A New Effective Robust Nonlinear Controller Based on PSO for Interleaved DC–DC Boost Converters for Fuel Cell Voltage Regulation

Samir Abdelmalek¹, Ali Dali², Maamar Bettayeb³, Azzeddine Bakdi⁴

¹Faculty of Technology, Department of Electrical Engineering, University of Medea, Algeria;
Email: samir_aut@yahoo.fr

²Renewable Energy Development Center (CDER), Algeria.
Email: a.dali@cder.dz

³Department of Electrical and Computer Engineering, University of Sharjah, United Arab Emirates, and Center of Excellence in Intelligent Engineering Systems (CEIES), King Abdulaziz Univeristy, Jeddah, KSA.
Email: maamar@sharjah.ac.ae

⁴Department of Mathematics, University of Oslo, 0851 Oslo, Norway
Email: bkdaznsun@gmail.com

Abstract:

Output voltage regulation of DC–DC converters has recently gained an increasing attention to face the many system nonidealities. The fast switching behaviour is nonlinear time-varying, the presence of model and measurement uncertainties, and large variations, are all inherited challenges. The aim of the present work is to design a robust nonlinear controller that ensures satisfactory and robust output voltage regulation for a Proton-Exchange Membrane Fuel Cell (PEMFC) based on a DC–DC Interleaved Boost Converter (IBC). A state space model of the DC-DC IBC is first derived using the state space averaging technique and a mathematical model is constructed for the PEFMC. In this regard, a robust nonlinear controller and a Proportional Integral (PI) controller are proposed. The controllers are tuned though Particle Swarm Optimization (PSO) algorithm to estimate their good parameters assuring the desired performance is met. The Integral of Absolute Error (IAE) criterion is used to improve the dynamic performance of the overall controlled system. Furthermore, the closed loop stability is analysed using the Lyapunov stability theorem, and the effectiveness of the closed-loop system is validated under various operating

conditions of the PEMFC and load perturbations. Compared to other methods, the obtained results demonstrate a superior performance of the proposed control strategy in terms of its robustness to variations and uncertainties, smooth tracking of a varying set-point and faster transients.

Keywords— Interleaved boost converter; Proton-Exchange Membrane Fuel Cell; PSO algorithm; Nonlinear control; PSO-PI controller; Current ripples.

Nomenclature

V_c	The output voltage	E	The controlled voltage source
V_{fc}	The Fuel Cell source voltage	E_{oc}	Open circuit voltage (V);
L	The inductance	N	Number of cells;
C	The capacitance	A_f	Tafel slope (V);
D_1, D_2	The duty cycles of each phase	i_0	Exchange current (A);
I_{L1}, I_{L2}	The inductors current	T_d	The response time (at 95% of the final value)
I_{fc}	The fuel cell current,	R_{ohm}	Internal resistance (Ω);
I_R	The resistor load current	i_{fc}	Fuel cell current (A);
I_c	The capacitor current	V_{fc}	Fuel cell voltage (V).
u	The average duty cycle	x_h	Percentage of hydrogen in the fuel (%)
z	Number of moving electrons ($z = 2$)	y_h	Percentage of oxygen in the oxidant (%)
E_n	Nernst voltage (V)	V_{cref}	Desired voltage
α	Charge transfer coefficient	I_{fc_d}	Desired fuel cell current
P_{H2}	Partial pressure of hydrogen inside the stack (atm)	k_1, k_2, k_3	Parameters of the proposed controller
P_{O2}	Partial pressure of oxygen inside the stack (atm)	K_p, K_i	Parameters of the PI controller
k	Boltzmann's constant (1.38×10^{-23} J/K)	t	The iteration number;
h	Planck's constant (6.626×10^{-34} J s)	j	The particle number;
ΔG	Activation energy barrier (J)	p_j	The individual best solution of particle j at a given stage;
T	Temperature of operation (K)	p_g	The global best solution;
Kc	Voltage constant at nominal condition of operation	C_1, C_2	The acceleration parameters;
P_{fuel}	Absolute supply pressure of fuel (atm)	r_1, r_2	Random numbers uniformly distributed
P_{air}	Absolute supply pressure of air (atm)		
V_{fuel}	Fuel flow rate (l/min)		
V_{air}	Air flow rate (l/min)		
P_{H2O}	Partial pressure of water vapor (atm).		
w	Percentage of water vapor in the oxidant (%)		

