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Energy Storage Methods

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EECE 492 – Distributed Power System Management

Date submitted: April 6, 2012

Abstract

This paper provides a general introduction of various storage methods in five main categories: chemical energy storage, electrochemical energy storage, electrical energy storage, mechanical energy storage, and thermal energy storage. Among all storage methods, flow battery storage systems and flywheel energy storage systems are chosen to be investigated of their working principles, capacities, applications and future outlook in detail.

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1.0 Introduction

Electricity has become a necessity to humans in most countries over the past 100 years. Due to the fast growing population and the limited power source, power grids play an important role to ensure people can obtain electricity anywhere at any time. Currently, the total worldwide energy production exceeds 3400 GW while storage capacity is only 90 GW. In an economic point of view, the development of energy storage systems which have high efficiency and the ability to integrate in large-scaled electrical utilities is extremely important.

As the power grids become larger and more complicated, advanced energy storage needs to ensure their reliability and energy demand managements. This paper will briefly explain all kinds of energy storage methods. Flow battery storage systems and flywheel energy storage systems which are capable of grid energy storage will be investigated further. This paper will identify their advantages, disadvantages, applications, and future outlook.

2. Overview of Energy Storage

Storing energy became extremely important with the introduction of electricity since electricity must be available whenever needed and must be used immediately after being generated. Moreover, many renewable energy technologies such as solar and wind energy do not provide a reliable power generation; thus, energy storage is essential from the views of economy and practicality.

2.1 Grid Energy Storage

As the marked price difference between peak hours and non-peak hours for the distributed grid, it is beneficial to store the electrical energy when production exceeds consumption and use the stored energy in peak hours. Grid energy storage system allows power plants to scale in a minimum way, which results in an increased efficiency and lower cost of energy production. Also, with the use of grid energy storage, it can facilitate the use of intermittent energy sources which depends on the weather. [1]

2.2 Storage Methods

There are five main methods for energy storage: chemical energy storage, electrochemical energy storage, electrical energy storage, mechanical energy storage, and thermal energy storage.

Electrochemical energy storage is the earliest approach to store energy, which includes batteries and fuel cells. Both batteries and fuel cells were invented about the same time and have small power capacity and high cost. They both convert chemical energy to electrical energy. However, batteries have limited use and limited internal energy storage whereas fuel cells have an external fuel supply.

Chemical energy storage is the dominant storage method in both electrical generation and energy transportation. Chemical fuels, such as coal, gasoline, and diesel fuel, converts to mechanical energy first then to electrical energy using heat engines that sued for electrical power generation. In addition, for transportation, liquid hydrocarbon fuels are often the main sources. While most chemical fuels produce greenhouse gases, hydrogen is the only carbon-free chemical fuel. Although hydrogen is environmental friendly and can be produced from any primary energy source, it still cannot replace existing hydrocarbon fuels yet due to its more expensive cost.

Capacitors, supercapacitors, and superconducting magnetic energy storage (SMES) all belong to the electrical energy storage. Comparing to batteries, electrical energy storage generally has indefinite lifetime, higher efficiency, and higher power density, which can carry more current. Capacitors are able to deliver high current but only a very short period of time due to their low capacitance, which have high power density but low energy density. Supercapacitors are double-layer capacitors which have huge effective surface and are available in a reversible process. These capacitors have been improved to have higher permittivity and higher voltage-withstand capabilities. Their small leakage current enables longer time of energy storage and the efficiency of over 95%. SMES is used in large scaled application since it can provide megawatts of power. The energy is stored in DC and is released in AC. Although SMES is highly efficient, which is greater than 95%, the cost of required refrigeration for the system and superconducting wire limit its application. Currently, SMES is used to improve power quality and accommodate energy consumption in peak hours.

