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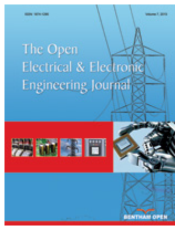

RESEARCH ARTICLE

Performance Analysis of Incremental Conductance MPPT with Simple Moving Voltage Average Method for Distributed PV System

Amjad Ali*, Wuhua Li and Xiangning He

College of Electrical Engineering, Zhejiang University, (310027) Hangzhou, China

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Abstract: In order to harvest photovoltaic energy efficiently, several methods exist, yet most of them failed to address the issues related to extract the maximum power under rapidly changing solar irradiance conditions. In conventional incremental conductance, large step size reduces tracking time but oscillation remains around maximum power point (MPP). However, small step size reduces the oscillation but results in slower tracking speed. This paper proposes a simple moving voltage average (SMVA) technique in conjunction with fixed step direct control incremental conductance (INC) maximum power point tracking (MPPT) method in order to reduce the photovoltaic (PV) generated voltage (V_{PV}) fluctuation and power losses under mismatching solar irradiance conditions in distributed PV system. Theoretical analysis and the simulation results revealed that the proposed SMVA technique provides fast and accurate tracking under mismatching irradiance conditions. Also, it significantly improves the voltage stability because of extremely small |dP/dV| around MPP as compared to the conventional fixed step direct control incremental conductance MPPT method. Finally, results show that the proposed method is suitable for distributed PV system under intermittent weather conditions not only in terms of voltage stability but also in overall system efficiency.

Keywords: Distributed PV system, Direct control incremental conductance (INC), DMPPT, Global maximum power point (GMPP), Maximum power point tracking(MPPT), Module integrated converters (MICs), Simple moving voltage average (SMVA).

1. INTRODUCTION

Growing concern about environmental issues and proliferating demand for green energy harvesting has diverted the attention of power producers for innovation and development in renewable energy technologies (RETs) to mitigate the energy crises and reduce the environmental impacts. Among all the RETS solar photovoltaic is considered as one of the most important energy source because of abundant sun light. Since solar energy is inexhaustible, free and clean. To harvest the maximum power from the PV it is necessary to implement a control strategy to identify the PV operating point characterized by the maximum power point (MPP). So far different MPPT algorithms have been proposed for optimization of PV output power, such as Perturb & Observe (P&O) [1 - 3], Incremental Conductance (INC) [4 - 6], hill climbing [6 - 8], neural network, fuzzy logic theory and genetic algorithm [9 - 11]. However it has been observed that, most of the MPPT methods are developed by assuming the solar irradiance is applied on the entire PV array uniformly. Unfortunately, the nonlinearity of solar irradiation is directly effecting the PV characteristic because of multiple local maxima (the mismatching problem) which can be exhibited by current-voltage (I-V) and power-voltage (P-V) curve of solar PV array, if the entire array does not receive uniform solar irradiation.

The conventional PV system configurations is connected with centralized inverters, where each PV array is connected to an inverter that uses passive components, such as large inductors and capacitors. Mismatching and partial shading problems among PV modules connected in series and parallel are the primary sources of the power losses in these types of centralized configurations [12]. Therefore, in order to mitigate mismatching problem, PV system with

* Address correspondence to this author at the College of Electrical Engineering, Zhejiang University, (310027) Hangzhou, China; Tel: +86 130-7368-0602; E-mail: aliamjad@zju.edu.cn

distributed maximum power point technique (DMPPT) connected with each PV module or array have been widely investigated in [12 - 19]. DMPPT improves the PV output power with respect to centralized MPPT, and offers additional features in terms of protection, particularly in case of malfunctioning, fire and output diagnostics. PV system configured based on DMPPT with DC-DC boost converter improve the overall system efficiency about 5% as compared with centralized MPPT system, reported in [20, 21].

Incremental conductance (INC) and perturb & observe (P&O) are commonly used MPPT techniques in distributed PV system, because both the algorithms operates in accordance with power against voltage (P-V) curve of PV module and tune the duty cycle of converter to ensure the next MPP point accordingly. In P&O steady state oscillation occurred because perturbation continuously changes in both the direction to maintain MPP under rapidly changing solar irradiance thus making the system less efficient and causing more power losses [3, 22, 23]. However, the conventional incremental conductance method determines the Slope of PV curve by varying the converter duty cycle in fixed or variable step size until the MPP is achieved. In this way, oscillation under rapidly changing solar irradiance is reduced with greater efficiency but due to complicated algorithm speed is slow [6, 24].

