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Electrical Energy Storage – An Overview

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ABSTRACT *Power grids attempt to realize stable power supply by optimally balancing supply and demand. However, as the use of solar power and other renewable energy sources, which have unstable output, continues to increase, power supply to the entire grid could become unstable. This poses a wide variety of challenges. To overcome such challenges, technology is needed that can store electric energy. Storing electrical energy in energy storing systems would equalize the electrical load and lead to efficient use of energy. Besides, energy storage systems can also serve as stand-by power sources in times of crisis. At the same time, providing continuous electricity in areas with intermittent electricity or no electricity at all can be very challenging and expensive. The rising price of diesel fuel and other energy has resulted in escalated expenditure for power suppliers. These high operating expenses have led to the development of various energy storage systems.Of these, electric energy storage is poised to become an important element of the electricity infrastructure of the future. Proven storage technologies are in use today, while emerging storage technologies are expected to have improved performance and economy. This paper provides an overview of the various conventional energy storage systems along with the current technologies used for electric energy storage.*

Keywords: *Electrical Energy Storage (EES), Pumped Hydroelectric Storage, Compressed Air Energy Storage, Flywheel Energy Storage, Battery Energy Storage, Flow Battery Energy Storage, Superconducting Magnetic Energy Storage*

I. INTRODUCTION

Electric power generation from variable generation is growing at very high rates throughout the world. This growth has been powered by a combination of effects including dropping in prices for wind and solar generation, increasing concern over burning fossil fuels, and government policies.The electricity grid must ensure that the power supply and demand are equal at any given moment. Constant adjustments to the supply are needed for predictable changes in demandas well as sudden changes from equipment overloadings and natural catastrophes. Energy storage plays a vital role in this balancing act and helps to create a more flexible and reliable grid system. When there is more supply than demand, such as during the night when low-cost power plants continue to operate, the excess electricity generation can be stored. During times when demand exceeds the supply, storage facilities can discharge their stored energy to the grid. Increasing dependence on variable renewable energy resources provide additional challenges that are raising concerns over the potential need for additional flexibility and optionality in power systems. Among the sources of flexibility and optionality is a wide range of energy storage technologies.

Pumping water back behind hydroelectric dams has been used for decades as a form of storage that absorbs excess capacity from the grid and returns capacity to the grid later when it is needed. Energy storage is also valued for its rapid response – most storage technologies can begin discharging power to the grid very quickly, while fossil fuel sources tend to take longer to ramp up. This rapid response is important for ensuring stability of the grid when unexpected increases in demand occur. In the future, as more storage technology options emerge and the world transitions to a cleaner energy economy, energy storage is poised to play an even greater role.

Electrical Energy Storage (EES)[1]-[8] technology refers to the process of converting energy from one form (mainly electrical energy) to a storage form and reserving it in various mediums; then the stored energy can be converted back into electrical energy when needed.[1]

Emerging storage facilities will allow us to store energy generated from wind and solar resources on shorter time frames to smooth variability, and on longer cycles to replace ever more fossil fuel. Charging storage facilities with energy generated from renewable sources would reduce greenhouse gas emissions and the dependence on fossil fuels.

While the electric grid does not necessarily need more storage now, storage capacity will become more important as wind, solar, and other variable renewable energy resources expand in the power mix. Studies have shown that the existing grid can accommodate a sizeable increase in variable generation, but there are many exciting technologies in development that could help us store energy in the future and support an even greater amount of renewable energy on the grid.

The focus of this paper is on electric energy storage devices in which electrical energy is absorbed at one time and released at some later time under control of an operator. Most such technologies convert electrical energy into another form for storage.

The rest of the paper is arranged as follows. The classification of electrical energy storage technologies isintroduced in section II. The various electrical energy storage technologies are discussed in section III to VIII. The conclusions are presented in section IX.

II. CLASSIFICATION OF ELECTRICAL ENERGY STORAGE TECHNOLOGIES

There are various methods that have been suggested for categorization of various Electrical Energy Storage (EES)[1]-[8]technologies. One of the most widely used methods is based on the form of energy stored in the system. It can be categorized into mechanical (pumped hydroelectric storage, compressed air energy storage and flywheels), electrochemical (conventional rechargeable batteries and flow batteries), electrical (capacitors, supercapacitors and superconducting magnetic energy storage), thermochemical (solar fuels), chemical (hydrogen storage with fuel cells) and thermal energy storage (sensible heat storage and latent heat storage) as shown in figure 1.

