Techniques of Energy Storage for Use in Distributed Generation Systems

Gang Zhang, Jian Xun Jin, Bing Feng Wang, and Yi Bing Shi
Center of Applied Superconductivity and Electrical Engineering
School of Automation Engineering
University of Electronic Science and Technology of China, ChengDu, China
zhanggang@uestc.edu.cn

ABSTRACT

Energy storage technology is one of the effective methods to ensure the quality of the electrical power supply and the effective operation of distributed generation. In this paper, several main energy storage technologies are presented with regard to their operation theories, structures, performances and present development. These technologies include battery energy storage, ultra-capacitors energy storage, superconducting magnetic energy storage, and flywheel energy storage.

1. INTRODUCTION

With economic development, electric load increases rapidly. A multitude of environment concerns are enhanced, therefore various energy sources are gradually utilized, such as wind power, solar energy, tide energy and hydrogen generation. Distributed generation is expected to play an important role in the future with growth in electric load, enhancing the economical efficiency and protection of the environment. The quality and safety of power supply must be guaranteed with the growth in load. The energy storage technology is one of the effective methods to ensure the quality of the power supply. Energy storage makes a distributed generator running more stable, even in the situation of large load fluctuation, and makes distributed generation units more flexible which can be dispatched from electric grid. The present studied storage technologies mainly include battery, ultra-capacitors, flywheel and superconducting magnetic energy storage, which are all paid great attention and developed rapidly.

This paper presents these energy storage systems having different operation theories and structures, and will be concluded with the benefits from their different performance and present development.

2. ENERGY STORAGE TECHNIQUES FOR TRANSMISSION AND DISTRIBUTION APPLICATION

Load shedding or generator dropping when power system disturbances occur can be avoided, if high-speed real or reactive power control is available. High speed reactive power control is usually possible through the use of flexible ac transmission system (FACTS) devices. However, the superior solution is synchronously to rapidly vary real power using energy storage systems without impacting the system. This is where energy storage technology can play a very important role in maintaining system reliability and power quality [1]. The configuration of an integrated energy storage system in FACTS is shown in Figure 1.

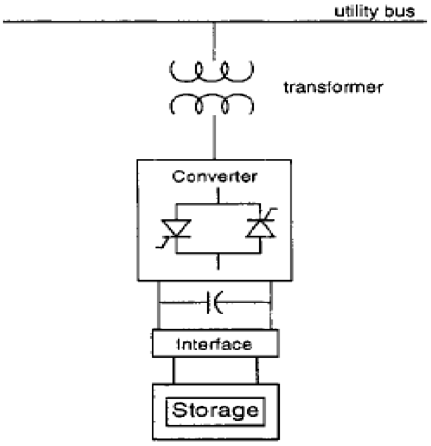

Figure 1: Integration of energy storage system into FACTS

Electrical energy in an ac system cannot be stored electrically. However, it can be stored by converting the ac electricity and storing it electromagnetically, electrochemically, kinetically, or as potential energy. Each energy storage system usually includes a power conversion unit to convert the energy from one form to another [2].

2.1. BATTERY ENERGY STORAGE SYSTEM (BESS)

Batteries, having energy stored electrochemically, are one of the most cost-effective energy storage technologies currently available. A battery system is composed of a set of low-voltage/power battery modules connected in series or parallel to achieve a desired electrical characteristic. BESS is especially suitable for use in a power system with fast response dynamic characteristics. This has been one of the most valued technologies in the short term energy storage and widely applied in small distributed generation. Most battery technologies are optimized for either power or energy, but not both. Furthermore, batteries that are designed for high power often cannot provide the repeated charge/discharge cycles that are required in many energy storage applications. There are many types of BESS actively under development.

