

Analysis and Design of Distributed MPPT System Suitable for Non-Uniform Solar Irradiation

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Abstract—Under the nonuniform solar insolation conditions, the photovoltaic (PV) power system exhibits a peculiar property of multimodal i - p or v - p characteristic and results in obtaining multiple local maxima and a global maximum power point (MPP). Due to the presence of such non ideal power characteristic, the conventional maximum power point tracking (MPPT) algorithms cannot track the actual global MPP successfully. Hence, this paper investigates and discusses the application of distributed MPPT (DMPPT) technique of approach, in order to capture the optimum global MPP effectively. This is ensured by analyzing the system's dynamic performance and tracking abilities. Such condition is not only helpful in improving the tracking efficiency of the system, but also enhances the transient performance under rapidly changing nonuniform solar irradiation.

Keywords— Distributed MPPT, Local maxima, Global MPP, Transient performance, Multimodal.

I. INTRODUCTION

The growing concern about environmental problems and proliferating demand for low-cost energy harvesting, have created immense interest in utilizing one of the renewable sources available i.e. solar energy. In such photovoltaic (PV) installations, PV arrays are specifically formed by assembling multiple numbers of PV modules in various configurations such as series, parallel, series-parallel, etc [1]; and bypass diodes are placed anti-parallel with small groups of series connected cells or PV modules [2]. The purpose of adding the bypass diodes is to protect the cells (or the modules) from localized heating effect, and to improve the power production of whole string under nonuniform solar irradiation or partial-shading conditions [3], [4], [2]. However, it has been shown that, under partial-shading condition, addition of bypass diodes makes the voltage versus power characteristic of PV array multimodal [3]. Due to the existence of such multimodal power characteristics (i.e, multiple local maxima and a global maxima), it is very difficult to detect the true maximum power point (MPP), and that difficulty would even be enhanced further if there exists a high amount of fluctuating solar irradiation. It is, therefore very essential to track and operate in that optimum global MPP, since the lack of available maximum power point tracking (MPPT) techniques under such conditions may cause in reduction of dynamic performances and overall system's efficiency [5].

However, recently it has been reported that, under the partial shading condition, the maximum utilization of total available MPP power of a PV system or the overall system's

efficiency can be improved in a better way by considering the module integrated converter (MIC) structure, where the sets of PV modules is connected in series with dc-dc power conditioner to form a string, and each of those dc-dc converter is controlled by its own inbuilt MPPT controller [6], [7], [8]. The objective of such self-controlled MIC architecture is to facilitate the operation of PV modules at different current levels thus maximizing the energy harvesting capability; and to improve the system robustness and reliability further [8], [6], [9]. However it was observed that, in most cases, the existing traditional MPPT methods are completely relied upon the so-called search-based Perturb & Observe (P&O) approach. They are implemented in digital platform by injecting high-frequency small-amplitude perturbations into the system to detect the sign of the power gradient. In [10], authors showed that under such situation the dynamic performance of a PV arrays (in terms of transient and steady state responses) can be highly affected by the frequency and amplitude of that perturbation or change. Hence, better steady-state performance can only be achieved by selecting the smallest possible value of the perturbation amplitude. This choice of perturbation amplitude however may cause to deteriorate the tracker's performance or transient response tremendously in the presence of frequent changes in solar insolation [11]. Furthermore, since the total efficiency is only determined by the product of both MPPT controller and power processing unit, it may thus reduce the efficiency of the overall system, which cannot be improved simply by increasing the perturbation amplitude. Because, greater the irradiation variation to be tracked, larger should be the perturbation amplitude. Further increment in perturbations even becomes imperative if array voltage is affected by any disturbance. It may result in some undesirable low-frequency or sub-harmonic oscillations in the system [10]. Furthermore, the dedicated control algorithm [2] proposed for extracting such optimal MPP is not self-sufficient. They have also some drawbacks like increased computational load [12], [13], complexity in hardware realization, and prolonged dynamic response which results in reduction of overall system's efficiency [14].

