Renewable and Sustainable Energy Reviews 67 (2017) 477–490

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A comprehensive review of Flywheel Energy Storage System technology

S.M. Mousavi G [a,*], Faramarz Faraji [b,c], Abbas Majazi [d], Kamal Al-Haddad [e]

[a] *Department of Railway Engineering, Iran University of Science and Technology, Tehran, Iran*
[b] *Tehran Regional Electric Company (TREC), Tehran, Iran*
[c] *Young Researchers and Elite Club, Science and Research Branch, Islamic Azad University, Tehran, Iran*
[d] *Department of Electrical Engineering, Damavand Science and Research Branch, Islamic Azad University, Damavand, Iran*
[e] *Electric Energy Conversion and Power Electronics, École de Technologie Supérieure, Montreal, QC, Canada, H3C 1K3*

ARTICLE INFO

Article history:
Received 27 December 2015
Received in revised form
19 March 2016
Accepted 10 September 2016
Available online 17 September 2016

Keywords:
Flywheel Energy Storage
Renewable energy
Energy storage

ABSTRACT

Energy storage systems (ESSs) play a very important role in recent years. Flywheel is one of the oldest storage energy devices and it has several benefits. Flywheel Energy Storage System (FESS) can be applied from very small micro-satellites to huge power networks. A comprehensive review of FESS for hybrid vehicle, railway, wind power system, hybrid power generation system, power network, marine, space and other applications are presented in this paper. There are three main devices in FESS, including machine, bearing, and Power Electronic Interface (PEI). Furthermore, advantages and disadvantages all of them have been presented. In addition a brief review of new and conventional power electronic converters used in FESS, have been discussed. Finally, practical ways to develop this technology in the future are presented.

Contents

* Corresponding author.
E-mail addresses: sm_mousavi@iust.ac.ir (S.M. Mousavi G), Faraji_u@yahoo.com (F. Faraji), abbasmajazi@gmail.com (A. Majazi), kamal.alhaddad@ele.etsmtl.ca (K. Al-Haddad).

http://dx.doi.org/10.1016/j.rser.2016.09.060
1364-0321/

1. Introduction

Energy Storage Systems (ESSs) play a very important role in today's world, for instance next-generation of smart grid without energy storage is the same as a computer without a hard drive [1]. Several kinds of ESSs are used in electrical system such as Pumped Hydro Storage (PHS) [2], Compressed-Air Energy Storage (CAES) [3], Battery Energy Storage (BES) [4], Capacitor Storage (CS) [5], Super capacitors Energy Storage (SCES) [6], Superconducting Magnetic Energy Storage (SMES) [7], Thermal Energy Storage (TES) [8], Hydrogen Storage System (HSS) [9], and Flywheel Energy Storage System (FESS) technologies. Flywheel (named mechanical battery [10]) might be used as the most popular energy storage system and the oldest one [11]. Flywheel (FW) saves the kinetic energy in a high-speed rotational disk connected to the shaft of an electric machine and regenerates the stored energy in the network when it is necessary [12]. First use of FW regurgitates to the primitives who had applied it to make fire and later, FWs have been used for mechanical energy storage [13]. Then this technique has been applied in several applications such as potter wheels [14], windmills, grindstone, and spinning and etc. One of the first “innovative” dissertations on the hypothetical stress limitations of rotational disks (isotropic only) is the seminal work by Stodola [15]. Investigations for FESS have been continued rapidly in research centers and academic works after the expansion in energy cost [13]. The largest rating of a FW applied in electrical application has been built by Japan Atomic Energy Research Institute (JAERI) [16]. In contrast to other energy storage units, the FW has several benefits, including high energy efficiency, fast response speed, strong instantaneous power, low maintenance, long lifetime and environment-friendly features [17–19]. Disadvantages of the FW are considered as follows: instantaneous output is not very high because it uses devices with permanent magnet in the rotor to remove the losses based on the magnetic coupling in the device [20–22]. Moreover, like other superconductor applications, superconducting FESS requires costly cryogenic cooling devices and the cryogenic cooling system not only enhances the total capital cost of superconducting FESS but also reduces the overall energy storage efficiency [23,34]. Generally, non-negligible amount of electricity is consistently essential during the energy storage period to keep cryogenic environment. A concept of storing cold thermal energy has been introduced to minimize the cooling load of the cryogenic cooling system in [23]. In addition, there are no determined standards for operation and protective regulations for FWs. Another challenge for FW performance analysis is the lack of historical operational data [24]. A high overall efficiency is one of the main issues for viable FW construction, also a mitigation of the total losses [25]. Installed cost is 1–1.4 times more than batteries [26]. Storage increase is not easy and needs units of comparable size. The FESSs can be classified as high-speed (10,000–100,000 rpm) and low-speed (less than 6000 rpm) [27–32]. Low-speed FWs, nominal value at hundreds of megawatts, have been implemented in high-energy physics facilities based on their high reliability and rugged construction [33]. High-speed FESS is a novel technology and produces better response speed, electric efficiency and cycling characteristics than low-speed FESS. High-speed FESS has high energy density but low power rating that is usually limited by cost (five times more than low-speed FESS) and the awkwardness of cooling [34–37]. Not only the rotational speed impacts on the material, length, and geometry of the FW but also it affects the kind of bearing and the kind of electrical machine [38]. In developed power industries, with the advances of light weight and high strength composite material, power electronics and control technology, FESS can be represented as a viable choice to conventional chemical battery systems [39].

Several papers have reviewed ESSs including FESS. Ref. [40] reviewed FESS in space application, particularly Integrated Power and Attitude Control Systems (IPACS), and explained work done at the Air Force Research Laboratory. A review of the suitable storage-system technology applied for the integration of intermittent renewable energy sources has been introduced in [41] and also future trends have been proposed. Refs. [42,43] reviewed ESSs in automotive and vehicle applications. Ref. [18] has presented a review of ESSs for transport and grid applications, and hybrid ESSs and power electronic interfaces (PEI) have been investigated in this study. Refs. [44,45] have reviewed ESSs in power network and investigated future research in this field. In Ref. [46] ESSs in railway application has been reviewed. A review and simulation of flywheel for an isolated wind power system has been presented in [47]. A brief overview of FESS for different applications has been proposed in [25,48].

All above review papers present different applications of FESS in brief. A comprehensive review of FESS for hybrid vehicle, railway, wind power system, hybrid generation system, power network, marine, space and other applications are represented in this paper. Thus, advantages and disadvantages of three essential devices including: machine, bearing, and Power Electronic Interface (PEI) in FESS represented. Although, conventional and new PEI are concisely reviewed in FESS. Also, future trend is proposed about this improving technology. This paper is organized as follows: Section 2 presents FESS structure theoretically. In Section 3 applications of FESS in industries are reviewed. Finally, future trends and conclusion are represented in Section 4.

2. Fess structure theory

The typical overview of FESS operation can be described as an electric supply charges the FW that stores energy in the form of kinetic energy. The amount of stored energy is based on the form, mass, and rotational speed of the FW [49]. Moreover in the charging mode, the FW is speeded up in its rotational motion to store the kinetic energy. Then the kinetic energy is maintained in the standby mode. When the stored energy is required, the FW begins to discharge the kinetic energy [13].

2.1. Rotor (Flywheel)

Several years ago, steel has been used but it has not allowed improvement of high speed, since the material has not withstood the load. Later, alloys of, e.g., titanium or aluminum alloys were applied. The newest solution is composite materials in 1970s that allowed the development of speeds up to 100,000 rpm and high power density at the same time [10,11]. The kinetic energy stored in a FW is corresponding to the moment of inertia and to the square of its rotational speed as follows:

$$E = \frac{1}{2}J\omega^2, \quad J = \int r^2. \quad dm = m\ .\ r^2 \tag{1}$$

where $E$is kinetic energy stored in the FW, J represents moment of inertia andω represents the angular velocity of the FW, m is the mass of the cylinder and $r$represents the radius. The maximum energy density with regarding volume and mass, respectively as follows:

$$e_v = K\sigma_{\theta.u} \qquad e_m = K\frac{\sigma_{\theta.u}}{\rho} \tag{2}$$

where e_v and e_m are kinetic energy per unit volume or mass, respectively, K is the shape factor, ρ is mass density and $\sigma_{\theta.u}$ is maximum stress in the FW.

2.2. Motor/generator

An electrical machine is the electromechanical interface of the FESS in which the rotor stores kinetic energy [50]. While the machine operates as a motor, energy is transferred to the FW and charge the energy storage device. And when the machine works as a generator, FESS is discharged. There are various types of machines that can be used with the FW such as follows:

2.2.1. Permanent magnet synchronous machine (PMSM)

PMSM has become the most common choice for FESSs according to its high efficiency [48]. PMSM has low rotor losses because of its rotor flux generated by permanent magnet; it has high energy density based on robust rotor structure; and the machine overall efficiency is high. It is appropriate for high speed applications [24,39,46,51–62]. PMSM can mitigate hysteresis losses camper to synchronous machine. But PMSMs are more expensive, less rugged and more sensitive to temperature in contrast to an induction machine (IM) [63]. The idle losses based on eddy currents in the stator, low ruggedness and high cost are the problems with PMSM.

2.2.2. Induction machine (IM)

IM can be considered as the best alternative in high power applications. As they have rough construction, low cost, high torque, high robustness, and high reliability [64]. The key problem with IM is speed limitation [44] and [64]. In order to overcome this problem, four solid-rotor topologies including: a) smooth solid-rotor, b) slitted solid-rotor, c) coated solid-rotor, and d) caged solid-rotor, are appropriate options, in the last decade. Doubly fed induction machine (DFIM) has been arisen as a motor/generator for FESS applications [65–72]. And also it has been applied since they allow mitigating power electronics sizing [64].

2.2.3. Brushless direct current machine (BLDCM)

BLDCM has been represented as a synchronous machine that has a permanent magnet in the rotor and functions in a self-controlled mode to control the current in the stator windings using an inverter. High power density, high efficiency, relatively wide rotational speed rang, mechanical stability, compact design, no electromagnetic interference, and low maintenance cost are the advantages of BLDCM [73–82].

2.2.4. Switched reluctance machine (SRM)

SRM is a good choice for FESS applications where as it has more simple structure and has low idle losses, having the ability to work in the harsh operational environments (ambient temperatures of around 400 °C) good robustness and a wide speed range (from zero to several thousand rpm) [83]; but the machine has high torque, current ripples and flux also the awkwardness of torque control at low speeds. Its control becomes simpler than IM if it operates at high speeds [84].

2.2.5. Homopolar machine (HM)

The AC homopolar machine is also well-known as the homopolar synchronous machine and the homopolar inductor alternator [85]. The HMs are able to offer encouraging advantages of robust rotor structure, low idling losses, improved reliability, and thus, they are noticeably attractive for long-term high-speed operation, which is essential for great importance in FESSs [85–96].

2.2.6. Synchronous machine (SM)

An isolated power system based on FW generators and examples for the satisfying suppression of torsional resonances in SMs of power supply have been presented in [97]. To stabilize oscillating torques, two new thyristor-controlled devices which are coupled to the stator winding of the SM have been improved, installed, tested, and continuously worked in the pulsed power supply of a tokamak experiment. It causes the same effect as an enhanced natural damping in the rotating shaft assembly for oscillation modes.

2.2.7. Bearingless machine (BM)

A BM mixes the functions of both magnetic suspension and torque generation together in a single machine [98,99]. The BM possesses the merits of an uncomplicated structure, compactness, and reduced cost in contrast to the magnetic bearing [100–102]. Various BM have been progressed so far, such as bearingless SRM, bearingless reluctance machine, bearingless IM, bearingless BLDCM, bearingless PMSM, Lorentztype slotless BM, and bearingless slice machine [103–109]. The BM can be applied in high-speed FESSs [110–112].

2.3. Rotor bearing

One of the important points in the FESS is the design of bearings. Appropriate design can reduce losses and maintenance requirements. Mechanical bearings were the first types of bearing, they have high friction and losses, and low lifetime when they are used in high-speed. Therefore they need lubrication and require periodic maintenance due to wearing. When the magnetic bearing have been appeared in 1980s [10], long lifetime, high fast response, high load capacity, low losses, and available high-speed were possible. Complicated control system is the main defect of magnetic bearing, even though in case of the magnetic bearings failure/overload, FESSs still need auxiliary mechanical bearings [17]. There are three types of magnetic bearings as follows:

2.3.1. Permanent (Passive) magnetic bearing (PMB)

PMBs include permanent magnets and must be mixed with another type of bearings since they are inherently unstable. The most attractive features of PMBs are very low losses due to lack of current and low cost. But they don't have low damping capability and active control [113]. And they cannot provide a stable suspension in all dimensions and are able to be used as an auxiliary bearing [34,113].

2.3.2. Active magnetic bearing (AMB)

AMBs are used as auxiliary bearings to reduce vibrations of the rotor [114], and contain coils which vary the electromagnetic forces due to the shaft position gaining stability by using a feedback system [48]. They have low-loss suspension of the rotating mass, better control ability, a high stiffness characteristic, and long lifetime, but high power loss based on existence of the biased current [115]. The mixed use of AMBs and mechanical bearings can reduce the complication of control and make the system viable, cost-effective and more stable [39]. They require complex control strategy that should be sensitive to electromagnetic disturbance [58,116–118].

2.3.3. *Superconducting magnetic bearing (SMB)*

SMBs are considerably appropriate for high-speed application, since the low energy losses in high-speed lead to free friction, long life, and self-stability. SMB works at very low temperature so it needs a cryogenic cooling system in order to avoid bearing failure. High temperature superconductors (HTS) can be used to improve the SMB and the cooling system. But a disadvantage is the requirement of cryogenic refrigeration and high cost even though, there are recent progress of innovative scheme for the cryogenic insolation that can decrease the refrigeration costs [119–139,22,67,76,77,114,117]. In [77] to reduce the cooling and total cost, SMB and PMB have been used together. A HTS bearing was designed for a FESS to measure the loss and learn how to reduce loss [124]. Hull et al. [125] have presented results of experiments with a small diameter rotor which uses HTS bearings for levitation and rotates in vacuum at kHz rates. Bearing losses are represented as a function of rotor speed. Same author et al. [133] have introduced a simple assumption for sub-synchronous whirl in systems with HTS bearings and indicate that theoretical predictions of the onset criteria match with experimental data, and It is showed how it is possible to damp the whirl from a theoretical context and explain a practical approach to achieve this that has had success in their laboratory experiments. Dynamics of the FESS are developed and charge-discharge characteristics are explained in [139]. Two types of ESSs with a FW rotor supported by SMBs are reported in [130]. Both systems contained a rotor and SMBs at the ends of the rotor. The rotor of fist systems is driven by applying an air turbine and another one is driven by brushless motor. To improve the dynamics of the passive type SMBs, a new method for both types of FESSs is developed. A PMB and a SMB bearings have been presented for a FESS in [135]. The PMB presented a considerable stiffness in spite of being an axial bearing. Two topologies of thrust SMB were investigated: a Halbach array and a flux shaper. The Halbach array can decrease the stray field and enhance the magnetic induction that makes it possible to increase the levitation force over 50% for the operational region. The mathematical frame of a dynamic mechanical model for HTS bearings has illustrated in [126]. Even in the presence of eccentricity and speed changes, this model was able to calculate the dynamic rotor position, and it was revealed that loss-models can be incorporated, so the dynamic model can describe the experimental spin-down curves very well. The comparison of the numerical analysis and the experiment in the SMB of the 10 kWh FW has been done in [127]. It was found that the induced current in the PM rotor, one of the most important cause of the rotational loss, was proportionate to the angular velocity, the secondary current did not have to be included while simulating and modeling for the higher-accuracy calculation the interaction between relative SMB segments had to be considered. From these findings, moving to next calculation for the large SMB system and the system that needed high-accuracy simulation was possible. Three topologies for the optimal structure of permanent magnet rotor were represented and their magnetic field characteristics were investigated in [131]. Ref. [138] has represented magnetic bearing sets to work in a FW system. First, two PMB topologies were compared and a new magnetic arrangement was presented and allowed significant increase in levitation and radial forces. The technology of superconducting bearing has been reviewed by Hull [134].

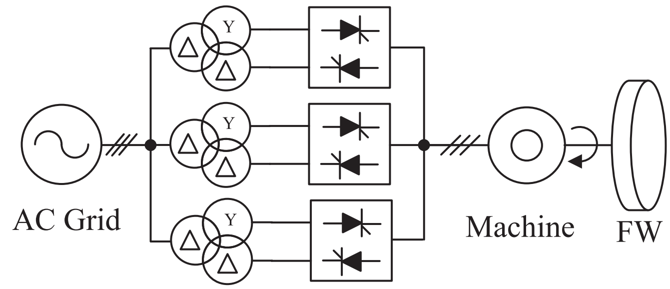

Fig. 1. Cycloconverter.

2.4. *Power electronic interface*

This subsection presents a brief overview of PEIs in FESS. As the development has been introduced in power electronics in the 1960s, the frequency and amplitude of the voltage both have become easier to be controlled [140]. Thus it was found that if a power converter and electrical machine are connected to a FW, a novel technique of storing electrical energy can be achieved [11]. PEIs play main role in FESS. Also different topologies can be used in FESS. (In this subsection, all converters that are connected to FW operate in bidirectional mode). Cycloconverter is one of the AC-AC family converters that are usually used in medium voltage and high power applications (see Fig. 1) [141]. The switches that are usually used in Cycloconverter are thyristors. This topology has disadvantages such as high Total Harmonic Distortion (THD), complex control, low power factor, requiring many switches in conventional types. AC-DC-AC configuration is used mostly in FESS [142]. This configuration is also known as back-to-back (BTB) topology. In BTB topology, grid side converter, converts the AC voltage to DC voltage and then DC voltage converts to the arbitrary AC voltage and frequency by machine side converter (see Fig. 2). In wind applications, FESS is usually connected to a common dc-link using a DC-AC converter (see Fig. 3) [143]. This configuration also can be used in other applications (e.g.: Uninterruptible Power Supply UPS) [144]. Also another configuration can be used for wind power (see Fig. 4) [145]. The boost converter can be connected the common dc-link of BTB configuration in FESS to increase the DC voltage (see Fig. 5) [30]. Also DC-DC plus DC-AC configuration can be used in FESS [78] (see Fig. 6). When conventional two level topologies are used, the high voltage level is limited, to overcome this problem; the multilevel converters (Neutral Point Clamped, Cascade H Bridge, and Flying Capacitor) can be a good choice. Nabae et al. [146] have introduced NPC in 1981. NPC converter can be used in FESS [147] (see Fig. 7), it has many advantages compare to conventional two level ones such as the low harmonic distortion of the voltage and current generated, the limitation of voltage transients dv/dt, the small size of the required filter elements, the high efficiency of the system, and the reduced common-mode voltages. Thus NPC can use other configuration in FESS including: DC-DC plus NPC (see Fig. 8), two-level conventional converter plus NPC (Fig. 9), and BTB NPC (see Fig. 10) [57]. AC-AC Matrix Converter (MC) is another PEI for FESS [55], which converts directly AC-AC. MC has a significant advantage; they do not have capacitor in their structures. Therefore, dc-link

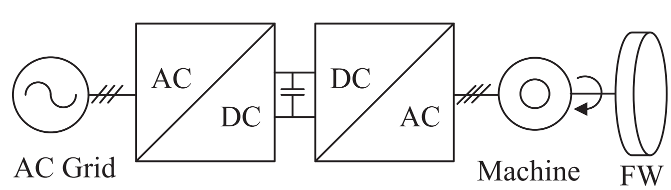

Fig. 2. BTB topology.

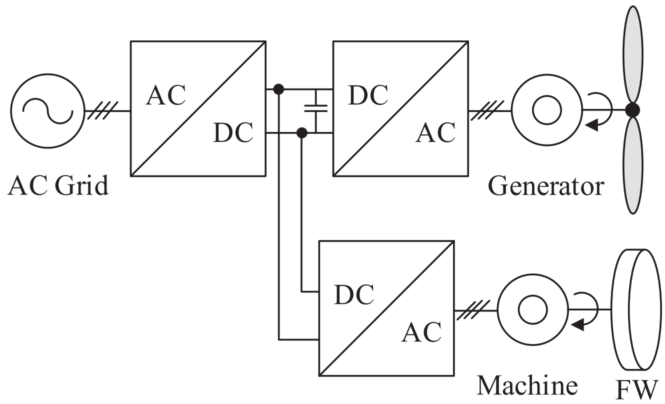

Fig. 3. BTB plus DC-AC converter connected in DC-link.

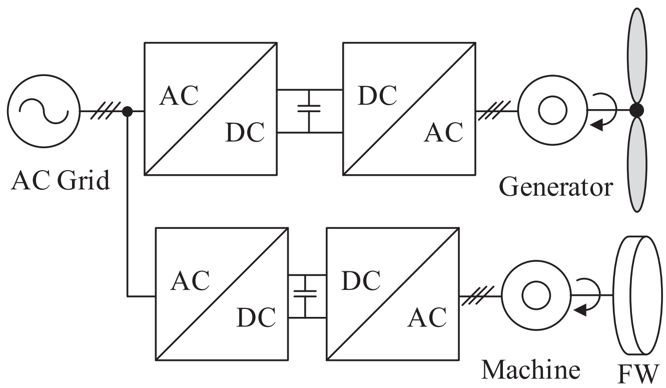

Fig. 4. BTB plus DC-AC connected directly to the grid.

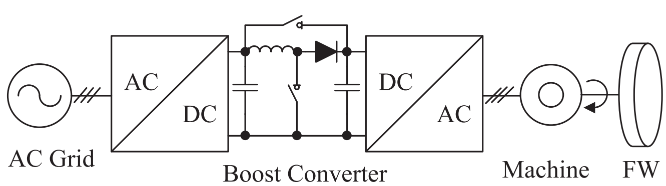

Fig. 5. BTB configuration with boost converter connected to DC-link.

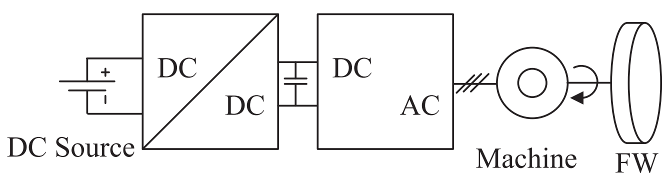

Fig. 6. DC-DC plus DC-AC configuration.

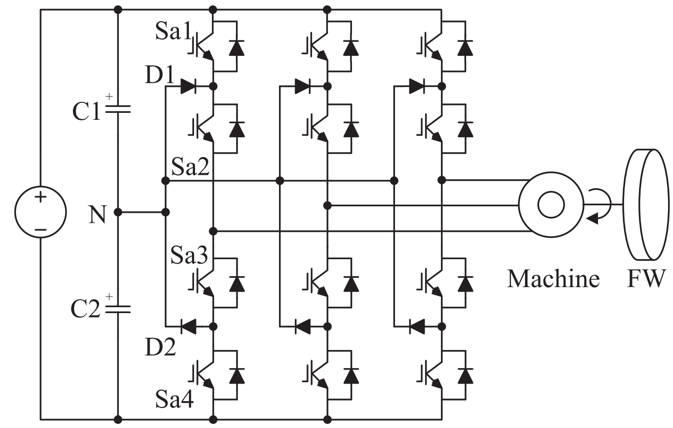

Fig. 7. Three-level NPC converter.

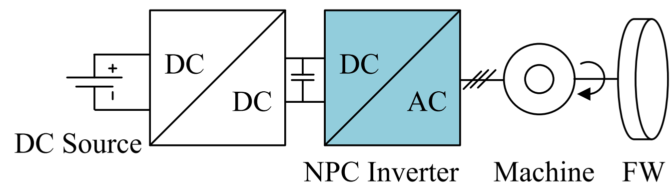

Fig. 8. DC-DC plus NPC.

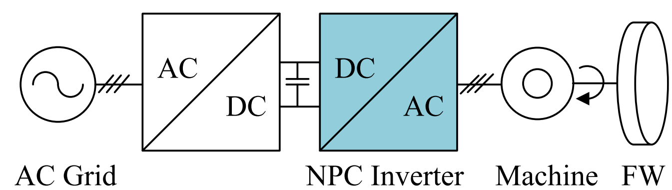

Fig. 9. AC-DC conventional two level converter plus NPC.

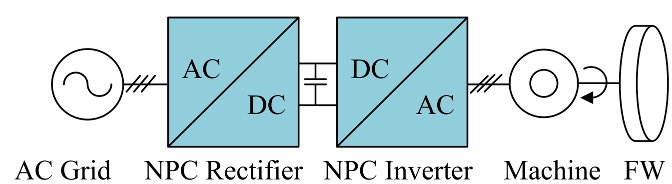

Fig. 10. BTB NPC topology.

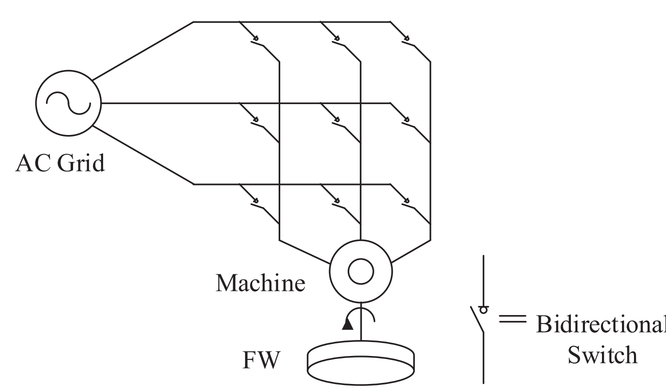

Fig. 11. Direct MC.

capacitor balancing problem is eliminated, the weight and volume of the converter are significantly reduced, and it has a compact structure. This converter firstly has been introduced by Gyugi and Pelly [148]. There are two classical configurations for MCs, direct (Fig. 11) and indirect topologies (Fig. 12). MCs have several disadvantages: output gain is limited in 86.6%, high THD, need to more complex control, and need to high protection system. Z-Source Converter (ZSC) is other option for FESS [50] (Fig. 13). This topology has been introduced in [149] and it is able to produce an output voltage lower or higher than the input voltage. ZSC can be designed with DC-AC, AC-AC, AC-DC, and DC-DC topologies.

3. Fess applications

Currently FESSs are applied in various applications. They are implemented to support very small micro-satellites to very large power network applications. This section reviews FESS in modern and industrial applications as follows:

3.1. Fess in electric vehicle

Automotive industry plays an important role in today's world since the transportation sector consumes one third of the energy

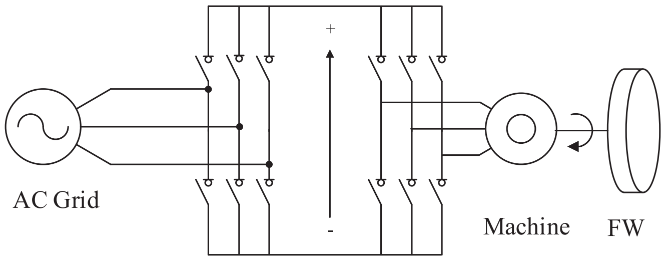

Fig. 12. Indirect MC.

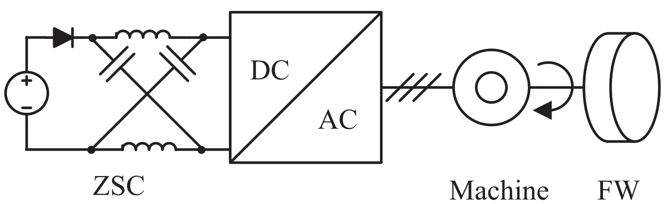

Fig. 13. Z-Source Converter plus DC-AC converter in FESS applications.

in Europe [150]. Furthermore, one quarter of the world's carbon dioxide emissions are caused by the transportation sector [151]. Electric vehicles have a better energy-efficiency than classical gasoline powered ones and helps to the combination of Renewable Energy (RE) for more carbon emission mitigation [152]. Applying a FW for vehicle propulsion is not a new concept. The steam engine has been developed to give better efficiency and power after the years of Industrial Revolution. Large FW has been built for huge engines. Perhaps "Gyrobus" was the most common application for transportation system. Oerlikon built "Gyrobus" [13]. Various FW – based hybrid vehicle concepts came out in the literature since 1970s, where the FW has been used to develop the fuel economy in buses and other passenger vehicles. Furthermore, other applications for FW also have been proposed, such as for cranes, excavators, commuter train, and fork lift trucks [153]. A study of the novel FESS for vehicular applications with magnetic bearings and materials has been performed at the University of Austin, Texas in 1999 [154,155]. Concepts for boosting performance have been presented for passenger vehicles and racing cars since 2000s, thus high-speed compact FW (rotating at 64,000 rpm) has been used in formula one race cars. This technology called Kinetic Energy Recovery System (KERS). The most disadvantage of the FW is adding a high weight (25 kg) to the system. The FESS can mainly serve three functions in the vehicle: 1) regenerative braking 2) load-averaging and 3) prime mover/prime energy source. The third one only proposes a theoretical probability that has not been reached yet based on the limitation of energy density of FWs so far [150]. Hybrid vehicles are described as having more than one power source. The most convenient hybrid configurations contain a primary power source, like an internal combustion engine (ICE), coupled to an energy storage device. In hybrid vehicles, FESS might be connected to mechanical transmissions for braking energy restoration and the provision of extra power due to acceleration. The size of FW and depth-of-discharge must be selected for a specific application, and it has a direct impact on transmission efficiency. During acceleration in automotive vehicles, FESS with mechanical transmissions let power argumentation and regenerative braking, although new method of analysis and optimization for mechanical FW systems has been proposed in [156]. Modern FWs manufactured from composite materials have been indicated to combine high specific power and specific energy, making them applicable for automotive regenerative braking applications and the common charging period is the order of 10 s [154,157,158]. More flexible power train operations can be allowed by FW with electrical transmissions. Direct continuously variable transmissions or power split continuously variable transmissions for FW application have been investigated in [159–166]. In these studies, the size of FW and depth-of-discharge have been assigned fixed values. A 100 kW FESS due to vector control technique for hybrid bus has been developed in [53]. The peaking vehicle control strategy used in this study is suitable for the transit bus and this strategy will keep a high state of charge (SOC) of the FW all the times and high performance of the bus is guaranteed [167,168]. The design and optimization of a high-speed FESS for utility vehicles in urban traffic FW was replaced between a low power (LP) DC/DC converter and a high power (HP) BTB converter in which LP side converter provided constant power by battery for FW and HP side converter provided acceleration and breaking energy [58]. For parallel hybrid electric vehicle, the stability of an idle speed control (ISC) loop is investigated, and the ISC loop considered in this paper has been successfully applied on an industrial standard electronic control units in [169]. Berkel et al. [170] have proposed a dynamic simulation scheme for a mechanical hybrid powertrain that supports three hybrid functionalities to mitigate fuel consumption: 1) efficient operation of the engine, 2) recuperation of brake energy for later use and 3) engine shut off during vehicle standstill. The results reveal that, with optimal control of the mechanical hybrid powertrain and in spite of the relatively low energy storage capacity of the FW, significantly high fuel storing of between 18% and 35% can be achieved due to the selected driving cycle. Same author et al. [171] have introduced the scheme of a real-time executable energy controller for a mechanical hybrid powertrain with FW which is based on optimal control. Dragicevic et al. [172] have investigated the design of a fast DC charging station (FCS) for hybrid electric vehicles (HEVs) which was coupled to at a remote location. Power rating of this recent technology can increase to a 100 kW and it showed an important challenge in distribution systems for its board acceptance. A power balancing strategy due to a local ESS has been represented in this study. Low speed FW has been chosen as a means of storing energy because it presents high power density. Decentralized supervisory control was done in this paper. For grid and FW interface, this study represents references for inner current loops of active converters. This paper also represented two control strategies for counter balancing the adverse effect of HEV FCS on electric utility. Same author et al. [142] have proposed a power balancing strategy for the FCS applying a novel Distributed Bus Signaling (DBS) control method that is based on a low-speed FESS. The proposed strategy was developed in detail for charging just one HEV, but it can be simply developed to support a number of HEVs. A new method of analysis and optimization for mechanical FW systems has been proposed in [156]. Electric braking operations indicated that the motor produces electromagnetic torque that works against the rotor direction. There are basically three types of electric braking manners: dynamic braking, regenerative braking, and plug braking. Regenerative braking is widely applied in the energy storage FWs and electric vehicles [34,173]. For attitude control FW with small inductance BLDCM, an accurate braking torque control method has been proposed in [174]. In this paper first, precise torque estimation has been achieved due to the torque coefficient estimation whose harmonic information has been fitted by neutral network and corrected by temperature. Secondly, a hybrid braking torque control structure which integrated plug braking and dynamic braking has been represented to achieve smooth and continuous torque. Thirdly, the torque fluctuation which is induced by supplying voltage descent, during dynamic braking has been suppressed by suggestive predictive braking torque control scheme. Forth, the large braking torque ripple induced by low winding impedance, high winding voltage, and three phase inverter modulation during plug braking has been mitigated by digitized low-pass filter and the proposed noncommutation phase current circulatory sampling. Furthermore, for each braking mode, various PWM modulation patterns and the most applicable operating conditions have been investigated. Finally, the superiority and the validity of the suggestive braking torque control method have been verified by experimental consequences on the BLDCM that is applied in attitude control FW.

3.2. Fess in railway

In order to improve the quality of railway [175], as well as reuse the regenerating energy, FESS is a good choice. FW systems are still in development for energy saving of light weight railway vehicles nowadays. Burch noted that a 44 t FW storing 34 kW h was installed on the Torino-Modane mountain railway [13] in 1911, and in 1988, FW was located in the Keihin Electric Express Railway at Zushi post in Japan to store regenerating energy. This system is currently working [46,176]. In some countries the main part of the commuter trains applies electrical energy for propulsion and it is provided by overhead wire. The FESS is suitable for a train energy management with a diesel generator set for electricity supply in place of an overhead wire. This system is technically more complicated than overhead wire for braking energy recovery [153]. An explanation of how the system was installed to London Underground's Piccadilly line for a train application and was represented some of the information from these tests. Also in New York the 1Mw FW installation at the Far Rockaway line was the first installation of its kind in the world studied [177]. The first railway hybrid locomotive applied on rails was “New Energy Train”. The Japanese company JR-EAST has built this suburb train [178]. “Rail Power” is the first builder Canadian company which produces hybrid locomotives assembling diesel in an industrial way and accumulator batteries is produced in this company [179]. In addition, FWs were set on the roof of trams for catenary free operation in Rotterdam, the Netherland also for catenary free operation, FWs were installed on the roof of trams [180]. The project “ACE2″ in 2003 and “SA2VE” in 2006 both were launched with the joint purpose of power consumption levelling and recovering braking energy [181]. Adding the energy storage to a high-speed rail locomotive contain the following advantages [182]: 1) better acceleration at high-speeds, 2) reduced trip time, 3) reduced weight based on reduced prime mover power rating, 4) developed fuel efficiency, 5) reduced rail board cost based on reduced weight. A power management system for high-speed rail locomotives with FESS is represented [182]. The reuse of regenerative energy from vehicle braking is the important benefit of using energy storage in electrical railways. Furthermore it can increase electrical railway energy efficiency. In contrast to the common heat by friction braking system, regenerative brake decelerates the train by changing its kinetic energy into electricity and it can be fed back to the power grid in a short time or stored until required [183]. This can be implemented in different ways by the use of electromechanical, elastic, kinetic, hydraulic, and pneumatic accumulators. Pneumatic ESSs took seldom in consideration for vehicular application based on their low energy density and efficiency [13,46]. Moreover when the prime mover is providing more power than is required to maintain the preferred speed down the track. While the train is in the station, this additional energy can be charged in FW [182]. The needed power level of novel commercial electric railway like the 100 Kw FESS from Urenco installed in Paris subway could not achieve by FESS with a single FW unit [177]. Therefore suitable designed FW unit into standard module and coupling these modules in parallel, the FW array energy storage system (FAESS) can be improved to obtain higher energy and power whilst keeping the cost at an acceptable level [183]. In German electric railway system FESs had been used and a large number of cost saving has been obtained in [184]. A developed locomotive propulsion system has been reported in [185]. FW can provide 2 MW energy density during 3 s. An Auxiliary Resonant Commutated Pole Inverter topology is used to enable high frequency switching with acceptable losses. This technique provides zero voltage and zero-current switching in the main and auxiliary power leg and has been indicated to effectively lower switching losses in higher power bus converters and power motor drive. The development of efficiency of DC power supplied railway with applying FESS has been reported in [186], in this paper FESS can save the regenerated energy during braking in place of heat; then this saved energy can be applied to compensate system disturbances and imbalance periods. A 100 kW h superconducting FESS has been applied to mitigate the peak power of the electric railway system in [184] furthermore, economic advantages had been estimated. Currently Alstom Transport and Williams grope [187] came to an agreement to improve the FW systems called “William Hybrid Power FW” to fit on Alstom Citadis trams in [188]. Due to reported Kinetic Traction System (KTSi) (pentadyne prior to 2010) specifies 10 million cycles with a Round-Trip Efficiency of 83% and an expected service life of 20 years. Thus the considered cost of FESS is about US$1 million 1 MW [189].

