Supertwisting Sliding Mode based MPPT and Adaptive SPWM for PV-Fuel Cell Hybrid System with 2-level Boost Converter

Ruhi Zafer Caglayan
Graduate School of Natural and Applied Sciences, Gazi University
Computer Engineering, Faculty of Engineering, TED University
Ankara, Turkiye
ruhizaf08@gmail.com

Korhan Kayisli, *Senior Member*, IEEE
Electrical Electronic Eng.,
Eng. Fac.,
Gazi University
Ankara, Turkiye
korhankayisli@gazi.edu.tr

Fırat Hardalac
Electrical Electronic Eng.,
Eng. Fac.,
Gazi University
Ankara, Turkiye
firat@gazi.edu.tr

Mariacristina Roscia
University of Bergamo
Bergamo, Italy
http://orcid.org/0000-0001-9422-9508

***Abstract*— Renewable energy sources are increasingly integrated into modern power systems due to their sustainability and environmental benefits. This paper presents a hybrid energy conversion system that combines photovoltaic (PV) and fuel cell sources connected to a common DC bus through two-level boost converters. To maximize energy extraction from both sources under varying operating conditions, a Super-Twisting Sliding Mode Control (STSMC)-based Maximum Power Point Tracking (MPPT) algorithm is employed. The proposed MPPT approach ensures fast and accurate tracking while significantly reducing the chattering effect commonly associated with conventional sliding mode controllers. The regulated DC-link voltage supplies a half-bridge inverter, where an adaptive Sinusoidal Pulse Width Modulation (SPWM) strategy based on STSMC is implemented to enhance output voltage quality and maintain stable operation under source and load variations. The proposed system is modeled and evaluated in the MATLAB/Simulink environment. Simulation results demonstrate effective MPPT performance, stable DC-link voltage regulation, and satisfactory AC output characteristics, confirming the effectiveness of the proposed control strategy for hybrid renewable energy applications.**

Keywords—Photovoltaic Panel (PV),Fuel Cell, Super Twisting Sliding Mode Control, Super Twisting Algorithm, Sinusoidal Pulse Width Modulation

I. INTRODUCTION

Electrical energy generation based on fossil fuels requires continuous fuel consumption, leading to concerns regarding resource depletion, environmental pollution, and greenhouse gas emissions. Consequently, the transition toward sustainable and low-carbon energy systems has become a major focus of research and development efforts worldwide. The increasing integration of renewable energy technologies is driven by environmental regulations, growing energy demand, and the need for reliable and resilient power systems. Among renewable energy sources, photovoltaic (PV) systems and fuel cells have attracted significant attention due to their clean energy production, high efficiency, and suitability for distributed generation applications. Despite these advantages, renewable energy systems are often affected by environmental and operating conditions, resulting in fluctuations in power generation and challenges in maintaining stable system operation. Furthermore, variations in load demand may adversely affect power quality and overall system performance. Therefore, advanced control and energy management strategies are essential to maximize energy utilization, regulate the DC-link voltage, and ensure reliable AC power generation under dynamic operating conditions.

Hybrid energy systems integrating photovoltaic (PV) and fuel cell sources have been extensively investigated to enhance power supply reliability, operational flexibility, and energy availability. In such configurations, PV systems typically serve as the primary energy source under favorable environmental conditions, while fuel cells provide supplementary power during periods of low solar irradiation or increased load demand. To maximize the utilization of available renewable energy, Maximum Power Point Tracking (MPPT) techniques are widely employed. Among various MPPT approaches, Super-Twisting Sliding Mode Control (STSMC) has emerged as an attractive solution due to its robustness against parameter uncertainties, fast convergence characteristics, and reduced chattering compared with conventional sliding mode control methods. In addition to efficient energy extraction, the DC/AC conversion stage plays a critical role in determining the overall performance of the system. The control strategy applied to the inverter directly influences output voltage quality, harmonic distortion, dynamic response, and conversion efficiency. Conventional Sinusoidal Pulse Width Modulation (SPWM) techniques generally employ a fixed modulation index, which may result in suboptimal performance under varying source and load conditions. Consequently, adaptive modulation and control strategies have gained considerable interest for improving system stability, power quality, and dynamic performance in renewable energy applications.

