Energy Control of a Hybrid Wind Energy Conversion System with Fuel Cell Support

Sabrine Soltani
Laboratory of Computer Science for Industrial Systems (LISI), LR11ES26, INSAT, University of Carthage, Centre Urbain Nord BP 676 - 1080 Tunis Cedex, TUNISIA
sabrin.soltani01@gmail.com

Mohamed Abbes
Department of Electrical Engineering, ENSIT, University of Tunis
Tunis, Tunisia
mohamed.abbes@esstt.rnu.tn

Slah Farhani
Laboratory of Computer Science for Industrial Systems (LISI), LR11ES26, INSAT, University of Carthage, Centre Urbain Nord BP 676 - 1080 Tunis Cedex, TUNISIA
slah.farhani@issatkr.rnu.tn

Faouzi Bacha
Department of Electrical Engineering, ENSIT, University of Tunis
Tunis, Tunisia
Faouzi.Bacha@esstt.rnu.tn

***Abstract*—This paper presents an advanced control strategy for a hybrid wind energy conversion system (HWECS) integrating a doubly-fed induction generator (DFIG) with a fuel cell. Due to the intermittent nature of wind energy, maintaining power balance and system stability represents a major challenge. To overcome this issue, a hybrid configuration composed of a wind turbine, power electronic converters, and a fuel cell is proposed.**

An efficient Energy Control strategy based on PI controllers is developed to ensure optimal power sharing between the wind source and the fuel cell according to wind conditions and load demand. The proposed control scheme includes DC bus voltage regulation, fuel cell power control and inverter control for grid or load interfacing. In addition, a realistic fuel cell dynamic model is considered to evaluate its impact on system performance under variable operating conditions.

The proposed system is modeled and simulated in MATLAB/Simulink under various operating conditions such as fluctuating wind speed and variable load demand. Simulation results demonstrate that the proposed control effectively ensures system stability, improves energy utilization, and guarantees continuous power supply.

***Keywords*—DFIG, inverter, boost converter, Fuel Cell, Energy Control, PI controller.**

I. Introduction

The rapid advancement of renewable energy systems, especially wind energy, has been fueled by the growing demand for clean and sustainable energy. Wind energy conversion systems have received considerable attention due to their environmental advantages and scalability, [1].

The challenges of ensuring a stable and reliable power supply arise from the inherent intermittency and variability of wind resources, [2], [19].

To overcome these limitations, hybrid energy systems combining multiple energy sources have been proposed. Among these, the integration of wind energy with fuel cells has emerged as an effective solution. Fuel cells provide a reliable backup power source and enhance system stability during low wind conditions.

In this context, the implementation of an efficient Control Energy Control becomes essential to coordinate power flow between different sources and ensure optimal system performance. The control of energy must be capable of making real-time decisions based on system conditions such as wind power availability and load demand.

This work proposes a hybrid DFIG–fuel cell wind energy conversion system with a PI-based control strategy for power regulation under wind speed variations. A realistic fuel cell dynamic model is considered to evaluate the impact of fuel cell response on the overall system performance and grid power stability.

II. System Modeling

A hybrid energy system can operate with or without the presence of a conventional energy source such as a diesel generator or a micro gas turbine, as well as with or without an energy storage device. The storage system helps ensure a better supply of electrical loads during periods when the primary energy resource is unavailable. However, the limited storage capacity and its high cost represent significant drawbacks. Therefore, to minimize reliance on storage systems, hybrid energy systems have been increasingly adopted.

The structure of a hybrid energy system may include a photovoltaic system, a wind turbine, a hydropower generator, or a combination of multiple renewable energy sources. The selection of these sources is based on a techno-economic analysis.

In our work, we focused on making the appropriate technical choice of components for our wind–fuel cell hybrid energy system.