2.1.1 LEAD-ACID BATTERIES

Although with low energy density and limited cycle life, lead-acid batteries are most widely utilized as a mature technology. Lead-acid batteries possess some typical merits of inexpensive, abundant raw material, and being produced in the large capacities. They especially suit for photovoltaic generation and are favoured in mobile and stand-by applications. High-power lead-acid batteries as automotive ones have reached a point where these products are highly reliable in normal use and lives of 4-5 years are quite normal. Lead-acid batteries have a fundamental problem that thin plates are required to optimize their high-power capability, but thinner plates have shorter operating lives [3]. And they will pollute environment after scrapped.

2.1.2 NICKEL-CADMIUM

Nickel-cadmium (Ni-Cd) batteries can be optimized for both high power and long life, because these batteries do not show any degradation of their internal hardware over time and their operating lives are independent of plate thickness. Ni-Cd batteries provide very long lives, and are typically quite resistant to abuse. Although Ni-Cd batteries are considerably more expensive per watt-hour than lead-acid, for high power applications they are often less expensive on a life cycle costing basis, particularly where long operating life is beneficial [3]. This technology is mainly used in small scale applications such as mobile telephones and portable laptop computers. Ni-Cd batteries prefer fast charge to slow charge and pulse charge to DC charge [4]. They allow recharging at low temperatures. In fact, Ni-Cd batteries are the only battery types that perform well under rigorous working conditions. They have long shelf life of five years storage. Ni-Cd batteries have some limitations: they have a moderate energy density, require periodic full discharges to prevent memory, otherwise, will gradually lose their performance, and contain toxic metals.

2.1.3 NICKEL METAL HYDRIDE

Nickel Metal Hydride (Ni-MH) batteries have higher energy density and less memory compared with Ni-Cd and only mild toxins. High specific capacity of Ni-MH batteries has close relation with their self discharge and cycle life. Along with increase of high specific capacity, high capability of discharge and charge, retaining charge and cycle life all fall [5]. Most of developments are proceeding for telecom and satellite applications. Ni-MH cells connected in series can also provide a high voltage of 150V for hybrid vehicles. Ni-MH is less durable than Ni-Cd, cycling under heavy load and storage at high temperature reduces the service life, and the performance starts to deteriorate after 200-300 cycles if repeatedly deeply cycled [4]. Ni-MH suffers from high self-discharge, which is 50% higher than that of Ni-Cd. It is short storage of three years. Ni-MH is regarded as an interim step to lithium-ion.

2.1.4 LITHIUM ION BATTERIES

Lithium ion batteries are the newest types which promise very high energy density, high operating voltage, good cycling capability and long life in stationary applications. The positive of lithium ion batteries is $LiCoO_2$, and negative is carbon material. It charges and discharges through lithium ion of positive ingoing and outgoing negative. The self-discharge of lithium ion batteries is less than half that of nickel-based batteries, and no periodic discharge is needed because of no memory. The battery contains no toxic substances, does not cause explosion and is not prone to combustion. Limited discharge current of less than 2C, the need for safety circuits and aging (especially in high ambient temperatures) are negative attributes of this battery. Manufacturers recommend storage temperatures of 5-40°C. In addition, the battery should be partially or fully charged during storage.

Lithium ion batteries are limited in applications of bulk energy storage due to cost. The manufacture cost is about 40 percent higher than nickel-cadmium because that Co resources are scarce then $LiCoO_2$ is expensive. However, it is quite likely that megawatt-level lithium ion batteries will emerge in the applications for high power and short duration discharges in the future. At present, the lithium ion battery of 10,000Ah has been commercialized. For example, Thunder Sky Co. provides the lithium ion battery which nominal capacity is 10,000Ah, nominal voltage 3.6V, and weight 350kg [6]. In addition, lithium ion batteries applied as 100kW uninterrupted power supply (UPS) and 14kW peak backup are in the status of testing.

2.1.5 COMMERICAL DEMOND IN FUTURE

Figure 2 expresses the demand for various batteries in past and future [7]. Because of low cost and dependable service, lead-acid is the most commonly used secondary battery at all times, and will hold a steady increase through to the year 2012. Improvements in energy density and charging characteristic are still an active research area. Lithium-ion is the fastest growing and most promising battery of today. They may start to take over some lead-acid applications along with the price reduced and the service life prolonged as it is absolutely superior to lead-acid in performances. Ni-Cd will be replaced with Ni-MH. In fact, Ni-Cd is preferred over Ni-MH for its high durability and reliable service, but some countries will ban its use by 2006 for environmental reasons. It is worth for Ni-MH to improve in capacity and durable grade.

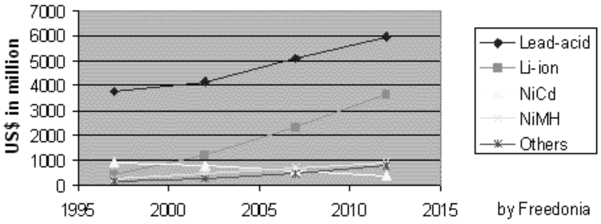

Figure 2: Demand for batteries

2.2 ULTRA-CAPACITORS

Ultra-capacitors, also know as super-capacitors, differ from conventional capacitors as well as batteries. Ultra-capacitors, consisting of two symmetric electrodes and an ionic electrolyte, accumulate and deliver energy through the absorption-desorption of electrolyte ions in the positive and negative plates and electrochemical process with electric charge transfer. For the superior ultra-capacitors performance, the ions sizes and pore sizes where the sorption process takes place, should be matched so that the pores in negative electrode are good recipients for cations and the pores in positive electrode are good recipients for anions [10]. There are three types of electrode materials suitable for ultra-capacitors, which are: high surface area activated carbons, metal oxide and conducting polymers. Figure 3 shows the capacitors structure.

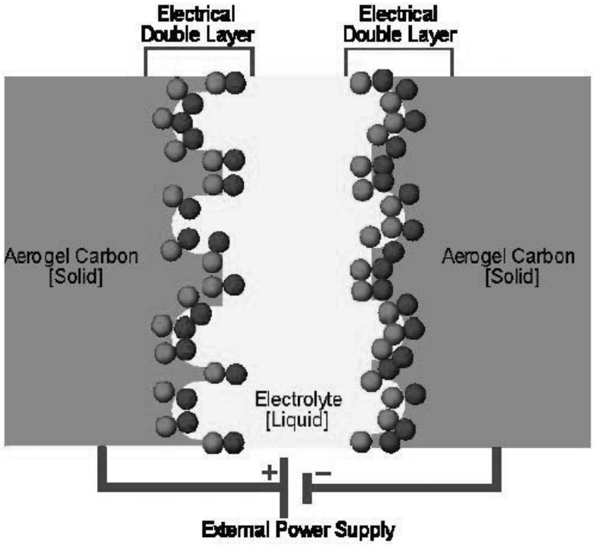

Figure 3: The ultra-capacitors structure

Ultra-capacitors have high energy storage capability due to increasing the area of the plates, increasing the permittivity, and decreasing the distance between the plates through the use of a porous electrolyte. The energy stored on the capacitor is shown in Equation (1),

$$E = \frac{1}{2} C V^2; \qquad C = \frac{\varepsilon A}{d} \tag{1}$$

where C is the capacitance, V is the voltage between the plates, ε is the permittivity of the dielectric, A is the area of the plates, and d is the distance between the plates. Large capacitance exhibited was demonstrated to arise from a combination of the double-layer capacitance and pseudo-capacitance associated with surface redox-type reactions. The large capacitance of ultra-capacitors mainly arises from pseudo-capacitance function [8]. Ultra-capacitors exhibit up to 1,000 times greater capacitance than conventional capacitors.