Considering mismatching conditions which produces significant fluctuation in PV output voltage (V_{PV}) under rapidly changing solar irradiance, which directly effects the PV system output efficiency and causes over all system degradation [25, 26]. So far, no considerable work has been done to minimize the fluctuations of V_{PV} terminal voltage of DMPPT controller which is directly related to optimize the efficiency and reduce the MPP tracking time. SMVA technique with direct control method for centralized MPPT has been reported in [26].

This paper introduces, a novel concept based on SMVA in concurrence with fixed step direct control INC- MPPT method to extract maximum power and reduce the V_{PV} fluctuation for distributed PV system. Using SMVA, we examined the variability of V_{PV} among different DMPPT configurations with mismatching conditions to aggregate the plant output at varying timescales. For the proposed method, simulations in MATLAB/Simulink are performed and a comparative analysis with conventional fixed step direct control incremental conductance method is illustrated. The comparison results revealed that the proposed SMVA method provides better output by eliminating the steady state oscillations and high output with fast and accurate response under fast changing solar irradiation.

2. PHOTOVOLTAIC MISMATCH MECHANISM ANALYSIS

Mismatching conditions among PV array may occur due to differences in temperature, insolation, manufacturing tolerance, aging, *etc*. Regardless of the cause of mismatching, this situation manifest as an asymmetry in the current-voltage (I-V) and power-voltage (P-V) losses of PV system as depicted in Fig. (**1**). The output characteristic of PV system shows malfunctioning between different local maximum power point (LMPP), which causes an incorrect tracking of the global maximum power point (GMPP) [14].

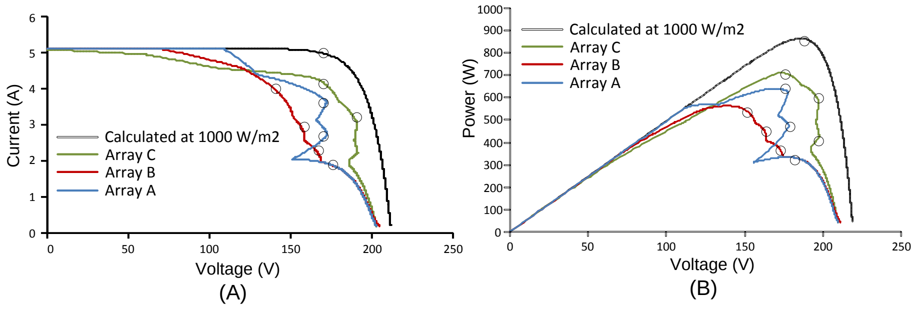

Fig. (1). (A) IV characteristic curves, **(B)** PV characteristic curves of PV array at 1000 W/m^2 and mismatch irradiance levels at array A,B and C.

This energy loss during LMPP to GMPP tracking is known as mismatching losses. These mismatching losses are very difficult to quantify, as it would be necessary to know the individual functioning of every single PV panel to measure them. Nevertheless, it is widely reported that this phenomenon can considerably reduce the performance of PV systems [24].

3. DISTRIBUTED MAXIMUM POWER POINT (DMPPT) METHODS

Continuously increasing demand and penetration of solar PV in power generation system provokes necessity of different new ideas for maximum power extraction from PV system by using different architectures. Distributed maximum power point tracking (DMPPT) is one of the most reliable and effective way to extract maximum energy from PV modules. Three different architectures of DMPPT are shown in Fig. (**2**). In Fig. (**2a**) PV modules individually connected with micro converter are directly connected with grid and where in, Fig. (**2b**) DMPPT with front end DC optimizer is connected with centralized grid converter which is also known as module integrated converters (MICs). The DC optimizer architecture is further divided into two different topologies known as adequate control structure and redundant control structure as shown in Fig. (**2b-1** and **b-2**), respectively. In MICs topology PV modules are connected with micro converters and their outputs are connected in series to form a string. MICs DMPPT architecture allow MPPTs individually to operate at different current levels and to inject its maximum potential power into the central converter. The third DMPPT configuration is named minimal power processing architecture as shown in Fig. (**2c**). In this topology small fraction of the generated power is processed by the DC-DC converters in order to adjust and balance the modules operating point [27 - 29]. Minimal power processing architecture is also further divided into three different topologies as shown in Fig. (**2c-1**) shuffling converters, Fig. (**2c-2**) returned energy current converters (RECC) with feed-back power flow, and Fig. (**2c-3**) feed-forward current converters.

