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# The Flywheel Energy Storage System: A Conceptual Study, Design, and Applications in Modern Power Systems

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***Abstract*—While energy storage technologies cannot be considered sources of energy; they provide valuable contributions to enhance the stability, power quality and reliability of the supply. Many storage technologies have been developed in an attempt to store the extra AC power for later use. Among these technologies, the Flywheel Energy Storage (FES) system has emerged as one of the best options. This paper presents a conceptual study and illustrations of FES units. After brief introduction to the FES system and its theory of operation, the paper focuses on the important role of the FES system in enhancing the operation of the distribution network. Supported by illustrated circuits, the paper describes the major role of each part of the FES system in the improvement of the power quality of the network. Then it discusses a newly proposed design of the FES system that emerged recently, which includes the use of Superconducting Magnetic Bearings (SMB) and Permanent Magnetic Bearings (PMB). In conclusion, the paper analyzes the FES systems great potentials that could be exploited in improving the reliability of the electrical system.**

***Index Terms*—flywheel energy storage system, energy storage, superconducting magnetic bearings, permanent magnetic bearings, power system quality, power system reliability, design of flywheel**

## I. INTRODUCTION

A Flywheel Energy Storage (FES) system is an electromechanical storage system in which energy is stored in the kinetic energy of a rotating mass. Flywheel systems are composed of various materials including those with steel flywheel rotors and resin/glass or resin/carbon-fiber composite rotors. Flywheels store rotational kinetic energy in the form of a spinning cylinder or disc, then use this stored kinetic energy to regenerate electricity at a later time. The amount of energy stored in a flywheel depends on the dimensions of the flywheel, its mass, and the rate at which it spins. Increasing a flywheel's rotational speed is the most important factor in increasing stored energy; doubling a flywheel's speed quadruples the amount of stored energy [1]. Flywheels can respond rapidly, as both a source and a sink for electricity. This has made them a valuable technical solution for frequency regulation in electric power grids. Flywheels are considered one of the most cost-effective storage technologies for high power (rapid discharge) applications, where they compete directly with batteries. Despite high capital manufacturing and construction costs, the advantage of the long life span of the flywheels has made it a strong choice for power quality applications. In addition, there are many other features that make flywheel storage systems a promising solution for future energy needs. These features include pollution-free operation with a maximum amount of stored energy, which is mainly affected by the weight and shape of the rotor, and the high efficiency of the storage process including the efficiency of the energy conversion [2], [3].

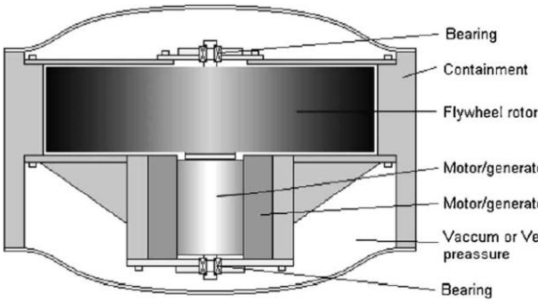

Figure 1. Basic scheme of the FES system

### A. Principle of Operation

A flywheel stores energy in a rotating mass. Depending on the inertia and speed of the rotating mass, a given amount of kinetic energy is stored as rotational energy. The main idea is that the flywheel is placed inside a vacuum containment to eliminate any friction-loss that might be caused by the air and suspended by bearings for stable operation. Then, depending on the need of the grid, the kinetic energy is transferred either in or out of the flywheel which is connected to a machine that works as either the motor or generator. In the motor mode, electric energy supplied to the stator winding is converted into torque and applied to the rotor, causing it to spin faster and thus gaining kinetic energy. While in the generator mode, the kinetic energy stored in the rotor would apply torque which is converted to the needed amount of electric energy. Fig. 1 shows the basic layout

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of a flywheel energy storage system. Also, necessary power electronic devices are set up with the system in order to control the power in and output, speed, and frequency of the flywheel system in response to the condition of the grid.

The kinetic energy stored in a flywheel is proportional to the mass and to the square of its rotational speed according to the following equation:

$$E_k = ½\, I\, w^2 \qquad (1)$$

where $E_k$=kinetic energy, $I$=moment of inertia, $W$=angular velocity of the flywheel.

