Current collector optimizer topology to improve maximum power from PV array under partial shading conditions

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Abstract. The power generated from photovoltaic (PV) series-parallel (SP) array topology is greatly harmed by partial shading phenomenon. Power losses due to shadow may reach up to 30% of total power expected, depending on PV array topology and climate conditions. This paper presents a current collector optimizer (CCO) topology to enhance the power harvest from the PV array under partial shading conditions. A comparative study is carried out using MATLAB/Simulink in order to illustrate the effectiveness of the proposed topology. According to results, the global maximum power generated by CCO topology is substantially increased compared to traditional SP array topology, while the mismatch power losses are significantly reduced during different shading patterns.

1. Introduction

Over recent decades, the problems of energy shortage and environmental contamination have become critical research issues worldwide. Thus, the trends of employing distributed generation systems (DGSs) based on renewable energy are drawing more and more attention to reduce energy crisis and carbon emission. Among all various DGSs, solar photovoltaic (PV) systems are rapidly growing in electricity markets and are expected to continue this trend throughout the near future. Nevertheless, the unit cost of energy obtained from PV systems is still high; accordingly, this paper focuses on decreasing the costs by increasing the energy efficiency of the PV system [1–4].

Central inverter technology is one of the most common topologies of the PV installation, which interfaces a large number of panels that configured in series-parallel (SP) combination to the grid. However, the SP array topology suffers from partial shading effects. Due to the presence of bypass diodes, the PV array characteristics are deformed and exhibit multiple peaks, one of which is global. The power losses due to shadow may reach up to 30% of total power expected, that forces researchers to look for different technologies for the interconnection of the PV modules [5,6].

One of the solutions to partial shading effects is AC-module inverters, where the individual control for each module improves the energy efficiency of PV system. The prime downsides of AC-module inverters are high expenditure and increased system complexity since the number of micro-inverters is proportional to that of PV modules [7–9]. Other solutions to eliminate local maximum power points (MPPs) and increase maximum power are using differential power processing (DPP) converters and voltage or current equalizers. A portion of the produced power of unshaded modules is transmitted to shaded ones so that all the modules operate close to each individual MPP. Several types of DPP converters and equalizers have been created and presented in literature [7,10–16]. In fact, the number
of switches in DPP converters and equalizers can demonstrate a good hint about system intricacy due to each switch requiring a controller circuit including its accessories [8].

This paper aims at evaluating the performance of 10 kW PV array by using current collector optimizer (CCO) topology. The main objectives are to improve the power extracted from PV array during partial shading condition, avoid the misleading power losses due to local MPPs and eliminate the power losses associated with circulating currents between PV generators. A comparative study is provided to illustrate the effectiveness of the proposed topology.

2. Current collector optimizer (CCO) concept

A schematic of the proposed CCO topology is as shown in Figure 1. As can be seen, every eight modules or substrings are connected to CCO as a single stack and then these stacks may be connected in series-parallel combination to the grid through an inverter. Figure 2 illustrates the circuit diagram of the CCO. This circuit is a modified circuit that is used to collect the current from MHD-generator electrodes’ which have different voltages [17].

![Figure 1. A schematic diagram of the CCO topology.](image1)

![Figure 2. The circuit diagram of the CCO.](image2)

As depicted in Figure 2, all PV generators negative terminals’ are connected to a common negative line while each positive terminal is connected to thyristor-bridge and then all bridges are gathered in common positive line. The H-bridges are interconnected with each other through eight capacitors and transformers. The bridge valves’ are triggered as in ordinary H-bridge. Therefore, the upper and lower capacitors between adjacent PV generators alternatively change their polarities every half cycle. Forced commutation of thyristors is carried out during discharge of coupling condensers.

The coupling transformers are symmetrically linked to each other concerning the power production section center. Their function is to compensate the voltage difference among parallel PV modules; under mismatch condition, to a current consolidation point $v_{stak}$. The total power of a single stack
CCO is defined by the sum of all PV generator current and the average voltage of the PV modules, further details about operation of CCO can be found in [8,9].

\[
V_{\text{stack}} = \frac{1}{8} \sum_{p=1}^{8} v_p
\]

(1)

\[
i_{\text{stack}} = \sum_{p=1}^{8} i_p
\]

(2)

\[
P_{\text{stack}} = v_{\text{stack}} \times i_{\text{stack}}
\]

(3)

Where \(v_{\text{stack}}\) is the stack voltage, \(i_{\text{stack}}\) is the stack current, \(P_{\text{stack}}\) is the stack power, \(i_p\) are the currents generated by PV modules, and \(e_p\) are the voltage across PV modules.

3. Simulation example

In this section, a case study is performed on MATLAB/Simulink to compare the performance of CCO topology and SP array topology under partial shading conditions. For the purpose of simulation, a commercial PV module, i.e. Suntech Power PLUTO250-wdb, has been selected. The most important parameters of this module are given in Table 1. The PV module is represented by single exponential model as described in references [18,19] and the corresponding characteristics at different irradiation levels are shown in Figure 3.

| Parameter                  | Value |
|----------------------------|-------|
| Output power at MPP        | 250 W |
| Voltage at MPP             | 30.8 V|
| Current at MPP             | 8.12 A|
| Open circuit voltage       | 37.1 V|
| Short circuit current      | 8.75 A|

Table 1. Module parameters.

