Flywheel Energy Storage System for Power Quality Improvement
Application: A Review

Chen ZHOU¹, Hao-jie YU¹, Wei-qiang QIU²,*, Bo YANG¹, Yi-bin TAO¹ and Zhen-zhi LIN²

¹China Electric Power Research Institute, Nanjing 210003, China
²College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China

*Corresponding author

Keywords: Flywheel energy storage system, Power quality, Frequency regulation, Voltage support.

Abstract. Flywheel energy storage system (FESS) plays an important role in improving the power quality for the power system with high-penetration renewable energy sources, due to its advantages of high power density, quick response time, long cycle life and high energy efficiency. This paper presents a review of FESS for power quality improvement application. The main components are introduced and the literatures about the development of FESS are also discussed. Moreover, the FESS based technology for frequency regulation and voltage support is discussed, and some recent research works and the related waveforms are reviewed to confirm the effectiveness and performance.

Introduction

With the ever increase of renewable energy sources (RESs) such as wind turbines and photovoltaic generation, the massive clean power starts to be transmitted to the user side through power network, reducing the carbon dioxide emissions and delaying the fossil energy consumption significantly [1]. However, due to the intermittent, highly erratic and weather-dependent characteristics of RESs, the situation becomes worse in term of power quality, degrading the stability and security of power system clearly [2]. In order to address this problem, the energy storage systems (ESSs) are employed to provide a reliable solution.

In recent years, as the advance of the basic subjects such as physics, chemistry and materials, the ESSs have developed various categories, e.g., battery energy storage system (BESS) [3], pumped hydroelectric storage (PHS) [4] and flywheel energy storage system (FESS) [5–7], which have difference in power level, energy level, response time and storage form [8]. Currently, the ESSs applied in power system have been implemented technologically, and some issues have been successfully solved according to the ESS nature, for example, smoothing power fluctuation by the BESS and matching demand with supply by the PHS [8]. Similarly, due to the fact that electrical disturbances are frequent but short, the FESS with the main attributes of high power density, instantaneous response time and long life cycle has provided a reasonable solution for power quality improvement.

This paper will focus on the current status of the FESS for power quality improvement application, and pick up on the recent literatures in this subject. In first part of the following sections, the main components of FESS are discussed in detail. The characteristics and the technical advance of FESS are also introduced in this section. Moreover, the FESS applications for the power quality improvement, including frequency regulation and voltage support, are reviewed. The effectiveness of FESS will be verified by the waveforms selected from there papers.

Composition and Characteristics of Flywheel Energy Storage System

Compared with other ESSs, it is different for FESS that the energy is stored as kinetic energy in the flywheel rotor. When FESS absorbs energy from the grid, its flywheel rotor will accelerate. On the
contrary, the kinetic energy can be transformed into the electrical energy, accompanied by the decelerating rotor. The main components of FESS include a flywheel rotor, bearings, a dual-functional electric machine (can be used as a motor and generator), a housing and a bidirectional power converter. Otherwise, there are some other auxiliary devices, such as vacuum pump and cooling system, applied in FESS according to the specific type [6]. A typical structure of FESS is shown in Fig.1.

![Figure 1. A typical structure of FESS.](image)

In FESS, the flywheel rotor is used as the storage medium and its performance is determined by the rotor shape and material. The stored kinetic energy is linearly proportional to the moment of inertia and the square of its angular velocity, and therefore FESS is classified into two groups: low speed FESS (up to 10,000 rpm and heavy material) and high speed FESS (up to 100,000 rpm and light material) [5]. The bearings are to support the flywheel rotor and ensure its high-speed rotation without mechanical friction stably. The dual-functional electric machine is an energy conversion hub, in which electrical energy and mechanical energy are interchangeable in charging process or discharging process. The housing provides a low-pressure environment for flywheel rotor to reduce wind resistance loss under high-speed rotation [6]. On the other hand, the housing plays a protective role if flywheel bursts by the high centrifugal force. The bidirectional power converter equipped between FESS and power grid is to achieve the stable storage and release of electrical energy.

