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Boost DC-DC Converter Design for Improved Performance and Stability of Fuel Cell Using Model Predictive Control and Firefly Optimization Algorithm

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Abstract— *DC-DC converters play a crucial role in fuel cell power generation systems, serving as an interface between the fuel cell and the load. Boost converters have gained popularity due to their ability to increase input voltage. However, the performance and efficiency of DC-DC converters in fuel cell power systems have posed significant challenges. This study proposes the use of Model Predictive Control (MPC) and the Firefly Optimization Algorithm (FA) for designing and controlling boost DC-DC converters in the most efficient manner. Initially, stability analysis and precise modeling techniques were employed to optimize the characteristics of boost DC-DC converters in fuel cell power generation systems. Subsequently, the predictive control method, utilizing the Firefly optimization algorithm, was applied to enhance converter performance under diverse conditions. The outcomes of the designed control system were compared with conventional methods. Both predictive control and the Firefly optimization algorithm were integrated into the design and control processes of boost DC-DC converters in fuel cell. Based on the simulation results and stability evaluations, the application of the Firefly algorithm and predictive control led to a significant improvement, increasing the system efficiency by approximately 4.7%. These findings highlight the effectiveness of the proposed approach in enhancing the performance of DC-DC boost converters in fuel cell.*

Keywords—Fuel cell, DC-DC converters, model predictive control, stability, controllability, firefly optimization algorithm, system efficiency.

1. Introduction

Due to the many advantages which include high efficiency, low emissions, significant energy generation potential, and a variety of fuel sources, fuel cells have emerged as a new and successful technology in the power generation sector [1–3]. One of the most adaptable and well-liked energy sources in the power generation sector is said to be fuel cells. Fuel cells, however, have their own problems, much like any other technology. [4–6]. As a vital link between fuel cells and the load, DC-DC converters are fundamental to the system and must operate at peak efficiency. Due to its capacity to raise input voltage, the boost converter has emerged as one of the most popular DC-DC converters. However, there are issues with boost DC-DC converter performance and efficiency in fuel cell power generation systems. To pinpoint stability and performance concerns in boost DC-DC converters used in fuel cell power generation systems, precise stability analysis and modelling are required [7–9]. With the use of precise modelling approaches, the performance-influencing elements of boost DC-DC converters are discovered, and their pertinent parameters optimized. The selection and optimization of the inductor and capacitor values is one of the main difficulties in the design of boost DC-DC converters [10, 11].

The efficiency, stability, and output voltage ripple of the converter are highly dependent on the values of the inductor and capacitor. Therefore, for the converter to operate at its best, these parameters must be optimized. The control method is another element that impacts how well boost DC-DC converters function. The most commonly used control approach for DC-DC converters is proportional-integral-derivative (PID) control. However, PID control has limits in handling uncertainties, nonlinearities, and disturbances, which might impair the performance of the converter [12, 13]. To solve these issues, the predictive control method is presented. Predictive control is a model-based control method that employs a dynamic model of the system to forecast the future behavior of the system and compute the appropriate control action. Predictive control has been demonstrated to be successful in controlling uncertainties, nonlinearities, and disturbances, making it suited for boost DC-DC converters in fuel cell power production systems [14–16]. Predictive control model is an advanced control strategy used to improve the performance of dynamic systems. This approach can greatly improve system control by forecasting the future behavior of the system. However, in some circumstances,

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this model may suffer from mistakes that degrade control precision or induce errors in system control. For this reason, the adoption of optimization methods can considerably increase the performance of the predictive control model [17–19].

Optimization algorithms are methods that are used to discover the best value of an objective function in optimization issues. These algorithms are used to address optimization issues in various domains of engineering, computer science, basic science, economics, and other scientific fields. Evolutionary, gradient, and stochastic process-based algorithms might be cited as some of the optimization algorithms. Stochastic-based optimization algorithms are methods that are designed to solve optimization issues utilizing a random process, some of which are firefly, genetics, and ant search. In the realm of DC-DC booster converters in fuel cell, the Firefly algorithm is used to improve controller parameters [20–23]. The controller's purpose is to track the reference voltage while minimizing the output voltage ripple and ensuring the stability of the system.

Given the relevance of DC-DC converters in fuel cell power generation systems, research to improve their performance and efficiency is vital. In this paper, the design and optimal control of boost DC-DC converters in power generation systems are examined utilizing the predictive control approach and the Firefly optimization algorithm. The purpose is to increase the performance and efficiency of boost DC-DC converters in diverse situations.

