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Review of Flywheel Energy Storage Systems structures and applications in power systems and microgrids

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ABSTRACT

Flywheel Energy Storage System (FESS) is an electromechanical energy storage system which can exchange electrical power with the electric network. It consists of an electrical machine, back-to-back converter, DC link capacitor and a massive disk. Unlike other storage systems such as the Battery Energy Storage System (BESS), FESS is an environmentally-friendly short- or medium-term energy storage system, which has the capability of numerous charge and discharge cycles. These characteristics make the FESS a suitable choice for different applications in the power system such as power quality improvement, power smoothing, renewable energies integration support, stability improvement, etc. This paper presents an overview on the structures and applications of FESS in power system and Microgrid (MG) and also challenges, problems and future works discussed. It can be a driver for development of FESS applications and also recommends suggestions to use its advantages in other areas. Investigation of different studies shows that FESS, as a developing technology, can play an effective role in the operation of the present and future power system and MG.

1. Introduction

Nowadays, the electric power system is quickly developing and needs more power generation units and transmission lines. This fact increases the complexity of the control and management of the power system. On the other hand, growth in new types of electric demand leads to different problems such as power quality issues for system operators [1–3]. In addition, by the expansion of the power system area, the protections of these systems will be more complex [4].

Growth of energy consumption, recent advances in generation technologies and environmental considerations lead to application of renewable energies such as solar and wind turbine units, and new small-scale electrical energy systems such as fuel cells. These types of energy resources, which are usually dispersed in network, are called distributed generations (DGs) [5]. By increasing the penetration of these units, due to the small capacity and stochastic nature of these DGs, many problems such as power quality or imbalance between supply and demand may occurred in Microgrids (MGs) [6,7]. To overcome these drawbacks of DGs, the Energy Storage System (ESS) can be applied as a common solution. ESS can inject or store energy in power systems and MGs when it is required. The ESSs can be used in Flexible AC Transmission Systems (FACTS) devices [8] to increase the transfer limit of transmission lines or improve the power quality in MGs and power systems [9]. Large ESS can supply electrical power for several hours in power systems. Moreover, ESS can release huge energy in a few seconds for applications used in military [4,10–12].

Flywheel Energy Storage System (FESS), as one of the popular ESSs, is a rapid response ESS and among early commercialized technologies to solve many problems in MGs and power systems [12]. This technology, as a clean power resource, has been applied in different applications because of its special characteristics such as high power density, no requirement for periodic maintenance, no pollution, long lifetime, high cycle efficiency (about 85%), etc [13–15].. Although this energy storage system has relatively high capital cost (5000 $/kWh), it has low annual operation and maintenance cost (19 $/kW-year) [12]. The main characteristic of the FESS is its low energy density and high power density, which makes it suitable for short-term applications [16]. In addition, while other energy storage, such as BESS or FC, may require temperature control system, this ESS do not any controlled temperature environment. Fig. 1 shows an example of the FESS application in a MG.

The FESS, as a fast response ESS, can provide a large power in fraction of second. In addition, its long lifetime and high efficiency (90–95%) are two of the main advantages of this ESS [18]. In addition, it has a low stand-by losses (over several minute to several hours) compared to other ESS. Todays, the application of this ESS has been

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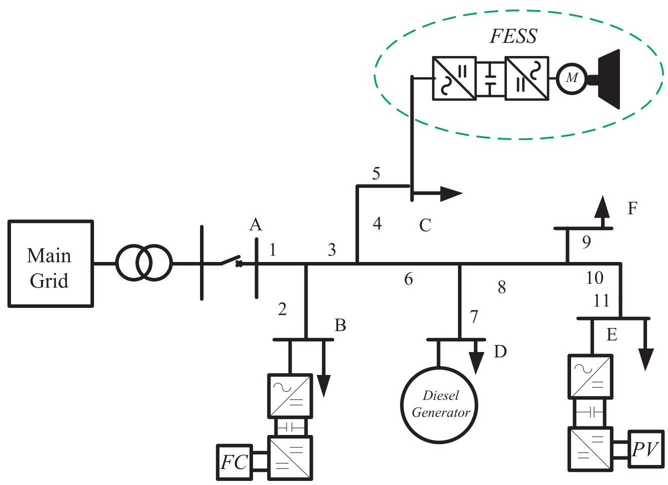

Fig. 1. MG and application of FESS [17].

increased in different aspects of man life. Electrical vehicle, space projects, military equipment and power system applications are some cases of different applications of it. Different review works have been written in ESS area which have been focused on different aspects, characteristics and applications of BESS, thermal ESS and other ESS [19,20]. However, a comprehensive review on the FESS and its application has not presented. Due to the mentioned advantages of the FESS, a review on its applications can be useful for future studies and researchers to know different aspects of FESS. It can be a driver for development of FESS applications and also recommends suggestions to use its advantages in other areas. In this paper, a comprehensive review on different structures and applications of the FESS in power system and MG has been presented. The advantages, challenges and future work in this area have been discussed.

The main contributions of the paper are summarized as follows:

1) This paper presents the first comprehensive review on the FESS structure. Two types of FESSs exist: low-speed and high-speed FESSs. The usage of the magnetic bearings, vacuum enclose, and composite disk are some characteristics of high-speed FESS and in a low-speed structure, mechanical bearings and steel flywheel are used where vacuum enclose is not required. These differences results in different applications of them which are investigated in this paper.
2) The FESS application in MG is comprehensively presented and reviewed in this paper. Also, its application in power system is discussed.
3) A discussion on future and challenges of this subject is presented.

The rest of the paper is as follows:

A review of FESS structures is carried out in the next section from mechanical as well as electrical points of view. In Section 3, different applications of this storage system are studied and reviewed. Finally, a conclusion of the paper is presented in the last section.

2. Flywheel Energy Storage System Structure

2.1. Physical structure

2.1.1. Flywheel

Flywheel, as the main component of FESS, is a rotating disk that has been used as a mechanical energy storage device. For several years, as its primary application, flywheel has been used for smooth running of machines. Two kinds of materials have been used in the flywheel disks [21]. Before 20th century, steel was used in its structure. However, due to advances, composite materials have been tested in

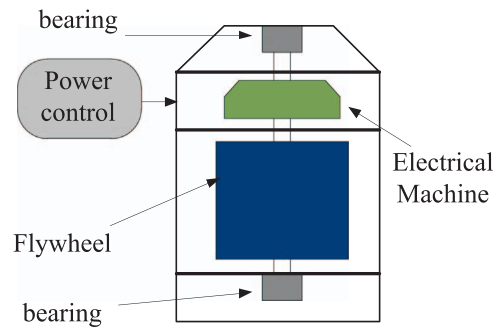

Fig. 2. High speed FESS [12].

the flywheel structure. The difference between steel and composite materials is their rotational stress limitations. The composite-based flywheel can support higher speeds and rotational stress threshold than the steel-based ones [22]. Therefore, composite materials can be used in high-speed flywheels (up to 100,000 rpm) with lower weight and steel, which has more weight, can be applied in lower speed ones (up to 10,000 rpm) [8,13,23]. The main problem of composite material is its cost, which is expected to be decreased in future. This material provide a high power density in low occupied volume.

As shown in Fig. 2, FESS as an electromechanical storage system, can store the electrical energy in kinetic energy form in its rotating mass. The stored energy in the flywheel can be calculated as follows [24]:

$$E_{FW} = \frac{1}{2} J\omega^2 \tag{1}$$

Where, E_{FW} is the stored energy in the flywheel and J and ω are moment of inertia and angular velocity of rotor, respectively. As it can be seen in (1), in order to increase stored energy of flywheel, two solutions exist: increasing in flywheel speed or its inertia. The moment of the inertia depends on shape and mass of the flywheel. Generally, rotor is a solid cylindrical object. So, for a mass of m, radius of r, length of a and mass density of ρ, J can be calculated as follows:

$$J = \frac{1}{2} m\, r^2 \;=\; \frac{1}{2}\rho\, a\, \pi\, r^4 \tag{2}$$

By increasing disk radius or using high density material, it is feasible to store more energy. Flywheel operation can be formulated by using a simplified mechanical equation as follows:

$$J\frac{d\omega}{dt} = T_{em} \;-\; f\omega \tag{3}$$

Where, T_{em} is the electromechanical torque and f is the friction coefficient.

2.1.2. Bearings

One of the most important mechanical components of FESS is its bearings. Two possible types of bearings can be used in FESS structure: a) mechanical bearings and b) magnetic bearings. Mechanical bearings have been usually used for low-speed flywheels and have some disadvantages such as high friction, high losses, need of lubrication and maintenance and low lifetime. Magnetic bearings levitate around the moving rotor shaft in the FEES without any physical contact, as shown in Fig. 2. Due to their low friction, these bearings decrease losses and support the system to reach high speeds [25,26]. There are two types of magnetic bearings: passive and active. Passive bearings are made of permanent magnets, while another type consists of a coil and feedback system, which makes it more stable than passive bearings as well as more expensive [27,28].

As a result of using magnetic bearing, the speed of the disk can be increased. Therefore, aerodynamic friction is increased which causes aerodynamic losses. To overcome this problem, disk and magnetic

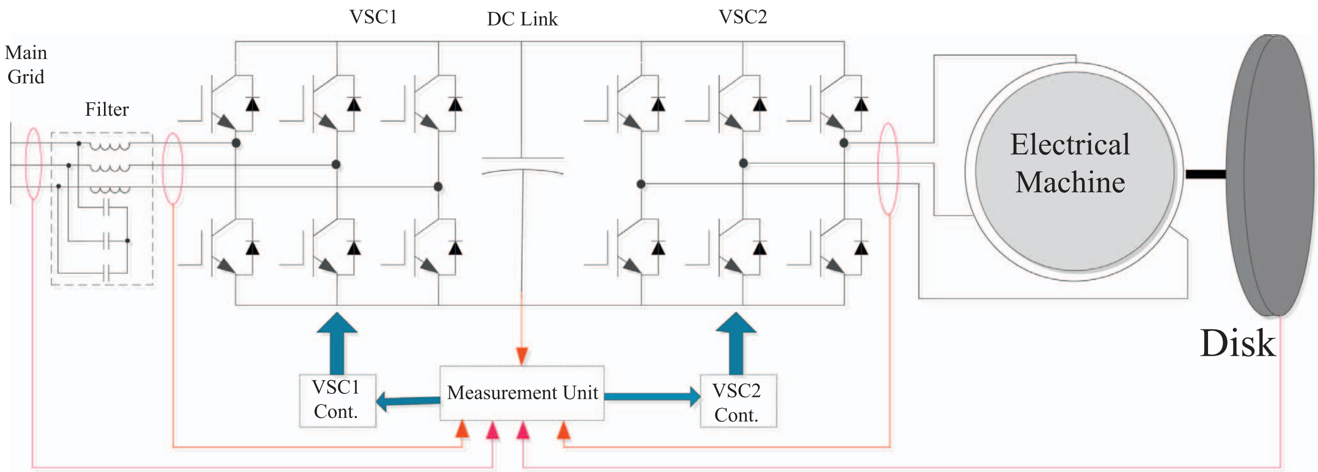

Fig. 3. Detailed electrical diagram of FESS.

bearing are confined in the enclosure that has low pressure air or helium [29]. This section increases the costs as well. Although the magnetic bearings are already expensive, it is expected in future their costs will be reduced and their application for FESS become more economical.

2.2. Electrical aspects of FESS

Fig. 3 shows detailed electrical diagram of FESS. As shown in Fig. 3, the FESS has a massive disk, an electrical machine, a large capacitor in DC link, LC filter in its input, control system of FESS and two Voltage Source Converters (VSCs), which are interconnected back to back. In the following, the role of different electrical components are described.

2.2.1. Electrical machine

An electrical machine is a requisite component of the FESS. The machine can be controlled to convert the electrical energy to kinetic energy and vice versa as described in next section. Different types of electrical machines have been used in the FESS structure such as Induction Machine (IM) [30–33], Permanent Magnet Synchronous Machine (PMSM) [34–37], Synchronous Homopolar Machine (SHM) [38,39] and Switched Reluctance Machine (SRM) [40,41].

In [30], an IM-based FESS with Direct Torque Control (DTC) and Field Oriented Control (FOC), has been implemented. In [31], DTC has been used to control both DC link voltage and IM flux. A complete description of DTC and its application for IM has been presented in [32]. Due to the application of IM with at least one pair of poles, the FESS has low speed (about 3000 rpm) in these studies. The speed can be increased to almost twice of its nominal speed by operating in the flux weakening region using DTC method [30]. IM can be established with low-cost and high-strength material. In addition the linear and nonlinear model of the IM based FESS have been carried out in [42] and some simplifications for the FESS model has been done in this study.

PMSM is usually used for high-speed applications. In [34] and [35], design considerations of PMSM for FESS application have been investigated and it is shown that the PMSM has high efficiency (about 95%) [34] and low losses [35], even for high speed (about 50000 rpm). By the application of the PMSM, ultra-high-speed FESS can be built. A PMSM-based FESS and its experimental results at 32000 rpm speed has been presented in [36]. The results of this study show that the proposed design is able to operate in the range of 150,000–300,000 rpm. PMSM need no excitation and no winding for its rotor leading to a decrease in its complexity. These types of machines have been used in FESS with high power density [37].

SHMs have low rotor losses and are constructed from robust materials resulting in high–performance FESS [38]. The rotor of these machines can be used as energy storage device of FESS. SHM with high power factor and high efficiency can be used for high-speed FESS. The SHM-based FESS can operate in 30,000–60,000 rpm range and has an average efficiency of 83% [39].

By using SRM, we can achieve high-speed operational range. Similar to IM, the SRMs are more robust and have less production cost than PMSM [41]. Although SRM is very robust and has no idle losses, it needs excitation and has a low power factor and high rotor eddy current losses [43]. Moreover, there are other types of electrical machines that are similar to PMSM such as the Axial-Flux Permanent Magnet (AFPM) [13,44] and brushless DC machine [45] that have been used in FESS.

As mentioned, different machines can be used in the FESS structure, which is related to its application. The IM is applied for low speed FESS while other machines usually can be used for high speed FESS.

2.2.2. Electrical interface

The electrical machine is connected to the power system or MG by a power converter as the electrical interface. If energy flows from the main grid to the FESS, the electrical machine will be accelerated and this leads to an increase in stored energy. If the electrical machine (or disk) speed decreases, the FESS will be discharged. The converters help to exchange power between FESS and the main grid by controlling the electrical machine.

The converter may be an AC to AC converter such as a matrix converter which is used in [46,47]. This type of converter leads to an increases the reliability [46] and power density [48]. An experimental prototype of FESS with matrix converter has been presented in [47]. Generally, back-to-back converters are used in the FESS structure [49–51]. This type of power converter includes two VSCs which are connected back-to-back using DC link capacitor. The converter, which is near to the electrical machine, controls its speed and flux for active power control of the FESS. By using another converter, DC link voltage is controlled [49]. If the energy is stored in the FESS, the machine-side and grid-side converters operate in rectifier and inverter operational mode and vice versa [50]. Recently, the optimization of power electronics interface has been attended; In [52], a high efficiency electrical interface for the FESS by Zero Voltage Transition (ZVT) and Zero Current Transition (ZCT), has been proposed which leads to improvement of energy saving from 2.5% to 3.5%. A low speed FESS using DC machine, has been modeled which has a buck-boost convertor [53]. A controller has been designed to determine the charging and discharging rates of the FESS by regulating the DC voltage of the machine terminal. Some characteristics of low speed and high speed FESSs have been listed in Table 1.

Table 1
Comparison between low and high speed FESSs [13,58–60].

Property	Low speed FESS	High speed FESS
Disk material	Steel	Composite
Electrical machine	IM, PMSM, SRM	PMSM, SRM
Bearing	Mechanical or mixed (magnetic and mechanical)	Magnetic
Main application	Power quality	Traction and aerospace industry
Cost	Low	High

3. FESS applications

In different researches, FESS has been used for many applications and different purposes such as: Flexible AC Transmission System (FACTS), power quality improvement, Uninterruptable Power Supply (UPS) systems, power smoothing, stability improvement, aircrafts and military projects, hybrid vehicles and renewable energy resources integration. Fig. 4 shows diagram of FESS applications in the power systems and MGs.

In the following subsections, a review of these applications and their details are presented. There are several industrial and governmental companies which have used the FESS in their facilities such as NASA Glenn research center (for aerospace projects), Piller power system Ltd. and Active Power Company (as backup source), Japan Atomic Energy Center (for pulsed power generation), Boeing Phantom Works (for peak shaving) and Beacon Power Company (for frequency stability) [54–57].

3.1. Aircraft application

The FESS can be established in the space aircrafts, satellite and International Space Station (ISS) as attitude control, momentum management, primary electrical energy storage and backup energy storage system [61–71]. The FESS for the ISS application has served as a flight experiment in [62,63]. The main purpose of that project was to upgrade the storage system and evaluation of replacing Battery Energy Storage System (BESS) with FESS. The evaluations have shown that BESS has a 3–5 year lifetime while FESS has at least a 20-year lifetime. In addition, this chemical ESS has the problem of pollution of environment while the FESS is environmental friendly and can discharge in a few seconds without heat generation. Furthermore, the FESS has not the stand-by loss that the BESSs have. Therefore, the FESS application was more efficient. Researches showed that this application is cost saving for ISS [67]. The FESS has been used to control the satellite attitude in [71].

The FESS efficiency is a key parameter and the total efficiency of the FESS includes charge, discharge and inverter efficiency. A comparison between BESS and FESS shows that FESS efficiency is 98.5% and BESS has efficiency of 91% [63]. Another important parameter in FESS is its mass and volume [68]. The FESS has less volume and mass compared with chemical energy storage systems. In addition, thermal limitation is wider for FESS [66]. In [64], high speed (70 krpm) FESS has been used beside BESS for its charging control. They reduce the size of photovoltaic (PV) panels, help the attitude control system and increase reliability. The high power capacity FESS can store more solar energy achieved by the PV panels to provide it for the night of spacecraft orbit.

In spacecraft and aircraft applications, more than 40,000 charge/discharge cycles are usually required. BESS can only support about 10,000 charge/discharge cycles. These high charge/discharge cycles of FESSs indicate a longer lifetime of at least 10–20 years. In addition, the High-Temperature Superconductor (HTS) magnet flywheel has 100,000–150,000 charge/discharge cycles [65]. Small bearing losses, high rotor speed and low weight and mass are some of the high-speed FESS characteristics. In addition, the high efficiency of the FESS and good life-time have attract many researches for future space project by countries.

3.2. High power density applications

As mentioned before, FESS can provide high power density (1000–2000 W/L). Also, other complex and expensive technologies such as supercapacitor and Superconducting Magnetic Energy Storage (SMES) can provide this power density [18]. Among these ESSs, the FESS can full charge state to full discharge state within several seconds.

In [72], by increasing the FESS rotor mass, a pulsed power application for the aircraft launch system has been produced. In this application, FESS speed was 5,600 rpm in which stored energy and peak phase current were 126 MJ and 6400 A, respectively. In addition, FESS has been used in navy ships for its startup or power quality improvement [73]. A HSM-based FESS with high performance power control method has been proposed for high power pulsed system in [74] and analytical analyses for a high speed FESS in such applications have been presented in [75]. The fast response and high power density of the FESS made it as a suitable ESS for pulsed power generator.

3.3. In FACTS devices

Some FACTS devices have a DC link in their structures combined with an energy storage system such as supercapacitor, FESS or BESS. Static Synchronous Compensator (STATCOM) [76,77] and Dynamic Voltage Restorer (DVRs) [46,78] are two important types of these devices. Connection of FESS in the DC link of FACTS devices has been investigated in some works [65,66]. Fig. 5 shows two examples of such applications [76].

In [76], to alleviate the problems of wind generation such as fluctuations in the distribution network, DSTATCOM equipped by FESS has been used. A fast-response DC voltage source should be used in DSTATCOM to mitigate these problems. FESS can be a proper candidate in this application.

The Voltage sag, as an important power quality problem in the power system, can be mitigated by DVR. The DC link in the DVR

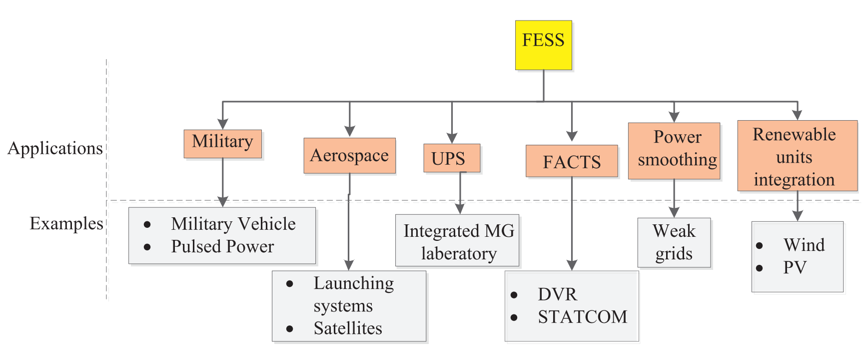

Fig. 4. General diagram of FESS applications in the power system and MG.

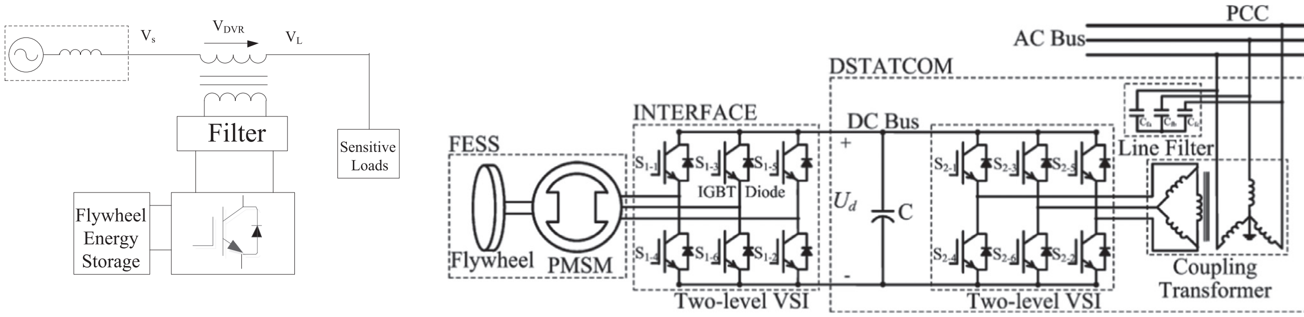

Fig. 5. FESS applications in FACTS devices [77].

structure can be fed by an electrical energy storage system such as FESS. An application of FESS coupled with DVR has been presented in [78]. A DVR is connected in series with the load and is used to compensate voltage sag, which might have occurred due to a fault in the power system or load changes such as motor starting [79]. Moreover, using FESS for compensation of voltage sag has been implemented in [79,80]. To increase the survivability of the shipboard power system that is vulnerable to voltage dips, a FESS has been used in [80].

In [81], to compensate unbalance in grid generation and load voltage, a new FACTS device based on FESS, called flexible power conditioner, has been presented. Due to FESS characteristics such as its fast response, it can quickly exchange active and reactive power and enhance power system stability [82]. Table 2 listed a brief review on these applications.

FACTS devices due to many advantages such as improvement in performance of long distance AC transmission line and power flow control, are developing. One of the main components which can affect FACTS devices performance is ESS. The FESS due to high speed response is one of the best candidates for these applications in future.

3.4. Uninterruptible power supplies (UPSs)

In some researches, FESS has been used in the UPSs [83–90]. A hybrid system, including a low-speed FESS and a generator, has been used as UPS to limit voltage fluctuations lower than 2% [88]. BESS and the bulky capacitor have been substituted with FESS in 1996 [83], which makes the size and weight of the UPS system smaller and lighter. A single phase FESS-based UPS with overall efficiency of 80% has been presented in [84]. To increase the efficiency of FESS-based UPS, a new FESS structure using helium in the enclosure, has been proposed in [85], to compensate the momentary voltage drops. In [86], Fuel Cell (FC) as a green energy resource that can store energy has been compared with FESS as a short-term and clean energy storage system. As shown in [73], although FESS can permit only a short ride through, it is reliable and can provide huge power in a few seconds. As shown in [87], due to the fast response of FESS, the electrolyte capacitor, filter reactor and battery can be eliminated in the previous UPS structure. In addition, application of the FESS combined by other storage systems such as BESS, has been proposed to mitigate the DC voltage ripple [91].

FESS has been used in [89] to support loads in emergency conditions after main AC system disconnection. Longer lifetime and no pollution lead researchers to use of FESS instead of BESS in the UPS structure. In [92], an integrated MG laboratory including DGs, FESS and diesel generator has been investigated. FESS alongside diesel generator play UPS role for fast balancing of power in MG. Fig. 6 shows FESS application in the UPS structure as described in [90].

Table 2
A Brief review on different application of the FESS in FACTS devices.

Type	Application	Related references
FACTS devices	flexible power conditioner	[81,82]
Custom power devices (CUPs)	DSTATCOM	[76,77]
	DVR	[46,78]

3.5. Power smoothing (power leveling)

Some energy resources in the power system or MG have a fluctuating nature. This decreases system reliability. Renewable energy resources such as wind generation, have an intermittent and unpredictable nature. Fig. 7 shows the effect of the FESS in smoothing output power of wind generation units [93]. It has been implied that ESS, which has a small energy density and fast ramp rate such as FESS, can be used as a power smoothing and peak shaving device. The localization of the FESS is very important to achieve optimal operation for the system. A scheme for capacity allocation of hybrid ESSs has been investigated in [93].

In [41,94–100], the application of the FESS in wind conversion units has been studied. In [101], it has been concluded that among all storage systems, FESS is a good solution for power smoothing of wind generation units, considering its rapid response to output power variations. In [41], a high-speed SRM-based FESS has been investigated for power smoothing. The active power of wind generation units can be controlled more efficiently by coupling a DSTATCOM with FESS as expressed in [95]. In [96,97], rotor current decoupling of DFIG-based FESS has been realized by using the artificial neural network to control its injected power and for power leveling.

A hybrid system including adiabatic compressed air energy storage system and FESS, has been proposed in [102] to overcome the problem of wind generation units. In this application, due to unbalance of wind generation and load requirement, the compressed air energy storage system compensates low frequencies and high amplitude oscillations, where FESS deals with high frequencies and low amplitude oscillations. In [100], a new V/f control method has been proposed and the dynamic response of the FESS, which leads to better grid power leveling, has been improved.

3.6. Vehicles

Many researches in traction and vehicular applications are used the FESS as a storage system, which can store large amounts of energy in its rotating mass [11,103–109]. The application of the FESS reduces pollution [103] and losses [105], increases efficiency [104] and has faster response, lower weight, higher capacity and shorter charging time in vehicles and trains compared with batteries [106]. FESS has been usually used in large vehicles such as buses [11]. The effect of FESS characteristics on vehicle operation and optimization of vehicle power and FESS torque has been presented in [108,109]. A diesel-electric plant can be replaced by FESS in a heavy haul locomotive [110]. Although this application requires an intelligent energy management system, it can decrease fuel consumption and pollution emission. Recently, the application of the FESS in commercial and industrial devices has been employed [107]. The FESS can provide high specific

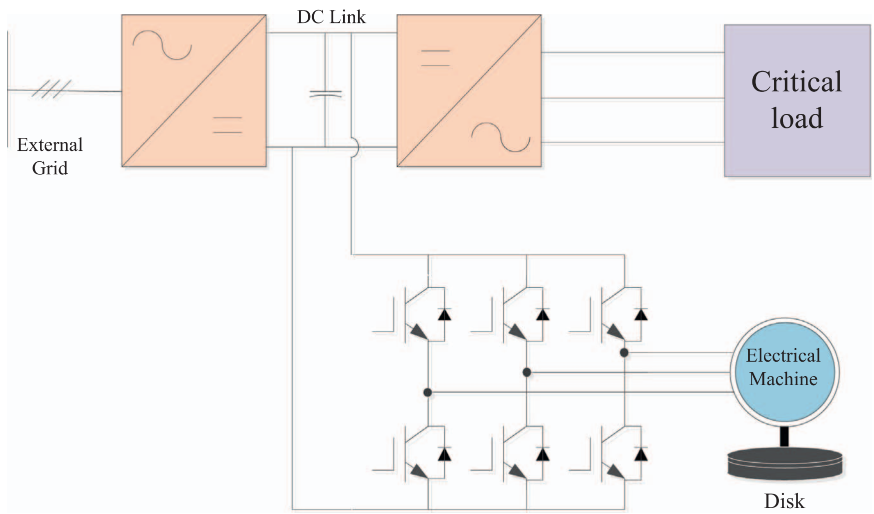

Fig. 6. FESS application in UPS structure [90].

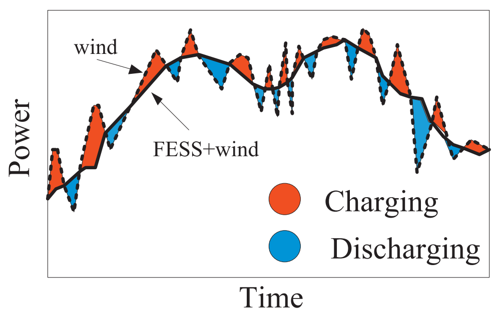

Fig. 7. Output power of wind generation units with and without using FESS [93].

power and energy for instantaneous load variations. The FESS has been used along with other energy resources such as BESS in vehicles, called hybrid vehicles [107]. This leads to an increase in BESS lifetime. As mentioned before, the FESS has high specific power while BESS has high specific energy. In [111], the application of the FESS in light rail transit, reduces the whole cost about 11%.

3.7. Stability improvement and maintenance

Unbalance between generated power and consumer requirements may occur and leads to instability. ESSs can help voltage stability by storing or consuming electrical energy and improve voltage in different areas of the power system. In this field, the FESS due to its characteristics is an alternative device for BESS and other storage devices. As investigated in [30,81,112–123], the FESS application can be used for stability improvement (dynamic or transient) and enhances voltage and frequency variations in power systems and MGs.

In [112], the FESS has been used to enhance dynamic stability of an offshore wind farm and reduce its power fluctuations. The control strategy of the proposed IM-based FESS, which used a back to back converter, has been described in [112]. In addition, the FESS can be used for transient stability improvement of power systems [121] because of its ability to inject or absorb large amounts of electrical energy in a few seconds. The obtained results presented in [96,124], show that the FESS with fuzzy controller tuned by a neural network, has significant impact on stability improvement.

The application of the FESS for frequency regulation has been discussed in many works [116,117,124]. In [117], the FESS has been used to stabilize voltage and frequency of the islanded power system including diesel generator, hydro and wind units. This scheme can improve the dynamic performance of the power system and reduce the fuel cost of the diesel generator.

In addition, the FESS can be used for the frequency stabilization of the power system. In [116], a small power system of wind farms equipped by FESS has been investigated. The wind farms have output power fluctuations that influence the power system frequency. A FESS and its control strategy have been presented by the authors in [116,117] to improve frequency behavior of the power system. In [125,126], 200 units of FESS with a total capacity of 20 MW (large-scale), established by the Beacon power company, have been introduced to regulate frequency of a power system in 15 min. The FESS and Fuel Cell (FC) have been used for frequency regulation in a MG and it has been shown that the frequency in MG has been improved by these devices. During low load period, the power as mechanical energy, in the FESS and as hydrogen gas, in FC can be stored. During high load period, this procedure can be reversed [127].

In [128,129], a cooperative control strategy consisting of primary and secondary control has been proposed, for all micro-sources and storage systems. Storage systems such as FESS due to their fast response, participate in the primary control and other resources, such as FC and Micro Turbine (MT), participate in the secondary control of frequency. Another classification of operation modes of storage systems has been expressed in [114]. Three control strategies for FESS in islanded MG, including PQ control, droop control and V/f control, have been investigated. Three mentioned strategies have been applied and the effects of each method on the stability of the MG have been investigated in [114]. The PQ control is the flywheel control strategy only in the grid-connected mode of the MG. During islanded mode, the PQ control has to be switched to droop control or V/f control methods. Fig. 8 shows these three control strategies.

It is expected in future, development in the FESS area by increasing its energy density and investigating the feasibility of its modular application, will improve the power system stability.

3.8. Application of FESS for renewable energy resources integration

Although fossil fuel based power plants are the major types of electrical energy providers usually, several problems such as environmental pollutions, fuel cost and increasing demand of electrical energy, lead to an increase in renewable energy usages [10,130–132]. Wind turbines and PV solar systems are two major types of renewable energy resources. As a power generation unit, the unpredictable nature of solar radiations and wind speeds cause fluctuation and unreliable generation. These characteristics limit their applications in stand-alone systems. To solve this problem, using a storage system such as FESS or BESS, has been studied in [115,132–134]. The ESSs can capture the produced power by renewable energy resources and inject it to power

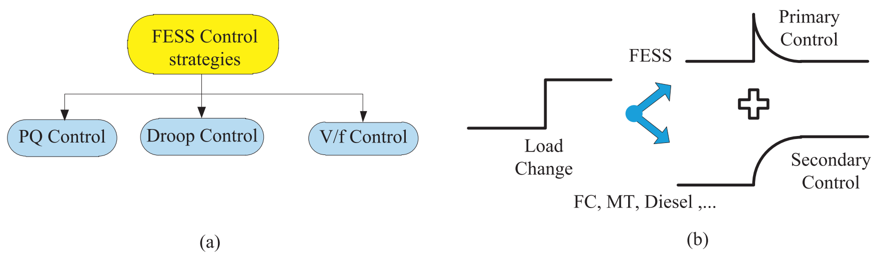

Fig. 8. a) FESS control strategies and b) Primary and secondary frequency control.

system or MG when it is necessary.

Power systems comprising these storage systems, can provide sufficient power when a sudden deficiency in the generation of wind or solar generation units occurs. Variations in their output power usually occur for a short period of time and a short term ESS such as FESS is suitable for these situations compared to BESS. In [132], a supervisory control for a MG including FESS, PV and wind, has been presented. The goal of the proposed dynamic power control is feeding all the loads and preventing black-out occurrence in the system, when Maximum Power Point Tracking (MPPT) strategy has been run for both renewable energy resources.

3.8.1. FESS with wind generation units

Fig. 9 shows the FESS application alongside the wind turbine in two sample structures. It has been discussed in different literatures [30,31,76,77,95,135–141]. In [136], the control of the wind turbine including Doubly Fed Induction Generator (DFIG) and IM-based FESS, has been studied and FOC has been described and applied to the machine side converter. As mentioned in [30], the FESS with the new Direct Torque Control (DTC) method has been used for variable-speed wind generators to improve the dynamic behavior of the FESS. In [76,77], due to intermittency of wind, the FESS is used along with DSTATCOM. The FESS active power has been controlled by using a fuzzy logic controller to smooth the output active power of the wind turbine in [95]. Distributed control scheme for the FESS and wind generation units has been proposed in [142] which has been improved dispatch problem by using local information.

In [135,137], active power smoothing of wind fluctuations has been provided by using a fuzzy logic controller for the FESS. In [136,138], the operation and control of the DFIG-based wind turbine, which has a matrix converter associated with IM-based FESS, has been presented and it has been shown that this solution is technically feasible. The application of the FESS for wind farms with HVDC links, has been presented in [143]. The FESS has improved both transient and steady state behavior of system including wind farm due to surge power absorption of FESS. The low maintenance requirements and high initial cost are some characteristics of the proposed structure.

3.8.2. FESS with solar generation units

PV panels are used to convert the energy of sunlight to electrical energy. The radiation of the sun is varies during the day or seasons of a year. Consequently, the generated electrical energy is not constant. In [144], a review on problems of photovoltaic system and the solution has been done. The main problems are voltage fluctuation, voltage rise, reverse power flow, voltage flicker and effect on system frequency. As a solution for these problems, different ESSs such as BESS, SMES, etc. have been proposed in literature. Electrical storage systems such as FESS can absorb additional power generated by PVs or compensate lack of power due to weather condition variations [145–151].

In [145], an experimental test has been carried out to investigate the application of the FESS in PVs to enhance the voltage regulation problem which occurs at light loads. The test has been done for different speeds of the FESS and the results were acceptable. The coordination of the FESS and PV has been implemented in [146] that increases system reliability. In [147], a FESS has been used alongside PV power plant to compensate unpredictability of the solar energy. Also in [148], a micro-FESS has been applied to a system including PV panels and it has been indicated that the application of the FESS controlled by an appropriate control method, can compensate the variations of the PV generation. The authors in [149], have applied a high-speed FESS-based PV which has been controlled by MPPT and was cost-effective. Fig. 10 shows the application of the FESS along with PV.

The application of the FESS beside solar units has helped to overcome some problems such as uncertainty and power fluctuation of these units.

4. Discussion

The FESSs have some characteristics, which cause to prefer to other ESSs in different applications. It has long life-time and almost unlimited charge/discharge cycles which BESS (as a mature technology) has not this characteristics. The FESS can discharge in few seconds a large amount of power, which is suitable for pulse power generation, power system stability and frequency regulation. Although the FESS has high investment cost, it has low maintenance cost. In despite of BESS and supercapacitors which have chemical material, the FESS has not any pollution and is environmental friendly.

Two main structure of FESS exist: low- speed and high-speed. The low-speed FESS consists of steel rotor, no vacuum enclose, mechanical bearings and low speed electrical machine such as IM. The high–speed FESS type has vacuum enclose, composite rotor, magnetic bearings and high speed electrical machine such as PMSM. Since the stored energy in the FESS is related to inertia and speed of disk, the low speed FESS has steel disk with higher inertia and lower speed, while the high-speed

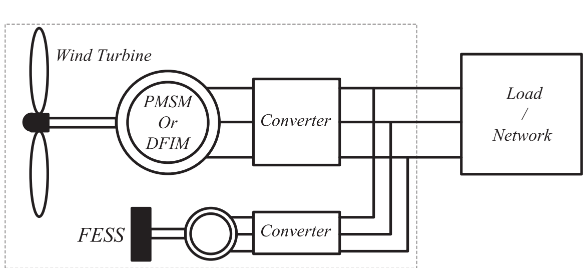

Fig. 9. FESS application alongside wind turbine; two possible structures [137].

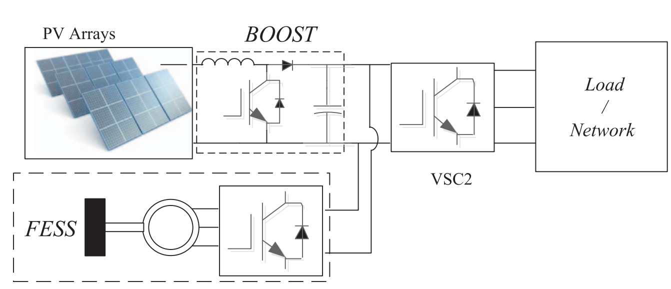

Fig. 10. FESS application alongside PV [147].

FESS has composite disk with lower inertia and high speed. In higher speed, the magnetic bearings and vacuum enclose are very important which leads to less friction compared to mechanical ones. The only advantages of low-speed FESS than high-speed one are low initial cost and less complexity in its structure.

One of the main problems of the FESSs is their high initial cost. The electrical aspects of the FESS are matured. It is expected that in future by progress in other technologies such as material, electromagnetic and mechanical engineering, the speed of the FESS will be increased and its cost will be reduced. In addition, as mentioned before, the FESS has high power density and low energy density which limits its application. This problem can be solved by application of several of this ESS as a farm of FESS to provide high energy density. This farm are now used as 20 MW FESS farm for frequency regulation. The increment of its efficiency can be done in future by research development.

Nowadays, the power system and MG require more flexibility. The FESS can improve the reliability and security of system. It can provide huge power in fraction of seconds; consequently, it can be used in UPS. In the other hand, the huge FESS can store large amount of power in low-load hours of grid and inject this power in peak hours of network. The FESS can be applied for frequency regulation in power system and participate in auxiliary service market. It can response to control signal of operator more quicker than conventional generators in power system. It is expected in future, development in the FESS area by increasing its energy density and investigating of its modular application, will improve the power system stability.

Due to increasing awareness of people and governments to environmental aspects such as reduction of CO_2 emission and using of clean energy, the application of renewable energies have been increased. In other hand, the intermittency and uncertainty of these generations are the main challenge of them. In this situation, the FESS will be used to provide a reliable and continuous power for consumers.

5. Conclusion

In this study, the FESS structures and its applications in power systems and MGs have been investigated and an overview of previous studies has been presented. The following conclusions can be drawn based on this study:

Two types of FESS exist: low-speed and high-speed FESSs. These two types are different from each other in their physical structure and application. The usage of magnetic bearings, vacuum enclose, and composite disk are some characteristics of high-speed FESS and in a low-speed structure, mechanical bearings and steel flywheel are used and vacuum enclose is not required.

The FESS has some characteristics that make it a desirable storage system among other storage systems. FESS is completely environmentally-friendly and has no pollution. It is able to charge/discharge for numerous cycles without any depreciation, consequently having a high life-time and low maintenance requirement.

The above characteristics make it suitable for applications that need a short- or medium-term energy storage system. Its presence in aerospace and military projects, FACTS devices, UPSs, renewable energy resources are some of these applications which have been reviewed.

Although the FESS has many advantages, but some drawbacks such as low energy density and high initial cost limit its usage for some high technological applications such as space projects, military services, and so on. Nowadays, the BESS has wide areas of applications in power systems. It is expected by progress in different areas of FESS structure, the BESS can be replaced with FESS. In the future, the application of composite rotor for the FESS will be developed extensively, and its speed will be increased which leads to increase in the power density of FESS.

References

[1] Bollen MH. Understanding power quality problems, 3. New York: IEEE press; 2000.

[2] Wood AJ, Wollenberg BF. Power generation, operation, and control. John Wiley & Sons; 2012.

[3] Divya K, Østergaard J. Battery energy storage technology for power systems—an overview. Electr Power Syst Res 2009;79:511–20.

[4] Kondoh J, Ishii I, Yamaguchi H, Murata A, Otani K, Sakuta K, et al. Electrical energy storage systems for energy networks. Energy Convers Manag 2000;41:1863–74.

[5] Katiraei F, Iravani M, Lehn PW. Micro-grid autonomous operation during and subsequent to islanding process. Power Deliv IEEE Trans 2005;20:248–57.

[6] Xu L, Chen D. Control and operation of a DC microgrid with variable generation and energy storage. Power Deliv IEEE Trans 2011;26:2513–22.

[7] Xiaoyong C, Yongli L, Weiya Z, Nan W, Wei X. Active disturbance rejection control for a flywheel energy storage system. Ind Electron IEEE Trans 2015;62:991–1001.

[8] Ribeiro PF, Johnson BK, Crow ML, Arsoy A, Liu Y. Energy storage systems for advanced power applications. Proc IEEE 2001;89:1744–56.

[9] Carrillo C, Feijóo A, Cidrás J. Comparative study of flywheel systems in an isolated wind plant. Renew Energy 2009;34:890–8.

[10] Ibrahim H, Ilinca A, Perron J. Energy storage systems—characteristics and comparisons. Renew Sustain Energy Rev 2008;12:1221–50.

[11] Vazquez S, Lukic SM, Galvan E, Franquelo LG, Carrasco JM. Energy storage systems for transport and grid applications. Ind Electron IEEE Trans 2010;57:3881–95.

[12] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy 2015;137:511–36.

[13] Bolund B, Bernhoff H, Leijon M. Flywheel energy and power storage systems. Renew Sustain Energy Rev 2007;11:235–58.

[14] Li Y, Li Y, Ji P, Yang J. Development of energy storage industry in China: a technical and economic point of review. Renew Sustain Energy Rev 2015;49:805–12.

[15] Pearre NS, Swan LG. Technoeconomic feasibility of grid storage: mapping electrical services and energy storage technologies. Appl Energy 2015;137:501–10.

[16] Zhao H, Wu Q, Hu S, Xu H, Rasmussen CN. Review of energy storage system for wind power integration support. Appl Energy 2015;137:545–53.

[17] Zaker B, Arani AK, Gharehpetian G. Investigating battery energy storage system for frequency regulation in islanded microgrid. In: presented at the 3rd Iranian regional CIRED conf., Tehran, Iran; May 2015.

[18] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: a critical review. Prog Nat Sci 3/10/2009;19:291–312.

[19] Zidar M, Georgilakis PS, Hatziargyriou ND, Capuder T, Škrlec D. Review of energy storage allocation in power distribution networks: applications, methods and future research. IET Gener Transm Distrib 2016;10:645–52.

[20] Singh TC, Prasad GS, Samantaray C, Sahu C, Kumari A, Mohapatra S. Design features of energy storage systems for green buildings: an economic comparison with off-grid and on grid solutions; 2016.

[21] Genta G. 3 – the flywheel. In: Genta G, editor. Kinetic energy storage. Butterworth-Heinemann; 1985. p. 47–168.

[22] Gabrys CW. High performance composite flywheel, ed: Google Patents; 2003.

[23] Bitterly JG. Flywheel technology: past, present, and 21st century projections. Aerosp Electron Syst Mag IEEE 1998;13:13–6.

[24] Liu H, Jiang J. Flywheel energy storage—an upswing technology for energy sustainability. Energy Build 2007;39:599–604.

[25] Sotelo GG, de Andrade R, Ferreira AC. Magnetic bearing sets for a flywheel system. Appl Supercond IEEE Trans 2007;17:2150–3.

[26] Werfel F, Floegel-Delor U, Rothfeld R, Riedel T, Goebel B, Wippich D, et al. Superconductor bearings, flywheels and transportation. Supercond Sci Technol 2012;25:014007.

[27] Ren M, Shen Y, Li Z, Nonami K, Modeling and control of a flywheel energy storage system using active magnetic bearing for vehicle. In: International conference on information engineering and computer science, ICIECS 2009; 2009, p. 1–5.

[28] Bleuler H, Sandtner J, Regamey Y, Barrot F. Passive magnetic bearings for flywheels. Solid Mech Appl 2005.

[29] Hebner R, Beno J, Walls A. Flywheel batteries come around again. Spectr IEEE 2002;39:46–51.

[30] Cimuca G, Breban S, Radulescu MM, Saudemont C, Robyns B. Design and control strategies of an induction-machine-based flywheel energy storage system associated to a variable-speed wind generator. Energy Convers IEEE Trans 2010;25:526–34.

[31] Idjdarene K, Rekioua D, Rekioua T, Tounzi A. Wind energy conversion system associated to a flywheel energy storage system. Analog Integr Circuits Signal Process 2011;69:67–73.

[32] Mansour M, Rachdi S, Mansouri MN, Mimouni MF. Direct torque control strategy of an induction-machine-based flywheel energy storage system associated to a variable-speed wind generator. Energy Power Eng 2012;4:255.

[33] Alan I, Lipo TA. Induction machine based flywheel energy storage system. Aerosp Electron Syst IEEE Trans 2003;39:151–63.

[34] Nagorny AS, Dravid NV, Jansen RH, Kenny BH, Design aspects of a high speed permanent magnet synchronous motor/generator for flywheel applications. In: International conference on electric machines and drives, IEEE; 2005, p. 635–41.

[35] Haichuan C, Baoquan K, Da Z, Weili L, Xiaochen Z. Research on loss of high speed

permanent magnet synchronous motor for flywheel energy storage. In: 16th International symposium on electromagnetic launch technology (EML); 2012, p. 1–6.
[36] Wensen W, Hofmann H, Bakis CE, Ultrahigh speed permanent magnet motor/generator for aerospace flywheel energy storage applications. In: International conference on electric machines and drives, IEEE; 2005, p. 1494–1500.
[37] Sough ML, Depernet D, Dubas F, Boualem B, Espanet C. PMSM and inverter sizing compromise applied to flywheel for railway application. In: vehicle power and propulsion conference (VPPC), IEEE; 2010. p. 1–5.
[38] Amodeo S, León A, Chiacchiarini H, Solsona I, Busada C. Nonlinear control strategies of a flywheel driven by a synchronous homopolar machine. Ind Electron ISIE IEEE Int Symp 2007:227–32.
[39] Tsao P, Senesky M, Sanders SR. An integrated flywheel energy storage system with homopolar inductor motor/generator and high-frequency drive. Ind Appl, IEEE Trans 2003;39:1710–25.
[40] de Andrade R, Sotelo GG, Ferreira AC, Rolim LG, da Silva Neto JL, Stephan RM, et al. Flywheel energy storage system description and tests. Appl Supercond, IEEE Trans 2007;17:2154–7.
[41] Cárdenas R, Peña R, Pérez M, Clare J, Asher G, Wheeler P. Power smoothing using a flywheel driven by a switched reluctance machine. Ind Electron IEEE Trans 2006;53:1086–93.
[42] Nair S, Senroy N. Dynamics of a flywheel energy storage system supporting a wind turbine generator in a microgrid. Int J Emerg Electr Power Syst 2016;17:15–26.
[43] Gruber W, Hinterdorfer T, Sima H, Schulz A, Wassermann J. Comparison of different motor-generator sets for long term storage flywheels. Power Electron Electr Drives Autom Motion (SPEEDAM) Int Symp 2014:161–6.
[44] Nguyen TD, Tseng KJ, Zhang S. On the modeling and control of a novel flywheel energy storage system. Ind Electron (ISIE) IEEE Int Symp 2010:1395–401.
[45] Siostrzonek T, Pirog S, The flywheel energy storage with brushless DC motor – the practical results. In: 12th international power electronics and motion control conference, 2006, EPE-PEMC 2006; 2006. p. 1541–5.
[46] Wang B, Venkataramanan G, Dynamic voltage restorer utilizing a matrix converter and flywheel energy storage. In: Industry applications conference, 42nd IAS annual meeting. conference record of the 2007 IEEE; 2007. p. 208–15.
[47] Gamboa P, Pinto SF, Silva JF, Margato E, A flywheel energy storage system with matrix converter controlled permanent magnet synchronous motor. In: 18th international conference on electrical machines. ICEM 2008; 2008, p. 1–5.
[48] Friedli T, Kolar JW, Rodriguez J, Wheeler PW. "Comparative Evaluation of three-phase AC–AC matrix converter and voltage DC-link back-to-back converter systems,". Ind Electron, IEEE Trans on 2012;59:4487–510.
[49] Schettino H, Gama V, Carvalho R, Goncalves de Oliveira J, Bernhoff H. Implement Control AC/DC/AC Convert Double Wound flywheel Appl 2011.
[50] Samineni S, Johnson BK, Hess HL, Law JD. Modeling and analysis of a flywheel energy storage system with a power converter interface. In: International conference on power systems transients (IPST), New Orleans, USA; 2003.
[51] S. Xu, H. Wang, Simulation and analysis of back-to-back PWM converter for flywheel energy storage system. In: 15th international conference on electrical machines and systems (ICEMS). Vol. 2012; 2012, p. 1–5.
[52] Gurumurthy S, Agarwal V, Sharma A, .High efficiency Bi-directional converter for flywheel energy storage application.
[53] Elsayed AT, Youssef TA, Mohammed OA. Modeling and control of a low speed flywheel driving system for pulsed load mitigation in DC distribution networks. In: 2015 IEEE industry applications society annual meeting; 2015. p. 1–6.
[54] Hadjipaschalis I, Poullikkas A, Efthimiou V. Overview of current and future energy storage technologies for electric power applications. Renew Sustain Energy Rev 2009;13:1513–22.
[55] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy 2015;137:511–36.
[56] P. p. s. p. E. s. n.d. (2016, 24 June). ⟨http://www.piller.com/en-GB/205/energy-storage⟩.
[57] B. P. Company. (2016, 24 June). ⟨http://beaconpower.com/renewable-integration/⟩.
[58] Sapowith AD, Handy WE. Composite-flywheel burst-containment study. CA (USA): Lawrence Livermore National Lab; 1982.
[59] Hayes R, Kajs J, Thompson R, Beno J. Design and testing of a flywheel battery for a transit bus. SAE Technical Paper; 1999.
[60] Sebastian R, Alzola RP. Flywheel energy storage systems: review and simulation for an isolated wind power system. Renew Sustain Energy Rev 2012;16:6803–13.
[61] TJ Pieronek, DK Decker, VA Spector, Spacecraft flywheel systems-benefits, and issues. In: Proceedings of the IEEE 1997 national aerospace and electronics conference. NAECON 1997; 1997, p. 589–93.
[62] Edwards J, Aldrich J, Christopher DA, Beach RF, Barton JR, Flight test demonstration of a flywheel energy storage system on the international space station. In: Proceedings of the IEEE 1997 national aerospace and electronics conference. NAECON 1997; 1997, p. 617–21.
[63] Christopher DA, Beach R, Barton J. A flywheel energy storage system test on the international space station. In: Proceedings of the 32nd intersociety energy conversion engineering conference. IECEC-97; 1997. p. 1762–6.
[64] Beaman BG, Rao GM. Hybrid battery and flywheel energy storage system for LEO spacecraft. In: the thirteenth annual battery conference on applications and advances; 1998. p. 113–6.
[65] Lee E. A micro high-temperature superconductor-magnet flywheels with dual function of energy storage and attitude control. In: Proceedings of IEEE sensors; 2002. p. 757–62.
[66] Lee S. A micro HTS renewable energy/attitude control system for micro/nano satellites. Appl Supercond IEEE Trans 2003;13:2263–6.
[67] Wagner RC, Boyle DR, Decker K. Commercialization of flywheel energy storage technology on the international space station. In: 2002 37th intersociety energy conversion engineering conference. IECEC'02; 2004. p. 146–150.
[68] Thompson RC, Beno JH, Pak TT. Advanced flywheel technology for space applications. In: 2002 37th intersociety energy conversion engineering conference. IECEC'02; 2004. p. 153–6.
[69] Kenny BH, Kascak PE, Jansen R, Dever T, Santiago W. Control of a high-speed flywheel system for energy storage in space applications. Ind Appl IEEE Trans 2005;41:1029–38.
[70] Aydin K, Aydemir MT. A control algorithm for a simple flywheel energy storage system to be used in space applications. Turk J Electr Eng Comput Sci 2013;21:1328–39.
[71] Aydin K, Aydemir MT. Sizing design and implementation of a flywheel energy storage system for space applications. Turk J Electr Eng Comput Sci 2016;24:793–806.
[72] Swett DW, Blanche JG. IV, Flywheel charging module for energy storage used in electromagnetic aircraft launch system. Electromagn Launch Technol 2004;2005:551–4.
[73] McGroarty J, Schmeller J, Hockney R, Polimeno M. Flywheel energy storage system for electric start and an all-electric ship. Electr Ship Technol Symp IEEE 2005:400–6.
[74] Amodeo SJ, Chiacchiarini HG, Solsona JA, Busada CA. High-performance sensorless nonlinear power control of a flywheel energy storage system. Energy Convers Manag 2009;50:1722–9.
[75] Talebi S, Nikbakhtian B, Toliyat HA. Analytical model-based analysis of high-speed flywheel energy storage systems for pulsed power applications. In: Electric ship technologies symposium, 2009. ESTS 2009, IEEE; 2009. p. 65–72.
[76] Suvire G, Mercado P. DSTATCOM with flywheel energy storage system for wind energy applications: control design and simulation. Electr Power Syst Res 2010;80:345–53.
[77] Suvire GO, Mercado PE. Improvement of power quality in wind energy applications using a DSTATCOM coupled with a flywheel energy storage system. In: Power electronics conference. COBEP'09. Brazilian; 2009. p. 58–64.
[78] Weissbach R, Karady G, Farmer R. Dynamic voltage compensation on distribution feeders using flywheel energy storage. Power Deliv IEEE Trans 1999;14:465–71.
[79] Ishak R, Rashidi F, Ismail RR. Motor starting sag mitigation using flywheel system. In: Proceedings of the 9th WSEAS/IASME international conference on electric power systems, high voltages, electric machines. Genova, Italy; 2009.
[80] Samineni S, Johnson BK, Hess HL, Law JD. Modeling and analysis of a flywheel energy storage system for voltage sag correction. Ind Appl IEEE Trans 2006;42:42–52.
[81] Chen Z, Zou X, Duan S, Wei H. Flexible power conditioner based on flywheel energy storage. Elektron Elektro 2011;115:3–8.
[82] Li G, Wen J, Cheng S, PAN Y. Investigation on start and cut-in of the multi-function flexible power conditioners. Autom Electr Power Syst 2006;30:17–22.
[83] Hockney RL, LeBlanc PL. Powering of remote node locations using flywheel energy storage. In: 18th international telecommunications energy conference. INTELEC'96; 1996. p. 662–7.
[84] Junling C, Xinjian J, Dongqi Z, Haigang W. A novel uninterruptible power supply using flywheel energy storage unit. In: The 4th international power electronics and motion control conference. IPEMC 2004; 2004. p. 1180–4.
[85] Suzuki Y, Koyanagi A, Kobayashi M, Shimada R. Novel applications of the flywheel energy storage system. Energy 2005;30:2128–43.
[86] Zanei G, Cevenini E, Ruff H, Ulibas O. Integrated systems for UPS: New solutions in the power quality chain. In: 29th international telecommunications energy conference. INTELEC 2007; 2007. p. 582–6.
[87] Ando I, Shibata J, Haga H, Ohishi K. Long life ups based on active filter and flywheel without electrolytic capacitor. In: 2007 european conference on power electronics and applications; 2007. p. 1–10.
[88] Kato S, Cheng M-m, Sumitani H, Shimada R. Semiconductor power converterless voltage sag compensator and UPS using a flywheel induction motor and an engine generator. In: Power conversion conference-Nagoya, 2007. PCC'07; 2007. p. 1680–5.
[89] Kimura N, Sonoda M, Morizane T, Taniguchi K, Kurokawa F. Emergency power supply using flywheel and doubly fed induction generator. In: 31st international telecommunications energy conference. INTELEC 2009; 2009. p. 1–6.
[90] Zhou L, Ping Qi Z. Modeling and control of a flywheel energy storage system for uninterruptible power supply. In: International conference on sustainable power generation and supply. SUPERGEN'09; 2009. p. 1–6.
[91] Lashway CR, Elsayed AT, Mohammed OA. DC voltage ripple quantification for a flywheel-battery based hybrid energy storage system. In: 2016 IEEE applied power electronics conference and exposition (APEC); 2016. p. 1267–72.
[92] Bo Z, Xuesong Z, Jian C. Integrated microgrid laboratory System. Power Syst, IEEE Trans 2012;27:2175–85.
[93] Zhao P, Wang J, Dai Y. Capacity allocation of a hybrid energy storage system for power system peak shaving at high wind power penetration level. Renew Energy 3//2015;75:541–9.
[94] Davies TS, Larsen N, A regenerative drive for incorporating flywheel energy storage into wind generation systems. In: Proceedings of the 24th intersociety energy conversion engineering conference. IECEC-89. Vol. 4; 1989, p. 2065–9.
[95] Suvire G, Mercado P. Active power control of a flywheel energy storage system for wind energy applications. IET Renew Power Gener 2012;6:9–16.
[96] Abdel-Khalik A, Elserougi A, Massoud A, Ahmed S. A power control strategy for flywheel doubly-fed induction machine storage system using artificial neural network. Electr Power Syst Res 2013;96:267–76.