Abbreviations

PEMFC	Proton-Exchange Membrane Fuel Cell
IBC	Interleaved Boost Converter
PI	Proportional Integral
PSO	Particle Swarm Optimization
IAE	Integral of Absolute Error
FCs	Fuel Cells
EVs	Electric Vehicles
MPC	Model Predictive Control
LTI	Linear Time-Invariant
PSO-PIC	PSO-tuned PI controller
PSO-RNC	PSO-tuned robust nonlinear controller

1- Introduction

In the last few decades, Fuel Cells (FCs) have emerged as a potential alternative solution to fossil-fuel energy sources [1]. In addition, they are considered among the most promising technologies for electrical power generation [2]. Fuel cells are capable of converting chemical energy directly into electrical energy, without any intermediate step. The electrical efficiency of FCs is therefore considerably higher than the other traditional sources for generating electrical power. Fuel cells are widely used in a broad range of applications, and mainly in the transport industry and electric Vehicles (EVs) [3] as a replacement for conventional engines. FCs are also used for low power generation as they offer many advantages such as low operating temperature, fast response to load changes, high power density, low corrosion, very low noise and environmental friendliness [1, 2, 4,5]. Types as well as advantages and drawbacks of fuel cell membranes are all summarized in [6]. However, the connection of FC elements and the system operation should accomplish technical qualifications to ensure a high-power quality and reliable generation [7, 33]. Power quality problems may cause many effects such as irregular switching [39, 40], hardware damages [41], and overheating; and while the FC output voltage and power are highly dependent on the connected load, effective and robust controllers of FC converters must be adopted to control the power flow and maintain a smooth and safe power generation.

DC-DC boost converters are usually required in industrial power applications of low output voltage such as renewable energy sources. Due to their increasing scope of utilization, these devices are becoming a subject of increasing interest, and they are classified into many different topologies [8, 9]. In general, DC-DC converters are employed to adapt the voltage and current levels between sources and loads while guarantying a low power loss in power generation systems [10, 11]. The DC-DC converter is an essential part of the fuel cell power generation to control the delivered power/voltage. Incorporating PEMFC dynamics with a classical DC-DC converter makes the voltage regulation task quite challenging [12]. In this context, the interleaved boost DC-DC converter (IBC) can be used [13] to meet this challenge. The IBC is considered as a good solution due to its merits, such as high efficiency, increasing the power level and minimizing the current stress on the power switches [14, 32]. IBCs also reduce the current ripple in the input and output circuits, manage the high FC current by sharing between two legs, have a soft switching through a quasi-resonance technique, and have a fault tolerant capability in case of a power switch fault [15]. Other advantages of the IBCs are their faster dynamics, light weight, higher efficiency, and low input voltage applications.

With regard to the literature, different kinds of control strategies were employed for interleaved boost DC-DC converters for different applications such as adaptive control [16], robust control [10], nonlinear model predictive control (MPC) [17], state feedback control [18, 25], sliding mode fuzzy PID control [19], robust adaptive neural network control [20, 21], adaptive sliding mode control [22, 23], intelligent control [24], and Optimal Robust Linear Quadratic Regulator (LQR) [26]. However, among the aforementioned control techniques, the problem of designing an optimal robust nonlinear controller was not reported before. Therefore, the aim of this work is to design a robust and highly effective nonlinear control law based on PSO algorithm. The objective of the design is to address the system nonlinear time varying behaviour, aim for optimal performance in face of large variability, and increase robustness to uncertainties and disturbances.

The contributions of this work can be highlighted as follows: i) Use of a new topology based on DC-DC IBC rather than the classical boost DC-DC converter for improving fuel cell output regulation, ii) Design and validation of a novel robust nonlinear controller for output voltage regulation under varying loading conditions, iii) The proposed strategy and the controller have their parameters

tuned using PSO algorithm, and iv) Validation and comparison of the proposed controller design against other techniques.

The remaining of this paper is organized as follows. Analytical modelling of the physical DC-DC IBC system is firstly introduced in Section 2. Section 3 then presents a mathematical model for the fuel cell and the entire system as shown in Fig. 1. A step by step design of the nonlinear controller is detailed in Section 4. Section 5 is dedicated to parameter optimization using the PSO algorithm for both robust nonlinear and conventional PI controllers. Validation and test results are presented in three scenarios and discussed in Section 6 in addition to comparisons. The key aspects of this paper are summarized in the last section including also some concluding remarks and suggestions for future work.

Fig 1. Simplified structure of the PEMFC-DC-DC-IBC system.

2- Developed State Space Model of the IBC

Recently, IBCs are often used in various energy systems and applications of low output voltage, mainly as power electronic interfaces in renewable energy sources such as photovoltaic power systems and fuel cells. Fig. 2 represents a schematic diagram of a DC-DC interleaved boost converter versus a classical DC-DC boost converter. V_c is the output voltage and V_{fc} is the Fuel Cell source voltage, the IBC is similar to a classical boost converter but contains two current inductances and controlled by two switches.