2. Structure and Description

The construction of the hybrid distributed generating system incorporating fuel cells is depicted in Fig. 1. A PEM (proton exchange membrane) fuel cell, an energy storage system, and DC/DC and DC/AC power converters are the main parts of this system.

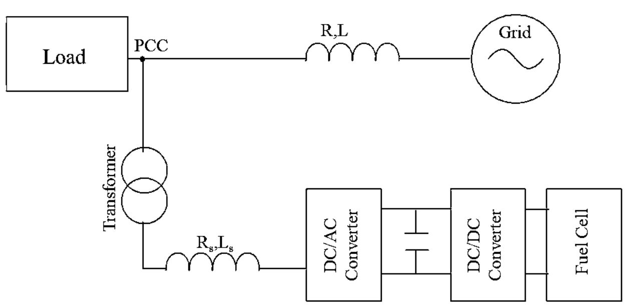

Fig. 1. Dispersed fuel cell production system.

2.1. Modeling of PEM

Due to their great efficiency and minimal influence on the environment, proton exchange membrane (PEM) fuel cells are being employed more frequently as distributed generation sources. Compared to other power generation technologies like wind and solar arrays, PEM fuel cells have advantages that can lower the costs of building a network. These advantages can be found in any part of the installed distribution system, regardless of where it is located. As a result, efficiency and dependability increase. Applying vital functions and requirements to the fuel cell system is essential to ensuring the secure and efficient integration of fuel cells with the electrical grid. This entails achieving the grid's required power quality requirements, maximizing the fuel cell system's control strategy for optimal efficiency and stability, and accurately simulating the fuel cell using an ion exchange membrane [24–26]. In order to achieve the necessary power output, save costs, and boost overall fuel cell system efficiency, proper fuel cell modelling can help to better understand the behavior of the fuel cell and offer insights for enhancing its performance. The fuel cell system must send a certain quantity of active and reactive power to the network and adjust to the time-varying characteristics of the load profile in order for fuel cells to be integrated into the power grid. Consequently, it is essential to develop efficient control mechanisms for fuel cell-based distributed generation systems to guarantee optimal and trustworthy performance [27, 28]. generation applications [29–32]. A proton exchange membrane fuel cell has been employed in this study. To maximize the effectiveness and performance of these systems, accurate fuel cell system modelling and the creation of appropriate control techniques utilizing simulation platforms like MATLAB are crucial. Equation (1) displays the fuel cell voltage based on the model's parameters:

$$V_{fc} = N_0 \left(E_0 + \frac{RT}{2F} \left(\ln \left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right) \right) \right) - rI_{f0} \quad (1)$$

P_{H_2}, P_{H_2O} and P_{O_2} are determined by equation (2):

$$\begin{aligned} P_{H_2} &= -\tfrac{1}{t_{H_2}} \left(P_{H_2} + \tfrac{1}{K_{H_2}} \left(q_{H_2}^{in} - 2K_r I_{fc} \right) \right) \\ P_{H_2}O &= -\tfrac{1}{t_{H_2O}} \left(P_{H_2O} + \tfrac{2}{K_{H_2O}} \left(K_r I_{fc} \right) \right) \\ P_{O_2} &= -\tfrac{1}{t_{O_2}} \left(P_{O_2} + \tfrac{1}{K_{O_2}} \left(q_{O_2}^{in} - K_r I_{fc} \right) \right) \end{aligned} \quad (2)$$

The constant K_r, which establishes the relationship between the quantity of hydrogen and the fuel cell current in the power generation system, is defined in Equation (3):

$$q_{H_2}^{r} = \frac{N_0 I}{2F} = 2K_r I \quad (3)$$

The reaction utilization factor (U_f), a critical variable that significantly affects the performance of the fuel cell in the power production system, can be calculated using Equation (4). The percentage of fuel that is involved in the chemical reaction is represented by this metric:

$$U_f = \frac{q_{H_2}^{in} - q_{H_2}^{out}}{q_{H_2}^{in}} = \frac{q_{H_2}^{r}}{q_{H_2}^{in}} \quad (4)$$

In order to maximize the effectiveness and cost-effectiveness of fuel cells in power production systems, a high utilization factor value must be attained. For optimum fuel cell performance, a number between 0.8 and 0.9 is typically regarded as acceptable [33, 34]. This shows that a larger proportion of the fuel is involved in the chemical reaction, increasing energy output and decreasing waste.

2.2. Converter circuit model

The circuit model of the DC/DC converter utilized in the fuel cell power generation system is shown in Fig. 2.

