A Sliding Mode Controller for Prediction of the Maximum Power Point Tracking of Hybrid Renewable Sources

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ABSTRACT:
The integration of a fuel cell and solar cell into a generator system presents an effective solution to numerous energy-related challenges. This system consists of solar panels, fuel cells, voltage converters, and a battery or supercapacitor. The performance of this electricity generation system is influenced by various factors, including load nature, system connection, and energy management. This study focuses on maximizing power point tracking in a grid-independent mode. To optimize efficiency, a DC/DC voltage converter is employed to align the load with the characteristics of the maximum power point. The algorithms used for maximum power point tracking are categorized into three groups: perturbation and observation (P&O), incremental impedance, and artificial neural networks (ANN). In this study, we introduce two novel algorithms based on neural networks and evaluate their performance in comparison to other neural networks. Additionally, we propose a control strategy based on a selected slip level for photovoltaic generators. The proposed approach demonstrates superior and more efficient performance compared to other methods, making it a promising technology for sustainable energy generation.

KEYWORDS: Artificial Neural Network; Sliding Mode Controller; Solar Panels; Maximum Power Point Tracking.

1. INTRODUCTION

The emergence of a new paradigm in the energy sector has been driven by a range of factors, such as the depletion of fossil fuel reserves, the adverse impact of fossil fuel consumption on the environment, and the escalating cost of fossil fuels [1–4]. This paradigm shift is characterized by a focus on enhancing energy security, safeguarding the environment, and optimizing energy system efficiency [5]. In light of this, alongside a heightened focus on alternative energy sources such as solar and wind, the utilization of hydrogen may be regarded as a highly viable choice for assuming the role of energy transporter within this novel energy delivery framework [6]. In recent decades, the technology of fuel cells has undergone rapid development as a fundamental method for the simultaneous provision of electricity and heat through electrochemical means. Fuel cells ideally utilize hydrogen and oxygen as inputs to generate electricity, heat, and pure water as outputs [7,8]. It is obtained through a process that does not involve

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combustion. In comparison to alternative techniques, these systems exhibit high efficiency and minimal environmental impact [9]. The utilization of solar cells for the electrolysis of water to generate hydrogen, which is subsequently utilized by fuel cells, presents a viable solution for harnessing solar energy [10]. This is because the electricity demand is highest during periods of low solar irradiance, such as at night. Therefore, the integration of fuel cells and solar cells is a feasible approach [11]. The individual in question evaluated solar energy as a viable option for generating affordable electricity [12]. This method is both environmentally friendly and secure and can be utilized in various contexts beyond the traditional power grid [13]. Examples include remote locations that require power for electric vehicles, as well as residential customers who are connected to the grid [14].

A hybrid generator comprising a fuel cell and a solar cell has been identified as a viable solution for a range of energy-related challenges [15–17]. The aforementioned system comprises a solar panel, fuel cell, DC/DC voltage converters, DC/AC voltage converters, and either a battery or supercapacitor [18]. For optimal performance, the power control of this system is bifurcated into two distinct parts. The topic of discussion pertains to the concept of maximum power point tracking (MPPT) [19]. The power-voltage relationship of fuel cells and photovoltaic cells exhibits a peak point, whereby the system's optimal operating point corresponds to this juncture, resulting in the maximum power load and the highest efficiency of the system [20]. The location of the maximum power varies in response to alterations in the inputs of the system. Specifically, for the solar panel, changes in temperature and light intensity, and for the fuel cell, modifications in hydrogen and oxygen gas pressure and temperature can affect the point of maximum power [21]. To enhance efficiency, it is necessary to adjust the load to the attributes of this point. This is accomplished through the use of a converter [22]. The DC/DC voltage existing between the load and the solar panel or fuel cell has been terminated [23]. The significance of this matter is substantial, as evidenced by the numerous approaches that have been proposed thus far.

The perturbation and observation (PnO) technique is a commonly employed approach for maximizing the power output of solar cells [24]. The simplicity and ease of implementation of the aforementioned method are noteworthy; however, its performance exhibits fluctuations in the vicinity of the operational point, and it fails to track the maximum power point and diverges in the presence of rapid changes in environmental conditions. The hill climbing method is an alternative approach for monitoring the peak power output in photovoltaic generators [25]. The functioning of the aforementioned approach relies on P&O of the duty cycle exhibited by electronic converters [26].

Studies present a range of intelligent techniques, including artificial neural networks [27], [28], fuzzy logic [29], and fuzzy-adaptive neural networks [30], for optimizing the maximum power radiation in photovoltaic generators. The utilization of non-linear controllers in photovoltaic generators is deemed appropriate owing to their non-linear attributes, resulting in an effective response. The sliding mode controller (SMC) is a nonlinear controller that is founded on variable structure theory [31]. The SMC is a popular choice for power electronic converters and photovoltaic generators due to its advantageous features, including ease of implementation, robustness against uncertainties, and appropriate dynamic response, as reported in literature sources [32]. The utilization of SMC has been observed in the regulation of current in DC-DC converters as well as in the single-phase inverter that is linked to the grid [33].

The present study introduces a novel neural network-based algorithm for MPPT. The aforementioned algorithm was subjected to investigation in the context of a neural network. The present study introduced a novel SMC algorithm, comprising two model-dependent components and a model-independent component. The algorithm in question involves a model-dependent component that calculates the working point value for maximum power, while the model-independent component tracks the precise value of the maximum power point. The investigation of the algorithm's steady state and dynamic response was conducted under varying conditions.

2. SYSTEM SIMULATION

A fuel cell is a device utilized for the conversion of chemical energy into electrical energy. Three types of fuel cells, namely polymer fuel cells, solid oxide fuel cells, and molten carbon fuel cells, are commonly considered for deployment in the electricity distribution network [34]. The fuel cell model utilized in the aforementioned plan is of the solid polymer electrolyte variety, known for its rapid start-up capabilities, typically taking only a few seconds. Table 1 presents the features of the fuel cell.

Table 1. The fuel cell parameters.

Variable	Value	Variable	Value
E_0^o (V)	59	C_h (F)	2100
K_E (V/K)	0.00075	R_T (Ω)	0.03
τ_e (S)	80	C (F)	0.1
λ_e (Ω)	0.00355	R_{ohm0} (Ω)	0.29
R_{act0} (Ω)	1.26	R_{conc0} (Ω)	0.09

Table 2 presents the specifications of the solar panel model that is deemed appropriate. Manufacturing enterprises furnish certain parameters pertaining to the three crucial aspects of the voltage-current characteristic of solar panels, namely the connection current value, short circuit voltage value, and maximum power point current voltage value, under standard conditions of temperature and specific light intensity. Additional parameters may be computed by inputting the numerical values of said three points into the simulation equations.

Table 2. The solar panel parameters.

Variable	Value	Variable	Value
I_{mp}	2.5 A	$I_{o,n}$	9.6×10^{-8} A
V_{mp}	22.8 V	I_{pv}	2.662 A
$P_{max,m}$	60 W	V_t	26 mV
I_{sc}	2.56 A	R_P	400
V_{oc}	30 V	R_S	0.3
K_v	-0.356 V/K	a	1.3
K_I	0.024 A/K	N_S	48

DC-DC voltage converters are employed to align the load characteristic with the maximum power point characteristic of solar panels and fuel cells [35]. The selection of the DC-DC voltage converter is contingent upon the magnitude of the voltage fluctuations. The present study employs a step-up DC-DC voltage converter to achieve load matching between the solar panel and fuel cell as in (1)-(3). The schematic of the directional boost converter that has been designed is illustrated in Fig. 1.

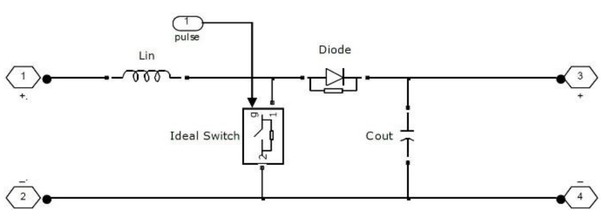

Fig. 1. DC-DC boost converter

$$L_{min} = \left[\frac{V_{\text{in (min)}} - V_{sat}}{I_{pkswitch}}\right] \quad (1)$$

$$I_{pksw\text{ itch}} = 2 * I_{\text{out}} \left[\frac{1}{1-D}\right] \quad (2)$$

$$C_{\text{out}} = \frac{I_{out}}{V_{\text{ripple}}} t_{on} \quad (3)$$

To ensure that a solar panel and fuel cell system function as a reliable power source with consistent voltage levels across varying loads, the incorporation of batteries is necessary. Fig. 2-a demonstrates that the V (DC-DC) voltage converters maintain a steady output voltage through the utilization of a battery. The battery plays a crucial role in storing and providing temporary power compensation. The present study employs a simulated lead-acid battery of the type specified in the software. The system described above exhibits optimal performance and maximum efficiency when the solar panel and fuel cell operate at their peak power output, achieved by adjusting the switching duty cycle (D) of the load from the perspective of the panel to set it at its maximum power point. The advancements in solar and fuel cell technologies have demonstrated significant progress from their initial stages to their current state, with potential for further development in the future. Fig. 2-b illustrates the variation in the solar panel output power curve in response to modifications in D.

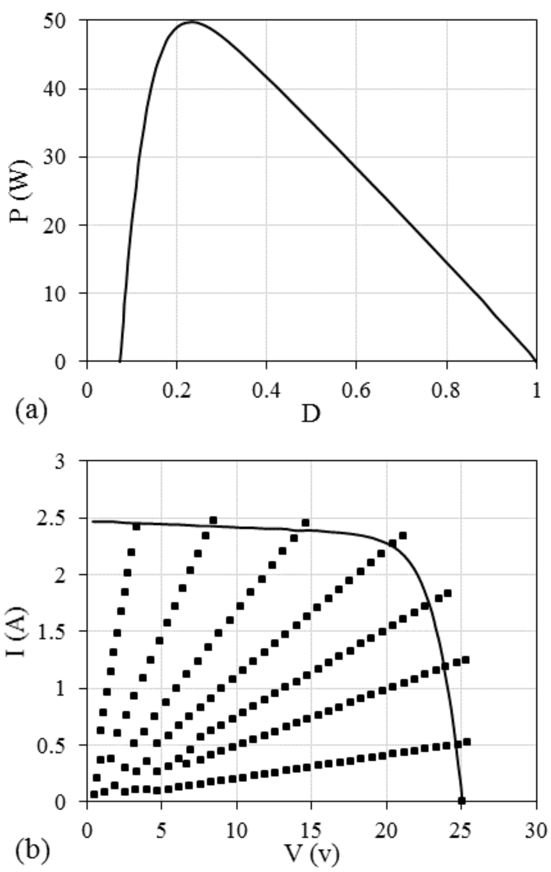

Fig. 2. a) current versus voltage,
b) Power versus switching duty cycle.

3. USING ANN TO MAXIMUM POWER POINT

TRACKING

The schematic for the controller utilized in achieving MPPT through the application of a neural network is depicted in Fig. 3-a. The neural network diagram depicts the formation and utilization of a first layer comprising two neurons, a hidden layer comprising five neurons, and an output layer comprising a single neuron. The solar panel's temperature and light intensity, as well as the fuel cell's gas pressure and stack temperature, serve as the input parameters for this network. The output value of this network corresponds to the voltage at the maximum power point. The investigation has been conducted on the element and complete recurrent neural network, also known as state reflection. The data utilized to train these networks was obtained through the SMC technique for both photovoltaic panels and fuel cells. The training process of said networks is founded upon the utilization of the error backpropagation technique.