According to the previous equation, the most efficient way to increase the stored energy is to speed up the flywheel. For steal rotors, the dominant shape is a solid cylinder, giving the following expressions for $I$:

$$I = ½\, r^2\, m = ½\, r^4.\, \pi.\, a.\, p \qquad (2)$$

where: $r$=radius, $a$=length of the radius, $m$=the mass of the cylinder, $p$=the density of the cylinder material.

The other dominating shape is a hollow circular cylinder, approximating a composite or steel rim attached to a shaft with a web, which leads to the next equation:

$$I = ¼\, m.\, (r_o^2 + r_i^2) = ¼\, \pi.\, a.\, p\, (r_o^4 - r_i^4) \qquad (3)$$

Table I shows the technical characteristics for the most common raw materials used in designing the flywheel energy units.

TABLE I. SOME CHARACTERISTICS FOR COMMON ROTOR MATERIALS

| Material | Density ($kg/m^3$) | Tensile Strength (MPa) | Max energy density (for 1 kg) | Cost ($/kg) |
|---|---|---|---|---|
| Monolithic material | 7700 | 1520 | 0. 05 kWh/kg | 1 |
| E-glass | 2000 | 100 | 0. 014 kWh/kg | 11. 0 |
| S2-glass | 1920 | 1470 | 0. 21 kWh/kg | 24. 6 |
| Carbon T1000 | 1520 | 1950 | 0. 35 kWh/kg | 101. 8 |
| Carbon AS4C | 1510 | 1650 | 0. 30 kWh/kg | 31. 3 |

## II. FLYWHEEL TECHNICAL CONSIDERATIONS

According to Boland (2007) the concept of having the kinetic energy stored in a spinning mass is not a new one. A great deal of research has been conducted on this topic over several decades, specifically focusing on the flywheel units and the methods to improve their efficiency and means of operation [3]. The following aspects have always been associated with the design and work of any flywheel energy system:

### A. Motor/Generator

Requirements for standardized electric power have made most flywheel system designers elect variable speed AC generators (to accommodate the gradual slowing of the flywheel during discharge) and diodes to deliver DC electricity. The two major types of machines used are the axial-flux and the radial-flux permanent magnet machines (AFPM and RFPM, respectively). There are numerous alternatives for the design of an AFPM machine such as the internal rotor, internal stator, multidisc, slotted or slot-less stator, rotors with interior or surface-mounted magnets. Unlike radial machines, axial machines can have two working surfaces, either two rotors combined with one stator or one rotor combined with two stators. The benefit of using a two-surface working machine is the increase in power output. The axial machines seem to have more advantages over the radial machines such as a planar adjustable air gap and easy cooling arrangements, which is important when working under low-pressure conditions. Fig. 2 shows a one-rotor two-stator AFPM configuration without the cable winding in the stators. It can be seen that the permanent magnets are an integral part of the flywheel rotor and the stators are fixed to the housing.

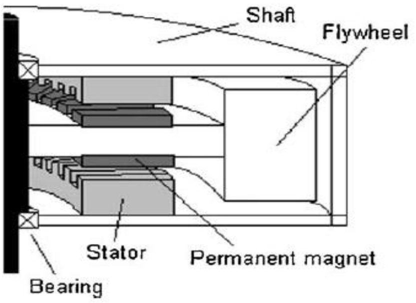

Figure 2. One-rotor two stator AFPM

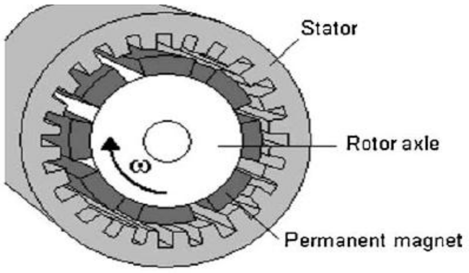

Figure 3. RFPM configuration

Much attention has been directed towards optimizing radial gap machines. In a RFPM machine the magnets can be surface mounted on the rotor axle surrounded by the stator, as in Fig. 3, or mounted in a ring enclosing the stator. The radial flux machine is mostly used in small-scale high-speed machines, where the tensile strength of the permanent magnets demands placement close to the rotating axle.

### B. High Voltage

All the different types of flywheel energy units developed today have one thing in common irrespective of any differences in design or operation; the ability to produce high voltage (over 36kV). However, the highest voltage attained so far is a 10-pole permanent magnet machine constructed in 2001 with a continuous voltage of 6.7kV and a peak voltage of 10kV. Therefore, the installation of transformers is required to deal with high voltage applications in the connected system which, of course, would result in greater losses to the overall flywheel system.

### C. *Number of Poles*

The performance of electrical machines has always been connected to the number of poles used in the design. In high-speed machines applications, the most common design so far is the two pole motor/generators. Depending on the axial or radial flux configuration, a multi-pole rotor can experience substantial electromagnetic axial or radial forces generated by the stator winding, if there is a net attractive force between a pole-pair and the stator. In a two-pole rotor, however, the only two poles are directly opposite one another, resulting in a net force on the rotor of approximately zero. Eliminating these forces reduces the load requirements on the bearings, which is particularly important if magnetic bearings are used.

### D. *Power Electronics*

The flywheel energy unit produces variable frequency AC current. To reliably operate the system, power electronics devices must be installed in order to keep the frequency constant so that it can be connected to the grid. Power converters for energy storage systems are based on SCR, GTO or IGBT switches. In an early stage of energy-storage development, SCRs were the most mature and least expensive semiconductor suitable for power conversion. However, due to the fact that an energized power line must provide external on/off signals to those switches, SCRs were replaced with Gate turn-off thyristors (GTOs), which do not depend on an energized line to function. The GTO devices can handle voltages up to 6 kV, currents up to 2000A and switching frequencies up to 1 kHz. Recently insulated gate bipolar transistors (IGBTs) have emerged. The IGBT is a solid-state switch device with ability to handle voltages up to 6.7kV, currents up to 1.2kA and, most important, high switching frequencies.

The technique used to produce AC current from DC is called Pulse-Width Modulation (PWM). Pulses of different length are applied to the IGBTs in the inverter, causing the DC current to be delayed by the inductive load and a sine wave is modulated. A fast switching frequency in the power converter improves emulation of the sine wave mainly by eliminating some of the higher order harmonics. The converters produce harmonics on both AC and DC sides: current harmonic on the AC and voltage on the DC. To deal with these harmonics, it is very essential to have both AC and DC filters installed to reduce the effect harmonics have on the overall performance of the system.

## III. Using the FES System to Improve Power Quality in Distribution Networks

For the proper operation of any electrical grid, energy demand must be met with the same amount of generated power, taking into consideration the losses in the system. To balance such an equation is not an easy task. Sometimes, due to regular increases in seasonal loads or shock loads, the power consumption is concentrated during a certain time zone in a day which makes the distribution grid requires reactive power (voltage) support in order to operate properly. It makes the network unstable and may lead to power-quality problems such as instantaneous interruption, voltage drop, lack of reactive power or active power, and etc. [4], [5]. Thus, the idea of installing a flywheel energy system in the distribution networks has emerged as a practical option to deal with power quality problems in the grid.

According to Al-Diab (2011) the flywheel energy storage system (FESS) could be exploited beneficially in dealing with many technical issues that appear regularly in distribution grids such as voltage support, grid frequency support, power quality improvement and unbalanced load compensation. FES systems have advantages such as a longer lifespan and lower requirements than battery systems, this makes them an important alternative to batteries in the UPS (Uninterruptable Power Supply) (6). The application of FES system in the distribution network will make it possible to strictly control and monitor the voltage and waveform of the power system, and the quality and the reliability in power supply will be greatly improved.

### A. *The Component of the FES System in the Distribution Network*

The FES system is composed of four parts, as shown in Fig. 4, from the following:

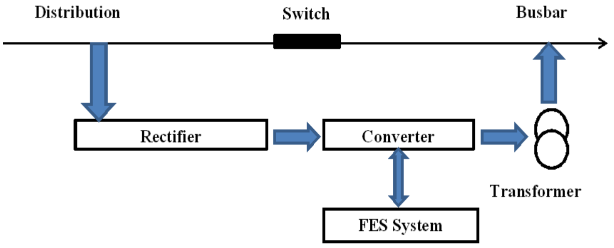

Figure 4. The components of the FES system in distribution networks

#### *1) Flywheel that stores energy*

Extractable flywheel energy is expressed as:

$$\Delta E = \frac{1}{2}.J.(\omega\, max^2 - \omega\, min^2) \tag{4}$$

where: $\Delta E$ : Extractable flywheel energy, $J$ : Flywheel moment of inertia, $\omega\ max$: Maximum flywheel operating speed, $\omega\ min$: Minimum flywheel operating speed.

The above formula clearly illustrates the advantages of high-speed flywheel operation. Since extractable energy is proportional to the square of the operating speed, low mass; high speed units can be designed to provide high energy densities. Therefore, the use of new composite materials with high $\sigma/\gamma$ parameter have suggested that the speed of the flywheel can be noticeably increased, leading to higher capacity FES systems. The optimal material for the flywheel is carbon fiber, the linear velocity of which can exceed 1000m/s.

#### *2) The bearing that supports the flywheel*

The bearing serves as the support of the flywheel. The electro-permanent magnetic bearing system is composed of permanent magnets, which support the weight of the flywheel by their repelling force, and electromagnets, which keep the flywheel stable. This sort of bearing can reduce the friction and lengthen the life span, but the controlling system of electromagnets is too complex. The flywheel is suspended by the repelling and pulling force, which is generated by the action of obstructing and passing magnetic flux through superconductor. This type of force can situate the flywheel automatically and there is no need for an electricity and complex position-controlling system.

### *3) The asynchronous motor/generator*

The electrical machine plays major role in the work of the FES system. The exchange of electrical/kinetic energy or vice versa is done via the machine which would operate as either a motor or a generator depending on the need of the system. When the flywheel unit stores energy, the machine operates as a motor and the flywheel accelerates. When the flywheel unit releases energy, the machine acts as a generator, and the flywheel decelerates. The electrical machine can be constructed in different ways. It can be made of an efficient permanent magnetic synchronous machine, or composed of both a synchronous generator and a coaxial asynchronous motor.

### *4) The AC power converter regulated by a microprocessor controller*

Composed of Inverter A, Inverter B and the microprocessor controller, as shown in Fig. 5, the power electronic devices play a major role in the FES system.

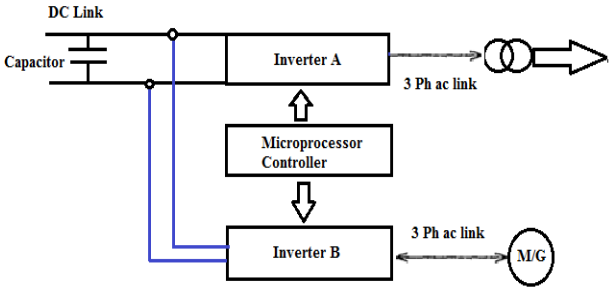

Figure 5. The layout of the power electronic devices in the FES system

Inverter B is used to transfer the DC power coming from the DC bus into a three-phase AC power that drives the electrical machine (M/G), which needs to receive controlled amplitude of the voltage and smoothed frequency as well. Because the machine is designed to operate at constant power during storage or release period, the frequency and amplitude of the voltage from Inverter B will have to meet the following equation:

$$\frac{U}{\sqrt{f}} = Constant \tag{5}$$

The same concept is applied to Inverter A, which inverts the DC power into three-phase AC power with adjusted frequency and voltage amplitude, but with this AC power transferred to the distribution network via the transformer. Then the microprocessor controller, composed of 80~196 chips, measures the real-time voltage or current of the power system and constantly sends signals to control Inverters A and B so that the FES system can work smoothly. A capacitor, as shown in Fig. 4, has to be installed in order to stabilize the DC voltage. However, since there is only little exchange of power between the inverters and the capacitor, only a small electrolytic capacitor would be needed to serve the purpose [5].

## IV. THE CONTROL METHOD OF THE FES SYSTEM

One of the great features of the FES system is not only its ability to provide reactive power to the network, but also its ability to provide active power in a short period of time. This requires the controlling system in the AC power converter to detect the distribution network at all times and to make correct judgments and control the inverters accordingly, which is the role of the controller in the FES system.

The main functions of the controller in FES system are the detection of the voltage drops in the grid, computation of the correcting current, generation of pulse width modulation and the shift of the DC-AC inverter into a rectifier and vice versa to charge or discharge the capacitor in the DC link in the absence or occurrence of voltage drops [4].

The control method is adopted for the voltage stability and modified as follows:

- The proportional coefficient is not a constant. It varies regularly with the voltage of the measured bus.
- When the error (the voltage sag) changes its sign, the integral plays a reaction role. Thus it is necessary to set the integral to zero in order to ensure the stability of the system.
- A neighborhood to zero is set to be -2% - +2%. Any error in this range is assumed to be zero.

Therefore, when the voltage of the measured bus is within 0.98Un-1.02Un, the controller keeps its old condition. When the voltage is within 0.80Un-0.98Un, the controller increases the duty ratio of Inverter A, and the voltage amplitude increases. The FES system supplies reactive power to the distribution network. When the voltage is above 1.02Un, the controller reduces the duty ratio and the voltage amplitude is reduced; the FES system then takes in reactive power from the distribution network. When the voltage is lower than 0.80Un or when there is a power cut, the controller opens the switch in Fig. 4, and, at the same time, gradually reduces the voltage and frequency of Inverter B in order to make the FES machine generate active power. When the interruption of power ends or when the distribution voltage comes back upwards of 0.80Un, the power generation process of the FES system ends [5]. In the absence of a voltage drop at the grid, the voltage of the DC link rises which means, the machine will run as a motor and the speed of the flywheel rises until it reaches its maximum where a speed limiter is used to stop the power flow when the maximum speed is reached. The limiter based on the flywheel speed and the voltage drop detection information is used to disconnect the FESS from the grid by switching off the converter in the stable mode [6].

## V. BASIC DESIGN APPROACH

There are two approaches in designing a flywheel unit:

- The first stage is to obtain the amount of energy required for the desired degree of smoothing in addition to the moment of inertia needed to absorb that determined energy.
- The second stage is to define the flywheel geometry, which caters to the required moment of inertia in a reasonably sized package.

### A. *Design Parameters*

There are many parameters to be considered in the design of the flywheel energy unit:

*1) Speed fluctuation*

The speed fluctuation is defined as the change in the shaft speed during a cycle, given by the following equation:

$$F_1 = W\max - Wmin \tag{6}$$

*2) Coefficient of speed fluctuation*

The coefficient of speed fluctuation is one of the parameters set by the designer. The smaller this chosen value, the larger the flywheel would be and the greater the cost and weight to be added to the system. However the smaller coefficient would result in the smoother operation of the flywheel energy unit. The coefficient can be found by the following equation:

$$C_f = \frac{W\max - Wmin}{W} \tag{7}$$

where $W$: the nominal angular velocity.

The typical value of $C_f$ is set to be between 0.01 up to 0.05 for precision machinery work.

*3) Design equations*

The kinetic energy in a rotating machine is given by

$$E_k = \tfrac{1}{2} I w^2 \tag{8}$$

The kinetic energy in any system could thus be found from

$$E_k = E_1 - E_2$$

$$E_k = \tfrac{1}{2} Is\,(2w_{avg})\,(C_f w_{avg}) \tag{9}$$

$$E_1 - E_2 = C_f I w^2$$

The above equation can also be used to obtain an appropriate flywheel inertia Im corresponding to the known energy exchange Ek at a specific value of coefficient $C_f$.

### B. *Flywheel Energy Design Using SMB and PMB*

The Flywheel energy storage approach is currently considered as one of the most successful figures of energy storage, and many attempts have been made to improve this technology. Among these latest developments is the use of a superconducting magnetic bearing (SMB) together with a permanent magnetic bearing (PMB). According to Komori (2011) this approach has resulted in higher energy storage compared with conventional flywheel systems, and would lead to reduced overall costs and cooling costs. One of the main issues in operating the flywheel system is the large vibration transmitted to the rotor during operation, causing difficulties in controlling the speed of the rotation. The purpose of this specific design, using SMB and PMB, is to support the rotor in the flywheel system; the main function of the SMB is to suppress the vibrations in the rotor, while the PMB passively controls and maintains the position of the rotor [7].

*1) Description of the design*

Fig. 6 shows a schematic description of the flywheel energy storage system using a SMB and a PMB. It should be noted that the SMB is placed into the bottom of the system's rotor, while the PMB is set at the top of the flywheel rotor. This is because the damping effect of the SMB is effective if it is placed in the lower side of the rotor, while PMB has no damping effect [8]. The flywheel is constructed so that the center of gravity is lower than the center of the supporting point. Thus, the center of gravity still lies in the center position of the upper magnet of the SMB part, which would give the system more inertia and make it more stable under both rotating and non-rotating condition [7].

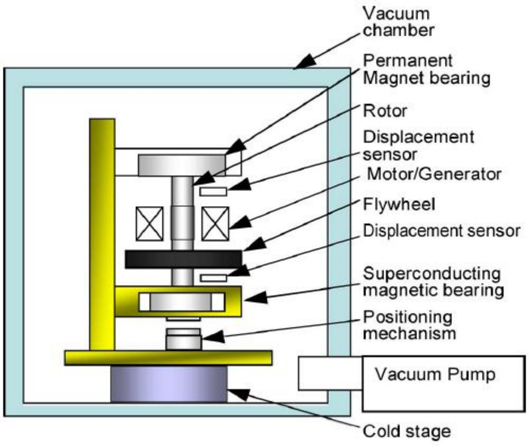

Figure 6. The design of the flywheel unit using PMB and SMB

*2) Structure of PMB*

As shown in Fig. 6, the permanent magnetic bearing (PMB) is composed of two rotor magnets, two stator magnets and inserted non-magnetic spacers between the stator magnets. The spacers adjust the repulsion force in the axial direction without influence on the repulsion force in the radial direction. There are many advantages gained by using the PMB in the design of the flywheel system; there would be no friction in the bearing section of the flywheel, no need for maintenance, and no need for a control unit since the PMB does not need one [7], [8].

*3) Structure of SMB*

In order to suppress vibrations and to obtain greater balance of the rotor's weight, a structure of SMB with radial and axial is preferred. Fig. 7 shows the simple shape of the SMB which consists of a circle-shaped high-temperature superconductor, along with four circle-shaped neodymium magnets [7].

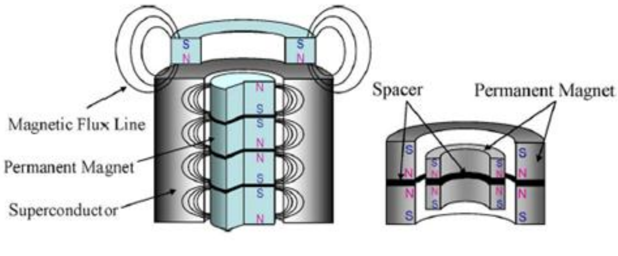

Figure 7. Structure of SMB (left) and PMB (right)

After the addition of the SMB and the PMB into the flywheel energy system, the energy storage feature in the flywheel system along with the stiffness of the PMB and the overall maximum rotational speed system is clearly improved. This design is found to be very effective in dealing with any kind of instantaneous voltage drops in the network [9].

### C. *The Cost of the FES Project*

The cost for the flywheel energy system varies based on the need for storage, with the difference in the design of the proposed flywheel system. Even though a flywheel is not a completely new technology, its usage as a storage system and for improvement of power quality of the grid has contributed significantly recent pricing schemes. Current costs are largely based on experience building demonstration projects. Significant near-term cost reductions are projected due to organizational learning and economies of scale in future deployments [10].

## VI. THE LATEST DEVELOPMENT OF THE MOTOR/GENERATOR FOR THE FES SYSTEM

According to Yali (2011) the Motor/Generator is the core dynamic component for the FES system. So far, except for very few applications of special or new structure motors such as synchronous homopolar machines, disc-type motors, printed circuit windings, three types of motors have been widely used, including the Induction Motor, the RM and the PMM [11].

### A. *Induction Motor/Generator (IM/G)*

- *1996:* Researchers in Japan developed a 0.2kWh, 16500rpm FES device with IM/G, which first used high strength carbon fiber for the flywheel and was capable of preferable stability at high speed. In August of 1996, a 5500kWh, 74,000kg, 4m diameter FES system which used a doubly-fed IM/G rated 26.5MVA, with 12 poles and 90% for line frequency regulation on a 132kV bus was installed and commissioned at the Chujowan substation of the Okinawa Electric Power Company in Japan.
- *2000:* Roberto Ardenas of the University of Magallancesin Chile introduced an IM/G for FES system with the following ratings: 2.5kW, 380V, 7A, 28/4 (slots/poles), rated speed of 1460 rpm and rotational inertia of 1.8kgm2.
- *2009:* The Integrated Research Institute of Tokyo and the Institute of Technology collaborated with the Fuji Electric Device Technology Corporation to develop an 11kW IM/G for 61Wh, 700kg, out diameter of 200mm and axial length of 135mm FES system which couldbe apply to voltage sag compensator and UPS power source.

### B. *Reluctance Motor/Generator (RM/G)*

- *2006:* Roberto Ardenas of University of Magallanes in Chile researched a 1, 000rpm-2, 000 rpm FES system for power smoothing using a 2.5kW, 8/6, 0.9 switched RM, it was the first experimental implementation to the RM flywheel system for power smoothing applications.
- *2008:* Pentadyne Power Corporation of Los Angeles manufactured an FES system using a 120kW, 4 poles and 25,000-54,000rpm synchronous RM for UPS application. With DSP controller and three-phase inverter, the system realized of rectifier and stability by a model based feed forward controller and a PI feedback compensator.
- *2010:* Pentadyne Power Corporation of Los Angeles developed a carbon fiber flywheel of GTX for UPS, and with a 200kW, 350V–590V (DC voltage), 400A of short time current, weight 590kg, 4 poles synchronous RM/G in a vacuum, the prototype as shown in Fig. 3. Stator cooled in liquid. Synchronous RM provided constant power output for DC bus.

### C. *Permanent Magnet Motor/Generator (PMM/G)*

#### *1) PMM/G with the traditional structure*

- *2006:* Researchers at University of Michigan conducted the control method of 32kW, 2 poles PMM/G for electric and hybrid electric vehicles FES system, and proposed an advanced optimal control scheme, which had the good performance to maximize power density and minimize machine size and weight.
- *2008:* Paulo Gamboa of institute Superior de Engenharia de Lisboa in Portugal designed a 30Wh, 2,500rpm FES system. It was applied to dynamic voltage restorer to mitigate voltage sags and prevented the voltage ripple in power system. PMM/G parameters were: charge power of 2.9kW, maximum speed of 3,000rpm and rotational inertia of 4.2kgm$^2$, discharge power 200kW in time 0.5S, torque constant 1.39Nm/A.
- *2009:* Yu Li of Nanjing University of Information Science & Technology in China applied 2D FEA to design a 20,000rpm, 6/4 high speed PMM/G for a FES system. The stator outer diameter was 60mm, maximum voltage was 110V, and efficiency was 82%. The model had been optimal redesigned aiming at deducing the iron loss, and it was valid has been proved by the results.

### 2) Halbach structure PMM/G

- *2002:* Power System Laboratory of Korea and Electric Power Research Institute cooperated with Korea Electric Power Corporation to develop a 300W FES system with Superconducting magnetic bearing and high efficiency coreless 4 poles Halbach structure PMM/G, the rotor outer diameter was 44mm, stator inner diameter was 53mm. The FES system with a horizontal axle mounted can run smoothly up to 20,000rpm in a vacuum. The coreless Halbach structure M/G was effective on transferring electrical energy to the rotating composite flywheel in the kinetic forms.
- *2008:* A research conducted at Chungnam National University of Korea on a 5kWh, 215kg, FES system project. A 30kW class Halbach PMM/G with double-sided rotor and coreless three-phase winding stator has been analyzed for rotor magnetization and stator winding current. The torque was 14.3N at 20,000rpm, maximum voltage of output inverter was 350V, sine pulse width modulation current was 64A. Results showed that the dynamic Halbach PMM/G for the FES system was efficient even for a heavy flywheel, also can run in constant speed for a long time.

## VII. Improving the Reliability Using FES Systems

The FES systems offer great chances to enhance the reliability indices of an electric utility. Furthermore, the potentials in saving energy during the hours when there is excessive amount of energy and then consume them during the peak hours would lead to a great reduction in the generation cost. In addition, a reliable FES system leads to a secure operation in the system and reduces the chances of any major fault may occur due to the increase demand in specific time. Also, FES systems can be developed to serve in the solar energy projects. The ability to store the extra energy and reuse it again would be greatly beneficial in the solar systems, even for the small scale projects, such as the residential and commercial consumers that have solar systems in their roofs or/and buildings.