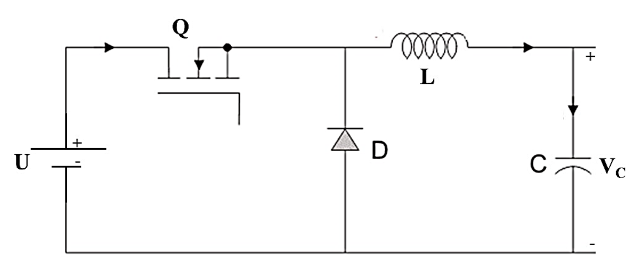

Fig. 2. Equivalent circuit of boost DC/DC converter.

A list of equations that characterize the system's dynamic behavior is provided below:

$$\begin{array}{l} \dot{i}_L = -\frac{R}{L} i_L - \left(\frac{1-d}{L}\right) v_C + \frac{U}{L} \\ \dot{v}_C = \left(\frac{1-d}{C}\right) i_L - \frac{i_O}{C} \\ y = v_C \end{array} \tag{5}$$

where i_L stands for inductor current, v_C for capacitor voltage, i_O for output current, U for input voltage, R for inductor resistance, L for inductor inductance, and d for the duty cycle of the power switch. Considering the DC-DC converter's operating conditions as follows:

$$\begin{array}{l} \tilde{i}_L = i_L + I_{LO} \\ \tilde{v}_C = v_C + V_{CO} \\ \tilde{d} = d + D \end{array} \tag{6}$$

The output voltage is denoted by V_{CO}, the average cell current is represented by I_{LO}, and the average duty cycle in the DC-DC converter is represented by D. Equation (7) is produced by substituting equation (6) into equation (5):

$$\begin{array}{l} \left[\begin{array}{c} \dot{\tilde{i}}_L \\ \dot{\tilde{v}}_C \end{array}\right] = \left[\begin{array}{cc} -\frac{R}{L} & \frac{D-1}{L} \\ -\frac{D-1}{C} & 0 \end{array}\right] \left[\begin{array}{c} \tilde{i}_L \\ \tilde{v}_C \end{array}\right] \\ + \left[\begin{array}{c} \frac{V_{CO}}{L} \\ -\frac{I_{LO}}{C} \end{array}\right] \tilde{d} + \left[\begin{array}{c} \frac{\tilde{d} V_C}{L} \\ -\frac{\tilde{d} i_L}{C} \end{array}\right] \\ \tilde{y} = \tilde{v}_C = \left[\begin{array}{cc} 0 & 1 \end{array}\right] \left[\begin{array}{c} \tilde{i}_L \\ \tilde{v}_C \end{array}\right] \end{array} \tag{7}$$

3. MPC CREATION AND IMPLEMENTATION

The dynamic system's equilibrium points 7 is equal to:

$$\tilde{i}_L = 0, \ \tilde{v}_C = 0 \tag{8}$$

The system's controller is intended to reduce the capacitor voltage to zero by altering the duty cycle d in response to variations in forward current. This makes sure that under various load conditions, the output voltage reaches the desired value. The system is linearized around its equilibrium point in order to accomplish this, producing the following equations:

$$\begin{array}{l} \dot{x} = Ax + Bu \\ y = Ex \\ x = \left[\begin{array}{c} \tilde{i}_L \\ \tilde{v}_C \end{array}\right], \ u = \tilde{d} \\ , A = \left[\begin{array}{cc} -\frac{R}{L} & \frac{D-1}{L} \\ -\frac{D-1}{C} & 0 \end{array}\right], \ B = \left[\begin{array}{c} \frac{V_{CO}}{L} \\ -\frac{I_{LO}}{C} \end{array}\right] \\ , \ E = \left[\begin{array}{cc} 0 & 1 \end{array}\right] \end{array} \tag{9}$$

We use the model predictive technique to construct the controller, which necessitates that we evaluate the system's controllability. The controllability matrix, which is defined as follows, can be used to determine the system's controllability.

$$\begin{array}{l} \phi_C = \left[\begin{array}{cc} B & AB \end{array}\right] \\ = \left[\begin{array}{cc} \frac{V_{CO}}{L} & -\frac{R}{L}\frac{V_{CO}}{L} - \frac{D-1}{L}\frac{I_{LO}}{C} \\ -\frac{I_{LO}}{C} & -\frac{D-1}{C}\frac{V_{CO}}{L} \end{array}\right] \end{array} \tag{10}$$

The controllability matrix C has full rank, as seen by the constraints on the output voltage ($V_{CO} > 0$) and the duty cycle $0 < D < 1$. This suggests that even when the current I_{LO} is 0, the system is fully controlled. Complete controllability in terms of physics refers to the ability to independently set the output voltage and current to any desired value. This article's goal is to keep the output voltage constant at the desired level for various loads in a fuel cell power generating system. Several elements should be taken into account when designing the predictive controller, including the following [35–37]:

1) Convergence to the equilibrium point quickly
2) Rapid responsiveness and stability of the system
3) The system's operational restrictions
4) The predictive controller's sensitivity to system characteristics and disturbances
5) The impact of parameter modifications on the performance of the prediction controller
6) The requirement to adjust the prediction controller's settings
7) The examination of the system's operational constraints
8) The requirement to select the proper system model
9) Choosing the best forecasting control algorithm
10) Determining and improving the quantity of ideal forecasting intervals

A key variable in the predictive controller is the duty cycle parameter d, which has a value between 0 and 1. It should be noted that a higher duty cycle could prevent the system from establishing itself.

$$\begin{array}{l} 0 < d < 1 \Rightarrow -D < \tilde{d} = -Kx \\ < 1 - D \end{array} \tag{11}$$

The descriptions given above emphasize the necessity of striking a compromise when building a predictive controller between the rate of convergence to the equilibrium point, transient responsiveness, and the practical constraints of the actual system. A predictive controller was created and tested on a sample system in the simulation portion of this study to compare its performance against a highly accurate average model of the system. To guarantee the controller operates optimally and steadily, it is crucial to take into account the performance requirements of the fuel cell power production system when building and testing the controller. As a result of the mode predictive controller's great sensitivity to system parameters and disturbances, it can make steady-state errors in the real system response if the parameters change significantly or are not exactly stated at the outset. This problem can also be made worse by disregarding key factors like switching losses, direct voltage, and diode resistance. The predictive controller can be supplemented by an integral controller based on equation (12) to solve this issue. The integrator's use can slow down the system's reaction, which is a significant disadvantage even if it can reduce steady-state faults. Therefore, it is vital to strike a compromise while developing the controller for the fuel cell power generation system between steady-state accuracy and system response time.

$$\tilde{d} = -Kx + K' \int \tilde{y}(t) dt \tag{12}$$

4. PROPOSED CONTROL

We can list the following as shortcomings of the suggested model: inaccuracy in system modelling, improper modelling of environmental circumstances, disregard for external impacts, lack of model adaptation, and lack of model dynamics. In this article, the Firefly algorithm was utilized to address the aforementioned flaws and obtain ideal performance. The predictive control model in MPC control can be strengthened by using the optimization technique known as the firefly algorithm. The parameters of the model can be enhanced using the Firefly algorithm, and the system output can be predicted more precisely.

4.1. Firefly algorithm

The Firefly optimization algorithm is used to optimize the parameters of the controller in the predictive control method. The Firefly optimization algorithm is a metaheuristic optimization algorithm inspired by the flashing behavior of fireflies. The Firefly algorithm has been shown to be effective in solving complex optimization problems in various fields. The Firefly algorithm works by simulating the flashing behavior of fireflies.

The brightness of a firefly is proportional to its fitness value, and the brightness decreases with distance between fireflies. The algorithm starts with an initial population of fireflies, and then the fireflies move towards brighter fireflies until the optimal solution is found. In the context of boost DC-DC converters in fuel cell power generation systems, the Firefly algorithm is used to optimize the controller parameters. The Firefly algorithm searches for the optimal values to achieve the desired performance of the converter. The algorithm takes into account the nonlinearities and uncertainties in the system, ensuring that the controller is robust and performs well under different operating conditions. The predictive control method is used to regulate the output voltage of the boost DC-DC converter. The predictive control method uses a dynamic model of the system to predict the future behavior of the system and calculate the optimal control action. The dynamic model takes into account the nonlinearities and uncertainties in the system, ensuring that the controller is robust and performs well under different operating conditions. The predictive control method is implemented using the Firefly algorithm. The controller regulates the output voltage by adjusting the duty cycle of the converter. The light intensity at a distance r is represented by the formula $I = I_0 e^{-\gamma r}$, which is a combination of light absorption $I = I_0 e^{-\gamma r}$ formulas, resulting in equation (13). The attractiveness of a firefly (β) is calculated using similar formulas and equation (14):

$$I = I_0 e^{-\gamma r^2} \approx \frac{I_O}{1+\gamma r^2} \tag{13}$$

$$\beta = \beta_0 e^{-\gamma r^m} \approx \frac{\beta_O}{1+\gamma r^m} \tag{14}$$

The level of a Firefly's attractiveness is determined by the parameter m in the Firefly algorithm, where m is a non-negative value. When m is zero, the firefly's allure is constant, no matter how far away it is. The attractiveness of the firefly, however, drastically declines with increasing distance as the value of m rises. In other words, the firefly's attraction never reaches zero, and its value is consistently higher than one. The spatial position and the reciprocal of the square of the distance are functions of the parameter γ , which is employed in the light intensity formula. It is advised to use the distance-based parameter $\Gamma = 1/\sqrt{\gamma}$ in order to remove the dependence on spatial position. whose former position was and is being drawn to the firefly in position by lighter, is determined using equation (15), which in this case represents a random vector with a uniform or Gaussian distribution. The mutation coefficient is α , and the light absorption coefficient is γ. Until the algorithm approaches convergence, the value of can be increased or decreased, and this change can be either linear or exponential [17, 38–42].

$$x'_i = x_i + \beta_0 e^{-\gamma r^m}(x_j - x_i) + \alpha\varepsilon_i \tag{15}$$

Fig. 3 depicts the Firefly algorithm's execution procedure.

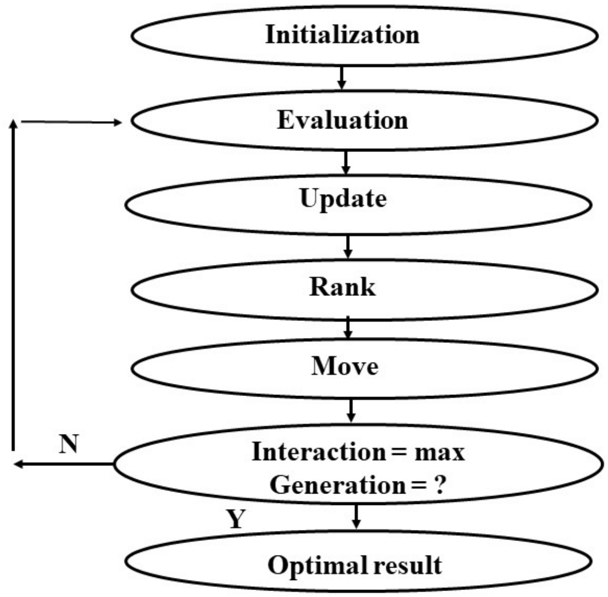

Fig. 3. Firefly algorithm.

5. Simulation

This section focuses on the analysis of the Firefly algorithm-based predictive controller's performance for a hypothetical fuel cell power generation system. This investigation's main goal is to assess how well the suggested control technique works in reducing steady-state errors and enhancing the system's response time. This section focuses on the analysis of the Firefly algorithm-based predictive controller's performance for a hypothetical fuel cell power generation system. This investigation's main goal is to assess how well the suggested control technique works in reducing steady-state errors and enhancing the system's response time. Fig. 4 shows the new control structure's implementation procedure.

Suppose:

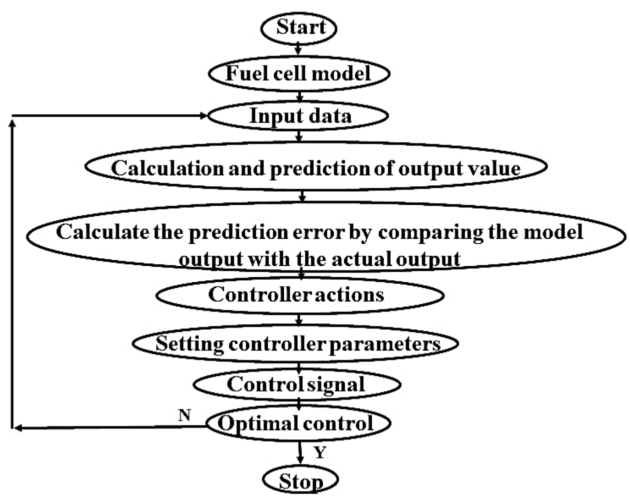

Fig. 4. The procedure for putting in place a new control system.

$$\begin{array}{l} U = 200v,\ V_{CO} = 400v \Rightarrow\ D = 0.5, \\ I_O = \left[\begin{array}{cc} 40 & 80 \end{array}\right] A \Rightarrow\ L_{LO} = \left[\begin{array}{cc} 80 & 160 \end{array}\right] A \\ L = 12mH,\ C = 2500\mu F,\ R = 0.001\Omega \end{array} \tag{16}$$

The main goal of the control strategy design is to maintain output voltage stability for various loads ($I_O = 80A$ and $I_O = 160A$). The open loop system's pole values, $POL = [-0.0417 + j91.2871, -0.0417 - j91.2871]$, are near the imaginary axis and show a steady convergence to the desired equilibrium position. Fig. 5 shows the controller's performance on the nonlinear averaging system. Figs. 5-(a) and 5-(b) exhibit Control of the input current and output voltage in the converter's nonlinear average model, demonstrating how quickly the system error approaches zero. Fig. 5-(c) provides proof that the condition $-D = -0.5 < \tilde{d} = -Kx < 1 - D = 0.5$ is true.

Fig. 6 provides a comprehensive visualization of the controller's performance, specifically concerning the precise model of the DC-DC converter. In Figs. 6-(a) and 6-(b), the input current and output voltage in the accurate converter model with the

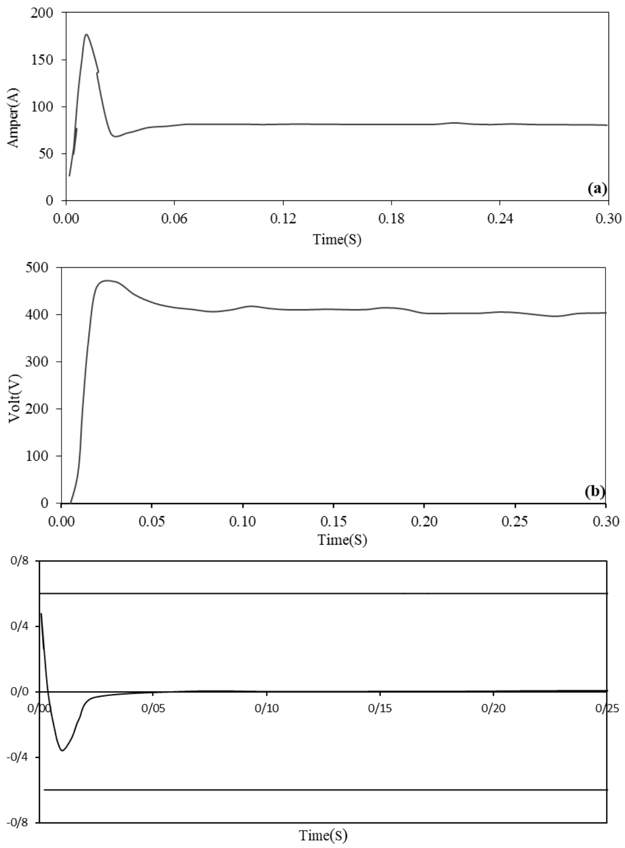

Fig. 5. Control of the input current (a), output voltage (b), and control signal (c) in the nonlinear average model of the converter.

predictive controller are meticulously portrayed. The striking results unequivocally demonstrate the system's resilience. Despite fluctuations in the output current, stabilized at the value of 0.73, the system's output voltage and current consistently converge towards the predefined nominal values. These findings underscore the robustness and effectiveness of the predictive controller, affirming its ability to maintain stability and accuracy even under varying operational conditions. Such conclusive evidence solidifies the pivotal role of the proposed methodology.

However, a closer look at the output voltage in Fig. 6 reveals that it approximates the target value with a reasonably consistent error rather than following it exactly. In comparison, the system's average has zero inaccuracy. The reason for this is that the typical system does not take into account unknown characteristics such as the direct voltage of the diode, its resistance, switching losses, and fluctuations in the input voltage brought on by the fuel cell. The accurate model of the DC-DC converter accounts for these factors, which cause a permanent mistake in the output. The Firefly method was applied in this article in an effort to zero out the output's permanent inaccuracy. The light absorption coefficient (0.1-1) and step size (0.1-0.01) are taken into account in the firefly method, which has 100 worms and repeat steps. Fig. 7 displays the simulation outcomes based on the precise converter model.

The simulation results illustrate the successful convergence of the converter's output voltage to the predetermined nominal value, demonstrating precise and error-free operation. Notably, the enhanced prediction capabilities facilitated by the Firefly algorithm are visually evident in Fig. 8, underscoring the algorithm's effectiveness. To further validate the efficacy of the designed control approach, an additional simulation was conducted. This simulation introduced variations in the load current within the DC connection, ranging from $A60$ to $A80$.