4. PROPOSED METHOD

Previously, Stevenson and Porter [30], Hansun *et al.* [31, 32], and Popoola [33, 34] have proposed soft computing filters to overcome the limitations using discrete algorithms. But simple moving average method is still considered as the best method by many researchers due to its ease in implementation, reliability and applications. The proposed simple moving voltage average (SMVA) filter is also capable of completely eliminating the ripples in V_{PV}, while only using half the memory and less than half the number of operations per cycle (less computational overhead) as compared to previously used digital filters. So far SMA filter is effectively used by different scholars [35, 36] in engineering due to its characteristic to remove noise in random samples and compute the monitoring values to predict the future data. Furthermore, the moving average filter (MAF) is also well documented and explained in the discrete signal processing literature [37, 38].

The novelty of the proposed SMVA approach is its implementation in conjunction with traditional fixed step direct control INC method to control the ramp-rate of the V_{PV} output fluctuation under intermittent weather conditions. The proposed simple moving voltage average strategy is developed by following the equations -1 & 2. Where X(n) and Y(n) are input and output parameters of the SMVA respectively, and (N) is the size of the moving average window, which holds the number of samples of the input signal as per defined limit and operates by averaging the number of points from the input signal to produce each point in the output signal [39]. The longer the moving average, the more is the lag because they are based on past PV voltage data. Despite this lagging, moving average help smooth the V_{PV} action and filter out the noise. In contrast, a large moving average contains a number of past PV data that slow it down.

$$\sum_{n-(N-1)}^{n} X(k) = \sum_{n-N}^{n-1} X(k) - X(n-N) + X(n) \tag{1}$$

$$Y(n) = \frac{1}{N} \sum_{n-(N-1)}^{n} X(k) \tag{2}$$

A certain size of SMVA window is shown in Fig. (**3**), where (N) is moving along with the array size compiled from the input signal, one element at a time, and the average of all elements in the current window is the output of the SMVA. When calculating successive values, a new value comes into the sum and an old value drops out by replacing each data point with the average of the neighboring data points defined within the span.

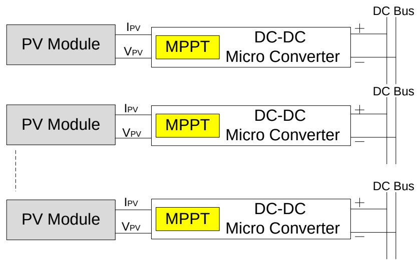

Fig. 2(a). Distributed maximum point tracking architectures with micro converters.

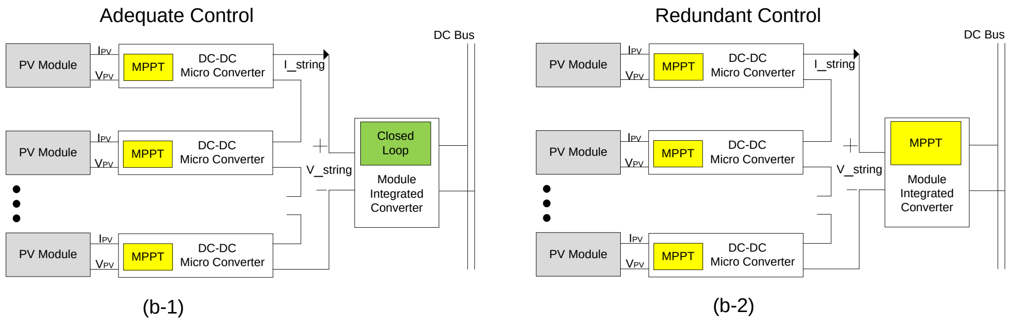

Fig. 2(b). Distributed maximum point tracking architectures with front-end DC optimizers.

