Indonesian Journal of Electrical Engineering and Computer Science
Vol. 33, No. 3, March 2024, pp. 1378∼1386
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v33.i3.pp1378-1386

Gym’s hybrid system for off-grid renewable energy solutions

Abdelfattah El Azzab, Abdelmounime El Magri, Rachid Lajouad, Ilyass El Myasse, Aziz Watil, Hassan Ouabi
Laboratory of Electrical Engineering and Intelligent Systems, ENSET Mohammedia Hassan II University, Casablanca, Morocco

Article Info

Article history:

Received Oct 15, 2023
Revised Nov 19, 2023
Accepted Dec 1, 2023

Keywords:

AC/DC/DC converters
Hybrid system
Nonlinear control
Squirrel cage induction generator
Stationary bikes

ABSTRACT

The primary objectives behind transitioning from fossil fuels to green energy sources, with a particular focus on reducing both electricity costs and carbon emissions. This transition has prompted various sectors and sports bikes, to embrace renewable energy alternatives, with a specific emphasis on technologies such as photovoltaic systems, energy storage solutions, and power generation from machines. The core subject of investigation in this paper is the application of renewable energy sources within sports bikes, with a particular emphasis on a hybrid system. This hybrid system incorporates DC/DC, AC/DC, and DC/AC converters to meet the energy requirements of the facility. The central aim of the research is to identify the most economically efficient scale for a self-sufficient hybrid photovoltaic system that integrates stationary generators and battery storage. The research seeks to optimize the balance between cost-effectiveness and sustainable energy provision in the context of sports facilities.

Corresponding Author:

Abdelfattah El Azzab
Laboratory of Electrical Engineering and Intelligent Systems, ENSET Mohammedia Hassan II University Casablanca, Morocco
Email: elazzab.abdelfattah96@gmail.com

1. INTRODUCTION

The global shift from conventional to renewable energy is crucial due to escalating environmental damage and fast resource depletion [1], [2]. The adoption of renewable energy is increasing to meet growing global energy needs [3], [4]. Enhanced use of existing renewable sources provides clear benefits, while the development of hybrid systems creates research opportunities [5], [6]. In contrast, power generators for sports bikes convert physical energy into electricity, while photovoltaic (PV) systems directly convert solar energy into electricity, known for cost-effectiveness [7]-[9]. Renewable energy sources can independently power sports facilities and offer efficient resource utilization [10]. Optimizing hybrid systems with renewable sources requires a thorough assessment of target functions, connecting various sources to an isolated microgrid through a DC-Bus [11]. Evaluating renewable energy systems, whether single or multiple sources, necessitates considering long-term performance evolution [12], [13].

By leveraging energy source complementarity and temporal distribution, a hybrid system combines athlete-generated and battery-stored energy to compensate for sunlight shortages. Using an AC/DC converter for stationary generators and a photovoltaic DC/DC converter results in a more stable gym power supply with smaller system components. This approach is ideal for gyms with ample solar potential, power-generating machines, and effective resource complementarity, as shown in Figure 1.

The document is structured as follows: Section 2 explains the conversion of stationary bikes and the storage system. In section 3 covers the photovoltaic system conversion. In section 4 presents simulation results and performance evaluations. In section 5 concludes the paper.

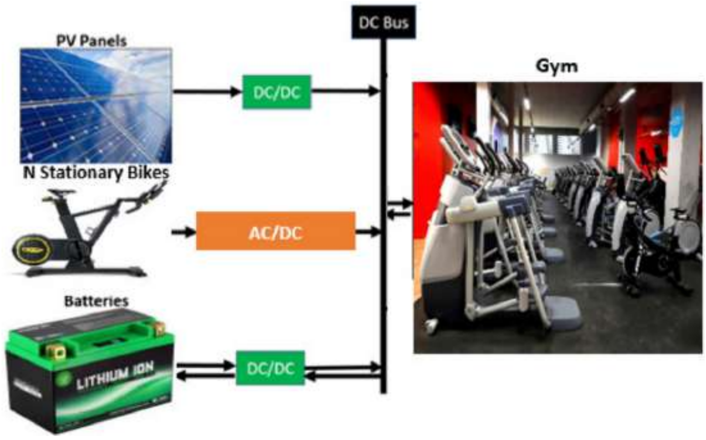

Figure 1. Hybrid system overview

2. STATIONARY BIKES CONVERSION AND STORAGE SYSTEM

2.1. Structure and system description

In Figure 2, the depicted system comprises N stationary bikes equipped with squirrel cage induction generators, and these generators are interconnected to AC/DC converters arranged in parallel with the DC-Bus voltage [14]. To facilitate efficient energy management, a buck-boost DC/DC converter is employed to oversee the charging of Li-ion batteries under conditions conducive to favorable load resistance R states. The charging process is regulated using pulse width modulation (PWM) technology [15]. This arrangement demonstrates a sophisticated approach to harnessing energy from stationary bikes, optimizing the conversion process, and efficiently managing energy storage for subsequent use. The use of AC/DC converters, combined with the buck-boost DC/DC converter and PWM control, showcases an integrated system designed for enhanced energy harvesting and storage in the context of stationary bike power generation.