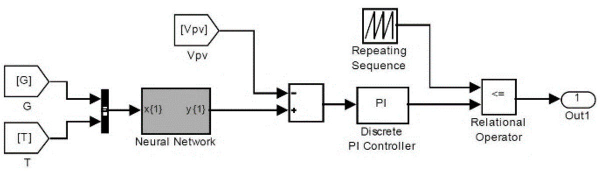

Fig. 3. Controller scheme via ANN

The neural network described previously can be utilized to derive the voltage value corresponding to the maximum power. This value can then be employed to determine the control signal of the voltage converter, denoted as D_{mpp}. Various techniques exist for computing (D_{mpp}) by utilizing the maximum power voltage. The PI controller was employed to compute the control signal value, with its coefficients being fine-tuned through a process of trial and error. The error signal or input of the PI controller is constituted by the disparity between the maximum power voltage and the instantaneous voltage.

The efficiency comparison of various MPPT techniques is conducted using (4) [36].

$$\eta_T = \frac{1}{n}\sum_{i=0}^{n} \frac{P_i}{P_{max,i}} = \frac{1}{n}\sum_{i=0}^{n} 1 - \frac{P_l}{P_{max,i}} \qquad (4)$$

The variable P_i represents the maximum power output of a given solar panel, denoted as $P_{max,i}$. Pl is loos power and n is sample size.

The aforementioned refers to either unrealized potential or underutilized resources, as well as a single instance of data collection. Fig. 4 presents the simulation outcomes for the aforementioned four networks pertaining to the photovoltaic system and fuel cell, respectively. The aforementioned findings pertain to the velocity of tracking at the onset of tracking, the highest level of power during swift alterations, and the precision of tracking as a percentage of losses.

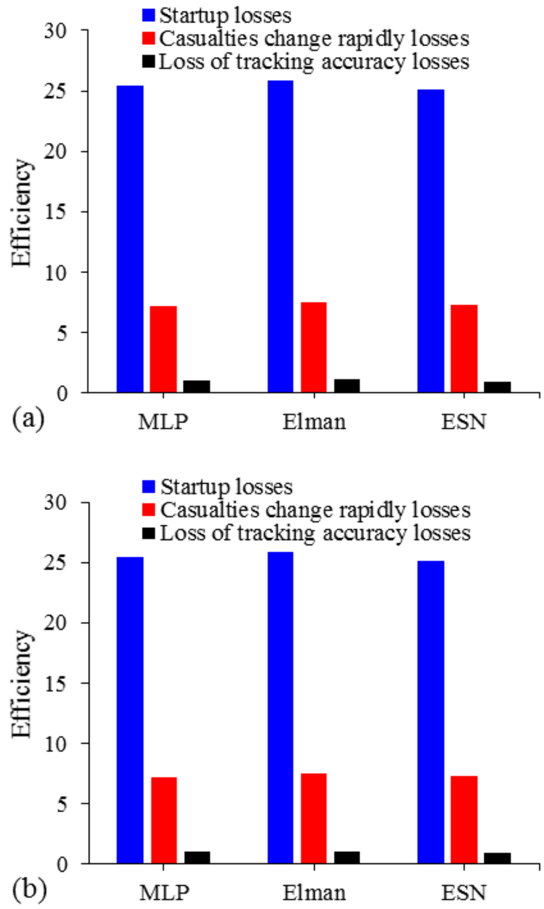

Fig. 4. Comparing the losses of a) photovoltaic system and b) fuel cell in different neural networks studied.

Table 3 displays the efficacy of various networks utilized for fuel cell generators and solar panels. As shown in this table, the ESN network exhibits superior efficacy compared to other networks.

Table 3. Efficacy of various networks.

Network	Efficiency
MLP	0.91
Elman	0.94
ESN	0.97

4. NUMERICAL RESULTS

This section presents a simulation of a photovoltaic generator utilizing a SMC designed in MATLAB/SIMULINK. The results of the simulation are analyzed for continuous conduction mode (CCM). Photovoltaic cells of a model are utilized for simulation purposes, wherein they are arranged in a configuration of 56 cells in series and 60 cells in parallel. In order to evaluate the efficacy of the suggested controller, a comparative analysis is conducted between the outcomes derived from the implemented controller and those obtained from the proposed approach, while taking into account the presence of P&O. The P&O technique is a widely recognized approach in which the magnitude of the perturbation increments significantly affects both the velocity and precision of tracking.

