for open-circuit voltage. Then, after the V_{OC} is defined, fraction of it (82% of V_{OC}) will be stored as reference voltage for MPPT operation.

The flowchart (Figure 1) show that as soon as the FOCV parameter is tracked, the MPPT system will start to initialize and track for the actual MPP parameter by INC. The FOCV MPP estimation is refined by INC process. At the steady state, the MPPT will evaluate the solar condition by monitoring the gradient of PV operating parameter. In the case of rapid changes in solar condition, the MPPT system will detects for large steepness in PV parameter. Therefore, the DFMPPT will stop the direct MPP tracking to determine for the FOCV parameter. However, if the changes in PV operating condition are small, the MPPT will continue search for MPP by INC process.

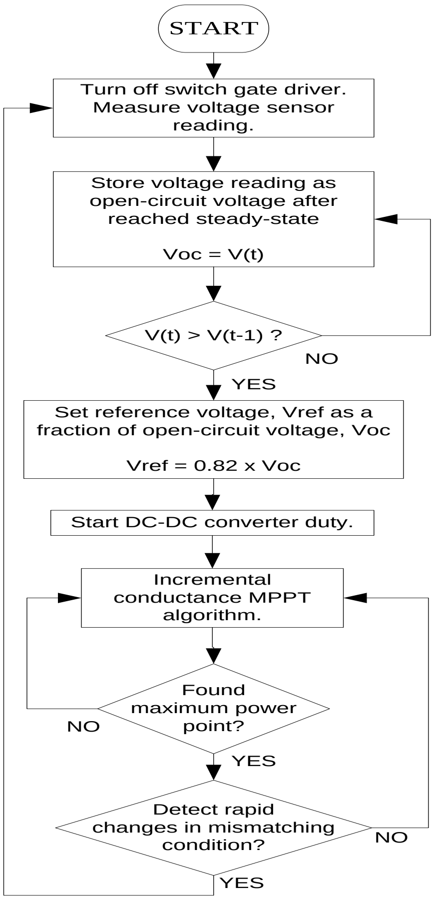


Figure 1. Flowchart of high-speed MPPT algorithm

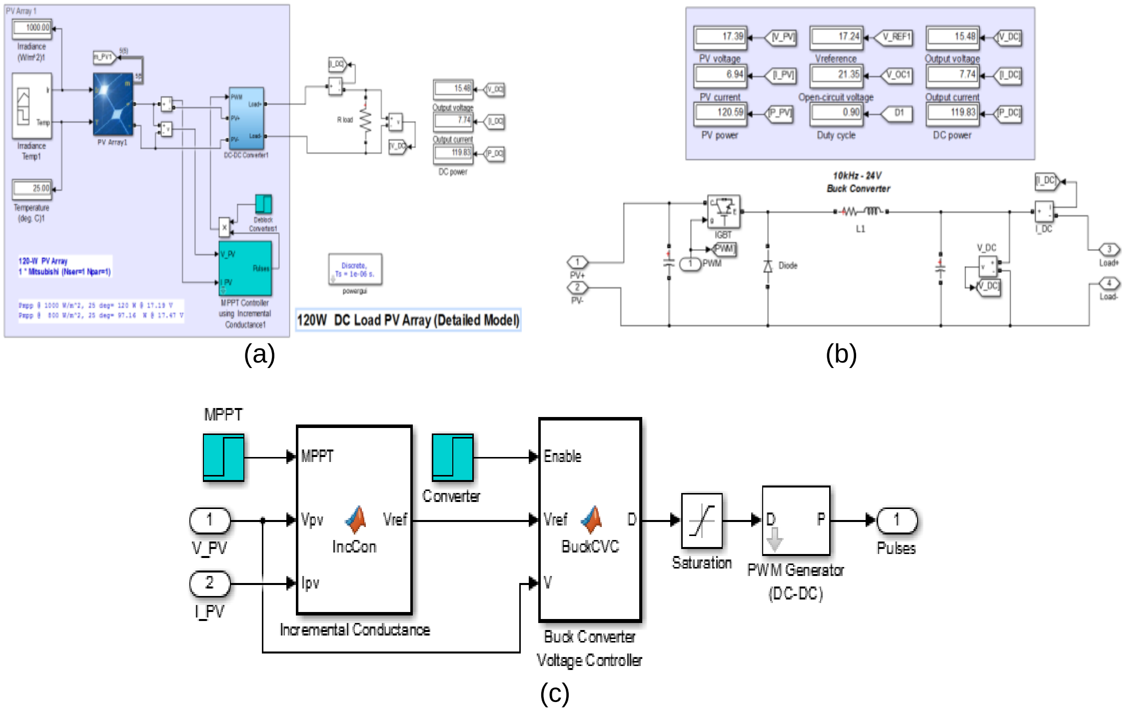
2.2. Simulation Model

The simulation of the DFMPPT technique is carried out using MATLAB Simulink® R2015a. The model consists of a single PV panel connected to buck converter with DC load. The converter is controlled by MPPT block according to voltage, and current sensor at the PV source. Model of the PV module being used is Mitsubishi EE120MF5F. The buck converter is calculated accordingly referred to [13, 14], and the parameters are for switching frequency, F_{SW}, inductance, L, and capacitor, C are, 31.3182kHz, and 100μF respectively.

2.2.1. Single PV Module

Figure 2(a) show the Simulink model for the whole PV system. The DC-DC converter block is located between PV module and the load. Figure 2(b) show the internal view of the DC-DC converter used for simulation, which reveals buck converter. Based on the algorithm flowchart as shown in Figure 1, the buck converter will start to operate at the time, t=0.001 second. Figure 2(c) show sub-system blocks inside of the MPPT block; consisting of MPP tracker block and converter voltage controller (CVC). The MPPT will track for MPP based on voltage and current sensor, and will provide voltage reference for CVC to operate. The CVC will provide output for pulse width modulation (PWM) generator. The MPPT will start track for FOCV parameter as the converter is activated with 0% duty cycle. The MPPT will then provide the reference voltage to the CVC for converter to operate.