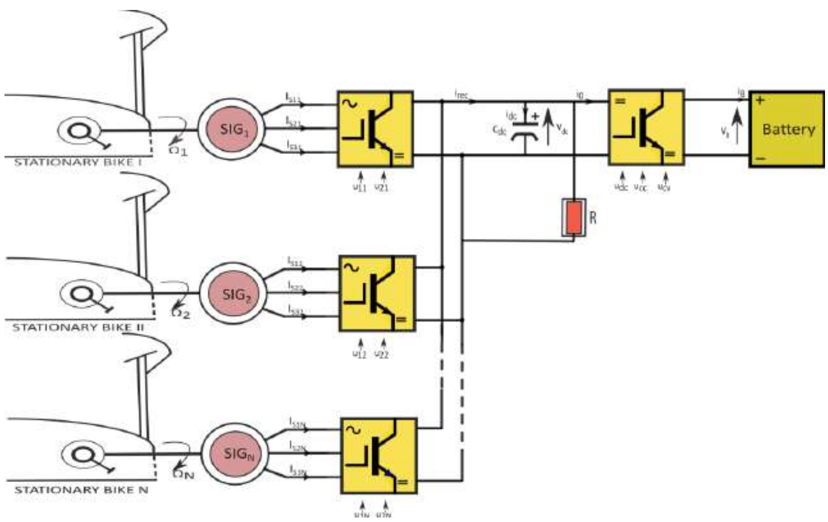

Figure 2. Conversion process of stationary bikes and storage systems

2.2. System modeling

The mathematical model presented is as (1)-(9), depicting the analyzed system, is derived using standard Kirchhoff laws, where k ranges from 1 to N. The complete model in the (α, β) coordinate system is as (1)-(9) [16].

$$\dot{x}_{1i} = -\frac{f}{J}x_{1i} + \frac{M_{sr}}{L_r}\frac{p}{J}(x_{3i}x_{4i} - x_{2i}x_{5i}) - \frac{T_{Gi}}{J} \tag{1}$$

$$\dot{x}_{2i} = \frac{R_r M_{sr}}{\sigma L_s L_r^2}x_{4i} + \frac{pM_{sr}x_5}{\sigma L_s L_r}x_{1i} - \gamma x_{2i} + \frac{V_{dc}}{\sigma L_s}u_{1i} \tag{2}$$

$$\dot{x}_{3i} = \frac{R_r M_{sr}}{\sigma L_s L_r^2}x_{5i} - \frac{pM_{sr}x_{4i}}{\sigma L_s L_r}x_{1i} - \gamma x_{3i} + \frac{V_{dc}}{\sigma L_s}u_{2i} \tag{3}$$

$$\dot{x}_{4i} = -\frac{R_r}{L_r}x_{4i} + \frac{R_r}{L_r}M_{sr}x_{2i} - px_{1i}x_{5i} \tag{4}$$

$$\dot{x}_{5i} = -\frac{R_r}{L_r}x_{5i} + \frac{R_r}{L_r}M_{sr}x_{3i} + px_{1i}x_{4i} \tag{5}$$

$$\dot{x}_6 = \frac{1}{C_{dc}}\sum_{i=1}^{N}(u_{1i}x_{2i} + u_{2i}x_{3i}) - \frac{1}{RC_{dc}}x_6 - \frac{u_{34}}{C_{dc}}x_7 \tag{6}$$

$$\dot{x}_7 = -\frac{r_0}{l_0}x_7 - \frac{1}{l_0}x_8 + \frac{u_{34}}{l_0}x_6 \tag{7}$$

$$\dot{x}_8 = \frac{1}{C_0}x_7 - \frac{1}{R_b C_0}x_8 + \frac{1}{R_b C_0}x_9 \tag{8}$$

$$\dot{x}_9 = \frac{1}{R_b C_b}x_8 - (\frac{1}{R_b C_b} + \frac{1}{R_p C_b})x_9 \tag{9}$$