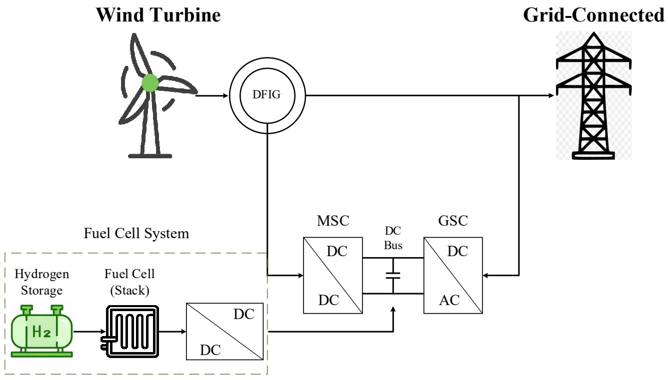


Fig.1 : **Architecture Diagram of a Wind–Fuel Cell Hybrid Power System**

A. *Modeling of the DFIG*

The doubly fed induction generator (DFIG) is an electrical machine. Its three-phase rotor windings are similar to the stator windings of a squirrel-cage induction machine but are connected to a slip-ring assembly, which allows access to the rotor voltages and currents, [3].

By adjusting the rotor voltages, the machine is able to operate in both sub-synchronous and super-synchronous regimes, acting either as a motor or as a generator, regardless of the rotor speed.

The general equations of the wound-rotor induction machine, expressed in the three-phase reference frame, are presented as follows, [4], [5]:

$$V_{sd} = R_s \times I_{sd} + \frac{d\emptyset_{sd}}{dt} - \omega_s \times \emptyset_{sq} \quad (1)$$

$$V_{sq} = R_s \times I_{sq} + \frac{d\emptyset_{sq}}{dt} - \omega_s \times \emptyset_{sq} \quad (2)$$

$$V_{rd} = R_r \times I_{rd} + \frac{d\emptyset_{rd}}{dt} - \omega_r \times \emptyset_{rd} \quad (3)$$

$$V_{rq} = R_r \times I_{rq} + \frac{d\emptyset_{rq}}{dt} - \omega_r \times \emptyset_{rd} \quad (4)$$

And,

$$\emptyset_{sd} = L_s \times I_{sd} + L_m \times I_{rd} \quad (5)$$

$$\emptyset_{sq} = L_s \times I_{sq} + L_m \times I_{rq} \quad (6)$$

$$\emptyset_{rd} = L_r \times I_{rd} + L_m \times I_{sd} \quad (7)$$

$$\emptyset_{rq} = L_r \times I_{rq} + L_m \times I_{sq} \quad (8)$$

Where:

- R_r and R_s denote the rotor and stator resistances, respectively;
- L_r , L_s and L_m represent the rotor, stator, and magnetizing inductances, respectively.

The machine's mechanical behavior is modeled using the following equation:

$$J\frac{d\Omega}{dt} = C_{em} - C_r - k_f \quad (9)$$

Where J and K_f represent the rotor moment of inertia and thefriction coefficient, respectively.

The electromagnetic torque (C_{em}) can be expressed as:

$$C_{em} = p\frac{L_m}{L_s}\left(I_{rq}\emptyset_{sd} - I_{rd}\emptyset_{sq}\right) \quad (10)$$

The active and reactive power sat the stator output are given by:

$$P_s = \frac{3}{2}\left(V_{sd} \times I_{sd} + V_{sq} \times I_{sq}\right) \quad (11)$$

$$Q_s = \frac{3}{2}\left(V_{sq} \times I_{sd} + V_{sd} \times I_{sq}\right) \quad (12)$$

Where P_s and Q_s denote the active and reactive powers of the stator, respectively.

B. *Grid side converter modeling (Inverter)*

The three-phase inverter is composed of three legs, each leg including two power switches (MOSFET, IGBT...).

As illustrated in the schematic diagram in Fig.2, every switch has an anti-parallel diode installed, [6], [7].