## VIII. Conclusion

Flywheel storage energy system is not a new technology; however, the deep interest in applying its principle in power system applications has been greatly increasing in the recent decades. Furthermore, research has been applied to exploit the great feature the FES can offer, which mainly exposed in power quality improvement and enhancement of the network reliability and stability. Also, advancements in the design of the flywheel energy units, composite materials, and power electronics devices have strongly presented the FES technology as vulnerable alternative to the electromechanical batteries, especially that FES systems have the features of storing and releasing energy in very fast time with very high operational efficiency. Besides, Flywheels are now used intensively in many applications related to power system such as telecommunications, utilities load leveling, and even in some additional applications in satellite engineering as well. In addition, it has been concentrated lately in distribution sectors of electrical power. Most of the distribution networks are exposed to voltage dips problems, and FES system, associated with its power electronics converters, offer effective compensation for the network [12]. Moreover, many researchers have started conducting studies to evaluate the high possibility of having FES systems with intermittent power system sources such as wind and solar systems [13]. This paper tried to demonstrate the concept of many technical papers on FES system. After illustrating the basic operational design and way of work, this paper described the role of the FES systems in the control of reactive power and power quality in distribution network. After that, a brief basic design and newly design of flywheels using SMB and PMB have been illustrated in some detail. The paper concluded with the recent developments in flywheels industry that can offer the FES systems in the future to be great solution to solve the power system reliability problems in the low-voltage distribution network.

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## References

[1] T. Aanstoos, J. P. Kajs, W. Brinkman, H. P. Liu, A. Ouroua, and R. J. Hayes, “High voltage stator for a flywheel energy storage system,” *IEEE Trans. Magazine*, vol. 37, no. 1, pp. 242-247, 2001.

[2] I. Vajed, Z. Kohari, L. Benko, V. Meerovich, and W. Gawalek, “Investigation of joint operation of a superconducting kinetic energy storage (Flywheel) and solar cells,” *IEEE Transactions on Applied Superconductivity*, vol. 13, no. 2, Jun. 2003.

[3] B. Bolund, H. Bernhoff, and M. Leijon, “Flywheel energy and power storage System,” *Renewable and Sustainable Energy Reviews*, vol. 11, no. 2, pp. 235-258, 2007.

[4] J. C. Zhang, L. P. Huang, Z. Y. Chen, and S. Wu, “Research on flywheel energy storage system for power quality,” in *Proc. International Conference on Power System Technology*, 2002, pp. 496-499.

[5] J. C. Zhang, Z. Y. Chen, L. J. Cai, and Y. H. Zhao, “Flywheel energy storage system design for distribution network,” in *Proc. IEEE Power Engineering Society Winter Meeting*, 2000, pp. 2619-2623.

[6] A. Al-Diab and C. Sourkounis, “Integration of flywheel energy storage system in production lines for voltage drop compensation,” in *Proc. 37th Annual Conference on IEEE Industrial Electronics Society*, Melbourne, VIC, 2011, pp. 3882-3887.

[7] M. Subkhan and M. Komori, “New concept for flywheel energy storage system using SMB and PMB,” *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3, Jun. 2011.

[8] K. Murakami, M. Komori, and H. Mitsuda, “Flywheel energy storage system using SMB and PMB,” *IEEE Transactions on Applied Superconductivity*, vol. 17, no. 2, Jun. 2007.

[9] H. Mitsuda, M. Komori, A. Inoue, and B. Nakaya, “Improvement of energy storage flywheel system with SMB and PMB and its performances,” *IEEE Transactions on Applied Superconductivity*, vol. 19, no. 3, Jun. 2009.

[10] Beacon Power, Response to the New York Energy Highway Request for Information (RFI), May 30th, 2012. Official Report.

[11] Y. L. Yu, Y. X. Wang, and F. Sun, “The latest development of the motor/generator for the flywheel energy storage system,” in *Proc. International Conference on Mechatronic Science, Electric Engineering and Computer (MEC)*, Jilin, 2011, pp. 1228-1232.

[12] Y. L. Yu, Y. X. Wang, and F. Sun, “Dynamic voltage compensation on distribution feeders using flywheel energy storage,” *IEEE Transactions on Power Delivery*, vol. 14, no. 2, Apr. 1999.

[13] T. Zouaghi, F. Rezeg, and A. Bouazzi, “Design of an electromechanical flywheel for purpose of renewable energy storage,” in *Proc. International Renewable Energy Congress*, Sousse, Tunisia, Nov. 5-7, 2010.

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