In order to overcome such aforementioned drawbacks, recently various MPPT techniques have been proposed and successfully implemented for both grid-connected as well as stand-alone PV systems [15], [16], [17], [18], [11], [19]. Among them, the sliding-mode (SM) controlled based MPPT techniques are efficient not only due to nullifying the low-frequency disturbances [20], but also for

achieving the fast dynamic responses [16], [17], [11]. However, since they require a P&O based searching MPPT algorithm [31], [32],[33] therefore cannot be quite suitable for tracking MPP under rapidly changing irradiation conditions; especially when one considers its dependency on rapidly changing solar insolation and temperature, and when there also exist multimodal.

By taking into consideration the above mentioned views, this paper proposes an alternative way of extracting global MPP of a multimodal stand-alone PV system. This is achieved by using the concepts of a simple but robust analog MPPT controller [21], and module integrated converter (MIC) architecture [22], [4], [23]. The major advantages of this approach is that, it is an analog SM Controlled technique which is fast and relatively simple to realize in hardware and it inherently acts as a global attractor at MPP. Moreover, the modular converter architecture also increases the energy harvesting during the partial shading conditions. In order to illustrate these points, the paper is organized as follows.

II. AN OVERVIEW OF ANALOG MPPT METHOD

In order to study the effectiveness of this technique, we first revisit the behavioral characteristics of PV array under rapidly changing solar irradiation.

A. Multimodal Characteristics of PV Array:

Real photovoltaic systems mainly consist of multiple numbers PV modules and they are connected in various possible topological configurations [1]. Usually cells in such type of modules are assumed to be equal or of same type, but such assumption is not valid if some manufacturing tolerances and aging-related parametric mismatches are taken into consideration. Moreover, due to nonuniform solar irradiance and different possible orientation of module configurations, some cells in module or few combined modules in string may operate in excessive reversed-bias voltage. It reduces the effective output power and produces very high photo-current, which may cause severe damage to the series cells due to localized heating. In order to overcome this problem, anti-parallel bypass diodes are connected across a group of series cells. The main idea is, to limit the current by turning it on in reversed-bias region and provides an alternate current path to flow, so that, cells of a module no longer carry the same existing current as the shadowing one [24], [25]. Normally, this can be achieved by doing a one to one connection between each bypass diode and sub-panel PV string [22]. However, this measure makes the voltage versus power characteristics multimodal and results in existence of multiple local maxima, and one true global maximum. Due to the presence of such multimodal characteristics, tracking of global maximum is not an easy task. One cannot achieve it simply by calculating the power gradient dp/dv (where p is the PV array power and v is the array voltage) or, by iteratively changing the duty ratio or reference voltage of the intermediate dc-dc optimizer. Moreover, since the optimum MPP changes its value and shifting its position suddenly (say, from point **A** to **B** and vice-versa which is depicted in Fig. 1) under rapidly

changing weather conditions, it is very difficult to track and detect such global point.

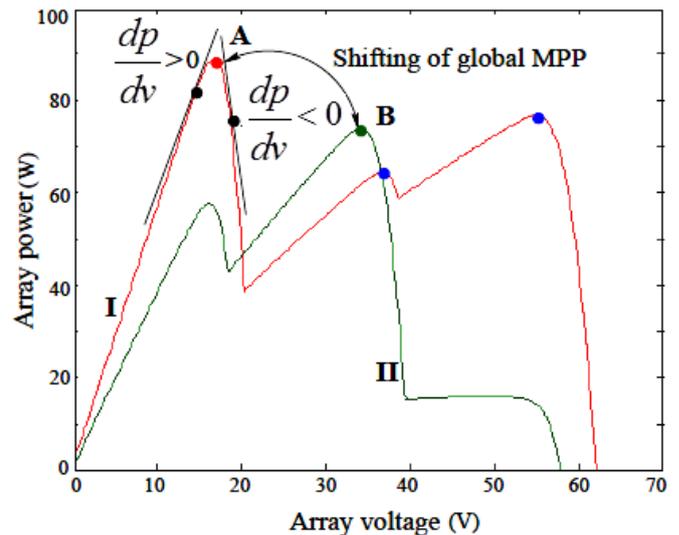


Fig. 1. Representative diagram showing v-p characteristics of PV array under different values of nonuniform solar irradiation G and ambient temperature T_a . (I) when $G = (1500, 500, 400)$ W/m² and $T_c = 25^\circ\text{C}$, and (II) when $G = (1000, 100, 600)$ W/m² and $T_a = 35^\circ\text{C}$. The other parameter values are mentioned in Table I.

