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Battery Energy Storage Technologies for Sustainable Electric Vehicles and Grid Applications

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Abstract. The energy consumption in worldwide has been increasing rapidly, due to increase in world population. This energy consumption growth is apparently impacting on the environment and the society. This has accelerated the development and deployment of Renewable Energy Sources (RES) harvesting technologies and facilities. The global electricity production by RES by the end of 2016 is accounted to 24.4%. This increase in RES has highlighted the next big challenge, storage of energy when demand is lower than the supply. There are many energy storage technologies existing from decades. Battery technologies have the highest cost reduction potential at the moment. Battery technologies are delivering significant advances in a wide range of industries, from electrical vehicles to renewable power. From the discovery of electrical energy, there is a great need to store the electrical energy generated for use on demand. Energy Storage Systems (ESS) is used to store the excess electricity when a power production is greater than consumption. ESS play very important role for off-grid storage applications to back up Renewable Energy such as Solar and Wind power, used by people who live or work in remote areas. Electrical energy can be stored in different forms including Electrochemical- Batteries, Kinetic Energy-Flywheel, Potential Energy-Pumped Hydro, and Compressed Air (CAES). This paper gives the current state of battery storage technologies, its main challenges, its applications and actions for future.

1. Introduction

In large scale power generation systems such as solar and wind energy generation systems, there is a need to store excess energy generated by them and supply the stored energy during the peak hours. This energy storage needs an efficient and enhanced operating system called Hybrid Energy Storage Systems. Due to the increasing demand to counter global warming, the role of energy storage technologies in the field of renewable energy generation and hybrid automobile systems are becoming increasingly important [1]-[2]. The applications of Energy Storage Systems (ESS) are wide spreading in many sectors such as electronic portable devices, electric traction systems and propulsion systems, automatic vehicles and stationary systems, lighting, standby power and remote area power supply. Continuous improvements in renewable energy sources generation and energy storage technologies should take place in order to meet the increasing energy demand of the variable energy sources. The deployment of ESS are increasing in worldwide markets and expected to grow 40% annually in the next decade, adding to 80 GW of new storage system capacity, with the 2 GW existing today. There is



a great need to increase the consciousness to the customers regarding, efficient energy consumption paired with smart home metering with operative load management, for the growth of ESS [3]-[4].

The modern power grids are ensuring the proper usage of devices for storage of bulk energy generated by Renewable Energy Sources such as Solar and Wind. Static batteries and other energy storage devices are encouraged in these systems to shift energy usage over time. The transportation system is also significantly modernizing, bringing the new environmental friendly means of transport such as Plug-in Electric Vehicles (PEVs). Efficient storage devices are needed for proper storage of energy generated by RES. Over a history of 150 years, lead-acid battery provides efficient output performance ranging from low to high temperature zones with ensured reliability. These battery technologies are still progressing and expanding technically. Recycling technologies of these lead-acid batteries already exist [5]-[6]. There is need of increasing widespread need of new storage devices which can be attained by using lithium ion secondary battery and lithium ion capacitor. Lithium ion capacitor uses electric double layer capacitor, consisting of active carbon cathode and lithium ion secondary battery as anode. It has superior input and output performance with in short time window.

Lithium ion capacitors are forming the next generation energy storage device. The major characteristics of ESS include energy density, power density, charging speed, life span, cost, weight and size. Batteries and super capacitors are forming the main options for ESS. Batteries are having higher energy density with low cost per watt-hour, but they have low specific power and short life cycle. Whereas, super capacitor has high peak power, long life cycle but relatively low energy density and high cost per watt-hour. However, combining both these technologies form a Hybrid ESS (HESS) with all the advantages. This paper gives the various energy storage technologies, their importance and applications [7]-[9].

2. Energy Storage Technologies

The electrical energy can be stored by transforming it into other forms such as mechanical, chemical, thermal, electrochemical. The type of energy produced, duration of storage and application will affect the characteristics of Energy Storage Systems which is derived by mathematical equation as:

$$ST(t) + PR(t) = SU(t) \quad (1)$$

Where $ST(t)$ is the power stored in the ESS which is taken as function of time, which is considered as negative when charging and positive when discharging the power. $PR(t)$ is the produced power by Generation station which is installed. This can be supplied to ESS or to grid or which can also lost by dissipation in network. The supply profile $SU(t)$ is the time function of time. The actual power supplied is give as $A * SU(t)$; where A is the scalar quantity accounting for storage dissipation and that is gives as:

$$ST(t) + PR(t) = A * SU(t) \quad (2)$$

It is not easy to calculate the value of 'A'; it needs clear understanding of the systems loss rate as a function of time. The power loss is given as

$$P_{Loss} = \int_{t_1}^{t_2} PR(t)dt - A \int_{t_1}^{t_2} SU(t)dt \quad (3)$$

The average system efficiency of ESS can be expressed as:

$$\eta_{ESS}^{total} = \frac{A \int_{t_1}^{t_2} SU(t)dt}{\int_{t_1}^{t_2} PR(t)dt} \quad (4)$$

The revenue earned by the renewable generation or ESS of the micro-grid is a function of actual supply profile $A * SU(t)$ and time dependent model of electricity tariff. Hence the ESS must ensure that the desired supply profile should always be met when it is added with production profile for the efficient and reliable operation of micro-grid.

