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REVIEW ARTICLE

Comparative analysis of various global maximum power point tracking techniques for fuel cell frameworks

Mohammad Junaid Khan[1], Rashid Mustafa[2], Pushparaj Pal[3,*]

[1] *Department of Electrical and Electronics Engineering, Mewat Engineering College (Waqf), Haryana 122107, India*

[2] *Departments of Electronics and Communication, KIPM College of Engineering and Technology, Gorakhpur 273001, India*

[3] *Department of Electronics and Communication, National Institute of Technical Teachers Training & Research, Chandigarh 160001, India*

*** Corresponding author:** Pushparaj Pal, pushprajpal@gmail.com

ABSTRACT

The efficiency and performance of fuel cell (FC) systems heavily rely on their ability to track the maximum power point (MPP) of the FC stack. This research article presents a comprehensive review and comparative analysis of various global maximum power point tracking (GMPPT) techniques developed for FC systems. These techniques aim to optimize power extraction from FCs, enhance system efficiency, and improve overall performance. Through a detailed investigation and evaluation of different GMPPT methods, this study sheds light on the advancements made in this field, identifies key challenges, and provides recommendations for future research directions. The findings of this research contribute to the development of more efficient and reliable FC systems for diverse applications.

Keywords: FC systems; GMPPT techniques; perturb and observe (P&O); incremental conductance (INC); hill climbing search (HCS); fractional open-circuit voltage (FOCV); artificial intelligence (AI); neural network (NN); fuzzy logic control (FLC); genetic algorithm (GA); sliding mode control (SMC); adaptive control

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1. Introduction

An FC system is a clean and efficient energy conversion technology that generates electricity through an electrochemical reaction. It operates based on the principle of converting the chemical energy of a fuel directly into electrical energy without the need for combustion. FCs offer several advantages over traditional energy conversion technologies, including high efficiency, low emissions, and versatility in fuel sources[1]. At the core of an FC system is the FC itself, which consists of an anode, a cathode, and an electrolyte. The fuel, typically hydrogen, is supplied to the anode, while an oxidant, often oxygen from the air, is supplied to the cathode. The fuel and oxidant react in the presence of the electrolyte, which acts as a catalyst, to produce electricity, water, and heat[2]. The electrochemical reaction in an FC is typically represented by the equation:

$$\text{Fuel } (H_2) + \text{Oxidant } (O_2) \rightarrow \text{Electricity} + \text{Water} + \text{Heat} \quad (1)$$

The electricity produced by the FC can be used to power various devices and systems, ranging from small portable electronics to large-scale power generation applications. FCs can operate continuously as long as the fuel and oxidants are supplied, making them suitable for both stationary and mobile applications. FC systems are designed with various components to support the operation of the FC and ensure efficient energy conversion. These components include fuel and oxidant supply systems, control systems, cooling systems, and power conditioning systems[3]. The overall system is often complemented by energy storage devices, such as batteries or super-capacitors, to provide a stable power supply during transient load demands or when the FC is not operating at its peak efficiency.

FC systems offer several advantages, including high energy conversion efficiency, low emissions (mainly water vapour and heat), quiet operation, and fuel flexibility. They can utilize a variety of fuels, including hydrogen, natural gas, methanol, and even renewable resources like biomass or wastewater. The scalability and modularity of FC systems make them suitable for a wide range of applications, including transportation (such as FC vehicles), residential and commercial power generation, and portable power solutions[4].

FC technology has made significant advancements; challenges still exist, such as cost reduction, durability improvement, and the establishment of a reliable hydrogen infrastructure. Ongoing research and development efforts aim to address these challenges and further enhance the performance, efficiency, and reliability of FC systems, paving the way for their increased adoption and integration into a sustainable energy landscape. The proposed clock diagrams of various MPPT techniques for FC frameworks are shown in **Figure 1**.

