Intissar DARWICH[1], **Mariam CHOUKET** [1], **Islem LACHHAB** [2], **Lotfi KRICHEN**[1,*]

J. Electrical Systems 18-1 (2022): 150-162

Regular paper

Online Self-tuning BI-Objective Particles Swarm Optimized Controllers for FC/UC Hybrid Electric Vehicle

Journal of Electrical Systems

A particle swarm optimization (PSO) for PI regulator parameters is proposed to improve dynamic performances and control strategies for fuel cell hybrid electric vehicle FCHEV. The chosen structure is the combination of a primary energy system (Fuel Cell) with an auxiliary storage device (Ultra Capacitor). A bi-objective PSO (Bi-PSO) based PI controllers is investigated. Twice online and offline PSO based PI regulators based on integral absolute error IAE are evaluated under mutable conditions. Matlab Simulink is used to compare the both suggested optimization methods. The results show that PI regulators with online self-tuning by Bi-PSO algorithm based on IAE index achieves the best response in terms of hydrogen consumption and traction system stability.

Keywords: FCHEV, Vehicle speed, DC link, PSO algorithm, PI parameter, online optimization.

1. Introduction

The penetration of fuel cell electric vehicles in automotive industry has increased due to their economic feasibility and environmental impacts. Therefore, FC used for propulsion offers pollution free power generation, high energy conversion efficiency and flexibility of current-voltage levels [1]. From many types of FC available in the market, the proton exchange membrane FC is chosen as the more appropriate for traction applications for several considerations [2]: a high-power density, fast starts up, extended life time, low operating temperature and high efficiency comparing to other types. Although, an FCEV needs an energy storage device to supply dynamic power, while the FC system delivers stationary power [3]. For this work, ultra-capacitors are selected to be the secondary energy source for many reasons [4-6]: a better power density than of batteries, a higher energy density than of usual capacitors and a lifetime with millions of cycles.

Generally, an electric system containing two or more energy sources, such as FCEV, needs a DC bus to guarantee the power flow of energy sources and to supply a steady voltage for traction electrical motors. For that an adequate energy management is required to supervise the multi-component system. Various management strategies are presented in literature. Authors in [7] apply a stiffness coefficient model to manage the power flow of FC/battery vehicle. The authors in [8] use an optimal control based on Minimum Principle method for FC hybrid vehicle. Authors in [9-11] focus on fuzzy logic controller for EV in different ways. Authors in [12] apply a multi-objective optimization based on dynamic programming and Pareto optimal solution. In [13] and [14], authors use a genetic algorithm to control electric vehicles.

---

[*] Lotfi KRICHEN: National Engineering School of Sfax, Control and Energy Management Laboratory (CEM_Lab) BP 1173, 3038, Sfax, Tunisia, Tel.: (+216) 74 274 418 / Fax: (+216) 74 275 595, E-mail: lotfi.krichen@enis.tn

[1] National Engineering School of Sfax, BP 1173, 3038, Sfax, Tunisia.

[2] Higher Institute of Computer Science and Multimedia of Gabes, BP 122, 6033, Gabes, Tunisia.

Recently, several studies in literature are interested to the Particle Swarm Optimization method. In [15], authors use the PSO method and the genetic algorithm to control PV-FC-Diesel-Battery electric vehicle. Authors in [16] develop a PSO algorithm to determine a driving guidance for full electric vehicle. The electric vehicle system presented in this work is controlled using the Particle swarm optimization algorithm. The vehicle configuration adopted is presented in [17]. In view of the fact that the DC voltage must be rigorously stable to guarantee a greatest power flow and that the vehicle speed must follow the reference one, the DC link and the speed controllers should be adequate. The PSO method is employed in order to minimize the DC voltage and the vehicle speed fluctuations by determining the optimal PI controllers' parameters. In the first part of this paper, the vehicle model is presented. Then, two PSO approaches are implemented for offline and online self-tuning regulators to minimize the IAE index. The software simulation results, documented in the third part, shows the effectiveness of self-tuned PI controllers based on PSO in supplying steadied dc bus voltage and efficient energy consumption. The final part draws discussions and conclusions.

2. FCHEV configuration

The FCHEV configuration regroups FC system and UC stack to supply the traction system via adapting stages and converters [18]. Figure 1 describes the vehicle model structure.

