A Technical Overview of Different Energy Storage Technologies with Renewable Source

haripal TIWARI
Department of Electrical Engineering
MNIT, Jaipur, India
Email:harpaltiwari@yahoo.com

ashish SAINI
Department of Electrical Engineering
SURESH GYAN VIHAR UNIVERSITY
Mahal Jagatpura, Jaipur
Email:ashishsaini27@gmail.com

Abstract: Successful operation of electrical grid requires that generation will follow the demand. But it is not feasible when renewable energy sources are connected to the grid. Consequently it creates a lot of problem like voltage fluctuation and grid congestion. These problems can be solved by using energy storage technologies. The main characteristics, merits and demerits of energy storage technologies are introduced. Finally, a qualitative comparison between different energy storage is also made.

Index Terms - Energy Storage Technologies, Power Electronics, Reliability, Power Quality

I. Introduction

Energy storage devices are required to store the energy and use this energy at later stage especially in blackouts or the places where we don’t have any generation. At large scale, it is economical to store the off peak energy from conventional power plants and extra generation from renewable sources. At the time of peak the same energy is released when consumption are higher than generation.

With the increased penetrations of renewable sources in the overall electricity generation, the up gradation of energy storage technology is crucial. Renewable energy sources are wind, solar tidal etc. The characteristics of these are intermittent in nature and not dispatchable. Sometimes these are available at the time of off-peak but not available at the time of peak. The main problems of these are grid congestion and rapid change of output from conventional power plant as they are load following power plant. In order to address the problem associated with renewable, energy storage technology is a prominent solution.

Energy storage technologies play an important role in power system. Energy storage technology has some benefits in the power systems which are as follows:

- Integrations of Renewable Sources with Energy Storage System Enhances Effective Load Carrying Capability [1]
- Efficient Use of Renewable Sources
- Improves Reliability of Power System
- Maximization of Renewable Energy Contribution
- Provides VAR Compensation [2]
- Can Be Used As Ancillary Services [3]

There are different energy storage technologies that are being used by different power utilities. These technologies are as follows:

(a) Compressed Air Energy Storage (CAES)

(b) Hydrogen Energy Storage

(c) Pumped Hydro Energy Storage

(d) Battery Energy Storage

(e) Flywheel Energy Storage

(f) Superconducting Magnetic Energy Storage

(g) Super Capacitors Energy Storage

This paper provides brief description of the above mentioned technologies. The main factors are cost (capital and (O & M), life cycle, storage capacity and efficiency. Each technology is suitable for a particular application. The working principle of each technology, their characteristics, merits and demerits are explained.

Section II describes the CAES technology while section III describes the hydrogen energy storage. Pumped hydro energy storage is introduced in section IV. Section V describes the Battery energy storage and flywheel energy storage is in section VI. Super magnetic energy storage and super capacitor energy storage are introduced in section VII and VIII respectively. A qualitative comparison of different energy storage technologies is available in section IX. In the end power electronics devices are stated in X and Conclusions are stated in section X1.

II. Compressed Air Energy Storage (CAES)

It uses the off peak energy of conventional power plants to generates compressed air and stored it in gas wells or aquifers. These compressors are driven by the motor set. At later stage the high pressurized compressed air used to drive the air turbine to generate electricity. Currently there are two plants is in operation, one in McIntosh (USA) another in Huntorf (Germany) [4] [5].

Energy Stored = $PVl_n \frac{P_a}{P_b}$

The Main Characteristic of CAES Technology

- Uses Off - Peak Electricity of Conventional Power Plants
- Energy is Stored as Mechanical Energy
- High Storage Capacity 538000 M^3, and High Output 110 Mw Up to 26 Hours Of Mcintosh Power Plant
- Uses Gas as a Fuel to Heat Up the Air Before Fed to Air Turbine
- High Pressure Tolerance 50* 10^5 To 75* 10^5 Pascal

The Advantages of CAES are:[6] [7]

- Reaches Zero Load to Full Load in Less Than 15 Minutes
- Consumes 1/3 Amount of Gas in Comparison to Gas Power Plant
- Sells Off - Peak Power at Higher Rate at the Time of Peak and Generates Revenue
- Feeds Reactive Power To Transmission Line