Mechanical	Electrochemical	Electrical
a) Pumped Hydro Storage b) Compressed Air Energy storage c) Flywheel Energy Storage	a) Battery Energy Storage (Secondary battery) b) Flow Battery Energy Storage	a) Capacitorsand Supercapacitors b) Superconducting Magnetic Energy Storage
Thermochemical	**Chemical**	**Thermal**
a) Solar fuels	a) Hydrogen fuel cells	a) Thermal heat storage

Fig. 1. Classification of Electrical Energy Storage technologies based on the form of stored energy

Each of these technologies is discussed in the following sections.

III. ENERGY STORED IN MECHANICAL FORM

Examples of energy stored in mechanical form includes the Pumped Hydroelectric Storage, Compressed Air Energy Storageand Flywheel Energy Storage.

a) Pumped Hydroelectric Storage

Pumped Hydroelectric Storage [1],[9]is an EES technology which has a long history and large energy capacity. Currently, the installed capacity is 168GWas per DOE Global Energy Storage Database reportsin 2017. These represents over 96% of worldwide bulk storage capacity and contributes to about 3% of global generation. A typical Pumped Hydroelectric Storage plant uses two water reservoirs which are separated vertically. During the off-peak hours, the water is pumped into the upper level reservoir, while during the peak hours, the water is released back into the lower level reservoir. During this process, the water drives the turbine units which in turn drive the generators machines to produce electricity. The amount of energy stored in pumped storage systems is a function of the difference in height between the two reservoirs and the total volume of water stored. The rated power of these plants depends on the water pressure and flow rate through the turbines and rated power of the pump/turbine andgenerator/motor units.

Plants with power ratings ranging from 1 MW to over 3 GW having around 70–85% cycle efficiency and more than 40 years lifetime are currently present[1]. The nature of the operation of such systems means that their applications mainly involve energy management in the fields of time shifting, frequency control, non-spinning reserve and supply reserve. The drawback of such plants is the restriction of site selection, along with long construction time and high initial investment.

b) Compressed Air Energy Storage

Compressed Air Energy Storage[10]-[12]also comes under the mechanical category of EES. Compressed air energy storage involves compressing air using inexpensive energy so that the compressed air may be used to generate electricity when the energy is cheaper.The energy is thus stored in the form of high pressure air. To convert the stored energy into electric energy, the compressed air is then released into a combustion turbine generator system. As the air is released, it is heated and then sent through the system's turbine. As the turbine spins, it rotates the generator to generate electricity. For larger plants, compressed air is stored in underground geologic formations, such as salt formations, aquifers, and depleted natural gas fields. For smaller plants, compressed air is stored in tanks or large on-site pipes such as those designed for high-pressure natural gas transmission (in most cases, tanks or pipes are above ground). These can store power of over 100 MW with a single unit.[1]

These system can be built to various capacities. The practical usesof large-scale plants involve grid applications for load shifting, peak shaving, and frequency and voltage control. It can work with intermittent renewable energy applications, especially in wind power, to smooth the power output. The major hindrance in implementing large-scale plants is identifying suitable geographicallocations which is responsible for deciding the initial investment cost of the plant. Relative low round trip efficiency is another drawback of these systems.

c) Flywheel Energy Storage

Flywheel electric energy storage systems [13][14]consists of a cylinder with a shaft that can spin rapidly within a robust enclosure. A magnet levitates the cylinder, thus limiting friction-related losses and wear. The shaft is connected to a motor or generator. The electric energy is converted by the motor or generator to kinetic energy. This kinetic energy is stored by increasing the flywheel's rotational speed. The stored (kinetic) energy is converted back to electric energy via the motor or generator, slowing the flywheel's rotational speed.