Fig. 9 illustrates how load fluctuations affect the DC link voltage

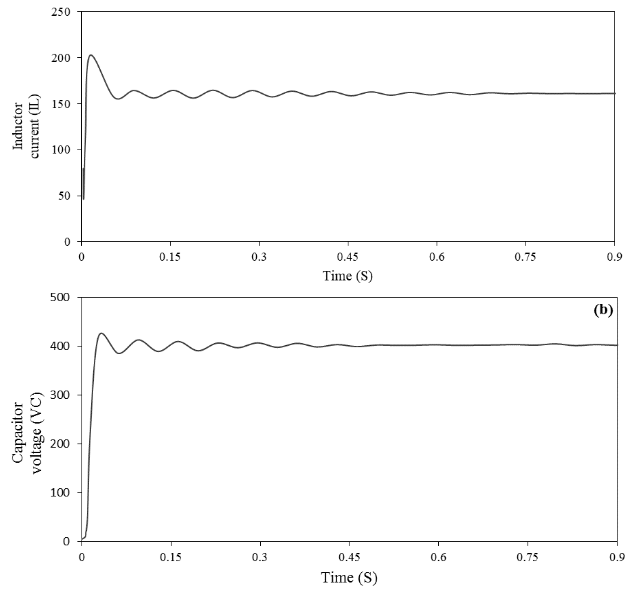

Fig. 6. In an accurate converter model with a predictive controller, input current (a) and output voltage (b).

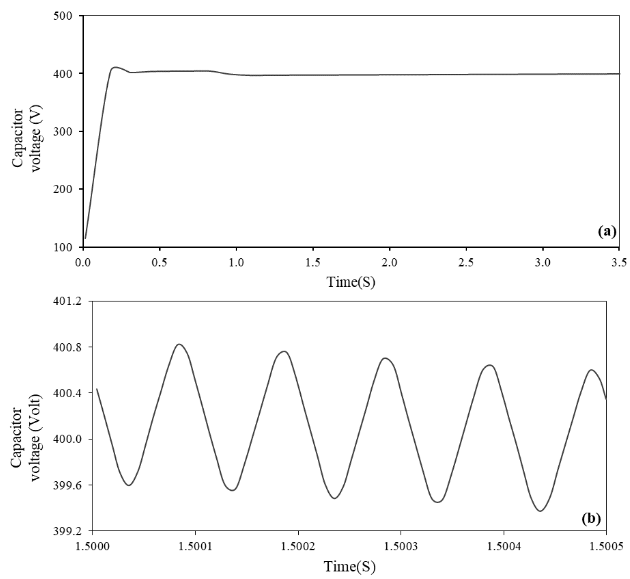

Fig. 7. In the exact model of the converter with the firefly algorithm, input current (a) and output voltage (b).

as well as the output voltage and current (9-(a, b)) of the fuel cell. The output voltage of the DC-DC converter is maintained at $400V$ (9-(c)) despite variations in load. Additionally, as the load current increases, the fuel cell's output voltage decreases.

Fig. 10 shows the nonlinear average converter model's input current and output voltage control as well as the predictive controller's control signal $\tilde{d}$, which represent typical operation. Fig. 10-(c) reveals that the admission criteria have not been met, though.

6. CONCLUSIONS

In this study, we utilized a predictive control approach in conjunction with the Firefly algorithm to conduct an in-depth analysis of the performance and optimization of a boost DC-DC converter within fuel cell power generation systems. The primary objective was to exploit the capabilities of the Firefly algorithm

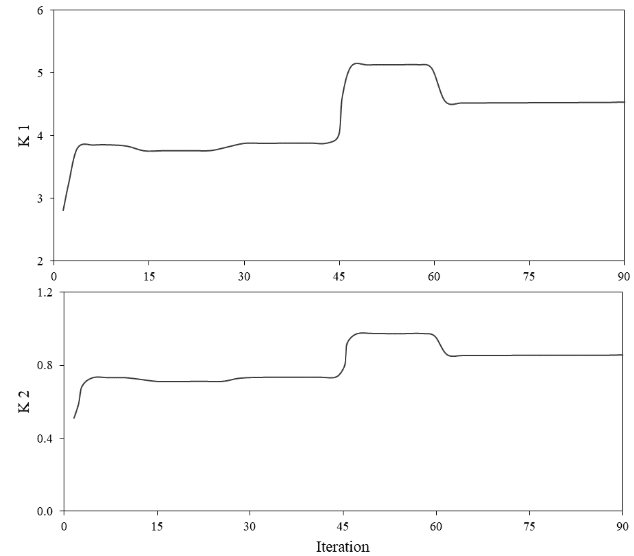

Fig. 8. Variations of predictive control gains using firefly algorithm.