State-space averaging is an alternative representation in which the converter is considered to operate in ON and OFF modes. A non-linear model is constructed to represent the operation for

each mode and a unified average state-space model is obtained for the converter. The average model of the interleaved boost DC-DC converter is the same as the traditional boost DC-DC converter except that it contains two current inductors [26]. The dynamics of the IBC converter are represented by [26]:

$$\begin{cases} L_1 \frac{dI_{L1}}{dt} = V_{fc} - V_c(1 - D_1) \\ L_2 \frac{dI_{L2}}{dt} = V_{fc} - V_c(1 - D_2) \\ C \frac{dV_c}{dt} = I_{L1}(1 - D_1) + I_{L2}(1 - D_2) - I_R \end{cases} \quad (1)$$

such that:

$$\begin{cases} I_{fc} = I_{L1} + I_{L2} \\ D_1 = D_2 = 1 - u \\ L_1 = L_2 = L \end{cases} \quad (2)$$

where L and C are respectively the inductance and the capacitance, D_1 and D_2 are the duty cycles of each phase (one is shifted by a half period from the other). I_{L1} and I_{L2} are the inductors currents, I_{fc} is the fuel cell current, $I_R = V_c/R$ is the resistor (R) load current and I_c is the capacitor current.

Fig 2. Voltage regulation of : (a) the fuel cell interleaved DC-DC boost converter, (b) DC-DC boost converter.

The average model of System (1) may then be expressed as follows:

$$\begin{cases} \dot{I}_{fc} = \frac{2}{L} V_{fc} - \frac{2}{L} V_c u \\ \dot{V}_c = \frac{1}{C} I_{fc} u - \frac{1}{RC} V_c \end{cases} \quad (3)$$

where u is the average duty cycle.

The system state space vector $x = [\int V_c, V_c, I_{fc}]^T$ includes the measurable output voltage (V_c) and the fuel cell current (I_{fc}) (shown in Fig.2), the other state ($\int V_c$) is introduced to improve the robustness of the controller design. The augmented nonlinear model is then described as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{1}{RC}x_2 + \frac{1}{C}x_1u \\ \dot{x}_3 = -\frac{2}{L}x_2u + \frac{2}{L}V_{fc} \end{cases} \quad (4)$$

where $x_1 = \int V_c$, $x_2 = V_c$ and $x_3 = I_{fc}$.

Manipulating the system of Eq (4), the average state-space model can be written as:

$$\dot{X}(t) = \mathcal{A} X(t) + \mathcal{B} u(t) + \mathcal{T} \quad (5)$$

where the associated matrices are given by:

$$\mathcal{A} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{1}{RC} & 0 \\ 0 & 0 & 0 \end{bmatrix}, \mathcal{B} = \begin{bmatrix} 0 \\ \frac{1}{C}x_1 \\ -\frac{2}{L}x_2 \end{bmatrix}, \mathcal{X} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}, \mathcal{T} = \begin{bmatrix} 0 \\ 0 \\ \frac{2}{L}V_{fc} \end{bmatrix}$$

3- Fuel Cell Mathematical Model

In this section, a complete mathematical model is constructed to represent a fuel cell stack through a controlled voltage source in series with a constant resistance as shown in Fig. 3.

The controlled voltage source (E) is expressed as [27]:

$$\begin{cases} E = E_{oc} - N A \ln\left(\frac{i_{fc}}{i_0}\right) \frac{1}{s^{\frac{T_d}{3}+1}} \\ V_{fc} = E - R_{ohm}i_{fc} \end{cases} \quad (6)$$

where,

E_{oc} : open circuit voltage (V);

N : number of cells;

A : Tafel slope (V);

i_0 : exchange current (A);

T_d : the response time (at 95% of the final value) (sec);

R_{ohm} : internal resistance (Ω);

i_{fc} : fuel cell current (A);

V_{fc} : fuel cell voltage (V).

Fig 3. Fuel cell stack model.

