IMPLEMENTATION OF DIRECT MPPT TECHNIQUE FOR EXTREMELY FAST CHANGING IRRADIANCE

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Abstract

Photovoltaic cells require of Maximum Power Point Tracking (MPPT) algorithms to ensure the amount of power extracted is maximized. True seeking, direct duty cycle control MPPT algorithms are a simple and straightforward solution that can provide high tracking efficiency. In these algorithms the duty cycle is traditionally modified to reach a new steady state prior performing a new MPPT iteration. Therefore, the MPPT update period must be larger than the converter's settling time to reach a new steady state, which limits the dynamic tracking performance. This work proposes a novel direct duty cycle control method that does not require the converter to achieve steady state in between MPPT updates. The proposed method benefits from the natural oscillations occurring in the converter to obtain extreme dynamic tracking improvements while maintaining simple implementation with no need of employing temperature or irradiance sensors. The scheme being introduced combines MPPT concepts with large-signal geometric control to achieve a reliable, high-performance solution very suitable for applications with rapidly changing irradiance such as wearable technology and rooftop EV. The proposed one validated by simulations and experimental results.

Introduction

With an increasing penetration level of Photovoltaic (PV) systems, challenging issues related to the grid integration have been arisen in the last decade. One of the emerging power quality problems for grid-connected PV systems is the inter harmonics, which are defined as the frequency components that are non-integer times of the fundamental frequency [1] Recent studies have reported that PV inverters are the potential source of inter harmonic emission for PV systems, which have been observed both in the laboratory testing environment and the field measurements [2]–[6]. Although the inter harmonics standard regarding the emission limit is still under development, the inter harmonics can cause grid voltage fluctuations, flickering, and unintentionally disconnection of PV systems. Thus, the inter harmonics emission in PV systems should be avoided and mitigations are needed

According to the previous studies [3]–[6], the Maximum Power Point Tracking (MPPT) operation is one of the main causes for inter harmonics in PV systems. In particularly, the perturbation of the PV arrays voltage during the Maximum Power Point (MPP) searching inevitably induces power oscillations at the dc side, especially during the steady-state operation. This power oscillation contains a series of low-order frequency components, which is reflected in the frequency components of the amplitude of the output current ji_gj. When multiplying the amplitude of the output current with the phase angle sin($_g$), the output current i_g will contain a certain amount of inter harmonic frequencies due to the amplitude modulation following the control diagram in Figure 1.

To address this issue, a model to predict the inter harmonic characteristic in PV systems has been proposed in [8], where the results from the inter harmonic model agree well with the field observation in [6]. It has been demonstrated in [8] that the inter harmonic characteristic is strongly dependent on the MPPT algorithm parameters such as the perturbation step-size and the sampling rate f_{MPPT}. As discussed in [8], the inter harmonic emission can be effectively alleviated by reducing the sampling rate of the MPPT algorithm. However, this will inevitably slow down the tracking performance of the MPPT algorithm [9], which may reduce the MPPT efficiency and thus the PV energy yield, especially during changing environmental conditions (e.g., solar irradiance and ambient temperature). Thus, there is a trade-off between the inter harmonic emission and the MPPT efficiency when selecting the sampling rate of the MPPT algorithm.

With the above motivation, a new mitigating solution for inter harmonics in PV systems is proposed in this paper. The proposed method randomly switches the operation between a fast and slow sampling rate of the MPPT algorithm. By doing so, the inter harmonics in the output current can be effectively reduced due to the distribution of the frequency spectrum. On the other hand, the MPPT performance of the proposed method can be maintained similar to the case when employing a fast MPPT sampling rate. This paper is organized as follows: the inter harmonics in PV systems are discussed in Section II, where the impact of the MPPT sampling rate is considered. Then, the inter harmonic mitigating solution is proposed in Section III, and its performance is validated experimentally in terms of inter harmonic reduction and also MPPT efficiency. Finally, concluding remarks are given in Section IV.