The state variables are selected as follows: $x_{1i} = \overline{\Omega}_{1i}$, $x_{2i} = \overline{i}_{s\alpha i}$, $x_{3i} = \overline{i}_{s_\beta i}$, $x_{4i} = \overline{\phi}_{r\alpha i}$, $x_{5i} = \overline{\phi}_{r_\beta i}$, $x_6 = \overline{v}_{dc}$, $x_7 = \overline{i}_l$, $x_8 = \overline{v}_b$, $x_9 = \overline{v}_c$. Where $\overline{\Omega}_{1i}, \overline{i}_{s\alpha i}, \overline{i}_{s_\beta i}, \overline{\phi}_{r\alpha i}, \overline{\phi}_{r_\beta i}$, T_G the average variables for the i^{th} stationary bicycle, including angular speed, stator currents, rotor fluxes, and generator torque, $\overline{v}_{dc}$, $\overline{i}_l$, $\overline{v}_b$ and $\overline{v}_c$ are respectively represent the DC/DC converter input voltage, inductor current, battery voltage, and battery internal voltage, respectively. The parameters γ and σ are defined as:

$$\sigma = 1 - \frac{M_{sr}^2}{L_s L_r} \quad ; \quad \gamma = \frac{M_{sr}^2 R_r + L_s^2 R_s}{\sigma L_s L_r^2}$$

The stator voltages $v_{s\alpha i}$, $v_{s\beta i}$ produced by the asynchronous generator, can be individually regulated through the rectifier with the commands u_{1i} and u_{2i}. These voltages are determined based on the control action and the rectifier's output voltage.

$$v_{s\alpha i} = v_{dc}u_{1i} \quad ; \quad v_{s\beta i} = v_{dc}u_{2i}$$

The rectifier's output current i_r is calculated using the following relationship.

$$\overline{i}_r = \sum_{i=1}^{N}(u_{1i}x_{2i} + u_{2i}x_{3i})$$

The switching signals u_{1i} and u_{2i} are represented in the reference frame (α, β) and are generated using a PWM circuit based on the three-phase duty cycle values (s_{1i}, s_{2i}, s_{3i}). These duty cycle values are binary inputs that can take on finite set values, either ($s_{ii} = 0$ if S_{ii} is off and $S_{ii}^{'}$ is on) or ($s_{ii} = 1$ if S_{ii} is on and $S_{ii}^{'}$ is off). The internal structure of the AC/DC/DC converters and the Li-ion battery is illustrated in Figure 2.

2.3. Design and analysis of controllers

Designing a regulator for electromagnetic torque and rotor flux magnitude: applying the nonlinear backstepping control, taking into consideration the following tracking errors [17].

$$z_{1i} = T^*_{emi} - T_{emi} \tag{10}$$

$$z_{2i} = \Phi^{*2}_{ri} - (x^2_{4i} + x^2_{5i}) \tag{11}$$

The torque and flux control laws of stationary generators are given as (12).

$$\begin{pmatrix} u_{1i} \\ u_{2i} \end{pmatrix} = \begin{pmatrix} \varphi_{0i} & \varphi_{1i} \\ \varphi_{2i} & \varphi_{3i} \end{pmatrix}^{-1} \begin{pmatrix} -\zeta_{1i} z_{1i} - \dot{T}^*_{emi} + \mu_{3i} \\ \zeta_{3i} z_{3i} + \zeta_{2i} z_{2i} (2\dfrac{R_r}{L_r} - \zeta_{2i}) + \mu_{4i} \end{pmatrix} \tag{12}$$

With,

$$\varphi_{0i} = \frac{pM_{sr}v_{dc}}{\sigma L_r L_s} x_{5i} \varphi_{1i} = -\frac{pM_{sr}v_{dc}}{\sigma L_r L_s} x_{4i}$$

$$\varphi_{2i} = \frac{2R_r M_{sr}v_{dc}}{\sigma L_r L_s} x_{4i} \varphi_{3i} = \frac{2R_r M_{sr}v_{dc}}{\sigma L_r L_s} x_{5i}$$

Where ζ_1, ζ_2 and ζ_3 are positive design parameters.
And,

$$\mu_{3i} = \frac{pM_{sr}}{L_r}(\gamma + \frac{R_r}{L_r})(x_{2i}x_{5i} - x_{3i}x_{4i}) - \frac{(pM_{sr})^2}{\sigma L_s L_r^2} x_{1i}(x^2_{4i} + x^2_{5i}) - \frac{p^2 M_{sr}}{L_r} x_{1i}(x_{2i}x_{4i} + x_{3i}x_{5i}) \tag{13}$$

$$\mu_{4i} = 4\Phi^*_{ri}\dot{\Phi}^*_{ri} + 2(\dot{\Phi}^{*^2}_{ri} + \Phi^*_{ri}\ddot{\Phi}^*_{ri}) - \frac{2R_r M_{sr} p}{L_r} x_{1i}(x_{3i}x_{4i} - x_{2i}x_{5i}) - \frac{2R_r^2 M_{sr}^2}{L_r^3 \sigma L_s}(x^2_{4i} + x^2_{5i}) + 2M_{sr}(\frac{R_r}{L_r} + \gamma)$$

$$(x_{2i}x_{4i} + x_{3i}x_{5i}) - 2(\frac{R_r}{L_r M_{sr}})^2 (x^2_{2i} + x^2_{3i}) \tag{14}$$

Controllers for DC voltage and battery current: to ensure the stability of the DC-Bus and regulate battery current, the following errors are presented as (15)-(18) [18], [19].

$$z_4 = x_6 - v^*_{dc} \tag{15}$$

$$z_5 = i_b - i^*_b = \frac{1}{R_b}(x_8 - x_9) - i^*_b \tag{16}$$

$$u_{dc} = \frac{1}{x_7}[\sum_{i=1}^{N}(u_{1i}x_{2i} + u_{2i}x_{3i}) + C_{dc}\zeta_4 Z_4 - C_{dc}v^*_{dc}] \tag{17}$$

$$u_{cc} = \frac{1}{x_6}[\lambda_1 z_5 + \lambda_2 z_6 + \lambda_3 x_7 + \lambda_4 x_8 + \lambda_5 x_9] \tag{18}$$

With,

$$\lambda_1 = -(1 - \zeta_5^2) l_0 C_0 R_b$$

$$\lambda_2 = -(\zeta_5 + \zeta_6) l_0 C_0 R_b$$

$$\lambda_3 = r_0 + \alpha_1 l_0$$

$$\lambda_4 = 1 - (\frac{\alpha_1}{R_b C_0} + \frac{\alpha_2}{R_b C_b}) l_0 C_0$$

$$\lambda_5 = [\frac{\alpha_1}{R_b C_0} + (\frac{1}{R_b C_b} + \frac{1}{R_p C_b})\alpha_2] l_0 C_0$$

Where ζ_4, ζ_5, ζ_6 are positive design parameters.

Table 1. Controller parameters

Regulators	Symbol	Value
Generator torque and flux regulators	$\zeta_{1i}, \zeta_{2i}, \zeta_{3i}$	$15.10^2, 5.10^2, 50$
DC-Link voltage regulator	ζ_4	10^4
Current battery regulator	ζ_{5i}, ζ_{6i}	10^2, 10,

Table 2. Characteristics of the system

Parameters of the system	Notation	Value
	Induction machine	
Nominal power	P_n	3.63 KW
Stator resistor	R_s	0.77 Ω
Rotor resistor	R_r	0.31 Ω
Stator cyclic inductor	L_s	0.076 H
Rotor cyclic inductor	L_r	0.043 H
Rotor resistor	R_r	0.22 Ω
Mutual inductor	M_{sr}	0.045 H
Rotor intertia	J	11.6 Nm/rd/s^2
Viscous resistance	f	0.017 Nm/rd/s
Number of pole pairs	p	2
	AC-DC-DC converters	
DC-Bus capacitor	C_{dc}	410 μF
Inductor	l_0, r_0	16/0.3 mH/Ω
	Battery	
Battery capacitor	C_0	550 μF
Battery ESR	R_b	0.6 Ω
Battery EPR	R_p	1.1 KΩ
Battery capacitance	C_b	600 F

3. PHOTOVOLTAIC CONVERSION SYSTEM

The photovoltaic system is analyzed using SimPowerSystems and SimElectronics, utilizing electronic components and integrating power point tracker (MPPT) control perturb and observe (P&O) [20]. The MPPT algorithm's purpose is to optimize the PV system's power output [21]. The boost converter model, which employs the P&O algorithm, is shown in Figures 3 and 4. The primary focus is on constructing the DC-DC converter model, specifically the boost converter, allowing the MPPT controller to adjust the duty cycle, affecting the input-output voltage ratio [22]. In essence, changing the duty cycle adjusts either the PV system's output voltage or the boost converter's input voltage, with the input voltage of the boost converter considered as the photovoltaic system's output [23]. A PV panel generates electrical power and employs MPPT with the P&O algorithm. An additional boost converter is used to stabilize the DC-Bus voltage [24]. Solar panels are made up of multiple cells arranged in parallel and series configurations, producing energy influenced by weather conditions like solar radiation and temperature [25]. In Figure 5, the model is a SunPower SPR-400E-WHT-D multicrystalline silicon panel with 14 cells in parallel for a max current of 82.18 A and 6 cells in series for a max voltage of 511.8 V. This panel serves as the primary energy source, following the stationary generator system when athletes aren't using stationary bikes. The photovoltaic power optimization depends on the battery's state of charge (SOC). When this condition is met, the MPPT control function regulates the DC-Bus voltage, as shown in Figure 5.

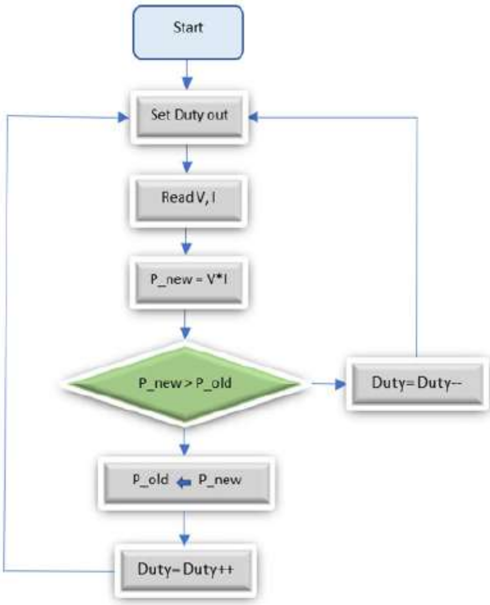

Figure 3. P&O algorithm

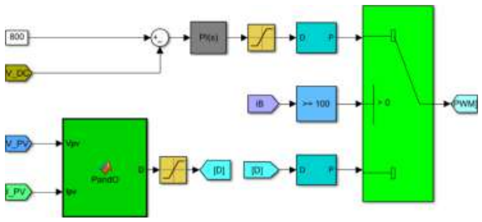

Figure 4. PWM signal of the boost converter

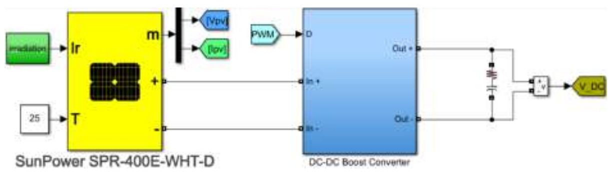

Figure 5. Chain of photovoltaic system conversion

4. SIMULATION RESULTS AND PERFORMANCE EVALUATION

The MATLAB/SIMULINK simulation results align with the initial objectives and are examined in detail for each goal. To validate theoretical findings, the system in Figure 2 was tested with two stationary bikes (N = 2), considering the values in Tables 1 and 2. Figure 6 illustrates the successful torque tracking objective, with each stationary bike (T_{em1} or T_{em2}) operating at its optimal torque level. These values closely match their respective references T^*_{em1} or T^*_{em2} with precision and robustness. Figure 7 demonstrates the successful tracking of the rotor flux controller to its reference $\phi_r{}^*$. Figure 8 affirms the steady control of the DC-Bus voltage, converging towards the target voltage $v_{dc}{}^*$=800 V. This result is achieved through the well-designed backstepping control-based controller and the MPPT control of the photovoltaic system, crucial for DC-Bus regulation. Figures 9 and 10 showcase the storage system's effective performance and resilience, with battery current rapidly converging to its reference $i_b{}^*$=100 A in Figure 9. Figure 10 illustrates how the battery's state of charge (SOC) varies based on energy flow within the DC-Bus, charging during excess energy availability and discharging to power the sports hall's loads. The primary goal of minimizing energy consumption costs is achieved by favoring renewable energy sources (photovoltaic system and stationary bike generators) when coupled with a storage system. Figure 11 displays a robust hybrid system effectively combining various energy sources to meet the sports facility's energy demands. As exemplified in Figure 11, the storage system compensates for slow responses and low irradiation during [0s, 0.125s], while during [1.5s, 2s], it charges gradually when the photovoltaic and stationary bike energy generation meets demand, then discharges within [2s, 2.625s] to fulfill the hall's energy needs.

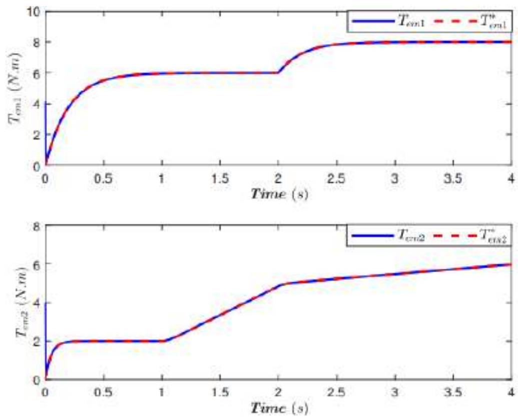

Figure 6. Electromagnetic torques of stationary bikes

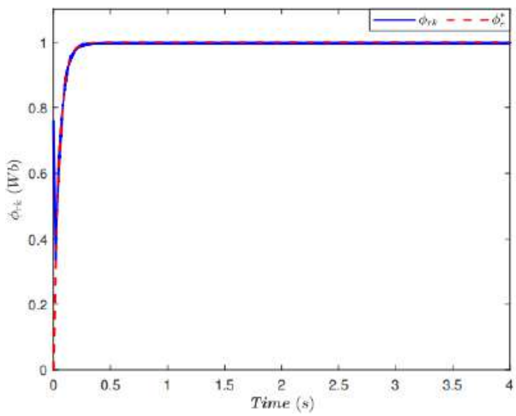

Figure 7. Flux rotor

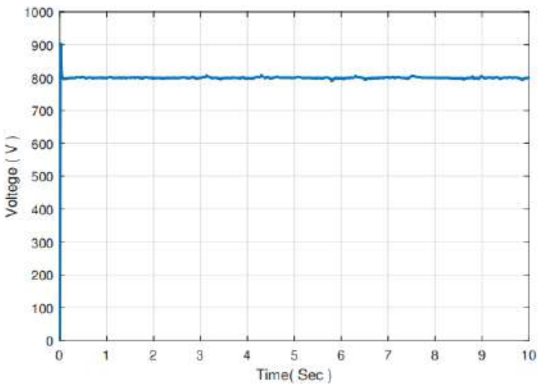

Figure 8. DC-Bus voltage

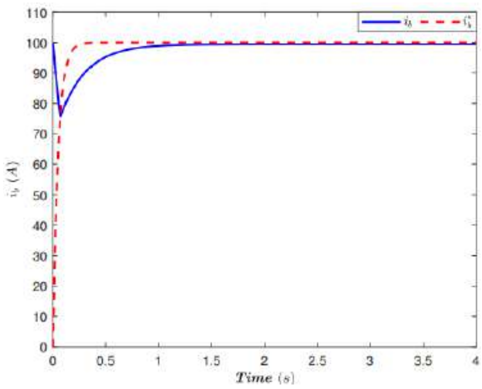

Figure 9. Current of the battery

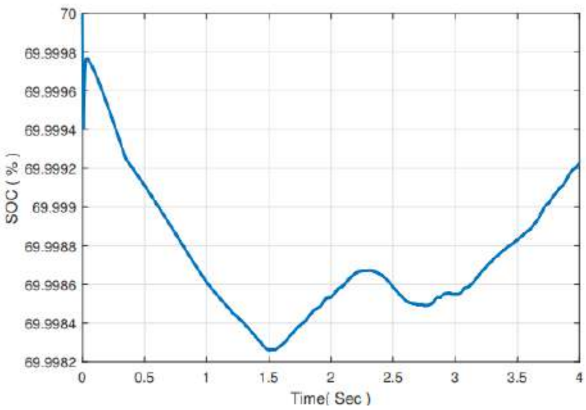

Figure 10. SOC of the battery

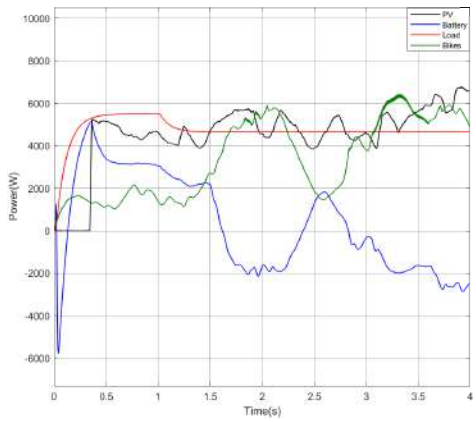

Figure 11. Power management

5. CONCLUSION

This article is part of the drive for fitness centers to optimize their electricity consumption. It aligns with the ambitious global goals for renewable energy sources within the framework of climate change mitigation and reducing electricity costs. With the utilization of electricity generated from stationary bikes, modern sports facilities can establish their autonomous micro-grid through a hybrid system that combines multiple energy sources, including stationary bike generators, photovoltaic energy, and a storage system.

Governed by an energy management algorithm, this system ensures a balance between the gym's energy demand and the supply from the hybrid system.

REFERENCES

[1] A. Rahman, O. Farrok, and M. M. Haque, "Environmental impact of renewable energy source based electrical power plants: solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic," *Renewable and Sustainable Energy Reviews*, vol. 161, 2022, doi: 10.1016/j.rser.2022.112279.

[2] A. Abdulmula *et al.*, "Micropower system optimization for the telecommunication towers based on various renewable energy sources," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 2, pp. 1069–1076, 2022, doi: 10.11591/ijece.v12i2.pp1069-1076.

[3] Y. Majeed *et al.*, "Renewable energy as an alternative source for energy management in agriculture," *Energy Reports*, vol. 10, pp. 344–359, 2023, doi: 10.1016/j.egyr.2023.06.032.

[4] A. S. Alhattab, A. N. B. Alsammak, and H. A. Mohammed, "An intelligent mitigation of disturbances in electrical power system using distribution static synchronous compensator," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 30, no. 2, pp. 633–642, May 2023, doi: 10.11591/ijeecs.v30.i2.pp633-642.

[5] V. L. Trinh and C. K. Chung, "Renewable energy for SDG-7 and sustainable electrical production, integration, industrial application, and globalization: review," *Cleaner Engineering and Technology*, vol. 15, 2023, doi: 10.1016/j.clet.2023.100657.

[6] M. Junus, Marjono, Aulanni'am, and S. Wahyudi, "In Malang, Indonesia, a techno-economic analysis of hybrid energy systems in public buildings," *Bulletin of Electrical Engineering and Informatics (BEEI)*, vol. 11, no. 5, pp. 2434–2441, 2022, doi: 10.11591/eei.v11i5.3795.

[7] F. Di Giacomo *et al.*, "High efficiency CH3NH3PbI(3-x)Cl x perovskite solar cells with poly(3-hexylthiophene) hole transport layer," *Journal of Power Sources*, vol. 251, pp. 152–156, 2014, doi: 10.1016/j.jpowsour.2013.11.053.

[8] M. R. B. Khan, J. Pasupuleti, J. Al-Fattah, and M. Tahmasebi, "Energy management system for PV-battery microgrid based on model predictive control," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 15, no. 1, pp. 20–26, 2019, doi: 10.11591/ijeecs.v15.i1.pp20-26.

[9] A. Sakhrieh, J. Al Asfar, and N. A. Shuaib, "An optimized off-grid hybrid system for power generation in rural areas," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 2, pp. 865–872, 2022, doi: 10.11591/ijpeds.v13.i2.pp865-872.

[10] A. Watil, A. El Magri, R. Lajouad, A. Raihani, and F. Giri, "Multi-mode control strategy for a stand-alone wind energy conversion system with battery energy storage," *Journal of Energy Storage*, vol. 51, p. 104481, 2022, doi: 10.1016/j.est.2022.104481.

[11] M. Haugen, H. Farahmand, S. Jaehnert, and S. E. Fleten, "Representation of uncertainty in market models for operational planning and forecasting in renewable power systems: a review," *Energy Systems*, 2023, doi: 10.1007/s12667-023-00600-4.

[12] I. El Myasse et al., "Observer and nonlinear control design of VSC-HVDC transmission system," *International Journal of Electrical Power and Energy Systems (IJPES)*, vol. 145, p. 108609, 2023, doi: 10.1016/j.ijepes.2022.108609.

[13] E. Awada, E. Radwan, and M. Nour, "Robust sliding mode controller for buck DC converter in off-grid applications," *Bulletin of Electrical Engineering and Informatics (BEEI)*, vol. 11, no. 5, pp. 2425–2433, 2022, doi: 10.11591/eei.v11i5.3705.

[14] A. El Azzab, R. Lajouad, A. El Magri, A. Watil, I. El Myasse, and H. Ouabi, "A green innovative sports bike based on an induction generator with a nonlinear controller," *2022 IEEE 3rd International Conference on Electronics, Control, Optimization and Computer Science, ICECOCS 2022*, 2022, doi: 10.1109/ICECOCS55148.2022.9983081.

[15] M. Mohammed, "Bi-directional charging system design for a set of li-ion batteries located at angstrom laboratory campus of uppsala universiti," 2023.

[16] I. E. L. Myasse, A. E. L. Magri, M. Kissaoui, R. Lajouad, A. Watil, and C. Berrahal, "Adaptive nonlinear control of generator load VSC-HVDC association," *IFAC-PapersOnLine*, vol. 55, no. 12, pp. 782–787, 2022, doi: 10.1016/j.ifacol.2022.07.408.

[17] I. El Maysse *et al.*, "Nonlinear observer-based controller design for VSC-based HVDC transmission systems under uncertainties," *IEEE Access*, vol. 11, pp. 124014–124030, 2023, doi: 10.1109/ACCESS.2023.3330440.

[18] J. D. Barros, L. Rocha, and J. F. Silva, "Backstepping control of NPC multilevel converter interfacing AC and DC Microgrids," *Energies*, vol. 16, no. 14, 2023, doi: 10.3390/en16145515.

[19] N. Debdouche, L. Zarour, H. Benbouhenni, F. Mehazzem, and B. Deffaf, "Robust integral backstepping control microgrid connected photovoltaic System with battery energy storage through multi-functional voltage source inverter using direct power control SVM strategies," *Energy Reports*, vol. 10, pp. 565–580, 2023, doi: 10.1016/j.egyr.2023.07.012.