The open circuit voltage E_{oc} , the Tafel slope A and the exchange current i_0 are expressed as follows:

$$\begin{cases} E_{oc} = K_c E_n \\ i_0 = \frac{z F k (P_{H_2} + P_{O_2})}{R h} \exp\left(\frac{-\Delta G}{RT}\right) \\ A = \frac{RT}{z \alpha F} \end{cases} \quad (7)$$

where

$$R = 8.3145 \text{ J/(mol K)}$$

$$F = 96485 \text{ A s/mol}$$

z = number of moving electrons ($z = 2$)

E_n = Nernst voltage (V)

α = charge transfer coefficient

P_{H_2} = partial pressure of hydrogen inside the stack (atm)

P_{O_2} = partial pressure of oxygen inside the stack (atm)

k = Boltzmann's constant (1.38×10^{-23} J/K)

h = Planck's constant (6.626×10^{-34} J s)

ΔG = activation energy barrier (J)

T = temperature of operation (K)

K_c = voltage constant at nominal condition of operation

The rates of conversion of hydrogen (U_{fH_2}) and oxygen (U_{fO_2}) are determined in Block 1 in Fig. 3 as follows [21, 27]:

$$\begin{cases} U_{fH_2} = \frac{60000RTi_{fc}}{zF P_{fuel} V_{fuel} x_h\%} \\ U_{fO_2} = \frac{60000RTi_{fc}}{zF P_{air} V_{air} y_h\%} \end{cases} \quad (8)$$

where

P_{fuel} = absolute supply pressure of fuel (atm)

P_{air} = absolute supply pressure of air (atm)

V_{fuel} = fuel flow rate (l/min)

V_{air} = air flow rate (l/min)

x_h = percentage of hydrogen in the fuel (%)

y_h = percentage of oxygen in the oxidant (%)

The partial pressures and the Nernst voltage are determined in Block 2 in Fig. 3 as follows [21, 27]:

$$\begin{cases} P_{H_2} = (1 - U_{fH_2}) x_h\% P_{fuel} \\ P_{O_2} = (1 - U_{fO_2}) x_h\% P_{air} \\ P_{H_2O} = (w - 2 y_h\% U_{fO_2}) P_{air} \\ E_n = 1.229 - \frac{44.43}{zF} (T - 298) + \frac{RT}{zF} \ln \left(P_{H_2} P_{O_2}^{\frac{1}{2}} \right) \\ E_n = 1.229 - \frac{44.43}{zF} (T - 298) + \frac{RT}{zF} \ln \left(\frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{P_{H_2O}} \right) \text{ for } (T > 373K) \end{cases} \quad (9)$$

where

P_{H_2O} = partial pressure of water vapor (atm).

w = percentage of water vapor in the oxidant (%).

4- Proposed Controller Design

On top of the overall PEMFC-DC-DC-IBC model, an appropriate switching technique is developed in this section to ensure the optimal desired output in the presence of load disturbances and model uncertainties. It was illustrated that the average state space LTI representation of the converter is quite sensitive to the changes in the input voltage, output load variations, disturbances, and modelling as well as sensor uncertainties. For this reason, a PSO-based Robust Nonlinear Controller, called PSO-RNC, is designed to correct for the aforementioned drawback and to continuous and optimal set-point tracking of the desired voltage (V_{cref}) by acting on the duty cycle (u) of the IBC switch.

4.1- Main results

The controller design procedure for the DC-DC IBC includes three steps; virtual control inputs are developed during the first two steps, and the actual control input is designed in the last step.

Let us define the following variables that define the error dynamics of the system studied Eq.(4) :

$$\begin{cases} e_1 = \int (V_{cref} - V_c) dt \\ e_2 = V_{cref} - V_c \\ e_3 = I_{fcd} - I_{fc} \end{cases} \quad (10)$$

with $\dot{V}_{cref} = 0$.

The derivative with respect to time of the Eq.(10) are :

$$\begin{cases} \dot{e}_1 = e_2 \\ \dot{e}_2 = -\dot{V}_c = -\frac{1}{C} I_{fc} u + \frac{1}{RC} V_c \\ \dot{e}_3 = \dot{I}_{fcd} - \frac{2}{L} V_{fc} + \frac{2}{L} V_c u(t) \end{cases} \quad (11)$$

Eq. (11) presents the error dynamics and can be considered in terms of a control problem where the system to be controlled is a nonlinear system with a control input $u(t)$. As long as the control input ($u(t)$) can stabilize the nonlinear system, the error vector $e = [e_1, e_2, e_3]^T$ converges to zero as time $t \rightarrow \infty$. This implies that the trajectory of the controlled system Eq. (11) asymptotically approaches the target $[\int V_{cref}, V_c, I_{fcd}]^T$.

The design procedure of the controller is recursive. At the i th step, the i th-order subsystem is stabilized using Lyapunov function V_i by the design of a virtual control Φ_i and a control input function u_i .

Step 1. Let $z_1 = e_1$, then we can obtain its derivative:

$$\dot{z}_1 = \dot{e}_1 = e_2 \quad (12)$$

where $e_2 = \Phi_1(z_1)$ is introduced as a virtual control input.