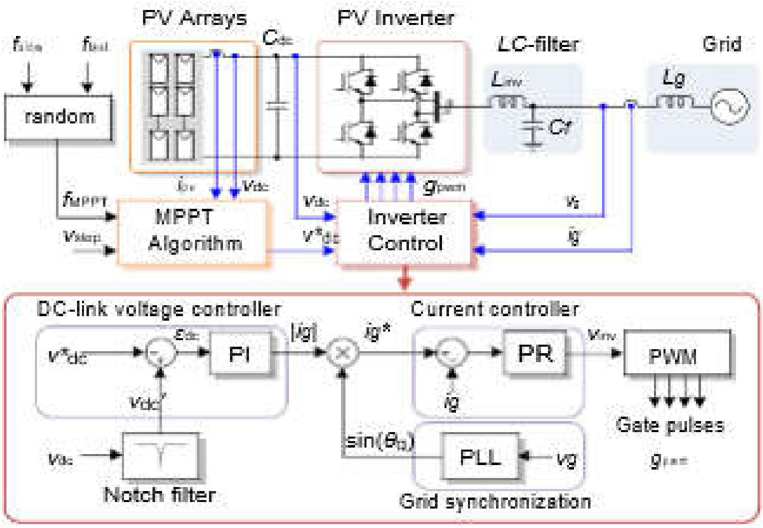

Fig. 1. System diagram and control structure of single-stage single-phase PV inverter (PI - Proportional Integral, PR - Proportional Resonant, PWM - Pulse Width Modulation, PLL - Phase-Locked Loop).

TABLE I

PARAMETERS OF THE SINGLE-PHASE GRID-CONNECTED PV SYSTEM.

PV rated power	3 kW
DC-link capacitor	C_{dc} = 1100 F
LC-filter	L_{inv} = 4.8 mH, C_f = 4.3 F
Grid-side inductance	L_g = 2 mH
Switching frequency	f_{inv} = 8 kHz
Controller sampling frequency	f_s = 20 kHz
Grid nominal voltage (RMS)	V_g = 230 V
Grid nominal frequency	f_g = 50 Hz

Inter Harmonics in Photovoltaic Systems

System Configuration

The experimental test in this paper is conducted based on the single-stage single-phase PV inverter shown in Figure 1, where the system parameters are given in Table I. In this configuration, the PV inverter is employed to control the power extraction from the PV arrays and convert it to the ac power delivered to the grid [10]. In order to maximize the PV energy yield, the operating voltage of the PV arrays (i.e., corresponding to the dc-link voltage v_{dc}) is determined by the MPPT algorithm during the operation. The dc-link voltage v_{dc} is regulated through the control of the output current i_g by a current controller, where the phase angle of the output current sin ($_g$) is obtained using a Phase-Locked Loop (PLL).

Maximum Power Point Tracking

The MPPT algorithm is essential for the PV system in order to maintain the operating point of the PV arrays close to the MPP and thus maximize the energy yield during the operation. In this paper, the Perturb and Observe (P&O) MPPT algorithm is employed [9], where the perturbation step-size v_{step} and the MPPT sampling rate f_{MPPT} are the MPPT parameters.

One important characteristic of the P&O MPPT algorithm (and also other hill-climbing MPPT methods) is the power oscillation during the steady-state operation [9]. This behavior is shown in Figure 2, where the PV inverter operates under

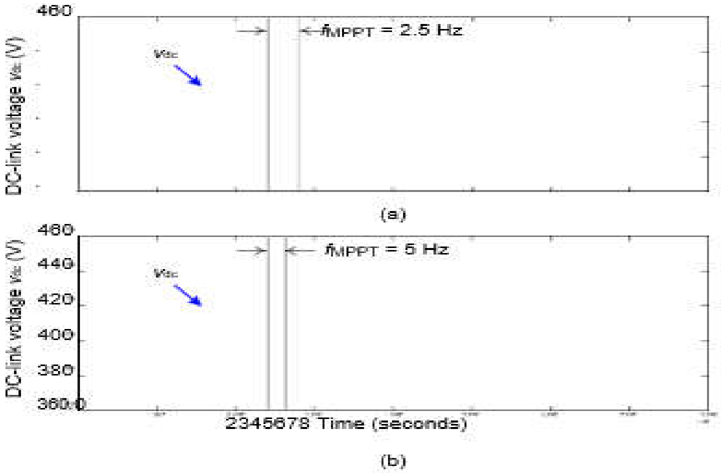

Fig. 2. Experimental waveforms of the dc-link voltage vdc of the PV inverter operated at 10 % of the rated power (i.e., 0.3 kW) with the MPPT sampling rate of: (a) fMPPT = 2.5 Hz and (b) fMPPT = 5 Hz.