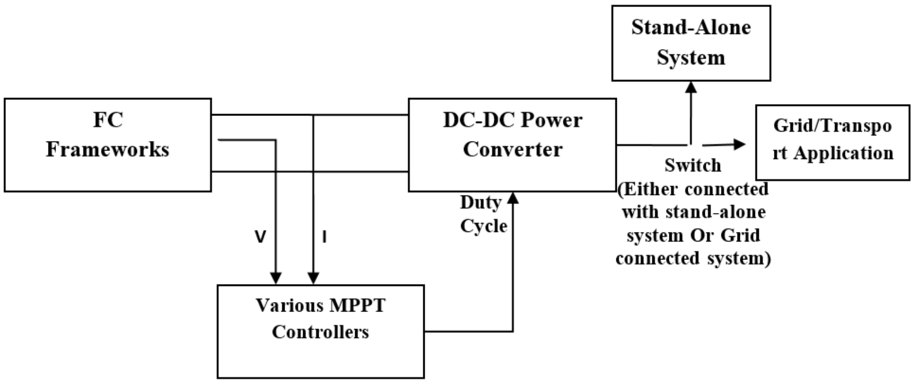

Figure 1. Proposed clock diagrams of various MPPT techniques for FC frameworks. *V* and *I* represent the voltage and current sensors respectively.

These are the sections that make up this manuscript: The description of conventional GMPPT is found in Section 2. Section 3 provides Advanced GMPPT Techniques. The Performance Metrics of FC model is described in Section 4. Section 5 presents the findings and the discussion, and Section 6 provides a summary of the study.

2. Conventional GMPPT techniques

Various GMPPT techniques are described one by one in detail.

2.1. P&O method

The P&O method is one of the most widely used conventional GMPPT techniques. It operates by perturbing the operating point of the FC system and observing the resulting change in power output. The method compares the power output at the current operating point with the previous one to determine the direction of perturbation required[5]. If the power increases, the perturbation continues in the same direction; otherwise, it is reversed. This process continues until the maximum power point (MPP) is reached. The P&O method has the advantage of simplicity and low computational complexity, making it suitable for real-time implementation. However, it may suffer from oscillations around the MPP, especially under rapidly changing environmental conditions. Additionally, the P&O method may converge to a local MPP instead of the global maximum in certain situations.

2.2. INC method

The INC method is another conventional GMPPT technique commonly employed for FC systems. This method utilizes the relationship between the power and the conductance of the FC stack[6]. It calculates the incremental change in conductance and compares it with zero to determine the direction of perturbation. The INC method continuously tracks the sign of the INC and adjusts the operating point accordingly. When the conductance is positive, indicating that the system is moving away from the MPP, the operating point is adjusted in the opposite direction. Conversely, if the conductance is negative, indicating that the system is moving closer to the MPP, the operating point is adjusted in the same direction.

Compared to the P&O method, the INC method offers better tracking efficiency and faster convergence to the MPP. It is less prone to oscillations and has a higher likelihood of reaching the global maximum. However, the INC method requires additional sensors or complex algorithms to measure or estimate the conductance, which may increase system complexity and cost.

MPPT techniques are used in various energy systems, including FCs, to optimize power output and efficiency. The MPPT algorithm ensures that the system operates at its MPP under different operating conditions, such as variations in temperature, load, and FC characteristics. Two commonly used MPPT techniques for FCs are the HCS method and the FOCV method.

2.3. HCS method

The HCS method is an iterative algorithm that continuously adjusts the operating point of the FC to track the MPP. The algorithm operates by incrementing or decrementing the operating point until a power increase is achieved[7]. A step-by-step explanation of the HCS method is

a) Initialization: start with an initial operating point (voltage/current) for the FC system.

b) Power calculation: measure the power output of the FC system at the current operating point.

c) Increment/decrement: slightly increase or decrease the operating point and calculate the new power output.

d) Power comparison: compare the new power output with the previous power output.

e) Decision making: if the new power output is higher, proceed to the new operating point and repeat steps 2–4. If the new power output is lower, reverse the direction of adjustment and repeat steps 2–4.

f) Convergence: continue the iterations until the power output no longer increases significantly. At this point, the algorithm has reached the maximum power point.

The HCS method is relatively simple to implement and provides good tracking accuracy. However, it can suffer from oscillations around the MPP, especially under rapidly changing environmental conditions.