For the design of $\Phi_1(z_1)$ in order to stabilize z_1 -subsystem Eq.(12), we can select the following Lyapunov function:

$$V_1 = \frac{1}{2} z_1^2 \quad (13)$$

The time derivative of V_1 is given below:

$$\dot{V}_1 = z_1 \dot{z}_1 = z_1 \Phi_1(z_1) \quad (14)$$

By introducing $\Phi_1(z_1) = -k_1 z_1$, $k_1 > 0$, $\dot{V}_1$ is negative definite. This implies that the z_1 -subsystem Eq.(12) is asymptotically stable. Since the virtual control function $\Phi_1(z_1)$ is estimative, the following error is define as :

$$z_2 = e_2 - \Phi_1(z_1) \quad (15)$$

Then one can obtain the following (z_1, z_2) -subsystem:

$$\begin{cases} \dot{z}_1 = e_2 \\ \dot{z}_2 = \dot{e}_2 - \dot{\Phi}_1(z_1) = -\frac{1}{c} I_{fc} u + \frac{1}{RC} V_c - \dot{\Phi}_1(z_1) \end{cases} \quad (16)$$

Step 2. Adding and subtracting $-\dot{\Phi}_1(z_1)$ to the Eq.(12), the (z_1, z_2) -subsystem can then be represented as follows:

$$\begin{cases} \dot{z}_1 = e_2 - \Phi_1(z_1) + \Phi_1(z_1) = \Phi_1(z_1) + z_2 \\ \dot{z}_2 = \dot{e}_2 - \dot{\Phi}_1(z_1) = -\frac{1}{c} I_{fc} u + \frac{1}{RC} V_c - \dot{\Phi}_1(z_1) \end{cases} \quad (17)$$

In a same manner, taking I_{fc} as an independent input such that a stabilizing control law $\Phi_2(z_1, z_2)$ can get as:

$$\Phi_2(z_1, z_2) = I_{fcd} = \frac{c}{u} \left(z_1 - \dot{\Phi}_1(z_1) + \frac{1}{RC} V_c + k_2 z_2 \right) \quad (18)$$

Substitute Eq.(18) into Eq.(17) and consider a second augmented Lyapunov function candidate $V_2 = V_1 + \frac{1}{2} z_2^2$, then the time derivative of V_2 is:

$$\dot{V}_2 = -k_1 z_1^2 + z_2 z_1 + z_2 \dot{z}_2 = -k_1 z_1^2 - k_2 z_2^2 \leq 0 \quad (19)$$

where $k_2 > 0$. Define a new error variable as $z_3 = e_2 - \Phi_2(z_1, z_2)$. In the control point of view, it can be computed that if the error variables z_3 approaches zero, the asymptotical stability of the (z_1, z_2) -subsystem can be ensured. Consider Eq.(17), by adding and subtracting $-\frac{1}{c} \Phi_2(z_1, z_2) u$ to the subsystem z_2 , then the final subsystem is define as :

$$\begin{cases} \dot{z}_1 = \Phi_1(z_1) + z_2 \\ \dot{z}_2 = -\frac{1}{c} I_{fc} u + \frac{1}{RC} V_c - \dot{\Phi}_1(z_1) - \frac{1}{c} \Phi_2(z_1, z_2) u + \frac{1}{c} \Phi_2(z_1, z_2) u \\ \dot{z}_3 = \dot{e}_2 - \dot{\Phi}_2(z_1, z_2) = -\frac{2}{L} V_{fc} + \frac{2}{L} V_c u(t) \end{cases} \quad (20)$$

$$\begin{cases} \dot{z}_1 = \Phi_1(z_1) + z_2 \\ \dot{z}_2 = \frac{1}{c} z_3 u - z_1 - k_2 z_2 \\ \dot{z}_3 = \dot{e}_2 - \dot{\Phi}_2(z_1, z_2) = -\frac{2}{L} V_{fc} + \frac{2}{L} V_c u(t) \end{cases} \quad (21)$$