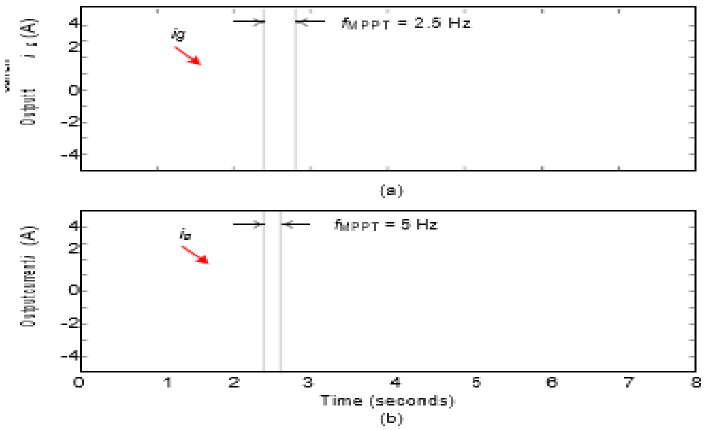

Fig. 3. Experimental waveforms of the output current ig of the PV inverter operated at 10 % of the rated power (i.e., 0.3 kW) with the MPPT sampling rate of: (a) fMPPT = 2.5 Hz and (b) fMPPT = 5 Hz.

Constant solar irradiance condition. Two MPPT sampling rates of 2.5 Hz and 5 Hz are employed to demonstrate the performance of the PV system with different MPPT sampling rates. Comparing the operating condition with two times difference in the sampling rate can clearly demonstrate their impact on the inter harmonic characteristics. It can be seen that the PV arrays voltage oscillates within three operating points, which correspond to the “top of the hill” in the power-voltage characteristic of the PV arrays. This is achieved when the sampling rate is properly selected below the PV-power settling time as discussed in [11]. Notably, the frequency of the oscillation is proportional to the MPPT sampling rate.

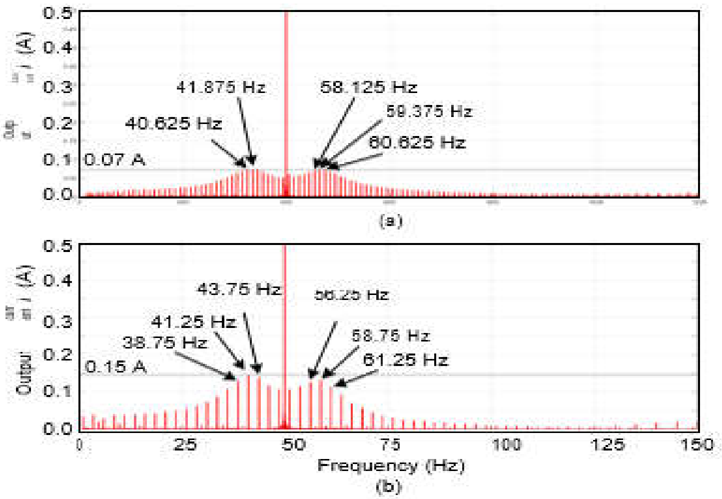

Fig. 4. Frequency spectrum of the output current ig of the PV inverter operated at 10 % of the rated power (i.e., 0.3 kW) with the MPPT sampling rate of: (a) fMPPT = 2.5 Hz and (b) fMPPT = 5 Hz.

Inter Harmonic Characteristics

Since the amplitude of the output current is determined by the response of the dc-link voltage controller following the control diagram in Figure 1, the power oscillation will also be reflected in the output current as it is shown in Figure 3. When analyzing the frequency spectrum of the output current, the inter harmonics can be observed as it is shown in Figure 4.

From the frequency spectrum of the output current shown in Figure 4, it can be seen that the peak amplitude of the inter harmonics increases from 0.07 A to 0.15 A when the MPPT sampling rate increases from 2.5 Hz to 5 Hz. Moreover, the distance between the consecutive inter harmonic frequencies is also proportional to the MPPT sampling rate. These inter harmonic characteristics have been explained with the model in [8], where the inter harmonic emission is more pronounced when applying a high MPPT sampling rate.

Mitigation of Inter Harmonics

In this section, the mitigation of the inter harmonics through the modification of MPPT sampling rate is proposed, and its performances are evaluated experimentally.

Modifying MPPT Sampling Rate

Conventionally, the P&O MPPT algorithm is implemented with a fixed sampling rate, where a high sampling rate offers a high MPPT efficiency during fast changing environmental conditions [12]. However, as it has been shown in Figure 4(b), this can introduce certain inter harmonics in the output current.

