Voltage Control Scheme for Multilevel Interfacing PV Application: Real-Time MRAC-Based Approach

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Abstract

Cascaded H-bridge multilevel inverters (CHB-MLIs) have a proper structure and significant advantages like filter-less topology due to their desired output voltage levels and being suitable for employing isolated DC voltage sources that have been utilized in multi-sources applications such as photovoltaic (PV) power generation. However, unbalanced DC voltage sources of the DC/DC output section or fast voltage variations can decrease the output voltage quality and make some undesired fluctuations and harmonics, affecting the load behavior in different applications. To overcome these problems, a new real-time voltage control technique has been proposed to regulate the output voltage magnitude properly. This aim can be obtained by employing the model reference adaptive control (MRAC) technique for voltage regulation to improve total harmonic distortion (THD), and to decrease some harmonic orders (HOs) magnitude, especially lower harmonics (3rd, 5th, and 7th). Therefore, the proposed solution is designed to stabilize the dynamic error originating from the DC side. At the same time, the DC voltage sources are interfaced with variations, where they do not have equal magnitudes with each other. The effectiveness of the proposed control technique has been verified by simulation in MATLAB/Simulink.

1. Introduction

Inverters (DC/AC) are one of the integral parts of renewable energies such as photovoltaic (PV) and wind turbine systems. Multilevel inverters (MLIs) are introduced to provide better output voltage characteristics than the conventional two-level inverters. In recent years, MLIs have gained much attention in medium-voltage and high-power due to their various advantages such as lower electromagnetic interference, the lower voltage stress on power switches, an improvement in THD, and a reduction in massive filtering requirements. The classical MLIs are classified into diode clamped MLI (DC-MLI), flying capacitor (FC-MLI), and cascade H-Bridge MLI (CHB-MLI) [1]. In high-level inverter topologies, there is a limitation of complexity and number of clamping diodes for the DC-MLIs, and there is an increment in the number of required capacitors and complexities of considering DC-link balancing for FC-MLIs. Among these classical MLI topologies, the CHB-MLI has the least components for various levels. This topology consists of a series of H-bridge cells synthesized to the desired voltage from several isolated DC sources, which is suitable for PV applications and can be obtained from isolated PV modules. There is a growing interest in reduced component counts MLIs [2] and [3]. Still, the classical topologies have essential applications in most critical areas. Due to the overall efficiency of the entire system, modulation strategies are a crucial part of DC/AC converters. The purpose of a modulation signal is to control the output voltage/current characteristics, especially losses (both conduction and switching losses), THD, and individual harmonics content. There are different types of modulation strategies that are proposed for utilization in MLIs [4-6]. Three major types of modulation strategies are utilized in MLIs based on the switching frequency; low/fundamental, high, and variable switching frequency. In low/fundamental switching frequency, selective harmonic elimination (SHE), optimal switching angles (OSAs), space vector control (SVC), and nearest level control (NLC) are the major methods [7]. The OSA modulation strategy can minimize the harmonics in the inverter voltage waveform. This modulation strategy is a very flexible and perfect solution; by calculating the switching angles, it is possible to control the output voltage/current harmonics (to control the output voltage/current) and increase the output quality.

PI and fuzzy logic controllers are conventional controllers have some disadvantages like a slow dynamic response, high starting overshoot in some cases, and sensitivity to controller gains [8]. Model predictive control (MPC) is an advanced control technique, which is utilized in both industry and academia. Fast dynamic response and handling constraints are the benefits of this controller [9] and [10]. The main issues with the MPC controller are the weighting factor design process and real-time implementation [11]. The model reference adaptive control (MRAC) is one of the main techniques of adaptive control. It is a combination of a parameter estimator, which generates parameter estimates online [12]. These parameters are completely unknown and could change with time in an unpredictable manner. This controller is a way of adjusting the controller characteristics in response to changes in the plant and disturbance dynamics distinguishes one scheme from the other. This controller is a special type of nonlinear feedback control, which has useful capabilities and interesting properties that can be profitably incorporated into the design of control systems. Some benefits of adaptive control are as follows: utilizing time-varying systems uncertainty does not matter, the ability to eliminate noises and disturbances, and different types of control tools such as linear control [13]. There are many kinds of applications of the adaptive controller in converters [14] and [15].