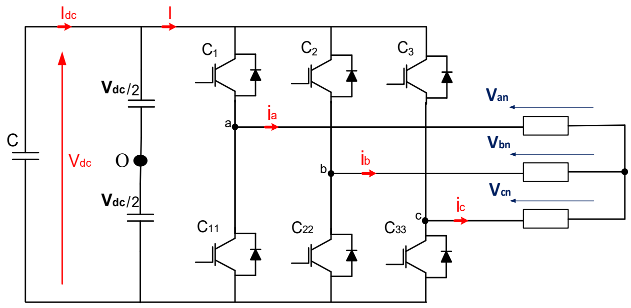


Fig.2 : Three phase inverter topology

We are able to write (13), because we have a balanced three-phase system:

$$V_{an} + V_{bn} + V_{cn} = 0 \quad (13)$$

$$\begin{pmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{pmatrix} = \begin{pmatrix} V_{ao} + V_{on} \\ V_{bo} + V_{on} \\ V_{co} + V_{on} \end{pmatrix} \quad (14)$$

Substituting (13) into (14) gives:

$$V_{on} = -\frac{1}{3}\left(V_{ao} + V_{bo} + V_{co}\right) \quad (15)$$

The system of simple voltages is written in the matrix form (17).

$$\begin{pmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}\begin{pmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{pmatrix} \quad (16)$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \times \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \times \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} \quad (17)$$

C. *Modeling of a DC-DC boost converter*

A DC-DC boost converter is a type of power converter that generates an output voltage higher than its input voltage. For this reason, it is also known as a step-up converter. The circuit configuration of a DC-DC boost converter is shown below [8].

A standard boost converter, depicted in Fig. 3, consists of essential elements such as an insulated gate bipolar transistor (IGBT), an inductor, a diode, and an output capacitor. This topology is intended to increase the input voltage to a higher output voltage level.

The system operates using pulse-width modulation (PWM), in which a constant duty-cycle reference is continuously compared with a high-frequency carrier signal to generate the PWM control pulses.

This signal, in turn, controls the switching behavior of the IGBT, thereby regulating the energy transfer and output voltage, [9].

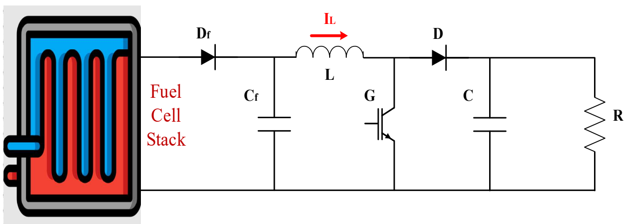


Fig.3 : DC–DC Boost Converter for Fuel Cell Stack Applications

D. *Fuel Cell System*

In recent years, a wide range of models for PEM fuel cells have been developed utilizing Electrochemical Impedance Spectroscopy (EIS) as a characterization method, exhibiting varying levels of complexity and accuracy [10], [11]. However, most of these models are limited to steady-state analysis, whereas evaluating performance under dynamic operating conditions remains essential. Moreover, many existing approaches rely on partial differential equations, which increase model complexity and make parameter identification more challenging. Therefore, a simplified yet sufficiently accurate model, based on the physicochemical phenomena occurring within the cell, has been adopted [12], [13], [14], [18].

The fuel cell acts as a secondary energy source. It provides power when wind energy is insufficient and ensures continuous energy supply.

The realistic fuel cell model used in Scenario 3 includes a first-order dynamic response characterized by a time constant. This response is slower than the wind speed variations, which explains the transient mismatch observed between generated and demanded power. Consequently, the PI controller exhibits reduced effectiveness under realistic fuel cell dynamics.

Table 1 presents the parameters of our system, including their corresponding symbols and values.

TABLE I. PARAMETERS OF SYSTEM

	Parameters	Values
DFIG Parameters	Nominal power (Ps)	800 W
	Rotor speed (n)	160 rad/sec
DC/DC Boost Parameters	DC-bus voltage	650 V
	Duty cycle	0.566
Fuel Cell Parameters	Voltage at 0 A	282 V
	Voltage at 1 A	265 V
	Nominal voltage	258 V
	Nominal current	2 A

III. PROPOSED CONTROL STRATEGY OF THE FUEL CELL

Fig.4 presents the proposed fuel cell system, which includes a boost converter connected to the DC link of the wind energy generation system. The power delivered by the Fuel Cell is controlled by a PI (Proportional-Integral) controller which generates the duty cycle variation (delta d).