Mechanical energy storage has pumped storage hydroelectricity, compressed air energy storage (CAES), and flywheel energy storage. Using the excess electricity at off-peak hours, pumped storage pumps water up to the reservoirs and releases it to retrieve the energy needed in peak hours. Similarly, CAES stores off-peak hour energy by compressing air and releases energy at peak hours by heating the compressed air with the exhaust heat of a combustion turbine. Electricity is then produced when the heated air flows through an expansion turbine. Lastly, where energy source is not continuous, flywheels are often used to store energy by increasing its spinning speed. The moment of inertia resists the changes in rotational speed as a way of storing rotational energy. A mechanical load will be applied to a flywheel to release the energy, which results in a decrease of its rotational speed.

Thermal energy storage is the storage or removal of heat. The common ones are the production of ice and hot water. However, the storage for heat is less common than using thermal storage for heat removal.

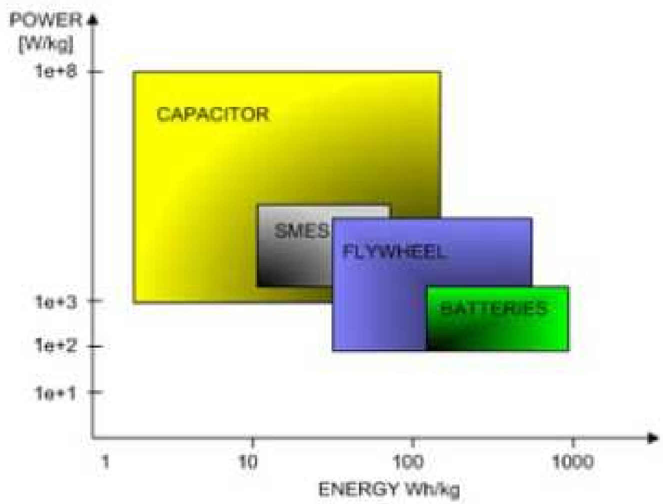

Figure 1: Specific power and specific energy ranges [12]

3. Battery Energy Storage Systems (BESS) – Flow Battery

Since the battery has been invented in 1800, it has become a common power sources for both household and industrial application. As the scale of power grid becomes larger and larger, controlling peak energy usage, power quality and environmental problems has become an important issue in power networks. The BESS which uses rechargeable batteries are recognized to be one of the best ways to apply in distributed power sources and regulating power networks.

Flow batteries are electrochemical storage systems which can be recharged by simply putting in fresh electrolyte to replace the used electrolyte if no power source is available. The tanks that store the electrolyte are separated from the batteries. Among all the available electrolytes, vanadium-vanadium and zinc-bromine are the most common electrolytes nowadays.

3.1 Working Principle

The flow battery is also called the redox flow battery since the functioning of a flow battery is based on an oxidation and a reduction reaction to crease a flow of electricity. A flow battery consists of two external electrolyte tanks and two parallel electrodes separated by an ion exchange membrane, forming two half-cells. Each half cell is recharged by pumping externally stored electrolytes during operation.

Here, the vanadium redox flow battery (VRFB) is demonstrated as an example. The VRFB is charged and discharged by the oxidation and reduction reaction through the valence change of Vanadium ion. Before discharging process, VO_2^+ is in the positive electrode and V^{2+} is in the negative electrode. During discharging process, VO_2^+ is reduced to VO^{2+} and the H^+ moves from the positive electrode to the negative through the ion-exchange membrane. In the meanwhile, V^{2+} is oxidized to V^{3+} at the negative electrode, which e^- moves from the negative electrode to the positive through the external circuit. [4] The full ionic equations can be shown as follows:

Discharging:

Positive electrode reaction:

$VO_2^+ + 2H^+ + e^- <-> VO^{2+} + H_2O$

Negative electrode reaction:

$V^{2+} <-> V^{3+} + e^-$

Total cell reaction

$VO_2^+ + 2H^+ + V^{2+} <-> VO^{2+} + H_2O + V^3$

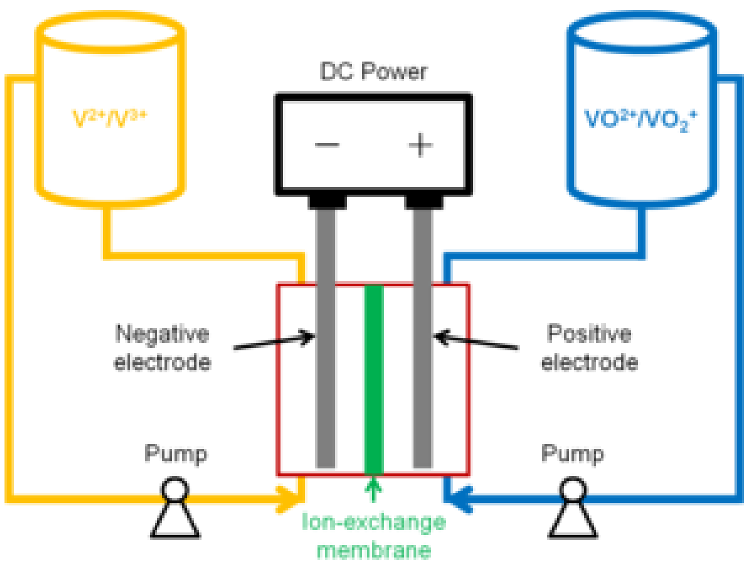

Figure 2: Schematic of a vanadium redox flow battery [5]

While power source is available, charging process can be achieved by switching the external electric circuit.

Usually, the cell consists of several unit cells connected in parallel for electrolyte circulation and connected in series for electric circuit. The parallel electrolyte circulation ensures that the concentration of the electrolyte in each unit cell remains the same.

3.2 Lifetime and Efficiency

Vanadium redox flow batteries (VRFB) can generally undergo around 14,000 cycles. Although VRFB can be fully charged and discharged without reducing life expectancy, proton exchange membrane and the pumps are the limiting factors, where each of them can be replaced. [7] Also, by modifying the electrolyte solution, the flow battery can increase the energy storage capacity by 70% and expand the temperature range. This will result in a reduced size of flow batteries and an efficiency of approximately 87% according the United States Department of Energy's Pacific Northwest National Laboratory. [9]

3.3 Application and future outlook

Because flow batteries have long life cycle, quick response time, and overload operation ability, they are widely used in grid-level system, uninterruptible power supply (UPS), and electric vehicles. However, due to the more complicated system requirements, such as pumps, sensors, flow and power management, flow batteries are not yet used in many commercial applications. Also, "VRBs are not a viable option for cars. The energy density of gasoline equals 13,000 watt-hours per kilogram, while the typical VRB is still not much better than a lead-acid battery—about 40 watt-hours per kilogram." [7]

In order to commercialize flow battery system, round trip energy-storage efficiency, cost of energy storage in terms of $/kWh, and cost for the power capacity of $/kW are the main research topics in the future. For example, designing a flow battery system with minimum pumping and shunt current losses can be significant for stacks of large numbers of cells. Furthermore, electrolytes and membranes can be improved so that the cost can be lower and the power density can be increased. [8]

4. Flywheel Energy Storage Systems (FESS)

Flywheel Energy storage systems is a mechanical storage which stores electricity into rotational energy. It is an energy storage system that requires little maintenance and has no environmental issues.

4.1 Working Principle

The flywheel energy storage consists of three parts: flywheel, motor/generator, and power electronic system. When the power generation exceeds consumption in a system, the motor converts electrical energy to rotational energy by spinning up the flywheel. On the contrary, the generator produces current flow out of the system slowing the flywheel down. For power electronic system, it includes a three phase transistor converter that works as a rectifier to enable bidirectional power flow and stabilize DC voltage. [12]

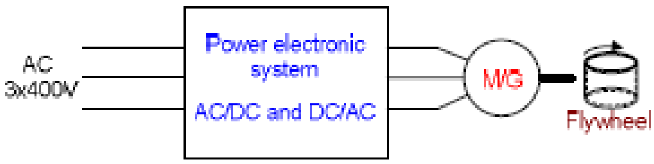

Figure 3: Schematic view of the flywheel energy storage system [12]

The kinetic energy of a flywheel is given by

$$KE = \frac{1}{2} I\omega^2$$

where KE is the kinetic energy, I is the moment of inertia, and ω is the angular velocity of the flywheel.