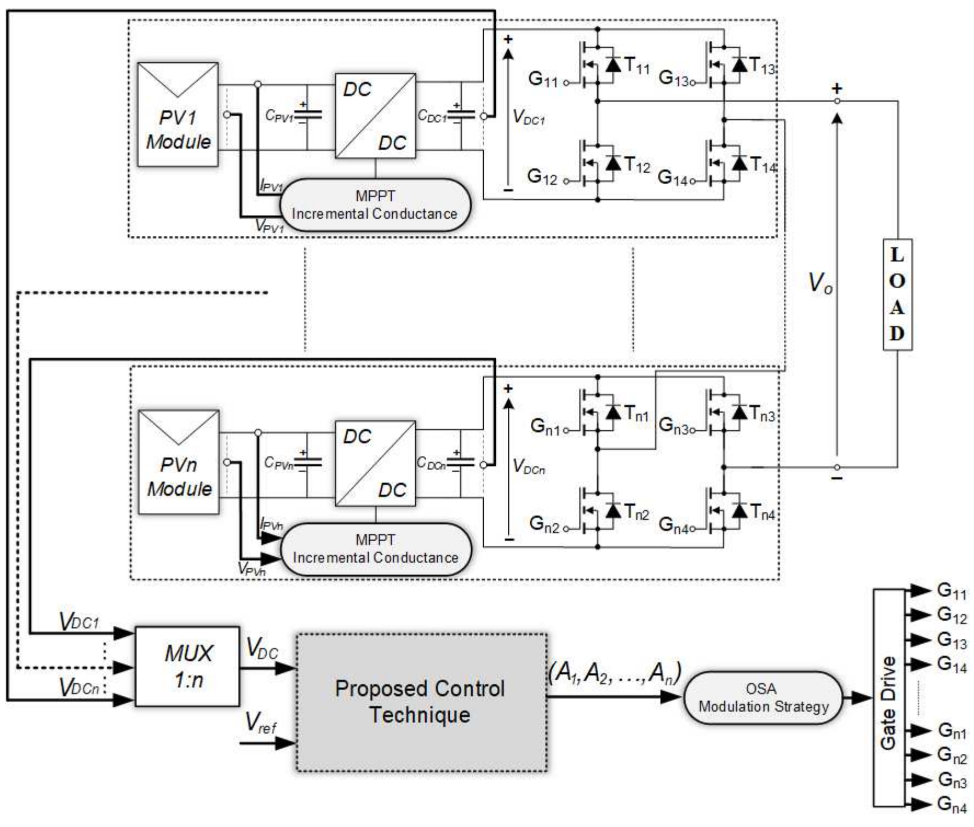

Fig. 1: System configuration consist of PV modules, DC/DC boost converter, CHB-MLI, OSA modulation strategy, and control block diagrams.

Motivated by the previous discussions, a new real-time modulation method is proposed to regulate the output voltage magnitude. In addition, it will improve the voltage THD and its harmonics content especially the lower ones (3^{rd}, 5^{th}, and 7^{th}) by employing an adaptive controller in a closed-loop system for a single-phase MLI. By utilizing the proposed solution, an accurate control process can be applied to the harmonics, and it is possible to minimize their magnitude one by one. The proposed control technique is suitable for PV applications that have variable conditions such as changes in irradiation and temperature that cause variations in the DC link.

2. System configuration and voltage unbalanced problems

CHB-MLI configuration is a perfect topology in PV power generation due to its multiple isolated DC sources. Fig. 1 presents a general schematics of the utilized system configuration. At each pack, there are one PV module, a DC/DC boost converter, and a CHB inverter. PV modules generate power, and then the DC/DC link is used to increase the voltage magnitude and obtain the maximum power of the modules. An incremental inductance algorithm is employed for the maximum power point tracking (MPPT) section to control the switching states of the DC/DC converter. The output voltage of the DC/DC converters is considered as the input of the adaptive control system. The OSA modulation strategy organizes the output voltage levels and then sends the firing signals to the gate drivers. There are four ways to determine the value of the DC voltage sources: unary, binary, trinary, and proposed algorithms [3]. This study uses a unary method to value the DC sources. Therefore, the strategy is to generate the output voltage levels by equal DC sources. During this process, MRAC has an important role in determining the switching angles for each output voltage level. In this case, four packs of the PV modules, DC/DC converters, and DC/AC inverters (CHB-MLIs) are required to prepare a 9-level inverter.