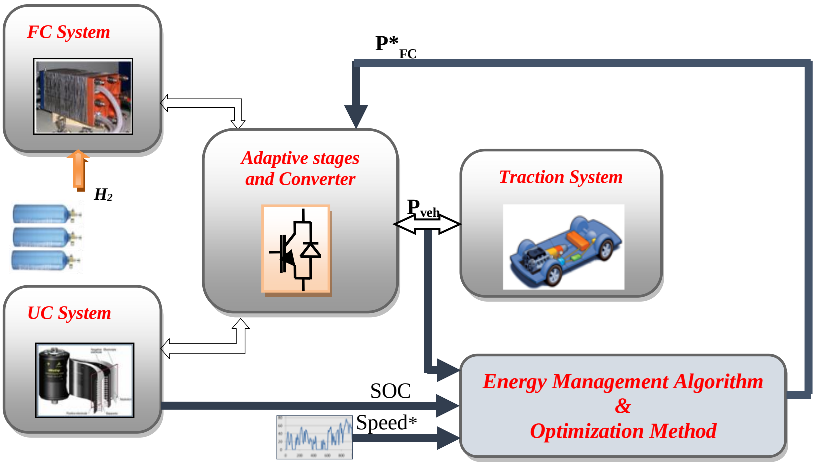

Fig. 1. FC/UC hybrid electric vehicle Structure.

The model parameters are presented in Table 1.

Table. 1. Vehicle parameters

Electric power	30 kW
Maximum speed	120 km/h
Acceleration	0 to 100 km/h in 10s
Weight	850

2.1. Energy sources

2.1.1. FCS stack modeling

Our choice focuses primarily on the proton exchange stack [19, 20]. The output voltage of an elementary cell is determined by the following equation:

$$V_{FC} = E_{NERST} - \underbrace{(V_{conc} + V_{act} + V_{ohm})}_{\Delta V_{FC}} \tag{1}$$

Where ΔV_{FC} recap the concentration, activation and ohmic losses and E_{NERST} present the open circuit voltage relying on the cell temperature T, the partial pressure of oxygen P_{O_2} and hydrogen P_{H_2} . The E_{NERST} potential is labeled in the following equation:

$$E_{Nerst} = 1.229\text{-}0.85\ 10^{-3}\ (T\text{-}298.15) + 4.3085\ 10^{-5}\ T\ (Ln(P_{H_2}) + \frac{1}{2} Ln(P_{O_2})) \tag{2}$$

The sufficient FCS power provides the traction system the ability to establish driving at a gentle speed. The amount of power pack is represented by Equation 3:

$$P_{FC}(i) = n_{FC} . V_{FC,cell}(i) . i . A_{FC} \tag{3}$$

Where i is the current density, n_{FC} the FC cells number installed in series and A_{FC} design the active cell area.

3.1.2. UC pack modeling

Thanks to its combination with an UC pack, the FC system increases its lifetime and reduces in the other hand its fuel consumption. UC, an auxiliary energy source, supply the power lack during acceleration.

An UC pack is an association of super-capacitors units. The maximum voltage defines the number of capacitors in series, the total capacitance governs the number of capacitors connected in parallel to the bank as symbolized in figure 2.

The total pack resistance and capacity are calculated as follows:

$$R_{SC\ total} = \frac{N_s}{N_p} ESR \tag{4}$$

$$C_{SC\ total} = \frac{N_p}{N_s} C \tag{5}$$

The State Of Charge SOC is the main parameter operating for optimized energy management system, clarified by the present equation.

$$SOC = \frac{C V_{UC}}{C V_{UC,\max}} = \frac{V_{UC}}{V_{UC,\max}} = \frac{Q(t)}{Q\max} \tag{6}$$

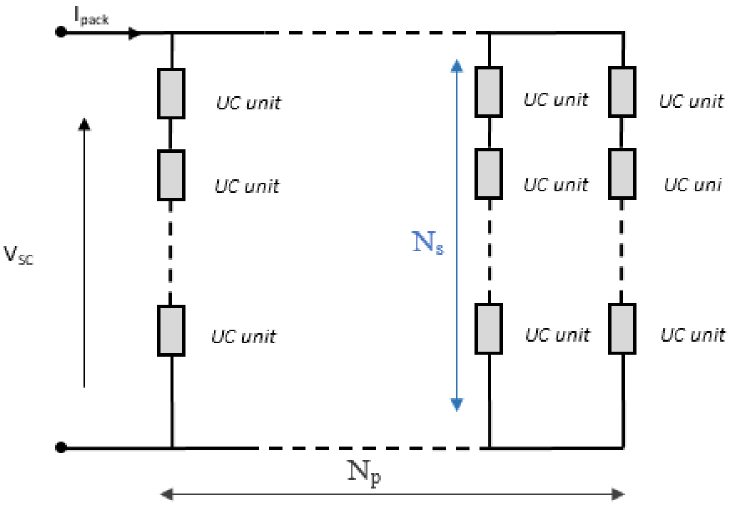

Fig. 2. Ultra-Capacitor bank modeling.

