Vol.13 Iss.1 pp.38-46 International Journal of Control, Energy and Electrical Engineering (CEEE)

Sliding Mode Control and Optimization of a Flywheel in a Photovoltaic Energy Storage System

Borhen Torchani[#1], Anis Sellami[#2], Germain Garcia[*3]

[#] *University of Tunis, ENSIT, LISIER, Tunisia*

[1]bourhen@gmail.com

[2]anis.sellami@ensit.rnu.tn

[*]*Laas, Lille, France*

[3]germain@laas.fr

***Abstract*— This article proposes a sliding mode control (SMC) method to control and optimize the operation of a flywheel in a photovoltaic energy storage system. The primary objective is to regulate the flywheel's speed to ensure efficient energy storage and release while guaranteeing system stability and robustness against variations in solar irradiance and load. The system is modeled in detail, including the photovoltaic system, the boost converter, and the flywheel. The sliding mode control is designed by defining a sliding surface based on the speed error, then calculating the equivalent control and discontinuous control to force the system to converge to this surface. Stability and convergence are demonstrated using Lyapunov theory, ensuring that the speed error converges to zero in finite time. Finally, the article explores the optimization of the flywheel's operation by adjusting the SMC parameters, such as the convergence gain and the discontinuous control gain. Numerical simulations is used to validate the system's performance under different operating conditions.**

***Keywords*— Photovoltaic system, Flywheel system, Boost converter, Sliding mode control, Optimization.**

I. Introduction

Photovoltaic energy is one of the most promising renewable energy sources to address current energy and environmental challenges. By directly converting solar energy into electricity, photovoltaic systems provide a clean and sustainable solution. However, the intermittency of solar irradiance and variations in energy demand require efficient storage solutions to ensure a stable and continuous power supply. Among storage technologies, flywheels stand out for their ability to store energy in kinetic form, offering advantages such as long lifespan, high power density, and reduced environmental impact ([1]-[6]).

System control plays a crucial role in optimizing the performance of energy systems, particularly in photovoltaic systems coupled with storage devices. Among advanced control methods, sliding mode control (SMC) stands out for its robustness against uncertainties and disturbances ([7]-[11]). This technique, based on nonlinear system theory, forces the system to follow a predefined sliding surface trajectory using a discontinuous control. It is particularly suited to photovoltaic systems, where variations in solar irradiance and load can induce significant disturbances.

In a photovoltaic system coupled with a flywheel, regulating the flywheel's speed is essential to ensure efficient energy storage and release. However, rapid variations in solar irradiance and load make this regulation complex. A robust and precise control strategy is required to maintain the flywheel's speed at a reference value while ensuring system stability. The objective of this article is to use SMC to control and optimize the operation of a flywheel in a photovoltaic energy storage system. Specifically, we aim to model the photovoltaic system, the boost converter, and the flywheel to establish a comprehensive understanding of the system dynamics. Based on this modeling, we design a SMC strategy to regulate the flywheel's speed, ensuring efficient energy storage and release while maintaining system stability. The stability and convergence of the proposed control method are rigorously demonstrated using Lyapunov theory,

ISSN: 1737-9288

guaranteeing that the speed error converges to zero in finite time. Finally, we optimize the flywheel's operation by adjusting the SMC parameters, such as the convergence gain and the discontinuous control gain, to enhance performance under varying operating conditions. This integrated approach ensures robust and efficient control of the photovoltaic energy storage system, contributing to more reliable and sustainable renewable energy management.

The article is organized as follows: first, we present the system modeling, which includes the dynamic equations of the photovoltaic system, the boost converter, and the flywheel, providing a detailed understanding of the system's behavior. Next, we focus on the SMC, where we design the sliding surface and calculate the equivalent control and discontinuous control to ensure robust regulation of the flywheel's speed. Following this, we conduct a stability and convergence analysis using Lyapunov theory, demonstrating that the system's speed error converges to zero in finite time and guaranteeing stability under varying conditions. Subsequently, we apply the developed results to a numerical system model through simulations, validating the performance of the proposed control strategy under different operating scenarios. Finally, we conclude with a summary of the results and discuss future perspectives, highlighting the contributions of this work to the optimization and control of photovoltaic energy storage systems.