The CVC will continuously adjust the duty cycle, D until the PV voltage, V_{PV} is equal to the desired reference voltage, V_{REF} from the MPPT block The CVC converter uses variable duty cycle step size, $\Delta\delta$ to enhance the operating voltage traction of the PV source to the reference voltage by means of speed and accuracy.



(a) (b) (c)

Figure 2. (a) Model diagram of whole PV system with MPPT; (b) Buck converter circuit diagram with parameter display; (c) MPPT block diagram

The mathematic expressions of the CVC block is as shown in (2), and (3). The variable step size is defined as following;

$$\text{Duty cycle step size, } \Delta\delta = \begin{cases} N\cdot\frac{V_{REF}}{V_{PV}}, & |V_{REF}<V_{PV} \\ N\cdot\frac{V_{PV}}{V_{REF}}, & |V_{REF}>V_{PV} \\ N, & |V_{REF}\neq V_{PV} \end{cases} \quad (2)$$

where N is the specified step size gain as 0.00001. The gain is obtained by experimenting to achive quick system response and highest stability. The duty cycle for CVC can be expressed as following;

$$\text{Duty cycle, } D_n = \begin{cases} D_{n-1}+\Delta\delta, & |V_{REF}< V_{PV} \\ D_{n-1}-\Delta\delta, & |V_{REF} > V_{PV} \\ D_{n-1}, & |V_{REF} = V_{PV} \end{cases} \quad (3)$$

2.2.2. Distributed String Connected PV System

The model for string connected of PV module is shown in Figure 4 with mismatch condition having different irradiance value to the PV module. Module 1 is having irradiance of 1000W/m2, while module 2 has irradiance of 710W/m2.

The circuit parameter of the DC-DC converter and the output load for the DFMPPT in Figure 4 is exactly the same as the one in Figure 2. The MPPT and CVC function block also have the exact same coding. For benchmarking purpose, the performance of DFMPPT is compared with performance of PV string without MPPT with same load parameter, and also with the CMPPT architecture.

3. Results and Discussion

3.1. Single PV Module

The simulation output of the PV system time plot shown in Figure 3, and data summarized in Table 1. Referring to Figure 3, the current ripple at the initial time is due to the forward-reverse inrush of PV current working in discontinuous current mode. It does not a concern since it does not affect the whole system. As shown in Figure 3 the DFMPPT start MPP tracking at time t=0.005sec. The MPP is reached at time t=0.0067 sec. Therefore, the MPPT response time is 1.7ms. The MPPT efficiency is calculated using Equation (4);

$$\text{MPPT efficiency, } \eta_{\text{MPPT}} = \frac{P_{\text{MPPT}}}{P_{\text{MPP(rated)}}} \tag{4}$$

where the P_{MPPT} is the MPP tracked by DFMPPT, while $P_{\text{MPP(rated)}}$ is the rated maximum power point as specified by PV module manufacture in STC.