One solution to reduce the dominant inter harmonics in the output current is by employing a random sampling rate for the

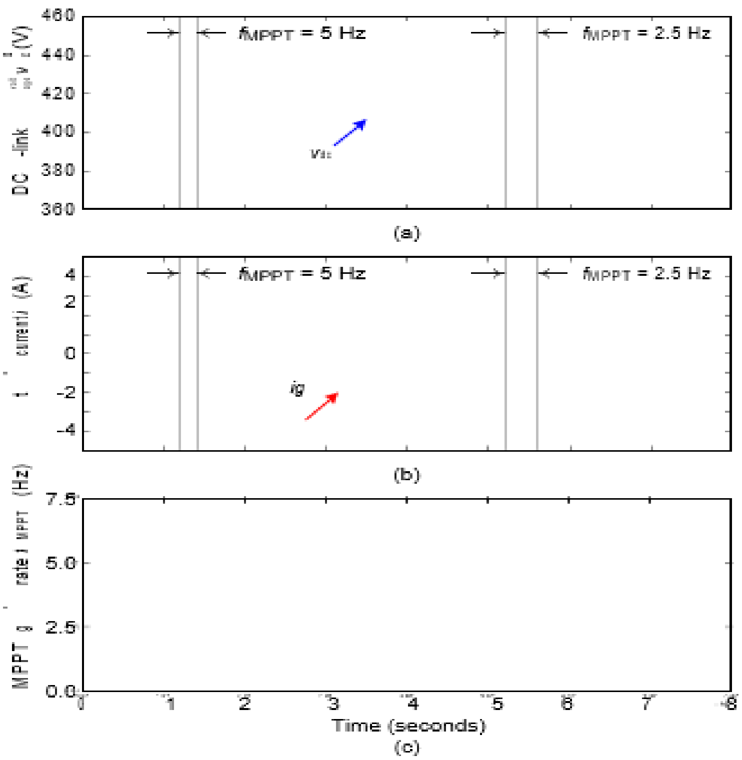

Fig. 5. Experimental results of the PV inverter operated at 10 % of the rated power (i.e., 0.3 kW) with randomly applied MPPT sampling rate of fslow = 2.5 Hz and ffast = 5 Hz: (a) dc-link voltage vdc, (b) output current ig, and (c) MPPT sampling rate fMPPT.

MPPT algorithm. This idea is similar to the random Pulse-Width Modulation (PWM) discussed in the previous research for the PWM switching harmonic reduction [13]. However, in the proposed method, the random selection of the sampling rate is applied at the MPPT algorithm. One simple way to implement this method is by randomly select the MPPT algorithm sampling rate either at a high f_{fast} or low f_{slow} value during the operation, which can be summarized as:

$$f_{MPPT} = \begin{cases} f_{fast}; & \text{when} \quad X \quad 0{:}5 \\ f_{slow}; & \text{when} \quad \text{otherwise} \end{cases} \qquad (1)$$

where X U (0; 1) is a random variable with uniform distribution between 0 and 1. Notably, there are also other ways to randomly generate different sampling rates during the operation, which is an interesting aspect for future research.

This principle is demonstrated in Figure 5, where the MPPT sampling rates are f_{slow} = 2.5 Hz and f_{fast} = 5 Hz. notably, the other control parameters are kept the same as in the previous cases in Figs. 2 and 3. It can be seen from the experimental results in Figure 5(a) that the perturbation of the dc-link voltage becomes more arbitrary due to the randomly applied MPPT sampling rate. It is worth to mention that the proposed method can also be applied to other hill-climbing MPPT methods (e.g., incremental conductance algorithm) as well since the MPPT implementation is in principle similar.

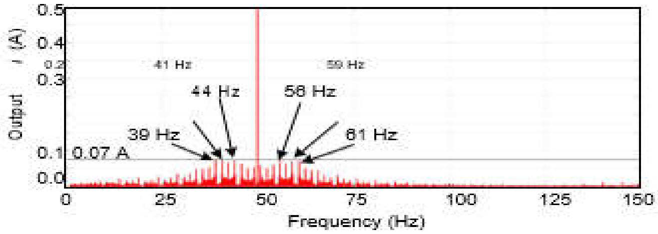

Fig. 6. Frequency spectrum of the output current ig of the PV inverter operated at 10 % of the rated power (i.e., 0.3 kW) with randomly applied MPPT sampling rate of fslow = 2.5 Hz and ffast = 5 Hz.