2.4. FOCV method

The FOCV method is based on the observation that the FC voltage is proportional to the power output. This method estimates the MPP by determining the voltage that corresponds to a fraction of the open-circuit voltage (OCV) of the FC[8]. The FOCV method works with the following points.

a) Open-circuit voltage measurement: measure the open-circuit voltage of the FC, which represents the voltage when there is no load connected.

b) Fraction calculation: calculate a fraction (usually between 0.7 and 0.9) of the open-circuit voltage. This fraction is used to estimate the MPP voltage.

c) Voltage comparison: continuously measure the voltage of the FC system and compare it with the calculated fraction of the open-circuit voltage.

d) Tracking adjustment: if the measured voltage is higher than the calculated fraction, decrease the operating point voltage. If the measured voltage is lower, increase the operating point voltage.

e) Convergence: continue adjusting the operating point voltage until the measured voltage matches the calculated fraction. At this point, the algorithm has reached the estimated MPP.

The FOCV method is relatively straightforward to implement and provides stable tracking. However, it relies on accurate OCV measurements and may have reduced accuracy under rapidly changing operating conditions. Both the HCS and FOCV methods are widely used in MPPT systems for FCs. The choice of method depends on factors such as system complexity, accuracy requirements, and environmental conditions.

3. Advanced GMPPT techniques

Artificial Intelligence (AI)-based methods for FCs involve the application of machine learning and other AI techniques to optimize the performance, efficiency, and control of FC systems. These methods leverage the capabilities of AI to learn from data, make predictions, and adapt to changing conditions[9]. There are few AI-based methods commonly used in FC applications.

3.1. AI-based GMPPT methods

AI-based methods enable FC systems to adapt, optimize, and improve their performance based on changing conditions and requirements. They provide opportunities for enhanced control strategies, fault detection, optimization of operational parameters, and better overall system efficiency and reliability.

a) Neural networks: NNs are a type of machine learning model that can learn complex patterns and relationships from data. In FC applications, neural networks can be trained on historical data to predict and optimize various parameters, such as power output, efficiency, and fuel consumption. They can also be used for fault detection and diagnostics, enabling early detection of issues and improving system reliability.

b) Genetic algorithms: GAs are optimization techniques inspired by the process of natural evolution. These algorithms involve generating a population of potential solutions, evaluating their fitness, and applying genetic operators like mutation and crossover to produce new generations of solutions. In the context of FCs, GAs can be used to optimize parameters such as operating conditions, control strategies, and component sizing to achieve better performance and efficiency.

c) Reinforcement learning: reinforcement learning is a branch of machine learning that involves an agent learning through interactions with an environment to maximize a reward signal. In FC systems, reinforcement learning can be applied to control algorithms, allowing the system to learn optimal control policies based on feedback from the environment. This approach can adapt to changing operating conditions and optimize FC performance in real time.

d) Support vector machines: SVMs are machine learning models that can perform classification and regression tasks. SVMs can be utilized in FC applications for tasks such as fault detection and diagnostics. By training an SVM on labeled data representing different fault conditions, the model can classify new data and identify potential faults or anomalies in the FC system.

e) Fuzzy logic control: fuzzy logic is a mathematical approach that deals with approximate reasoning and handling uncertainty. Fuzzy logic control can be employed in FC systems to create intelligent control strategies that can handle imprecise or uncertain inputs. By incorporating linguistic variables and rules, FLCs can make decisions and adjust system parameters based on real-time sensor inputs and system states.

3.2. Model-based methods

Model-based methods for FC systems involve the development and utilization of mathematical models that describe the behavior and characteristics of the FC system. These models can be used to design control algorithms and optimize system performance. Two commonly used model-based methods for FC systems are the SMC method and the AC method.

3.2.1. SMC method

The SMC method is a robust control technique used in FC systems to regulate the system variables and ensure stable and accurate control. The SMC method works by creating a sliding surface, which is a mathematical construct that defines the desired behaviour of the system[10]. The SMC method works with the following points.

a) Model development: develop a mathematical model of the FC system that captures its dynamics and behaviour.

b) Sliding surface design: design a sliding surface based on the system variables and control objectives. The sliding surface represents the desired behaviour of the system.

c) Control law design: design a control law that drives the system states towards the sliding surface. The control law generates control signals to regulate the system variables.

d) Sliding mode dynamics: when the system states are away from the sliding surface, the control law induces a sliding motion, where the states move along the sliding surface.

e) Reaching phase and stabilization: the control law drives the system states towards the sliding surface, and during the reaching phase, the states converge to the sliding surface. Once on the sliding surface, the control law stabilizes the states and maintains them on the sliding surface.