Moment of inertia: $$I = \frac{1}{2}mr^2 = \frac{1}{2}r^4 a\rho$$

where r is the radius, *a* is the length of the cylinder, m is the mass, and is the density.

Angular velocity: ω = (2*pi*n)/60, where n is rated speed in rpm.

In order to reduce friction, the modern flywheel uses carbon-fiber composite which has a higher tensile strength than steel and is less heavy. Moreover, the modern flywheel is suspended by magnetic bearings inside a vacuum chamber which do not require any lubrication or generate significant heat component. The new magnet bearings use the combination of a superconducting magnetic bearing (SMB) and a permanent magnet bearing (PMB). “The SMB mainly suppresses the vibrations of the rotor and the PMB passively controls the position of the rotor.”[13] As shown in figure 4, SMB is in the lower part and PMB is in the upper part of the system. As magnet windings in SMB need to be cooled down below their critical temperature, it is more effective to have SMB in the lower part.

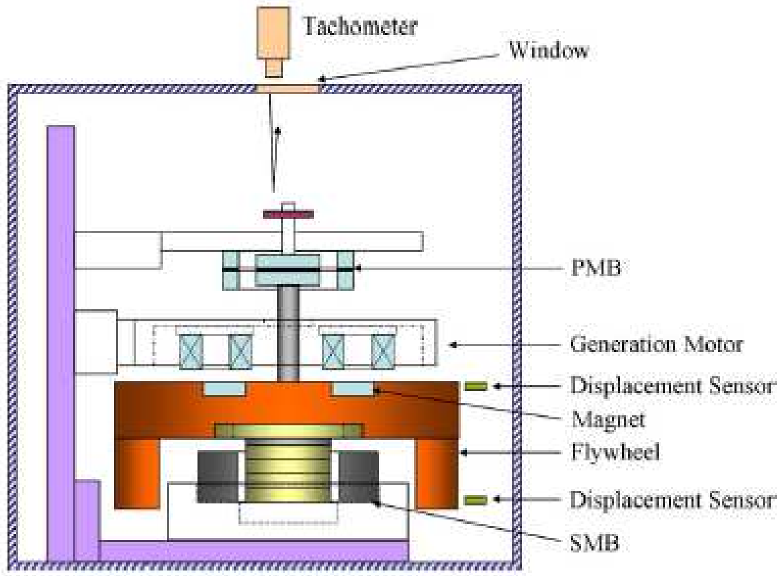

Fig. 2. New flywheel energy storage system using PMB and SMB.

Figure 4: New flywheel energy storage system using PMB and SMB [13]

4.2 Capacity and efficiency

Advanced FESS which have their flywheels made of carbon-fiber composite and suspended by magnetic bearings can spin at speeds from 20,000 to over 50,000 rpm in a vacuum chamber. They have a capacity of 3kWh to 133kWh and an efficiency of 90%. [14]

4.3 Advantages and disadvantages of FESS

Table 1 is a summary of advantages and disadvantages of FESS.

Advantages	Disadvantages
Power and energy are nearly independent	Complexity of durable and low loss bearings
Fast power response	High capital cost (10 times more expensive than pumped hydroelectric)
High cycle and calendar life	Material limits at around 700M/sec tip

	speed – low energy density
Relatively high round-trip efficiency (97% mechanical efficiency, 85% round trip efficiency)	Potentially hazardous failure modes (for traditional bearings only)
Short recharge and discharge time	Short discharge time

Table 1: summary of advantages and disadvantages of FESS [15]

As shown in the table 1, the short discharge time can be seen as an advantage and a disadvantage because it can be used to improve power quality yet is limited in large scale applications. Figure 4 shows a comparison of flywheel discharge time and power rating with other energy storage systems.