B. Choice of DC-DC Converter and MIC Architecture:

The conventional centralized MPPT techniques which were able to maximize the energy yielded by PV array, under unimodal operating conditions, may not be quite suitable [26]. They may converge to local maxima without detecting the true MPP, and thus, results in a significant power loss unless the module output voltage is adjusted accordingly. While dedicated MPPT algorithms proposed for such inhomogeneous operating condition [12], [13], [30] are also too complex to implement. They are slow enough and require more cost for fabrication process [27], [29].

However, recently it has been depicted that, without tracking of such global MPP, the optimum power under partial-shading conditions can be efficiently extracted by using the concepts of decentralized MIC architecture [22], [4]. In which, the dc-dc converters like buck, boost, buck-boost converters are independently controlled. They are connected either in series or in parallel with a group of series connected cells to provide a better tracking capability under any parametric mismatch or disturbances. However, the choice of these converters topology is not unique. Although previous investigation on employing boost converter in parallel configuration had shown some attractive features, that is, the ability to increase the output voltage with less number of converter modules; but their limited operating region governed by PV module’s characteristics strongly restricts the domain of application areas respectively [28]. While in series configuration, small size and low cost buck converter operated in high switching frequency is a better choice. Because, large number of modules used in utility-based installations are inherently adding the voltages together without requiring an additional step-up from the power converters [22].

III. ANALOG TECHNIQUE FOR DMPPT

A. System Architecture:

With these views discussed above, this paper proposes an analog based DMPPT technique as shown in Fig. 2 (a). It mainly consists of three PV modules having three autonomous series-connected synchronous buck converters or optimizers [22], and each of them comprises of an input capacitor C, an inductor L, and two controllable switches S₁ and S₂ governed by a simple and robust analog MPPT controller. The idea of creating such autonomous series architecture is, not only to extract the global peak power over a wide range of output array voltages, but also to detect quickly under any disturbances (see Fig. 1). This can be easily achieved by controlling each power optimizer independently, so that, the output voltage V₀^g (where g = 1, 2, 3) can vary according to their maximum extracted power. In other words, each module voltage v_g is forced to update iteratively in order to track and converge at its maximum MPP voltage, which is proportional to the maximum power [4], [22]. Therefore, under such consequences, the total output voltage of the series connected DMPPT system can be expressed as a sum of all MPPT optimizers as:

$$V_0 = \sum_{k=1}^3 V_0^g$$

where V₀^g is the MPP voltage of g-th optimizer. Here, this is obtained by using analog controllers [21] and they are realized by sensing both module voltage v and current i_{pV}, and thereby obtaining the value of power p by using a multiplier circuit. The output voltage and power of each module are then fed to the analog differentiators to order to detect the trend of v and p respectively. Moreover, the signals after the differentiators dv/dt and dp/dt are fed to the comparators C₁ and C₂ having zero reference values. The comparators essentially generate the binary signals S_p, S_v ∈ (0, 1), which are further used as the input states of exclusive-OR circuit and then sampled further by employing S-R flip-flop clocked at constant switching frequency having time period T. However, the functionality of controlling blocks such as; differentiators, comparators and switching, and their mathematical description are discussed in the next section.