The fuel cell serves as the primary energy source and supplies the boost converter.

The boost converter is used to increase the voltage to the level of the DC link used by the WECS.

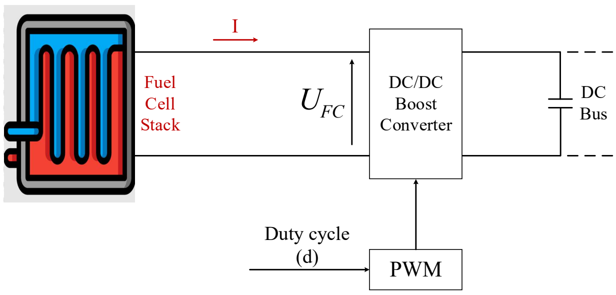


Fig.4 : Proposed System Configuration for the Fuel Cell

A PI (Proportional–Integral) controller is a widely used control strategy in industrial applications for regulating process variables. It functions within a feedback control loop, combining proportional and integral actions to maintain the desired system performance and ensure accurate tracking of reference values, [15], [16], [17].

This controller uses a closed-loop feedback strategy to ensure that the actual output of a process remains as close as possible to a predefined setpoint. In some situations, a constant output may also be applied when appropriate. Fig.5 illustrates the block diagram of this control approach.

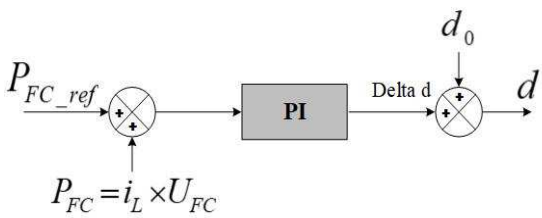


Fig.5 : PI Controller Tuning Method

Where: $P_{ref} = P_{moy} - P_r$

With: $P_{moy} = 630\ W$; Average power; it represents the mean value of the power over a given period of time;

And P_r : Reference power; it is the desired power that the control system aims to achieve.

The fuel cell is mainly intended as a secondary source for power balancing under insufficient wind conditions. However, it also contributes to mitigating moderate transient power fluctuations in order to improve grid power stability. Due to the inherent slow dynamics of the fuel cell, its compensation capability remains limited for fast transients.

IV. Simulation Results

In this section, the dynamic performance of the proposed control strategy is evaluated through a step-change in active power. In order to verify developed control methods, three operation scenarios were simulated.

- Scenario 1: Operation using the Wind generation system
- Scenario 2: Operation using hybrid energy generation system (DFIG + Fuel Cell)
- Scenario 3: Operation with a realistic model of the fuel cell

A. Scenario 1: Operation using the Wind generation system

Fig. 6 illustrates the dynamic response of the DFIG rotor speed. The system maintains a constant speed of 160 rad/s, aligning perfectly with the reference ω_{ref}. At t=0.2s, the speed exhibits a negligible transient deviation of less than 1%, despite the introduction of an aerodynamic torque fluctuation.

The rotor speed remains regulated around 160 rad/s due to the DFIG vector control strategy, independently of the fuel cell contribution.

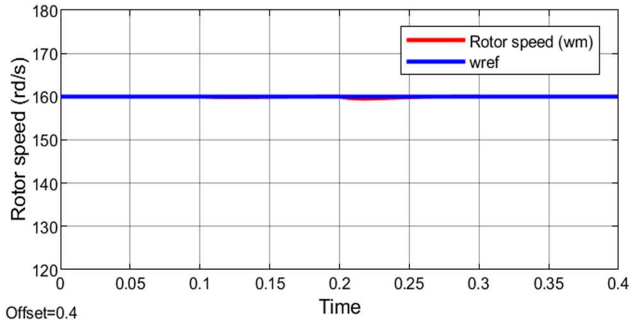


Fig.6 : Rotor speed

Fig.7 shows the variation of rotor currents during the operation of the WECS. As observed, the currents closely track the references with a very small steady-state discrepancy. A fast dynamic response is observed, with the system reaching the setpoint rapidly. The speed remains stable over time, indicating good control performance and robustness against disturbances.