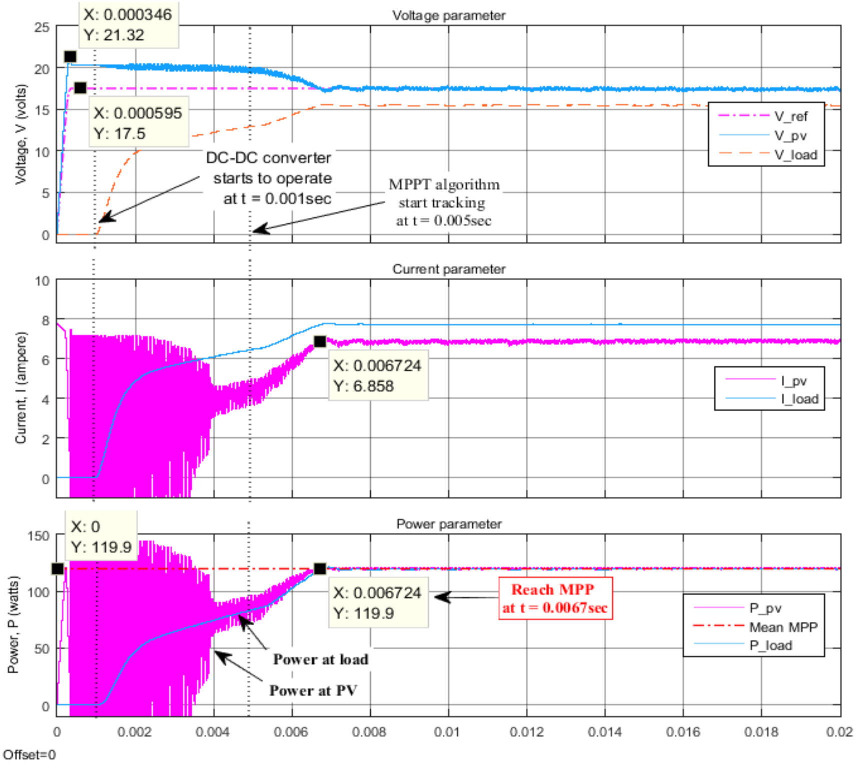


Figure 3. Simulation result for DFMPPT with single module

Table 1. Summarized simulation result for single module with DFMPPT

Parameters	Value
Tracked open-circuit voltage, V_{OC}	21.32V
Fractional open-circuit voltage reference, V_{ref}	17.5V
Maximum power point voltage, V_{MPP}	17.2
Time taken to reach MPP	1.7ms
Average maximum power point by DFMPPT, P_{MPP}	119.9W
Rated maximum power, P_{MPP} (at STC)	120.23Wp
Efficiency of single module DFMPPT	99.7%

3.2. Distributed String Connected PV System

For the string case the simulation output waveform for module 1 (located on top, refer to Figure 4 is plotted on Figure 5. The MPPT system initialize at time, t = 0.001 second and achieve the peak power at time, t = 0.006065 second. The tracked steady-state peak power is

119.9W. While the simulation output waveform for module 2 (located on bottom, refer Figure 4 is plotted on Figure 6. The MPPT system initiate at time, t=0.001second, and reach MPP at t=0.006065second. The tracked MPP at irradiance level of 710W/m2 is 86.65W.