These systems use electricity to accelerate or decelerate the flywheel, i.e. the stored energy is transferred to or from the flywheel through an integrated motor/generator. For reducing wind shear and energy loss from air resistance, these systems can be placed in a high vacuum environment. The amount of energy stored is dependent on the rotating speed of flywheel and its inertia.

Such systems can be classified into two groups viz. low speed systems which uses steel as the flywheel material and rotates below 6000 and high speed systems which uses advanced composite materials for the fly-wheel, such as carbon-fiber, which can run up to 100000 rpm[1].The low speed FES systems are used for short-term and medium/high power applications. High speed FES systems use non-contact magnetic bearings to mitigate the wear of bearings, thereby improving the efficiency.

Normally, Flywheel Energy Storage Systems devices can supply sufficient power in a short time period with modest capacity. The main weakness of these systems is that flywheel devices suffer from the idling losses during the time when the flywheel is on standby. This can lead to relatively high self-discharge.

IV. ENERGY STORED IN ELECTROCHEMICAL FORM

The energy stored in electrochemical for is now discussed, examples of which are the various secondary batteries and the flow battery.

a) Battery energy storage [15]-[16]

A Battery Energy System consist of two or more electrochemical cells connected in series, parallel or series-parallel. Through an electrochemical reaction, these cells produce electricity of a desired voltage and amp-hour. Primary elements of a cell include the container, two electrodes (anode and cathode), and electrolyte material. The electrolyte is in contact with the electrodes. Current is created by the oxidation-reduction process involving chemical reactions between the cell's electrolyte and electrodes.

When a battery discharges through a connected load, electrically charged ions in the electrolyte that are near one of the cell's electrodes supply electrons (oxidation) while ions near the cell's other electrode accept electrons (reduction), to complete the process. The process is reversed for to charge the battery, which involves ionizing of the electrolyte.

These batteries may be used in a wide variety of applications including power quality assurance, transmission and distributionrescheduling, voltage regulation, spinning reserve,load leveling, peak shaving, transportation systems, and integration with renewableenergy generation plants.

One of the advantage of Battery Energy Systems is the relative short time for construction and locational flexibility. On the other hand, these suffer from shorter life, increased maintenance and low cycling times. Further, the disposal or recycling of dumped batteries is an important point of concern when toxic chemical materials are used.

A wide variety of chemistries are used in the manufacturing of batteries, the more prominent ones being the lead-acid, nickel-cadmium (NiCad), lithium-ion (Li-ion), sodium/sulfur (Na/S), zinc/bromine (Zn/Br), vanadium-redox, nickel-metal hydride (Ni-MH), and others.

1) Lead–acid batteries[1],[16]

The most widely used rechargeable battery is the lead–acid battery where the cathode is made of PbO_2, anode of Pb, with sulphuric acid as the electrolyte. Lead–acid batteries have fast response times, duration, small daily self-discharge rates relatively high cycle efficienciesand low capital costs. They arecommonly installed in uninterruptible power supply (UPS)systems, in renewable and distributed powersystems, as back-up power supplies for data and telecommunication systems, energy management applications and transportation system.

2) Lithium-ion batteries[16]

In these batteries, the cathode is made of a lithium metal oxide, such as $LiCoO_2$ and $LiMO_2$, and the anode is made of graphitic carbon. The electrolyte is normally a non-aqueous organic liquid containing dissolved lithium salts, such as $LiClO_4$. The main advantages of Li-ion batteries, compared to otheradvanced batteries, are their high energy density, high efficiency, fast response time, small dimensions, lesser weight, and long cycle life.

3) Sodium-sulphur (NaS batteries)[16]

These batteries use molten sodium and molten sulfur as the two electrodes, and employs beta alumina as the solid electrolyte. The reactions normally require a high temperature of the order of 600 K to ensure the electrodes are in liquid states, which leads to a high reactivity. The advantages of this battery are it relatively high energy density, almost zero daily self-discharge, higher rated capacity and high pulse power capability. Further, these batteries use inexpensive, non-toxic materials which helps in good recyclability. The limitations include high operating cost and the requirement of an auxiliary system for ensuring its operating temperature. This battery is used widely in combined power quality and peak shaving applications.