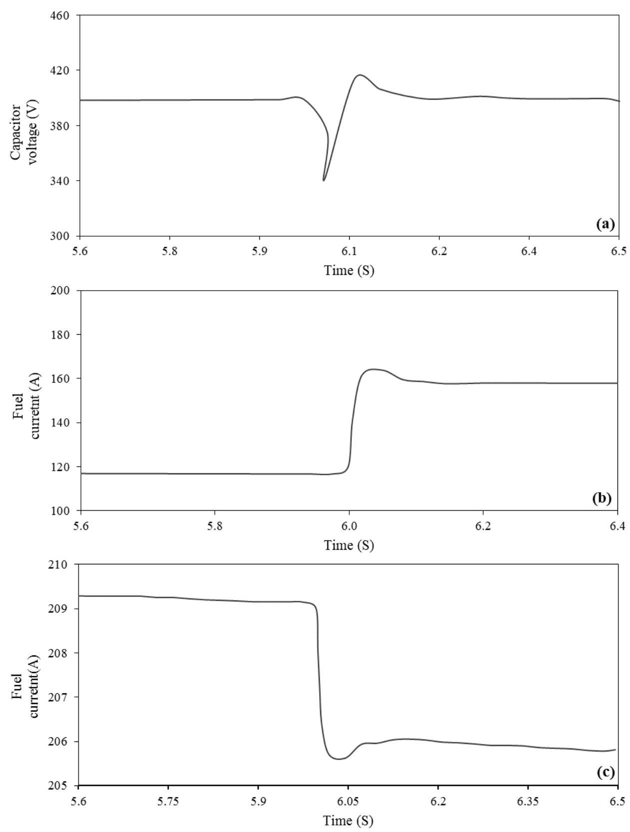

Fig. 9. The precise converter model's input current, fuel cell voltage, and output voltage with a change in load at the instant $t = 6$ seconds for the suggested controls (a, b, and c).

and predictive control methodology to significantly augment the efficiency and performance of fuel cell power generation systems. To achieve this objective, we initially developed a precise mathematical model for the boost DC-DC converter, employing fundamental electronic equations and rigorous system modeling techniques.

Subsequently, the Firefly algorithm was deployed to optimize the system's performance by implementing predictive control strategies. The simulation results demonstrated a remarkable enhancement in

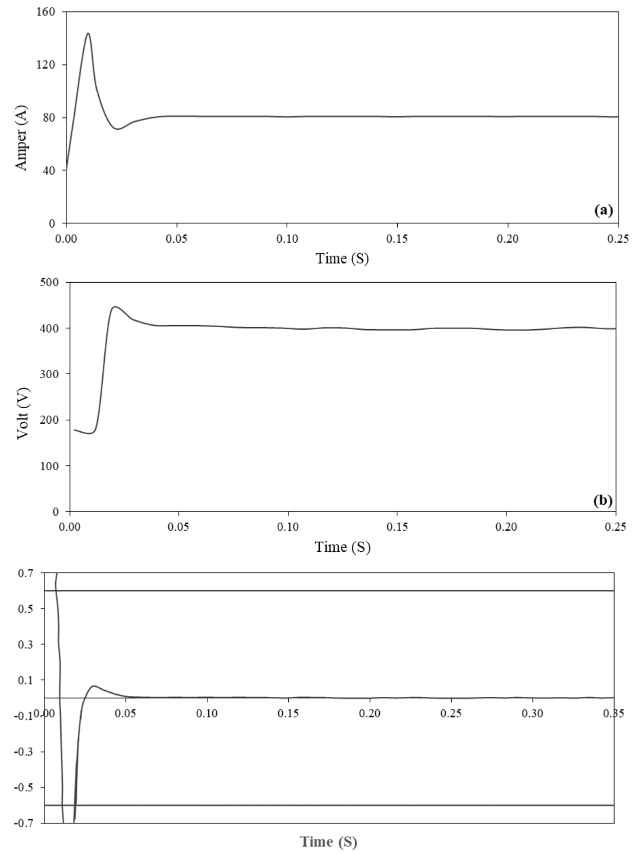

Fig. 10. (a, b) The nonlinear average converter model's input current and output voltage control, and (c) the predictive controller's control signal $\tilde{d}$.

the efficiency and performance of the fuel cell power production system, with an improvement of approximately 4.7% achieved. Notably, the incorporation of the Firefly algorithm in the design of the boost DC-DC converter controller facilitated the system's output to reach its optimal state, showcasing robust performance under diverse load conditions. The accuracy of the converter was further validated using the Firefly algorithm in medium-sized models, confirming its suitability for practical applications.

Furthermore, our findings indicate that the integration of the Firefly algorithm and predictive control methodology can serve as highly effective reactive approaches for managing and enhancing power generation systems. This innovative approach not only advances the existing knowledge in the field but also paves the way for the development of advanced power generation systems integrating highly efficient and effective DC-DC converters.

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