Research Article

Various Energy Storage Devices and Their Control Techniques

SNEHA PATIL
M.Tech Candidate
Bharti Vidyapeeth University College of Engineering
Pune

Abstract—**Like several other renewable energy resources, wind energy is also a dilute energy source and has an unpredictable and discrete nature which makes it unreliable as a continuous source of electricity. But from the consumer point of view, the electricity must be continuous and must have standard values to allow healthy operating conditions to the equipment. Non- conventional energy sources have satisfied these needs efficiently but because of their environmental impact there is a demand for technology to harvest energy from renewable energy sources. In order to enhance the continuity of renewable energy sources various energy storage devices are used throughout the world. In today's date 125 GW of electricity is stored in the various storage devices. They allow storage and utilization of electricity according to the system conditions. Use of controllers enables the smoothening of intermittent nature non-conventional wind energy sources. This paper reviews the various energy storage devices that can be used with non- conventional energy resources to improve their reliability and continuity. An overview of the various control techniques to connect the storage devices is also included.**

Keywords-**energy storage, battery, ultracapacitor, superconducting magnetic energy storage (SMES)**

I. INTRODUCTION

Deregulation in the power sector has led to several changes in their operational requirements. The complexity in power system is increasing with the raising electrical loads and power transfer. This also affects the security of the system. Because of engineering, financial and environment limitations the generation and transmission systems fall short to meet the growing needs. The concern about power quality is also increasing. Therefore there is a need for power system which can operate more flexibly has greater controllability. During a disturbance in power systems generator may not be able to generate a rapid response and maintain the system stability. A fast control of real or reactive power may avoid conditions like generator drooping or load shedding. FACTS controllers allow such control of high speed reactive power and in some cases they also allow real power control by circulating power with- in the converters or by the power flowing in the same line or from other lines from the same substation. But there is a requirement to develop a solution to fulfil the need of rapid real a d reactive power control without affecting the system by circulating power. This can be achieved by torage devices. They can make the system more reliable and increase the power quality by quickly damping the oscillations, fast response to the sudden load variations, maintaining load profile by controlling real and reactive power. Earlier energy storage devices had power converters to regulate the power by interrupting the current or by regulation of voltage but recent trends in power electronics have made the technology more suitable for the existing power systems. The energy storage technologies were seen as large scale storage technique earlier but now the application is seen as more appropriate for maintaining stability and for improving power quality.

II. APPLICATIONS IN TRANSMISSION AND DISTRIBUTION SYSTEMS

Electricity can't be stored as ac but it can be converted to alternative forms like electromagnetic, electromechanical, potential or kinetic energy. The energy storage technique comprises of a power conversion system which converts ac into either of the alternate forms of energy.

The application of energy storage technique can be characterised by the volume of energy that the device is capable of storing within itself and the rate of energy transfer between the device and the power system. The earlier is a characteristic of the device while the latter is influenced by peak power rating of the power converting system and rate of response of the device.

By integrating the energy storage technology along with FACTS or power electronics can be used for energy storage. Their application may be enlisted as damping oscillations, improving dyanamic stability, control of tie line power, serve as a short term spinning or supplementary reserve, damping subsynchronous resonance, improving power quality.

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Table 1: Various energy storage applications along with their required discharge time and storage capacities

STORAGE NEED	DISCHARGE TIME	STORAGE CAPACITY
It has ability to match generation and demand. Shift generated energy from off peak hours to peak hours.	Minutes - Hours	kW - MW
Meet the variations of supply and demand conditions. Storage technology can avoiding the use of fossil fuels for peaking stations.	Hours	MW
Load following service with thermal generators to ensure a constant output.	Minutes - Hours	MW
Absorb and supply energy as per the demand. Eliminate momentary difference between the two.	Seconds - Minutes	MW
Provide reserve capacity during interruptions or contingencies.	Hours	MW
Maintain voltage and frequency at required levels during a large disturbance which demands fast response.	Milliseconds - Seconds	kW - MW
Maintain power quality during events of sags, swells and transient conditions	Milliseconds - Seconds	kW - MW
Transmission support and to improve the performance of transmission and distribution system by eliminating the variations instantly.	Milliseconds - Seconds	kW - MW
Viable alternative to eliminate congestion issues instead of installing new transmission lines.	Hours	kW - MW

III. BATTERIES

The storage mechanism of batteries is a chemical process. When installed in a power system the batteries store power within them while healthy network conditions and during any unhealthy operation they release energy by discharging. They are the most primitive and tested energy storage devices. They have an efficiency of 60- 80% which is determined by the number of charge discharge cycles, the nature of electrolyte and the environmental conditions [1].