The Disadvantages of CAES are

- Due to High Pressure, Air Leakage from Pipes, Valves or Surrounding Structure
- Geographic Structure Reliance for High Pressure
- Heat Recovery Adiabatic Not Available Yet
- High Noise of Compressors
- It Requires Long Natural Gas Pipelines, if Site is Far Away

III. Hydrogen Energy Storage

Hydrogen energy storage is the fast growing energy storage technology. This type of storage uses electrolyzer to split water into hydrogen and oxygen. Hydrogen is stored in tanks, and fuel cells or IC engines use this hydrogen to generate electricity [8]. Hydrogen can be stored as gas, liquid or solid storage medium. As a gas it stored in high pressurize steel tanks which can bear pressure upto $350*10^5$Pa. However carbon – fibre-wrapped composite tanks can bear pressure up to $700*10^5$ Pa. at temperature 30 to 50^0C [9] [10].But at this high pressure 12 to 16% energy is lost. In liquid storage medium it is cooled at a temperature of (-253^0C) by the heat exchangers but approximate 30% of energy is lost to produce liquid hydrogen. As a solid storage medium it uses sodium alanate to store the hydrogen and it is an ongoing research on this type of storage method. For gas storage medium

Stored Energy = -$\frac{\Delta HP}{RT}$

Characteristics of Hydrogen Storage

- It is the Lightest Element and Low Volume Energy Density
- No Natural Source of Hydrogen
- Hydrogen is an Energy Carrier Not an Energy Source
- The Combustion of Hydrogen in Per Unit Mass Gives Three Times More Energy Than Petrol and Six Times More Energy Than Coal.

Advantages of Hydrogen Storage [11]

- High Energy Density
- Implemented in Different Type of Storage From kW to MW.
- Used for Transportation Purpose
- There is no CO2 Emission

Disadvantages of Hydrogen Storage

- Expensive to Make by Electrolyzer Procedure
- Highly Inflammable
- Volumetric Hydrogen Density is not High
- Reactive with Halogens and Oxidants Causing Fire

IV. Pumped Hydro Energy Storage

Pumped hydro plant is the one of the oldest energy storage technologies. This type of storage medium consists of two reservoirs which are situated at different altitude. At the time of off – peak demand, power is used to pump the water from lower reservoir to higher reservoir. At the time of peak demand the same water is released into lower reservoir where it is used to rotate the hydraulic turbine to generate electricity.
In this type of storage medium the pumping and generation can be done by a single unit. The plant is able to change between pumping and operation modes in the period of some minutes [4]. The efficiency of such type of plant depends upon the hydro turbine, the size of plant and the height between lower and upper reservoir [11].

Energy Stored = mgh

Characteristic of Pumped Hydro Plant

- Water Stored as Potential Energy
- Uses Two Reservoirs to Store Water

Advantages of Pumped Hydro Storage

- Implemented in Different Type of Storage, < 100 MW up to 2000 MW
- Store the Energy for Long Time up to Six Months

Disadvantages of Pumped Hydro Storage [11]

- Specific Geographic Location for Such Type of Storage
- Political Procedure for Construction of Such Type of Storage System
- High Construction Cost. The Capital Cost of Such Type of System is $1000/ kW

V. Battery Energy Storage (BESS)

In this system batteries are composed of electrochemical cells. Each cell consists of electrolyte having a positive and negative electrode.

When battery is charged there are some reactions in electrochemical cells to store the energy and reaction is reversed when battery is discharged. The current technology in batteries includes Lead acid batteries, nickel cadmium, sodium sulphur, lithium Ion and sodium nickel chloride [12].

Characteristic of Battery Energy Storage

- Energy is Stored in the Form of Chemical Energy
- Implemented in Different Sizes Ranging from 100 W To Several MW
- Connected in Series Parallel Combination to Change Their Power Capacity for Different Applications.

