

High-Efficiency Model Predictive Current Control for Dual Stage Grid-Connected PEMFC System

Badreddine KANOUNI ¹, Abd Essalam Badoud ¹ and Saad Mekhilef ²

¹Department, Faculty, Electrical Engineering Department
University of Ferhat Abbas Setif 1, Setif, Algeria

²Department, F School of Software and Electrical Engineering, Swinburne,
Victoria, Australia

*Corresponding author; Email: badreddine.kanouni@univ-setif.dz.

Article Info	ABSTRACT
Article history: Received , 15/02/2024 Revised , 20/05/2024 Accepted , 25/05/2024	This work introduces an improved control technique for a dual-stage grid-connected proton exchange membrane fuel cell (PEMFC) power system, using model predictive current control. The first step (Boost Converter) is subjected to the use of a maximum power point tracking (MPPT) technique known as fuzzy logic. Moreover, the use of a two-level inverter serves as an intermediary component for injecting the electricity obtained from the Proton Exchange Membrane Fuel Cell (PEMFC) into the utility grid. A model predictive current control strategy has been developed with the objective of regulating the grid current and achieving synchronization between the grid voltage and current, with the ultimate goal of achieving a power factor of unity. The results obtained from numerical simulations conducted inside the Matlab/SimulinkTM environment demonstrate that the proposed Maximum Power Point Tracking (MPPT) approach effectively achieves precise tracking of the Maximum Power Point (MPP) while minimizing power oscillation in a stable state, even in the presence of temperature variations. Additionally, the MPCC ensured the integration of the extracted power into the network while maintaining a low level of total harmonic distortion (THD %) in the grid currents.
Keywords: PEMFC DC-DC FUZZY LOGIC MPC THD	

I. Introduction

The proposition to decrease carbon dioxide emissions and attain carbon neutrality has greatly accelerated the rate of low-carbon energy transition in tackling worldwide climate change.[1] The development of renewable energy has led to substantial advancements, especially in grid-connected renewable systems, which have seen a major improvement in their ability to allow the passage of energy[2].

PEMFC's excellent attributes make it well-suited for various applications, such as portable gadgets, automotive applications, and emerging energy production technologies [3,4]. This is particularly significant in light of the rapid development observed in these areas. The primary benefits of PEMFC include: 1) The proposed system exhibits a high level of power generation efficiency. 2) The system demonstrates a minimal impact on the environment, resulting in low levels of pollution. 3) The system's installation sites are subject to fewer restrictions, allowing for greater flexibility. 4) The system operates with reduced noise emissions, ensuring a quieter environment. 5) The system features a modular structure, facilitating ease of assembly and disassembly. Alternatively, there are two distinct topologies available for grid-connected systems: the single-stage topology and the dual-stage topology[5]. The initial phase is employed to amplify the voltage of the fuel cell and precisely monitor and optimize the peak power production. Unforeseeable variations in temperature and pressure

have a detrimental effect on the energy produced by PEMFC systems. To enhance the performance of PEMFC systems, various control strategies have been suggested in the literature, which involve the integration of a DC/DC converter. These techniques aim to ensure the efficient utilization of available PEMFC power and enable the system to deliver maximum power output like : P&O [6] and InC [7] are widely recognized as traditional MPPT control approaches that are commonly employed. These approaches have significant limitations and are not effective in dynamic environmental conditions due to the substantial oscillation observed near the maximum power point (MPP). Furthermore an intelligent MPPT technique such as ANFIS [8], ALO[9], and PSO[10], have been subjected to exploitation in an effort to mitigate the previous disadvantages. Nevertheless, these methodologies are intricate and are implemented with the utmost rigor in practical applications.

In order to connect the PEMFC's output to the electrical grid, the following step is to use a DC/AC inverter. Virtual flux-oriented control (VFOC) or grid-voltage-oriented control (VOC) is a standard control approach for three-phase grid-connected systems [5], One significant drawback of this control scheme is its heavy dependence on the precise adjustment of the current PI settings and the precision of coordinate transformations. In order to address those drawbacks, several researchers have suggested alternative controllers such as FL and MPC in the context of grid-connected power converters[11]. Model Predictive Control (MPC) is a robust approach to address the challenges posed by process uncertainty and nonlinearity, as well as handle constraints associated with spatial state variables. By determining a model for the prediction of the whole system, the best control can be accomplished by choosing the control mode that minimizes the evaluation function.