[20] R. I. Jabbar, S. Mekhilef, M. Mubin, and K. K. Mohammed, "A modified perturb and observe MPPT for a fast and accurate tracking of MPP under varying weather conditions," *IEEE Access*, vol. 11, pp. 76166–76176, 2023, doi: 10.1109/ACCESS.2023.3297445.

[21] S. B. Hamed *et al.*, "A robust MPPT approach based on first-order sliding mode for triple-junction photovoltaic power system supplying electric vehicle," *Energy Reports*, vol. 9, pp. 4275–4297, 2023, doi: 10.1016/j.egyr.2023.02.086.

[22] Y. Yasa, "A system efficiency improvement of DC fast-chargers in electric vehicle applications: bypassing second-stage full-bridge DC-DC converter in high-voltage charging levels," *Ain Shams Engineering Journal*, vol. 14, no. 9, 2023, doi: 10.1016/j.asej.2023.102391.

[23] K. Jouili and A. Madani, "Nonlinear lyapunov control of a photovoltaic water pumping system," *Energies*, vol. 16, no. 5, 2023, doi: 10.3390/en16052241.

[24] M. Y. Abdulateef, M. H. Ali, and M. A. Hussen, "Estimation of loads for off-grid solar photovoltaic systems," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 2, pp. 918–925, 2022, doi: 10.11591/ijpeds.v13.i2.pp918-925.

[25] A. T. Hamada, O. Z. Sharaf, and M. F. Orhan, "A novel photovoltaic/thermal (PV/T) solar collector based on a multi-functional nano-encapsulated phase-change material (nano-ePCM) dispersion," *Energy Conversion and Management*, vol. 280, 2023, doi: 10.1016/j.enconman.2023.116797.

BIOGRAPHIES OF AUTHORS

Abdelfattah El Azzab he's a state engineer in electrical engineering at ENSAM Casablanca. He is currently working on his doctorate in the field of automatic control, energy transmission and power converters at Hassan II University in Casablanca, Morocco. His research focuses on adaptive control, nonlinear control, and observer design, with applications to renewable energy conversion systems. He is also founder of the Centre Privé de l'Étudiant (CPE), a center specializing in the field of study abroad and professional training in collaboration with international universities. He can be contacted at email: elazzab.abdelfattah96@gmail.com.

Abdelmounime El Magri he received the Aggregation of Electrical Engineering from ENSET, Rabat, Morocco, in 2001, the Ph.D. degree in Electrical and control engineering from University Mohammed V, Rabat; in 2011. Currently, he is Professor at the Normal School of Technical Education, Mohammedia, University Hassan II, Casablanca, Morocco. His research interests include nonlinear system identification, nonlinear control, adaptive control, power, and energy systems control. He has coauthored several papers on these topics. He can be contacted at email: magri mounaim@yahoo.fr.

Rachid Lajouad he was born in 1974. He received Ph.D. degree in electrical engineering from Mohammed V University, Rabat, Morocco, in 2016. Currently, he is a professor at the Hassan II University, Casablanca, Morocco. His research interests include optimization, observation and nonlinear control of AC machines, and renewable energy. He has published several journal/conference papers on these topics. He can be contacted at email: dsa.lajouad@gmail.com.

Ilyass El Myasse received his Master's degree in Control, Industrial Computer, Signals, and Systems from Cadi Ayyad University of Marrakech, Morocco, in 2020. Currently, he is preparing his Ph.D. in the field of automatic control, transmission energy, and power converters at Hassan II University of Casablanca, Morocco. His research interests include adaptive control, nonlinear control, and observer design, with applications on power systems and renewable energy conversion systems. He can be contacted at email: ilyaselmyasse@gmail.com.

Aziz Watil received her Master's degree in Control, Industrial Computer, Signals, and Systems from Cadi Ayyad University of Marrakech, Morocco, in 2017. Received his Ph.D. in Electrical Engineering and Automatic from Hassan II University of Casablanca, Morocco, in 2022. His research interests are focused on the modeling of dynamical systems, optimization, nonlinear control, and observer design for many applications including electric power systems, renewable energy conversion systems, and electric vehicles. He can be contacted at email: azizwatil@gmail.com.

Hassan Ouabi received his Master's degree in Electronics and Embedded Systems from the Faculty of Science and Technique (FST) in Errachidia, Morocco, in 2020. Currently, he is pursuing his Ph.D. in the field of controlling and optimizing energy in hybrid systems at Hassan II University of Casablanca, Morocco. His resarch interests include nonlinear control, optimization and management of the energy, and observer design, with applications on power systems, renewable energy conversion systems, and hydrogen technology. He can be contacted at email: ouabihassan829@gmail.com.