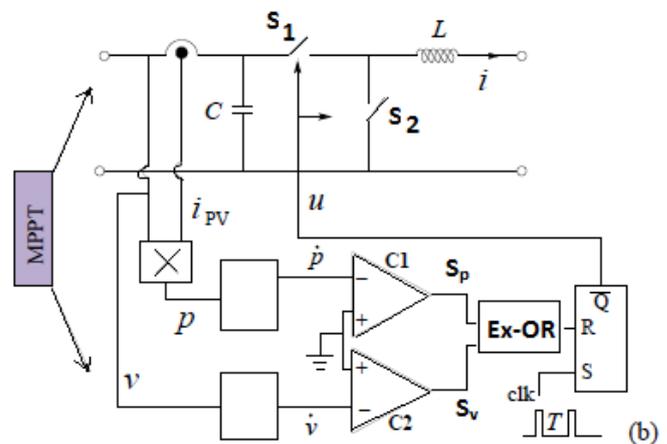
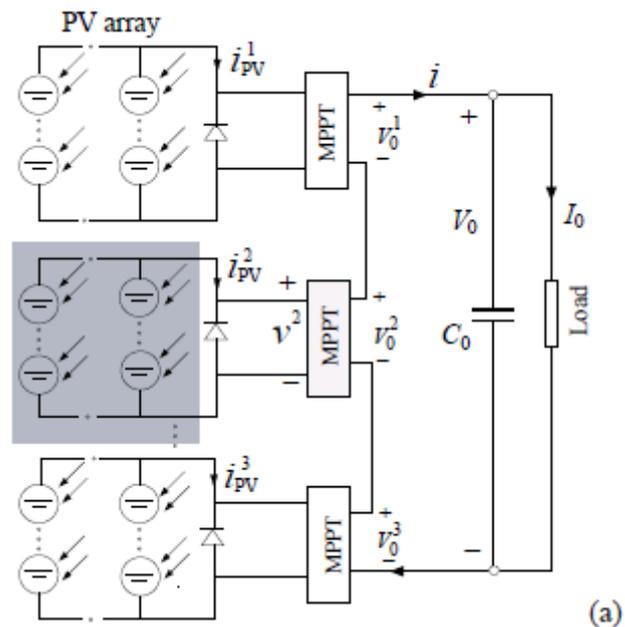


Fig. 2 (a) & (b) depicting DMPPT with MIC architecture. (b) Zoomed-in version of proposed MPPT system. The components values are as depicted in Table I respectively

B. Dynamics under Analog MPPT Controller:

To understand the applicability of such MIC based analog MPPT controller in sequential process, we therefore first concentrate and discuss on single time-invariant v-p characteristic by neglecting the effects due to aging-related parametric mismatch. Ideally, the MPP of a PV array may vary with temperature parameters as (y₁, y₂, y₃...); we can easily write the time derivatives of each module power dp/dt, as shown below:

$$\frac{dp}{dt} = \frac{dp}{dv} \frac{dv}{dt} + \frac{dp}{dy_1} \frac{dy_1}{dt} + \frac{dp}{dy_2} \frac{dy_2}{dt}$$

Where n = $\frac{dp}{dy_1} \frac{dy_1}{dt} + \frac{dp}{dy_2} \frac{dy_2}{dt}$ which is denoted as noise parameter. Due to this parameter, an accurate estimation of module voltage at MPP V_{mpp} is not trivial.

1. *Obtaining dp/dv Using Analog Differentiators:*
 One should therefore, require a continuous adjustment of module output voltage v in order to achieve the MPPT efficiently. It is important to note that for a unimodal $v - p$ characteristics, the MPP (V_{mpp} , P_{max}) can only be obtained theoretically if the condition $dp/dv = 0$ is satisfied. The MPP can be successfully captured if it acts as a global attractor; that is, irrespective of any initial voltage, it will always forced to converge towards the MPP if it satisfies the conditions (see Fig. 1):

$$\frac{dp}{dv} > 0 \text{ if the condition } v - V_{MPP} > 0 \text{ is satisfied;}$$

$$\frac{dp}{dv} < 0 \text{ if the condition } v - V_{MPP} < 0 \text{ is satisfied;}$$

Similarly, $\frac{dp}{dv} = 0$ if the condition $v - V_{MPP} = 0$ is satisfied further.

Depending on the value of power gradient dp/dv , the voltage across the input capacitor v will be increased or decrease towards the V_{mpp} point. If $dp/dv > 0$ is satisfied, v will increase. Otherwise, it will decrease towards V_{mpp} . The simplest functional form that would confirm this objective can be expressed in terms of differential form as:

$$\frac{dv}{dt} = -c(v - V_{mpp})$$

where c is a positive number associated with the dynamic response of the MPPT controller. After substituting (4) into (2), and using the switching logic from (3), we therefore obtain a control law:

$$\frac{dp}{dv} = \frac{p}{v} \text{ ----- (1)}$$

having the control algorithm $\dot{v} = c \frac{p}{v}$ which is mentioned in [21], is realized further.