The OSA strategy concept is organizing the switching angles at low switching frequencies, where it is possible to form the output voltage function. Therefore, there is an ability to control the output voltage characteristics such as root mean voltage square (V_{rms}), THD, and harmonic order magnitudes. Fig. 2 presents the output voltage waveform and the switching angles for a 9-level inverter and their positions at each level. For the first level, the output DC-link magnitude equals the DC voltage of pack one. For the second level, the output DC-link magnitude equals the DC voltage of pack two, and the same process for the rest of the levels. Based on the OSA concept, it is possible to control the output voltage magnitude by changing the switching angles at each level. It directly affects the on- and off-times for the power switches. In this modulation strategy, the output voltage waveform is symmetric, which means that it is possible to achieve the output voltage function of a 9-level inverter by considering four switching angles (a quarter of the waveform) and then form the Fourier series as follows:

$$V_{L1} = \sum_{i=1,3,5}^{h} \frac{4V_{DC1}}{i\pi} (\cos iA_1 t) \tag{1}$$

$$V_{L2} = \sum_{i=1,3,5}^{h} \frac{4V_{DC2}}{i\pi} (\cos i(A_1 + A_2)t) \tag{2}$$

$$V_{L3} = \sum_{i=1,3,5}^{h} \frac{4V_{DC3}}{i\pi} (\cos i(A_1 + A_2 + A_3)t) \tag{3}$$

$$V_{L4} = \sum_{i=1,3,5}^{h} \frac{4V_{DC4}}{i\pi} (\cos i(A_1 + A_2 + A_3 + A_4)\, t) \tag{4}$$

$$V_{out} = V_{L1} + V_{L2} + V_{L3} + V_{L4} \tag{5}$$

where (V_{L1}, V_{L2}, V_{L3}, and V_{L4}) are the output voltage function at each level, (A_1, A_2, A_3, and A_4) are the switching angles at each level, (V_{DC1}, V_{DC2}, V_{DC3}, and V_{DC4}) are the DC output voltage of the boost converter of each pack, and V_{out} is the output voltage function for a 9-level inverter.

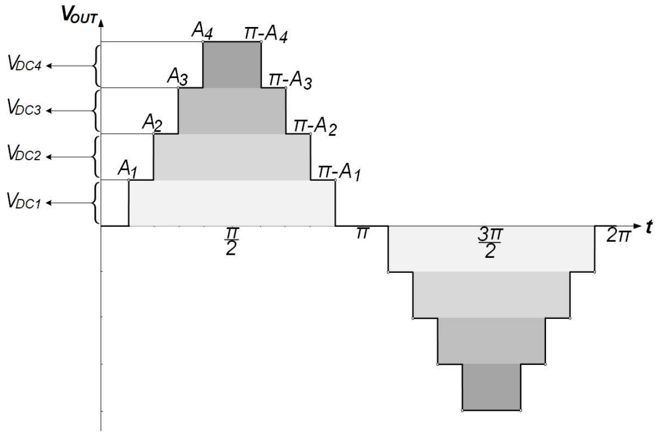

Fig. 2: Switching angles and DC voltage magnitudes of the CHB-MLI converter.

After forming the output voltage function, defining the cost functions to control the output voltage is in the process. Then, implementing the voltage regulation and controlling the output voltage characteristics such as minimizing the THD and setting constraints on the harmonic order magnitudes are achievable. Based on IEEE STD-519, there are several rules for the output voltage specifications; for example, the number of counted harmonics are equal to 49 and they need to be reduced. Therefore, the desired cost functions to cover all the restrictions and STDs items are as follows:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T {V_{out}}^2 dt} \tag{6}$$

$$THD = \sqrt{\frac{\sum_{i=3,5,7}^{h} {V_i}^2}{V_1}} \tag{7}$$

$$HO = \sum_{i=1,3,5}^{h} \frac{4}{i\pi}(V_{DC1}\cos iA_1 t + V_{DC2}\cos i(A_1 + A_2)t + \cdots + V_{DCi}\cos i(A_1 + A_2 + \cdots + A_i)t) \tag{8}$$

where V_1 is the value of the fundamental term of the output voltage, V_i is the value of harmonics and h is the number of harmonics that are considered for minimization.

