Enhanced Energy Management Strategy for Standalone Systems Integrating Fuel Cells, Batteries, and Supercapacitors

Zahra Mokrani[1], *Adel* Oubelaid[1], *Djamila* Rekioua[1], *Toufik* Rekioua[1], *Shwetank* Avikal[2], *Mohit* Bajaj[3,4,*]

[1] Université de Bejaia, Faculté de Technologie, Laboratoire de Technologie Industrielle et de l'Information, Bejaia 06000, Algeria
[2] Department of Management Studies, Graphic Era (Deemed to be University), Dehradun-248002, India
[3] Department of Electrical Engineering, Graphic Era (Deemed to be University), Dehradun-248002, India
[4] Graphic Era Hill University, Dehradun, 248002, India

Abstract. Hybrid systems combining fuel cells with battery and supercapacitor storage offer a promising solution for efficient and flexible energy management. Fuel cells, which convert chemical energy into electrical energy, provide a clean and sustainable power source but face challenges like slow response times and limited power density. Integrating batteries and supercapacitors addresses these issues: batteries offer high energy density and stable power supply over longer durations, while supercapacitors deliver rapid bursts of energy and quick charge-discharge cycles. Effective power management in hybrid fuel cell systems is crucial for maximizing efficiency, performance, and lifespan while ensuring reliable energy supply. The hybrid system consists of a PEM fuel cell, batteries, and a supercapacitor (SC) and introduces a power management strategy to ensure the supply of the load.

1 Introduction

Numerous systems based on renewable energy conversion have been developed and proposed as sustainable solutions for generating unlimited and environmentally friendly energy [1-2]. A hybrid power system integrates various energy sources and storage mechanisms to meet demand and manage load fluctuations. The PEM fuel cell is considered an advantageous energy solution, especially for transportation and stationary cogeneration applications, due to its high efficiency, low operating temperature, high power density, quick start-up, and durable design [3].

PEM fuel cells are suitable for portable, mobile, and residential applications. Typically, they are combined with hybrid energy storage systems to enhance dynamic performance and extend the fuel cell's lifespan.

This hybrid approach leverages the strengths of each component, ensuring a reliable and responsive power system [4]. Batteries handle energy storage and steady-state power demands, while supercapacitors manage peak loads and transient conditions. This synergy enhances overall system performance, efficiency, and lifespan, making hybrid fuel cell systems suitable for applications ranging from electric vehicles to renewable energy grids. Such systems can significantly contribute to reducing reliance on fossil fuels and advancing sustainable energy technologies [5-8].

This study concentrated on energy management within a hybrid storage system that includes PEM fuel cells, batteries, and supercapacitors. Each subsystem was modeled and simulated using MATLAB/Simulink.

* Corresponding author: thebestbajaj@gmail.com

2 Modeling of the Studied System

The global system proposed in Figure 1 combines a proton exchange membrane fuel cell (PEMFC), batteries and supercapacitors to supply a standalone system.

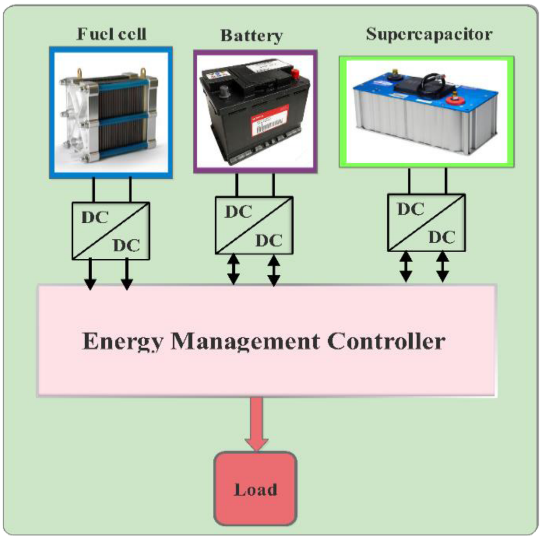

Fig. 1. Proposed energy management system

2.1 Supercapacitor Modelling

In order to depict the response of the supercapacitor (SC) during rapid charging and discharging cycles, we adopt the equivalent electrical circuit comprising two RC branches, as suggested by [15-16] and illustrated in Figure 2 [20-21].