Several studies have investigated hybrid PV–fuel cell energy systems using various energy management, optimization, and control techniques. In early studies, Zhang et al. proposed a fuzzy state machine-based energy management strategy for a PV–fuel cell–battery system designed for unmanned aerial vehicle applications [1]. Similarly, Elgammal and El-Naggar developed a control framework for a wind–PV–fuel cell–battery hybrid system, where PI controllers were optimized using a multi-objective

particle swarm optimization algorithm [2]. To improve control performance under dynamic operating conditions, Nureddin et al. introduced a deep neural network-based control approach for PV–fuel cell systems integrated into microgrids [3]. More recently, Aeggegn et al. proposed an adaptive neuro-fuzzy inference system (ANFIS) for controlling boost and bidirectional buck–boost converters in solar, fuel cell, and battery-supported microgrids [4].

Recent research has increasingly focused on application-oriented implementations and system-level performance improvements. Agajie et al. conducted a techno-economic assessment of grid-connected PV–fuel cell–battery systems for educational facilities [5], while Vendoti et al. developed an ANFIS-based MPPT technique for smart electric vehicle charging applications powered by PV–fuel cell systems [6]. In addition, several studies have explored advanced converter topologies and specialized applications. Sivaram et al. proposed a PV–fuel cell-fed multiport DC–DC converter for water irrigation systems [7], whereas Nagesh et al. investigated a multiport converter architecture for PV–fuel cell–battery integration [8]. Furthermore, Cakmak et al. examined a PV–fuel cell-powered electric vehicle charging station using fuzzy logic-based control [9], and Baidas et al. evaluated PV–hydrogen fuel cell systems for cellular base station applications [10].

The integration of hydrogen technologies with renewable energy systems has also attracted considerable attention. Urs et al. compared PV–reversible fuel cell and PV–battery systems in terms of cost-effectiveness and energy efficiency [11], while Jahanbin and Berardi analyzed the relationship between energy performance indicators and the levelized cost of energy in hydrogen-based building energy systems [12]. In a subsequent study, Urs et al. investigated the application of bifacial PV modules combined with reversible fuel cells for sustainable building applications [13]. More recently, Babatunde and Olanrewaju presented a comprehensive techno-economic and multi-criteria decision-making analysis of a solar–fuel cell–electrolyzer desalination system [14].

Although the existing literature demonstrates significant progress in energy management strategies, converter topologies, and application-specific implementations of PV–fuel cell hybrid systems, relatively limited attention has been devoted to adaptive AC-side control methods that simultaneously address maximum power extraction and inverter performance. In particular, the integration of robust MPPT algorithms with adaptive modulation strategies remains an open research area. In previous work, Caglayan et al. introduced an adaptive SPWM-based control structure for PV systems directly connected to DC/AC converters [15]. Building upon this foundation, the present study proposes a hybrid PV–fuel cell system in which maximum power extraction is achieved through a Super-Twisting Sliding Mode Control (STSMC)-based MPPT algorithm, while AC-side power conversion is realized using an adaptive SPWM strategy. The proposed approach aims to enhance power extraction capability, DC-link stability, and output voltage quality under varying source and load conditions.

II. Methodology

A. Photovoltaic Panel

For the design of the photovoltaic (PV) panel equivalent model, accurate mathematical representation is required. The formulations used in this study are derived based on the models presented in [16–19]. The output current of the PV cell can be expressed as,

$$I_{Photo} = I_D + I_{R_P} + I_{PV} \quad (1)$$

The photo-generated current is defined as,

$$I_{Photo} = \left[I_{sh} * c_{cell} * \left(T - T_{Ref}\right)\right] * \frac{s}{s_{ref}} \quad (2)$$

The diode current is given by,

$$I_D = I_{sat} * \left(e^{\frac{C_{bolt} * V_{PN}}{T_{kelvin}}} - 1\right) \quad (3)$$

In Eqs. (1)–(3), I_{Photo} represents the photo-generated current of the PV cell, I_D is the diode current, and I_{R_P} denotes the current through the shunt resistance. I_{sh} is the short-circuit current of the PV cell, and c_{cell} is the temperature coefficient of the cell. T and T_{Ref} indicate the operating and reference temperatures, respectively, while T_{kelvin} represents the absolute temperature. The parameter s corresponds to solar irradiance, and s_{ref} is the reference irradiance value. I_{sat} is the diode saturation current, C_{bolt} denotes the Boltzmann constant, and V_{PN} is the voltage across the p–n junction of the diode.

The equivalent PV panel model based on these equations is illustrated in Fig. 1.

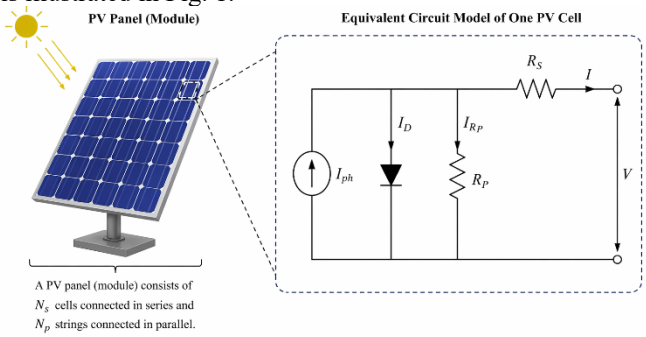


Figure 1. PV panel and equivalent circuit model of single PV cell

B. Fuel Cell

Fuel cells operate based on electrochemical reactions, and their working principle differs from wind and solar energy conversion systems. The output voltage of a fuel cell is affected by several loss components that occur during operation. In the fuel cell voltage model, four main terms are considered: the ideal source voltage (V_{fuel}), activation losses $(V_{activation})$, ohmic losses (V_{ohm}), and concentration losses $(V_{concent})$. These components represent the major factors that reduce the practical output voltage of the fuel cell. The mathematical model of the fuel cell voltage is obtained based on the studies reported in [19]–[21]. Accordingly, the output voltage of the fuel cell can be expressed as,

$$V_{FC} = V_{fuel} - V_{activation} - V_{ohm} - V_{concent} \quad (4)$$

where V_{fuel} represents the ideal reversible voltage of the fuel cell, $V_{activation}$ denotes the voltage drop due to activation losses, V_{ohm} corresponds to ohmic losses caused by internal resistances, and $V_{concent}$ represents concentration losses related to mass transport limitations. A schematic representation of the fuel cell is illustrated in Fig. 2.

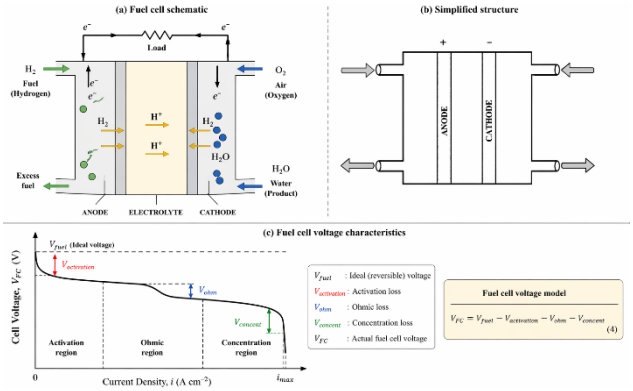


Figure 2. Shematic diagram and voltage characteristics of a fuel cell

C. 2 Level Boost

The two-level boost converter can be considered as an extended form of the conventional boost converter, providing a higher voltage gain. In this study, a ladder-type high-level boost converter topology is selected. In the ladder structure, the number of voltage levels (or stages) is determined by the number of diodes used in the circuit. The diode count is defined as $2N-1$, where Nrepresents the number of levels. Accordingly, the value of Ncan be obtained based on the number of diodes. The voltage gain of the ladder-type boost converter is expressed as [22–24]:

$$G_V = \frac{V_{out}}{V_{in}} = \frac{N}{1-D} \tag{5}$$

where $V_{out}$and V_{in}represent the output and input voltages, respectively, $D$is the duty cycle, and Ndenotes the number of levels in the converter structure. The two-level ladder-type boost converter topology used in this study is illustrated in Fig. 3.

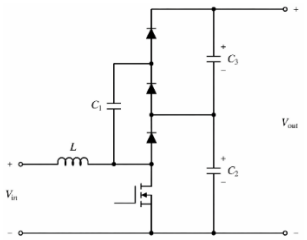


Figure 3. Two-level ladder-type boost converter topology used in the proposed hybrid energy system

D. Super Twisting Sliding Mode Control

Super-Twisting Sliding Mode Control (STSMC) is an advanced form of conventional Sliding Mode Control (SMC) and is widely used in Maximum Power Point Tracking (MPPT) applications for renewable energy systems. However, as reported in [1], MPPT-based control strategies can also be adapted for modulation techniques such as adaptive Sinusoidal Pulse Width Modulation (SPWM).

In this study, STSMC and the Super-Twisting Algorithm (STA) are employed for different stages of the system. Specifically, STSMC is applied to the DC/DC converter to achieve effective MPPT operation [19], while the Super-Twisting control approach is utilized on the DC/AC side for adaptive SPWM generation. The corresponding control structures are illustrated in Fig. 4.

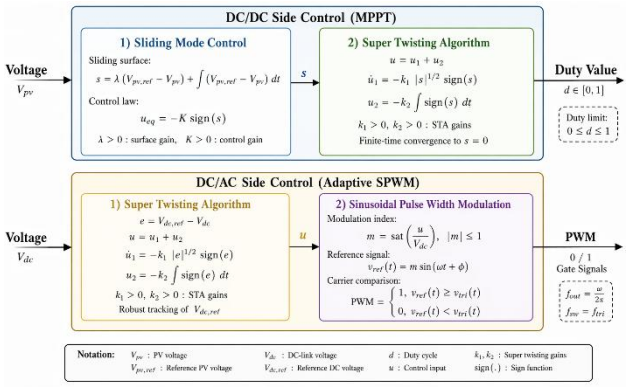


Figure 4. Proposed STSMC-based control scheme for DC/DC (MPPT) and DC/AC (adaptive SPWM) stages.

III. Simulation Study

In this section, the performance of the proposed PV–fuel cell hybrid energy system is evaluated through MATLAB/Simulink simulations. The objective of the simulation study is to analyze the effectiveness of the STSMC based MPPT method and the adaptive SPWM strategy under steady-state conditions.

The overall system configuration is shown in Fig. 5. The structure consists of two main energy sources: PV array and a fuel cell. Each source is connected to a dedicated two-level boost DC/DC converter. These converters are responsible for stepping up the input voltages and transferring the extracted energy to a common DC-link.

The MPPT process for both PV and fuel cell sources is carried out using the STSMC method. The controller generates the required duty cycle signals to ensure that each source operates at its maximum power point. The outputs of the DC/DC converters are combined at the DC-link, forming a stable DC voltage level.

On the AC side, a single-phase half-bridge inverter is used to convert the DC-link voltage into AC form. The inverter is controlled using an adaptive SPWM strategy based on the Super-Twisting Algorithm. This control approach adjusts the modulation index dynamically to improve output voltage quality and system stability.

The simulation model includes detailed representations of the PV panel and fuel cell based on the parameters given in Tables I and II. All simulations are performed under constant environmental and operating conditions to evaluate the steady-state performance of the proposed control structure.

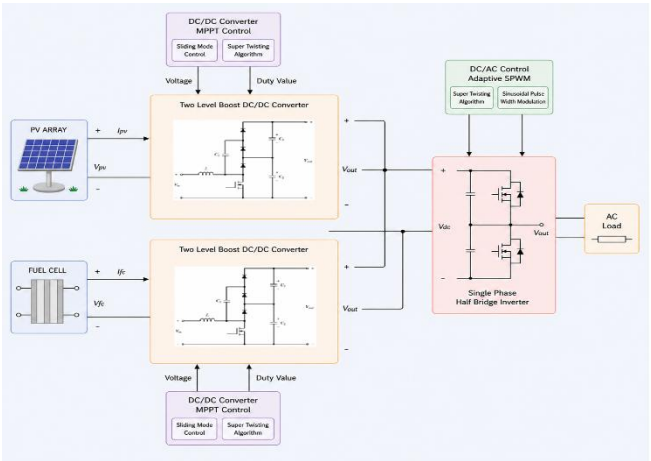


Figure 5. Proposed Model

TABLE I. PV PANEL PARAMETERS

Parameter	Value
Cell Per Module (N)	320
Open Circuit Voltage (V_{oc})	194.568
Short Circuit Current (I_{sc})	42.0224
Maximum Power Point Voltage	155.5
Maximum Power Point Current	39.396
Voltage coefficient	-0.36099
Current coefficient	0.102
Diode Saturation Current	$1.5679*10^{-9}$
Diode Ideality	0.98603
Shunt Resistance	365.3967
Series Resistance	0.39229

The values given in Table I and II are calculated by using MATLAB Simulink ready toolboxes (PV Array and Fuel Cell)

TABLE II. FUEL CELL PARAMETERS

Parameter	Value
Open Circuit Voltage	227.5
Nominal voltage	155.5
Nominal Current	466
End Voltage	129.5
End Current	787
Number of cell	20
Resistance	0.07271
Exchange current	0.25548
Alpha	0.057377

IV. RESULTS

The simulation results are presented in Figs. 6–9. Fig. 6 shows the output voltage of the PV system, while Fig. 7 illustrates the voltage characteristics of the fuel cell. These results confirm that both sources operate in a stable manner under the applied control strategy.

Figure 8 presents the DC-link/output voltage of the system. It can be observed that the voltage remains stable with low ripple, indicating effective DC/DC conversion and proper MPPT operation.

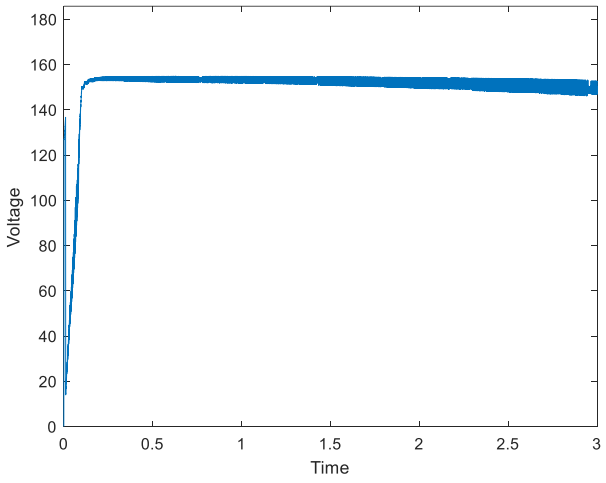


Fig. 6. PV Voltage

Figure 9 shows the output current delivered to the load. The current waveform demonstrates consistent behavior, which confirms that the inverter operates correctly under the adaptive SPWM control.

Overall, the simulation results verify that the proposed STSMC-based MPPT and adaptive SPWM approach ensures stable system operation and satisfactory output performance.

For all simulation load value is changes at 0.8 second time intervals to wanted Load, Load/2.655, and Load again.

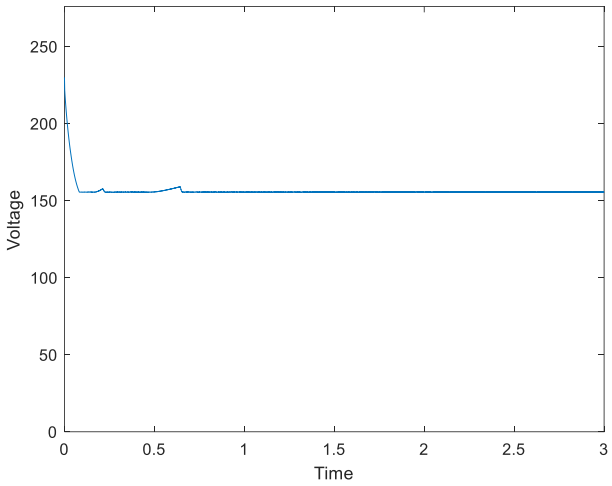
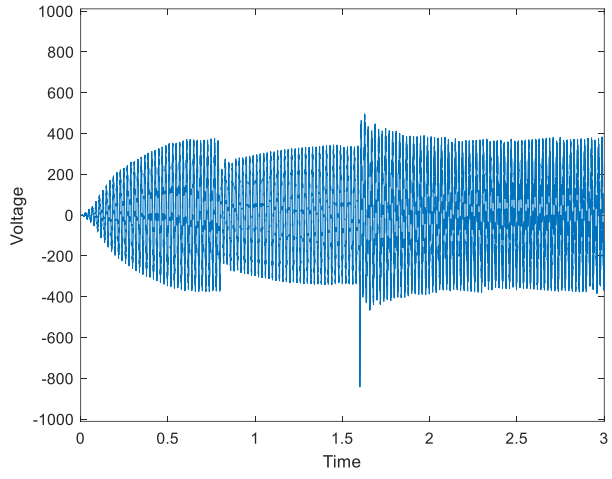