4) Nickel-cadmium (Ni-Cd) batteries[17]-[18]

This battery uses nickel hydroxide and metallic cadmium as the two electrodes and an aqueous alkali solution as the electrolyte. The main advantages of this battery is its relatively high robust reliabilities and low maintenance requirements. However, its main drawback is the environmental hazard which ensued on account of the fact that cadmium and nickel are toxic heavy metals.

b) Flow Battery Energy Storage

The fundamental difference between conventional batteries and flow cells[19] is that energy is stored as the electrode material in conventional batteries but as the electrolyte in flow cells.

The electrolytes are stored externallyin tanks and pumped through the electrochemicalcell that converts chemical energy directly toelectricity and vice versa. The operation is based on reduction-oxidation reactions of the electrolyte solutions. During the charging phase, one electrolyte is oxidized at the anode and another electrolyte is reduced at the cathode, and the electrical energy is converted to the electrolyte chemical energy. The above process is reversed during the discharging phase.

The power is definedby the size and design of the electrochemical cellwhereas the energy depends on the size of thetanks. With this feature, flow batteries canbe fitted to a wide range of stationary applications.One of the biggest advantages of flow batteries is that they can be almost instantly recharged by replacing the electrolyte liquid, while simultaneously recovering the spent material for reenergization. Further, they have a very small self-discharge.The limitations of flow batteries include relatively high manufacturing costs, more complicated system requirements, low performance resulting from non-uniform pressure drops and the reactant mass transfer limitation.

Flow batteries can be classified into the categories of redox flow, hybrid flow and membraneless batteries. Important flow battery technologies used include vanadium redox (VRB), zinc bromine (ZnBr) and polysulfide bromine (PSB).

V. ENERGY STORED IN ELECTRICAL FORM

Another important category of energy storage is the electrical form whose examples includes the capacitors, supercapacitors and superconducting magnetic energy storage.

1) Capacitors and Supercapacitors

A capacitor consists of two or more electrical conductors separated by a thin layer of insulator (ceramic, glass, plastic film, etc.). When a capacitor is charged, energy is stored in the dielectric material in an electrostatic field. Its maximum operating voltage is dependent on the breakdown characteristics of the dielectric material. Capacitors are capable of storing small quantities of electrical energy and conducting a varying voltage. They possess higher power density and shorter charging time in comparison to traditional batteries. Their limitations, however, are limited capacity, relatively low energy density and high energy dissipation due to the high self-discharge losses. Consequently, capacitors can be used for power quality applications including high voltage power correction and smoothing of the output of power supplies.

Electrochemical double-layer capacitors, also known as supercapacitors [20]-[22] or ultracapacitors,contain two conductor electrodes, an electrolyte and a porous membrane separator. Owing to their structure, they possess the characteristics of traditional capacitors and electrochemical batteriesand fillthe gap between them becauseof their extremely high cycle stability, and very high power and energy storage capability and theirmany orders of magnitude higher energystorage capability when compared to traditionalcapacitors. The energy is stored in the form of static charges on the surfaces between the electrolyte and the two conductor electrodes. The high-performance supercapacitorsuse nanomaterials to increase electrode surface area for enhancing the capacitance.

Supercapacitors have long cycling times and high cycle efficiency. However, they suffer from the high daily self-discharge rate and the initial cost. They find place for short-term storage applications, which includes supplying pulse power in power quality applications, solenoid and valve actuation and UPS.

2) Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage[23]-[25]is based on electrodynamicprinciple where the energy is stored in the magneticfield created by the flow of dc in asuperconducting coil, which is kept below itssuperconducting critical temperature. The components of this storage system includes a coil made ofsuperconducting material, power conditioning equipment and acryogenically cooled refrigeration system.A commonly used superconducting material for the coil is Niobium–Titanium having a superconducting critical temperature of 9.2 K. The magnitude of stored energy is determined by the self-inductance of coil and the current flowing through it. The main advantage of this storage system is the very fast response time i.e. the power can be supplied instantaneously. Further, these systems have a relatively high power density, fast response time, very fast full discharge time, high overall round-tripefficiency, long lifetimeand a very high poweroutput provided instantaneously for a short period oftime. On the other hand, the limitations include the high capital cost, high daily self-discharge and an impact on the environment due to the strong magnetic field. Besides, the superconducting coil is sensitive to small temperature variations which can cause the loss of energy.