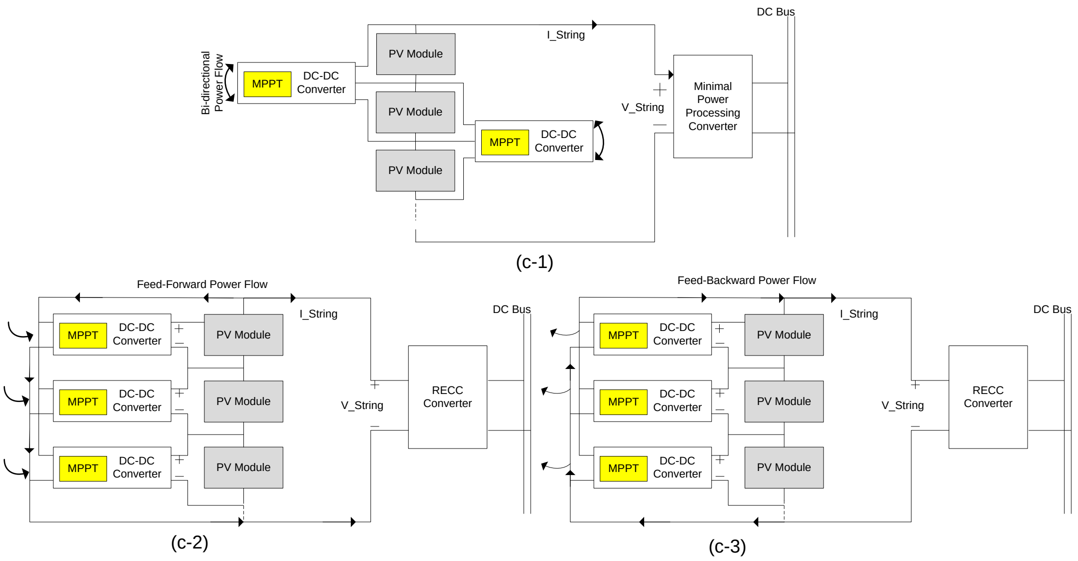

Fig. 2(c). Distributed maximum point tracking architectures with minimal power-processing: (**c-1**) shuffling converter with bi-directional power flow, (**c-2**) RECC with feed-forward flow and (**c-3**) RECC with feed backward flow.

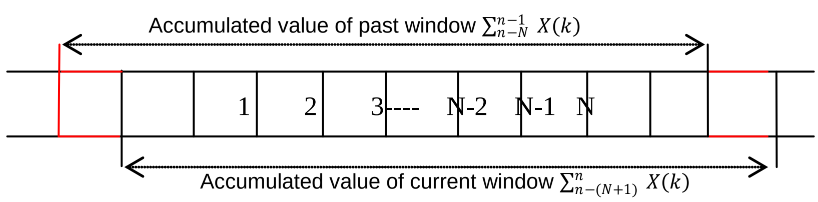

Fig. (3). Schematic of Simple moving average (SMA) [38].

In technical analysis, the number of sample points N is stochastic. It depends on non-uniformity of solar irradiance one is concentrating on. One characteristic of the SMVA is that if the data have an intermittent fluctuation, then applying SMVA of that period will eliminate that variation (the average always containing one complete cycle). If 20 measurements M_1 through M_{20}, are available, the successive 5 period simple moving averages, for example, are as follows:

$$SMVA_5 = \frac{M_1 + M_2 + M_3 + M_4 + M_5}{5}$$
$$SMVA_6 = \frac{M_2 + M_3 + M_4 + M_5 + M_6}{5}$$
$$SMVA_7 = \frac{M_3 + M_4 + M_5 + M_6 + M_7}{5} \qquad \textbf{(3)}$$
$$.$$
$$SMVA_{20} = \frac{M_{16} + M_{17} + M_{18} + M_{19} + M_{20}}{5}$$

Technically, it is not possible to compute a 5 period moving average until 5 periods data are available. For this reason, the first moving average in the above example starts with $SMVA_5$. In Fig. (**4**), an output signal of SMA is given where fluctuated (noisy) signal is smoothed by following the equation-3, with 20 data points.

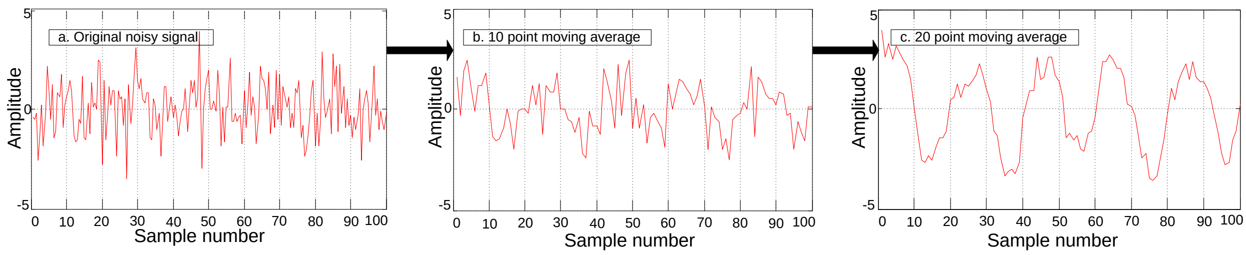

Fig. (4). SMA fluctuated (noisy) signal smoothing with different N point.