The basic classification of Electrical Energy Storage Systems is as given in Figure.1.

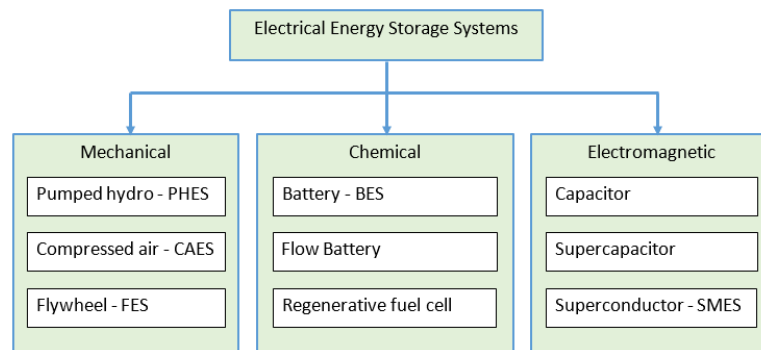


Figure.1 Basic Classification of Electrical Energy Storage Systems

3. Mechanical Energy Storage Systems

In this type of ESS, energy is converted from electrical to mechanical form. These systems work on the principle of potential energy; kinetic energy pressurized gas and forced spring. During off-peak hours the electrical energy from the grid is consumed and stored in mechanical form and it will be used during peak hours when the grid is in need. The most common Mechanical Storages Systems are: Pumped Hydro Storage (PHS), Flywheel energy Storage (FES), and Compresses Air Energy Storage (CAES).

3.1. Pumped Hydro Storage (PHS)

The largest readily available highly concentrated renewable energy storage system of the world with 125 GW generation, with 96% of world's electric storage capacity and 3% of global generation. This is the most used technology for high-power applications. The principle used is during off-peak hours, the system pump water to the reservoir using electricity and during peak hours, water is used to activate the turbines and to generate high content of electricity for peak-hours. They have a conversion efficiency of about 65-80%. The storage capacity of this system depends upon two factors: Height of the waterfall and the volume of the water. The mass of 1 ton falling 100m generates 0.272 kWh. The main drawback of this system is it needs site-specific boundaries, large capital investment. It takes long time for construction and 10 to 15 min reaction time. And the main issue is larger size as compared to new technologies.

3.2. Compressed Air Energy Storage Systems (CAES)

They are equipped with motor/generator set, compressor, expander, turbine train and a storing cavity. In this air which is compressed is used as an energy source later. The compressed air is stored in tank and used to store energy during off peak hours from any renewable sources. This pressured air is pumped into underground and used to drive gas turbine to generate electricity when required. Emission of CO₂ is less, no gasoline fuel is used, light weight, low cost, quick start up, cost of storage is reduced, can start quickly, flexible as it can operate under high pressure, helps in grid stability, Air can be transported easily, fuel can be easily stored, light weight, free from fire hazard. Applications are air hammers; atomize paints and air cylinder for automation.

3.3. Flywheel Energy Storage (FES):

In this system an angular momentum of the flywheel mass is used to store the power in the form of kinetic energy. They are operated for short duration of time about 1-100 seconds with a power of 80 kW. They have high power and energy density with an infinite number of charge-discharge cycles and used for stabilizing voltage and frequency. The state of charge (SoC) of FES is a function of moment on inertia and angular speed which are readily available to measure as

$$E = \frac{1}{2}mr^2(w_{max}^2 - w_{min}^2) \quad (5)$$

Where, E is a useful energy of the flywheel. The efficiency of FES system is about 85% to 90%.The FES systems require lower maintenance than batteries and are practically least affected by the temperature fluctuations and depth-of-discharge (DoD). They have the ability to rapidly charge-

discharge within few minutes. They suffer with high standby losses and nearly 20% of self-discharge per hour occurs in the stored capacity. They are costly and relatively behind in commercial success.

4. Chemical Energy Storage Systems

There are wide varieties of Electro-chemical Energy storage technologies which are used in various applications such as from stationary to mobile application and also for powering consumer's electronics to large industrial facilities. Various types of battery storage technologies are as follows:

4.1. Battery Energy Systems (BES)

4.1.1. Lithium-ion (Li-ion) Batteries

Lithium-ion Batteries are made up of metal oxide as positive electrode as cathode and porous carbon, a negative electrode called anode. During discharging state ions flows from anode to cathode when the circuit is closed generating electricity. During charging state the direction of ion flow reverses. Many types of Li-ion batteries exist. Lithium Cobalt Oxide Batteries (LiCoO₂) uses cobalt oxide as cathode and graphite carbon as anode. They have high specific energy which is popular in applications like mobile phones, laptops and digital cameras. The operating range of Li-cobalt cells is between 3 – 4.2V. Their specific energy density varies from 150 Wh/kg to 240 Wh/kg. They can reach up to 1000 charge/discharge cycles. The disadvantage of Li-cobalt are short life-span, low thermal stability because of which leads to overheating when the cell is charged at a current higher than its capacity, limited specific power capabilities.

4.1.2. Lithium Manganese Oxide (LiMnO₂)

They make use of lithium manganese oxide as cathode. Their design creates a 3-dimensional spinal structure which enables better ions flow on the electrode. They have high thermal stability and good safety. They are suitable for high load applications such as electric vehicles and power tools. The main disadvantage of this type of batteries is having lower life cycles maximum up to 700 cycles. They can provide an operating range of 3-4.2 V. Their specific energy density varies between 100 and 150 Wh/kg.

4.1.3. Lithium Nickel Manganese Cobalt Oxide (NMC)

These batteries are most successful systems as the combination of Nickel-manganese-cobalt as cathode. They are used for higher capacity, lower current or lower capacity, and higher current applications. These batteries are used for various applications like electric vehicles, medical devices and industrial applications. Other advantage is to reduce the cost of the battery due to the replacement of cobalt with nickel at the cathode. The operating range of NMC is 3-4.2 V. specific Energy density varies from 150-220 Wh/kg. They have life cycle up to 2000 cycles.

4.1.4. Lithium Iron Phosphate: (LFP – LiFePO₄)

These batteries use iron phosphate in the cathode which contains low resistance and gives good electrochemical performance. The main advantage of this batteries are good thermal stability, high tolerance to full charge conditions, long life cycle, and lower stress for high voltages operated at longer periods and high current ratings. They are used in applications like high load currents and as starter battery in vehicles. They have higher self-discharged and lower nominal voltage. The nominal operating voltage is around 3.2 V which reduces their specific energy density to 90-120 kWh/kg. They have life cycles up to 2000.

4.1.5. Lithium Nickel Cobalt Aluminium oxide (LiNiCoAlO₂, NCA)

These batteries are similar to NMC. They have higher energy density of 200 – 260 Wh/kg. They operate at a voltage of 3 – 4.2 V. They have life cycle of 500 cycles. They are very costlier than Li batteries. They are used mostly in industrial applications and electric power trains.

4.1.6. Lithium Titanate

These batteries use titanate in the anode instead of graphite, cathode can be Li-manganese oxide or NMC. They have good performance at extreme temperatures and does not form a solid electrolyte interface film or lithium plating when charging in low temperatures or during fast charging. They are used in electric power trains and uninterruptible power supplies. The main disadvantages of these batteries are higher cost and low specific energy density of 50 Wh/kg. They operate at a voltage of 1.8-2.85 V. They have a life cycle up to 7000 cycles.

4.2. Flow Batteries

Flow batteries are an electrochemical cell which comes between conventional battery and a fuel cell. When two liquid electrolytes circulate through a common core which consists of two electrodes, positive and negative which are separated by membrane then the energy is provided. This circulation creates an ion exchange between the cathode and anode generating electricity. The reverse process is used to charge the battery. The main difference between conventional batteries and flow batteries is that, in flow batteries energy is stored in the electrolyte. Therefore the battery capacity is dictated by its volume. Several types of flow batteries are available. The most important one is the Redox flow batteries in which electricity is generated due to the difference in potential of the two tanks. The materials used in redox flow batteries are Vanadium-Polyhalide, Vanadium Chromium, and Hydrogen-Bromium.

4.3. Lead-Acid Batteries

These batteries consist of flat lead plates which are immersed in a pool of electrolyte. One plate is covered with a paste of lead dioxide which acts as positive and the other is made of sponge lead which acts as negative. Separator is placed between both the plates. The main difference of these batteries compared to other batteries they have very long charging times, compared to discharge. They require addition of water to the electrolyte, as excess electrons lead to hydrogen generation and hence water loss. They require low maintenance. They are used in applications like back-up for emergency power, UPS and automotive and traction. The energy density varies between 30 to 50 Wh/kg, their operating cell voltage is 2V and they can go up to 300 life cycles.