[97] Daoud MI, Abdel-Khalik AS, Elserougi A, Massoud A, Ahmed S, Abbasy NH. An artificial neural network based power control strategy of low-speed induction machine flywheel energy storage system. J Adv Inf Technol 2013;4:61–8.
[98] Diaz-Gonzalez F, Bianchi FD, Sumper A, Gomis-Bellmunt O. Control of a flywheel energy storage system for power smoothing in wind power plants. Energy Convers IEEE Trans 2014;29:204–14.
[99] Cárdenas R, Peña R, Asher GM, Clare J, Blasco-Giménez R. Control strategies for power smoothing using a flywheel driven by a sensorless vector-controlled induction machine operating in a wide speed range. Ind Electron IEEE Trans 2004;51:603–14.
[100] Sun X-D, Koh K-H, Yu B-G, Matsui M. Fuzzy-logic-based control of an induction motor for a DC grid power-leveling system using flywheel energy storage equipment,". Ind Electron IEEE Trans 2009;56:3161–8.
[101] Howlader AM, Urasaki N, Yona A, Senjyu T, Saber AY. A review of output power smoothing methods for wind energy conversion systems. Renew Sustain Energy Rev 2013;26:135–46.
[102] Zhao P, Wang M, Wang J, Dai Y. A preliminary dynamic behaviors analysis of a hybrid energy storage system based on adiabatic compressed air energy storage and flywheel energy storage system for wind power application. Energy 2015;84:825–39.
[103] Hoolboom GJ, Szabados B. Nonpolluting automobiles. Veh Technol IEEE Trans 1994;43:1136–44.
[104] Rutberg P, Ivanov V, Kasharsky E, Kustov N, Rovinsky P. Electrotransmission of alternating current with flywheel for wheel transport facility. In: 9th Mediterranean electrotechnical conference, 1998. MELECON 98; 1998. p. 1152–6.
[105] Beno J, Thompson R, Hebner R, Flywheel batteries for vehicles, In: Proceedings of the 2002 workshop on autonomous underwater vehicles; 2002, p. 99–101.
[106] Richardson MB, Flywheel energy storage system for traction applications. In: International conference on power electronics, machines and drives. (Conf. Publ. No. 487); 2002, p. 275–9.
[107] Ren G, Ma G, Cong N. Review of electrical energy storage system for vehicular applications. Renew Sustain Energy Rev 2015;41:225–36.
[108] Gao Y, Gay SE, Ehsani M, Thelen RF, Hebner RE. Flywheel electric motor/generator characterization for hybrid vehicles. In: IEEE 58th vehicular technology conference. VTC 2003-Fall.; 2003. p. 3321–5.
[109] X. X. Fu, X. Xie. The control strategy of flywheel battery for electric vehicles. In: IEEE international conference on control and automation, ICCA; 2007. p. 492–6.
[110] Spiryagin M, Wolfs P, Szanto F, Sun YQ, Cole C, Nielsen D, . Application of flywheel energy storage for heavy haul locomotives. Applied energy.
[111] Rupp A, Baier H, Mertiny P, Secanell M. Analysis of a flywheel energy storage system for light rail transit. Energy 2016;107:625–38.
[112] Wang L, Yu J-Y, Chen Y-T. Dynamic stability improvement of an integrated offshore wind and marine-current farm using a flywheel energy-storage system. Renew Power Gener, IET 2011;5:387–96.
[113] Wang M-H, Chen H-C. Transient stability control of multimachine power systems using flywheel energy injection. In: IEE proceedings generation, transmission and distribution; 2005. p. 589–96.
[114] Wu X, Zhang Y, Arulampalam A, Jenkins N. Electrical stability of large scale integration of micro generation into low voltage grids. Int J Electron 2005;1:1–23.
[115] N Hamsic, A Schmelter, A Mohd, E Ortjohann, E Schultze, A Tuckey, et al., Increasing renewable energy penetration in isolated grids using a flywheel energy storage system. In: international conference on power engineering, energy and electrical drives, 2007. POWERENG; 2007, p. 195–200.
[116] Takahashi R, Tamura J. Frequency stabilization of small power system with wind farm by using flywheel energy storage system. in: IEEE International symposium on diagnostics for electric machines, power electronics and drives, SDEMPED; 2007. p. 393–8.
[117] Takahashi R, Tamura J, Frequency control of isolated power system with wind farm by using flywheel energy storage system. In: 18th international conference on electrical machines, ICEM; 2008, p. 1–6.
[118] Wu J, Wen J, Sun H, Cheng S. A novel energy storage system based on flywheel for improving power system stability. J Electr Eng Technol 2011;6:447–58.
[119] Kohansal M, Gharehpetian G, Rahmatian M, Sanjari M. Multi-objective optimization of microgrid frequency and energy storage capacity. In: International conference on renewable energies and power quality (ICREPQ'12); 2012.
[120] Arghandeh R, Pipattanasomporn M, Rahman S. Flywheel energy storage systems for ride-through applications in a facility microgrid. Smart Grid IEEE Trans 2012;3:1955–62.
[121] Pillai A, Thomas P, Sreerenjini K, Baby S, Joseph T, Srecdharan S. Transient stability analysis of wind integrated power systems with storage using central area controller. In: Annual international conference on emerging research areas and 2013 international conference on microelectronics, communications and renewable energy (AICERA/ICMiCR); 2013, p. 1–5.
[122] Cheng MM, Kato S, Sumitani H, Shimada R. Flywheel-based AC cache power for stand-alone power systems. IEEJ Trans Electr Electron Eng 2013;8:290–6.
[123] Sheykholeslami A, Haeri H. Voltage and frequency control in smart distribution systems in presence of DER using flywheel energy storage system.
[124] Taj TA, Hasanien HM, Alolah AI, Muyeen SM. Transient stability enhancement of a grid-connected wind farm using an adaptive neuro-fuzzy controlled-flywheel energy storage system, In: IET renewable power generation; 2015.
[125] Lazarewicz ML, Ryan TM. Integration of flywheel-based energy storage for frequency regulation in deregulated markets. Power Energy Soc Gen Meet IEEE 2010:1–6.
[126] Capp FW, Lazarewicz ML, Arseneaux AJ, Dresens P, Rojas HA. Methods, systems and apparatus for regulating frequency of generated power using flywheel energy storage systems with varying load and/or power generation, ed: Google Patents; 2011.
[127] Vidyanandan K, Senroy N. Frequency regulation in a wind–diesel powered microgrid using flywheels and fuel cells. IET Gener Transm Distrib 2016;10:780–8.
[128] Kim J-Y, Jeon J-H, Kim S-K, Cho C, Park JH, Kim H-M, et al. Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation. Power Electron IEEE Trans 2010;25:3037–48.
[129] Palizban O, Kauhaniemi K, Guerrero JM. Microgrids in active network management—Part I: hierarchical control, energy storage, virtual power plants, and market participation. Renew Sustain Energy Rev 2014;36:428–39.
[130] Lund H, Münster E. Management of surplus electricity-production from a fluctuating renewable-energy source. Appl Energy 2003;76:65–74.
[131] Mathiesen BV, Lund H. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. IET Renew Power Gener 2009;3:190–204.
[132] Boukettaya G, Krichen L. A dynamic power management strategy of a grid connected hybrid generation system using wind, photovoltaic and flywheel energy storage system in residential applications. Energy 2014;71:148–59.
[133] Lee D-J, Wang L. Small-signal stability analysis of an autonomous hybrid renewable energy power generation/energy storage system part I: time-domain simulations. Energy Convers, IEEE Trans 2008;23:311–20.
[134] Ray PK, Mohanty SR, Kishor N. Proportional–integral controller based small-signal analysis of hybrid distributed generation systems. Energy Convers Manag 2011;52:1943–54.
[135] Suvire GO, Molina MG, Mercado PE. Improving the integration of wind power generation into AC microgrids using flywheel energy storage. Smart Grid IEEE Trans 2012;3:1945–54.
[136] Ghedamsi K, Aouzellag D, Berkouk E. Control of wind generator associated to a flywheel energy storage system. Renew Energy 2008;33:2145–56.
[137] Cimuca GO, Saudemont C, Robyns B, Radulescu MM. Control and performance evaluation of a flywheel energy-storage system associated to a variable-speed wind generator. Ind Electron IEEE Trans 2006;53:1074–85.
[138] Belfedhal S, madjid Berkouk E. Modeling and control of wind power conversion system with a flywheel energy storage system. Int J Renew Energy Res (IJRER) 2011;1:152–61.
[139] Rong X, Xiaoru W, Jin T. Operation control of flywheel energy storage system with wind farm. In: Control conference (CCC), 2011 30th Chinese; 2011. p. 6208–12.
[140] Ažubalis M, Baranauskas A, Tamulis G. Wind power balancing using flywheel energy storage system. Elektron Ir Elektro 2013;19:19–22.
[141] Yao J, Zhou T, Hu W, Chen Z, Shen Q, Yu M. Enhanced control for a direct-driven permanent synchronous generator wind-power generation system with flywheel energy storage unit under unbalanced grid fault. Electr Power Compon Syst 2015;43:982–94.
[142] Cao Q, Song Y-D, Guerrero JM, Tian S. Coordinated control for flywheel energy storage matrix systems for wind farm based on charging/discharging ratio consensus algorithms,". IEEE Trans Smart Grid 2016;7:1259–67.
[143] Daoud MI, Massoud AM, Abdel-Khalik AS, Elserougi A, Ahmed S. A flywheel energy storage system for fault ride through support of grid-connected VSC HVDC-based offshore wind farms. IEEE Trans Power Syst 2016;31:1671–80.
[144] Shivashankar S, Mekhilef S, Mokhlis H, Karimi M. Mitigating methods of power fluctuation of photovoltaic (PV) sources – a review. Renew Sustain Energy Rev 2016;59:1170–84.
[145] MEl Deeb, Hisham, Ahmed Massoud DDDD, Daoud M. Maximum power transfer of PV-fed inverter-based distributed generation with improved voltage regulation using flywheel energy storage systems. In: Qatar foundation annual research conference; 2014.
[146] Vajda I, Kohari Z, Benko L, Meerovich V, Gawalek W. Investigation of joint operation of a superconducting kinetic energy storage (flywheel) and solar cells. Appl Supercond IEEE Trans 2003;13:2169–72.
[147] Abbezzot C, Tran T, Poggi P, Serre-Combe P, Perrin M, Muselli M. Using a flywheel associated to PV power plant in order to increase the integration of PV into island electrical grid. Bilbao, Spain; Mar 2013.
[148] Ye S, Sun B, Application of flywheel battery in solar power system. In: International conference on energy and environment technology, ICEET'09; 2009, p. 533–6.
[149] Ramli MA, Hiendro A, Twaha S. Economic analysis of PV/diesel hybrid system with flywheel energy storage. Renew Energy 2015;78:398–405.
[150] Kan H, Chau K, Cheng M. Development of doubly salient permanent magnet motor flywheel energy storage for building integrated photovoltaic system. In: Sixteenth annual IEEE applied power electronics conference and exposition, 2001. APEC; 2001, p. 314–20.
[151] Eltantawy AB, Salama MM, El-Fouly TH, Allen G. Enhancing storage capabilities for active distribution systems using flywheel technology. Electr Power Compon Syst 2015;43:1133–40.