2.2. Vehicle Modeling

The rolling resistance F_{roll}, the effort of aerodynamic resistance F_{aer} and the resistance of mounted side F_{slope}depict the load force of the vehicle [21, 22]. The total power required for vehicle dynamics can be draught as:

$$P_{load} = (M_{veh}\frac{Speed_{veh}}{dt} + F_{roul} + F_{aer} + F_{slope})\,Speed_{veh} \tag{7}$$

The resisting forces are given by equations 8, 9 and 10 as follow:

$$F_{roll} = M_{veh}.g.f_r \tag{8}$$

$$F_{aer} = \frac{1}{2}.\rho_a.A_f.C_x.V_{veh}^2 \tag{9}$$

$$F_{slope} = M_{veh}.g.\sin(\alpha) \tag{10}$$

Where α the slope of the road M_{veh} is the vehicle weight, g standard gravity, f_r is the resistance coefficient of the tire rolling, ρ_a is the air density, C_x is the aerodynamic drag coefficient, A_f is the front area of the vehicle and V_{veh} is the vehicle speed.

3. Bi-Objective PSO algorithm

3.1. PSO

Variety optimization approaches exist in literature. Thanks to its flexibility and fast convergence, this work focuses on Particle swarm optimization algorithm. This robust approach, which is inspired from the behavior of swarm individuals, was developed by

Kennedy and Eberhart [23]. Each member within a swarm is called particule.it is noticed that particles within a group look to share the information among them.

Each particle has two variables state: it is characterized by its current velocity, its current position. The next position depends from the previous individual experience, it is administrated by equation 11:

$$x(t+1) = x(t) + v(t+1) \tag{11}$$

The updated velocity of each particle moves according best values of p_{best} which design the best last position of the particle and g_{best} which design best position acquired from its neighbor at each iteration. The velocity expression is governed by equation12.

$$v(t+1) = w\ v(t) + r_1 c_1(t)\,(p_{best}(t) - x(t)) + r_2 c_2(t)\,(g_{best}(t) - x(t)) \tag{12}$$

Where $x(t)$ design the current particle position, $v(t)$ design the particle velocity, w is the weighting function (inertia factor), $c_{1,2}$ are learning factors and $r_{1,2}$ are randomly distributed between 0 and 1.

The PSO algorithm is subdivided on four steps:

1. PSO initialization such us the PI gains of each regulator is adjusted following a restricted interval.
2. Evaluate IAE index of each particle
3. Update individual and global bests
4. Update velocity and position of each particle with PSO equations

These steps are repeated until stopping criteria is met.

The PSO algorithm is summarized in figure 3.

3.2. Offline tuning PI controllers by Bi-OPSO

3.2.1 Speed Control

The speed control is governed by a PI regulator to determine the traction force reference. The gains are offline tuned.

The outcomes attained by this approach for the PI parameters control are the following ones: kp (speed) = 3570; ki (speed) = 7650.

3.2.2. DC Link Voltage Control

The DC bus voltage must be well regulated, thus a voltage controller is necessary to adapt the production sources to the consumption traction system. Proportional integral controller "PI" control the DC bus voltage at 700V.

The offline method was put on to regulate the parameters of the PI controllers in order to reduce the IAE index (fitness function). As a result, kp (DC link) = 0.0092; ki (DC link) = 0.0198 are obtained.