Fig. 7. Fuel Cell Voltage



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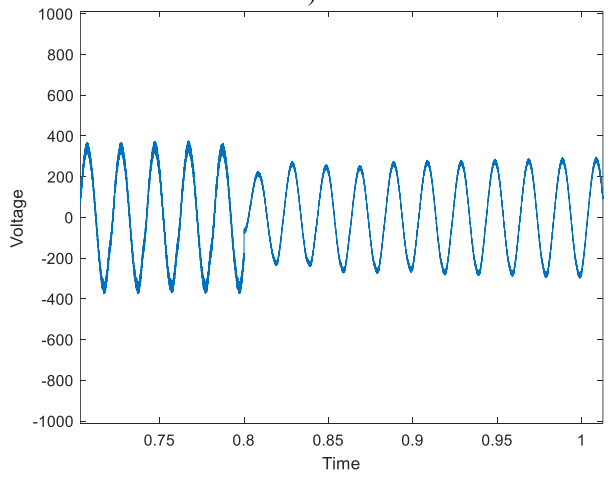
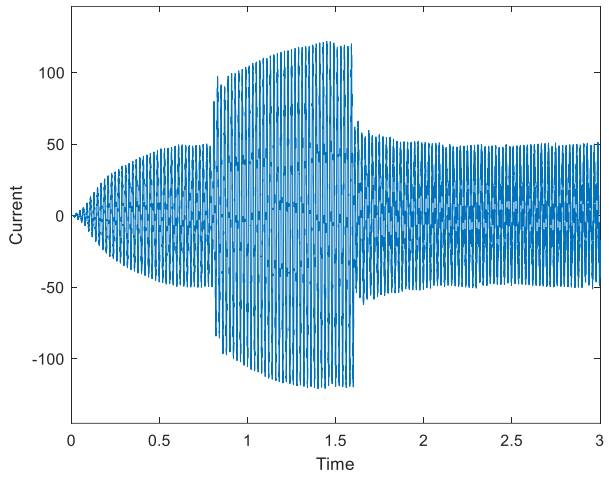


b)

Fig. 8. Output Voltage a) whole signal b) zoomed version



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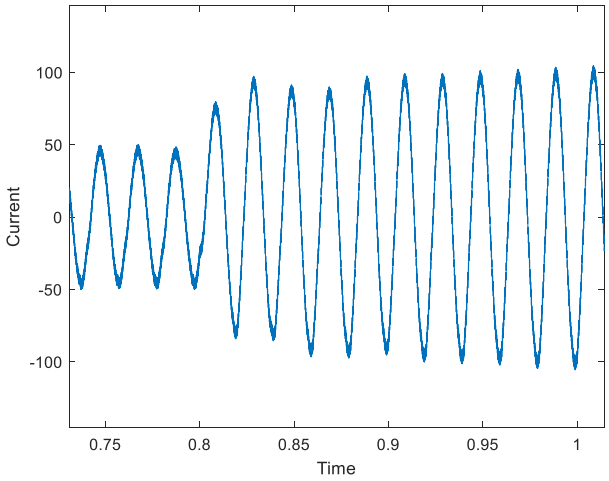

b)

Fig. 9. Output Current a) whole signal b) zoomed version

V. Conclusion

In this study, a hybrid PV–fuel cell energy system with a two-level boost converter structure was presented. A STSMC based MPPT method was applied to both energy sources to improve power extraction performance. On the AC side, an adaptive SPWM strategy based on the Super-Twisting Algorithm was implemented to regulate the inverter operation.

The simulation results show that the proposed control approach provides stable DC-link voltage and acceptable AC output characteristics. The MPPT method enables both PV and fuel cell sources to operate effectively at their maximum power points. In addition, the adaptive SPWM method improves the inverter performance by adjusting the modulation index according to system conditions.

The proposed system operates in a stable manner under the considered conditions, and the results indicate that the proposed structure is suitable for hybrid renewable energy applications.

Future work may include testing the system under variable environmental conditions such as changing irradiance and load variations, as well as implementing the control structure in real-time applications.

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