This paper utilizes model predictive current control (MPCC) to design a control scheme for a dual-stage grid-tied PEMFC system. A proposed FL-MPPT to effectively control the first stage and achieve precise and rapid power control of a PEMFC, even in the presence of temperature variations. Next, a PI controller is utilized to effectively regulate the DC-Link voltage to its desired reference value. Additionally, a proposed solution for effectively managing the injection of power generated by PEMFC into the grid involves the utilization of high-quality MPCC. In addition, numerical simulations using the Matlab/Simulink environment are conducted to validate the enhanced performance of the proposed control scheme. Fluctuations in temperature.

Continuing with the structure of this paper: Section 2's description of the globe system. Section 3: a three-phase inverter controller using the FCS-MPC method The findings of the simulation are presented and discussed in Section 4. The final section is Section 5.

II. Description of the Proposed System

The papers are sequentially numbered within a single publication year. The grid-connected system shown in Figure 1 is a PEMFC system with a dual-stage topology. The system has the following components: a PEMFC a DC/DC boost converter, three-phase inverters, and a passive filter consisting of inductor and resistance. The preceding aspects are interconnected in a sequential manner.

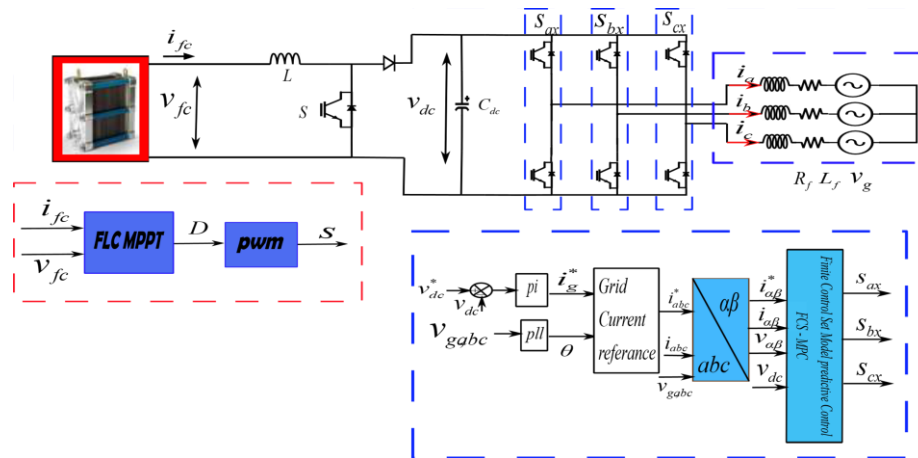


Figure. 1 single stage three level F-type grid-tied PEMFC power generation system.

III. Control of the Global System

The control of the entire system consists of three distinct phases. The first step is MPPT using integral fuzzy logic control. The second phase involves the regulation of the DC-Link voltage and the implementation of grid current control using FSC-MPC. The processes are depicted in Figure 1, along with several control blocks.

III.1. Fuzzy Logic Control:

The FLC was employed in this research to monitor the MPP. This decision was made due to the limitations associated with traditional MPPT techniques, such as the P&O and INC methods. These drawbacks include oscillations around the MPP and a prolonged time required to achieve steady-state conditions. Several researchers have suggested utilizing a FLC approach for MPPT in PEMFC to enhance the response of PEMFC systems. The adoption of the fuzzy logic approach is widely acknowledged as a model-free technique capable of effectively handling imprecise inputs and regulating non-linear systems. The components of the Fuzzy Logic Controller (FLC) system include the fuzzification interface, inference rules, and defuzzification interface.

Equations (1) and (2) represent the inputs to the Fuzzy Logic Controller (FLC), while D represents the output.

$$dE(k) = E(k) - E(k-1) \quad (1)$$

$$E(k) = \frac{P_{FC}(k) - P_{FC}(k-1)}{I_{FC}(k) - I_{FC}(k-1)} \quad (2)$$

The FLC method comprises seven membership functions, namely: negative great (NG), negative (NN), negative small (NS), zero (ZZ), positive small (PS), positive (PP), and positive great (PG). For example, in the event that the error value is deemed as "NG" and the corresponding change in error is also significantly negative, denoted as "PG," the predetermined rules dictate that the subsequent variable duty cycle be assigned as "Z." This iterative process persists until the optimal MPP is attained. The rules of the FLC can be found in Table I below.