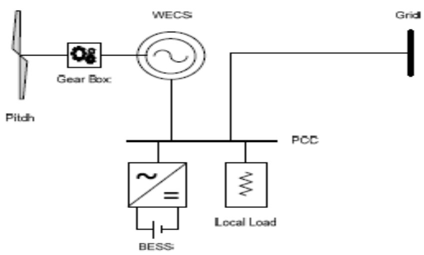

Fig.1: A battery connected to wind energy conversion system

Despite of all the qualities, batteries cannot withstand large rate of cycling, it need more area for storage of large amount of energy, their life cycle is short and discharge capacity is limited. Since it operates on chemical process, the batteries have to be checked for adequacy of water level and corrosion of it terminals. The presence of chemicals may lead to operational hazards. Its disposal can also be a major challenge. When a battery is used in the system, the control mechanism becomes more complicated and the costs are elevated.

IV. CONTROL TECHNIQUES OF BATTERIES

There are several research works related to use of batteries to the wind energy conversion system. A major part of them have performed simulation, analysis as well as discussion of combination of batteries with capacitors or the combination of batteries and flywheels and also for combination of batteries along with thermal energy storages. A novel technique for application of dual batteries is seen in [2]. In this study the control technique is to charge one battery with WECS while the other on simultaneously gets discharges into the grid. Batteries that allow direct connection with dc link of a permanent magnet synchronous generator (PMSG) base wind installation are cited in [3]. A 240 volts nickel- cadmium battery is applied for providing a backup supply to a small hybrid plant having wind turbines and diesel generator sets. A novel technique of STATCOM applied to batteries shown in [4] proves that the charging and discharging cycles of batteries can be improved. Battery connected system can be an established technique that has a grid integrated wind- solar hybrid system. A battery storage system connected to a stand- alone solar energy generation plant with the use of a simpler controller is seen in [5]. A hybrid power system with combination of solar, wind and diesel generators with batteries are popular.

V. ULTRACAPACITORS

Ultracapacitors have the features of capacitors as well as batteries. They don't operate on any chemical process like batteries. This gives an excellent cycling ability.

$$C = \varepsilon \, {}^{A}\!/_{d} \qquad (1)$$

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Where, Ɛ is dielectric constant of the membrane, D is Thickness of the membrane, A is Surface area of the electrodes

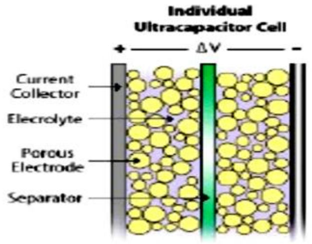

Fig. 2: various components inside an ultracapacitor

Unlike batteries they are more efficient and economical. They have lesser power density than batteries and therefore the total area occupied by the bank is too large [6].

VI. APPLICATIONS RELATED TO ULTRACAPACITORS

In order to improve the ability of wind installations to supply energy at the instant of lesser wind velocity, they are connected to a battery and ultracapacitor hybrid system. [7] has pioneered a novel technique to combine ultrcapacitors with fuel cells. It also includes a comparative account for the connection of ultracapacitors to hydro- power plant and thermal power plant. The analysis of the capability of ultracapacitors to satisfy the load demand of a stand-alone solar panels and its capability for matching the demand in a micro grid when they are applied to a photovoltaic panel. Also a recent energy storage having ultracapacitors and batteries are analysed for micro grid system are seen whereas in application of ultracapacitor and battery storage for hybrid electric vehicles in [8].

VII. FLYWHEELS

A flywheel consists of a rotating mass which stored energy in the form of kinetic energy. When the shaft is moved faster, the energy gets stored and to extract energy from the flywheel the shaft is slowed down to lower speeds. The distribution of mass density in rotor, its geometric radius and consequently its moment of inertia determine the capacity to store energy [9].

$$E = {}^{1}/_{2} I w^2 \quad (2)$$

$$I = \int p(x)\, r^2 dx \quad (3)$$

Where, E is stored energy in Joules, I is Moment of inertia in kg/m^2, w is angular speed in rad/s, p is mass density in kg/m^3, r is radius of rotor in metresand x is position of rotating axis. For storage applications related to power systems the storage capacity required is more and this can be satisfied by large flywheels. As the size increases the losses produced because of friction are increased. If the flywheels are operated for longer durations their efficiency will drop. Therefore they don't permit storage for longer durations [10]. Flywheels can be used for improving power quality in a power system.

VIII. CONTROL TECHNIQUES OF FLYWHEELS

Flywheel energy storage can also be applied in the dc link of a full converter range type wind turbines to enhance the power quality. But the presence of flywheel within the converter station limits this application to future systems and cannot be applied to already existing ones. [11] put forth a novel technique to combine flywheels with STATCOM to enhance the power quality of fixed speed wind turbines.