VI. ENERGY STORED IN THERMOCHEMICAL FORM

The solar fuel is the best example of energy stored in thermochemical form. In comparison to other forms, the Solar fuel is a relatively new technology. There are various approaches to produce solar fuels which include natural photosynthesis, artificial photosynthesis and the thermochemical approaches. A number of fuels can be produced by solar energy including solar hydrogen and carbon-based fuels. These fuels can be stored and in due course aid in electricity generation.[1]

In the first two approaches for producing solar fuels, solar energy is captured via photosynthesis and then stored in chemical bonds. The third viz. the thermochemical approach uses thermal processes for solar fuels production, which involve the generation of very high temperatures in a closed environment to split water into its constituent parts. Consequently, this method requires strong sunlight compared to the other two approaches. After the solar radiant energy is concentrated by heliostats, an endothermic chemical transformation is carried out in a reaction vessel. The reaction produces hydrogen and/or carbon monoxide and/or other materials.

Solar fuel technology is still in the research stage. The important features of this system is the high specific energy. The limitations include the requirement of large area for concentrating sunlight.

VII. ENERGY STORED IN CHEMICAL FORM

Examples of energy stored in chemical form include the fuel cell.[26]A typical hydrogen storage system consists of an electrolyzer, a hydrogen storage tank and a fuel cell. An electrolyzer is an electrochemical converter which splits water with the help of electricity into hydrogen and oxygen. It is an endothermic process, i.e. heat is required during the reaction. Hydrogen is stored under pressure in gas bottles or tanks, and this can be done practically for an unlimited time. To generate electricity, both gases flow into the fuel cell where an electrochemical reaction which is the reverse of water splitting takes place: hydrogen and oxygen react and produce water, heat is released and electricity is generated. For economic and practical reasons oxygen is not stored but vented to the atmosphere on electrolysis, and oxygen from the air is taken for the power generation.

Their application fields include military, space application, utility, transportation, distributed generation, backup power and portable devices.

The merits of this system is higher efficiency, quieter operation, lesser negative environmental effects, compact design and easy scaling. These systems combined with hydrogen production and storage can provide primary electrical power, heating/cooling or backup power, and transportation power. Due to the separate processes, such systems can provide power independence in energy production, storage and usage. The challenge posed by this system is the disposal of exhaust fuel cells when toxic metals are used as electrodes or catalysts.

VIII. ENERGY STORED IN THERMAL FORM

Thermal energy storage systems [27] store available heat by various means in an insulated repository. This heat can then be used later for various domestic and industrial applications including space heating or cooling, hot water production or electricity generation. Such systems are important for the integration of renewable energy sources.

A thermal energy system normally consists of a storage medium in a reservoir/tank, a packaged chiller or built-up refrigeration system, piping, pump, and controls. Based on the range of operating temperature, they can be classified into two groups, viz. low-temperatureand high-temperature systems.

These systems can store large quantities of energy without any major hazards and its daily self-discharge loss is small. Besides, the system has good energy density and specific energy, with low initial cost. On the other hand, the limitations includes the low cycle efficiency. Such systems have been used for a wide variety of applications including load shifting and electricity generation for heat engine cycles.

IX. CONCLUSION

This paper provides an overview of the various types of EES technologies along with their merits, demerits, applications. The Pumped Hydro Storage have been deployed worldwide, mainly due to their technological maturity. Each of these systems have their own sets of merits and limitations. Many of these are still in the development stage and it is expected that some breakthrough in battery or fuel cell can completely change the future course of EES. The energy capacity and the self-discharge of EES systems are the major factors in deciding the associated suitable storage duration. From the overview, it is clear that there is no suitable commercialized technology for seasonal energy storage at present.

It is expected that in the near future, using a suitable hybridization[28][29] of various technologies, EES would be able to meet the power requirements.Currently, apart from Pumped Hydro Storage, most of the EES technologies are not cost-effective or mature enough for yielding the desired performance and output. The success of EES, hence, will depend on the advances and breakthroughnot only in the individual technologies but also on the eruption of various hybrid combinations.

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