Table I. FLC base rule

E/dE	NG	NN	NS	ZZ	PS	PP	PG
NG	Z	Z	Z	NG	NG	NG	NN
NN	Z	Z	Z	NS	Nn	NN	NN
NS	NS	Z	Z	Z	NS	NS	NS
ZZ	NN	NS	ZZ	ZZ	Z	PS	PP
PS	PS	PP	PP	PS	Z	Z	Z
PP	PP	PP	PP	Z	Z	Z	Z
PG	PG	PG	PG	Z	Z	Z	Z

III.2. Regulation of DC Link Control

In this section, the PI controller is utilized for two primary purposes. The first objective is to regulate the DC-Link voltage to its designated reference value. Additionally, the PI controller is employed to estimate the Grid reference I_g .

III.3. Model Predictive Current Control

The limited number of switching states in electronic power converters is typically used to the benefit of model predictive control algorithms. Because of this property, exhaustive search methods can be used to find the best possible state that meets the specified control requirements. The various switching states of the converter are dictated by the gating signals originating from legs S_a , S_b , and S_c . These states are then represented in vectorial form :

$$S = \frac{2}{3} (S_a + aS_b + a^2S_c) \quad (3)$$

$a = e^{j\pi/3}$ Each switching state corresponds to a certain combination of inverter phase voltages. The output voltage state vector of the inverter is defined as a consequence of the given conditions.

$$v = \frac{2}{3}(v_{aN} + av_{bN} + a^2v_{cN}) \quad (4)$$

Predictive control is used for the purpose of regulating the electrical system's current by using mathematical modeling to predict the subsequent state of the plant that requires control.

The equation provided was subjected to analysis using the Kirchhoff rule on the inverter side, as seen in Figure 1

$$: v = Ri + L \frac{di}{dt} + v_g \quad (5)$$

Where R and L represent the inductor and resistor of the grid filter. By using the Euler-Forward equation. The grid current can be approximated as:

$$\frac{di}{dt} = \frac{i(k+1) - i(k)}{Ts} \quad (6)$$

By using equation (5) and (6) the predicted grid current can written as follow:

$$i(k+1) = (1 - \frac{RL}{L})i(k) + \frac{T}{L}(v(k) - v_g(k)) \quad (7)$$

In order to translate the reference currents from the abc coordinate system to the $\alpha\beta$ coordinate system, a Clarke transformation is used. This transformation is then utilized to reduce the computing load associated with solving equation (7).

Lastly, the cost function is expressed as follows:

$$j = |i_{\alpha}^*(k+1) - i_{\alpha}(k+1)| + |i_{\beta}^*(k+1) - i_{\beta}(k+1)| \quad (8)$$

IV. Results and Simulation

Through the use of simulation within the Matlab/Simulink environment, the control strategy outlined in this work is confirmed. The current investigation makes use of the PEMFC stack, which is simulated with the help of the model presented in reference.[12] . The model has a total of 523 PEMFC units that are interconnected in a series configuration. Table I presents the electrical parameters of the global system.

In the context of MPCC, the designated value for the sampling period, denoted as " T_s ," is established as 0.00001 seconds.

During the simulation process, the system undergoes testing in the presence of varying temperature conditions while maintaining a constant pressure of 1 atmosphere.

Table.II. GLOBAL SYSTEM PAREMETRE

PEMFC parameter	Values
A	$70cm^2$
N	523
δ_1	0.994
δ_2	0.00354
δ_3	7.8×10^{-8}
δ_4	1.69×10^{-4}
λ	12
J_{max}	$1.7cm^{-2}$
Boost parameter	values
L	0.2H
C	1100 μF
Grid parameters	values
Grid voltage v_g	220V
Grid frequency f	50Hz

Grid indicator L_f	10mH
Grid resistance R_f	0.1 Ω

The simulation results obtained are shown in Figs.2 to 8.

The temperature profile shown in Fig. 3 is used to investigate the proposed control system. This profile has abrupt temperature variations, including a temperature step shift from 340K to 310K, followed by an additional shift to 325.15K, as seen in Fig. 3.

In Fig.4, the PEMFC output voltage is shown. The suggested fuzzy logic technique exhibits a precise trajectory with minimal voltage fluctuations under stable temperature conditions. Nevertheless, the occurrence of a rapid shift in temperature leads to the observation of immediate tiny fluctuations in the voltage of the PEMFC.

The efficacy of the suggested control can potentially be seen in Figures 3 and 5, which depict the output current and power of the PEMFC stack.

Fig.5 demonstrates the efficacy of fuzzy logic in achieving MPP tracking, as seen by the presence of minor power oscillations at a stable temperature condition of 340K.

During a span of 2 seconds, a significant and abrupt decline occurred, resulting in a fall from 340 Kelvin to 310 Kelvin. The control approach under consideration demonstrates efficient monitoring of the Maximum Power Point (MPP) with rapid response, while exhibiting minimal power fluctuations. In addition, notable increments from 310 Kelvin to 323.15 Kelvin occurred precisely at the 4-second mark. The control technique that has been suggested has a notable ability to accurately follow the maximum power point (MPP) while minimizing power fluctuations.

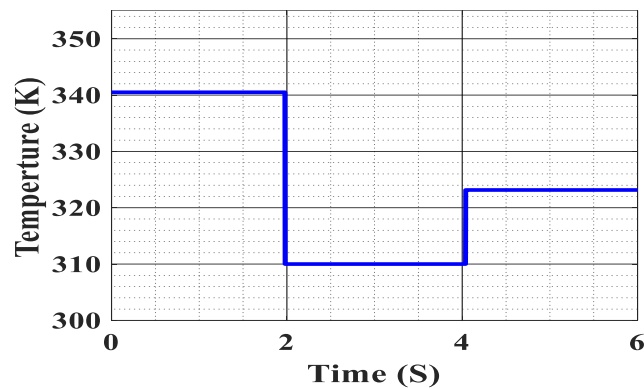


Figure. 2 TEMPERATURE VARIATION

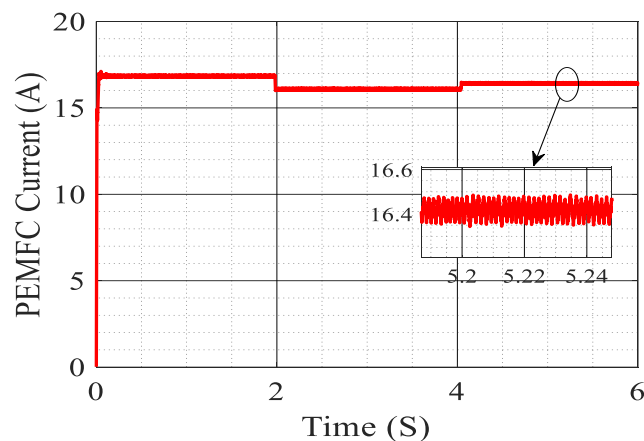


Figure. 3 PEMFC OUTPUT CURRENT.

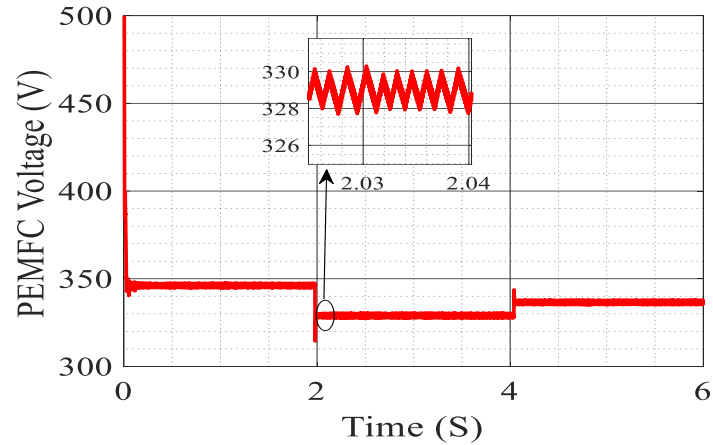


Figure . 4 PEMFC OUTPUT VOLTAGE

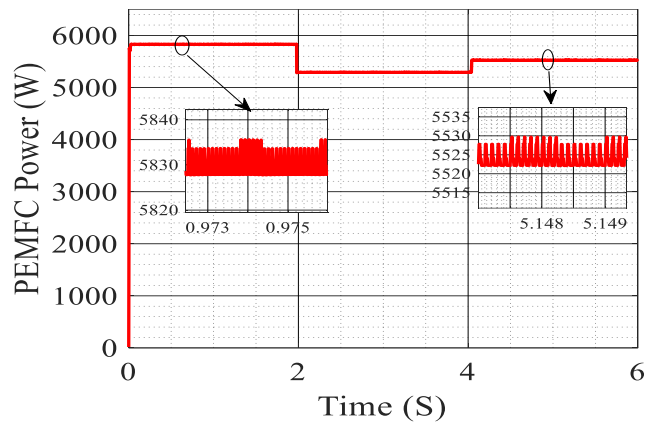
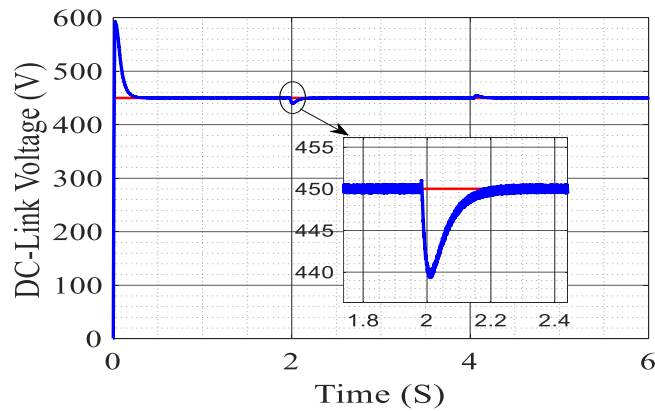


Figure .5 Pemfc Output Power.

The DC-Link voltage is effectively controlled to match its reference value during the whole test duration of [0s, 6s], as seen in Fig. 6. A discrepancy is seen at time intervals of 2 seconds and 4 seconds, causing a return to align with the reference. The observed divergence may be attributed to the abrupt shift in temperature.



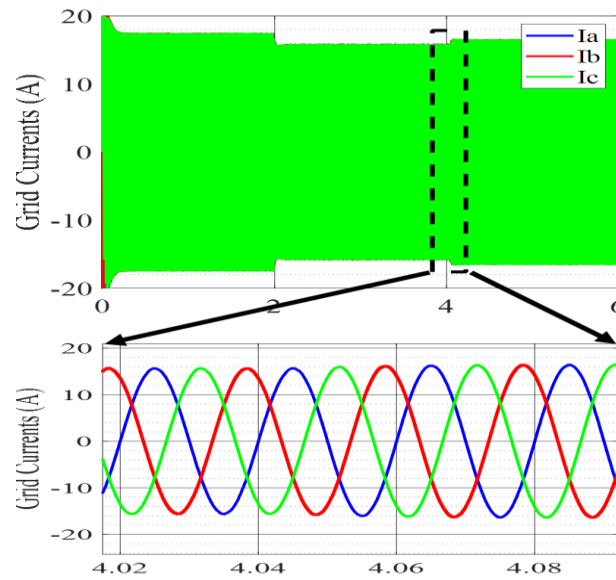


Figure 7. Waveform of Grid Current and its Zoom

Fig.8 illustrates the simulated responses of the grid voltage V_g and current I_a . It is significant to realize that the grid current exhibits a phase alignment with the grid voltage.

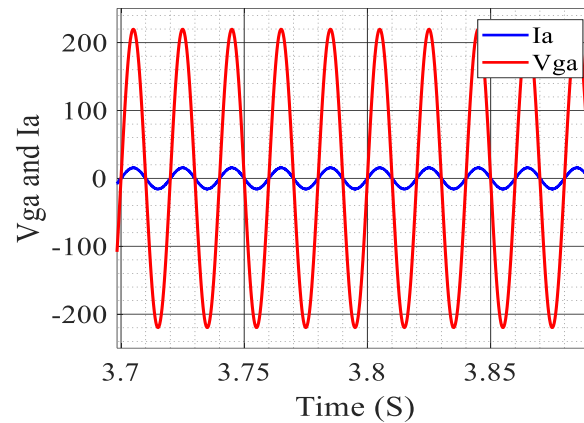


Figure .8 WAVEFORM OF GRID CURRENT AND GRID VOLTAGE.

Table III provides a summary of the THD for all temperature situations. From this table, we can see that the THD equals 0.53% in temperatures equal to 340K, 0.58 in temperatures equal to 310K, and 0.54% in temperatures equal to 323.15K. These results demonstrate the efficacy of the proposed FSC-MPC. We came to the conclusion that the THD of less than 0.60% satisfies the requirements of the IEEE 519 1992 standard for quality and accomplishment.

Table III. THD comparison

	340 K	310 K	323.15 K
THD%	0.53%	0.58%	0.54%

V. Conclusion

This research presents a novel control technique aimed at enhancing the performance of a dual-stage grid-tied PEMFC system. The control structure used in the suggested scheme is founded on model predictive current control. It encompasses three main components: MPPT control, DC-Link voltage regulation loop, and MPCC based. The purpose of this control structure is to enhance the performance of the system across various temperature circumstances. The electricity generated by the PEMFC is transmitted to the electrical grid using a two-stage

configuration, which consists of a DC-DC boost converter and a three-phase voltage source inverter. A proposed FLC has been suggested as a means of achieving MPP tracking in a boost converter. In addition, the PI controller is used to ensure the consistent maintenance of the DC-Link voltage at the appropriate value and to estimate the reference currents for the MPCC scheme. The acquired simulation results validate the viability, efficacy, and enhanced performance of the suggested control method.

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