IX. COMPRESSED AIR ENERGY STORAGES

The operation of compressed air energy storages is based upon the concept of gas turbine generation. The compression and expansion processes of a conventional gas turbine generator are split into two different processes and the generated energy is stored as compressed gas. During normal operation of the grid the air is compressed and stored in an air tight container. The potential energy so absorbed can be utilized by heating this stored air. On heating the air expands and passes through a high pressure turbine. It is further added to fuel and combusted and the resultant exhaust can be expanded along a low pressure turbine [12]. A generator is connected to both the high as well as low pressure turbines. In contrast with other combustion engines, this device burns 1/3rd of the fuel and releases equally lesser pollutants per kWh generation.

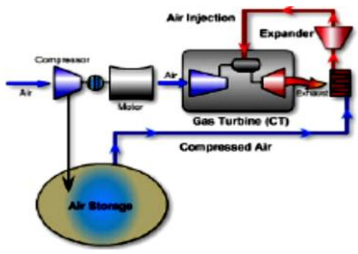

Fig. 3: block diagram and components of compressed air energy storage.

According to the ideal gas law,

$$PV = nRT \quad (4)$$

Where, P is the pressure of the gas (n/m^2), V is volume of the gas (m^3), T is the temperature of the gas (Kelvin), N is the number of moles, R is real gas constant= 8.31J/mol. K. If a frictionless piston is assumed in an isobaric process, the volumetric energy density is calculated as

$$E_{volume} = \frac{1}{V_o}\eta RT \int_{V_o}^{V}\frac{dV}{V} = \frac{1}{V_o}P_oV_o ln\frac{V_o}{V} = P_o ln\frac{V_o}{V} \quad (5)$$

Where, P_0 is the initial gas pressure (n/m^2), V_0 is initial volume (m^3), V is the final volume (m^3).

X. CONTROL TECHNIQUES OF CAES

Compressed air energy storage system with a capacity of 290 MW and 110 MW already exists in Alabama and Germany. As mentioned in [13] the rating is so high since the storage is only for few hours. A stochastic marketing model is developed in [14] to analyse the effect of generation of wind farms after investing in compressed air energy storage. This analysis shows that investment in these storages near wind turbines can give higher future returns. [15] depicts the security constraint of combination of wind energy conversion system and compressed energy storage system for optimally scheduling the generator units and hence minimize the price of electricity supply.

XI. PUMPED HYDRO STORAGE SYSTEM

Pumped hydro storage system is among the most widely used storage systems. It operated as per the energy requirements.

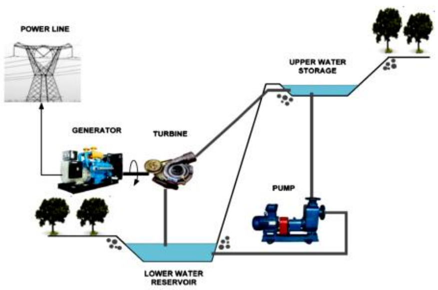

Fig. 4: A typical layout of a pumped hydro energy storage system

During healthy operating conditions the generating station pumps up the water to the higher level and as the demand of electricity increases, the water stored at height will flow at the downstream reservoir. While flowing downwards, the water will pass through a hydro turbine which is coupled to a generator. This system has an efficiency of 65- 80% and is affected by the components as well as losses due to friction, phenomenon like turbulence and viscous drag [16]. The efficiency of pumped hydro energy storage system is calculated by considering the ratio of energy supplied to the consumer to the energy consumed while pumping the water. The energy consumed while pumping water is given by

$$E_{pumping} = \frac{pghV}{\eta_p} \quad (6)$$

$$E_{generator} = pghV\eta_g \quad (7)$$

Where, p is Mass density, g is Constant of gravity, V is Volume of water, h= Height of upstream reservoir, η_p= Efficiency of pumping water, η_g= Efficiency of supplying electricity to the grid. The efficiency is influenced by the height of the reservoir. Therefore, the installation and constructional expenses are more. The application of this storage technique is limited to large power demands.

XII. SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

The superconductor coil gets its high storage efficiency by the combining three ideas i.e., current flow without any losses, generation of magnetic field and storage of electricity in the magnetic field. Unlike other storage devices the SMES coil stores energy by circulating the current inside the superconducting coil.