The power comparison between the designed controller and the P&O method is illustrated in Fig. 5. The comparison is made during the time when the solar radiation undergoes multiple changes, specifically from 1000 to 600, then to 1200, followed by 700, and finally to 500. The ambient temperature remains constant at 25 °C.

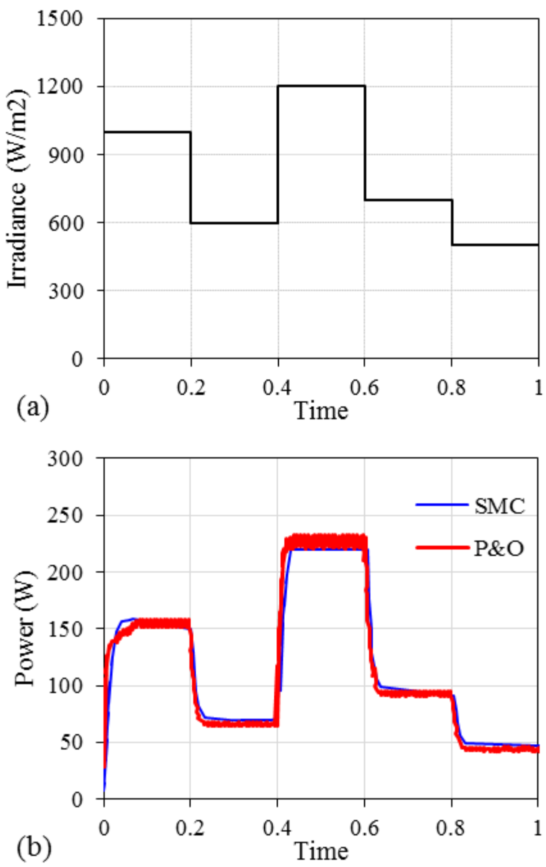

Fig. 5. a) Variations of radiation at the temperature of 25 °C, b) Comparison of SMC and P&O during radiation change.

The power comparison between the designed controller and the P&O method is depicted in Fig. 6. The comparison is made under the conditions of constant solar radiation and ambient temperature.

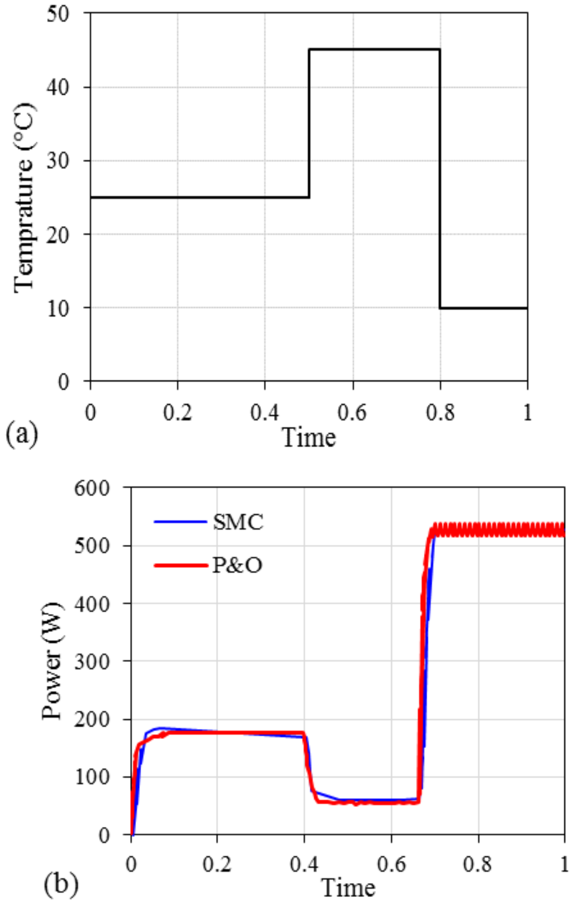

Fig. 6. a) Variations of temperature at the radiation of the 800 (W/m^2), b) Comparison of SMC and P&O during temperature change

Table 4 displays the efficacy of various networks utilized for fuel cell generators and solar panels. As can be seen in this table, the SMC and ANN method exhibits superior efficacy compared to P&O.