Ultra-capacitors have the advantages of high power density (over 18kW/kg), fast charge and discharge in seconds, long life (over ten years), compact structure, and low maintenance. Unlike batteries, ultra-capacitors can be cycled virtually an unlimited number of times, and without danger of overcharge or memory. Aging does not affect ultra-capacitors much. On the other hand, ultra-capacitors have some limitations. The gravimetric energy density of ultra-capacitors is low, only 1 to 10Wh/kg. This energy density is high in comparison to a regular capacitor but reflects only one-tenth that of Ni-MH batteries. The self-discharge is considerably higher than that of batteries. Ultra-capacitors are unable to deliver the full electric charge, because that the voltage of ultra-capacitors is linear and drops evenly from full voltage to zero. Using a DC-to-DC converter could make full electric charge being delivered, which would just add costs and introduce a 10 to 15 percent efficient loss [9]. Ultra-capacitors have low voltage, but then higher voltage can be obtained by serial connection of ultra-capacitors. If more than three capacitors are connected in series, voltage balancing is required to prevent any cell from reaching over-voltage.

Rather than operate as a main battery, ultra-capacitors are most applicable for high peak-power and low-energy situations. They perform the tasks such as reactive power compensation, current harmonic reduction, load unbalance compensation, and smoothing of pulsating loads. So ultra-capacitors have high potential to be used in distributed generation. Moreover, a new energy source by combining ultra-capacitors with batteries in parallel is being paid attention to. Because ultra-capacitors can supply a large burst of current, but cannot store much energy, conversely, batteries can store mass amounts of energy without expensive and inefficient units, however, cannot provide the current that the ultra-capacitor can. The storage and peak current characteristics desired can be achieved by the means.

Ultra-capacitors have sufficient potential in improving energy density and reducing cost. High specific capacitance electrode materials, especially low price carbon and metal oxide, are studied further. At present, the ultra-capacitors of 4,500F, made of SkeletonC carbon electrode and AN-electrolyte, have been developed by SkeletonC Nanolabtory, which energy storage is 16.4kJ, specific energy 9.2Wh/kg, rated voltage 2.7V, rated current 800A, series resistance 0.2mΩ, power at rated current 3.0kW/L, and power matched impedance 18.4kW/L [10]. High energy ultra-capacitors, which rated power is in kW~MW and discharge duration is several hours as energy management, is under research and development.

2.3 SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

It was not until the 1970s that SMES was first proposed as an energy storage technology for power systems. Most of the conceptual work on SMES up to the late 1980s was for the large-scale energy storage application. SMES stores energy in the form of dc electricity that is the source of a dc magnetic field. SMES devices contain three major components: a superconducting magnet (i.e. a superconducting coil) and its cryogenic enclosure, a refrigeration system to maintain the magnet at a cryogenic temperature, and an interface between the direct current in the magnet and the ac power grid. Figure 4 shows the components of SMES systems. The inductively stored energy (E) and power (P) of SMES devices can be expressed as following Equation (2),

$$E = \frac{1}{2} L I^2; \qquad P = \frac{dE}{dt} = LI\frac{dI}{dt} = VI \tag{2}$$

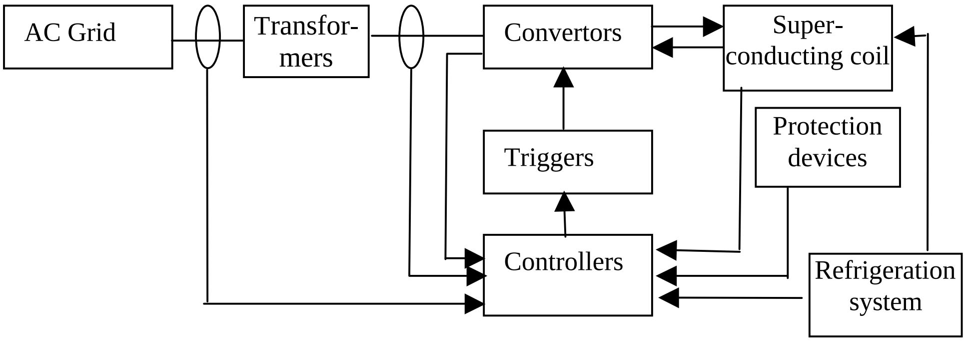

Figure 4: Components of SMES systems

where L is the inductance of the coil, I is the dc current flowing through the coil, and V is the voltage across the coil. Since energy is stored as circulating current, energy can be drawn from a SMES unit with almost instantaneous response with energy stored or delivered over periods ranging from a fraction of a second to several hours. Moreover, due to inductance of superconductor and no resistance loss, the current in a closed inductor does not disappear for a long cycle.