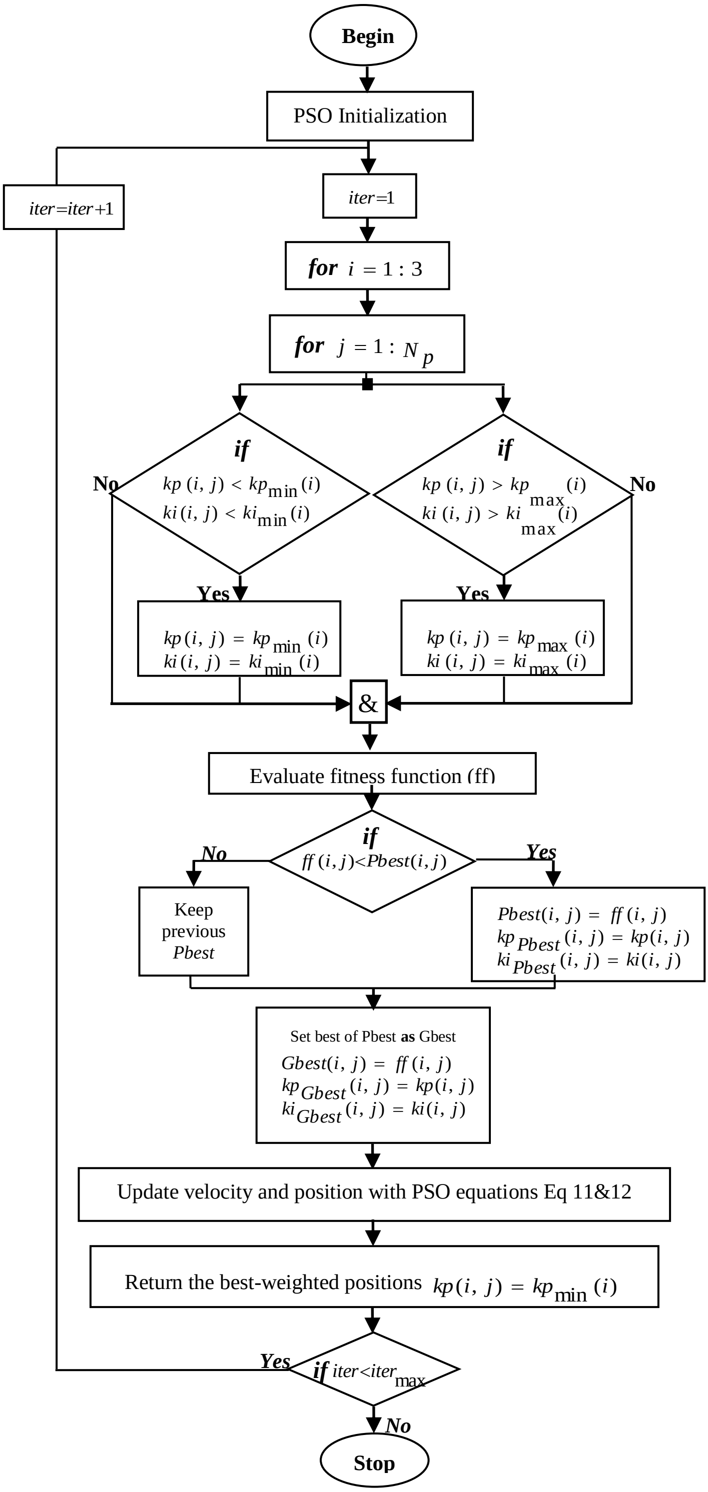

Fig. 3. Particle Swarm Optimization process.

3.3. Online tuning PI controllers by Bi-PSO

The proposed dynamic bi-loop controller is a progressive regulation concept capable of improving the FCHEV system response.

The self-tuning speed and DC link voltage based on Bi-PSO control structure is illustrated in figure 4. In this bi-loop scheme control, the proportional and integral gains are self-regulating by PSO algorithm so as to reduce the global error and to improve FCHEV dynamic. To add, the main objective of on line approach is to reduce the fluctuations of vehicle speed and variations.

To evaluate the effectiveness of the control system, a fitness function is carried out. The latest uses the error between measured value and the desired value which is named integral absolute error (IAE). It is stated by the following equation:

$$\min FF = \min IAE = \min \int_0^T |e(t)| dt \tag{13}$$

Where e(t) refers to the error.

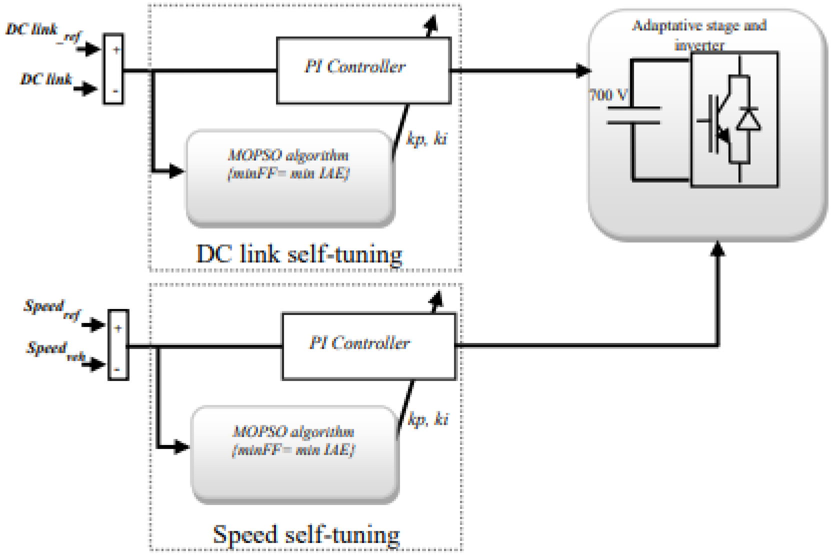

Fig. 4. Speed and DC link voltage controllers with online PSO-based PI regulators.

The proportional and integral gains of the PI regulators are online self-tuning by PSO approach in order to optimize the fitness function.

PSO algorithm get started to change parameters of the PI controllers. When the gap between the reference and the measured value is upper than the prearranged error, kp and ki gains are modified and updated. The online PSO algorithm turns off working when the error is minor than the prearranged error.

4. Simulations and discussions

Simulations test presents a drive cycle in order to highlight the effectiveness of the self-tuning bi-loop PI controllers based on PSO compared with offline adjusted PI regulator.

The EMS and optimization method are responsible for governing the FCHEV system in order to produce the demanded power for the traction system and validate the effectiveness of on line PSO controllers in supplying stabilized dc bus voltage and in tracking speed reference.

