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Optimal control of a multilevel DC-link converter photovoltaic system for maximum power generation

I. Abdalla, J. Corda, L. Zhang*

School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom

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ABSTRACT

This paper describes a new algorithm for optimal control of a PV system under partial shading. A multilevel DC-link is the essential part of the proposed system and its control engages a voltage-hold perturbation and observation (VH–P&O) method combined with a PWM algorithm with permutation of PV sources. The algorithm enables achieving the maximum power generation for any number of PV and converter modules. The main features of the control are: (i) a continual operation of all PV sources, shaded and non-shaded, at their maximum power points, (ii) delivery of all extracted power from PV sources to the load and (iii) generation of multilevel output voltage waveform with a low total harmonic distortion.

1. Introduction

PV power generators are commonly structured by connecting the PV modules in series to meet the load voltage requirement. This configuration constrains that the same current flows through the chain. However, the characteristics of the chained PV modules are not exactly identical even when they are manufactured in the same batch. A more profound issue is the levels of illumination on individual PV cells which may be different. Even if a single cell in the series chain is shaded, the current through the whole chain would be reduced according to the shaded cell and consequently the overall power output of the whole PV chain drops significantly. Furthermore the shaded cell or cells may be destroyed due to the increased power dissipation on them resulting hot spots. A classical method to prevent high power dissipation on shaded cells has been to connect bypass diodes across a set of chained cells (normally 18). The drawback of such a method is that under uneven irradiance, when diode/s turn on to allow the current flowing through, the power from individual cells is lost.

Various other methods have been developed to address the problem of partial shading. One of them uses the Module-Integrated PV Converter (MIPC) scheme [1–4] which is formed from a series connection of modules comprising a PV panel and a DC/DC converter. This enables the control of each PV source output voltage for maximum power generation, while maintaining the same current value at the converter output terminal. However the problem with this scheme is that the converter for the shaded PV panel may only be able to maintain the current equal to that of the other modules when the irradiance difference is moderate.

Departure from the maximum power point (MPP) may be unavoidable for a shaded source with a larger light level discrepancy, and in this case the option may be to control the converter to bypass the shaded source. Another approach relies on connecting the PV sources into a number of clusters of nearly equal extracted power by using a switching matrix to reconfigure the clusters so that the PV sources of equal shading, hence equal power generation, are connected in parallel. The method was presented in Refs. [5,6] and implemented experimentally in Ref. [7]. Although tests have shown that this approach results in more power output than in the directly connected PV sources, the cluster which generates the least power will be bypassed completely. The third scheme, named the 'Generation Control Circuit' (GCC), uses a type of multilevel DC/DC converter with multiple DC/DC converters connected in series, each powered by a PV source [8]. The individual converter may be a buck-boost type and can be controlled to extract power from the PV sources and deliver it to the load directly. This idea was implemented in Ref. [9] using a fly-back converter allocated to each PV source.

* Corresponding author.
E-mail address: l.zhang@leeds.ac.uk (L. Zhang).

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The main issue with this scheme is that the PV sources cannot be controlled completely independently. Consequently, locating the MPP of one PV source does not mean that the other PV sources operate at their MPPs.

This paper presents a novel optimal control scheme for a PV system using a converter topology called the multilevel DC-link inverter. Similar to the MIPC above this system consists of multiple modules connected in series, each module has a PV panel with a switch-diode pair at its output terminals. A DC-AC bridge inverter is used at the output to convert the generated DC power into AC form [10]. The topology and control strategy enables the system to achieve the MPP tracking for all PV sources in a system under any irradiation conditions. An initial investigation [11] has demonstrated the basic converter topology and control concept. It has been shown that the scheme allows flexible control of each PV source to make it operating at its respective MPP corresponding to its light level. In the current paper a further improved control algorithm is presented which combines a voltage-hold perturbation and observation (VH–P&O) method and the PWM algorithm with permutation of PV sources for achieving the maximum power generation for any number of converter levels. The method is presented by both simulation study and practical experimental test, and the results show a significant enhancement of the PV system performance.

The paper is organised as follows. Section 2 describes the multilevel DC-link inverter topology. In Section 3 the new control algorithm which combines the VH-P&O scheme and permutation PWM strategy is presented in detail. Simulation study of the PV system and the control scheme, which is performed using a STATE-SPACE AVERAGE model for the multilevel DC-link inverter, together with the results obtained are discussed in Section 4. Finally, the experimental system and results obtained by testing are presented in Section 5.