 https://doi.org/10.1051/e3sconf/202456408001

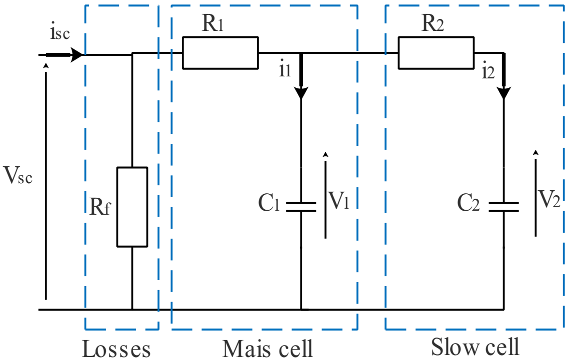

Fig. 2. SC model diagram

The primary capacitance C_1 is contingent upon the voltage V_1. It comprises a fixed capacity C_0 (in Farads) and a constant parameter C_v (in Farads per Volt), expressed as $C_1 = C0 + C_v V_1$. The R_1C_1 branch governs the instantaneous response of the supercapacitor during swift charging and discharging cycles, typically occurring within a few seconds [8].

The R_2C_2 element constitutes the prolonged branch, addressing the initial cell over an extended timeframe, typically spanning several minutes. It characterizes the internal energy redistribution upon completion of the charging or discharging process. The parallel resistance equivalent, denoted as R_f, signifies the leakage current and is disregarded during the rapid charging or discharging phases of the supercapacitor.

The circuit presented in Figure 3 is based on the following equations [8]:

$$U_{sc} = N_{s\_sc} V_{sc} = N_{s\_sc}(V_1 + R_1 i_{sc}) = N_{s\_sc}\left(V_1 + R_1 \frac{I_{sc}}{N_{p\_sc}}\right) \quad (1)$$

2.2 Battery Modelling

The model used in this paper is composed from two electrical elements: a voltage source and an internal resistance [17-19]:

$$V_{Batt} = E_b \pm n_{batt} R_{Batt}\, I_{Batt} \quad (2)$$

State of charge of the battery is given by the following equation:

$$SOC\ (\%) = 100\left(1 - \frac{I_{Batt}\ t}{C_{Batt}}\right) \quad (3)$$

2.3 Fuel Cell Modelling

A proton exchange membrane fuel cell (PEMFC) functions as an electrochemical device for converting energy. The voltage across the cell V_{PEMFC} is determined by the sum of the Nernst voltage E_{Nerst}, activation overpotential U_{act}, concentration overpotential U_{conc}, and resistive or ohmic overpotential U_{ohm} [9-14].

$$V_{PEMFC} = E_{Nernest} - V_{act} - V_{ohm} - V_{con}$$

$$E_{Nerst} = \alpha_1 + \alpha_2 \times (T_{PEMFC} - 298.15) + \alpha_3 \times T_{PEMFC} \times (0.5 \ln Po^*_{O_2} + \ln P^*_{H_2}) \quad (4)$$

$$E_{Nerst} = \alpha_1 + \alpha_2 \times (T_{PEMFC} - 298.15) + \alpha_3 \times T_{PEMFC} \times (0.5 \ln Po^*_{O_2} + \ln P^*_{H_2}) \quad (5)$$

$$V_{act} = \beta_1 + \beta_2 \times T_{PEMFC} + \beta_3 T_{PEMFC} \times ln(j \times 5 \times 10^{-3})$$

$$+\beta_4 \times T_{PEMFC} \times lnC^*_{O_2} \quad (6)$$

$$V_{ohm} = I_{PEMFC} \times (R_m + R_s) \quad (7)$$

$$V_{con} = -B\left(1 - \frac{j}{j_{max}}\right) \quad (8)$$

$$R_m = \frac{r_m \times e_m}{S_{cell}} \quad (9)$$

$$r_m = \frac{191.6\left[1 + 0.03 \times \left(\frac{I_{PEMFC}}{S_{cell}}\right) + 0.062 \times \left(\frac{T_{PEMFC}}{303}\right)^2 \times \left(\frac{I_{PEMFC}}{S_{cell}}\right)^{2.5}\right]}{\left[\left(\lambda_{H_2O/SO_3^-}\right) - 0.634 - 3 \times \left(\frac{I_{PEMFC}}{S_{cell}}\right) \times exp\left[4.18 \times \left(\frac{T_{PEMFC} - 303}{T_{PEMFC}}\right)\right]\right]} \quad (10)$$