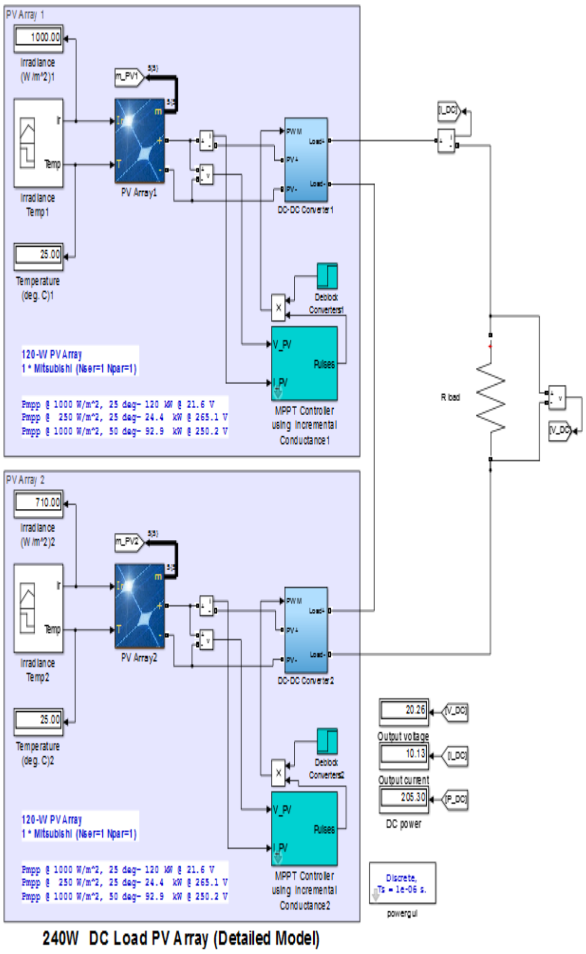


Figure 4. DFMPPT in string connection

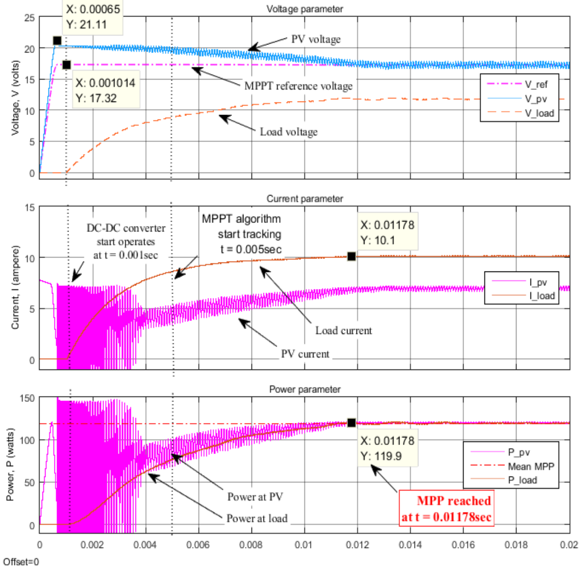


Figure 5. Simulation result for DFMPPT on module 1 (top)

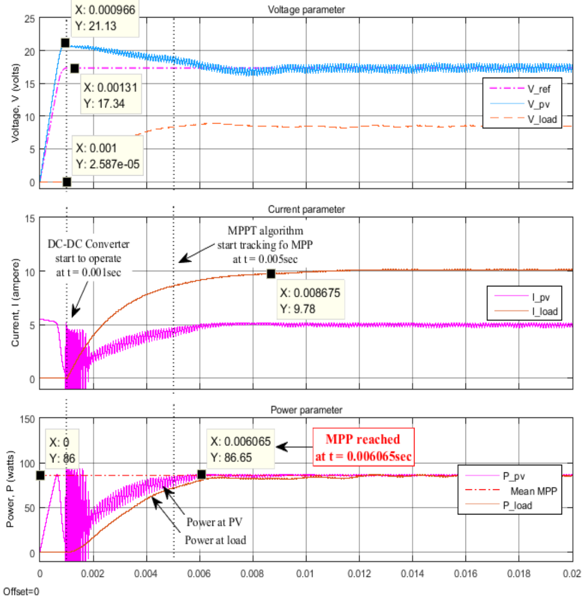


Figure 6. Simulation result for DFMPPT on module 2 (bottom)

Shown in Figure 7 is the simulation output waveform of the output load parameter of whole PV system consists of both module operating in string configuration. Both PV module track for MPP independent of one another. The PV system operated at mismatch condition by partial shading effect on bypass diode of the PV array. The DFMPPT yield peak output higher than the CMPPT while significantly improves the energy harvesting as compared with PV array without any MPPT. The DFMPPT is capable to drive three times more output than system without MPPT.