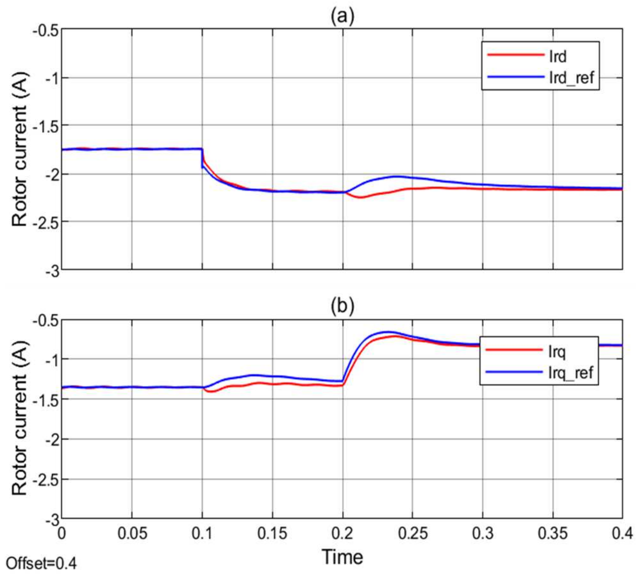
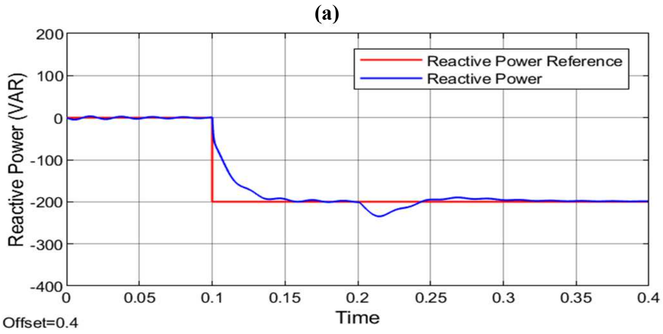


Fig.7 : Rotor currents in the direct (d) and quadrature (q) axis

Fig. 8 illustrates the dynamic behavior of reactive power and rotor power produced by the WECS. Firstly, the reactive power closely follows its reference value. A step change in reference occurs at approximately t=0.1s. As observed in Fig. 8(a), the system responds rapidly by decreasing the reactive power to track the new reference. A short transient is observed, characterized by a slight overshoot and damped oscillations before reaching steady state. The rotor power changes according to the aerodynamic power present in front of the turbine.

Therefore, it not possible to maintain constant power generation. As observed in Fig.8 (b), this power is fluctuating and can increases or decreases according to the instantaneous wind speed. Therefore, the objective of the integration of the Fuel cell id to mitigate these fluctuations by injecting a compensating power during the variations of the wind speed. Overall, the controller ensures good tracking performance and effective regulation of reactive power under varying operating conditions.

(a)



(b)