Furthermore, the flow chart of SMVA in conjunction with fixed step INC MPPT method is shown in Fig. (**5**) and model diagram is depicted in Fig. (**6**).

5. SYSTEM DESIGN DESCRIPTION

Total 600 watt PV system is designed consisting of three PV strings connected in series. Each string holds 2 PV panel in series producing 44 volts and 2.51 amperes which in turn is connected with another one in parallel producing 44 volts, 5.1 amps to generate approximately 200 watts under mismatching solar irradiation conditions. Furthermore, each PV string is connected with DC-DC boost converter known as micro converters with an input of 40 volts minimum to output of 90 volts maximum. The output of all the three micro converters is given as an input to module integrated converter (MIC) at input voltage range between 200-250 volts and output voltage range between 400-450 volts as shown in Fig. (**2b**).

6. SIMULATION RESULTS

To verify the effectiveness of the proposed technique for distributed MPPT (DMPPT) under mismatching solar irradiation conditions, simulations are performed in MATALB/Simulink according to Fig. (**2b-1** and **b-2**). MATLAB simulation model diagrams are shown in Fig. (**7**).

Different scenarios are performed to validate the effectiveness of the proposed SMVA model. At the first step adequate control model Fig. (**7B**) with constant temperature of 25C and mismatch (non-uniform) solar irradiance conditions range from 1000 W/m^2 to 400 W/m^2 at different time scales are applied to the fixed step direct control INC MPPT without the proposed SMVA technique at MIC to investigate V_{PV} voltage stability. After that by using the same parameters another simulation is performed with an additional block of the proposed SMVA model with fixed step direct control INC MPPT as shown in Fig. (**7A**). Simulation results are shown in Fig. (**8A**) V_{PV} before and Fig. (**8B**) after passing through SMVA block. It can be easily observed that the proposed SMVA technique performed better than the traditional fixed step direct control incremental conductance MPPT. Furthermore, Fig. (**8C** and **D**) are zoomed from Fig. (**8A** and **B**) at t= 0.03 to 0.04, where differences can be easily observed between Fig. (**8C** and **D**). In Fig. (**8C**), V_{PV} fluctuates between 44.77 to 45.0 volts with the fluctuation of 0.23 volts, whereas after passing through SMVA its fluctuation is between 44.9762 to 44.9816 and the fluctuation is reduced to 0.005 volts. Thus, the results clearly indicate that the proposed method works effectively to reduce the fluctuation and improve the stability of PV generated voltage, which improves not only MPPT controller processing speed but also the over all system efficiency.