Step 3. we choose the third augmented Lyapunov positive definite function described as follows:

$$V_3 = V_2 + \frac{1}{4} \frac{L}{C} z_3^2 \quad (22)$$

Using Eq. (20) and Eq.(12), V_3 can be derived as follows:

$$\begin{aligned} \dot{V}_3 &= -k_1 z_1^2 + z_2 z_1 + z_2 \dot{z}_2 + z_3 \dot{z}_3 \\ \dot{V}_3 &= -k_1 z_1^2 + z_2 \left(z_1 + \frac{1}{c} z_3 u - z_1 - k_2 z_2 \right) + \frac{L}{2C} z_3 \left(-\frac{2}{L} V_{fc} + \frac{2}{L} V_c u(t) \right) \\ \dot{V}_3 &= -k_1 z_1^2 - k_2 z_2^2 + \frac{1}{c} z_3 u z_2 + z_3 \left(-\frac{2}{L} V_{fc} + \frac{2}{L} V_c u(t) \right) \\ \dot{V}_3 &= -k_1 z_1^2 - k_2 z_2^2 + \frac{L}{2C} z_3 \left(-\frac{2}{L} V_{fc} + \frac{2}{L} V_c u + \frac{2u}{L} z_2 \right) \\ \dot{V}_3 &= -k_1 z_1^2 - k_2 z_2^2 + \frac{L}{2C} z_3 \left(-\frac{2}{L} V_{fc} + \frac{2u}{L} (V_c + z_2) \right) \end{aligned}$$

$$\begin{aligned}\dot{V}_3 &= -k_1 z_1^2 - k_2 z_2^2 + \frac{L}{2C} z_3 \left(-\frac{2}{L} V_{fc} + \frac{2u}{L} (V_c + e_2 - \Phi_1(z_1)) \right) \\ \dot{V}_3 &= -k_1 z_1^2 - k_2 z_2^2 + \frac{L}{2C} z_3 \left(-\frac{2}{L} V_{fc} + \frac{2u}{L} (V_c + V_{cref} - V_c - \Phi_1(z_1)) \right) \\ \dot{V}_3 &= -k_1 z_1^2 - k_2 z_2^2 + \frac{L}{2C} z_3 \left(-\frac{2}{L} V_{fc} + \frac{2u}{L} (V_{cref} - k_1 e_1) \right) \quad (23)\end{aligned}$$

The objective is to guarantee that $\dot{V}_3$, given by Eq.(23), is non-positive to satisfy the Lyapunov stability condition. So, the corresponding designed control law (u), which forces the system output to track the reference set point, is given by:

$$\begin{aligned}u &= \frac{L}{2(V_{cref} - k_1 e_1)} \left(-\dot{I}_{fc} + \frac{2}{L} V_{fc} - k_3 e_3 \right) \\ u &= \frac{L}{2(V_{cref} - e_{2d})} \left(-\dot{I}_{fc} + \frac{2}{L} V_{fc} - k_3 e_3 \right) \quad (24)\end{aligned}$$

To ensure that $\dot{V}_3$ is negative definite:

$$\dot{V}_3 = -k_1 z_1^2 - k_2 z_2^2 - \frac{L}{2C} k_3 z_3^2 \quad (25)$$

where k_1, k_2 and k_3 are positive constants to be heuristically determined using the PSO technique as presented in Section 5.

4.2. PI Controller Design

A second proposed solution consists of a PSO-optimized PI Controller, named PSO-PIC, designed to regulate the IBC output. This design is structured as follows [34]:

$$u(t) = 1 - U_{pi} \quad (26)$$

with

$$U_{pi} = K_p (V_{cref} - V_c) + K_i \int (V_{cref} - V_c) dt \quad (27)$$

This controller is implemented for comparison purposes. Its parameters K_p and K_i of the PI controller of Eq. (27) are heuristically tuned using the PSO technique as covered in the following section.

5- PSO-Based Controllers' Parameters

Particle Swarm Optimization is a stochastic population-based optimization technique inspired by the behaviour of birds and fish swarms. The PSO algorithm was developed by Eberhart and Kennedy in 1995 [1]. A candidate solution in a PSO optimization problem mimics a bird in the search space, which is called a particle. The PSO algorithm is used to determine possible solutions by moving particles randomly in accordance with some designed rules [2–5]. A general flowchart of PSO algorithm is given in Fig. 4.

There are two key factors that dominate the performance of standard PSO algorithm. The particle velocity and the particle position update. The $(t + 1)^{th}$ velocity is obtained as follows [28-30]:

$$V_j(t + 1) = w * V_j(t) + C_1 r_1 (p_j - X_j(t)) + C_2 r_2 (p_g - X_j(t)) \quad (28)$$

where t represents the iteration number; j is the particle number; the vector p_j is the individual best solution of particle j at a given stage; the vector p_g is the global best solution calculated from all the particles at t ; the constants C_1 and C_2 are the acceleration parameters; the vectors r_1 and r_2 are random numbers uniformly distributed between 0 and 1.