3. Voltage adaptive control strategy

The model-reference adaptive system is one of the well-known structures in adaptive control. The system has an ordinary feedback loop, and the error (e) of the systems is the difference between the output of the system and the reference model, which is a function of time and adapted parameters (θ). The purpose of an MRAC is to minimize this error such that the closed-loop system follows the reference model. To this end, a quadratic cost function (J) of the error signal (e) is considered as follows:

$$J(t,\theta) \triangleq \frac{1}{2}e^2(t,\theta) \tag{9}$$

In this way, adaption parameters are updated to minimize the cost function value. In the gradient descent method, adaption parameters are updated in the opposite direction of the gradient of the cost function (J). This adaptation rule can be presented as:

$$\frac{d\theta}{dt} = -\delta \frac{\partial}{\partial\theta} J(t,\theta) = -\delta e(t,\theta) \frac{\partial}{\partial\theta} e(t,\theta) \tag{10}$$

where δ is a real positive constant and called the adaption gain. The derivative $\partial e/\partial\theta$ is the sensitivity of the system. In the proposed approach, to apply the MRAC to a 9-level inverter, the following cost function is considered.

$$J(t,\theta) \triangleq \frac{1}{2} e^2(t,\theta) + \frac{1}{2} THD^2(t,\theta) + \frac{1}{2} \sum_{i=3,5,7}^{h} HO_i{}^2(t,\theta) \tag{11}$$

Minimizing the cost function (11) results in reducing the error signal, THD, and some specific harmonics. According to this cost function, the adaptation parameters are the switching angles given as

$$\theta = [A_1, A_2, A_3, A_4] \tag{12}$$

$$\delta = [\delta_1, \delta_2, \delta_3] \tag{13}$$

and the update rule of the parameters is given by

$$\frac{d\theta}{dt} = -\delta_1 e(t,\theta) \frac{\partial}{\partial\theta} e(t,\theta) - \delta_2 THD(t,\theta) \frac{\partial}{\partial\theta} THD(t,\theta) - \delta_3 \sum_{i=3,5,7}^{49} HO_i(t,\theta) \frac{\partial}{\partial\theta} HO_i(t,\theta) \tag{14}$$

Remark. The adaptation rule for the parameters (14) is obtained based on the gradient descent method. The gradient method often exhibits approximately linear convergence, i.e., the solution converges to an optimal point approximately as a geometric series [13].

In Fig. 3, the proposed adaptive controller is presented in block diagrams. The DC voltage magnitudes are inputs and switching angles of each level are the outputs for this algorithm. Replacing this controller in Fig. 1 completes our proposed control approach for the mentioned system.