2. *Detecting MPP Using Combinational Circuit topologies:*

However, realization of such algorithm $\dot{v} = c \frac{p}{v}$ in practice is

slightly difficult due to the presence of an algebraic loop. Since v appears on both sides, it would manifest a high frequency oscillation. One should need an analogue divider circuit, which is again undesirable. Moreover, divider circuit also causes many other imperfect operations and even, singularity problem when v becomes zero (in this case, it happens only when $v = V_{mpp}$). While by rearranging the

desired control algorithm into the form $\dot{v} = c p$ does not help either. This is because; squaring of v in fact not only destroys the useful information of its sign, but also increases the singularity problem at MPP. However, the problem of singularity can be resolved by redefining the control law (1) as

$$\frac{dp}{dv} = \text{sign}\left(\frac{p}{v}\right) = \text{sign}(B)$$

$$\text{Where } \text{sign}(B) = \begin{cases} +1 & \text{if } (B < 0) \\ -1 & \text{if } (B > 0) \end{cases} \text{ ----- (2)}$$

The above function can be easily realized by employing comparators followed by an exclusive-OR gate (see Fig. 2(b))

3. *Operation at Constant Switching Frequency:* Due to this switching logic (2), the trajectory of the modular converter system tends to travel towards B and in the neighborhoods of B it disperses with an infinitely high switching frequency. In other words, (2) contains the information on whether v should be increased or decreased to approach the actual MPP. Since Sign function in (2) has a discontinuity at the MPP, one cannot expect an equilibrium point at steady-state, rather the system dynamics is governed by high frequency thus resulting in more switching losses and reduces their total life span. Although such type of high frequency switching can be easily confined by incorporating a latch circuit into the controller structure (see Fig. 2(b)), but it may further cause to exhibit a rich complex oscillatory behaviors around the MPP which is shown in Fig. 3 respectively.

TABLE I

SPECIFICATION OF SELF CONTROLLED SUB MODULATED PV SYSTEM FOR NOMINAL IRRADIATION $G=1000 \text{ w/M}^2$ AND TEMPERATURE $T=25^\circ\text{C}$

Parameters (Buck Converter)	Values	Parameters (PV Array)	Values
Inductance L	10 μ H	Short circuit current Isc	3.8A
Input Capacitance C	100 μ F	Open circuit Voltage Voc	21.1V
Output Capacitance C _o	1000 μ F	Temperature Constant of Voc	-0.8 V/K
Switching Frequency fs	10-10 ³ kHz	Temperature Constant of Isc	0.0065 A/K
Load resistance	2-25 Ω	V _{mpp} , I _{mpp}	17.1V , 3.5A

C. *Modeling of single module PV system:*

In order to find the equivalent slow-scale dynamics of proposed controlled photovoltaic system, we consider a single module PV system as shown in Fig.4 and define the switching surface, $B = dp/dv$, as a function of input capacitor voltage v_C and inductor current i_L keeping the switching frequency fixed. Also, assume a large size capacitor (or battery load) is connected at the output terminal, so that, the system's output voltage is nearly constant or semi-constant.

Under this assumption, the dynamics of modular PV system can be described by set of differential algebraic equations as follows,

$$\frac{dv}{dt} = \frac{i_{pv}(v)}{C} - \frac{i}{C}u$$

$$\frac{di}{dt} = \frac{v}{L}u - \frac{V_0}{L}$$

where C_0 is the output capacitor to keep the terminal voltage V_0 constant or semi-constant, and u is the discontinuous control

$u=1$ for S is on and $u=0$ for S is off.

governed by switching logic (2).

While submodule PV array current $i_{pv}(v)$ is defined by a nonlinear algebraic equation

$$i_{pv}(v) = I_g - I_{sat} \exp(A)v - 1 + B$$

Where $A = \frac{v + i_{pv}(v)R_s}{\alpha V_T}$; $B = \frac{v + i_{pv}(v)R_s}{R_p}$

having panel saturation current I_{sat} , electrical charge q , Boltzman’s constant K , diode ideality constant a , thermal voltage $V_T = nsKT_c/q$ with ns cells in series and $p - n$ junction temperature T_c (in Kelvin), and the equivalent series and parallel resistance of the PV cell R_s and R_p , respectively.