Figure 3. Characteristics of module at different insolation levels: (a) I-V curves and (b) P-V curves.

Two simulation models are setup for 10 kW array farms of 40 modules. The first model is a traditional SP array farm constructed as 8 strings each of which consists of 5 series modules with bypass diodes, while the other is 5 stacks of CCO are connected in series as shown in Figure 3. Different shading patterns, as shown in Figure 4 are defined to represent the passage of clouds over the PV array farm. Each pattern consists of two different irradiation levels; the gray indicating the shaded module that receives solar irradiation of 0.6 kW/m² whilst the white indicating full illumination of the module, that is, 1kW/m².
Figure 4. Diagram of different shading patterns.

For all patterns, the temperature is assumed invariant at 25°C. The output characteristics of the array farm are found by sweeping the terminal voltage from 0 to array open circuit voltage that is 185.5 V. Figure 5(a) through Figure 5(j) show the corresponding P-V characteristics of models during different shading patterns, indicating the global MPP in each model.
Figure 5. The P-V characteristics at different shading patterns.

In case of conventional SP array topology, the P-V characteristics exhibit multiple MPP, involving a global and local MPPs, which increases the probability of false tracking of MPP and requires an advanced MPPT algorithm to track the global MPP. Also, the bypass diodes have not affected the characteristics for shading scenarios no. 1 and 10 because of identical illumination of complete columns. On the other hand, in case of CCO topology, the P-V characteristics have a unique MPP which easy to follow by a simple MPPT algorithm.

Table 2 provides a summary of simulation results, reporting the expected power from the array and the shading power losses for the two models under aforementioned shading scenarios. For each scenario and model, Table 2 also reports the corresponding global maximum power generated (GMPG) and mismatch power losses.

| Shadow No. | Expected array power | Shading power losses | Global maximum power generated (GMPG) | Mismatch power losses |
|------------|----------------------|----------------------|---------------------------------------|----------------------|
|            | SP                   | CCO                  | SP                                    | CCO                  |
| 1          | 8000                 | 2000                 | 7961                                  | 7996                 | 39         | 4          |
| 2          | 8000                 | 2000                 | 6361                                  | 7996                 | 1639       | 4          |
| 3          | 9200                 | 800                  | 7910                                  | 9147                 | 1290       | 53         |
| 4          | 9200                 | 800                  | 8158                                  | 9110                 | 1042       | 90         |
| 5          | 8000                 | 2000                 | 6399                                  | 7996                 | 1601       | 4          |
| 6          | 9000                 | 1000                 | 8108                                  | 8996                 | 892        | 4          |
| 7          | 8000                 | 2000                 | 6399                                  | 7996                 | 1601       | 4          |
| 8          | 8000                 | 2000                 | 6399                                  | 7996                 | 1601       | 4          |
| 9          | 9000                 | 1000                 | 7208                                  | 8996                 | 1792       | 4          |
| 10         | 6000                 | 4000                 | 5967                                  | 5992                 | 33         | 8          |

Expected array power is the sum of maximum power of the array modules’ at a given irradiance. It can be calculated from Figure 3, where the forecast maximum power generated from a single module at 1kW/m² is 250 W and at 0.6 kW/m² is 150 W. Shading power losses are the difference between the rated power of the array at standard test conditions (STCs) and expected array power at given atmospheric conditions. The rated power of the array at STCs can be calculated from datasheet, whereas the GMPG is obtained from Figure 3. A graphical illustration that compares the GMPG for both models during aforementioned shading patterns is as shown in Figure 6(a). As can be seen, the GMPG for CCO topology is better than SP topology for all shading scenarios.

Mismatch power losses are the difference between the expected array power and GMPG at given shading condition. The bar chart shown in Figure 6(b) gives a comparative mismatch power loss for the two models under different shading scenarios. As can be seen, the recorded mismatch loss for CCO model is comparatively low with respect to SP model. Another significant power loss that associated with SP model are the misleading losses due to the false tracking of MPP tracker. These additional losses are not found in CCO topology because the P-V curve has only one global MPP.
4. Conclusions
A CCO topology to enhance the power extracted from PV array under partial shading conditions have been presented in this paper. The traditional SP array topology was stacked through five stacks CCO, which were connected in series. Computer simulations were carried out on MATLAB/Simulink in order to assess the optimizer performance. According to results, the global maximum powers generated by using CCO topology were significantly increased compared to conventional SP array topology under different shading patterns. Subsequently, the mismatch power losses were substantially decreased as well as energy efficiency increased. In addition, local MPPs that found in case of SP approach were successfully eliminated by using the CCO circuit. Hence, the optimizer did not suffer from misleading power losses and only required a simple MPPT algorithm to follow the MPP under different environmental conditions.

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