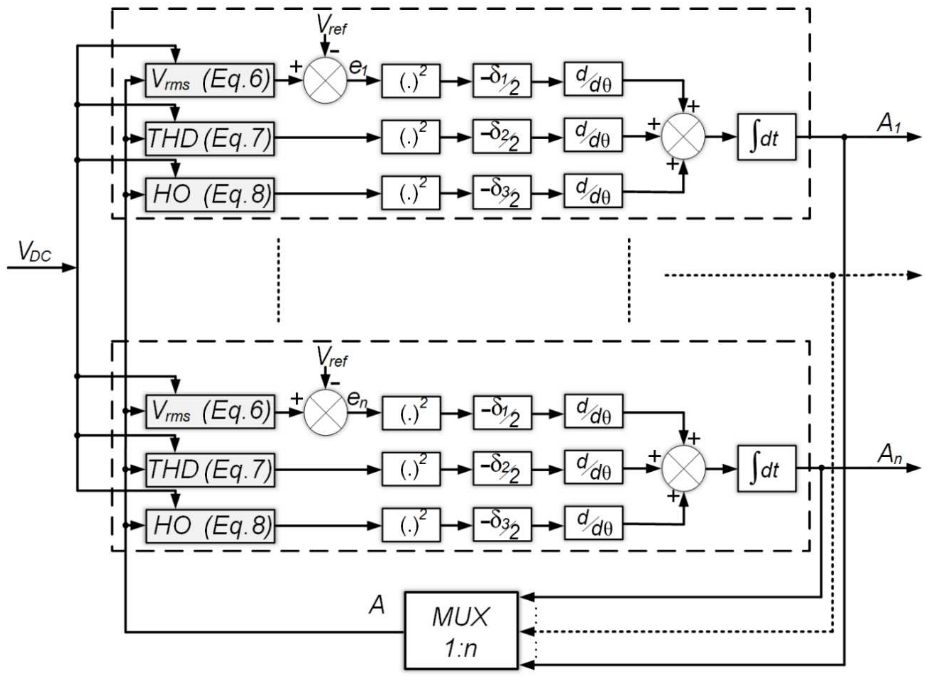

Fig. 3. Control block diagram of the proposed control technique.

4. Simulation results

To validate the proposed control technique, a single-phase 9-level CHB-MLI in MATLA/Simulink has been simulated. The proposed control technique has been tested for different values of the input voltage DC source with voltage ranges from 75 V to 95 V, and the sampling time ratio is equal to 50 µs. In this scenario, seven different conditions are applied to test the dynamic performance of the proposed solution. In the first step, all the DC sources are equal to $V_{DCi} = 75$ V. In the second to fifth steps, all the DC sources' values increase to $V_{DCi} = 95$ V for each step. In the sixth step, to analyze the dynamic response of the controller, all the DC source values are decreased to $V_{DCi} = 80$ immediately. For the final step, different values are referred to the DC sources randomly, they are equal to $V_{DC1} = 85$ V, $V_{DC2} = 75\ V$, $V_{DC3} = 90\ V$, and $V_{DC4} = 80\ V$.