II. System Modeling

A. Photovoltaic System

The photovoltaic system is modeled by the following equation:

$$I_{pv} = I_{ph} - I_0\left(exp\left(\frac{V_{pv}+I_{pv}R_s}{aN_sV_{th}}\right) - 1\right) - \frac{V_{pv}+R_sI_{pv}}{R_p} \quad (1)$$

The different variables and parameters of Eq. 1 are given as follows:
I_{ph}: Photocurrent (A)
I_0: Saturation current (A)
V_{pv}: Voltage of the PV module (V)
R_s, R_p: Series and parallel resistances (Ω)
a: Quality factor of the diode
N_s: Number of PV cells in series
V_{th}: Thermal voltage (V)

B. Boost Converter

The boost converter is used to increase the voltage of the photovoltaic system. Its dynamic equations are:

$$\begin{cases} L\frac{di_L}{dt} = V_{in} + (\mu - 1)V_{out} \\ C\frac{dV_{out}}{dt} = -i_{out} - (\mu - 1)i_L \end{cases} \quad (2)$$

where:
- i_L : Inductor current,
- V_{out} : Output voltage,
- μ : Duty cycle ($0 \leq \mu \leq 1$).

C. Flywheel

$$J\frac{dw}{dt}T_{in} - T_{out} - T_{loss} \quad (3)$$

where:
- J : Moment of inertia,
- w : Angular velocity,
- T_{in} : Input torque,
- T_{out} : Output torque,
- T_{loss} : Loss torque.

ISSN: 1737-9288

For simplicity, we assume T_{out} and T_{loss} are negligible, yielding:

$$J\frac{dw}{dt} = T_{in} \tag{4}$$

The input torque T_{in} is proportional to the current i_L:

$$T_{in} = k.i_L \tag{5}$$

III. Sliding Mode Control

A. Sliding Surface

The sliding surface S is defined based on the speed error $= w_{ref} - w$:

$$S = e + \lambda \int edt \tag{6}$$

where:
- λ : Positive design parameter.

B. Derivative of the Sliding Surface

The derivative of S is:

$$\dot{S} = \dot{e} + \lambda e \tag{7}$$

Since $e = w_{ref} - w$, we have $\dot{e} = -\dot{w}$. Substituting $\dot{w} = \frac{T_{in}}{J}$, we obtain:

$$\dot{S} = -\frac{T_{in}}{J} + \lambda(w_{ref} - w) \tag{8}$$

C. Equivalent Control u_{eq}

The equivalent control u_{eq} is calculated by imposing $\dot{S}$:

$$0 = -\frac{T_{in}}{J} + \lambda(w_{ref} - w) \Rightarrow T_{in} = J\lambda(w_{ref} - w)$$

Since $T_{in} = k.i_L$, we have:

$$i_L = \frac{J\lambda(w_{ref} - w)}{k} \tag{9}$$

D. Discontinous Control u_{disc}

The discontinuous control u_{disc} is added to ensure convergence to the sliding surface:

$$u_{disc} = -Ksign(S) \tag{10}$$

where:
- K : Discontinuous control gain,
- $sign(S)$: Signum function.

E. Total Control u

The total control is the sum of u_{eq} and u_{disc}:

$$u = u_{eq} + u_{disc} \tag{11}$$

IV. Stability and Convergence

A. Lyapunov Function

To prove stability, we use a Lyapunov function $V = \frac{1}{2}S^2$. Its derivative is:

$$\dot{V} = \frac{1}{2}S\dot{S} \tag{12}$$

Substituting $\dot{S}$ and T_{in}, we obtain:

ISSN: 1737-9288

$$\dot{V} = S\left(-\frac{k.i_L}{J} + \lambda\left(w_{ref} - w\right)\right) \quad (13)$$

Replacing i_L, we have:

$$\dot{V} = S\left(\frac{k.K}{J} sign(S)\right) \quad (14)$$

Since $S.sign(S) = |S|$, we obtain:

$$\dot{V} = \frac{k.K}{J}|S| \quad (15)$$

B. *Stability Condition*

To ensure $\dot{V} \leq -\eta|S|$, where η is a positive constant, we choose K such that:

$$\frac{k.K}{J} \geq \eta \Rightarrow K \geq \frac{J\eta}{k} \quad (16)$$

This ensures $\dot{V} \leq -\eta|S|$, guaranteeing the convergence of S to zero in finite time.

V. Numerical Simulation

In this section, we present the results of the numerical simulation of the photovoltaic system coupled with a boost converter and a flywheel, under SMC. The objective of this simulation is to validate the system's performance in terms of regulating the flywheel's speed, optimizing the boost converter's power, and ensuring robustness against variations in solar irradiance and load. To achieve this, we use the system's dynamic equations and the numerical parameters defined earlier, incorporating the initial conditions and control gains. The simulation is conducted over a period of 10 seconds.

We will analyze the boost converter's output power, the flywheel's speed, and the power generated by the photovoltaic system. These results will demonstrate the effectiveness of sliding mode control in optimizing and controlling the photovoltaic energy storage system, while ensuring robust and stable energy management under variable conditions. The different parameters of the system are provided below.

TABLE I
Photovoltaic Module Parameters

Photovoltaic current I_{ph}	8.5 A
Diode saturation current I_0	1.2 × 10⁻⁶ A
Series resistance R_s	0.2 Ω
Parallel resistance R_p	500 Ω
Thermal voltage V_t	0.0257 V (at 25°C)
Initial output voltage V_{pv}	30 V
Initial output current I_{pv}	7 A

TABLE III
Boost Converter Parameters

Inductance L	2 mH (0.002 H)
Output capacitance C	470 µF (0.00047 F)
Load resistance R	10 Ω
Initial output voltage V_{out}	50 V
Initial inductor current i_L	5 A
Initial duty cycle µ	0.5 (50%)

TABLE IIII
Flywheel Parameters

Moment of inertia J	0.1 kg·m²

ISSN: 1737-9288

Initial angular velocity w	100 rad/s
Reference angular velocity w_{ref}	150 rad/s
Torque constant k	0.05 N·m/A
Loss torque T_{loss}	0.01 N·m
Output torque T_{out}	0 N·m

TABLE IVV
SMC PARAMETERS

Convergence gain λ	10
Discontinuous control gain K	5
Initial speed error e	$50\ rad/s$

TABLE V
INITIAL CONDITIONS

Simulation time	0 to 100 second
Initial solar irradiance	$1000\ W/m^2$
Initial temperature	$25°C$

The figures generated by the simulation allow for an analysis of the behavior of the photovoltaic system coupled with a flywheel. The solar irradiance curve shows the variations in solar energy received over time, reflecting the step-like sunlight conditions. The photovoltaic power follows this irradiance, while the charging power varies in response to the difference between photovoltaic production and the load, adjusted by the SMC controller. The kinetic energy of the flywheel illustrates the accumulation and release of energy based on the system's needs, with variations linked to imbalances between production and consumption. Finally, the energy losses curve highlights the dissipations due to friction and aerodynamic drag, which increase with the flywheel's rotational speed. These losses, although small, affect the overall efficiency of the system. Together, these curves provide a comprehensive view of the energy dynamics and performance of the system.

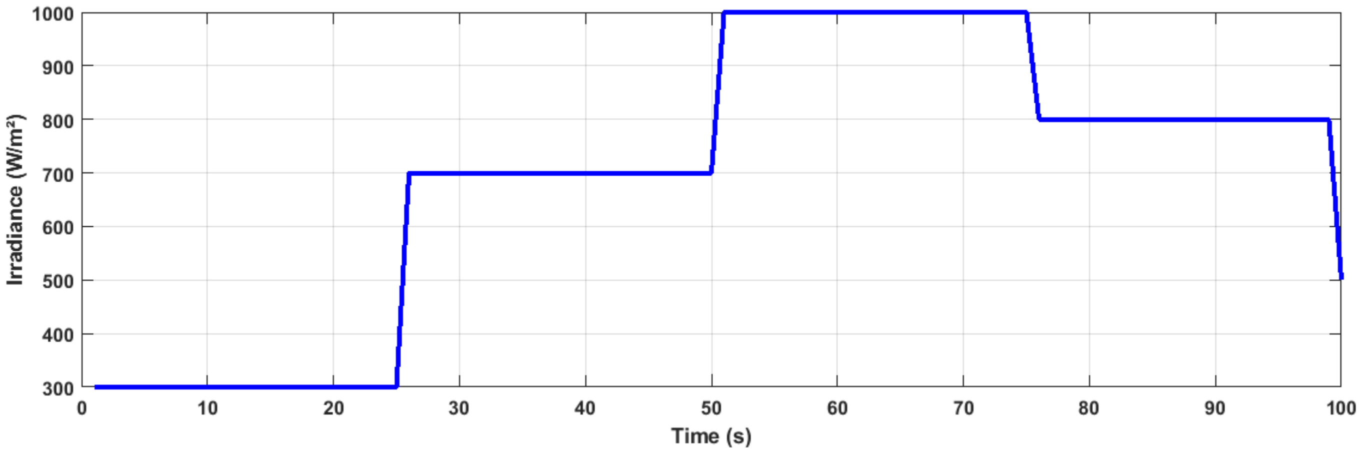

Fig. 1 Solar irradiance

The solar irradiance curve reflects the variations in solar energy received over time, modeled as a step-like function. The irradiance directly influences the photovoltaic power generation, as seen in the subsequent figures. The step changes in irradiance allow us to evaluate the system's response to sudden shifts in energy input, which is critical for assessing the robustness of the SMC controller.

ISSN: 1737-9288

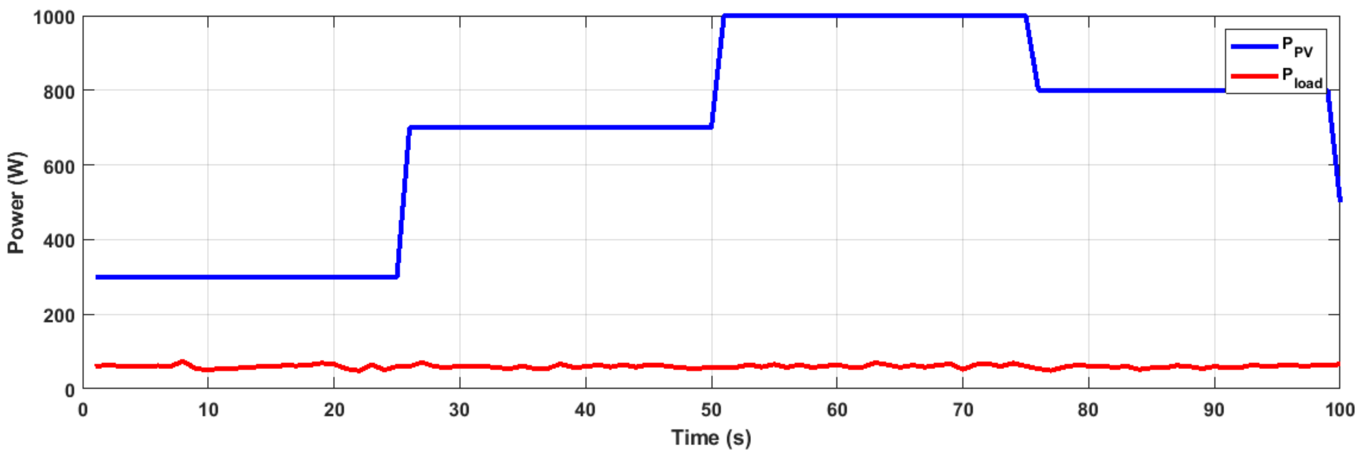

Fig. 2 Photovoltaic power and load

This figure compares the photovoltaic power output with the load demand over time. The photovoltaic power closely follows the solar irradiance profile, demonstrating the direct relationship between sunlight availability and energy generation. The load, on the other hand, represents the power demand, which may vary independently. The SMC controller ensures that the system adapts to the imbalance between production and consumption by regulating the charging and discharging of the flywheel. The figure highlights the controller's ability to maintain stability despite fluctuations in both power generation and load.

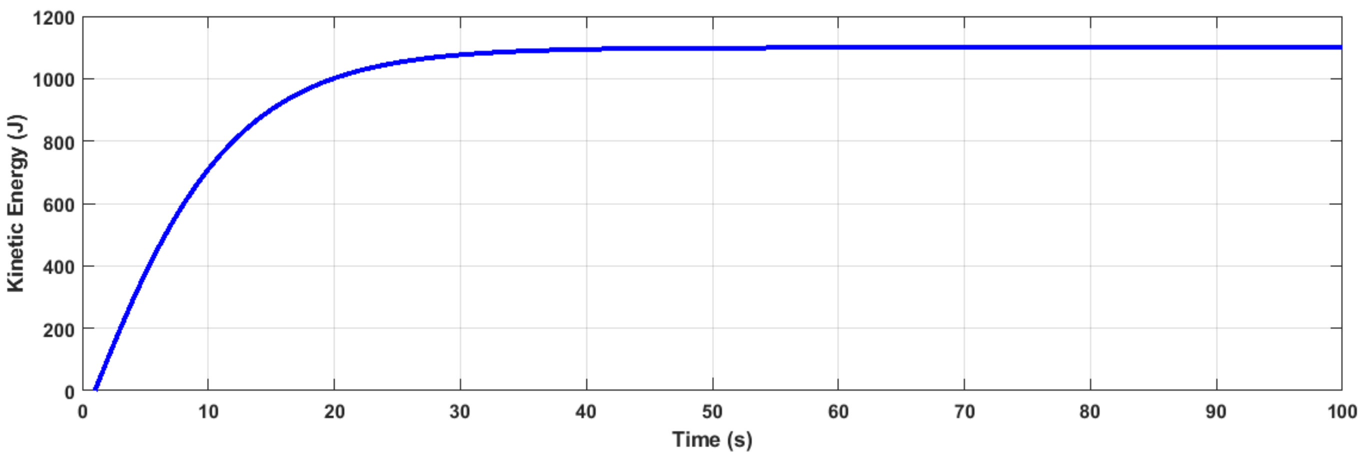

Fig. 3 Kinetic energy of the flywheel

The kinetic energy curve of the flywheel illustrates the energy storage and release dynamics. As the photovoltaic power exceeds the load demand, excess energy is stored in the flywheel, increasing its kinetic energy. Conversely, when the load demand exceeds the photovoltaic power, the flywheel releases energy to compensate for the deficit. The SMC controller ensures smooth transitions between these states, maintaining the flywheel's speed close to the reference value. This figure demonstrates the flywheel's role as an effective energy buffer, stabilizing the system under variable conditions.

ISSN: 1737-9288

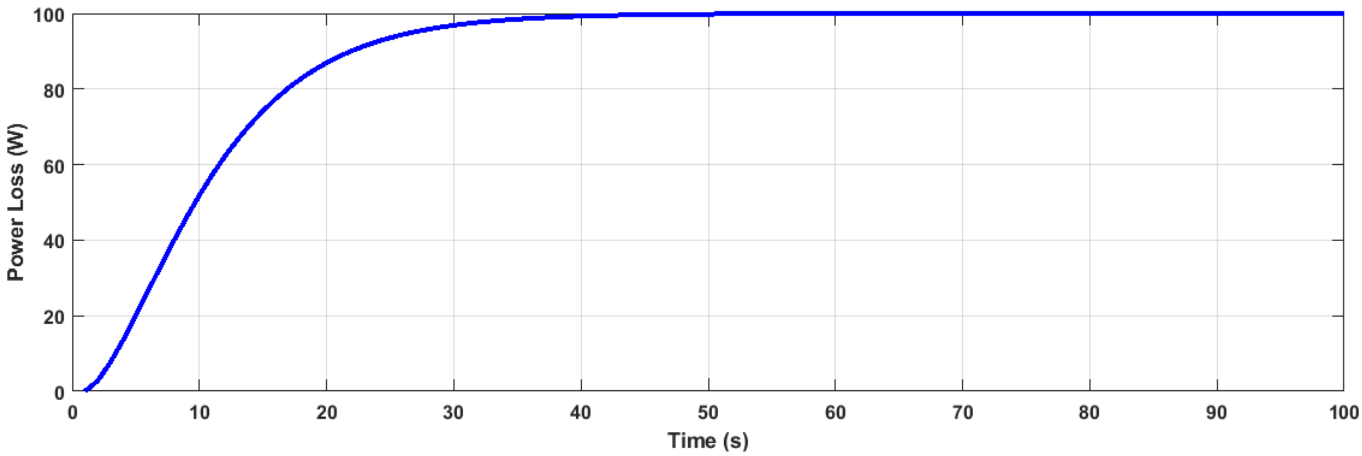

Fig. 4 Energy losses in the system

The energy losses curve highlights the dissipative effects within the system, primarily due to friction and aerodynamic drag in the flywheel. These losses increase with the flywheel's rotational speed, as expected from the system's dynamic equations. Although the losses are relatively small, they impact the overall efficiency of the system. The SMC controller minimizes these losses by optimizing the flywheel's operation, ensuring that energy dissipation is kept within acceptable limits. This figure underscores the importance of considering losses in the design and control of energy storage systems.

The simulation results demonstrate the effectiveness of the SMC controller in managing the photovoltaic system, boost converter, and flywheel. The system exhibits robust performance under varying solar irradiance and load conditions, with the flywheel effectively balancing energy supply and demand. The energy losses, while present, are minimized, ensuring high overall efficiency. These results validate the proposed control strategy and provide insights into the system's dynamic behavior under real-world operating conditions.

VI. Conclusions

The SMC control has proven to be an effective method for optimizing energy management in a photovoltaic storage system with a flywheel. By adjusting the charge/discharge power based on the discrepancy between photovoltaic production and load, the SMC control enables:

- Maximizing energy efficiency by balancing supply and demand.
- Reducing energy losses through optimized charge/discharge cycle management.
- Improving system stability by responding quickly to load fluctuations.

The integration of SMC control into hybrid systems combining multiple storage technologies opens promising prospects for simple and sustainable management of renewable energy.

As a future perspective: Integrating advanced and intelligent control strategies for better management of the energy stored in the flywheel.

References

[1] J. Zhao, Y. Liang, D. Fan, H. Ren, L. Zhu and X. Zhang, "Capacity Optimization of lithium Battery-Flywheel Hybrid Energy Storage System," 2023 3rd International Conference on Energy Engineering and Power Systems (EEPS), Dali, China, 2023, pp. 186-189, doi: 10.1109/EEPS58791.2023.10257085.

[2] L. Chitra, G. Selvakumar and S. Prakash, "A Comprehensive Analysis of Integrated Photovoltaic and Flywheel Energy Storage Systems," 2024 5th International Conference on Smart Electronics and Communication (ICOSEC), Trichy, India, 2024, pp. 313-318, doi: 10.1109/ICOSEC61587.2024.10722205.

[3] Mohamed Elkholy, Sarah Schwarz, Muhammad Aziz, Advancing renewable energy: Strategic modeling and optimization of flywheel and hydrogen-based energy system, Journal of Energy Storage, Volume 101, Part A, 2024, 113771,https://doi.org/10.1016/j.est.2024.113771.

[4] Rekioua, Djamila, Khoudir Kakouche, Abdulrahman Babqi, Zahra Mokrani, Adel Oubelaid, Toufik Rekioua, Abdelghani Azil, Enas Ali, Ali H. Kasem Alaboudy, and Saad A. Mohamed Abdelwahab. 2023. "Optimized

ISSN: 1737-9288

Power Management Approach for Photovoltaic Systems with Hybrid Battery-Supercapacitor Storage" *Sustainability* 15, no. 19: 14066. https://doi.org/10.3390/su151914066.

[5] Vijayalakshmi Mathivanan, Ramaprabha Ramabadran, Beemkumar Nagappan, Yuvarajan Devarajan, Assessment of photovoltaic powered flywheel energy storage system for power generation and conditioning, Solar Energy, Volume 264, 2023, 112045,https://doi.org/10.1016/j.solener.2023.112045.

[6] Xu, Kai, Youguang Guo, Gang Lei, and Jianguo Zhu. 2023. "A Review of Flywheel Energy Storage System Technologies" *Energies* 16, no. 18: 6462. https://doi.org/10.3390/en16186462.

[7] S. Li, W. Luo, R. Zhang, J. I. Leon, A. Marquez and L. G. Franquelo, "Improved Sliding Mode Control Strategy Based on Photovoltaic-Energy Storage Virtual Synchronous Generator System," *2024 IEEE 33rd International Symposium on Industrial Electronics (ISIE)*, Ulsan, Korea, Republic of, 2024, pp. 1-6, doi: 10.1109/ISIE54533.2024.10595808.

[8] Hamid Belghiti, Khalid Kandoussi, Ambe Harrison, Rania Benbba, Rabie El Otmani, Abdelkhalek Chellakhi, El Mostafa Sadek, Efficient and robust control of a standalone PV-storage system: An integrated single sensor-based nonlinear controller with TSCC-battery management, Journal of Energy Storage, Volume 95, 2024, 112630, https://doi.org/10.1016/j.est.2024.112630.

[9] Gursoy, M.; Zhuo, G.; Lozowski, A.G.; Wang, X. Photovoltaic Energy Conversion Systems with Sliding Mode Control. *Energies* **2021**, *14*, 6071. https://doi.org/10.3390/en14196071

[10] Ghosh, S., Roy, T., Pramanik, M., Mahmud, M.: A nonlinear double-integral sliding mode controller design for hybrid energy storage systems and solar photovoltaic units to enhance the power management in DC microgrids. *IET Gener. Transm. Distrib.* 16, 2228–2241 (2022). https://doi.org/10.1049/gtd2.12437

[11] Hany M. Hasanien, Marcos Tostado-Véliz, Rania A. Turky, Francisco Jurado, Hybrid adaptive controlled flywheel energy storage units for transient stability improvement of wind farms, Journal of Energy Storage, Volume 54, 2022, 105262, https://doi.org/10.1016/j.est.2022.105262.

ISSN: 1737-9288