On the other hand, the particle position is updated, through its current velocity, towards the optimal solution as follows [30, 31, 35]:

$$X_j(t + 1) = X_j(t) + V_j(t + 1) \quad (29)$$

Using this methodology, the PSO technique is employed to determine the optimum parameters of each of the previously designed controllers. The Integral Absolute value of the Error objective function is used in this work based on the input-output error, the maximum value of each computation process at a given stage is used as the update value.

Fig. 4 Flowchart for PSO-based tuning controller parameters.

The main objective function is given as follows [10, 11]:

$$IAE = \int_0^{\infty} |e(t)| dt = \int_0^{\infty} |e_2(t)| dt \quad (30)$$

where $e(t)$ is the instantaneous voltage tracking error as defined in Eq. (10).

Notice that Eq.(30) also represents the performance index of each design, namely the proposed PSO-optimized nonlinear robust controller (PSO-NRC) and PSO-based PI controller (PSO-PIC). The different steps used for tuning these controllers are illustrated in Fig. 5.

Fig. 5 Proposed Block diagram of PSO-based control design.

6- Results and Discussion

The overall system structure combining the PEMFC, the IBC, and different controllers as well as their parameters are detailed in this section. This is followed by evaluation and comparisons of the overall system performance for each controller design. The key parameters of the DC-DC IBC and the PEMFC are respectively listed in Table I and Table II.

Table I. Parameters of DC-DC interleaved boost converter.

Parameter	Value
L	$5000 \mu H$
R_L	0.15Ω
C	$1000 \mu F$
R_c	1000Ω
R	5Ω

where R_c is the parasitic resistance of the capacitor and R_L is the inductor resistance.

Table II. Operative parameters of a 6KW-48V fuel cell stack.

Parameter	Value	Components name
FC_{Eoc}	65	Voltage at 0 A (V)
FC_{V1}	63	Nominal operating Current (A)
FC_{Inom}	133.3	Voltage at 1 A (V)
FC_{Vnom}	45	Nominal operating Voltage (V)
FC_{Imax}	225	Maximum operating Current (A)
FC_{Vmin}	37	Minimum operating Voltage (V)
FC_N	65	Number of cells in series
FC_{Tnom}	65	Operating temperature (°C)
FC_{Nnom}	55	Nominal stack efficiency (%)
FC_{Vair}	300	Nominal air flow rate (L/min)
FC_{fuel}	1.5	Nominal supply pressure Fuel (bar)
FC_{Pair}	1	Nominal supply pressure Air (bar)
FC_{Ph2}	99.95	Nominal composition of H2 (%)
FC_{Po2}	21	Nominal composition of O2 (%)
FC_{Ph2o}	1	Nominal composition of H2O (Air) (%)
R_{ohm}	0.09604	
E	57.91	

The PSO-optimized parameters for the PSO-NRC and the PSO-PIC designs and their respective search ranges are listed in Table III and IV, respectively.

Table III. Selection of parameters used for PSO-based tuning of the proposed and the PI controllers.

PSO Parameters	Value	
	PSO- PIC	PSO-NRC (proposed controller)
C_1	1	1
C_2	3	3
w	0.8	0.8
Population size	100	100
Maximum iteration	20	5

Using the constructed PEMFC-DC-DC-IBC model, the gains k_1 , k_2 and k_3 of the proposed PSO-NRC design and K_p and K_i gains of the PI controller are heuristically tuned by minimizing the optimization problem given by Eq (28). This procedure is shown in Fig. 5, the optimum final gains are listed in Table V.

Table IV. Search range of the controller parameters

Controller parameters	Search range	
	Min	Max
k_1	30	40
k_2	15	20
k_3	5	15
K_p	0	0.1
K_i	1	15

Table V. Optimal parameters of both controllers.

PSO- PIC	$K_p = 0.0077, \quad K_i = 1.28$
PSO-NRC	$k_1 = 30.4131, \quad k_2 = 15.4350, \quad k_3 = 9.8251$

In order to verify the PEMFC-DC-DC-IBC performance using each of the designed controllers and check which one ensures the best tracking performance, the comparisons between the proposed and the PSO-based PI controllers are based on the dynamic output characteristics. Simulations are performed for three different cases, two different numerical simulation scenarios include output voltage variation, and a third scenario is simulated under load variation. The platform that was developed to simulate the system is depicted in Fig. 6.

Fig. 6. Proposed system/ control strategies.

6-1. Standard Test

A comparison between the two converters is considered in this scenario. Fig. 7 and 8 represent respectively voltages and currents response and steady-state variations using the interleaved boost converter versus the classical boost converter. Those results confirm the superiority of the IBC to reduce ripples compared to the classical boost converter. In addition to its robustness to input voltage and load variations, the proposed PSO-RNC designed for a PEFMC-DC-DC-IBC is highly effective in regulating the output voltage to optimally track a varying set-point.