In this context, $C^*_{O_2}$ represents the oxygen concentration within the cathode region, where β_i denotes specific constants, and S_{cell} indicates the active area of the cell. The term R_s represents the equivalent contact resistance for electrode conduction. T_{PEMFC} signifies the absolute operating temperature of the stack, with α_i representing corresponding constants.

3 Energy Management Controller

The energy management strategy outlined in this study aims to harness the rapid charging and discharging capabilities of supercapacitors, thereby alleviating the strain on fuel cells caused by sudden power requirements.

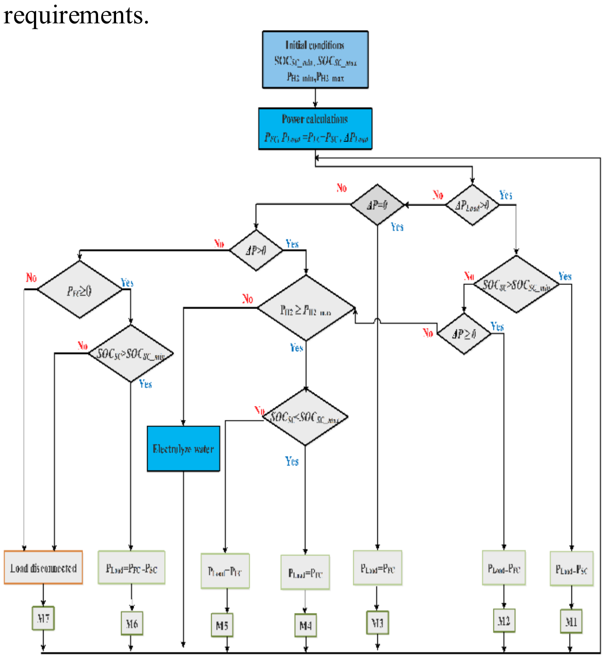

Fig. 3. Chart of the fuel cells/supercapacitor combination system.

The batteries come to supply the load demand when the available fuel energy is not enough, while the supercapacitors act in sudden and positive variation of the load power. Based on various tests conducted, the system functions in one of the depicted modes illustrated Figure 3.

 https://doi.org/10.1051/e3sconf/202456408001

4 Results and Discussion

In this section, the obtained results using MATLAB/Simulink are presented and extensively discussed. The simulation outcomes stem from the overall system depicted in Figure 1. The load power is set to 960W. We can see that the load power profile is a series of steps shifted in time with different amplitudes.

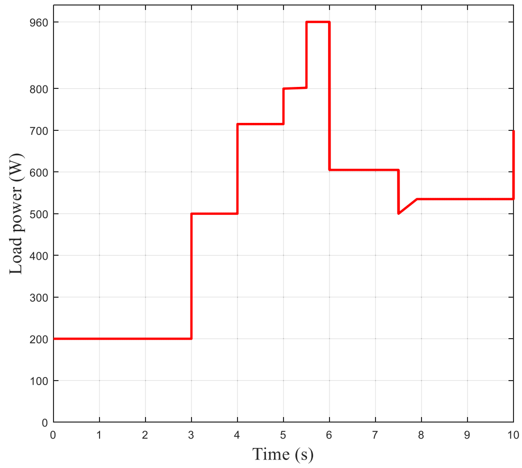

Fig. 4. Power load profile.

Figure 5 shows the obtained fuel cell, battery and supercapacitor powers. In addition to that, the reference load power is depicted also in figure 5 shown below.

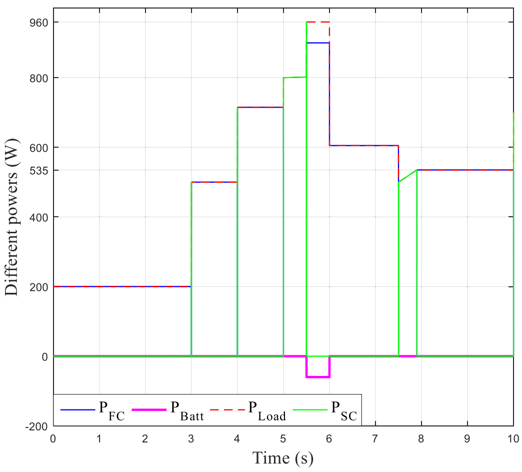

Fig. 5. Different powers profile.

Figure 6 shows the load power and the battery power on the same plot.We can notice that the battery gets charged during the time instant [5.5s,6s].

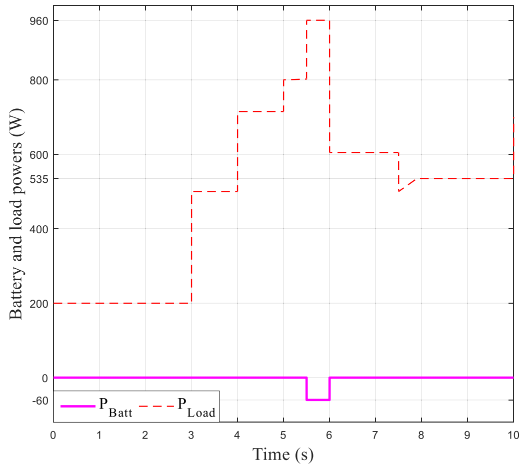

Fig. 6. Battery and Load powers.

Figure 7 shown below points out the battery state of charge during 10 seconds of simulation. We can notice that battery state of charge was constant during the first 5 seconds of simulation and this is due to the high load demand.

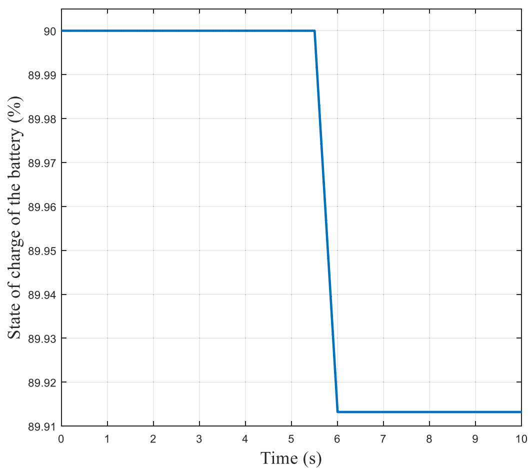

Fig. 7. State of charge of the battery.

Figures 8 and 9 show respectively battery voltage and current. The battery is feeding the load form 0 to 5.5s and from 6s to the end of simulation. When t is between 5.5 s and 6s, the battery is getting charged with a reference current equal to 2.5 A.

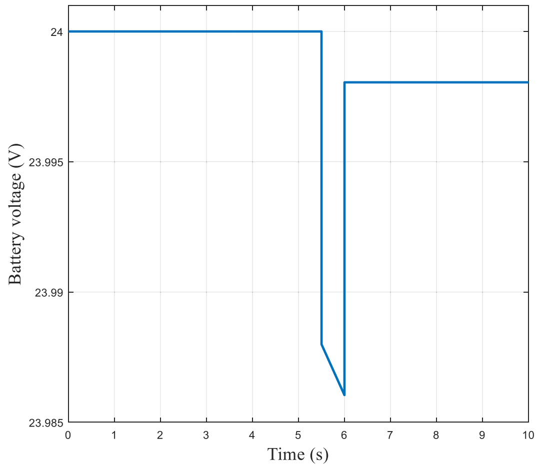

Fig. 8. Voltage of the battery.