4.4. Sodium Sulphur (NaS) Batteries

NaS batteries are a molten-salt battery type which uses molten sulphur as the positive electrode and molten sodium as a negative electrode. They are separated by an electrolyte solid ceramic sodium alumina. When the discharge is taking place sodium ions move through the electrolyte towards positive electrode generating electricity. They operate at higher temperatures greater than 300 °C. They have higher efficiency of about 90%. Specific energy is about 150 Wh/kg. They are used for peak shaving and for stabilising renewable energy output.

4.5. Regenerative Fuel Cell

Hydrogen the most important carbon-free fuel with highest energy content, considered as most versatile fuel. For storing 1 kg of H₂ at ambient temperature and pressure with a volume of 11 m³ is required. It acts as an electrical storage system, in which electricity splits water into its simple components of H₂ and O₂. Electrolysers are used for this process, a hydrogen gas reacts with the oxygen of air, producing electricity and water which can be reused and recycled to produce more hydrogen. The combination of fuel cell and electrolyser together is called as Regenerative fuel cells. Regenerative Fuel Cells are characterized as long-term energy Storage Systems devices. They have the highest specific energy with overall efficiency of 20-50%. They can be used for transport application. They are under development stage, practical applications are limited.

5. Electromagnet Energy Storage Systems

5.1. Capacitor and Supercapacitor

Two conducting metal-foil electrodes which are separated with a ceramic, glass or plastic-film as an insulating material will constitute a capacitor. When a suitable voltage is applied, energy is stored in the capacitor in the form of electrical field. They can be charged faster but however they have higher self-discharging rate and low energy-density. Supercapacitors which are also called as electrochemical capacitors or ultra-capacitors are storage devices with special characteristics between capacitors and batteries. They store the energy in the form of electrostatic field and have longer lifetime than batteries. They have higher efficiency of 95% because of their low resistance. They are used in applications like portable electronics, automotive industry, electric and hybrid electric vehicles during peak power demand. They also used for providing voltage sag compensation, intermittent renewable storage and smoothing applications. There is another new energy storage technology coming into existence for grid-scale applications called as electrochemical flow capacitors (EFC).

5.2. Superconductors

Superconductor Magnet Energy Storage systems consist of superconducting coil, power conversion system and cryogenically cooled refrigerator. In this case energy is stored in the form of magnetic field created by the flow of current in the coil. To maintain the superconducting state the device must have cooling temperature of -264°C , allowing permanent current flow through the inductor. They have higher efficiency of 98% with zero resistance, resulting with negligible energy loss. The main drawback of this type of storage system is that they have low-temperature superconducting coils, with higher cost and greater energy requirement for cooling. They also have susceptible daily self-discharge and negative environmental impact due to strong electromagnetic field.

6. Main Challenges for Battery Storage Technologies

The main challenges for all battery technologies in the market is the insufficient energy density for specific applications and mainly notable for EVs. When the application of batteries comes under stationary, then the battery volume is not the primary issue, but the challenges come in terms of battery cost. Li-ion batteries are the most prominent technologies particularly for mobile applications. Still these technologies need to face some challenges. They should improve their energy density, fast charging capabilities and cost of the battery. The use of cobalt oxides makes this technology expensive and unstable. LFP based compositions are safer but they also lack in terms of energy density and lower voltage. Li-ion batteries performance is also sensitive to external conditions and significantly reduces when exposed to higher or lower temperatures. The operating voltage also slightly reduces due to the usage of conventional materials in cathode. In terms of anode, promising materials are being investigated which are potential and increases its energy density but they lack scalability due to morphological changes.

Flow batteries primarily suitable for stationary applications receiving growing attention as they offer cost-effective energy solutions. The challenges still needs to be address include the high price of complexing agents which are used to stabilise the free iodine forming and to improve the overall performance of the electrolytes. The use of graphite as electrode material results large cell ohmic resistance and limited power density. There is a need to design an electrode which can improve flow of the electrolyte as well as better cyclic performance. Lead-acid batteries have their challenges in designing simple flat plate with low price and good lifecycle improving their performance in stationary applications. Future regulations are expected to prohibit lead batteries in vehicles. Sodium-sulfur operating temperatures of over 300°C implying they are only viable in large scale applications with dedicated infrastructure and high utilisation rates.

7. Conclusions

Many varieties of ESS technologies are currently available and many new technologies are coming into existence in future based on the demand for the storage of energy generated by RES. Electrochemical batteries are playing very important role in wide variety of applications such as consumer, industrial and military. The usage of batteries has increasing rapidly with advancing

technology, using low power and developing portable devices. The increased demand is another factor for the usage of battery-operated equipment from small portable devices to large electric vehicles and utility power grid. Batteries have many advantages compared to other power sources because of their efficient, convenient, reliable, very less maintenance and easy configuration to user requirements characteristics. With new innovative technologies ESS are becoming most prominent devices for storage of energy in various applications.

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