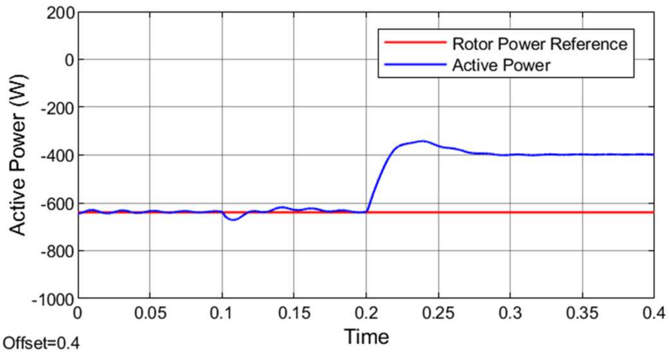
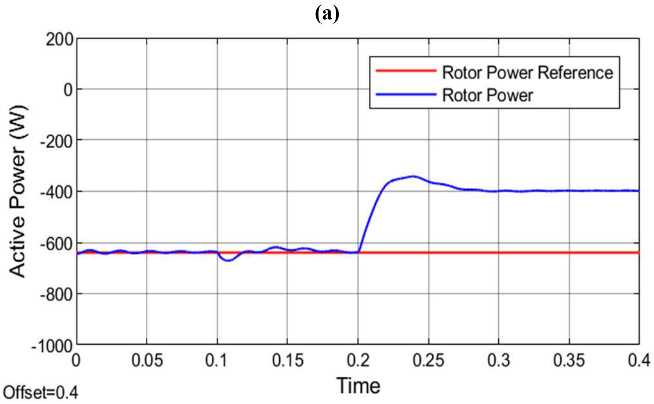


Fig.8 : Powers produced by the WECS. (a) Reactive power. (b) Rotor power

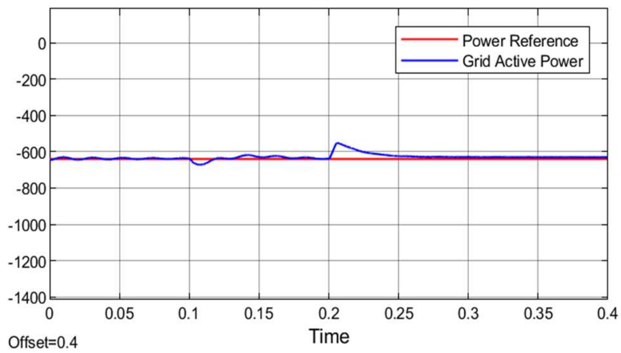
B. *Scenario 2: Operation using hybrid energy generation system (DFIG + Fuel Cell)*

Fig. 9 shows the power delivered to the grid using the Hybrid energy generation system. As observed, the integration of the fuel cell pack allows to maintain a constant power delivered to the grid even during wind speed variations. The PI-based control strategy allows an effective control of the produced power by the fuel cell. The fuel cell can effectively compensate the rotor power variations in order to inject constant power to the grid. However, these results are obtained using an ideal model of the fuel cell. The control behavior with a realistic model of the Fuel cell is analyzed in scenario 3.

(a)



(b)



(c)

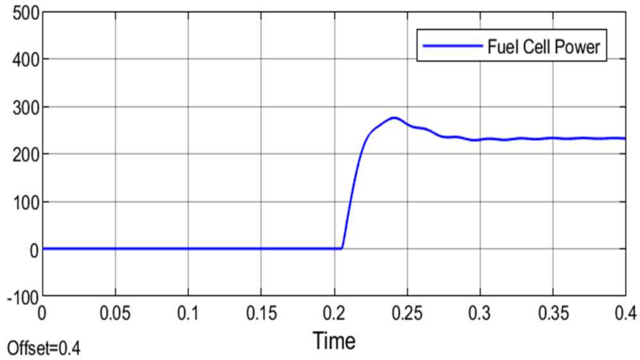
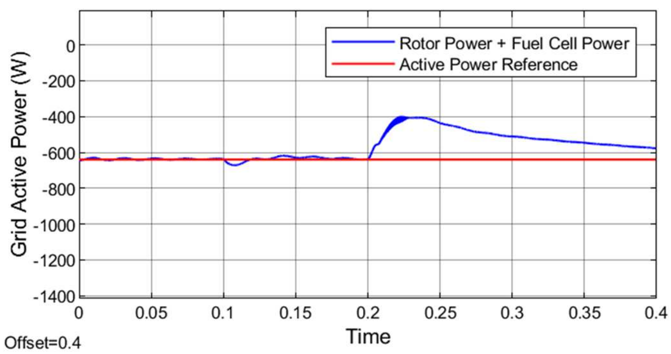


Fig.9 : Operation of the Hybrid energy generation system. (a) Power delivered by the WECS. (a) Power delivered to the grid using the hybrid energy generation system. (c) Power produced by the Fuell Cell.