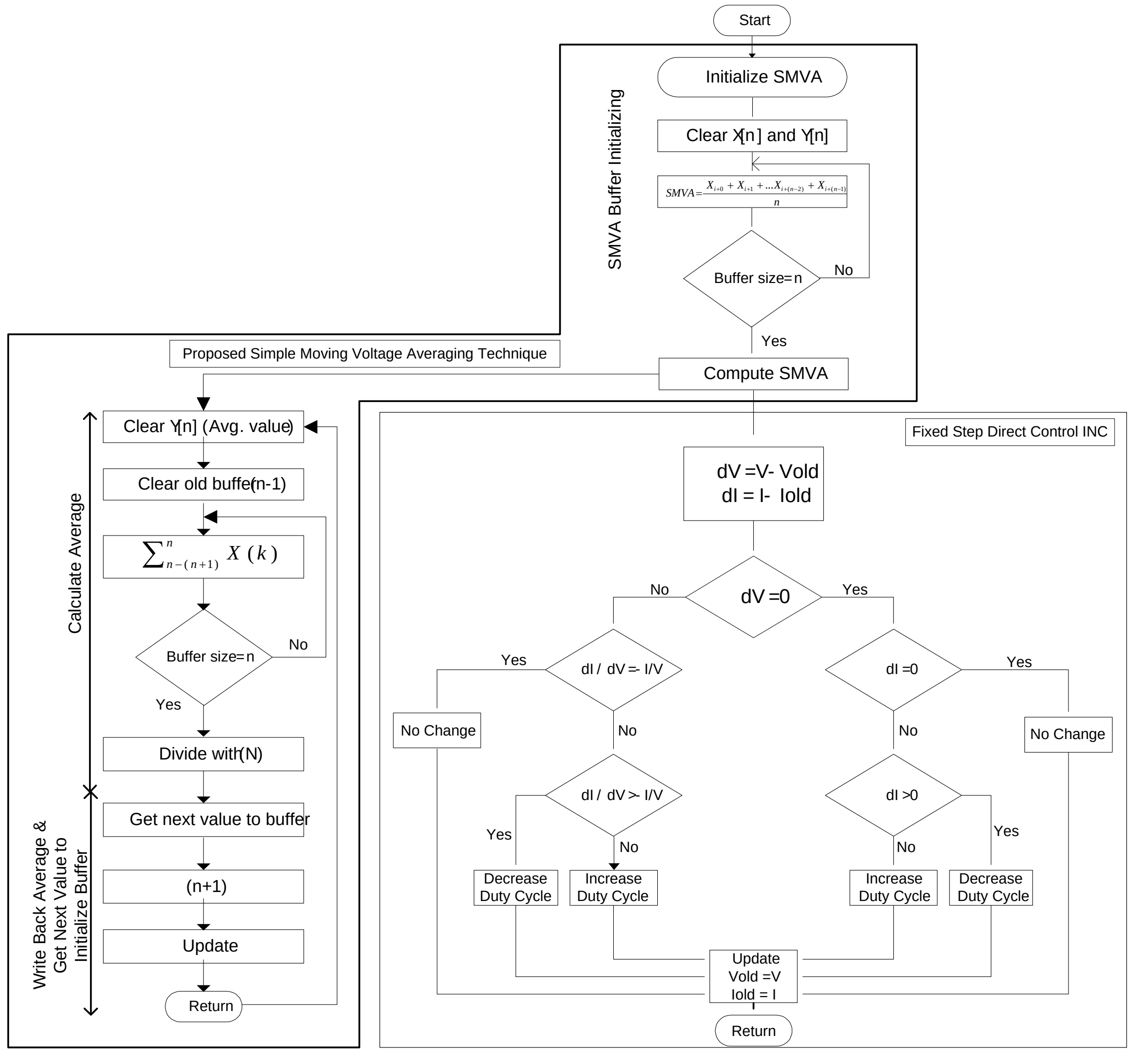

Fig. (5). Flow chart of proposed SMVA model with direct control incremental conductance.

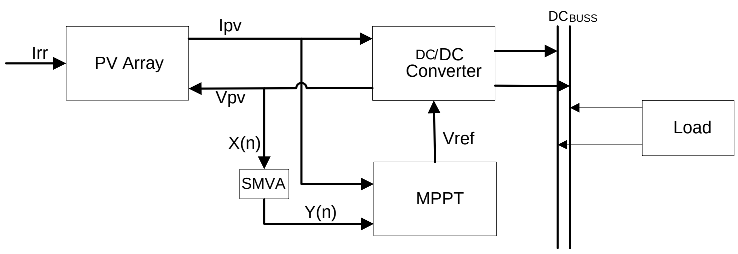

Fig. (6). Proposed SMVA with INC MPPT Connection.