To compare the performance of self-tuned PI controllers based on PSO with the off line one, the relative error (RE) and the Integral time absolute error (ITAE) is added to the error index. The two indexes are defined as follow:

$$\mathrm{RE} = \sum_{t=0}^{T} \frac{|\mathrm{e(t)}|}{y(t)} \tag{14}$$

$$ITAE = \int_{0}^{T} t\,|e(t)|\,dt \tag{15}$$

To study how much effective on line self-tuning PI controllers, instead of an identified cycle, the checkups are prepared under a drive cycle with acceleration tasks, presented in figure 5. This figure shows the vehicle speeds by both methods: online and offline PSO. It is observed that in transition period speed vehicle in online approach is more followed than the off line one.

The kp and ki parameters of the PI regulators are represented in figures 9 and 10; respectively. These figures illustrate how the parameters are modified during a change in the speed reference. However, kp and ki remain constant during all the simulation in the case of the offline optimization method. As can be seen in figure 7, the gap between the reference and the measured value is upper than the prearranged error in the offline method.

The result depicted in Figure 6 shows that the DC link voltage is more stable in the case of fixed gains weighed PI regulators than self-tuned Bi-OPSO-based one. The variations of kp and ki gains, shown in figure 11 and 12, permit to reduce greatly the DC link error. The error variation is displayed in figure 8.

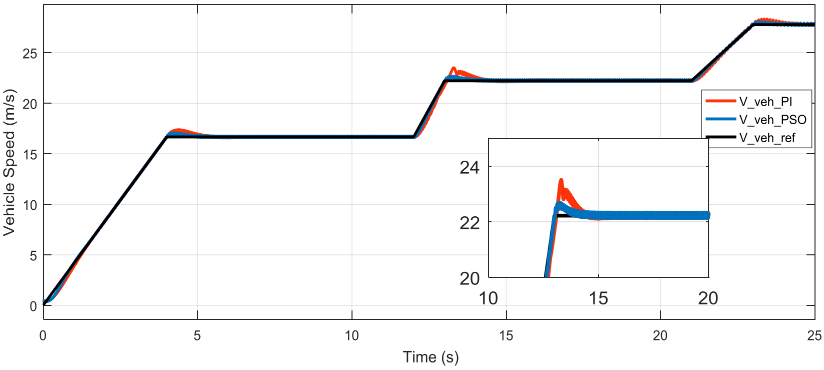

Fig. 5. Speed reference and vehicle response.

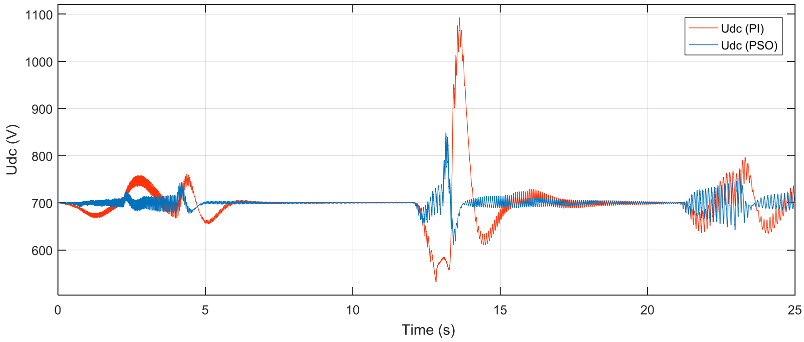

Fig. 6. DC link voltage.

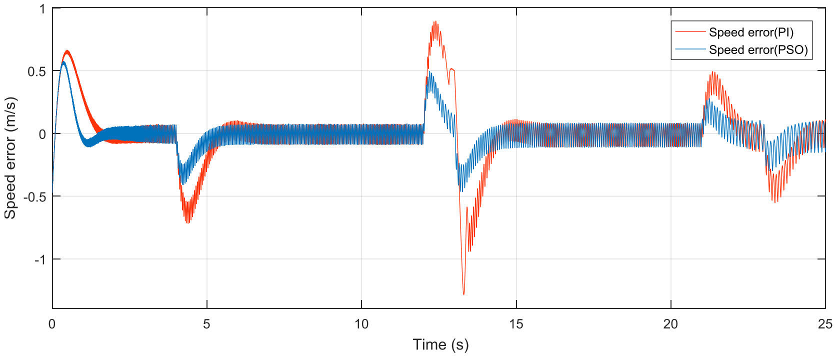

Fig. 7. Speed error variation.