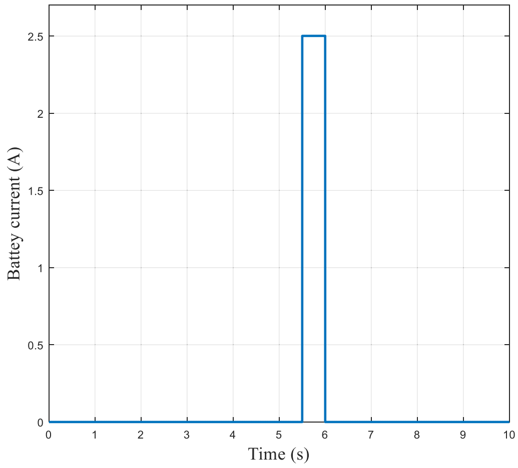

Fig. 9. Current of the battery.

From figure 10 one can see that The fuel cell supplies the load perfectly until t=3s, when the supercapacitor comes into operation as the load increases briskly from 200 to 500 Watts, to ensure continuous supply from the fuel cell during constant load demand.When the load demand reaches a peak of 900 watts, the energy produced by the fuel cell is not sufficient to meet the demand, so the batteries provide the necessary compensation.

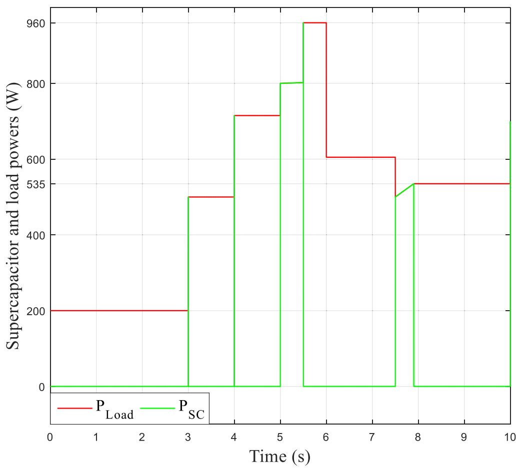

Fig. 10. Supercapacitor and load powers

Figure 11 and 12 show respectively the supercapacitor state of charge and its voltage of the 10 simultion seconds. One can see that when the supercapacitor is not activated, its state of charge remains constant. However, when it is feeding the load, its state of charge decreases and the slope decrease depends on the level of power request.

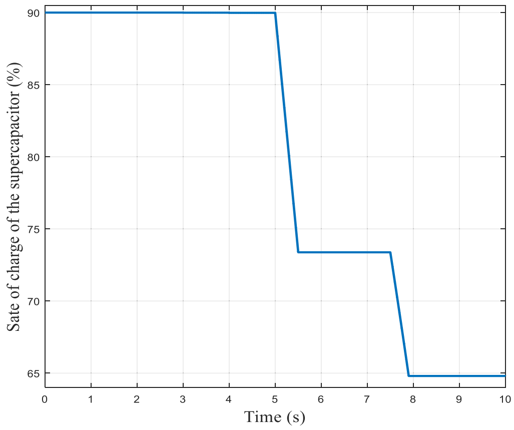

Fig. 11. State of charge of the supercapacitor.

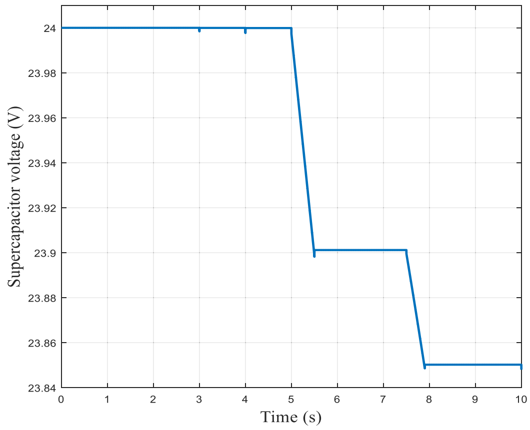

Fig. 12. Supercapacitor voltage.

Figure 13 mentioned below highlights the supercapacitor current obtained during the simulation of the hybrid energy system. One can notice that the supercapacitor delivers current peaks whose magnitude depends on the level of the power demand.

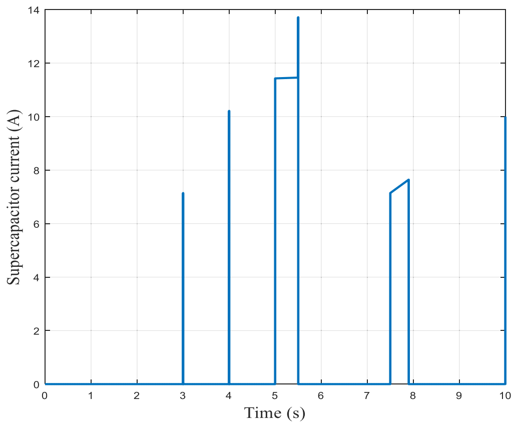

Fig. 13. Supercapacitor current (A).

5 Conclusion

This paper presents a study of a hybrid system featuring PEM fuel cells, batteries, and supercapacitors as a standalone power source. To guarantee a continuous power supply to the load, an energy management strategy is devised. The hybrid system's simulation model was developed using MATLAB/Simulink. The results validate the proposed energy management controller and demonstrate the system's efficiency.

References

1. Mokrani. Z, Rekioua. D, Mebarki. N, Rekioua. T, Bacha. S. Proposed energy management strategy in electric vehicle for recovering power excess produced by fuel cells, Int J Hydrogen Energy, 2017, 42, 19556-19575.
2. Mohamed, N., Bajaj, M., Almazrouei, S. K., Jurado, F., Oubelaid, A., & Kamel, S. (2023, June). Artificial Intelligence (AI) and Machine Learning (ML)-based Information Security in Electric Vehicles: A Review. In 2023 5th Global Power, Energy and Communication Conference (GPECOM) (pp. 108-113). IEEE.
3. G. Semwal, S. Sharma and T. Rawat, "A Review on Multiple Renewable Energy Resources, Battery Storage System and Demand Response in Contemporary Distribution System," 2023 International Conference on Sustainable Emerging Innovations in Engineering and Technology (ICSEIET), Ghaziabad, India, 2023, pp. 682-686, doi: 10.1109/ICSEIET58677.2023.10303588.
4. Mohamed, N., Almazrouei, S. K., Oubelaid, A., Elsisi, M., ElHalawany, B. M., & Ghoneim, S. S. (2022). Air-Gapped Networks: Exfiltration without Privilege Escalation for Military and Police Units. Wireless Communications and Mobile Computing, 2022(1), 4697494.
5. Abou Houran, M., Sabzevari, K., Hassan, A., Oubelaid, A., Tostado-Véliz, M., & Khosravi, N. (2023). Active power filter module function to improve power quality conditions using GWO and PSO techniques for solar photovoltaic arrays and battery energy storage systems. Journal of Energy Storage, 72, 108552.
6. Oubelaid, A., Taib, N., & Rekioua, T. (2022). Novel coordinated power sources switching strategy for transient performance enhancement of hybrid electric vehicles. COMPEL-The international journal for computation and mathematics in electrical and electronic engineering, 41(5), 1880-1919.
7. Kakouche, K., Oubelaid, A., Mezani, S., Rekioua, D., & Rekioua, T. (2023). Different control techniques of permanent magnet synchronous motor with fuzzy logic for electric vehicles: analysis, modelling, and comparison. Energies, 16(7), 3116.
8. Belaid, S., Rekioua, D., Oubelaid, A., Ziane, D., & Rekioua, T. (2022). Proposed hybrid power optimization for wind turbine/battery system. Periodica polytechnica Electrical engineering and computer science, 66(1), 60-71.
9. Rekioua D, Bensmail S, Bettar N. Development of hybrid photovoltaic-fuel cell system for stand-alone application. Int J Hydrogen Energy 2014, 39, 1604-1611.
10. Mokrani Z, Rekioua D, Rekioua T. Modeling, control and power management of hybrid photovoltaic fuel cells with battery bank supplying electric vehicle. Int J Hydrogen Energy, 2014, 39, 15178-15187.
11. Oubelaid, A., Shams, M. Y., & Abotaleb, M. (2022). Energy efficiency modeling using whale optimization algorithm and ensemble model. J. Artif. Intell. Metaheuristics, 2(1), 27-35.
12. Mezzai N, Rekioua D, Rekioua T, Mohammedi A, Idjdaren K, Bacha S. Modeling of hybrid photovoltaic/wind/fuel cells power system. Int J Hydrogen Energy, 2014, 39, 15158-15168.
13. Mebarki N, Rekioua T, Mokrani Z, Rekioua D, Bacha S. PEM fuel cell/battery storage system supplying electric vehicle. Int J Hydrogen Energy, 2015, 41, 20993-21005.
14. Rekioua, D., Mokrani, Z., Kakouche, K., Rekioua, T., Oubelaid, A., Logerais, P. O., ... & Ghoneim, S. S. (2023). Optimization and intelligent power management control for an autonomous hybrid wind turbine photovoltaic diesel generator with batteries. Scientific Reports, 13(1), 21830.
15. Ziane, D., Azib, A., Oubelaid, A., Taib, N., Rekioua, T., & Rekioua, D. (2022). Proposed power factor correction circuit based on the single-ended primary-inductor converter controlled by sliding mode control strategy used in an electric vehicle charging station. REVUE ROUMAINE DES SCIENCES TECHNIQUES—SÉRIE ÉLECTROTECHNIQUE ET ÉNERGÉTIQUE, 67(3), 241-245.
16. Oubelaid, A., Kakouche, K., Belbachir, N., Rekioua, T., Bajaj, M., Jurado, F., & Kamel, S. (2023, June). Efficient driveline architecture and torque distribution strategy for dual traction machines electric vehicles. In 2023 5th Global Power, Energy and Communication Conference (GPECOM) (pp. 86-91). IEEE.
17. Oubelaid, A., Mohamed, N., Taib, N., Rekioua, T., Bajaj, M., Parashar, D., & Blazek, V. (2022, December). Robust Controllers Design and Performance Investigation of a Vector Controlled Electric Vehicle. In 2022 2nd International Conference on Innovative Sustainable Computational Technologies (CISCT) (pp. 1-6). IEEE.
18. Oubelaid, A., Taib, N., & Rekioua, T. (2019, November). Performance assessment of a direct torque controlled electric vehicle considering driving cycles and real load conditions. In 2019 International Conference on Advanced Electrical Engineering (ICAEE) (pp. 1-6). IEEE.