The SMC method offers robustness against parameter variations, disturbances, and uncertainties in the system. It can provide accurate control and tracking of system variables even in the presence of external disturbances or model uncertainties.

3.2.2. AC method

The AC method is a control strategy that continuously adjusts the control parameters based on real-time measurements and system feedback. The AC method is particularly useful when the FC system's characteristics or operating conditions change over time[11]. The AC method works with the following points.

a) Model identification: develop or use a mathematical model of the FC system that captures its dynamics. This model is often an approximate representation of the actual system behaviour.

b) Parameter estimation: continuously estimate the unknown or time-varying parameters of the FC system based on real-time measurements and system feedback. This estimation process adapts the control algorithm to the changing system dynamics.

c) Control law design: design a control law that uses the estimated parameters to generate control signals for regulating the system variables.

d) Parameter update: continuously update the estimated parameters based on the measurement feedback. This update process ensures that the control algorithm adapts to the changing system conditions.

The AC method allows the FC system to adapt its control strategy and parameters to changing operating conditions, variations in FC characteristics, and uncertainties. It provides improved performance and stability over a wide range of operating conditions. Both the SMC and AC methods are model-based approaches that utilize mathematical models to design control algorithms for FC systems. The SMC method focuses on creating a sliding surface and achieving accurate control, while the AC method emphasizes parameter estimation and adaptation to changing system conditions. The choice of method depends on factors such as system complexity, desired control objectives, and the availability of accurate models and measurements.

4. Performance metrics

Performance metrics are used to assess and evaluate the effectiveness and efficiency of FC systems. These metrics provide quantitative measures that can be used for comparative analysis and evaluation[12]. There are some commonly used performance metrics for FCs:

a) Power output: power output is a fundamental metric that represents the electrical energy produced by the FC system. It indicates the system's capability to generate electricity and is usually measured in watts (W) or kilowatts (kW).

b) Efficiency: efficiency measures how effectively the FC system converts fuel into useful electrical energy. It is the ratio of electrical output power to the input energy or fuel consumed. Higher efficiency indicates better utilization of the fuel and improved overall performance.

c) Specific power: specific power is the power output per unit mass or volume of the FC system. It provides insights into the power density and compactness of the system. Higher specific power indicates a higher power output relative to the system's size or weight.

d) Voltage and current density: voltage density represents the electrical potential difference per unit area across the FC electrodes, while current density is the electrical current per unit area. These metrics provide information about the system's electrical characteristics and performance.

e) Response time: response time measures how quickly the FC system can respond to changes in load or operating conditions. A shorter response time indicates faster and more efficient system control.

4.1. Comparative study of MPPT techniques

Comparative analysis of MPPT techniques involves evaluating and comparing different methods to determine their effectiveness and performance. The goal is to identify the most suitable MPPT technique for a specific FC system. Comparative studies can be conducted based on several factors, such as tracking accuracy, convergence speed, computational complexity, and robustness against disturbances. Through such analysis, the strengths and weaknesses of each technique can be identified, helping researchers and engineers choose the most appropriate MPPT technique for their application.

4.2. Performance analysis under dynamic conditions

FC systems often operate under dynamic conditions, with variations in load, environmental conditions, and FC characteristics. Analyzing the system's performance under these dynamic conditions is crucial to understand its behaviour and optimising its operation. The performance analysis involves studying the system's response to changing inputs, such as load variations or transient events, and assessing metrics like response time, stability, and efficiency. It may also involve evaluating the performance of control strategies and MPPT techniques under dynamic conditions to ensure optimal and reliable operation of the FC system[13]. By conducting a comparative analysis and performance evaluation, researchers and engineers can gain insights into the strengths, limitations, and trade-offs of different FC systems, MPPT techniques, and control strategies. This knowledge can guide the selection, design, and optimization of FC systems for various applications.

Comparative analyses of different MPPT techniques are used in various FC systems. **Table 1** includes the references, MPPT technique, advantages, disadvantages, and research gaps associated with each MPPT technique.

