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Shading mitigation techniques: State-of-the-art in photovoltaic applications

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ABSTRACT

The Photovoltaic (*PV*) systems are gaining popularity for both standalone and grid connected applications. These systems offer benefits of being static, modular, environmental friendly; and converts light from the Sun, which is perennial source of clean and green energy. The energy conversion in *PV* system is although instantaneous, yet less efficient because of optical and electrical losses. The optical loss caused by *partial shading* reduces a *PV* system output greatly, if not properly mitigated. The shading mitigation techniques are therefore an integral part of *power conditioning unit* of all large *PV* systems. These mitigation techniques ensure global peak operation of *PV* plant under undesirable condition of partial shading. Multitudes of such mitigation techniques are available in literature; though each one of them exhibits some vulnerability. This paper therefore intends to present state-of-art in existing shading mitigation techniques. The review presents rationale behind the reported techniques and compares them on some common parameters of *control strategy, granularity, accuracy, tracking speed, complexity, efficiency and number of sensors* employed. This comprehensive review on shading mitigation techniques would certainly help researcher to select appropriate *MPPT* techniques for a given *PV* application.

1. Introduction

Rising concern over detrimental effect caused by irrational use of conventional sources have led to the development of environmental friendly renewable energy sources. The Photovoltaic's (*PV*) is one among the most popular renewable energy source. A *PV* system offers benefits of being modular, maintenance free and eco friendly.

The *PV* module is the basic unit that converts sun's energy into useable electrical energy. The environmental condition of solar radiation, temperature and load determine power output of a *PV* system. The *PV* system is always operated to deliver Maximum power to the load for given solar insolation and temperature. Maximum Power Point Tracker (*MPPT*) as shown in Fig. 1 performs this task. A *MPPT* is an electronic interface that adjusts operating point on *PV* module characteristics such that source impedance is always equal to load impedance according to maximum power transfer theorem. *DC-DC* converter facilitates the impedance transformation, which is an integral part of a *MPPT* [1].

A good number of *MPPT* techniques are available in literature. These conventional techniques are generally compared on the basis of accuracy, control complexity, tracking speed, and cost [2–6]. All these techniques guarantee optimal performance under uniform insolation but incapable of delivering maximum power under partial shading conditions. A *PV* module is partially shaded when cell/cells in the module, or modules in the string do not receive full available irradiance. Under partial shading conditions, the power-voltage (*P-V*) characteristics of *PV* array exhibits multiple peaks. The multiple peaks distract traditional *MPPT* method that may lead to *PV* mismatch caused by its operation at local peak. The *PV* mismatch is the difference between expected and actual power output of a *PV* module or array. The internal or external reasons can cause *PV* mismatch. The internal mismatch is caused by imperfections within *PV* modules such as poor solder bonds; impurities in silicon crystal etc. whereas external mismatch is attributed to converter losses and shadows [7].

Shading is the obstruction created by some objects that cause shadow. The opacity of shadow is defined as *shading factor (SF)*, with values lying between zero & one. The limiting values of *zero* and *one* correspond to two extreme cases of *full-irradiance* and *no-irradiance* respectively. The values close to *zero* indicate low shading and that close to *one* indicates higher shading effect, and any other value in-between represent partial shading. The *length* and *width* for shadow is defined by a factor called *shape*. The shadow *length* is decided by number of series connected shaded cells whereas number of parallel connected shaded cells determine the *width* of shadow. The shading effect may produce two effects [7]:

(i) The current in non-shaded cells may flow through the shaded cells; causing its operation in negative voltage region *(dissipating power*

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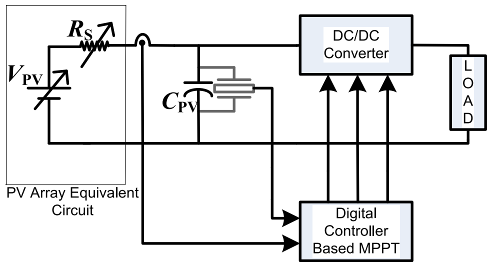

Fig. 1. *MPPT* controller for photovoltaic system [1].

than generating it),

(ii) The MPPT under shading may distract from global MPP, thus producing less energy.

The *Shading* occurs due to obstructions such as trees, buildings, bird droppings, passing clouds, or due to accumulation of dirt and dust. The self-shading between panels in parallel rows also obstructs solar radiation. The shadow occurs temporarily or for longer duration, and may accordingly be classified as *static* and *dynamic*. The static shading is due to slow change in sunlight angle during the day, whereas dynamic shading may be attributed to fast change such as moving clouds. The shading obstructions can also be classified as hard and soft sources. The sources which blocks light from a distance such as flying bird or nearby tree are known as soft sources, whereas sources that completely block light to reach *PV* modules are known as hard sources. The examples of hard sources are bird dropping, blanket or obstruction caused by building etc.