(a) Using interleaved boost converter

(b) Using the classical boost converter

Fig 7. Variations of load and fuel cell voltages using both converters (a) and (b).

(a) Using interleaved boost converter

(b) Using the classical boost converter

Fig 8. Variations of load and fuel cell currents using both converters (a) and (b).

6-2. First Scenario: Variation in the Input Voltage (V_{cref}) Set-Point

In this scenario, the system studied is subject to 5% decrease in the reference voltage V_{cref} at $t = 0.1$ s, and 5% increase in V_{cref} at $t = 0.15$ s. Fig. 9 demonstrates the performance of each of the two controllers, and it can be observed that the proposed controller can rapidly regulate the output voltage of the IBC. In addition, the closed-loop system using the proposed controller settles to the final value with a shorter Rise time compared to the PSO-PIC as demonstrated in Table VI.

Table VI. Rise time in seconds

Time (s)	[0.0 0.1]	[0.1 0.15]	[0.15 0.25]
PSO- PIC	0.0098	0.0100	0.0104
PSO-RNC	0.0059	0.0057	0.0063

Furthermore, for statistic comparison, the IAE criterion is employed for both methods and the corresponding results are summarized in Table VII. The results obtained confirm that the proposed PSO-NRC leads to a more reliable performance in terms of output regulation of IBC (load voltage) compared to the PSO-PIC according to the IAE criterion.

Table VII. Performance index of the proposed and PSO- PI controllers.

$IAE = \int_0^{\infty} e(t) dt = \int_0^{\infty} e_2(t) dt$			
Time (s)	[0.0 0.1]	[0.1 0.15]	[0.15 0.25]
PSO-PIC	0.0566	0.0468	0.1044
PSO-RNC	0.0408	0.0306	0.0796

Fig 9. Regulated output voltage of the IBC (Voltage tracking response).

The corresponding load, fuel cell currents and fuel cell voltage are respectively shown in Figs. 10 and 11. These figures demonstrate how the proposed control method greatly reduces the ripples of the load voltage as well as the fuel cell currents and voltage in the presence of variation of the load voltage.

Fig 10. Fuel cell and load currents response to input voltage variation.

Fig 11. Fuel Cell voltage under input voltage variation.

6-3. Second Scenario: Load Variation of -20% introduced at $t=0.05s$

Results of this scenario are summarized in Figs. 12 –14 showing the response of the regulated output voltage of the IB converter, fuel cell and load currents, and the fuel cell voltage after a -20% variation in load at $t = 0.05$ s. These responses illustrate the capabilities of the closed loop system using the proposed controller to withstand large and abrupt load variations and reach the reference voltage within a settling time of 0.01 s. The PSO-NRC also keeps the tracking of the output voltage with a smaller overshoot (8.83 instead of 9.01 for PI controller) and (0.97 instead of 5.31 for PI controller) when the system is subject to increase or decrease in load current. These observations are summarized in Table VIII.

Fig. 12. Regulated output voltage of the IB converter during load variation.

Table VIII. Overshoot during second scenario

	First overshoot	Second overshoot
PSO- PIC	9.01	5.31
PSO-NRC	8.83	0.97

Fig 13. Fuel cell and load currents response to load variation.

Fig 14. Fuel Cell voltage during load variation.

Consequently, in the presence of parameter uncertainties and load variations, one can see that the proposed controller is capable to achieve a robust voltage regulation performance and a smooth tracking of a varying set-point.

7. Conclusion

This work considered the important problem of the output voltage regulation of a PEMFC-fed DC-DC interleaved boost converter in presence of model uncertainties and abrupt large variations in the input voltage as well as the load. A complete representative model is first developed for the fuel cell and the DC-DC IBC system. The control problem was formulated using Lyapunov stability theorem and the controller's parameters were tuned using PSO algorithm in order to get a good tracking of the desired output. It was illustrated that the proposed controller is capable to ensure smooth regulation of the IBC output voltage under extreme cases. Robustness was verified through the tracking error against uncertainties in the parameters of the model and sudden variations. Furthermore, simulations and comparisons of results across various scenarios reflect the improved performance achieved by the PSO-RNC compared to the PSO-PIC in terms transient behaviour and minimum ripples during steady state. The constructed PEMFC-DC-DC-IBC model, the proposed regulation structure, and the control design will be extended in future works to indirect controllers and fault tolerant control as a response to involuntary faults and system mismatches based on references [36-38].

8. Conflict of interest

The authors declare that they have no conflict of interest.

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