SMES systems have some typical characteristics: fast response (milliwatts/millisecond) and high efficiency (charge-discharge efficiency over 95%), long life, high reliability, no limitation of ground, and no environment pollution. SMES systems can be used for large power or efficient energy management due to the capacity of their stored energy and power condition can be independently maintained in a wide range. The disadvantages are high cost, and the need for maintenance of the refrigeration system.

Strong electromagnetic force caused by high magnetic fields and coil current is a serious problem in SMES systems. In facing this problem, the concept of the Force-Balanced Coil (FBC) has been proposed which is a helically wound toroidal coil applied to SMES [11]. The FBS on the Virial limit line can minimize the structure requirement and reduce the mass of the structure to a quarter of that in the toroidal field coil case and 1/4~1/2 of that in the solenoid case. It is the most effective coil configuration for large scale SMES systems. The shapes of these coils are shown in Figure 5.

SMES system applications have been considered for 1) load levelling; 2) frequency support (spinning reserve) during loss of generation; 3) enhancing transient and dynamic stability; 4) dynamic voltage support (VAR compensation); 5) improving power quality; and 6) increasing transmission line capacity, thus enhancing overall reliability of power systems [2,12].

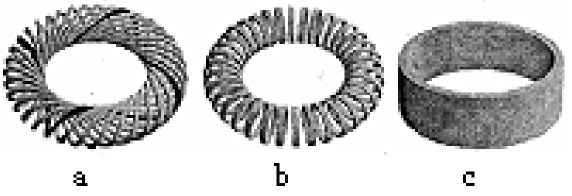

Figure 5: The shapes of superconductor coils. a: Force-Balanced Coil, b: toroidal field coil, c: solenoid coil

SMES, made of low temperature superconductors working at liquid helium temperature and used in limited range, is extremely expensive. The advent of high temperature superconductors (HTS) which are superconducting at liquid nitrogen temperature (77K) greatly promotes the various applications of superconductors. HTS winding has been made from BSCCO (Bi-2223) tape and used for electrical applications [13-14]. Although the production of the next generation HTS wire, Ni-based YBCO tape, is not easy manufactured at present, the YBCO tape has high utility and becomes convenient for a batch production. Potential development of practicable SMES will be based on HTS.

In many storage methods, the SMES is fairly suitable for huge energy storage, however the cost of the AC/DC converter is also expensive [11]. Further development continues in power conversion systems and control schemes. Evaluation of design and cost factors is analysed for various SMES system applications. Presently, middle and small size SMES are more prospective in applications than large one.

2.4 FLYWHEEL ENERGY STORAGE

FES is an electromechanical storage mode using the kinetic energy of a rotating mass. The typical system consists of three parts: a flywheel containing a rotor with a bearing, a motor/generator and a set of power converters. Figure 6 shows the components of FES systems. The motor/generator converts energy between electrical and mechanical forms. Stored energy depends on the moment of inertia of the rotor (I) and the square of the rotational velocity of the flywheel (ω), and the moment of inertia depends on the radius (r), mass (m), and height (h) of the rotor, as shown in Equation (3).

$$E = \frac{1}{2} I \omega^2; \qquad I = \frac{r^2 m h}{2} \tag{3}$$

During charge, an electric current which is converted by power electronics converters flows through the motor and accelerates flywheel rotating. During discharge, the generator produces current which is converted by power electronics and sent to power grid decelerating the flywheel.