C. *Scenario 3: Operation with a realistic model of the Fuel Cell*

Fig. 10 shows the power contribution of the fuel cell in the hybrid system when a realistic model is used. As observed, the fuel cell exhibits a slower dynamic response due to its inherent electrochemical characteristics. The output power gradually increases after t ≈ 0.2s, reflecting the activation of the DC-DC boost converter and the power-sharing strategy. The power delivered to the grid does not remain constant and the PI-based controller fails to track the variation of the rotor power.

(a)



(b)

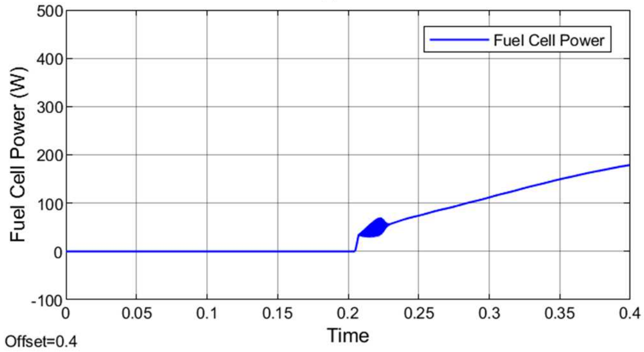


Fig.10 : Operation of the Hybrid energy generation system with a realistic model of the Fuel Cell. (a) Power delivered to the grid using the hybrid energy generation system. (b) Power produced by the Fuell Cell

The results demonstrate strong performance in tracking active and reactive power, along with stable behavior of electrical variables (currents) and mechanical variables (rotor speed) during disturbances.

CONCLUSION

The proposed fuel cell model effectively represents the key electrochemical phenomena, while the boost converter efficiently increases the voltage to meet the requirements of practical applications.

The simulation outcomes validate the proposed control approach, highlighting its ability to dynamically adjust both current and voltage while ensuring efficient power extraction from fuel cells. This contribution enhances fuel cell technology by tackling existing limitations and laying the groundwork for future progress in sustainable energy solutions.

REFERENCES

[1] Farhani, S. S. Alharbi, S. S. Alharbi, E. M. Barhoumi and F. Bacha, "Investigation and Analysis of Solar and Wind Energy Potential for Green Hydrogen Production via Alkaline Water Electrolysis," in *IEEE Access*, vol. 13, pp. 168878-168892, 2025, doi: 10.1109/ACCESS.2025.3607973.

[2] A. Kadri, H. Marzougui, A. Aouiti, F. Bacha, "Energy Management and Control Strategy for a DFIG Wind Turbine / Fuel Cell Hybrid System with Super Capacitor Storage System", University of Tunis Journal Pre-proof. Doi: https:/doi.org/10.1016/j.energy.2019.116518.

[3] N. Aouani, F. Bacha, R. Dhifaoui, "Control strategy of a variable speed wind energy conversion system based on a Doubly Fed Induction Generator " - IREACO International Review of Automatic Control, 2009.

[4] J. Morren1, S.W.h. de Haan1, P. Bauer1, J.T.G. Pierik, J. Bozelie, "Comparison of complete and reduced models of a wind turbine with Doubly-Fed Induction Generator" , Toulouse, ISBN: 90-75815-07-7. EPE 2003.

[5] H. Akagi, S. Ogasawara, H. Kim, "The theory of instantaneous power in three phase four wire systems and its applications" , electrical engineering in Japan, ol.135, n 3, PP.74-86, 2001.