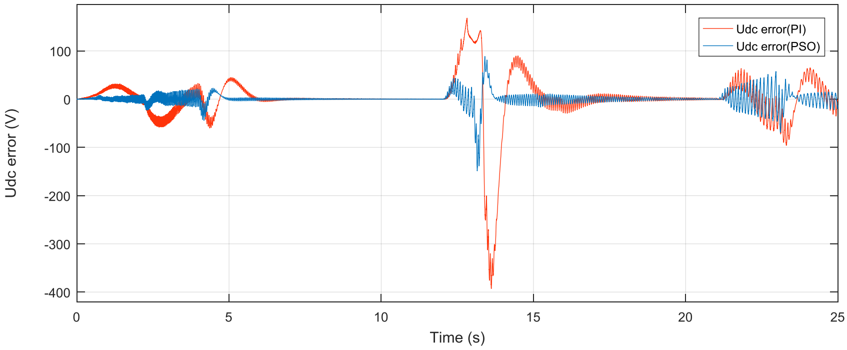

Fig. 8. DC link voltage error.

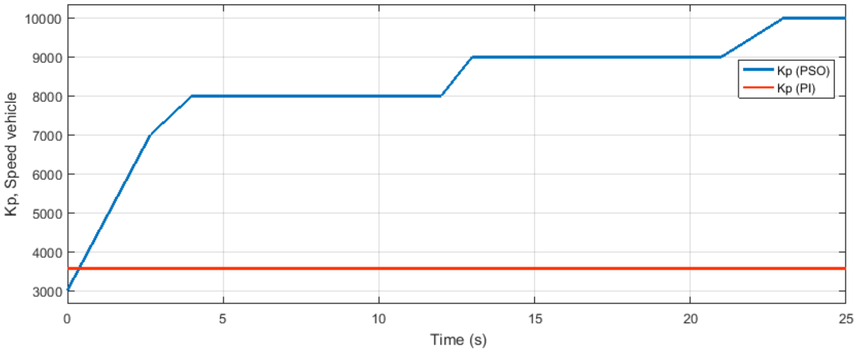

Fig. 9. k_p gain for speed vehicle controller.

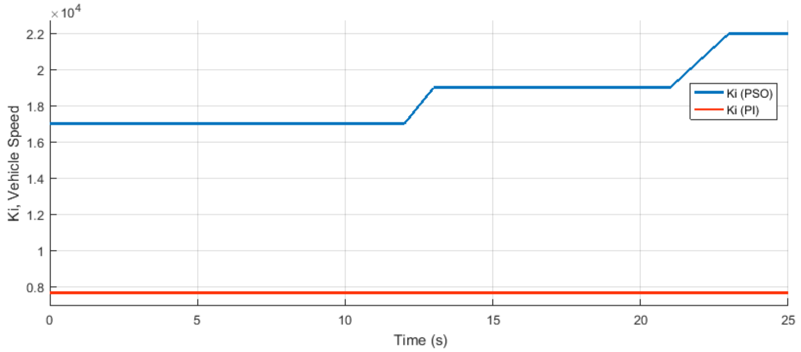

Fig. 10. k_i gain for speed vehicle controller.

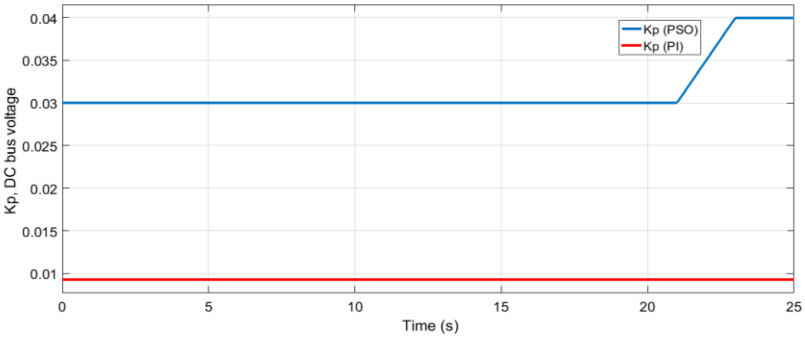

Fig. 11. k_p gain for DC link controller.

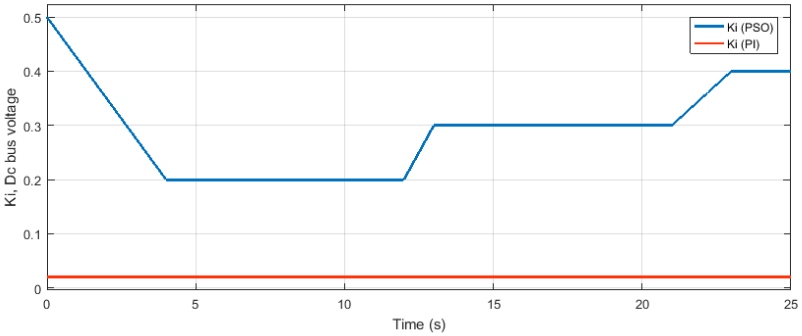

Fig. 12. k_i gain for DC link controller.