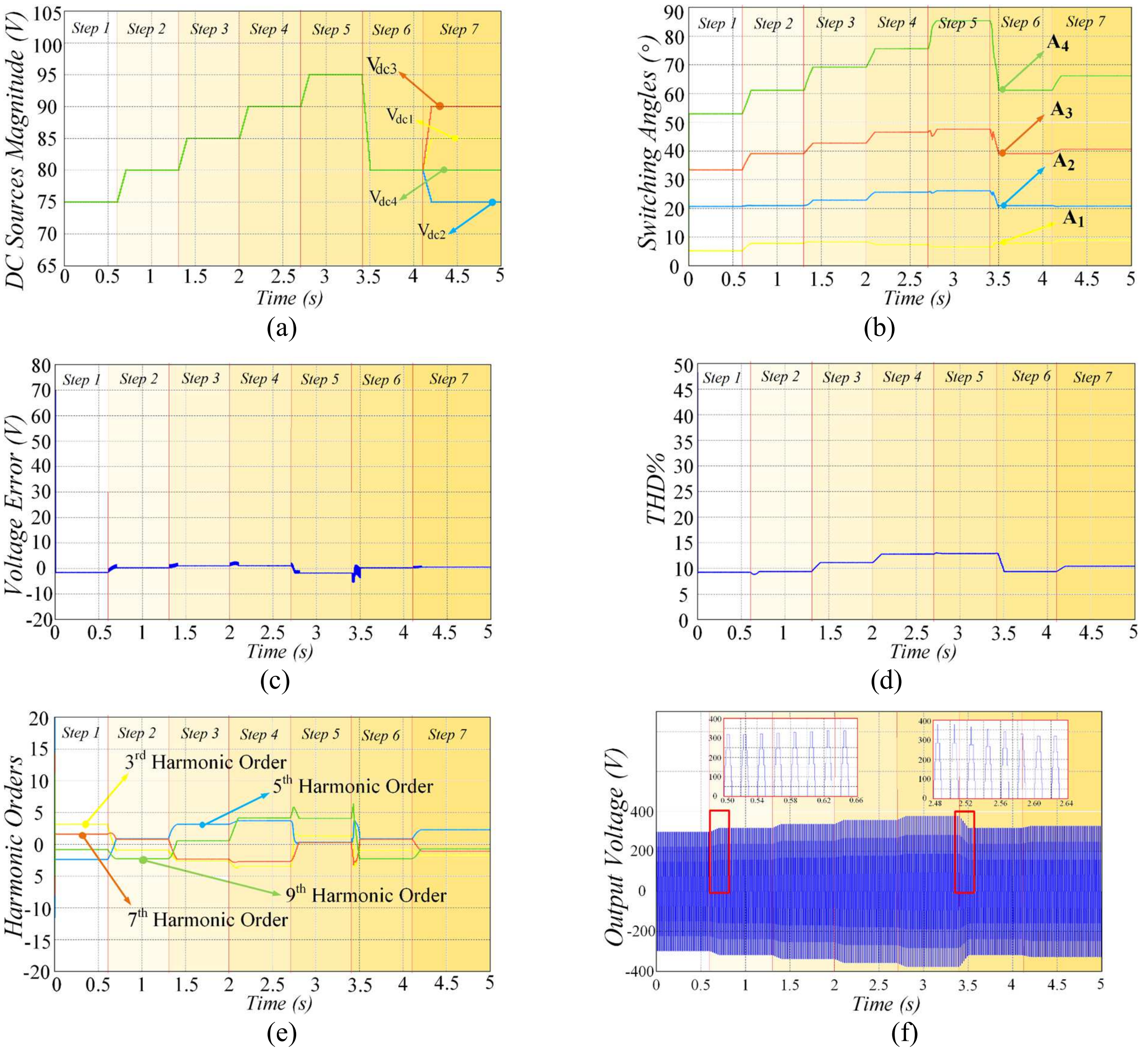

Fig. 4. Simulation results of the output characteristics and controllable parameters (a) Input DC voltage source, (b) Switching angles, (c) Error function of the output voltage, (d) THD% of the output voltage, (e) Different harmonic orders, and (f) Output voltage waveform.

Fig. 4 (a) depicts different steps for the DC voltage sources. In this study, the switching angles are the objective function utilized to optimize the cost functions. Therefore, switching angles take new positions as the DC voltage sources changes. Fig. 4 (b) presents the amplitude of different switching angles at each level of the 9-level inverter. It shows a fast dynamic response of the controller by playing with switching angles. The output voltage error is the main cost function optimized in real-time. The root-mean-square voltage is equal to 230 V all the time. Fig. 4 (c) presents the error magnitude of the output voltage for different steps of DC voltage sources. In addition to the voltage magnitude control, the THD function is optimized simultaneously in real-time. Fig. 4 (d) shows the THD magnitude where implementing the different scenarios for the input DC sources.

As it is a filter-less structure for the utilized topology, controlling the harmonics by employing the proposed control technique can be performed effectively. The magnitude of some specific harmonics are controlled, and they are limited based on the STDs by utilizing the HO's function (Eq. 11), which consists of 49 first orders of the output voltage harmonics. Fig. 4 (e) presents lower harmonic orders of 3^{rd}, 5^{th}, 7^{th}, and 9^{th} of the output voltage, whose amplitudes are lower than 5%. The output voltage waveform under the mentioned condition is illustrated in Fig. 4 (f) from 0 to 5 seconds. The variations of the DC voltage sources are clear at the peak of each voltage level. The controller aims to track the optimal switching angles under different DC voltage source conditions to improve the output voltage quality.

Conclusion

In this study, a new control scheme based on model-reference adaptive control (MRAC) is proposed by utilizing an optimal switching angle (OSA) modulation strategy in multilevel inverters (MLIs) having multiple isolated DC sources. The main cost function consists of the output voltage regulation, the total harmonic distortion (THD), and some low harmonic orders, which all are taken into account. The dynamic response of the proposed controller has been tested while the DC voltage sources have different magnitudes to keep the STDs. The proposed controller can determine the switching angles in real-time. In this online process, controlling the specified harmonic orders is possible. Besides, the proposed solution is a closed-loop system that makes it possible to control both the voltage magnitude and frequency. From a future work perspective, the proposed methodology can be extendable for higher output voltage levels. In addition, a higher number of switching angles can be considered at each level to obtain better results. Adding more cost functions based on IEEE STDs, testing the system under different load conditions and uncertainties, stability analysis of the whole system, and the experimental tests while MPPT section is operating could be suggested for future work.

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