Based on the mechanical and electrical structure, FESS is an environmental-friendly, fast-response and deeply-dischargeable ESS with long cycle life [9]. Besides, the design of energy and power ratings is decoupled, respectively determining by the flywheel rotor and the nature of electric machine and power converter [7]. In recent years, FESS develops rapidly with the advance of the materials, technology and control method. For the flywheel rotor, generally, the steel and the composite material are employed in low speed FESS and high speed FESS respectively. Composite flywheel has the higher specific energy and burst-safety, however, steel flywheel has a better energy per cost, which is summarized in [10] and a hybrid flywheel with a metallic energy storage element and a thin composite burst-rim is proposed to integrate material characteristics. In [11], a FESS with a shaftless, hubless and high-strength steel flywheel is introduced, doubling the energy density and making up for the shortcoming of low stored energy to a certain extent.

In order to reduce the loss in the FESS operating process, the magnetic bearings, including permanent magnetic bearings, active magnetic bearings and superconducting magnetic bearings, are used instead of the mechanical ball bearings [5, 6, 12]. Moreover, the housing made of high strength material is usually a vacuum container, eliminating the influence of air friction. Therefore, FESS has low maintenance requirement and a long life time (up to 20 years) under the low-loss environment. In addition, due to its core role, many electrical machines with high performance are utilized in FESS, such as inductor machine [13], switched reluctance machine [14] and permanent magnet machine [15], and the characteristics of the three are introduced in [16]. On the other hand, the research on the power converter is an important link that can effectively solve some bottlenecks and enhance the function. In [17], a novel topology of bidirectional converter applied in FESS was proposed to ensure zero switching power loss, which achieves a saving of power to the extent of 2.5-3.5% and an increase of about 4% in the available backup time. With the development of FESS components, the power density is more than 10 times greater than BESS, and up to 95% round-trip energy efficiency is
achieved [8, 9]. Last but not least, many advanced control methods, such as model predictive control and H-infinity control, utilized in electrical machine and power converter are proposed to ensure the robustness of FESS, the higher efficiency and the controllability of flywheel speed and DC link voltage [18-20].

The Application for Power Quality Improvement

In view of the excellent performance and unique characteristics of FESS, it has been employed in different fields: transportation, aircraft, harbor and power system [6, 21, 22]. In power system, the most suitable applications of FESS fall in the areas of high power and short duration, and therefore the FESS utilized to improve power quality has been widely recognized and concerned at present. In this section, the literatures about the power quality improvement including frequency regulation and voltage support by using FESS are reviewed, and some waveforms in this literature are also shown to demonstrate the effect visually.

Frequency Regulation

According to the power quality requirements, the system frequency and voltage should be kept an acceptable level. When the mismatch between supply and demand or the load switching happens, the frequency and voltage deviation will occur, endangering the security and reliability of power system. Power quality problems occur more frequently in microgrid with high-penetration renewable energy due to the intermittent and stochastic output of the renewable energy sources.

The nature of frequency fluctuation is to vary with the difference between supply and demand at any time. When the supply exceeds the demand, system frequency will be higher than frequency rating. Conversely, when the demand exceeds the supply, system frequency will lower than frequency rating. Therefore, the requirement for the frequency regulation that the selected ESS can achieve fast response, high charge/discharge rates and thousands of charge/discharge cycles in a year [5].

FESS is an appropriate alternate, which has been verified in existing papers [23-29]. In [23], a scheme based on FESS is proposed and the results based on area control error signals indicate the effectiveness of frequency regulation. A practical model of FESS for primary frequency control has been proposed in [24]. The results shows that the FESS not only regulates the system frequency, but also reduce the variation of a synchronous generator mechanical torque because of the compensation for wind energy system. In [25], a FESS is used to provide the virtual inertia and frequency support. In [26], an induction machine based FESS by the field oriented control was proposed to regulation the frequency of island microgrid, reducing the deviation and recovery time of frequency compared to the scenario without FESS. Moreover, a fuzzy PI controller based FESS applied in Auckland University of Technology (AUT) microgrid was proposed in [27], and the experimental waveforms of frequency regulation are shown in Fig.2. According to the definition of the paper, scenario 1 is lack of the FESS, scenario 2 has a FESS with the conventional PI controller and scenario 3 has a FESS with the proposed fuzzy PI controller. It can be seen that the system frequency can restore to the given frequency rapidly under the action of FESS.

![Figure 2](image_url)

Figure 2. (a) Frequency variations; (b) Diesel generator emulator active power generation; (c) FESS active power generation in scenario 1 (black), scenario 2 (red) and scenario 3 (blue) [27].

Integrating a FESS into the renewable generators is another method. In [28], a low-speed FESS is added a wind diesel power system to improve the dynamic operation in frequency regulation.
Moreover, a permanent magnet synchronous generator based wind-power generation system with the FESS, and the frequency regulation control strategy based on fuzzy proportional plus differential controller were introduced in [29], which improves the grid frequency stability through regulating the system’s equivalent inertia and damping.

Considering the disadvantage of FESS such as low stored energy and short duration time, the hybrid ESS is a pretty solution where a FESS is combined with a long-term ESS [30]. In [31], a hybrid ESS consisting of FESS and hydrogen powered fuel cell was utilized in a wind-diesel powered microgrid. Consequently, a fast load-frequency response with a reasonable duration was realized for frequency regulation. In [32], a Li-Ion battery-flywheel hybrid storage system was proposed to support the primary frequency regulation. The results showed that the use of FESS prolongs the battery aging because FESS replaces the battery in frequent charging and discharging during the frequency regulation with oscillation.

Voltage Support

Keeping the node voltage in a certain range is basic condition of power system operation. Generally, the voltage problems in power system are created by the load switching or faults, causing the voltage fluctuation and voltage sag. In this event, the sensitive load such as semiconductor production and sensitive microprocessors would be affected and even damaged. On the other hand, the line loss and the probability of insulation damage will be increased obviously. In order to cope with this problem, FESS will be used as dynamic voltage compensator or dynamic voltage restorer to suppress the voltage oscillation and compensate the voltage sag [33].

In [34], an energy manage system of FESS based on bi-level decision model was designed, where the upper layer model solve the charging/discharging power of FESS based on the state of FESS and wind power fluctuation and the lower layer model controls energy exchange based on dual-loop control. The result shows that the probability of voltage overrun decreases significantly. An integrated doubly fed induction generator-flywheel energy storage architecture was proposed in [35], mitigating oscillations and thus increasing wind energy penetration very effectively. Fig.3 represents some waveforms about the voltage and frequency regulation. After the system is disturbed by the load dynamics and reactive sink, the voltage and frequency can return to the ratings rapidly and hold the stability on the whole compared with the system without FESS.

![Waveforms of voltage and frequency regulation](image)

**Figure 3.** Response of doubly fed induction generator-flywheel energy storage during (a) load dynamic; (b) reactive sink at 100-102s [35].

For the voltage sag, the goal of using FESS is maintaining the voltage of the loads. In [36], a high-temperature superconductors FESS was presented, and it was tested in a hardware-in-the-loop system. Moreover, in [37], an AC/AC matrix converter, instead of the conventional AC/DC/AC converter, was employed in FESS to solve with voltage sag problem, leading to higher power density and increased system reliability. Furthermore, an input-output linearization AC voltage controller based FESS with an AC/AC matrix converter was introduced in [38]. In Fig. 4, there are some waveforms to verify its performance. It can be seen from the experimental waveforms that the load voltage remains balanced and stable even if a 40% voltage sag occurs.
At present, FESS has been commercialized and many FESS projects for power quality improvement have been in operation for years successful, such as a 2MW/4.58 kWh FESS located in Kodiak, US and a 1.6MW/5kWh FESS located in Tias, ES et al [7]. In China, nowadays, FESS is not a mainstream choice for grid application although the technology of domestic company is developing rapidly, and generally the FESS is more used in UPS and rail transportation.

Summary
This paper presents a review of FESS with respect to the components and its power quality improvement application. The main components of FESS is introduced and some recent literatures are reviewed to reveal the novel development in FESS technology. In addition, some papers related to the application for frequency regulation and voltage support are introduced, and the waveforms in these paper are shown in this paper to verify the effectiveness of FESS. Future work will be focused on the detail modelling of FESS for more applications.

Acknowledgement
This research was financially supported by National Key Research and Development Program (2018YFB0905500).

References
[1] Khare V, Nema S, Baredar P. Solar–wind hybrid renewable energy system: a review [J]. Renewable and Sustainable Energy Reviews, 2016, 58: 23-33.
[2] Lin Z, Wen F, Ding Y, et al. WAMS-based coherency detection for situational awareness in power systems with renewables[J]. IEEE Transactions on Power Systems, 2018, 33(5): 5410-5426.
[3] Li X, Wang S. A review on energy management, operation control and application methods for grid battery energy storage systems [J]. CSEE Journal of Power and Energy Systems, 2019.
[4] Pickard W F. The history, present state, and future prospects of underground pumped hydro for massive energy storage [J]. Proceedings of the IEEE, 2011, 100(2): 473-483.
[5] Amiryar M, Pullen K. A review of flywheel energy storage system technologies and their applications [J]. Applied Sciences, 2017, 7(3): 286.
[6] Arani A A K, Karami H, Gharehpetyan G B, et al. Review of flywheel energy storage systems structures and applications in power systems and microgrids [J]. Renewable and Sustainable Energy Reviews, 2017, 69: 9-18.
[7] Goris F, Severson E L. A review of flywheel energy storage systems for grid application [C] //IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society. IEEE, 2018: 1633-1639.

[8] Boicea V A. Energy storage technologies: The past and the present [J]. Proceedings of the IEEE, 2014, 102(11): 1777-1794.

[9] Yulong P, Cavagnino A, Vaschetto S, et al. Flywheel energy storage systems for power systems application[C]//2017 6th International Conference on Clean Electrical Power (ICCEP). IEEE, 2017: 492-501.

[10] Kale V, Secanell M. A comparative study between optimal metal and composite rotors for flywheel energy storage systems [J]. Energy Reports, 2018, 4: 576-585.

[11] Li X, Anvari B, Palazzolo A, et al. A utility-scale flywheel energy storage system with a shaftless, hubless, high-strength steel rotor [J]. IEEE Transactions on Industrial Electronics, 2017, 65(8): 6667-6675.

[12] Li W, Zhang G, Ai L, et al. Characteristics analysis at high speed of asynchronous axial magnetic coupler for superconducting flywheel energy storage system[J]. IEEE Transactions on Applied Superconductivity, 2019, 29(5): 1-5.

[13] Ye C, Yang J, Xu W, et al. A novel multi-unit out-rotor homopolar inductor machine for flywheel energy storage system [J]. IEEE Transactions on Magnetics, 2018, 54(11): 1-5.

[14] Ho C Y, Wang J C, Hu K W, et al. Development and operation control of a switched-reluctance motor driven flywheel [J]. IEEE Transactions on Power Electronics, 2018, 34(1): 526-537.

[15] Liu Z Q, Wang K, Li F. Design and analysis of permanent magnet homopolar machine for flywheel energy storage system [J]. IEEE Transactions on Magnetics, 2019.

[16] Pena-Alzola R, Sebastián R, Quesada J, et al. Review of flywheel based energy storage systems [C]//2011 International Conference on Power Engineering, Energy and Electrical Drives. IEEE, 2011: 1-6.

[17] Gurumurthy S R, Agarwal V, Sharma A. High-efficiency bidirectional converter for flywheel energy storage application [J]. IEEE Transactions on Industrial Electronics, 2016, 63(9): 5477-5487.

[18] Ghanaatian M, Lotfifard S. Control of flywheel energy storage systems in the presence of uncertainties [J]. IEEE Transactions on Sustainable Energy, 2018, 10(1): 36-45.

[19] Abbou A. $H_{\infty}$ current controller of WRIM based flywheel storage system under unbalanced stator voltage [J]. International Journal of Renewable Energy Research (IJRER), 2019, 9(2): 613-623.

[20] Shi C, Wei T, Tang X, et al. Charging–discharging control strategy for a flywheel array energy storage system based on the equal incremental principle [J]. Energies, 2019, 12(15): 2844.

[21] Faraji F, Majazi A, Al-Haddad K. A comprehensive review of flywheel energy storage system technology [J]. Renewable and Sustainable Energy Reviews, 2017, 67: 477-490.

[22] Binti Ahamad N B, Su C L, Xiao Z, et al. Energy harvesting from harbor cranes with flywheel energy storage systems[J]. IEEE Transactions on Industry Applications, 2019, 55(4): 3354-3364.

[23] Lazarewicz M L, Rojas A. Grid frequency regulation by recycling electrical energy in flywheels[C]//IEEE Power Engineering Society General Meeting, 2004. IEEE, 2004: 2038-2042.

[24] Peralta D, Cañizares C, Bhattacharya K. Practical modeling of flywheel energy storage for primary frequency control in power grids[C]//2018 IEEE Power & Energy Society General Meeting (PESGM). IEEE, 2018: 1-5.
[25] Yu J, Fang J, Tang Y. Inertia emulation by flywheel energy storage system for improved frequency regulation[C]//2018 IEEE 4th Southern Power Electronics Conference (SPEC). IEEE, 2018: 1-8.

[26] Khodadoost Arani A A, Zaker B, Gharehpetian G B. Induction machine-based flywheel energy storage system modeling and control for frequency regulation after micro-grid islanding[J]. International Transactions on Electrical Energy Systems, 2017, 27(9): 9-18.

[27] Mahdavi M S, Gharehpetian G B, Ranjbaran P, et al. Frequency regulation of AUT microgrid using modified fuzzy PI controller for flywheel energy storage system[C]//2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC). IEEE, 2018: 426-431.

[28] Sebastián R, Peña-Alzola R. Control and simulation of a flywheel energy storage for a wind diesel power system [J]. International Journal of Electrical Power & Energy Systems, 2015, 64: 1049-1056.

[29] Yao J, Yu M, Gao W, et al. Frequency regulation control strategy for PMSG wind-power generation system with flywheel energy storage unit[J]. IET Renewable Power Generation, 2016, 11(8): 1082-1093.

[30] Barelli L, Bidini G, Bonucci F, et al. Flywheel hybridization to improve battery life in energy storage systems coupled to RES plants [J]. Energy, 2019, 173: 937-950.

[31] Vidyanandan K V, Senroy N. Frequency regulation in a wind–diesel powered microgrid using flywheels and fuel cells [J]. IET Generation, Transmission & Distribution, 2016, 10(3): 780-788.

[32] Dambone Sessa S, Tortella A, Andriollo M, et al. Li-Ion battery-flywheel hybrid storage system: countering battery aging during a grid frequency regulation service [J]. Applied Sciences, 2018, 8(11): 2330.

[33] Farhadi-Kangarlu M, Babaei E, Blaabjerg F. A comprehensive review of dynamic voltage restorers [J]. International Journal of Electrical Power & Energy Systems, 2017, 92: 136-155.

[34] Li J, Bi J, Yan G, et al. Research on improving power quality of wind power system based on the flywheel energy storage system[C]//2016 China International Conference on Electricity Distribution (CICED). IEEE, 2016: 1-6.

[35] Ghosh S, Kamalasadan S. An energy function-based optimal control strategy for output stabilization of integrated DFIG-flywheel energy storage system [J]. IEEE Transactions on Smart Grid, 2016, 8(4): 1922-1931.

[36] Karrari S, Noe M, Geisbuesch J. High-speed flywheel energy storage system (fess) for voltage and frequency support in low voltage distribution networks[C]//2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS). IEEE, 2018: 176-182.

[37] Wang B, Venkataramanan G. Dynamic voltage restorer utilizing a matrix converter and flywheel energy storage [J]. IEEE transactions on industry applications, 2009, 45(1): 222-231.

[38] Gambôa P, Silva J F, Pinto S F, et al. Input–output linearization and PI controllers for AC–AC matrix converter based dynamic voltage restorers with flywheel energy storage: a comparison [J]. Electric Power Systems Research, 2019, 169: 214-228.