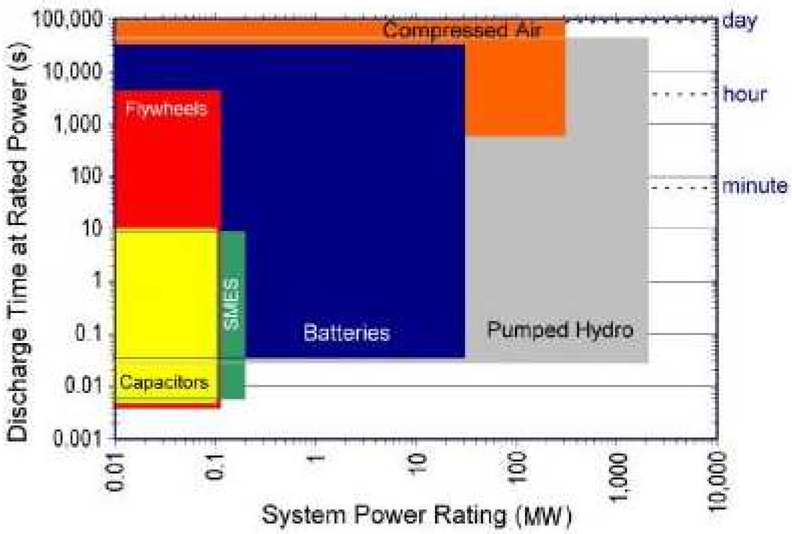

Figure 4: Comparison between flywheel storage system and other storage systems [15]

4.4 Application and future outlook

In addition to the main advantages of FESS such as short charge and discharge time, they are also very competitive economically in both price per unit power and energy.

Therefore, FESS is wildly used in space and power systems areas.

In the power system, FESS are mainly used for short term power storage and uninterruptible power supplies (UPS) due to their fast responses. For example, FESS are often connected to wind energy system to improve the fluctuated active power quality and voltage regulation since they store the electricity in overproduction and restore energy in underproduction.

FESS can also be operated with battery storage systems that have limited life span such as acid-lead battery storage systems. They can improve the battery life-time by allowing batteries to charge and discharge at nearly constant current values.

Currently, the main obstacle of flywheel usage is the amount of energy that it is able to store. However, this can possibly be overcome soon as better composite materials for flywheel are being developed. “US Flywheel Systems predicts that with better composites, specific energies of 200 Wh/kg (10 times higher than current specific energy density) and specific power of 30 kW/kg will be possible. [16]”

Boeing is also working on high temperature superconducting bearings which have losses only .1% per hour comparing to 1% per hour for magnetic bearings. However, due to the required energy for cooling, it has not been proven its effectiveness yet. [16]

Conclusion

Grid energy storage can increase the efficiency of the power plants and lower the cost of energy production by allowing power plants to scale in a minimal way. Grid energy storage can also facilitate the renewable energy technologies since it can store the exceeding energy to another form of energy and restore it back to electricity when needed.

This paper investigates flow battery storage systems and flywheel energy storage systems which both are capable of grid energy storage. The flow battery storage creates electricity through an oxidation and a reduction reaction. It can recharge and discharge without reducing its life span. By changing the electrolyte solution, the flow battery can increase energy storage capacity and efficiency. Flow battery storage systems are widely used in grid-level system, uninterruptible power supply and electric vehicles. However, due to the complexity of the design, flow batteries are not yet used in many commercial applications.

Flywheel energy storage systems (FESS) turn electricity into rotational energy. When charging, flywheel accelerates its rotational speed and vice versa. Current flywheel energy storage system reduces friction by implementing vacuum chamber and magnetic bearings, which allows the rotor to levitate. With its fast responses, FESS are often used to improve power quality in wind power systems and voltage regulation. Moreover, FESS require little maintenance, has no environmental issues, and have competitive price in power storage, making it an energy storage system with great outlook.

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