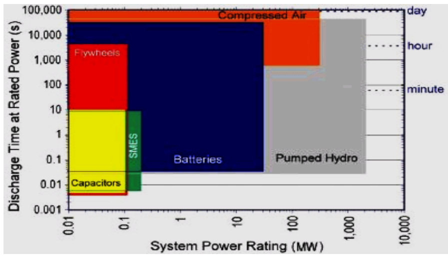

Fig. 5: Power rating and rate of discharge of various storage devices.

Due to absence of energy conversions from one form to another there are no significant losses [17]. SMES was developed to level the load and as a substitute for pumped hydro storages and therefore huge capacity was one of the primary considerations. SMES has the capability to discharge very quickly, for large energy storage capacity for a nominal cost and small dimension make it a promising option for pulsed power as well as stability issues. From the Fig. 5 it can be concluded that SMES has a lower rating whereas higher discharge durations. The major components of an SMES system are a superconductor coil, a refrigerant, power converting system as well as controlling system. Following sections discuss the various components and their technological attributions of the SMES unit.

XIII. CONTROL TECHNIQUES OF SMES

Various references describing the application of storage devices have discussed about the high Watt-hour storing capacity of superconducting magnetic energy storage devices. As cited in [18] the SMES unit is capable of storing up to 10 Mega Watts. For a shorter time duration the capability of an SMES unit is even increased since a coil having a radius of 150 metres to 500 metres is capable of supporting 5000 Mega Watt hour of loads. It is also mentioned that the SMES unit can even store about 1,000 - 10000 Mega Watt hours of energy. But the net worldwide installed capacity of SMES configurations is only 200 Mega Watts and the world markets already offer micro SMESs having a range between 1- 10 Mega- Watts and micro SMESs that have net capacity of 50 Mega-Watts are already in operation in United States for power quality enhancement or as backups to ensure continuity of power. [19] Comprises of a primitive method of applying the SMES unit for the uniform distribution of solar panels. In [20] a sophisticated model of SMES unit connected to solar panels. A

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voltage- current convertor with IGBTs is applied for inhibiting bidirectional power flow. Several goals are met in this study. They include, Smoothening out the distribution of energy obtained from solar panels throughout the day, provide real and reactive power supporting operations and to minimize transients due to load fluctuations. [21] Employs a distributed configuration of solar panels, fuel cells along with the SMES unit. SMES unit is used for wind turbines to improve the stability of the system and to smoothen the fluctuations in the energy. [22]. Analyses the effect of application of STATCOM along with a superconducting magnetic energy storage device with the grid. [23] Uses and SMES unit to improve transient stability when the wind velocity is varying. The configuration has an AC - DC converter operated by regulation of modulating index and phases angel. Reference [24] shows a novel technique for enrichment of wind energy conversion systems transient stability by using SMES. [25] have proposed similar SMES configurations and control strategies which includes a voltage source converter along with a chopper each comprising IGBT. The voltage source converter is controlled using pulse width modulation technique with a proportional integral controller is used to control chopper. [26] discusses the addition of SMES configuration to the SFIG based wind installations for improvement of stability of voltage of the generating units in the event of short- circuits on lines. A novel technique to determine the ability of SMES to improve voltage profile at point of common coupling in event of a swell in voltage level is elaborated in [27].

XIV. COMPARISON OF VARIOUS ENERGY STORAGE DEVICES

Table 2: Comparison of various energy storage devices

Storage	Advantages	Disadvantages	Applications
Battery	• Available in markets • High power capacity • High energy capacity	• Short life span • Lower cycling rate • Effect of temperature on performance	• Uninterrupted power supply • Power quality improvement • Grid integration of renewable resources • Peak shaving • Voltage and current limitations
Ultracap-acitor	• More efficiency • Faster cycling	• Lower energy density • Limited power system applications	• Power quality • Emergency power bridging • Consumer electronics • Pitch control of wind turbines
Supercon-ducting Magnetic energy storage	• Longer operating life • Higher efficiency • Faster cycling • Higher capacity	• Lower energy density • Larger production cost	• Power quality • Transmission and distribution systems • Stability of power system
Flywheel	• Long life • No environmental impact • Lower maintenance requirement • Fast recharing	• Lower energy density • Lower energy capacity • Higher standby losses	• Power quality • Defence
Compressed air	• Adequate energy and power capacity • Adequate life	• Geographical limitations • Requirement of fuel gas	• Spinning reserve • Arbitrage • Frequency regulation • Peak shaving
Pumped Hydro	• Higher power and energy density • Longer life	• Geographical constraints • Expensive construction • Longer planning & constructions • Slower cycling	• Spinning reserves • Arbitrage • Load leveling

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AUTHOR PROFILE

Sneha Patil, M.Tech Student in Electrical Power Systems, BVDU College of Engineering Pune.