Depending on Table 2, it is clear that enhancing strategy improves the dynamic behavior of FCHEV. The on line self-tuning PI controller with PSO algorithm sees a boost in dynamic performance compared with the offline strategy; for relative error speed and DC bus voltage 22.83% and 70.5% improvement, respectively. The results revealed that the online self-tuning PI controllers by Bi-OPSO algorithm attained the lowest error indexes and reducing the IAE speed index by 43.08% and IAE DC link index by 70.49% compared with offline tuning PI controllers by Bi-OPSO.

The total hydrogen consumption is calculated during the 25s drive cycle profile. The fuel consumption is reduced by 2.52% compared with the offline test.

Table. 2. Simulation results obtained with offline and online optimized controllers.

	PI	PSO IAE
RE $_{\text{Speed}}$	0.623	0.4808
Error $_{\text{Speed}}$	3.851	2.192
ITAE $_{\text{Speed}}$	46.08	25.77
RE $_{\text{DC link}}$	0.8626	0.2545
Error $_{\text{DC link}}$	603.8	178.2
ITAE$_{\text{DC link}}$	8143	2647
Hydrogen consumption (g)	3.98	3.88

5. Conclusion

A model of a traction system motorized by a FC/UC has been presented. In this traction system, bi-loop error-driven modified and weighted PI controllers are essential to achieve an optimized regulation. The goal of the Bi-OPSO optimized is to achieve the best responses and the best power flow. Compared with the online method, the offline tuning gains of conventional PI by PSO algorithm submit fluctuation speed and DC link responses. To avoid those drawbacks, the online self-tuning PI parameters are applied. In this work, an online self-tuning PI controller by PSO based on the IAE index have been carried out. The self-adjusting bi-loop regulators can guarantee the stabilization of the DC link voltage and efficient energy consumption. Software simulations were implemented, in which the traction system operate under variations in the speed reference. The results demonstrate that the online method control achieved the lowest IAE, ITAE and RE indexes compared with the offline conventional PI controller.

Abbreviations

FCHEV	Fuel Cell Hybrid Electric Vehicle
PSO	Particle Swarm Optimization
Bi-OPSO	Bi-Objective Particle Swarm Optimization
EMS	Energy Management System
ITAE	Integral Time Absolute Error
RE	Relative Error
IAE	Integral Absolute Error
FF	Fitness Function

Notation

The notation used throughout the paper is stated below .Indexes:

P_{FC}	The fuel cell power
P_{FC}^{*}	The fuel cell power reference
P_{veh}	The vehicle power
P_{UC}	The ultra-capacitor power
SOC	The state of the charge
i	The current density
V_{SC}	The total voltage of the UC pack
Q	The quantity of charge

F_{roll}	The rolling resistance
F_{aero}	The effort of aerodynamic resistance
F_{slope}	The resistance of mounted side
α	The slope of the road
Speed_{veh}	The vehicle speed
$x(t)$	The current particle position
$v(t)$	The particle velocity
w	The weighting function
p_{best}	The best last position of the particle at each iteration
g_{best}	The best position acquired from its neighbor at each iteration
k_p	Proportional gain
k_i	Integral gain
e (t)	error

Constants:

E_{NERST}	The open circuit voltage
T	The cell temperature
P_{O_2}	The partial pressure of oxygen
P_{H_2}	The partial pressure of hydrogen
n_{FC}	The FC cells number
A_{FC}	The active cell area
$R_{SC\ total}$	The total equivalent resistance
ESR	The equivalent serial resistance
N_s	The number of cells in series
N_p	The number of branches in parallel
$C_{SC\ total}$	The total equivalent capacitor
C	The capacitance of each UC unit
$V_{UC,\max}$	The maximum voltage of the UC pack
$Q_{\max}$	The maximum quantity of charge stored by the UC
M_{veh}	The vehicle weight
g	The standard gravity
f_r	The resistance coefficient of the tire rolling
ρ_a	The air density
C_x	The aerodynamic drag coefficient
A_f	The front area of the vehicle
$c_{1,2}$	learning factors
$r_{1,2}$	Randomly function between 0 and 1

Appendix

PSO parameters

c_1	2
c_2	2
Stopping criteria	50
Population size	10
w	0.7

References

[1] Savvas Tsotoulidis, Athanasios Safacas, "Analysis of a Drive System in a Fuel Cell and Battery powered Electric Vehicle", International Journal Of Renewable Energy Research, IJRER, Vol.1, No3, pp.31-42 ,2011.

[2] Taghizadeh M, Hoseintabar M, Faiz J. Frequency control of isolated WT/PV/ SOFC/UC network with new control strategy for improving SOFC dynamic response. Int Trans Electr Energy Syst. 2015;25:1748–1770. doi: 10.1002/ etep.1925

[3] Islem Lachhab, Lotfi Krichen, "Impact of Ultra-Capacitor Sizing Optimization on Fuel Cell Hybrid Vehicle", International Journal of Renewable Energy Research, IJRER, Vol. 5, No. 1, 2015.