FES has merits in energy storage such as high conversion efficiency, long life, no pollution, short period of construction, and little maintenance. It is fairly competitive for the application in distribution generation. FES has been considered for several power system applications, including power quality application as well as peak shaving and stability enhancement. There are instances of FES in wind-power generation systems [3,11].

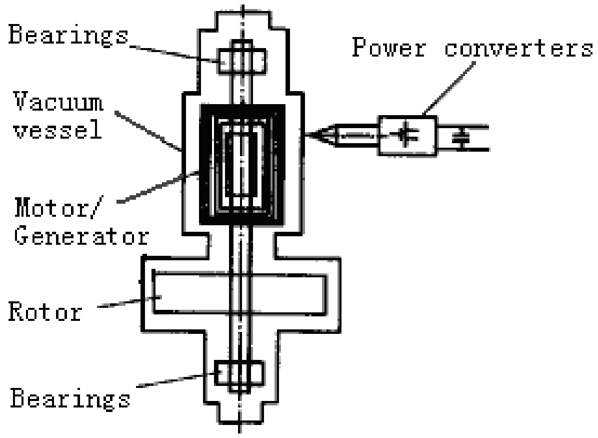

Figure 6: Components of flywheel energy storage devices

Before the 1980s, the FES technology developed slowly because of many unsolvable problems such as the driving of high speed flywheel, the high efficient energy converting, the friction of flywheel bearing, and the loss of wind resistance. With the developments of modern power electronics and high temperature superconducting magnetic bearing and the discovery of new high intensity materials (e.g. carbon-fibre and fibreglass), the FES technology is quickly growing and coming into utility.

Developers have explored monolithic metallic rotors for low-speed operation and low density, and high strength resin/carbon-fibre composite rotors that operate at very high speeds [15]. The flywheel and motor/generator operate in vacuum vessels to reduce air resistance and increase efficiency. Using superconducting magnetic bearings (SMBs) greatly reduce friction of the operation and increase life-span. The SMBs are composed of a ring-shaped superconductor and some permanent magnets. The rotor-flywheel is sandwiched between two disc-type stators, and a combination of active and passive magnet bearings allows the rotor-flywheel to spin and remains in magnetic levitation [16]. Thus, the efficiency of FES is up to 95%. Some countries • such as America, Japan, Germany, are developing high temperature superconducting magnetic bearing for high-velocity FES system. At the same time, a high tensile strength and low density material of rotor is further researched for increasing the energy storage capabilities, because the tensile strength and the density of the material are the factor that limits the energy storage capability of a flywheel.

2.5 OTHER TECHNOLOGIES

Some other large-scale energy storage technologies have been considered and applied for a scale for utility applications, including underground thermal, pumped hydro and compress air energy storage. They can be stored energy even to smooth out annual fluctuations with low energy losses. However, they can only be built in suited areas due to depending on geological formations and must be implemented as large systems.

3. COMPARING

As these energy storage technologies have different performances and applications, none of them are optimal for all purpose. Some of the key properties of the storage technologies are compared in Table 1.

Table 1: Some key properties of different storage technologies

Energy storage technology	Batteries	Ultra-capacitors	SMES	Flywheel
Efficiency	Low	High	Very high	High
Capital cost /Wh	Low	Moderate	High	Moderate
Lifetime	3-5 years	>10 years	Very long	Very long
Cycle times	$<10^4$	Unlimited	Unlimited	Unlimited
Maintenance	High	Low	Moderate	Low
Environment hazard	Some	Minimal	None	None
Energy density	Moderate	Very Low	High	High
Power density	Low	High	High	Moderate

Batteries are low capital cost of manufacture and short lifetime. Ultra-capacitors have high power density and low energy density. On the contrary, flywheel has moderate power density and high energy density. SMES technology possessed high energy density as well as power density. The different properties determine different applications of the energy storage technologies. Ultra-capacitors, SMES and Flywheel are superior to batteries, high efficiency, longer lifetime, unlimited cycle times, low maintenance, and little environment hazard. They are considered as only three energy storage technologies meeting the energy storage criteria in solar space power by Texas Space Grant Consortium. If batteries are stored the order of MWh energy, they are more expensive than other three energy storage technologies. In general, among the factors affecting the future potential of energy systems are the fundamental properties and nature of the storage systems, and also the type of materials used. If an energy storage technology will obtain broad applications, its cost must be reduced along with the improvement of property.

4. CONCLUSIONS

The combination of distributed generation and energy storage improves the energy efficiency. With wide applications of distributed generation, various energy storage technologies will be more widely applied. Among these storage technologies, ultra-capacitors and SMES can act as reactive power compensation, besides active power compensation. FES is easier realized than SMES, however SMES system is the most potential one in future applications. Although BESS has some disadvantages, it will continue to flourish and improve for good, sound maintenance practices.

REFERENCES

[1] Yang, Z.; Shen, C.; Zhang, L.; Crow, M.L.; Atcitty, S.; Integration of a StatCom and battery energy storage, IEEE Transactions on Power Systems, Vol. 16, No. 2, pp254 – 260, 2001.

[2] Ribeiro, P.F.; Johnson, B.K.; Crow, M.L; Arsoy, A; Liu, Y.; Energy storage systems for advanced power applications, Proceedings of the IEEE, Vol. 89, No. 12, pp 1744 – 1756, 2001.

[3] Corey, G.P.; Batteries for stationary standby and for stationary cycling applications part 6: alternative electricity storage technologies, Power Engineering Society General Meeting, 2003, IEEE, Vol. 1, pp164 – 169, 2003.

[4] “The nickel-based battery, its dominance and the future”,

http://www.batteryuniversity.com ,2003.

[5] Wu Ji-ming, Li Wen-shun, Zai Yun-xiao, Relations of specific capacity of Ni-MH battery with self discharge and cycle life, Chinese Battery Industry, Vol. 9, No. 4, 2004:197-199.

[6] “Battery”,http://www.thunder-sky.com/, 2006.

[7] “Battery statistics”,

http://www.batteryuniversity.com , 2004.

[8] Wang Xiao-Fen, Xie Jing-Ying, Kong Xiang-Hua, Progress of electrode materials for “supercapacitor” electrochemical capacitors, Chinese Jounal of Power Sources, Vol.25 pp166-170, Supp1, May 2001.

[9] “What's the role of the Supercapacitor”, http://www.batteryuniversity.com , 2003

[10] “supercapacitors”, http://www.skeletonnanolab.com, 2005

[11] Shimada, R.; Novel application of electric energy storage using flywheel/SMES, Power Electronics and Motion Control Conference, 2004. IPEMC 2004. Vol. 1, pp73 – 81, 20 on04.

[12] Beduz, C.; Yang, Y.; Richardson, R.N.; Norris, W.T.; Magnetic Energy Storage Using High Temperature Superconductors, AC and DC Power Transmission, Sixth International Conference on (Conf. Publ. No. 423), pp417 – 423, 29 Apr-3 May 1996.

[13] J.X. Jin, C. Grantham, Y.C. Guo, J.N. Li, R. Bhasale, H.K. Liu, and S.X. Dou, “Magnetic field properties of Bi-2223/Ag HTS coil at 77 K”, Physica C, Vol. 278, pp85-93, 1997.

[14] J.X. Jin, S.X. Dou, C. Grantham, and H.K. Liu, “Preparation of high T_c superconducting coils for consideration of their use in a prototype fault current limiter”, IEEE Transactions on Applied Superconductivity, Vol. 5, No. 2, pp 1051-1054, 1995.

[15] Chen Junling, Jiang Xinjian, UPS using flywheel energy storage, JTsinghua Univ (Sci & Tech), Vol.44, No.10, pp1321-1324, 2004 .

[16] C.Zhang, K.J Tseng, J.Zhon, A compact and efficient flywheel energy storage system with integrated magnetic bearings, Conference Proceedings IPEMC 2004. Vol.1, pp294-299, 2004.