To overcome complex behavior of multiple peaks under partial shading, many algorithms commonly known as mitigation techniques have been developed over the years and reported in literature. All these papers review one or more such techniques and briefly discuss its implementation strategies, merits and demerits in the bid to advance own ideas without going into comprehensive details of all available techniques. This paper reviews current state of art of shading mitigation techniques, classify and compare them so as to be a single reference for the available vast literature. As many as *107* papers that have appeared in reputed journals and international conference have been critically reviewed and lucidly presented. This review is a compilation of research articles and does not include references from the patent.

The paper is structured to present all important and distinctive mitigation techniques with their working principle and comparative merits/demerits. The techniques, which have slight modification, are put under multiple references. The methods that have little scientific contribution are not included in the review. All methods included in the review are critically compared on the author's defined selected parameters in tabular form, which is not available under one umbrella in the literature, otherwise. A critical comment from the author has been included as conclusion, which is distinct and exclusive.

The review article is designed to bring forth current advances in shading mitigation techniques for optimum utilization of omnipresent solar energy. The paper is organized into four sections. Section 2 discusses problem overview and prominent characteristics of solar *PV* under partial shading condition are discussed. Section 3 presents an overview of different methods of shading mitigation technique and review of different control technique that performs global peak under partial shading conditions. Section 4 discusses analysis and comparison of different circuit topologies and *MPPT* based techniques.

2. Problem overview

PV array characteristics gets modified under partial shading conditions, resulting in two scenarios:

(i) The shaded cells may have to carry current of non-shaded cells, causing hot spot effect,

(ii) Shaded cell may be allowed to produce its own reduced power depending on the shading factor.

In scenario (i), partial shading of solar cells induces disproportionate losses in the module resulting in local overheating commonly known as hot spot. Hot spot effect is undesirable as it can destroy the partially shaded cell/modules, affecting string output immensely. In fact, the shaded cells/module operates at negative voltage thus dissipating power rather than generating it. A bypass diode is normally provided with *PV* modules which shorts shaded *PV* module preventing it to work in negative voltage region that may otherwise cause undesirable power dissipation from a source. The presence of bypass diode however deforms current-voltage *(I-V)* characteristics of *PV* array, and power curves under partial shading condition exhibit multiple peaks. The existence of multiple peaks distracts *MPPT* and may cause its operation at local peak. In fact, the *MPPT* algorithm must operate at the maxima of all available peaks on *P-V* characteristics. The maximum among all possible peaks on *P-V* characteristic is termed as global peak. All *MPPT* technique and algorithm should be able to locate and operate at global peak, so as to deliver maximum possible power to load as output. In Scenario (ii), the modules receiving reduced insolation due to partial shading is allowed to generate power independently, commonly known as *Power Independence Principle (PIP)* and is marginally desirable.

Shading may be caused due to clouds, trees, poles, surrounding buildings or even a shadow of one *PV* array to other, and deposition of dust etc. Moreover, the shading effect on individual cell is also dictated by cell's own parameter such as shunt resistance. Fig. 2 depicts string of four modules under uniform and non-uniform insolation. In Fig. 2(a), all four modules get uniform insolation, thus have smooth *P-V* characteristics with single peak as shown with blue trace in Fig. 2(c). The *MPP* tracker has well defined objective of locating single power peak without distraction. In Fig. 2(b), all modules get non-uniform insolation, which leads to partial shading. The *P-V* characteristic under partial shading is not smooth and exhibits complex behavior with multiple peaks, if bypass diodes are used. This characteristic is shown with green trace in Fig. 2(c). The output power from partially shaded string is reduced as *MPPT* algorithm is likely to trap at one of the local peaks [8–10], making it to deliver reduced power to load at reduced efficiency. Bruendlinger et al. [11] have tested various commercially available inverters in partially shaded conditions and have found that the power loss due to shading may be as high as 70%.

Assuming that four *PV* modules are connected in a string and each module generates 75 *W* maximum (W_P) under STC corresponding to 1000 W/m^2, thus accumulating 300 W_P as string output. Trace '1' in Fig. 2(d) is a linearly decaying plot of string output against shading factor. As expected the string output will be 300 W_P at $SF=0$; and would give zero output corresponding to shading factor of 1. If each *PV* module is connected with a bypass diode; the shaded module would be completely bypassed and string output would now become constant as 225 W_P after deducting the contribution of shaded module. This is depicted by Trace '2' in Fig. 2(d). Now, assuming that one module in the string of four is partially shaded but not shorted by its bypass diode. Under this case, three *PV* module would contribute 75 W_P each, and partially shaded module would contribute anywhere between 0 and 75 *W*. The string output would now range between 225 *W* to 300 *W*, as shown by Trace '3' in Fig. 2(d) depending on opacity of shadow i.e. shading factor. This employs *PIP,* as each *PV* module in the string including shaded module is contributing power. In *PIP, all PV modules in the string are thus allowed to operate independently at their MPP.* In Fig. 2(d), the *PIP* has distinct advantage of delivering highest power output as compared to cases with or without bypass diode.