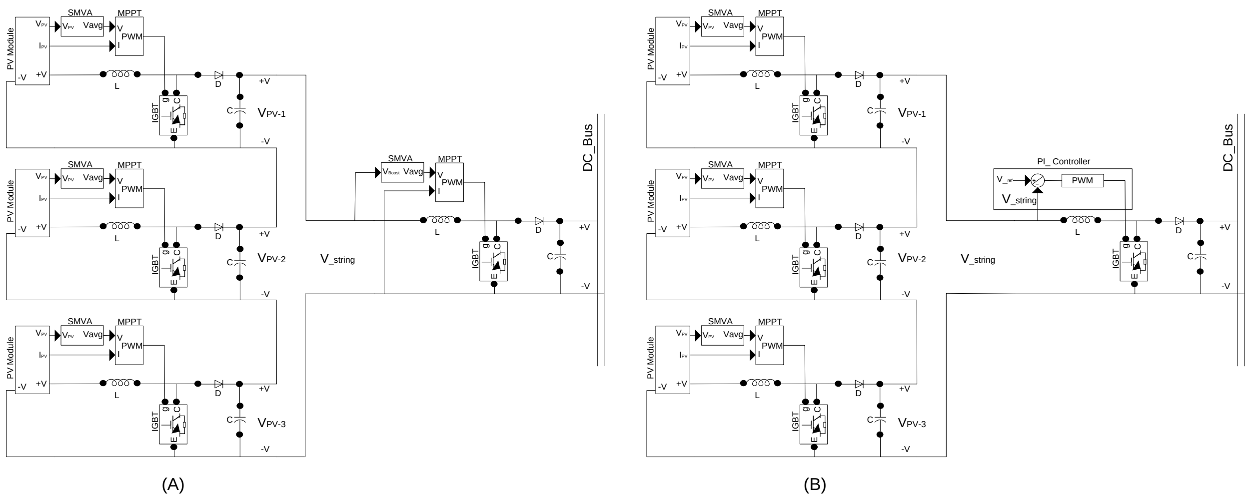

Fig. (7). Front-end DC optimizers MATLAB/Simulink model with **(A)** redundant control and **(B)** with adequate control.

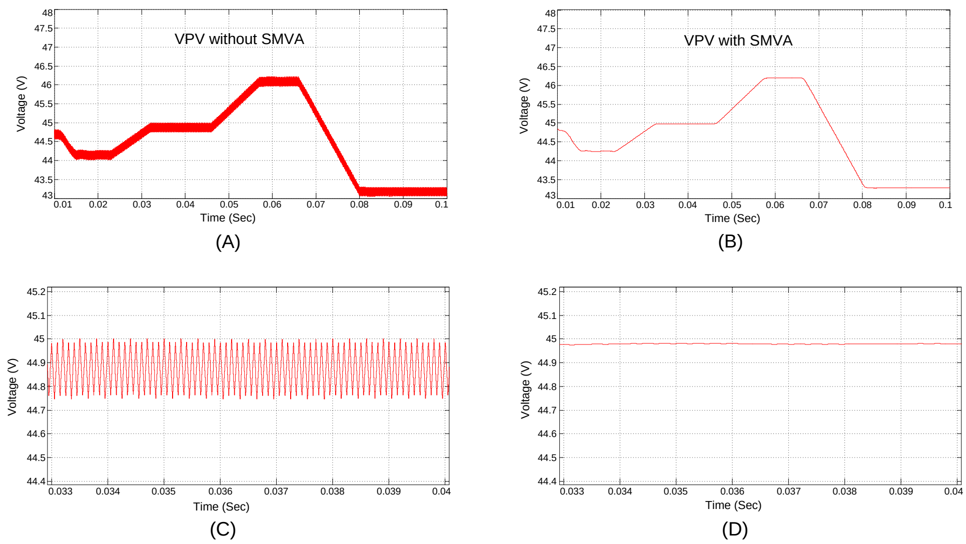

Fig. (8). V_{PV} as an input to MPPT **(A)** Without SMVA, **(B)** with SMVA and **(C)** & **(D)** are zoomed from **(A)** &**(B)**.

In Figs. (**9** and **10**), output voltage and power of all the three micro converters are depicted, respectively. In both the figures blue color is representing the output of proposed SMVA technique, whereas red is for traditional fixed step direct control INC method. It is very much clear in Fig. (**9**) that output voltage of the proposed SMVA technique is more stable during the solar irradiation fluctuations and mismatching conditions as circled in Fig. (**9A**-**C**). Simultaneously it has also been observed that during mismatching conditions the proposed SMVA technique produces higher output power because of extremely small ΔV=0.005 volts as shown in Fig. (**8D**) which not only improves MPPT tracking time but efficiency as well, as compared to fixed step direct control INC method.

Finally according to Fig. (**7A** and **B**) all the three PV strings are connected in series and the output of micro converters is given as input to module integrated converter (MIC). In this way four different scenario simulations were performed with complete PV system to examine the efficacy of proposed technique. In Table **1** the output voltage and Table **2**, the output power comparison between the proposed SMVA and fixed step direct control INC method are given. In both the tables it can be clearly observed that, the performance of the proposed SMVA technique is much better than fixed step direct control INC method at different duty cycle step size where Δd=(0.001, 0.003, 0.005 and 0.01). Even the output voltage and power of proposed techniques give greater efficiency at all the four different step sizs.