[6] S. SOLTANI, S. FARHANI, S. MARROUCHI and F. BACHA, « Integration of photovoltaic generator in a medium voltage electrical grid », 2025 IEEE International Conference on Advanced Systems and Emergent Technologies (IC_ASET), Hammamet, Tunisia: IEEE, May 2025, DOI: 10.1109/IC_ASET65966.2025.11232423.

[7] S. SOLTANI, H. GRISSA, S. FARHANI, and F. BACHA, « Sliding Mode Control of a Photovoltaic System Connected to the Electrical Grid», 2023 9th International Conference on Control, Decision and Information Technologies (CoDIT 2023), IEEE, Rome Italy, July 03-06, 2023. DOI: 10.1109/CoDIT58514.2023.10284117.

[8] S. Farhani, E. M. Barhoumi, A. Djerdir and F. Bacha, "Experimental Analysis of the Performances of Proton Exchange Membrane Fuel Cell Based Electric Vehicle," *International Journal of renewable energy*, 2021.

[9] R. H. G. Tan et L. Y. H. Hoo, « DC-DC converter modeling and simulation using state space approach », in 2015 IEEE Conference on Energy Conversion (CENCON), Johor Bahru: IEEE, oct.2015, p. 42-47. doi:10.1109/CENCON.2015.7409511.

[10] P. K. Panda, B. Sahoo, et S. Ramakrishna, « Hydrogen Production, Purification, Storage, Transportation, and Their Applications: A Review », Energy Technol., vol. 11, no 7, p.2201434, 2023, doi: 10.1002/ente.202201434

[11] I. Lahlouh, A. El Akkary, et N. Sefiani,« PID/Multi-Loop Control Strategy for Poultry House System Using Multi-Objective Ant Colony Optimization », Int. Rev. Autom. Control IREACO, vol. 11, no 5, p. 273, sept. 2018, doi:10.15866/ireaco.v11i5.14958.

[12] A. K. Rathore et A. K. Verma, Advanced Concepts and Technologies for Electric Vehicles.CRC Press, 2023.

[13] M. S. Reza, N. B. H. Ahmad, S. Afroze, J. Taweekun, M. Sharifpur, et A. K. Azad, « Hydrogen Production from Water Splitting through Photocatalytic Activity of Carbon-BasedMaterials », Chem. Eng. Technol., vol. 46, no 3, p.420-434, 2023, doi: 10.1002/ceat.202100513.

[14] K. M. Tiwari Monika Dabkara, S. Santhosh,N. Sandeep, Arun Kumar Verma, Harpal, « Introduction to Electric Vehicles », in Advanced Concepts and Technologies for Electric Vehicles,CRC Press, 2023.

[15] B. Bouaziz, F. Bacha and M. Gasmi, "High performance of fuzzy direct power control for PWM converters," *2012 16th IEEE Mediterranean Electrotechnical Conference*, Yasmine Hammamet, Tunisia, 2012, pp. 289-295, doi: 10.1109/MELCON.2012.6196435.

[16] S. Farhani, E. M. Barhoumi and F. Bacha, "Design and hardware investigation of a new configuration of an isolated DC-DC converter for fuel cell vehicle," *Ain Shams Engineering Journal,* 2021

[17] S. Farhani, E. M. Barhoumi, A. Djerdir and F. Bacha, "Study and Hardware Implementation of Floating Multiphase Boost Converter for Fuel Cell Electrical Vehicle". International Journal of Renewable Energy Research (IJRER), 2022, vol. 12, no 3, p. 1393-1403.

[18] H. Marzougui, A. Kadri, M. Amari and F. Bacha, "Frequency separation-based energy management strategy for fuel cell electrical vehicle with super-capacitor storage system," *2018 9th International Renewable Energy Congress (IREC)*, Hammamet, Tunisia, 2018, pp. 1-6, doi: 10.1109/IREC.2018.8362521.

[19] Bechir. Bouaziz, F. Bacha, GASMI, Moncef. « Wind energy conversion system with full-scale power converter and squirrel cage induction generator". *International Journal of Physical Sciences*, 2012, vol. 7, no 46, p. 6093-6104.