19. Mohammedi A., Rekioua D., Rekioua T., Bacha S. Valve Regulated Lead Acid battery behavior in a renewable energy system under an ideal Mediterranean climate. International Journal of Hydrogen Energy 41 (45), pp.20928-20938, (2016).
20. Rekioua, D., Kakouche, K., Babqi, A., Mokrani, Z., Oubelaid, A., Rekioua, T., ... & Abdelwahab, S. A. M. (2023). Optimized Power Management Approach for Photovoltaic Systems with Hybrid Battery-Supercapacitor Storage. Sustainability, 15(19), 14066.
21. Kakouche, K., Oubelaid, A., Mezani, S., Rekioua, T., Bajaj, M., Jurado, F., & Kamel, S. (2023, June). Energy Management Strategy of Dual-Source Electric Vehicles Based on Fuzzy Logic Control Considering Driving Cycles. In 2023 5th Global Power, Energy and Communication Conference (GPECOM) (pp. 92-97). IEEE.
22. Mokrani, Z., Rekioua, D., Mebarki, N., Oubelaid, A., Kakouche, K., & Rekioua, T. (2023). Power management strategy for photovoltaic system with hybrid storage (Batteries/Supercapacitors). RE&PQJ, 21(4).
23. Belaid, S., Rekioua, D., Oubelaid, A., Ziane, D., & Rekioua, T. (2022). A power management control and optimization of a wind turbine with battery storage system. *Journal of Energy Storage*, *45*, 103613.
24. Aissou, R., Rekioua, T., Rekioua, D., & Tounzi, A. (2017). Robust nonlinear predictive control of permanent magnet synchronous generator turbine using Dspace hardware (vol 41, pg 21047, 2016). International Journal of Hydrogen Energy, 42(5), 3419-3419.