Inter Harmonic Reduction

The consequence of randomly applying the MPPT sampling rate is also reflected in the perturbation rate of the output current. In Figure 5(b), the output current with the proposed randomly applied MPPT sampling rate of f_{slow} = 2.5 Hz and f_{fast} = 5 Hz is shown. The corresponding MPPT sampling rate during the operation is also demonstrated in Figure 5(c). When analyzing the frequency spectrum of the output current in Figure 5(b), it can be observed from the results in Figure 6 that the dominant inter harmonics in the output current can be reduced significantly. With the proposed method, the peak amplitude of the inter harmonics is 0.07 A, which is less than half of the case when employing a fast MPPT sampling rate in Figure 4(b). In fact, the frequency spectrum is more distributed due to the randomly applied perturbation of the output current. This is preferable since a certain inter harmonic component may trigger an un damped resonance, causing stability problem. Moreover, in the case of parallel-connected PV inverters, the stochastic behavior of perturbation has a high probability to counteract one another due to its randomness. This can potentially smooth out the total power oscillation and thereby further reduce the inter harmonics in the total output current.

MPPT Efficiency

The tracking performance of the MPPT algorithm is evaluated by means of the MPPT efficiency: MPPT= E_{pv}=E_{avai}, where E_{pv} and E_{avai} are the total extracted and available PV energy, respectively. The MPPT operation with different sampling rates under a trapezoidal solar irradiance condition is shown in Figure 7. According to the results, the higher MPPT sampling rate offers a better tracking performance during the changing solar irradiance condition. This can be observed by comparing the PV output power during the increasing solar irradiance condition (i.e., from t = 30 s to t = 60 s) in Figs. 7(a) and 7(b). In that case, the MPPT efficiency of the operation with f_{MPPT} = 5 Hz is 0.5 % higher than the case when applying f_{MPPT} = 2.5 Hz, resulting in a higher energy yield.

Considering the operation with the proposed randomly applied MPPT sampling rate in Figure 7(c), the tracking performance of the MPPT operation is somewhat in between the slow and the fast MPPT sampling rate operations. Although the PV output power cannot follow the change in the available power as fast as the case with f_{MPPT} = 5 Hz, it shows a

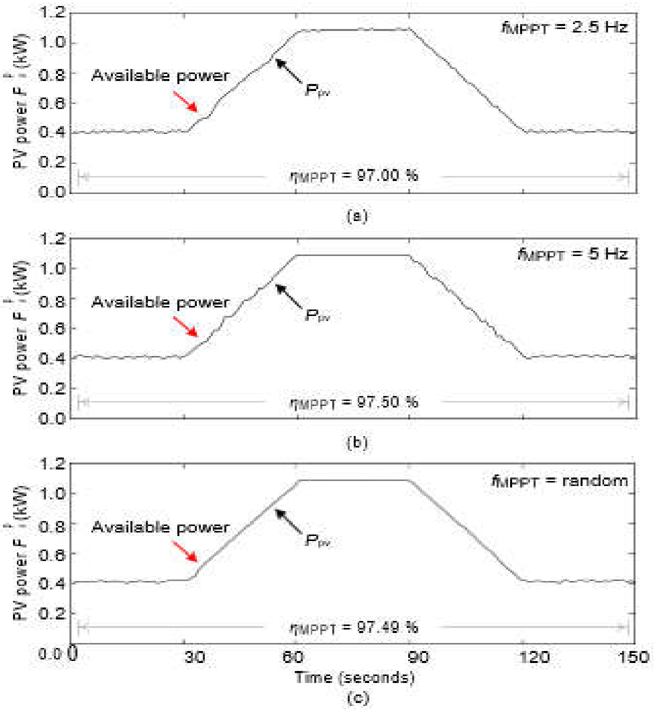

Fig. 7. Measured PV power extraction of the PV inverter under the trapezoidal solar irradiance condition with the MPPT sampling rate of: (a) fMPPT = 2.5 Hz, (b) fMPPT = 5 Hz, and (c) fMPPT = random.

Conclusion

With the conventional MPPT implementation, there is a trade-off between the inter harmonic emission and the MPPT efficiency when selecting the sampling rate of the MPPT algorithm. To solve this issue, a new mitigating solution for the inter harmonics in PV systems has been proposed in this paper. The proposed method modifies the MPPT algorithm by randomly selecting the sampling rate of the MPPT algorithm during the operation. By doing so, the frequency spectrum of the output current can be smoothen and the amplitude of the dominant inter harmonics can be significantly reduced. Moreover, the MPPT performance of the proposed mitigating solution can be maintained close to the conventional MPPT operation with a fast MPPT sampling rate, where similar tracking efficiency during a dynamic operating condition can be achieved. The performance of the proposed method has been validated experimentally under both steady-state (e.g., inter harmonics) and dynamic operations (e.g., MPPT efficiency).

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