2. Structure of the PV system based on multilevel DC-Link converter

Fig. 1 shows the configuration of a PV system comprising three PV units acting in conjunction with a multilevel DC-link converter. Each PV unit consists of a single PV source, a capacitor and a switch with a complimentary diode. The units are connected in series and any of them can be switched in or out of the chain by turning on or off its switch. When a unit is switched off, it is being bypassed by a diode. The three switches (SW1, SW2, SW3) operate at a high frequency and are controlled by the direct PWM method [12] to form a three-level positive DC voltage. The H–bridge inverter at the output serves to convert the multilevel DC voltage waveform to alternative positive and negative output voltage half-cycles of the required output frequency (e.g. 50 Hz). The generation of multiple voltage levels, combined with proper control, enables forming the approximate sinewave output.

3. Optimal control scheme based on permutation of PV sources

The optimal control scheme should maximise the power transferred from PV sources to the AC load or grid in different light conditions, and generate a nearly sinusoidal voltage with minimum harmonic distortion and DC offset. Ideally, it should also ensure equal switching utilisation and hence the losses. The solution presented in this paper comprises two parts: (i) Voltage-Hold Perturb & Observe (VH P&O) method for generation of the MPP reference voltage and (ii) PWM algorithm with permutation of PV sources for switching control.

3.1. The voltage-hold P&O method for reference voltage generation

A classical strategy for the PV maximum power point tracking is the perturbation and observation (P&O) method, which has been widely studied and used in the PV MPPT controllers (e.g. Refs. [13–17]). The two problems linked with this simple search method are that the terminal voltage may oscillate around a MPP, and the system may lose the MPP during rapid irradiance changes. Some improvements have been proposed for reducing the number of oscillations around MPP (e.g. Refs. [18,19]), but a slow speed of the response may result in an incorrect MPPT if the changes of irradiance are rapid.

The voltage-hold (VH) P&O method proposed here overcomes the above limitation in terms of oscillations around MPPs, which cause noise and slow down the search process, and also it can cope with rapid irradiance changes. For solving the problem of oscillating around a MPP, the algorithm uses variable searching step size. As soon as the irradiation change stops, the tracking step size is gradually decreased towards zero when reaching close to the MPP. When an irradiation change occurs, the tracking step size will be reset to the initial value to maintain the fast tracking. At a rapid irradiance change, which can be detected by measuring the light level and the number of changes within a fixed time interval, the algorithm stops the searching process and sets the reference voltage to the measured PV capacitor voltage which is essential tracking quantity. Subsequently the algorithm resumes the perturbation process for searching the MPP voltage along the I–V characteristic corresponding to the new light level.

The VH P&O method is applied in sequence to each PV unit at each sampling instant, to track individually their respective reference voltages. This may lead to different voltage values depending on the weather conditions and PV panel characteristics. For generating AC reference voltages these values are multiplied by a unity sinusoidal signal $\sin \omega t$ ($\omega = 2\pi \times 50$). (For example, in the system with three PV units, the reference voltages $v_{\text{ref1}}(t)$, $v_{\text{ref2}}(t)$ and $v_{\text{ref3}}(t)$ are generated as shown in Fig. 1.)

3.2. PWM algorithm with permutation of PV sources

The next step should naturally be generation of PWM signals for the switches of individual PV units. For maximum power extraction, the terminal voltage of each PV unit should be as close as possible to its individual reference voltage established by the VH P&O process. This also implies that with multiple PV units in a chain, the PWM reference signal for the whole system should be the sum of all individual reference voltages, i.e. $v_{\text{ref1}}(t) + v_{\text{ref2}}(t), \ldots + v_{\text{ref}(n)}(t)$. To meet these conditions and the criteria of equal switch utilisation and low waveform distortion, a novel PWM algorithm based on permutation of PV sources has been developed. The algorithm consists of three stages, which are performed within each PWM switching period T_s: the direct PWM [12], the sequential permutation of PV sources, and the AC output voltage generation.

In Stage 1, the direct PWM determines the output voltage levels and switch-on time intervals as follows. The reference voltages $v_{\text{ref}(j)}(t)\,(j = 1, \ldots n)$, obtained from VH P&O process, are normalised as

$$\bar{v}_{\text{ref}(j)} = \frac{\left| v_{\text{ref}(j)}(t) \right|}{V_L/n} \tag{1}$$

where the standard voltage level V_L equals V_{MPP} for a single source (panel) at the standard irradiance of 1000 W/m^2 and temperature