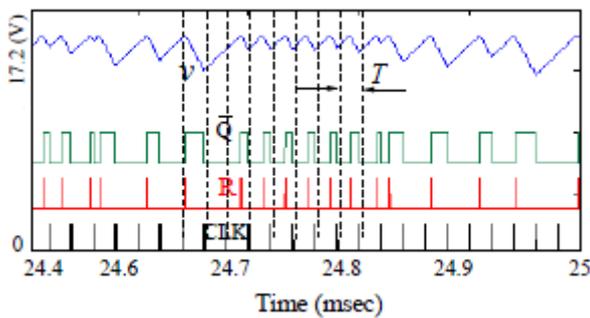


Fig. 3 Fast Scale Oscillatory behaviour of v under constant switching conditions.

Based on this formulation analysis, the dynamics of PV system using state equations mentioned above for DC-DC converter can be further written in compact form as below:

$$\frac{d}{dt} \begin{pmatrix} v \\ i \end{pmatrix} = f(v, i) + g(v, i)u$$

Where $f = \begin{pmatrix} i_{pv}(v)/C \\ -V_0/L \end{pmatrix}$; $g = \begin{pmatrix} -i/C \\ v/L \end{pmatrix}$

f and g explains about the state of the system.

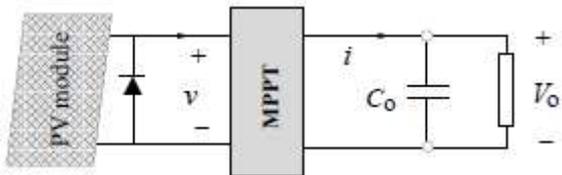


Fig. 4. Self-controlled Modular optimizer

IV. PERFORMANCE ANALYSIS

By choosing the filter parameters of dc-dc power optimizer and the load resistance, the dynamic performance in terms of transient and steady-state responses of controlled PV system are then investigated further to show its superiority over the commonly used MPPT controllers. Moreover, a conventional incremental-conductance (InC) based MPPT algorithm is considered to compare its tracking performance for equal irradiation fluctuations. Fig. 5 shows that under sudden irradiation fluctuation the proposed MPPT technique not only exhibits considerably smaller maximum peak overshoot without losing the steady-state performance or robustness of the system (especially at low value of solar insolation), but also takes less than 2 msec to settle, which is quite faster than that of InC algorithm.

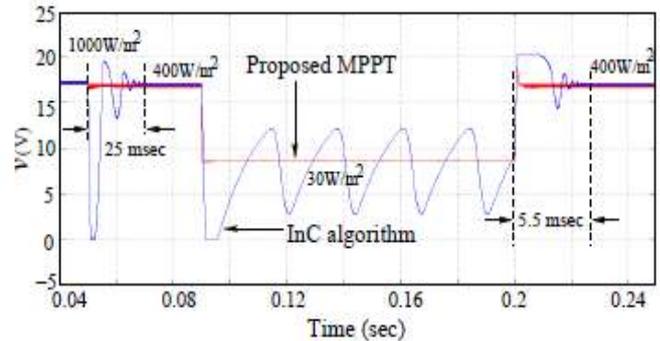


Fig. 5 Comparison of tracking performance under sudden irradiation fluctuations.

V. CONCLUSION

Nowadays, PV technology plays a phenomenal role as a clean, pollution and maintenance-free electrical energy source. Although many researchers have focused on MPPT algorithms for PV source applications, fewer have studied about the problem of partial shading effect for PV systems. Partial shading is one of the technical issues to be dealt with, not only because of under nonuniform irradiance, but also because traditional MPPT techniques can result in the inability to detect the true MPP of the PV source. This paper proposed a self-controlled MIC based DMPPT method for a partially shaded PV arrays. The technique has been analyzed by simulating under non homogeneous irradiance. The proposed DMPPT system also significantly improves the harvesting capacity of the maximum possible amount of energy of the PV sources under uniform and non-uniform irradiances respectively..

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