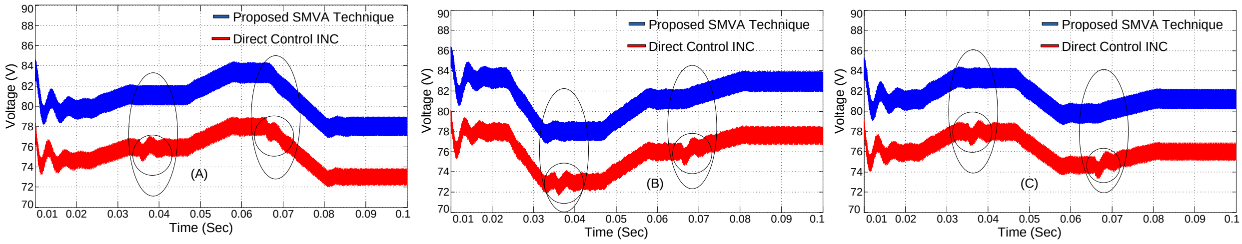

Fig. (9). Micro converters output voltage in **(A)** PV string-1, **(B)** PV string-2 and in **(C)** PV string-3.

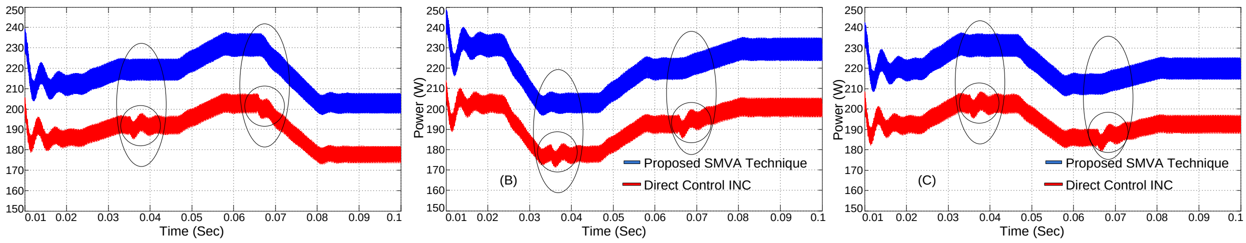

Fig. (10). Micro converters output power in **(A)** PV string-1, **(B)** PV string-2 and in **(C)** PV string-3.

Table 1. Output voltage comparison between proposed SMVA technique and INC at different duty cycles.

Output	Step size (Δd)							
	0.001		0.003		0.005		0.01	
	INC	Proposed (SMVA)	INC	Proposed (SMVA)	INC	Proposed (SMVA)	INC	Proposed (SMVA)
Maximum voltage (1kW/m^2)	402.94	407.84	403.38	407.84	401.29	407.84	395.2	403.23
Minimum voltage (0.2 kW/m^2)	369.29	373.4	369.5	373.4	367.4	373.4	362.03	369.19

Table 2. Output power comparison between proposed SMVA technique and INC at different duty cycles.

Output	Step size (Δd)							
	0.001		0.003		0.005		0.01	
	INC	Proposed (SMVA)	INC	Proposed (SMVA)	INC	Proposed (SMVA)	INC	Proposed (SMVA)
Maximum Power (1kW/m^2)	3082.7	3114.82	3051.11	3118.94	3010.37	3118.94	2933.82	3048.91
Minimum Power (0.2 kW/m^2)	2553.2	2612.39	2557.21	2614.3	2531.17	2614.3	2455.79	2555.88

Hence, simulation results proves that the proposed simple moving voltage average SMVA technique perform better at micro converters level in not only to reduce the fluctuation of PV generated voltage but also to improve the overall system efficiency during mismatching conditions because of very small |dP/dV| around maximum power point (MPP).

CONCLUSION

SMVA technique with fixed step direct control incremental conductance for distributed PV system under mismatching solar irradiance conditions is efficiently implemented. The MPP tracking time of the proposed method is less than that of the conventional methods under the same conditions. Furthermore, in terms of power level and stability of output voltage, the proposed method is not only able to track the MPP quickly without fluctuation but it also improves the dynamic and steady state performance of the PV system simultaneously. It has also been observed that, the combined use of the SMVA method improves INC's performances under constant and varying irradiation levels and has an ability to adopt intermittent environmental conditions. Even the proposed method can be easily implemented without any additional cost with respect to the fixed step direct control INC method.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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