The table provides a general overview, and the advantages, disadvantages, and research gaps mentioned may vary depending on the specific implementation and application of the MPPT techniques it's important to note that research in MPPT techniques is a dynamic field, and advancements are being made continually. Therefore, the research gaps mentioned above represent areas where further investigation and improvement are required to enhance the performance and effectiveness of the respective MPPT techniques.

Table 1. Comparative analysis of various MPPT techniques for FC systems.

References no.	MPPT technique	Advantages	Disadvantages	Research gap
[6], [14–19]	P&O	-Simple implementation -Fast convergence	-Prone to oscillations -May fail under rapidly changing conditions	Improving tracking accuracy and mitigating oscillation issues
[6], [8], [20–22]	INC	-Good tracking efficiency -Suitable for partially shaded conditions	-Sensitive to noise and measurement inaccuracies -Complex implementation	Enhancing noise immunity and addressing measurement inaccuracies
[7], [23–27]	FOCV	-Robust tracking under varying temperature and irradiance conditions	-Requires additional sensors -May be sensitive to system parameter variations	Reducing sensor requirements and improving robustness under parameter variations
[7], [28–32]	HCS	-Fast convergence -Suitable for rapidly changing environmental conditions	-May converge to local maxima -Can cause unnecessary power oscillations	Enhancing search algorithm to avoid local maxima and minimize oscillations
[8], [28], [33–35]	AI-based techniques (e.g., NNs, GAs)	-Adaptive and self-learning -Can handle complex system dynamics and uncertainties	-Requires extensive training and data collection -Higher computational complexity	Developing efficient training methods and reducing computational complexity

5. Challenges and future directions

FC technology has made significant progress, but several challenges remain to be addressed for its wider adoption and improved performance. Additionally, future research and development efforts aim to overcome these challenges and explore new directions. There are some key challenges and future directions in FC technology.

5.1. Effect of environmental variations

FC systems can be sensitive to variations in environmental conditions such as temperature, humidity, and altitude. These variations can affect the performance, efficiency, and durability of FCs. Future directions involve developing advanced thermal management systems, humidity control techniques, and materials that can withstand a wide range of environmental conditions. Additionally, research focuses on improving the system's adaptability and robustness to environmental variations through advanced control algorithms and optimization techniques.

5.2. Computational complexity

The implementation of advanced control algorithms, optimization techniques, and MPPT methods in real-time FC systems can be computationally demanding. Future directions aim to address the computational complexity by developing more efficient algorithms, leveraging parallel processing, and exploring hardware acceleration techniques. This would enable real-time implementation of complex control strategies and optimize the system's performance without compromising computational resources.

5.3. Real-time implementation

Real-time implementation of control strategies and MPPT techniques in FC systems is crucial for dynamic response and optimal operation. Future directions involve developing efficient and reliable real-time control hardware and software platforms that can handle the computational demands of FC systems. This includes the integration of advanced sensors, actuators, and communication interfaces to enable seamless real-time monitoring, control, and optimization of FC systems.

5.4. Hybrid GMPPT techniques

Hybrid MPPT techniques that combine the strengths of multiple methods are gaining attention. These techniques aim to enhance the tracking accuracy, robustness, and convergence speed of MPPT algorithms. Future directions involve exploring and developing hybrid MPPT techniques that intelligently combine different methods such as model-based approaches, AI-based algorithms, and heuristic optimization techniques. By combining the advantages of multiple techniques, hybrid MPPT methods can provide improved performance and adaptability across a wide range of operating conditions.

The challenges and future directions in FC technology revolve around enhancing system performance, efficiency, and durability under various environmental conditions, addressing computational complexity for real-time implementation, and exploring hybrid approaches to maximize MPPT accuracy and robustness. By overcoming these challenges and advancing technology, FCs can play a significant role in a sustainable and clean energy future.

6. Conclusion

This research article aims to contribute to the field of GMPPT techniques for FC systems by providing a comprehensive review and comparative analysis of various methods. The findings highlight the strengths and limitations of each technique, allowing researchers and engineers to make informed decisions when selecting the most suitable GMPPT approach for their specific application. By developing more efficient and accurate GMPPT techniques, the overall performance and reliability of FC systems can be significantly enhanced.

Conflict of interest

The authors declare no conflict of interest.

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