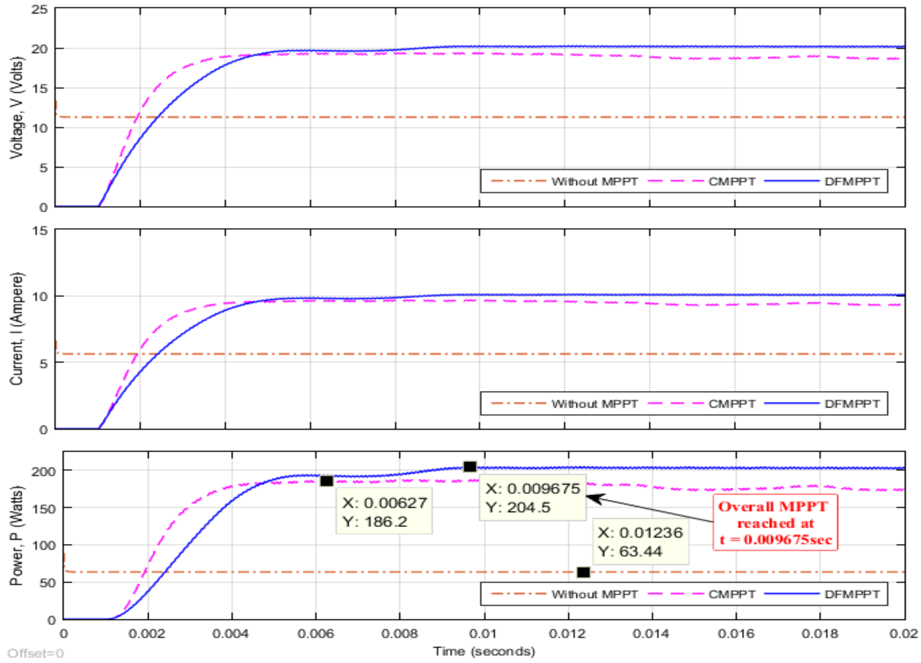


Figure 7. Simulation result of PV system on the load side

From the simulation result, the efficiency of the DFMPPT is producing 85.583% of the STC rated output power. From the plot, the CMPPT is able to produce 91% of the DFMPPT output. The MPPT response time are listed in the Table 2 is 8.675ms.

Table 2. Summarized simulation result for proposed DFMPPT for string configuration

Parameters for module 1	Value
Irradiance, G	1000W/m^2
Tracked open-circuit voltage, V_{OC}	21.11V
Fractional open-circuit voltage reference, V_{ref}	17.32V
Maximum power point voltage, V_{MPP}	17.2
Time taken to reach MPP (seconds)	6.7ms
Average maximum power point by DFMPPT, P_{MPP}	119.9W
Rated maximum power, P_{MPP} (at STC)	120.23Wp
Efficiency of single module DFMPPT	99.7%

Parameters for module 2	Value
Irradiance, G	710 W/m^2
Tracked open-circuit voltage, V_{OC}	21.13V
Fractional open-circuit voltage reference, V_{ref}	17.34V
Maximum power point voltage, V_{MPP}	17.37
Time taken to reach MPP (seconds)	1.06ms
Average maximum power point by DFMPPT, P_{MPP}	86W
Rated maximum power, P_{MPP} (at STC)	120.23Wp
Efficiency of single module DFMPPT	71.53%

Parameters for whole PV system by DFMPPT	Value
Time taken to reach global MPP (seconds)	8.675ms
Output power optimized by DFMPPT, P_{DFMPPT}	204.5W
Total peak power of PV system at STC	240.46Wp
Efficiency of DFMPPT at mismatch cond.$=\frac{P_{DFMPPT}}{2\times120.23Wp}$	85.583%

4. Conclusion

From the simulation result, the power output of the PV system is optimized by the proposed DFMPPT technique. The response time taken for a single panel to reach MPP at 1000W/m2 and 25˚C is 1.7ms, while for mismatched condition in string configuration; the response time to reach the global MPP is 8.675ms with different irradiation. As a contrast to the work in [8] with tracking speed of 1.75ms, the proposed method achieves peak power by 1.7ms. The efficiency of the DFMPPT for single module rated at 99.7%, while for string configuration, the efficiency is 85.583% from the simulation result. The MPPT technique discussed in this paper will improve the output efficiency of PV system during mismatch conditions. For the future work, the hardware implementation will be carried out to verify the performance of the DFMPPT method using low-cost microcontroller with one voltage and current sensor.

Acknowledgment

The author would like to thank Universiti Teknologi Mara Malaysia and Research Management Institute for the financial support through Fundamental Research Grant Scheme (FRGS/1/2016/TK10/UiTM/62/2) for this study

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