[4] Bo Long, Shin Teak Lim, Zhi Feng Bai, Ji Hyoung Ryu, Kil To Chong, "Energy Management and Control of Electric Vehicles, Using Hybrid Power Source in Regenerative Braking Operation", Energies 2014,7,4300-4315; doi:10.3390/en7074300

[5] Lei Zhang, Zhenpo Wang, Fengchun Sun, David G. Dorrell, "Online Parameter Identification of Ultracapacitor Models Usin the Extended Kalman Filter", Energies 2014, 7, 3204-3217; doi:10.3390/en7053204.

[6] Y. Eren, O. Erdinc, H. Gorgun, M. Uzunoglu, B. Vural, "A fuzzy logic based supervisory controller for an FC/UC hybrid vehicular power system", International Jorrnal of Hydrogen Energy 34 (2009) 8681–8694.

[7] Haitao Yun, Shude Liu, Yulan Zhao, Jianxin Xie, Chao Liu, Zhongjun Hou, Keyong Wang, "Energy management for fuel cell hybrid vehicles based on a stiffness coefficient model", International Journal of Hydrogen Energy, 40 (2015) 633-641.

[8] Zheng CH, Kim NW, Cha SW, "Optimal control in the power management of fuel cell hybrid vehicles", International Journal of Hydrogen Energy, 37 (2012) 655-63.

[9] M.C. Kisacikoglu, M. Uzunoglu, M.S. Alam, "Load sharing using fuzzy logic control in a fuel cell/ultracapacitor hybrid vehicle", International Journal of Hydrogen Energy 34 (2009) 14 97–1507.

[10] Y. Eren, O. Erdinc, H. Gorgun, M. Uzunoglu, B. Vural, "A fuzzy logic based supervisory controller for an FC/UC hybrid vehicular power system", International jorrnal of hydrogen energy 34 (2009) 8681–8694.

[11] Li CY, Liu GP, "Optimal fuzzy power control and management of fuel cell/battery hybrid vehicles", Journal of Power Sources, 192 (2009) 525-33.

[12] Liangfei Xu, Clemens David Mueller, Jianqui Li, Minggao Ouyang, Zunyan Hu, " Multi-objective component sizing based on optimal energy management strategy of fuel cell electric vehicles", Applied energy 2015; 157.

[13] Bin Wang, Zhongping Yang, Fei Lin and Wei Zhao, "An Improved Genetic Algorithm for Optimal Stationary Energy Storage System Locating and Sizing", Energies 2014, 7, 6434-6458; doi:10.3390/en7106434.

[14] S.Cauxa, W.Hankache, M.Fadel, D.Hissel, "On-line fuzzy energy management for hybrid fuel cell systems" International Journal of Hydrogen Energy 35 2010; 2134–2143.

[15] Adel A. A. El-Gammal, Adel M. Sharaf, " A Hybrid PV-FC-Diesel-Battery Efficient Schemes for Four-Wheel PMDC Electric Vehicle Drive System", International Journal of Renewable Energy Research, Vol.2, No.1, 2012.

[16] Sofiene Kachroudi, Mathieu Grossard, Neil Anroug, " Predictive Driving Guidance of full Electric Vehicles Using Particle Swarm Optimisation", IEEE transactions on Vehicular Technology, Vol 61, No 9, November 2012.

[17] Islem Lachhab, Lotfi Krichen, "An improved energy management strategy for FC/UC hybrid electric vehicles propelled by motor-wheels", International Journal of Hydrogen Energy 39 (2014) 571-581.

[18] Daoud Rezzak, Nasserdine Boudjerda, "Management and control strategy of a hybrid energy source fuel cell/supercapacitor in electric vehicles", International Transaction Electrical Energy Systems, DOI 10.1002/etep.2308

[19] Yanga S, Chellalia R, Lub X, Lia L, Boa C. "Modeling and optimization for proton exchange membrane fuel cell stack using aging and challenging P systems based optimization algorithm", Energy 2016;109:569e77.

[20] J.I. San Martin, I. Zamora, J.J. San Martin, V. Aperribay, E. Torres, P. Eguia, "Influence of the rated power in the performance of different proton exchange membrane (PEM) fuel cells", Energy 35 2010, 1898–1907

[21] Pei-Hsing Huang , Jenn-Kun Kuo and Chun-Yen Huang "A new application of the UltraBattery to hybrid fuel cell vehicles", INTERNATIONAL JOURNAL OF ENERGY RESEARCH 2016, DOI: 10.1002/er.3426.

[22] Richard T.Meyer, Raymond A. DeCarlo, Peter H. Meckl, Chris Doktorcik, and Steve Pekarek "Hybrid model predictive power management of a fuel cell battery vehicle", Asian Journal of Control, Vol. 15, No. 3, pp. 1–17, May 2013.

[23] Kennedy J, Eberhart R. "Particle swarm optimization", In Proceedings of IEEE international conference on neural networks, vol. 4; 1995. pp. 1942e8.