Journal of Energy Storage 122 (2025) 116674

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Review article

Flywheels in renewable energy Systems: An analysis of their role in managing intermittency

Carlos Matos [a], Enrique Rosales-Asensio [b], José A. Carta [a], Pedro Cabrera [a,*]

[a] Department of Mechanical Engineering, University of Las Palmas de Gran Canaria, Campus de Tafira S/n, 35017 Las Palmas de Gran Canaria, Canary Islands, Spain
[b] Department of Electrical Engineering, University of Las Palmas de Gran Canaria, Campus de Tafira S/n, 35017 Las Palmas de Gran Canaria, Canary Islands, Spain

ARTICLE INFO

Keywords:
Flywheel energy Storage Systems (FESSs)
Renewable energy integration
Grid stabilization
Microgrids
Dynamic energy Storage
Frequency regulation
Energy Storage technologies

ABSTRACT

This paper presents an analytical review of the use of flywheel energy storage systems (FESSs) for the integration of intermittent renewable energy sources into electrical grids and microgrids. An exhaustive search of scientific databases was first conducted which yielded 175 relevant articles encompassing 210 case studies. The studies were classified as theoretical or experimental and divided into two main categories: stabilization and dynamic energy storage applications. Of the studies considered, 48 % correspond to the former category and 52 % to the latter. Spain leads the way in terms of the development of experimental studies (18 of the 52 studies considered), followed by Australia (11). An examination was then conducted of the current uses, advantages, and limitations of FESSs. The results indicate a growing interest in research on FESSs and their implementation in renewable energy generation contexts. FESSs are characterized by their high-power density, rapid response times, an exceptional cycle life, and high efficiency, which make them particularly suitable for applications that require immediate power delivery and frequent cycling. However, challenges such as higher initial capital costs and integration into existing market designs hinder their widespread adoption. The discussion highlights the need for evolving market designs and regulatory frameworks that recognize the full value of FESSs, as well as continued technological advances to improve their economic viability. The study concludes that FESSs have significant potential to enhance grid stability and facilitate the integration of renewable energy sources, contributing to more sustainable and resilient electrical systems.

1. Introduction

Flywheels are among the oldest and most extensively utilized energy storage devices, having been employed for centuries to store usable energy for various purposes [1–3]. Their origins can be traced back to the potter's wheel, underscoring their longstanding role in human technological development [4]. Beyond pumped hydroelectric storage, flywheels represent one of the most established technologies for mechanical energy storage based on rotational kinetic energy [5].

Fundamentally, flywheels store kinetic energy in a rotating mass known as a rotor [6–9], characterized by high conversion power and rapid discharge rates [10]. They convert electrical energy into kinetic energy for storage and can swiftly revert it back to electrical energy when needed, effectively functioning as "mechanical batteries" [11–16]. This capability makes them an environmentally friendly alternative to electrochemical batteries, playing a critical role in sustainable energy transitions [17].

Advances in power electronics and materials science have facilitated the development of modern flywheel energy storage systems (FESSs) that can interface directly with electrical grids [18–20]. A typical FESS comprises a motor/generator unit, a bidirectional power converter [19,21], a rotor made of steel or composite materials [19,22], a bearing system—which may employ magnetic levitation—and a vacuum enclosure to minimize air friction losses [22,23]. The integration of electric machines, power electronics converters, and sophisticated control systems forms the foundation of energy transfer in FESSs [23].

FESSs can respond instantaneously to grid demands, providing rapid energy discharge to stabilize fluctuations [24]. Historically, flywheels have been used to smooth mechanical power transmission [9] and modern FESSs continue this legacy by mitigating variations between energy generation and load demand in electrical grids [24]. They offer several advantages in contemporary energy systems, particularly in applications requiring high power density and rapid response [5,8,23]. Their high power density makes them competitive for scenarios

* Corresponding author.
E-mail addresses: jcarta@dim.ulpgc.es (J.A. Carta), pedro.cabrerasantana@ulpgc.es (P. Cabrera).

https://doi.org/10.1016/j.est.2025.116674
Received 4 December 2024; Received in revised form 27 March 2025; Accepted 13 April 2025
Available online 18 April 2025
2352-152X/

integration of renewable energy sources: A survey, IEEE Trans. Ind. Electron. 53 (2006) 1002–1016, https://doi.org/10.1109/TIE.2006.878356.
[307] M. Ali, A. Iqbal, M. Khalid, A review on recent advances in matrix converter technology: Topologies, Control, Applications, and Future Prospects, Int J Energy Res 2023 (2023) 6619262, https://doi.org/10.1155/2023/6619262.
[308] L.C. Gili, J.C. Dias, T.B. Lazzarin, Review, Challenges and Potential of AC/AC Matrix Converters CMC, MMMC, and M3C, Energies 2022, Vol. 15, Page 9421 15 (2022) 9421. doi:https://doi.org/10.3390/EN15249421.
[309] A. von Jouanne, E. Agamloh, A. Yokochi, A Review of Matrix Converters in Motor Drive Applications, Energies 2025, Vol. 18, Page 164 18 (2025) 164. doi:https://doi.org/10.3390/EN18010164.
[310] S. Communication Support Centre, PM CTP CAT M A5 X 3 b02 | 2009-03-16, (2009).
[311] M.C. Argyrou, P. Christodoulides, S.A. Kalogirou, Energy storage for electricity generation and related processes: technologies appraisal and grid scale applications, Renew. Sust. Energ. Rev. 94 (2018) 804–821, https://doi.org/10.1016/J.RSER.2018.06.044.
[312] ARRA SGDP Hazle Spindle (20 MW Flywheel Frequency Regulation Plant) - Formerly Beacon Power | Department of Energy, (n.d.). https://www.energy.gov/oe/articles/arra-sgdp-hazle-spindle-20-mw-flywheel-frequency-regulation-plant-formerly-beacon-power (accessed March 21, 2025).
[313] X. Zheng, Z. Wu, G. Song, J. Zhang, P. Yang, Z. Zhang, X. Lu, Low-voltage ride-through control strategy for flywheel energy storage system, Energy Sci. Eng. 12 (2024) 1486–1502, https://doi.org/10.1002/ESE3.1683.
[314] L. Xiong, S. Guo, S. Huang, P. Li, Z. Wang, M.W. Khan, J. Wang, T. Niu, Optimal allocation and sizing of ESSs for power system oscillation damping under high wind power penetration, Int. J. Electr. Power Energy Syst. 153 (2023) 109385, https://doi.org/10.1016/J.IJEPES.2023.109385.
[315] P.F. Ribeiro, B.K. Johnson, M.L. Crow, A. Arsoy, Y. Liu, Energy Storage systems for advances power applications, Proc. IEEE 89 (2001) 1744–1756, https://doi.org/10.1109/5.975900.
[316] A.J. Ruddell, Flywheel energy storage technologies for wind energy systems, stand-alone and hybrid wind energy Systems: technology, Energy Storage and Applications (2010) 366–392, https://doi.org/10.1533/9781845699628.2.366.
[317] R. vor dem Esche, White Paper: Safety of Flywheel Storage Systems, 2016. https://www.stornetic.com/wp-content/uploads/2022/03/c-WhitePaper-Safety-of-Flywheel-Storages-Systems-Rev4.pdf (accessed March 20, 2025).
[318] Flywheel Energy Storage: Alternative to Battery Storage, (n.d.). https://www.bryceenergyservices.com/2024/10/05/flywheel-energy-storage-a-promising-alternative-to-batteries/ (accessed March 20, 2025).
[319] Í. Díez Olleros, Tecnología de los volantes de inercia, Universidad Politécnica de Madrid, 2018. https://oa.upm.es/51775/. (Accessed 20 March 2025).
[320] Huntkey & GreVault, The most Complete Analysis of Flywheel Energy Storage for New Energy Storage - Huntkey & GreVault Battery Energy Storage Systems. https://www.huntkeyenergystorage.com/flywheel-energy-storage/, 2023.
[321] International Renewable Energy Agency (IRENA), Electricity storage and renewables: Costs and markets to 2030, International Renewable Energy Agency (2017) 132. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf (accessed May 23, 2024).
[322] Batteries vs Flywheels, (2019). https://www.nj.gov/bpu/pdf/publicnotice/stakeholder/Omnes%20Energy%20BATTERIES%20vs%20FLYWHEELS_March%2019%202019.pdf#:~:text=4.%20Cycle%20Life%202000%20,Source%3A%20Electric%20Power%20Research%20Institute (accessed March 20, 2025).
[323] Top 5 Advanced Flywheel Energy Storage Startups - GreyB, (n.d.). https://www.greyb.com/blog/advanced-flywheel-energy-storage-startups/ (accessed March 20, 2025).
[324] J. Baffa, M. Hinrichs, Emerging Products Flywheel Energy Storage Study, (2016). https://www.dret-ca.com/wp-content/uploads/2020/05/sdge_flywheel_energy_storage_report_033017_final.pdf#:~:text=Flywheel%20Energy%20Storage%20Study%20DR12SDGE0001,TEST%206040%206050%206060%206070 (accessed March 20, 2025).
[325] Omnes Energy Develops Low Cost Utility Grade Flywheel Energy Storage Products | Utility Dive, (n.d.). https://www.utilitydive.com/press-release/20160615-omnes-energy-develops-low-cost-utility-grade-flywheel-energy-storage-produc/ (accessed March 20, 2025).
[326] EnWheel® | Stornetic, (n.d.). https://www.stornetic.com/our-technology/enwheel (accessed March 20, 2025).
[327] M. Arbabzadeh, J.X. Johnson, G.A. Keoleian, P.G. Rasmussen, L.T. Thompson, Twelve principles for green energy Storage in grid applications, Environ. Sci. Technol. 50 (2016) 1046–1055, https://doi.org/10.1021/ACS.EST.5B03867.
[328] U.S. Grid Energy Storage Factsheet | Center for Sustainable Systems, (n.d.). https://css.umich.edu/publications/factsheets/energy/us-grid-energy-storage-factsheet (accessed March 20, 2025).
[329] Red Eléctrica will install a flywheel to store energy and increase security of supply in isolated electricity systems | Red Eléctrica, (n.d.). https://www.ree.es/en/press-office/press-release/2013/10/red-electrica-will-install-flywheel-store-energy-and-increase (accessed March 20, 2025).
[330] Flywheel Energy Storage Market Size, Share, Growth by 2030, (n.d.). https://www.metastatinsight.com/report/flywheel-energy-storage-market (accessed March 20, 2025).
[331] The Energy Storage TCP''s Mission - IEA ES TCP, (n.d.). https://iea-es.org/energy-storage-mission/ (accessed May 28, 2024).
[332] A.H. Alami, Mechanical energy Storage for renewable and sustainable energy, Resources (2020), https://doi.org/10.1007/978-3-030-33788-9.
[333] T.H. Ss, S.T. Standard, T HR SS 80006 ST Renewable Energy Installations - Photovoltaic and Battery Systems. www.transport.nsw.gov.au, 2019. (Accessed 28 May 2024).
[334] G. Brumana, G. Franchini, E. Ghirardi, A. Perdichizzi, Techno-economic optimization of hybrid power generation systems: a renewables community case study, Energy 246 (2022) 123427, https://doi.org/10.1016/J.ENERGY.2022.123427.
[335] A. Eller, I. Mcclenny, D. Gauntlett, North American Energy Storage Copper Content Analysis Prepared for Copper Development Association 1 (2018) 1–42.
[336] G.M. Crawley, World Scientific Series in Current Energy Issues Volume 4 Energy Storage, (n.d.). www.worldscientific.com (accessed May 28, 2024).
[337] Portfolio Management Energy from Smart Grid Deliverable: Report/white paper on Ultracapacitor technology Unlocking New Possibilities through Innovative Energy Storage The Role of Ultracapacitors in the Energy Transition, (2020).
[338] E. Ela, F. Billimoria, K. Ragsdale, S. Moorty, J. Osullivan, R. Gramlich, M. Rothleder, B. Rew, M. Supponen, P. Sotkiewicz, Future electricity markets: designing for massive amounts of zero-variable-cost renewable resources, IEEE Power and Energy Magazine 17 (2019) 58–66, https://doi.org/10.1109/MPE.2019.2933281.
[339] J. Cochran, M. Miller, M. Milligan, E. Ela, D. Arent, A. Bloom, M. Futch, J. Kiviluoma, H. Holtinnen, A. Orths, E. Gomez-Lazaro, S. Martin-Martinez, S. Kukoda, G. Garcia, K.M. Mikkelsen, Z. Yongqiang, K. Sandholt, Market evolution: wholesale electricity market design for 21st century power Systems, Contract (2013), https://doi.org/10.2172/1260327.
[340] WindEurope, WindEurope position on Market Design: driving investments towards a climate-neutral and energy secure Europe, (n.d.). https://windeurope.org/wp-content/uploads/files/policy/position-papers/20220412-WindEurope-position-paper-on-electricity-market-design.pdf (accessed May 28, 2024).
[341] G. Fitzgerald, J. Mandel, J. Morris, H. Touati, The economics of battery energy storage how multi-use, customer-sited batteries deliver the most services and value to customers and the grid (n.d.). https://rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf (accessed May 28, 2024).
[342] R. Vor Dem Esche, Benefits of Flywheels for Grid Stabilization White Paper, 2017.
[343] M. Fotopoulou, P. Pediaditis, N. Skopetou, D. Rakopoulos, S. Christopoulos, A. Kartalidis, A Review of the Energy Storage Systems of Non-Interconnected European Islands, Sustainability 2024, Vol. 16, Page 1572 16 (2024) 1572. doi:https://doi.org/10.3390/SU16041572.
[344] Energy storage for electricity generation - U.S. Energy Information Administration (EIA), (n.d.). https://www.eia.gov/energyexplained/electricity/energy-storage-for-electricity-generation.php (accessed March 22, 2025).
[345] K. Xu, Y. Guo, G. Lei, J. Zhu, A Review of Flywheel Energy Storage System Technologies, Energies 2023, Vol. 16, Page 6462 16 (2023) 6462. doi:https://doi.org/10.3390/EN16186462.
[346] Flywheel energy storage tech at a glance – pv magazine International, (n.d.). https://www.pv-magazine.com/2022/09/15/flywheel-energy-storage-tech-at-a-glance/ (accessed March 22, 2025).

Journal information

×

JOURNAL OF ENERGY STORAGE

Publisher name: ELSEVIER

Journal Impact Factor ™

8.9	9
2023	Five Year

JCR Category	Category Rank	Category Quartile
ENERGY & FUELS *in SCIE edition*	29/171	Q1

Source: Journal Citation Reports 2023. Learn more

Journal Citation Indicator ™

1.31	1.23
2023	2022

JCI Category	Category Rank	Category Quartile
ENERGY & FUELS *in SCIE edition*	36/174	Q1

The Journal Citation Indicator is a measure of the average Category Normalized Citation Impact (CNCI) of citable items (articles and reviews) published by a journal over a recent three year period. It is used to help you evaluate journals based on other metrics besides the Journal Impact Factor (JIF).

Learn more

21