Table 4. Efficacy of various methods.

Radiation (W/m^2)	Efficiency		
	ANN	SMC	P&O
200	0.88	0.85	0.32
400	0.82	0.87	0.72
600	0.86	0.89	0.79
800	0.93	0.90	0.81
1000	0.94	0.92	0.86
1200	0.97	0.96	0.88

5. CONCLUSION

The integration of a fuel cell and a solar cell within a generator has been proposed as a viable resolution to a range of energy-related challenges. The aforementioned system comprises a set of components, namely solar panels, fuel cells, DC/DC voltage converters, DC/AC voltage converters, and either a battery or a supercapacitor. The performance of an electricity generation system is contingent upon various factors, including the nature of the load that is linked to the AC or DC system, the availability of an auxiliary generator, the connection or disconnection of the system to the local or national grid, and the mode of connection to the unidirectional or bidirectional network. This study examined the power generator operating in a mode that is not dependent on the grid.

The power regulation of the aforementioned system is bifurcated into two distinct components, namely, MPPT and energy management. This study focuses on the issue of MPPT.

The process of determining the maximum power of the power curve involves identifying the voltage at which fuel cells and photovoltaic cells generate the highest power output. When the operating point of the system aligns with this voltage, the system can achieve maximum power load and efficiency. However, the maximum power point is subject to variation based on factors such as solar panel input, temperature, and light intensity, as well as fuel cell hydrogen and oxygen gas pressure and temperature. To optimize efficiency, it is necessary to match the load to the characteristics of this point. This can be achieved through the use of a DC/DC voltage converter, which is positioned between the load and the solar panel or fuel cell. The significance of this issue is substantial, as evidenced by the numerous methodologies that have been proposed thus far for its execution.

The categorization of various algorithms utilized for MPPT can be classified into three distinct groups, namely: techniques founded on P&O, methods founded on incremental impedance, and algorithms founded on neural networks. The categorization of various algorithms utilized for MPPT can be classified into two distinct categories based on the model. These categories include the base model, which is model-dependent, and the free model, which is model-independent. The category of model-dependent techniques often includes neural network-based approaches, which may require periodic resetting due to temporal and solar panel characteristic variations.

The present study involved the modeling of a composite generator comprising a fuel cell, solar panel, battery, and voltage converters. The system under consideration is characterized by the ability to supply both DC and AC loads at a consistent voltage level, which is made possible by the inclusion of a battery. The present study introduces two novel algorithms for monitoring the maximum power point. The initial algorithm is founded on the principles of neural networks. This study examines the outcomes of an algorithm applied to various forms of progressive neural networks, including the static multilayer perceptron (MLP), model neural networks, and full recurrent neural networks (or state reflection). The objective of the algorithm is to monitor the maximum power point of both the fuel cell and solar panel. The study involved a comparison of the tracking speed and accuracy of losses as a percentage between the results obtained during the initiation of MPPT in rapid changes. The present study examines the superior performance of state reflection neural networks in comparison to other neural networks, as well as their notable speed. Additionally, the study affirms the positive correlation between higher education and increased financial gain.

The present study introduces the utilization of a SMC for the purpose of MPPT in photovoltaic generators. The slip signal level is evaluated based on the photovoltaic generator's power variation in response to changes in production voltage. Subsequently, a novel control strategy is proposed based on the chosen slip level. The study conducted numerical analyses on diverse disturbances using MATLAB/SIMULINK. The research evaluated the efficacy of the controller design and compared the P&O techniques. The study compared the productivity coefficient of the controller design and the P&O method in relation to variations in radiation level and temperature. The findings indicate that the proposed approach exhibits superior and more efficient performance.

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