Advantages of Battery Storage Technology [13] [14] [15]

- A Quick Time Response, Duration about 20 Milliseconds
- No Need to Connect to an Electrical System
- Easily Portable
- High Power and Energy Density (NaS Battery)
- Good Temperature stability (Nas Battery)
- Low cost (NaS Battery)
- Good safety (NaS Battery)
- Long Life Enabled by Easy Electrolyte Replacement (Flow Batteries)

Disadvantages of Battery Storage Technology

- Expensive
- Limited Life Cycle (Conventional Battery)
- Periodic Maintenance
- Needs Power Electronics Device for DC – AC Conversion

VI. Flywheel Energy Storage

This energy storage system consists of rotor which rotates at very higher speed when connected to supply. Flywheels resist change in their speed. Later on when energy is extracted from the system (rotor) it brings down the rotor to a lower speed and mechanical energy is converted back in to electrical energy. Composite materials are used for the rotor to reduce its weight and to gain higher speeds [4]. At the output power electronics devices are used to limit the output voltage and frequency range. Mathematically, stored energy and momentum of inertia is given below [16]

Stored Energy = $\frac{JW^2}{2}$

$$J = mr^2h$$

Where, r = radius of rotor
m = rotor mass
h = height of rotor.
w = angular velocity.

The flywheel can be implemented in the range of some kW up to 100 kW. The efficiency of this storage is in the range of 80% to 85%. This depends upon bearing and winding losses and the cycled time [11].

Characteristics of Flywheel Energy Storage

- Energy Stored in the Form of Kinetic Energy
- Speed of Advanced Flywheels 20,000 up to 50,000 rpm in a Vacuum Enclosure
- Classified as Low and High Speed Flywheel. The Border Between Two is 10,000 r/min [17]

Advantages of Flywheel Storage [12]

- Quick Recharge Capability
- High Power Density
- Only Bearings Maintenance Every 3 to 5 Years
- Long Life Cycle
- High Efficient Energy Storage

The Disadvantages of Flywheel Energy Storage [12]

- Low Energy Density
- High Cost
- Releasing of Energy in an Uncontrolled Manner
- Large Standby Losses
- Storage Expansion Are Not Easy

VII. Superconducting Magnetic Energy Storage (SMES)

When a direct current (D.C) passes through a super conducting coil it develops a magnetic field in it. The energy is stored in it at a superconducting critical temperature (-150°C) [4]. The specialty of this energy stored device is that when the coil is fully charged, the current through it remains constant.

Energy Stored = $\frac{LI^2}{2}$

Characteristic of SMES

- Energy Stored in the Form of Magnetic Field
- Act as a Current Source
- No Resistive Losses in the Superconducting Coi
- Switch Between Charging And Discharging in Some Milliseconds [11]
- Implemented in Many Sizes, Some kW to Some MW

Advantages of SMES [18] [19]

- Fast Response Time in Some Milliseconds
- Charge And Discharge Cycles are Unlimited
- Good Efficiency Up to 90%, Not Including Refrigeration system
- Quick Energy Transfer

Disadvantages of SMES [18]

- High Magnetic Field
- Conversion of AC-DC-AC Losses
- Expensive Energy Storage
- Low Energy Density
- Sensitive to Temperature

- Refrigeration Losses

VIII. Super Capacitors Energy Storage

Super capacitors are electrochemical capacitors (EC) or electrical double layer capacitors (EDLC).
The capacitors are consisting of two parallel electrode plates which are separated by a dielectric medium. It stores energy in the double layer at an electrode. There is not an ionic transfer but a chemical reaction [20] [21] [11].

Energy Stored = $\frac{CV^2}{2}$

The super capacitors have high power and energy density in comparison to battery and traditional capacitor.

Characteristic of Super Capacitors

- Energy Stored in the Form of Electrical Energy
- Very Less Volume in Comparison to Metallic Foil Type Capacitors
- Capacitance Can Be Increased By Minimizing the Distance Between the Plates and Increased Surface Area in Order to Increase Energy.

Advantages of Super Capacitors [4] [16]

- High Power Density
- Operate in Different Environment Conditions (Moist, Hot, Cold)
- No chemical change in the Electrode Causes Long Life Cycle
- Highly Efficient: Efficiency is a Function of Ohmic Resistance of the Conducting Path

Disadvantages of Super Capacitors [12]

- Low Energy Density due to no Chemical Reaction by Electrons
- