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Computational intelligence techniques for maximum power point tracking in PV systems: A review

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ABSTRACT

Maximum power point (MPP) tracking (MPPT) is an important technique for maximizing the power extraction from photovoltaic (PV) systems under varying climatic conditions. In an array of PV modules it is possible to observe multiple peaks in the power versus voltage (P-V) curve due to the current versus voltage (I–V) PV cell mismatch caused by differences in the received irradiance, such as occurs during partial shading. In these circumstances, the ability of the MPPT devices to track the global MPP of the PV array directly influences the system efficiency. In the literature, various MPPT techniques have been proposed. Among them, computational intelligence (CI) algorithm based MPPT methods have demonstrated the ability to find the global MPP. This paper presents a detailed and specific review of CI- based MPPT techniques. Each method type is classified into one of several subcategories according to its application strategy. The various ways of applying CI into MPPTs are analyzed in detail. The advantages and disadvantages of each method are discussed and compared. The purpose of this study is to provide a compendium on CI-based MPPT techniques for users to understand and select an appropriate method based on application requirements and system constraints.

1. Introduction

Maximum power point (MPP) tracking (MPPT) is one of the most important subsystems in a PV system. It is a well-known and well-studied topic under uniform irradiance conditions when there is a unique MPP in the power-voltage (P-V) characteristics. However, when there are spatial or temporal variations in the solar irradiance falling on a PV system, such as with partial shading caused by moving clouds, nearby trees or buildings, dust, etc., the P-V curve exhibits multiple peaks. Thus, the MPPT algorithm must have the ability to find the global MPP from amongst the localized power peaks. There is no unique MPPT technique, which can provide the 'best' performance for all operating situations for a PV generator. For a particular PV installation, the designer needs to select the best MPPT solution based on their needs. Theoretically, an ideal MPPT technique for PV system should have following characteristics:

1) Be able to accurately track the global MPP under partial shading conditions,
2) Be able to respond to rapid changing climatic conditions,
3) Is system independent and does not rely on the configuration of the PV arrays,
4) Is robust and stable under climatic disturbances and PV panel parameter variations,
5) Is simple to implement with low computational complexity and low system cost.

A full MPPT process requires both software and hardware. The software includes the MPPT algorithm and a closed loop controller, where the MPPT algorithm generates a reference signal (e.g. a reference voltage or duty ratio) used by the closed loop controller to move the terminal voltage of the PV array to the MPP. The terminal voltage is usually changed by adjusting the duty ratio of the pulse width modulation (PWM) signal sent to the power switches of the inverter/converter. In a grid connected PV system there are two basic types of inverter structure, namely the single-stage inverter and the two-stage inverter. In a single-stage inverter, the MPPT control and the inverter grid power control are merged into a single control process, while in the two-stage power conversion structure, the MPPT control and the inverter control are separated. More power conversion structures for PV systems can be found in [1–3]. It is important to note that improving the control strategy influences the quality of the power conversion (including the system stability, the steady-state error, the overshoot, the inverter total harmonic distortion, the dynamic response, etc.), but not the ability of the system to operate at the global MPP. The MPPT algorithm determines if the PV system is able to operate at the global MPP.

There are several review papers on MPPT under uniform and non-uniform conditions [4–11], including computational intelligence (CI, also referred to as soft computing techniques in this review) based MPPTs [12,13] which show various advantages, such as the ability to track the global MPP, system independence, simple implementation, low system cost, etc. However, most of the existing reviews simply listed the CI techniques used, along with a simple discussion of the advantages and disadvantages of each proposed method. Little detail on the various ways to apply these CI algorithms into MPPT was provided, which is important as the performance of the MPPT is influenced not only by the MPPT technique, but also by how it is applied to the PV system. The objective of our work is to review all the CI based MPPT techniques in the literature to give readers guidance on what factors need to be considered when choosing these CI techniques, including how users may improve the performance of these CI based MPPTs and how they may be implemented. Since a large number of variants for several methods, namely ANN, FL, and PSO, have been proposed, we further categorize them into several subcategories. For each type of method, not only the main principle behind the algorithm is introduced, but also

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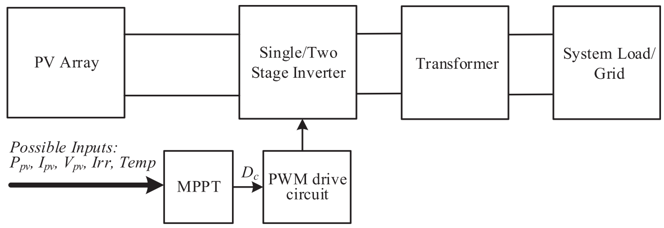

Fig. 1. The basic structure of a PV system with MPPT.

various ways of implementing each CI technique, their advantages and disadvantages, and comparisons of each CI based MPPT in terms of their tracking characteristics and limitations, are given.

The remaining sections of the paper is organized as follows. In Section 2, we introduce the concept of MPPT in PV systems, including two current problems, namely partial shading and rapid irradiance change. Additionally, in this section we introduce two of the more common "classical" MPPT techniques as these are often combined with other techniques, including CI, to form hybrid MPPT systems. In Section 3, we review CI-based MPPTs, giving a brief introduction to each technique including the various methods of application. Subsequently, in Section 4, we discuss important factors affecting the application of MPPTs and compare them based on their performance. In Section 5, we point out several challenges and potential topics which still need to be studied further. Finally, we concluded the review.

2. MPPT in PV systems

PV arrays generate electricity from the sunlight which is then converted from DC to AC power using a single/two-stage inverter so that it can be used either directly by the user (as in an off grid PV system) or fed into the AC power grid, possibly through a transformer (as in a grid connected PV system). To maximize the power transfer, an MPPT is used. Fig. 1 shows a typical PV system with an MPPT installed. Many other system structures can also applied, as in [1–3,14]. As the relationship between the output power of a PV module and its terminal voltage is nonlinear, and is positively correlated with irradiance intensity but negatively correlated with module temperature, for a small PV system consisting of two PV modules connected in series, a uniform increase in the irradiance at the module surface (at a constant temperature) will result in a change in the P-V curve from P_1 to P_2, as shown in Fig. 2. The MPPT aims to adapt the operating point of the PV system from A to the new MPP at E so as to extract as much power from the PV array as possible.

A typical grid connected PV system consists of multiple PV modules connected in series, to form strings, which may then be connected in parallel. This results in a number of different possible MPPT configurations, including centralized MPPT (where multiple strings are controlled by a single MPPT), string based MPPT (where individual strings have their own MPPT controller), through to fully distributed MPPT (where each PV module has its own MPPT controller).

2.1. MPPT under non-uniform irradiance

Classic MPPT algorithms work well under uniform irradiance, however PV systems are ubiquitous and operate under various climatic conditions. This has raised two import problems in MPPT: partial shading and rapid irradiance variation.

2.1.1. Partial shading

To track the unique MPP for PV systems under uniform irradiance conditions, classic MPPT techniques, such as perturb and observe (P&O) [15] and incremental inductance (INC) [16], (which will be introduced in the following sub-section), are sufficient. However, it is well know that if a cell or a small portion of a module in a series string is shaded, then instead of contributing to the power output, the shaded cell(s) will absorb power from the other (less shaded) cells in the string. This absorbed power is then converted into heat, contributing to hot spots that can damage the cell(s). Most commercial modules use bypass diodes across a series of cells (18–20 cells per diode) to overcome this effect. Thus, the shaded cells are bypassed and as a result, only the power from the shaded series (of cells) is lost. However, adding bypass diodes, results in the P-V curve exhibiting multiple peaks (e.g. F and G in Fig. 2) when parts of the PV module/string are shaded or if there is some mismatches among the PV modules. This may cause the classic MPPT techniques to become trapped at a local MPP, leading to power losses.

2.1.2. Rapidly changing irradiance

Another factor that influences the tracking efficiency is when the irradiance changes rapidly. In this scenario, conventional MPPT systems, such as P&O, may track in the wrong direction during the transient process. For example for a PV power P_1, in Fig. 2, the MPPT operating point oscillates either side of the MPP at point A. Then a rapid change in the irradiance occurs just when the algorithm perturbs from point A to B, which leads to a

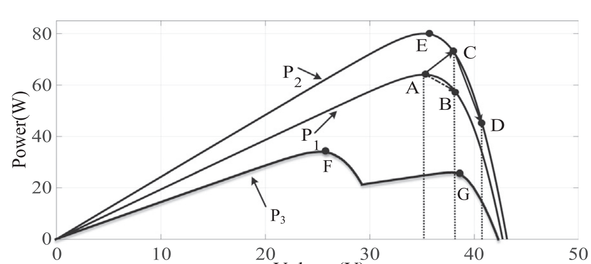

Fig. 2. The P-V curves for two series connected modules under different irradiance conditions.