3.3. Fess in wind power system

FESS can be respected as the best alternative for wind power according to its quick response and good dynamics [44]. In 1931 Ufimtsev, made a wind power plant using FW. Davies et al. and Infild et al. studied kinds of FES in wind-diesel system [190]. An adaptable speed generator can control not only its reactive power output but also its active power output quickly and independently, thus if the FW system is installed in wind farm, the reduction of the variations of both grid voltage and output of wind farm is practical [191]. The first FES plant of the Beacon power corporation has been installed in 2011 in Stephenton, New York with a 20 MW capacity in [192]. The isolated power system contain of main power supply, a wind farm and a consumer load. The FESS was installed near the wind farm. A modeling of power flows into a power station has been proposed in [147], this one was based on a variable speed wind generator connected to a FESS. A three level NPC converter was applied for the grid connection. FESS based on a squirrel-cage induction machine (SCIM) driven by a two level PWM AC/DC converter and system with and without FESS has been studied. The control method and the energetic performances of a low-speed FESS with a classical SCIM with experimental results to improve the quality of the electric power delivered by the wind generator have been investigated in [28]. The electrical part of the FW drive has been mainly examined in [193]. A FESS has been used for an isolated power system with a wind farm to improve the network frequency quality in [194]. The dynamic performance of a Distribution Static Synchronous Compensator (DSTATCOM) controller connected to FESS for improving the integration of a multilevel control technique and wind generators (WGs) into a power system has been presented in [195]. In [196] two kinds of methods were exposed, including flux-oriented controlled and Direct Torque Control (DTC) for an induction machine-based FESS coupled to a variable speed wind generator, that simulation and experimental results showed that DTC is a better option for this kind of application. A control design using a FESS to simultaneously achieve dynamic-stability improvement and power fluctuation reduction of a marine-current farm and offshore wind farm coupled to a power grid has been studied in [66]. A development of a multilevel control of DSTATCOM/FESS has been represented and each part of the control was in detail in [197]. Evaluation of the active power control of a FESS connected to a DSTATCOM controller has been presented in [59]. From the obtained results, it can be understood that the developed control algorithm works properly. The active power fluctuations from a WG are effectively compensated with DSTATCOM/FESS device. The improved system (DSTATCOM/FESS + WG) produces a smoother power response than a system without DSTATCOM/FESS, and the smoothing effect of the output power enhances with the number of FWs. finally it is deduced that the active power control represented for DSTATCOM/FESS obtains a very good management of the stored energy since the wind-power fluctuation are improved with the stored device never being overload or discharged. The electromechanical interactions in a FW system integrated a DFIG has been analyzed in [72]. This study is the advantage of reducing the converted size without important enhancing a moment of inertia of the FW that operates in a more limited speed range. When the system is applied for power smoothing or frequency response control for a wind farm with grid connection, it is risky that in the generating mode, negative damping in the shaft torsional vibration are produced by the machine. By coordinating the design of the mechanical shaft and the electrical machine controller, resonance should and can be avoided. Thus this study explained a control strategy, based on which a frequency-domain model is installed for prediction of the dynamic behavior of the FW shaft system. This model can be applied to the design of the electromechanical device. In which the FW system was a 5 MW 150 MJ. The control technique had two control modes for reactive power, voltage control, and power factor correction and one control mode for active power. The experimental validation and the design in scale-lab test benches for an energy management algorithm due to feedback control methods for a FESS device has been discussed in [54]. The objective of the FW was smoothing the net power that was injected to the grid by a wind turbine or by a wind power plant. Experimental results indicate that the quick wind power fluctuations could be mainly compensated through the FW support. To charge/discharge FW system with DFIG, a power control strategy has been proposed in [198]. The suggestive controller prevented over loading both the rotor BTB converter and stator winding. That is according to conventional vector control in which an artificial neural network was applied to improve the required rotor current component due to the FW instantaneous speed and the required grid power level. This technique has been represented for frequency support and power leveling to develop the quality of the electric power delivered by wind generator. For effective and proper management of the stored energy in a low capacity FESS that is applied to reduce the output power fluctuation of an aggregated wind farm, a supervisory control unit (SCU) mixed with short-time a head wind speed prediction has been proposed [199], in which the wind speed prediction design was improved by artificial neural network (ANN) that had benefits over the conventional prediction designs. The represented SCU-based control would help to mitigate the size of the ESS to minimize wind power fluctuation. For the energy-fed voltage source converter HVDC transmission systems during various AC side faults based on FESS, a backup power balancing technique has been presented in [200]. The represented technique aimed to avoid the DC link voltage rise during faults which mitigated the voltage and current stresses on the switching devices. An induction machine (IM) based FESS was coupled in parallel to the onshore side converter; thus during AC faults, the trapped energy in the DC link could be stored in the FW. During ordinary conditions, the FESS was ordinarily used for power leveling.

3.4. Fess in hybrid power generation system

Currently hybrid power generation extended widely [201,202] and use of the FESS can be improved the system. To realize high quality natural energy power generation system regarding wind power, energy capacity of FES availability and equipment factor of micro gas turbine generator, a method of electric power compensation for wind power generation applying biomass gas turbine generator and FW has been represented in [203]. For energy storage in the photovoltaic (PV) power system, FESS was applied and DC bus voltage can be settled by controlling of it. In this system, PV power source is connected to DC bus by one-way boost converter, and FW was coupled using bidirectional DC/DC converter. Moreover, there were DC loads on the bus linked by buck converter. DC bus was connected to the AC system by the bidirectional DC/AC converter. Besides corresponding control strategies and five different system operating modes have been proposed in [204]. To develop the integration of wind turbines into grid-interactive AC microgrides, a control aspects of FESS has been presented in [57]. Where three control modes were applied: frequency control, voltage control, active power stabilization. An integrated microgrid lab system with a reliable and flexible multi microgrid structure that is able to operate under fault and transition events has been reported in [205]. It consisted ESS and multiple distributed generation system and integrates with a diesel generator which serves as a backup power source and FES for quick balancing to supply uninterruptible power supply (UPS) services in participation with the diesel generator. A new converter and control scheme for FESS, for the preparation of grid frequency regulation and energy balancing in a smart grid contain of wind generators, and typical thermal units and PVs has been proposed in [206]. This scheme developed the system frequency response to disturbances. In a nonlinear and stochastic model of a microgrid (including: solar PV, wind turbine generator, FESS, battery ESS, fuel cells, and diesel energy generator), the use of fractional order controller has been revealed for suppressing the system frequency deviation in [207]. Simulation results indicated that under nominal operating condition, the fractional order proportional integral derivative controller is better than the standard PID controller and for large parametric uncertainty of the microgrid, better robustness was given. A universal supervisory strategy for a microgrid power generation system which contained wind and PV generation subsystems, an ESS, and domestic loads linked both to the hybrid power generators and to the grid, is investigated [208].

3.5. Fess in power network

FWs have illustrated potential as an energy storage device for many applications like power leveling, grid frequency support/control, and voltage sag mitigation based on their fast recharge time and high power density in contrast to other technologies [72]. For about 20 years, it has been a basic technology applied to limit power interruption in motor/generator [41]. If there is a significant change in the load on the generator in distributed generation (DG) network such as when a large motor turn on, the voltage will sag and it can lead to destroy power quality. Besides, adding FESS to a DG system can remove this problem. One of the basic commercial applications of FW in association with active filtering to develop frequency distortion on a high voltage power system line has been detailed in [209]. Dynamic voltage compensation on distribution feeders using FES has been investigated in [210]. A design of FESS for distribution network has been studied in [211]. Two applications of FW systems are as an UPS and for voltage support. These applications are described to support critical loads. The voltage compensation can be by series injection using series transformers, or from the shunt injection of power [30]. A design of FESS in power network has been represented in [212]. The strategy and control methods of the FESS for power quality were described in detail, and a new rapid technique to calculate the amplitude of sinusoidal current and voltage has been proposed that could develop the performance of the FESS. To increase transfer capability of power systems and develop transient stability, a self-organizing fuzzy neural network controller for FESS has been clarified in [213]. For the speed sensorless power leveling system, a fuzzy-logic-base V/F control of the IM has been represented [68]. Just two sensors containing one DC current sensor and one DC voltage sensor were used. The FW consist of two modes, specifically, the power control mode and the speed picking-up control mode. In the speed picking-up control mode, the rotating speed of the FW was detected based on DC link average of an inverter by regulating the output voltage and the output frequency according to fuzzy logic control. The power control mode contain of the inner current loop and the outer voltage loop. A power conditioning system consisting of an AC/AC matrix converter with FES was applied to cope with grid voltage sag problem. Suggested solution lead to increased system reliability and higher power density [55,214]. The new kinds of storage were applied for grid support and the methods they were integrated into the grid have been discussed in [215]. To store energy in rural Africa the design, modeling, and testing of a low-cost FW has been proposed in [216]. In which FW system could store 77 W h, which presents 25% of the intended energy requirement. Compare to lead acid batteries, a cost saving of 35% per kW h with rural system would be let when integrating the FW system into solar home systems. A control, modeling and experimental validation of a FESS device (3000 rpm) for microgrids have been presented in [217]. To dispatch regulation service between fast and slow power regulating resources applying a FESS and a traditional power generator, a novel coordinating algorithm has been introduced in [218]. The objective was to let the FW follow the quick changes in the regulation signals and allow the traditional generator compensate for the energy imbalance as the FW storage approximately fully charged or discharged. Therefor the FW compensates for the inaccuracies induced by the dead zone, response delay, and deviation features of the combined cycle unit (CCU) or hydro power plant (HPP). The application of the FES could be tuned to considerably mitigate the regulation adjustment of CCU or HPP. Less than an adjustment per hour was required for the CCU or HPP, that means the wear and tear on the CCU or HPP was no greater than arranging energy service. Furthermore, the FW will help to maintain the HPP output close to the most efficient operating point. The application of the active disturbance rejection control technique to develop the performance of FESS when it was designed for the DC microgrid applications has been represented in [78]. Otherwise, simulation and experimental results indicated that the new controller was more adaptive and more robust. It has a higher dynamic performance and a better anti-disturbance capability than the traditional PI controller. It includes a bidirectional buck-boost converter a three phase full bridge circuit.

3.6. Fess in marine

FW were used in Egypt in the 15th century BCE in ship [13]. Ship network is very different from land-grid, because ship operates in a variety of operating conditions. The ship network power quality changes frequently in a wide range [219]. On the electric propulsion ship, novel high power pulse electrical equipment may induce voltage fall, this is a critical problem. To solve this problem, an acceptable solution is to adopt energy storage technology [220]. There are different potential application for a FESS to promote future shipboard integrated power systems such as electric or dark start capability, single-generator operation, uninterrupted power to essential loads, pulse power load/systems, and bulk storage [221]. For voltage sag correction, a FESS based static series compensator in ship network has been modeled and simulated in [31]. Considering the control the IM connect with low-speed FW, indirect field oriented control with space-vector pulse and with modulation (SVPWM) is used. Sinusoidal PWM is applied to control the power system side converter. The effect of pulse loads on electrical system in a ship has been investigated with and without FESS [222], in which a simplified electric ship model including: the maim generator, generic pulse load, propulsion module, and FESS has expanded. Thus two schemes of the pulse load operation, with and without FESS have been investigated by monitoring main parameters like main generator, the angular speed of the FW and the propulsion motor. The bus voltage and system current have also been investigated. It was revealed that the FESS functions as a buffer between pulse load and the other parts of the power system, Such that the generator and propulsion motor are almost unaffected by the pulse load firing while the FESS is online. The FESS model was testified by comparing the energy used by the FW and to that taken by the pulse load. The idea of regenerating energy management for pulse load consisting of DC and AC loads, which need DC and AC power distribution systems, has been studied in [223], and it is shown that to regulate the voltage of a DC distribution system in the presence of pulse loads FW and prime-movers can be used in an electric ship that improves the stability of the overall system.

3.7. Fess in space

In the past, FW did not actually attract attentions for energy storage in earth satellites since they were heavy and their bearings would wear out. Moreover, recent developments are making FW practical for energy storage in satellites [224]. Perhaps the first idea of FESS in space applications is the study by Rose [225]. When Integrated Power and Attitude Control System (IPACS) have been introduced for satellites in 1970s for the first time [226,227]. In 1974, NASA report illustrated the result of a valuation of the IPACS concept [226]. NASA represented the IPACS studies [228]. For same time, spacecraft attitude control applying angular momentum wheels has been traditionally in existence [229]. An integration of these two connected concepts into the dual function of providing both attitude control and electrical power of space application applying FW has also been examined in [230,231]. A contrast between NiH2 battery and FW system for the EOS-AMI type spacecraft has illustrated that FW would be much smaller and lighter: 55% in volume reduction, 35% in mass reduction, and 6.7% in solar array area reduction [232]. For small satellites, an end to end energy momentum control system concept has been shown based upon high temperature superconductor (HTS) FW technology [233]. This integrated architecture represents attitude control and a voltage regulate spacecraft power bus. Lee et al. [173] have investigated attitude control system and an energy storage for micro-electromechanical system in spacecraft applying a high temperature superconductor magnet bearing system. Also same author et al. [234] have represented the improvement of an attitude control of three axis stabilized nano satellites, and an integrated micro high-temperature superconductor system for energy storage. The micro-HTS system including a FW/rotor, motor electronics, a cooling system, and motor/generator. The FW/rotor has been manufactured by using sintered NdFeB. A torque based FW control law for an IPACS applying singular value decomposition (SVD) has been represented in [235]. Additionally simultaneously energy storage and attitude control, a scheme for energy storage power applying kinetic energy feedback is represented in this paper to keep system energy balance. Adjustment of the optimal energy system FW power module technology to energy storage for electromagnetic aircraft launch system applications has been detailed in [236]. A new control algorithm for the discharge and charge modes of operation of FESS in space applications has been illustrated in [61]. The motor control portion of the algorithm applies sensorless field oriented control with position and speed estimates determined from a signal injection technique at low speeds and a back electromotive force technique at higher speed. The relationship between AMBs and SMBs originally and theoretically for the goal of energy storage and attitude control in spacecraft by FESS is presented [237]. Satellites usually possess four or motor-FW sets, each oriented along a separate rotational axis. Taking the smallest angle path usually limits a satellite to use only a few of its FWs. Therefore in order to perform a turn faster and avoid over burdening its motors, the satellite should take an alternate path. The longer path allows spacecraft make optimum use of all its FWs instantly while it may be less direct, generating more torque [238]. A sliding mode control of reaction FW-based BLDCM with buck converter for space applications has been presented in [73]. Therefore this paper reviewed the control approaches and modeling of DC/DC converters.

3.8. Other applications

Other applications of the FW can be mentioned as follows: for example, to store cold thermal energy as much as kinetic energy in the FESS an innovative concept has been proposed in [23] to mitigate required cooling energy in the time of energy storage period. Also for mobility loads and pulsed load leveling in a tactical vehicle, the University of Texas at Austin Center has designed and organized component test/development for a FESS [239,240]. Furthermore, FW was applied as energy source for the linear induction launcher [241–243]. Two types of pulse power supplies, a 100 MV A/100 MJ FW pulse generator and a capacitor bank were reported in [244]. To energize the short pulse magnets, the capacitor bank was applied and for the long pulse magnet, the pulse generator was applied to provide a 50 T flat-top pulse for 100 ms. Moreover a Gyroscopically stabilized robot has represented in [245]. The spinning FW functions as a gyroscope to stabilize the robot. And a prototype of miniature FESS has been designed and the dynamic of the system has been analyzed in [246].

4. Conclusion/future trends

This paper has been represented a comprehensive review of FESS in different applications which were lately attractive in researches and industries. Also PEIs, bearings, and machines in FESS have been concisely reviewed. Then their advantages and disadvantages have been discussed in brief, and their capabilities and limitations were mentioned as well.

Recently high speed FESS is required in various applications such as space applications. The available FESSs have the maximum speed of 100,000 rpm. To increase the speed of FESS in future, using the ultra-high speed machines (upper than 100,000 rpm) such as IM (e.g. 120,000 rpm [51]), and PMSM (e.g. 1,000,000 rpm [51]) are proposed. The high-speed bearingless machines are another options.

Multiphase machines are another attractive options for future study in FESS [247], and multilevel PEIs can be appropriate choice to drive it [248].

Progress in the advanced technology of manufacturing semiconductor and using multilevel converters has increased the FESS power significantly. NPC multilevel converter is a more appropriate option for FESS, compare to other multilevel converters. To date all NPCs that have been applied in FESS are conventional type [146]. And they have several disadvantages, and to overcome these disadvantages, new topologies including: Active NPC (ANPC), Stacked NPC (SNPC), Active Stacked NPC (ASNPC) can be good choices for future work.

One of the main disadvantages of the conventional MC is output gain that is limited to 86.6%, in order to overcome this problem, new topologies have been introduced in [249]. These topologies can increased output gain up to 1, therefore these topologies can be used in future studies for FESS.

ZSC has two main disadvantages such as more complexity and more passive components, to overcome these problems, quasi-Z Source Converter (qZSC) can be used [50]. And this topology is another choice for future investigations in FESSs. Also, multilevel ZSC (three and five levels [50]) and qZSC topologies can be studied in this field.

References

[1] Facts and figures. Electricity Storage Association; 2014.
[2] Rehman S, Al-Hadhrami Luai M, Alam Md Mahbub. Pumped hydroenergy storage system: a technological review. Renew Sustain Energy Rev 2015;44:586–98.
[3] Satkin M, Noorollahi Y, Abbaspour M, Yousefi H. Multi-criteria site selection model for wind-compressed air energy storage power plants in Iran. Renew Sustain Energy Rev 2014;32:579–90.
[4] Mousavi G. SM, Nikdel M. Various battery models for various simulation studies and applications. Renew Sustain Energy Rev 2014:477–85.
[5] Lifshitz D, Weiss G. Optimal control of a capacitor-type energy storage system. IEEE Trans Auto Control 2015;60(1):216–20.
[6] De D, Klumpner C, Patel C, Ponggorn K, Rashed M, Asher G. Modelling and control of a multi-stage interleaved dc–dc converter with coupled inductors for super-capacitor energy storage system. IET Power Electron 2013;6 (7):1360–75.
[7] Xun Jin J, Yuan Chen X, Qu R, Xin Y. A superconducting magnetic energy exchange model based on circuit-field-superconductor coupled method. IEEE Trans Appl Supercond 2015;25(3).
[8] Li G. Energy and exergy performance assessments for latent heat thermal energy storage systems. Renew Sustain Energy Rev 2015;51:926–54.
[9] Karellas S, Tzouganatos N. Comparison of the performance of compressed-air and hydrogen energy storage systems: karpathos island case study. Renew Sustain Energy Rev 2014;29:865–82.
[10] Bitterly JG. Flywheel technology: past, present and 21th century projections. IEEE AES Syst Mag 1998;13(8):13–6.
[11] Strzelecki R, Benysek G. Power electronics in smart electrical energy networks.London: Springer Press; 2008.
[12] Yogi-Goswami D, Kreith F. Energy conversion.Boca Raton, FL, USA: CRC Press; 2007.
[13] Genta G. Kinetic energy storage: theory and practice of advanced flywheel systems. Butterworth and Co. Ltd; 1985.
[14] Hull JR. Flywheels on a roll. IEEE Spectr 1997;34(7):20–5.
[15] Stodola A. Steam and gas turbines. McGraw-Hill, Inc; 1927.
[16] Epri Doe. Handbook of energy storage for transmission and distribution applications. Final Report. Cosponsor, U. S. Department of Energy; December 2003.
[17] Hebner R, Beno J, Walls A. Flywheel batteries come around again. IEEE Spectr 2002;39(4):46–51.
[18] Vazquez S, Lukic SM, Galvan E, Franquelo LG, Carrasco JM. Energy storage systems for transport and grid applications. IEEE Trans Ind Electron 2010;57 (12):3881–95.
[19] Kameno H, Miyagawa Y, Takahata R, Ueyama H. A measurement of rotation loss characteristics of high-Tc superconducting magnetic bearings and active magnetic bearings. IEEE Trans Appl Supercond 1999;9(2).
[20] Lee JP, Jeong NH, Han YH, Han SC, Jung S, Park BJ, et al. Assessment of the energy loss for SFES with rotational core type PMSM/G. IEEE Trans Appl Supercond 2009;19(3):2087–90.
[21] Lee JP, Han SC, Han YH, Sung TH. Loss characteristics of SFES with amorphous core for PMSM. IEEE Trans Appl Supercond 2011;21(3):1489–92.
[22] Lee JP, Park BJ, Han YH, Jung S, Sung TH. Energy loss by drag force of superconductor flywheel energy storage system with permanent magnet rotor. IEEE Trans Magn. vol. 44(11). 2008. p. 4397–400.
[23] Lee J, Jeong S, Han YH, Park BJ. Concept of cold energy storage for superconducting flywheel energy storage system. IEEE Trans Appl Supercond 2011;21(3):2221–4.
[24] Arghandeh R, Pipattanasomporn M, Rahman S. Flywheel energy storage systems for ride-through applications in a facility microgrid. IEEE Trans Smart Grid 2012.
[25] Bolund B, Bernhoff H, Leijon M. Flywheel energy and power storage systems. Renew Sustain Energy Rev 2007:235–58.
[26] Sears JR. TEX: the next generation of energy storage technology. In: Proceedings of the power systems world 2004 conference. Nov. 16–18, 2004.
[27] Cardenas R, Pena R, Perez M, Clare J, Asher G, Wheeler P. Power smoothing using a flywheel driven by a switched reluctance machine. IEEE Trans Ind Electron 2006;53(4):1086–93.
[28] 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. IEEE Trans Ind Electron 2006;53(4):1074–85.
[29] Akagi H, Sato H. Control and performance of a doubly-fed induction machine intended for a flywheel energy storage system. IEEE Trans Power Electron 2002;17(1):109–16.

[30] Weissbach RS, Karady GG, Farmer RG. A combined uninterruptible power supply and dynamic voltage compensator using a flywheel energy storage system. IEEE Trans Power Del 2001;16(2):265–70.
[31] Samineni S, Johnson BK, Hess HL, Law JD. Modeling and analysis of a flywheel energy storage system for voltage sag correction. IEEE Trans Ind Appl 2006;42(1):42–52.
[32] Cardenas R, Pena R, Perez M, Clare J, Asher G, Wheeler P. Power smoothing using a switched reluctance machine driving a flywheel. IEEE Trans Energy Convers 2006;21(1):294–5.
[33] Darrelmann H. Comparison of high-power short-term flywheel storage systems. In: Proceedings of the presented at the 21st international telecommunication energy conference. Copenhagen, Denmark; Jun. 1999. Paper 30-2.
[34] Anderade RD, Sotelo GG, Ferreira AC, Rolim LGB, de Silva Neto JL, Stephan RM, et al. Flywheel energy storage system description and tests. IEEE Trans Appl Supercond 2007:2154–7.
[35] Beacon Power. Available at: ⟨www.beaconpower.com⟩.
[36] Barton JP, Infield DG. Energy storage and its use with intermittent renewable energy. IEEE Trans Energy Convers 2004;19(2):441–8.
[37] Emadi A, Nasiri A, Bekiarov SB. Uninterruptible power supplies and active filter. CRC Press; 2005.
[38] Liu H, Jiang J. Flywheel energy storage—an upswing technology for energy sustainability. Energy Build 2007;39(5):599–604.
[39] Zhang C, Tseng KJ. A novel flywheel energy storage system with partially-self-bearing flywheel-rotor. IEEE Trans Energy Conv 2007;22(2):477–87.
[40] Babuska V, Beatty SM, BonkBJ, Fausz JL. A review of technology developments in flywheel attitude control and energy transmission systems. In: Proceedings of the IEEE aerospace, conference; 2004. p. 2784–800.
[41] Carrasco JM, Franquelo LG, Bialasiewicz JT, Galvan E, Guisado RCP, Parts MAM, et al. Power-electronic systems for the grid integration of renewable energy sources: a survey. IEEE Trans Ind Electron 2006;53(4):1002–16.
[42] Lukic SM, Cao J, Bansal RC, Rodriguez F, Emadi A. Energy storage systems for automotive applications. IEEE Trans Ind Electron 2008;55(6):2258–67.
[43] Ren G, Ma G, Cong N. Review of electrical energy storage system for vehicular applications. Renew Sustain Energy Rev 2015:225–36.
[44] Daoud M ohamad I, Abdol-Khalik AS, Massoud A, Ahmed S, Abbasy Nabbil H. On the development of flywheel storage systems for power system applications: a survey. IEEE Int Conf Electr Mag (ICEM) 2012:2119–25.
[45] Akinyele DO, Rayudu RK. Review of energy storage technologies for sustainable power networks. Sustain Energy Technol Assess 2014:74–91.
[46] Ratniyomchai T, Hillmansen S, Tricoli P. Recent developments and applications of energy storage devices in electrified railways. IET Electr Syst Transp 2014;4(1):9–20.
[47] Sebastian R, Alzola R Pena. Flywheel energy storage systems: Review and simulation for an isolated wind power system. Renew Sustain Energy Rev 2012:6803–13.
[48] Pena Alzola R, Sebastian R, Quesada J, Colmenar A. Review of flywheel based energy storage systems. In: Proceedings of the IEEE power engineering, energy and electrical drives, Conference. 2011.
[49] Nguyen TD, Tseng KT, Zhang S, Nguyen HT. A novel axial flux permanent-magnet machine for flywheel energy storage system: design and analysis. IEEE Trans Ind Electron 2011;58(9):3784–94.
[50] Amodeo SJ, Chiacchiarini HG, Oliva AR. High-performance control of a DC–DC Z-source converter used for an excitation field driver. IEEE Trans Power Electron 2012;27(6):2947–57.
[51] Gerada D, Mebarki A, Brown NL, Gerada C, Cavagnino A, Boglietti A. High-speed electrical machines: technologies, trends, and developments. IEEE Trans Ind Electron 2014;61(6):2946–56.
[52] You DJ, Jang SM, Lee JP, Sung THA. Dynamic performance estimation of high-power FESS using the operating torque of a PM synchronous motor/generator. IEEE Trans Magn 2008;44(11):4155–8.
[53] Lu X, Lakshmi Varaha Iyer K, Mukherjee K, Kar NC. Study of permanent magnet machine based flywheel energy storage system for peaking power series hybrid vehicle control strategy. In: Proceedings of the IEEE Conference. 2013.
[54] Diaz-Gonzalez F, Bianchi FD, Sumper A, Gomis-Bellmunt O. Control of a flywheel energy storage system for power smoothing in wind power plants. IEEE Trans Energy Conv 2014;29(1):204–14.
[55] Wang B, Venkataramanan G. Dynamic voltage restorer utilizing a matrix converter and flywheel energy storage. IEEE Trans Ind Appl 2009;45(1):222–31.
[56] Lee H, Shin BY, Han S, Jung S, Park B, Jang G. Compensation for the power fluctuation of the large scale wind farm using hybrid energy storage applications. IEEE Trans Appl Supercond 2012;22(3).
[57] Suvire GO, Molina MG, Mercado PE. Improving the integration of wind power generation into ac microgrids using flywheel energy storage. IEEE Trans Smart Grid 2012;3(4):1945–54.
[58] Abrahamsson J, Hedlund M, Kamf T, Bernhoff H. High-speed kinetic energy buffer: optimization of composite shell and magnetic bearings. IEEE Trans Ind Electron 2013;60(6).
[59] Suvire GO, Mercado PE. Active power control of a flywheel energy storage system for wind energy applications. IET Renew Power Gen 2012;6:9–16.
[60] Gowaid IA, Elserougi A, Abdel-Khalik AS, Massoud AM, Ahmed S. A novel open-stator-winding DFIM flywheel architecture for renewable energy applications. IEEE Power Eng Energy Electr Drives Conf 2013:222–8.
[61] Kenny BH, Kascak PE, Jansen R, Dever T, Santiago W. Control of a high-speed flywheel system for energy storage in space applications. IEEE Trans Ind Appl. vol. 41(4). July/Aug 2005. p. 1029–39.
[62] Jang SM, You DJ, Ko KJ, Choi SK. Design and experimental evaluation of synchronous machine without iron loss using double-sided halbach magnetized PM rotor in high power FESS. IEEE Trans Magn 2008;44(11):4337–40.
[63] 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. IEEE Trans Ind Electron 2004;51(3):603–14.
[64] Boldea I, Nasar SA. The induction machine design handbook. Third edition. Boca Raton London New York: CRC Press; 2010.
[65] Abdel-Khalik AS, Elserougi AA, Massoud AM, Ahmed S. Fault current contribution of medium voltage inverter and doubly-fed induction-machine-based flywheel energy storage system. IEEE Trans Sust. 2012.
[66] Wang L, Yu JY, Chen YT. Dynamic stability improvement of an integrated offshore wind and marine-current farm using a flywheel energy-storage system. IET Renew Power Gener 2011;5(5):387–96.
[67] Cansiz A, Yildizer I, Oral EA, Kaya Y. An effective noncontact torque mechanism and design considerations for an evershed-type superconducting magnetic bearing system. IEEE Trans Appl Supercond 2014;24(1).
[68] Sun XD, Koh KH, Yu BG, Matsui M. Fuzzy-logic-based V/f control of an induction motor for a DC grid power-leveling system using flywheel energy storage equipment. IEEE Trans Ind Electron 2009;56(8):3161–8.
[69] Alan I, Lipo TA. Induction machine based flywheel energy storage system. IEEE Trans Aerosp Electron Syst 2003;39(1):151–62.
[70] Wu J, Wen J, Sun H. A new energy storage system based on flywheel. IEEE Power Energy Soc Gen Meet 2009.
[71] Hahn Seung-Yong, Kim Woo-Seok, Kim Ji Hoon, Koh Chang-Seop, Hahn Song-Yop. Low speed FES with induction motor and generator. IEEE Trans Appl Supercond 2002;12(1).
[72] Ran L, Xiang D, Kirtley Jr JL. Analysis of electromechanical interactions in a flywheel system with a doubly fed induction machine. IEEE Trans Ind Appl 2011;47(3):1498–506.
[73] Gang L, Cong Z. Sliding mode control of reaction flywheel-based brushless DC motor with buck converter. Chin J Aeronaut 2013:967–75.
[74] Baszynski M, Pirog S. A novel speed measurement method for a high-speed BLDC motor based on the signals from the rotor position sensor. IEEE Trans Ind Inform 2013.
[75] Gurumurthy SR, Agarwal V, Sharma A. Optimal energy harvesting from a high-speed brushless DC generator-based flywheel energy storage system. IET Electr Power Appl 2013;7(9):693–700.
[76] Strasik M, Johnson PE, Day AC, Mittleider J, Higgins MD, Edwards J, et al. Design, fabrication, and test of a 5-kW h/100-kW flywheel energy storage utilizing a high-temperature superconducting bearing. IEEE Trans Appl Supercond 2007;17(2):2133–7.
[77] Subkhan M, Komori M. New concept for flywheel energy storage system using SMB and PMB. IEEE Trans Appl Supercond 2011;21(3):1485–8.
[78] Chang X, Li Y, Zhang W, Wang N, Xue W. Active disturbance rejection control for a flywheel energy storage system. IEEE Ind Electron 2015;62(2):991–1001.
[79] Zou J, Liu K, Hu J, Li J. A modified C-dump converter for BLDC machine used in a flywheel energy storage system. IEEE Trans Magn 2011;47(10):4175–8.
[80] Bist V, Singh B. PFC cuk converter-fed BLDC motor drive. IEEE Trans Power Electron 2015;30(2):871–87.
[81] Lee HW, Kim TH, Ehsani M. Practical control for improving power density and efficiency of the BLDC generator. IEEE Trans Power Electron 2005;20 (1):192–9.
[82] Chau KT, Chan CC, Liu C. Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles. IEEE Trans Ind Electron 2008;55 (6):2246–56.
[83] vaijayakumar K, Karthikeyan R, Paramasivam S. Switched reluctance motor modeling, design, simulation, and analysis: a comprehensive review. IEEE Trans 2008.
[84] Park JD, Kalev C, Hofmann HF. Control of high-speed solid-rotor synchronous reluctance motor/generator for flywheel-based uninterruptible power supplies. IEEE Trans Ind Electron 2008;55(8):3038–46.
[85] Severson E, Nilssen R, Undeland T, Mohan N. Magnetic equivalent circuit modeling of the AC homopolar machine for Flywheel energy storage. IEEE Trans Energy Conv 2015.
[86] Li W, Chau KT, Ching TW, Wang Y, Chen M. Design of a high-speed superconducting bearingless machine for flywheel energy storage systems. IEEE Trans Appl Supercond 2015;25(3).
[87] Severson E, Nilssen R, Undeland T, Mohan N. Outer-rotor AC homopolar motors for flywheel energy storage. IET Conf 2014:1–6.
[88] Duan GR, Wu ZY, Bingham C, Howe D. Robust magnetic bearing control using stabilizing dynamical compensators. IEEE Trans Ind Appl 2000;36 (6):1654–60.
[89] Tsao P, Senesky M, Sanders SR. An integrated flywheel energy storage system with homopolar inductor motor/generator and high-frequency drive. IEEE Trans Ind Appl 2003;39(6):1710–25.
[90] Jiancheng F, Xi W, Tomg W, Enqiong T, Yahong F. Homopolar 2-pole radial permanent-magnet biased magnetic bearing with low rotating loss. IEEE Trans Magn 2012;48(8):2293–303.
[91] Severson E, Nilssen R, Undeland T, Mohan N. Suspension force model for bearingless AC homopolar machines designed for flywheel energy storage. In: Proceedings of the IEEE GCC conference and exhibition. Doha, Qatar; November 17–20, 2013.

[92] Tsao P, Senesky M, Sanders S. A synchronous homopolar machine for high-speed Applications. In: Proceedings of the IEEE conference. 2002.
[93] Davey K, Filatov A, Thompson R. Design and analysis of passive homopolar null flux bearings. IEEE Trans Magn 2005;41(3):1169–75.
[94] Wang Q, Liu C, Zou J, Fu X, Zhang J. Numerical analysis and design optimization of a homopolar inductor machine used for flywheel energy storage. IEEE Trans Plasma Sci 2013;41(5):1290–4.
[95] Brauer HJ, deDoncker RW. Thermal modeling of a high speed SRM for vacuum cleaners. Proc EPE 2011:1–10.
[96] Koch R, Wagner R, Sander M, Gutt HJ. Development and test of a 300 W h/10 kW flywheel energy storage system. Proc Appl Supercond 1999:1055–8.
[97] Sihler C, Miri Amir M. A stabilizer for oscillating torques in synchronous machines. IEEE Trans Ind Appl 2005;41(3):748–55.
[98] Reichert T, Nussbaumer T, Kolar JW. Bearingless 300 W PMSM for bioreactor mixing. IEEE Trans Ind Electron 2012;59(3):1376–88.
[99] Asama J, Hamasaki Y, Oiwa T, Chiba A. Proposal and analysis of a novel single-drive bearingless motor. IEEE Trans Ind Electron 2013;60(1):129–38.
[100] Wang X, Zhong Q, Deng Z, Yue S. Current-controlled multiphase slice permanent magnetic bearingless motors with open-circuited phases: fault-tolerant controllability and its verification. IEEE Trans Ind Electron 2012;59(5):2059–72.
[101] Warberger B, Kaelin R, Nussbaumer T, Kolar JW. 50 N m/2500 W bearingless motor for high-purity pharmaceutical mixing. IEEE Trans Ind Electron 2012;59(5):2236–47.
[102] Li C, Hofmann W. Speed regulation technique of one bearingless 8/6 switched reluctance motor with simpler single winding structure. IEEE Trans Ind Electron 2012;59(6):2592–600.
[103] Schneeberger T, Nussbaumer T, Kolar JW. Magnetically levitated homopolar hollow-shaft motor. IEEE/ASME Trans Mechatron 2010;15(1):97–107.
[104] Grabner H, Amrhein W, Silber S, Gruber W. Nonlinear feedback control of a bearingless brushless DC motor. IEEE/ASME Trans Mechatron 2010;15(1):40–7.
[105] Stephens LS, Dae-Gon K. Force and torque characteristics for a slotless Lorentz self-bearing servomotor. IEEE Trans Magn 2002;38(4):1764–73.
[106] Quang Dich N, Ueno S. Analysis and control of nonsalient permanent magnet axial gap self-bearing motor. IEEE Trans Ind Electron 2011;58(7):2644–52.
[107] Bartholet MT, Nussbaumer T, Kolar JW. Comparison of voltage source inverter topologies for two-phase bearingless slice motors. IEEE Trans Ind Electron 2011;58(5):1921–5.
[108] Rodriguez EF, Santisteban JA. An improved control system for a split winding bearingless induction motor. IEEE Trans Ind Electron 2011;58(8):3401–8.
[109] Nussbaumer T, Karutz P, Zurcher F, Kolar JW. Magnetically levitated slice motors—an overview. IEEE Trans Ind Appl 2011;47(2):754–66.
[110] Recheis MN, Schweighofer B, Fulmek P, Wegleiter H. Selection of magnetic materials for bearingless high-speed mobile flywheel energy storage systems. IEEE Trans Magn 2014;50(4).
[111] Oshima M, Kitazawa S, Chiba A, Fukao T, Dorrell DG. Design and snalyses of a coreless-stator-type bearingless motor/generator for clean energy generation and storage systems. IEEE Trans Magn 2006;42(10):3461–3.
[112] Asami K, Chiba A, Rahman MA, Hoshino T, Nakajima A. Stiffness analysis of a magnetically suspended bearingless motor with permanent magnet passive positioning. IEEE Trans Magn 2005;41(10):3820–2.
[113] Filatov AV, Maslen EH. Passive magnetic bearing for flywheel energy storage systems. IEEE Trans Magn 2001;37(6):3913–24.
[114] Gotanda H, Amano R, Sugiura T. Mode coupling of a flexible rotor supported by a superconducting magnetic bearing due to the nonlinearity of electromagnetic force. IEEE Trans Appl Supercond 2011;21(3):1481–4.
[115] Yanliang X, Yanliangn D, Xiuhe W, Yu K. Analysis of hybrid magnetic bearing with a permanent magnet in the rotor by FEM. IEEE Trans Magn 2006;42(4):1363–6.
[116] Tsiotras P, Wilson BC. Zero- and low-bias control designs for active magnetic bearings. IEEE Trans Cont Syst Technol 2003;11(6):889–904.
[117] Shiraishi R, Demachi K, Uesaka M, Takahata R. Numerical and experimental Analysis of the rotation speed degradation of superconducting magnetic bearings. IEEE Trans Appl Supercond 2003;13(2):2279–82.
[118] Sivrioglu S, Nonami K. Active permanent magnet support for a superconducting magnetic-bearing flywheel rotor. IEEE Trans Appl Supercond 2000;10(4):1673–7.
[119] Lanzon A, Tsiotras P. A combined application of H_∞ loop shaping and μ-synthesis to control high-speed flywheels. IEEE Trans Cont Syst Technol 2005;13(5):766–77.
[120] Tsiotras P, Arcak M. Low-bias control of AMB subject to voltage saturation: state-feedback and observer designs. IEEE Trans Cont Syst Technol 2005;13(2):262–73.
[121] de Andrade, Jr R, Ferreira AC, Sotelo GG, Silva Neto JL, Rolim LGB, Suemitsu WI, et al. Voltage sags compensation using a superconducting flywheel energy storage systems. IEEE Trans Appl Supercond 2005;15:2265–8.
[122] Demachi K, Miura A, Uchimoto T, Miya K. Numerical analysis of rotation loss of superconducting magnetic bearing. IEEE Trans Appl Supercond 2001;11(1):1653–6.
[123] Floegel-Delor U, Rothfeld R, Wippich D, Goebel B, Riedel T, Werfel FN. Fabrication of HTS bearings with ton load performance. IEEE Trans Appl Supercond 2007;17(2):2142–5.
[124] Han YH, Hull JR, Han SC, Jeong NH, Sung TH, No K. Design and characteristics of a superconductor bearing. IEEE Trans Appl Supercond 2005;15(2):2249–52.
[125] Hull JR, Strasik M, Mittleider JA, Gonder JF, Johnson PE, McCrary KE, et al. High rotational-rate rotor with high-temperature superconducting bearings. IEEE Trans Appl Supercond 2009;19(3):2078–82.
[126] Kohari Z, Tihanyi V, Vajda I. Loss evaluation and simulation of superconducting magnetic bearings. IEEE Trans Appl Supercond. vol. 15(2). June 2005. p. 2328–31.
[127] Masaie I, Demachi K, Ichihara T, Uesaka M. Rotational loss modeling in superconducting magnetic bearing. IEEE Trans Appl Supercond 2006;16(2):1807–10.
[128] Jung S, Lee J, Park B, Jeong S, Ko J, Lee J, et al. Double-evaporator thermosiphon for cooling 100 kW h class superconductor flywheel energy storage system bearings. IEEE Trans Appl Supercond 2009;19(3):2103–6.
[129] Vajda I, Kohari Z, Benko L, Meerovich V, Gawalek W. Investigation of joint operation of a superconducting kinetic energy storage (flywheel) and solar cells. IEEE Trans Appl Supercond 2003;13(2):2169–72.
[130] Komori M, Uchimura Y. Improving the dynamics of two types of flywheel energy storage system with SMBs. IEEE Trans Appl Supercond 2005;15(2):2261–4.
[131] Yu Z, Zhang GM, Qiu Q, Hu L, Zhuang B, Qiu M. Analyses and tests of HTS bearing For flywheel energy system. IEEE Trans Appl Supercond 2014;24(3).
[132] Yubisui Y, Kobayashi S, Amano R, Sugiura T. Effects of nonlinearity of magnetic force on passing through a critical speed of a rotor with a superconducting bearing. IEEE Trans Appl Supercond 2013;23(3).
[133] Hull JR, Strasik M, Mittleider J, McIver C, McCrary K, Gonder J, et al. Damping of sub-synchronous whirl in rotors with high-temperature superconducting bearings. IEEE Trans Appl Supercond 2011;21(3):1453–9.
[134] Hull JR. Superconducting bearings. Supercond Sci Technol 2000;13:R1–15.
[135] Sotelo GG, Ferreira AC, de Andrade Jr. R. Halbach array superconducting magnetic bearing for a flywheel energy storage system. IEEE Trans Appl Supercond 2005;15(2):2253–6.
[136] Fang JR, Lin LZ, Yan LG, Xiao LY. A new flywheel energy storage system using hybrid superconducting magnetic bearings. IEEE Trans Appl Supercond 2001;11(1) [1675-1660].
[137] Sung Tae-Hyun, Han Young-Hee, Lee Jun-Sung, Han Sang-Chul, Jeong Nyeon-Ho, Oh Kwang-Seok, et al. Effect of a passive magnetic damper in a flywheel system with a hybrid superconductor bearing set. IEEE Trans Appl Supercond 2003;13(2):2165–8.
[138] Sotelo GG, de Andrade Jr. R, Ferreira AC. Magnetic bearing sets for a flywheel system. IEEE Trans Appl Supercond 2007;17(2):2150–3.
[139] Mitsuda H, Inoue A, Nakaya B, Komori M. Improvement of energy storage flywheel system with SMB and PMB and its performances. IEEE Trans Appl Supercond 2009;19(3):2091–4.
[140] Rashid Muhammad H. Power electronics handbook.Elsevier: Butterworth-Heinemann; 2011.
[141] Akagi H. Large static converters for industry and utility applications. IEEE Proc 2001;89(6):976–83.
[142] Dragičević T, Sučić S, Vasquez JC, Guerrero JM. Flywheel-based distributed bus signalling strategy for the public fast charging station. IEEE Trans Smart Grid 2014;5(6):2825–35.
[143] 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. IEEE Trans Ind Electron 2006;53(4):1074–85.
[144] Kusko A, Dedad J. Stord energy: short-term and long-term energy storage methods for standby electric power systems. IEEE Ind Appl Mag 2007;13(4):66–72.
[145] Awadallah MA, Venkatesh B. Energy storage in flywheels: an overview. Can J Electr Comput Eng 2015;38(2):183–93.
[146] Nabae A, Takahashi I, Akagi H. A new neutral-point-clamped PWM inverter. IEEE Trans Ind Appl 1981;IA-17:518–23.
[147] Bouhali O, François B, Saudemont C, Berkouk EM. Practical power control design of a NPC multilevel inverter for grid connection of a renewable energy plant based on a FESS and a wind generator. In: Proceedings of the 32th annual IEEE ind. electronic conference. 2006. p. 4291–6.
[148] Gyugi L, Pelly B. Static power frequency changers: Ttheory, performance, and applications. John Wiley and Sons. 1976.
[149] Peng FZ. Z-source inverter. IEEE Trans Ind Appl 2003;39(2):504–10.
[150] Buchroithner A, Andrašec I, Bader M. Optimal system design and ideal application of flywheel energy storage systems for vehicles. In: Proceedings of the 2nd IEEE energy on conference & exhibition, 2012/sustainable transportation systems symposym. p. 991–6.
[151] Saber A, Venayagamoorthy G. Plug-in vehicles and renewable energy sources for cost and emission reductions. IEEE Trans Ind Electron 2011;58(4):1229–38.
[152] Li Z, Guo Q, Sun H, Wang Y, Xin S. Emission-concerned wind- EV coordination on the transmission grid side with network constraints: concept and case study. IEEE Trans Smart Grid 2013;4(3):1692–704.
[153] Thoolen F. Development of an advanced high speed flywheel energy storage system [Ph.D. dissertation]. Dept. Mech. Eng., Technische Univ. Eindhoven, Eindhoven, The Netherlands; 1993.
[154] Flynn MM, Zierer JJ, Thompson RC. Performance testing of a vehicular flywheel energy system. In: Proceedings of the SAE world congress & exhibition. 2005.
[155] Hayes R, Kajs J, Thompson R, Beno J. Design and testing of a flywheel battery for a transit bus. Soc. Autom. Eng. SAE, Tech. Rep.. 1999.
[156] Read MG, Smith RA, Pullen KR. Optimisation of flywheel energy storage systems with geared transmission for hybrid vehicles. Mech Mach Theory 2015:191–209.

[157] Shah S. The design and development of a high speed composite flywheel for hybrid vehicles (Ph.D. Thesis). Department of Mechanical Engineering, Imperial College, London; 2006.
[158] Traci Richard M, Acebal R. Integrated thermal management of a hybrid electric vehicle. IEEE Trans Magn 1999;35(1).
[159] Brockbank C. Development of full-toroidal traction drives in flywheel based mechanical hybrids, In: Proceedings of the CVT hybrid international conference (CVT'10). Eindhoven University of Technology, Maastricht, The Netherlands; 2010.
[160] Brockbank C, Body W. Flywheel-based mechanical hybrid system: simulation of the fuel consumption benefits of various transmission arrangements and control strategies. In: Proceedings of the ASME 2010 international design engineering technical conferences & computers & information in Engineering conference. American Society of Mechanical Engineers, Montreal, Canada; 2010.
[161] Bottiglione F, Karbone G, Novellif ND. Mechanical hybrid KERS based on toroidal traction drives: an example of smart tribological design to improve terrestrial vehicle performance. Adv Tribol. 2013.
[162] Beachley NH. Continuously-variable transmission designs for flywheel hybrid automobiles. Proc Int Symp Gearing Power Transm 2013:393–8.
[163] Martinez-Gonzalez P. A study on the integration of a high-speed flywheel as an energy storage device in hybrid vehicles (Ph.D. Thesis). Department of Mechanical Engineering Imperial College, London; 2010.
[164] Bottiglione F, Mantriota G. Effect of the ratio spread of CVU in automotive kinetic energy recovery systems. J Mech Des 2013;135(6) [061001–061001].
[165] Frank AA, Beachley NH, Hausenbauer TC. The fuel efficiency potential of a flywheel hybrid vehicle for urban driving. In: Proceedings of the 11th intersociety energy conversion engineering conference. American Institute of Chemical Engineers, State Line, Nev.; 1976. p. 17–24.
[166] Barr A, Veshagh A. Fuel economy and performance comparison of alternative mechanical hybrid powertrain configurations. SAE Technical Paper. 2008.
[167] Hearn CS, Flynn MM, Lewis MC, Thompson RC, Murphy BT, Longoria RG. Low cost flywheel energy storage for a fuel cell powered transit bus. Prof IEEE Veh Power Propuls Conf 2007:829–36.
[168] Wang C, Liang X, Chapelsky C, Koval D, Knight AM. Application of flywheel system in series hybrid transit bus. In: Proceedings of the of IEEE vehicle power and propulsion conference. 2009. p. 1529–34.
[169] Kandler C, Koenings T, Ding SX, Weinhold N, Schultalbers M. Stability investigation of an idle speed control loop for a hybrid electric vehicle. IEEE Trans Cont System Technol. 2014.
[170] Berkel KV, Hofman T, Vroemen B, Steinbuch M. Optimal control of a mechanical hybrid powertrain. IEEE Trans Veh Technol 2012;61(2):485–97.
[171] Berkel KV, Titulaer R, Hofman T, Vroemen B, Steinbuch M. From optimal to real-time control of a mechanical hybrid powertrain. IEEE Trans Cont System Technol. 2014.
[172] Dragicevic T, Shafiee Q, Wu D, Meng L, Vasquez JC, Guerrero JM. Modeling and control of flexible HEV charging station upgraded with flywheel energy storage. In: Proceedings of the IEEE conference. 2014.
[173] Lee E. A micro-HTS renewable energy/attitude control system for micro/nano-satellites. IEEE Trans Appl Supercond 2003;13(2):2263–6.
[174] Zhou X, Fang J. Precise braking torque control for attitude control flywheel with small inductance brushless DC motor. IEEE Power Electron 2013;28(11):5380–90.
[175] Mousavi G SM, Tabakhpour L A, Fuchs Ewald F, Al-Haddad K. Power quality issues in railway electrification: a comprehensive prespective. IEEE Trans Ind Electron 2015;62(5):3081–90.
[176] Okui A, Hase S, Shigeeda H, Konishi T, Yoshi T. Application of energy storage system for railway transportation in Japan. In: Proceedings of the IEEE international power electronics conference. 2010. p. 3117–23.
[177] Richardson MB. Flywheel energy storage system for traction applications. In: Proceedings of the IEEE power electronics machines and drives conference. 16–18 April 2002.
[178] Osawa M, The Ne@Train, girst hybrid material in the world. Rail International, Bruxelles, Belgium; 2004. p. 9–86.
[179] Cousineau RL. Development of a hybrid switcher locomotive the railpower green goat. IEEE Instrum Meas Mag 2006;9(1):25–9.
[180] Lacote F. Rolling Stock and Manufacturers (part 2): Alstom – Future Trends in Railway Transportation'. 'Japan Railway & Transport Review 42' (East Japan Railway Culture Foundation (EJRCF); 2005). p. 4–9.
[181] Iglesias IG, Martinez JC, Tobajas C, Lafoz M, Tabarés LG, CV, et al. A kinetic energy storage system for railways applications. In: Proceedings of the eighth world congress on railway research. Coex, Seoul, Korea; 18–22 May 2008. p. 1–10.
[182] Wall Richard W, Johnson Brian K. Regenerative train control networks for gas turbine powered high-speed rail locomotive with flywheel energy storage. In: Proceedings of the IEEE conference. 2002.
[183] Zhou L, Tang X, Qi Z. Control method for flywheel array energy storage system in energy harvesting from electric railway. In: Proceedings of the IEEE conference. 2014.
[184] Lee H, Jung S, Cho Y, Yoon D, Jang G. Peak power reduction and energy efficiency improvement with the superconducting flywheel energy storage in electric railway system. Physica C 2013:246–9.
[185] Thelen RF, Herbst JD, Caprio MT. A 2 MW flywheel for hybrid locomotive power. In: Proceedings of the IEEE conference. 2003.
[186] Daoud MI, Abdel-Khalik AS, Ahmed S, Massoud AM. DC bus control of an advanced flywheel energy storage kinetic traction system for electrified railway industry. In: Proceedings of the IEEE conference. 2013. p. 6596–6601.
[187] Glickenstein H. Electric trams without the wires. IEEE Veh Technol Mag. Dec 2006. p. 50–4.
[188] Glickenstein H. Contactless payment debuts on London's busses, new and improved railways around the world: Williams hybrid power and Alstom transport to partner on energy storage technology for trams. IEEE Veh Technol Mag (IEEE Press). vol. 8(2). June 2013. p. 19–25.
[189] Gelman V. Comparison between wayside storage and reversible thyristor controlled rectifiers for heavy rail. IEEE Veh Technol Mag (IEEE Press). Dec 2013. p. 70–80.
[190] R. Hunter, and G. Elliot, Wind-Diesel Systems: A Guide to the Technology and its Implementation, 1994, Cambridge University Press.
[191] Takahashi R, Wu L, Murata T, Tamura J. An application of flywheel energy storage system for wind energy conversion. IEEE Conf 2005:932–7.
[192] Beacon Power Corporation. Performance of First 20 MW Commercial Flywheel Frequency Regulation Plant. available online: 〈http://www.beaconpower.com〉.
[193] Veszpremi K, Schmidt I. Flywheel energy storage drive for wind turbines. IEEE Conf 2007:916–23.
[194] Takahashi R, Tamura J. Frequency control of isolated power system with wind farm by using flywheel energy storage system. In: Proceedings of the IEEE electrical machines, Conference. 2008.
[195] Suvire O Gastón, Mercado, Pedro E. Improvement of power quality in wind energy applications using a DSTATCOM coupled with a flywheel energy storage system. IEEE Conf 2009:58–64.
[196] 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. IEEE Trans Energy Conv 2010;25(2):526–34.
[197] Suvire GO, Mercado PE. DSTATCOM with flywheel energy storage system for wind energy applications: control design and simulation. Elsevier – Electr Power Syst Res. vol. 80. 2010. p. 345–53.
[198] Abdel-Khalik AS, Elserougi A, Massoud A, Ahmed S. Control of doubly-fed induction machine storage system for constant charging/discharging grid power using artificial neural network. IET 2012.
[199] Islam F, Al-Durra Ahmed, Muyeen SM. Smoothing of wind farm output by prediction and supervisory-control-unit-based FESS. IEEE Trans Sust Energy 2013.
[200] Daoud MI, Massoud A, Ahmed S, Abdel-Khalik AS, Elserougi A. Ride-through capability enhancement of VSC-HVDC based wind farms using low speed flywheel energy storage system. IEEE Conf 2014:2706–12.
[201] Kalantar M, Mousavi G SM. Posicast control within feedback structure for a DC–DC single ended primary inductor converter in renewable energy applications. Appl Energy 2010:3110–4.
[202] Kalantar M, Mousavi G SM. Dynamic behavior of a stand-alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage. Appl Energy 2010:3051–64.
[203] Hara M, Yamamura N, Ishida M, Kamada Y, Maeda T, Wakita M. Method of electric power compensation for wind power generation using biomass gas turbine generator and flywheel. IEEE Conf 2007:243–8.
[204] Huizhi Z, Yongli L. Constant voltage control on DC bus of PV system with flywheel energy storage source (FESS). In: Proceedings of the IEEE the international conference on advanced power system automation and protection. 2011. p. 1723–7.
[205] Zhao B, Zhang X, Chen J. Integrated microgrid laboratory system. IEEE Trans Power Syst 2012.
[206] Ahmadi A R, Ghardashi F, Kabiri D, Sheykholeslami A, Haeri H. Voltage and frequency control in smart distribution systems in presence of DER using flywheel energy storage system. In: Proceedings of the IEEE 22nd international conference on electricity distribution. Stockholm; 10-13 June 2013.
[207] Pan I, Das S. Kriging based surrogate modeling for fractional order control of microgrids. IEEE Trans Smart Grid. 2014.
[208] 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. Elsevier, Energy; 2014. p. 1–12.
[209] Akagi H. Active filters and energy storage systems operated under non-periodic conditions. IEEE Conf 2000 [965-940].
[210] Weissbach RS, Karady GG, Farmer RG. Dynamic voltage compensation on distribution feeders using flywheel energy storage. IEEE Trans Power Deliv 1999;14(2):465–71.
[211] Zhang J, Chen Z, Cai L, Zhao Y. Flywheel energy storage system design for distribution network. IEEE Conf 2000:2619–23.
[212] Jiancheng Z, Lipei H, Zhiye C, Su W. Research on flywheel energy storage system for power quality. IEEE Conf 2002:496–9.
[213] Wang MH, Chen HC. Transient stability control of multimachine power systems using flywheel energy injection. IEEE Proc: Gener Transm Distrib 2005;152(5):589–96.
[214] Gambôa P, Fernando Silva J, Ferreira Pinto S, Margato E. Predictive optimal matrix converter control for a dynamic voltage restorer with flywheel energy storage. IEEE Conf 2009:759–64.
[215] Roberts BP, Sandberg C. The role of energy storage in development of smart grids. In: Proceedings of the IEEE. vol. 99(6); June 2011; p. 1139–44.
[216] Okou R, Sebitosi AB, Khan MA, Barendse P, Pillay P. Design and analysis of an electromechanical battery for rural electrification in Sub-Saharan Africa. IEEE Energy Conv 2011;26(4):1198–209.

[217] D´ıaz-Gonz´alez F, Sumper A, Gomis-Bellmunt O, Villafafila-Robles R. Modeling and Validation of a Flywheel Energy Storage Lab-Setup. 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Berlin; 2012.
[218] Jin C, Lu N, Lu S, Makarov YV, Dougal RA. A coordinating algorithm for dispatching regulation services between slow and fast power regulating resources. IEEE Trans Smart Grid. vol. 5(2). Mar 2014. p. 1043–50.
[219] Xu X. Research on marine combined electrical power plant and electric network power quality. Shanghai Marinetime University,Shanghai; 2007.
[220] Xie C, Zhang C. Research on the ship electric propulsion system network power quality with flywheel energy storage. In: Proceedings of the IEEE conference. 2010.
[221] McGroarty J, Schmeller J, Hockney R, Polimeno M. Flywheel energy etorage eystem for electric start and an all-electric ship. IEEE Electr Ship Technol Symp 2005:400–6.
[222] Kulkarni S, Santoso S. Impact of pulse loads on electric ship power system: with and without flywheel energy storage systems. IEEE Conf 2009:568–73.
[223] Saghaleini M, Mirafzal B, Edrington C. Regenerative energy management for pulse-loads in dual DC-AC micro-grids. IEEE Conf 2010:674–9.
[224] Oman H. International space station power storage upgrade planned. IEEE AESS Syst Mag 2003:32–9.
[225] Rose JB. An electro-mechanical energy storage system for space application. Energy conversion for space power, progress in astronautics and rocketry, vol. 3. Academic Press; 1961. p. 613–22.
[226] Notti JE, Cormack A, Schmill WC. Integrated power/attitude control system (IPACS) study. vols. I–2. NASA CR-2383, Rockwell International Space Division, Downey CA; April 1974.
[227] Anderson WW, Keckler CR. An integrated power/attitude control system (IPACS) for space application. In: Proceedings of the Slh IFAC symposium on automatic control in space. 1973.
[228] Hall CD. High speed flywheels for integrated energy storage and attitude control. Proc Am Control Conf 1997;3:1894–8.
[229] Applegate JF, McMillion JM, Smith RE. Design and operation of the Skylab attitude and pointing control system. In: The skylab results, advances in the astronautical aciences, vol. 31. Tarzana, CA: American Astronautical Society; 1975. p. 467–87.
[230] Pieronck TJ, Decker DK, Spector VA. Spacecraft flywheel systems—benefits and issues. In: Proceedings of the IEEE 1997 national aerospace and electronics Conference. vol. 2. Dayton, Ohio; July 14–17, 1997. p. 589–93.
[231] Christopher DA, Beach R. Flywheel technology development program for aerospace applications. In: Proceedings of the IEEE 1997 national aerospace and electronics Conference. vol. 2. Dayton, Ohio; July 14–17, 1997. p. 602–8.
[232] Truong LV, Wolff FJ, Dravid NV. Simulation of flywheel electrical system for aerospace applications. IEEE Conf 2000:601–8.
[233] Wilson TL. A high-temperature superconductor energy-momentum control system for small satellites. IEEE Trans Supercond 2003;13(2):2287–90.
[234] Lee E, Kim B, Ko J, Song C Young, Kim Seong-Jin, Jeong S, et al. An integrated micro-HTS system for energy storage and attitude control for three-axis stabilized nanosatellites. IEEE Trans Appl Supercond 2005;15(2):2324–7.
[235] Hong JY, Shijie X. Spacecraft attitude tracking and energy storage using flywheels. Chin J Aeronaut 2005;18(1).
[236] Swett DW, Blanche JG. Flywheel charging module for energy storage used in electromagnetic aircraft launch system. IEEE Trans Magn 2005;41(1):525–8.
[237] Tang J, Fang J, Tong W. Superconducting magnetic bearings and active magnetic bearings in attitude control and energy storage flywheel for spacecraft. IEEE Trans Appl Supercond 2012;22(6).
[238] Bedrossian M, Karpenko M, Bhatt S. Sophisticated algorithms boost performance on the cheap. IEEE Spect 2012:54–61.
[239] Beno JH, Thompson RC, Werst MD, Manifold SM, Zierer JJ. End-of-Life design for composite rotors. IEEE Trans Magn 2001;37(1):284–9.
[240] Aanstoos TA, Kajs JP, Brinkman WG, Liu HP, Ouroua A, Hayes RJ, et al. High voltage stator for a flywheel energy storage system. IEEE Trans Magn 2001;37(1):242–7.
[241] Balikci A, Zabar Z, Czarkowski D, Levi E, Birenbaum L. Flywheel motor/generator set as an energy source for coil launchers. IEEE Trans Magn 2001;37(1):280–3.
[242] Balikci A, Zabar Z, Birenbaum L. Improved energy utilization of linear induction launchers by considering each section as an individual sub-luncher. IEEE Trans Magn 2009;45(1):241–3.
[243] Balikci A, Zabar Z, Birenbaum L, Czarkowski D. On the design of coilguns for super-velocity launchers. IEEE Trans Magn. vol. 43(1). Jan 2007. p. 107–10.
[244] Li L, Ding H, Peng T, Han X, Xia Z, Chen J, et al. The pulsed high magnetic field facility at HUST, Wuhan, China and associated magnets. IEEE Trans Appl Supercond 2008;18(2):596–9.
[245] Xu Y, Au S Kwok-Wai. Stabilization and path following of a single wheel robot. IEEE/ASME Trans Mechatron 2004;9(2):407–19.
[246] Komori M, Akinaga N. A prototype of flywheel energy storage system suppressed by hybrid magnetic bearings with $H\infty$ controller. IEEE Trans Appl Supercond 2001;11(1):1733–6.
[247] Keyin W, Dezhi L, Jin M, Yangbin O, Xiaofei Z, Junquan C. Design and simulation of a 12-phase flywheel energy storage generator system with linearly dynamic load. IEEE Trans Appl Supercond 2010;20(3):1050–4.
[248] Levi E. Multiphase electric machines for variable-speed applications. IEEE Trans Ind Electron 2008;55(5):1893–909.
[249] Koiwa K, Itoh JI. Experimental verification for amatrix converter with a V-connection AC chopper. In: Proceedings of the European conference on power electronics and applications. Birmingham, UK; 2011. p 1–10.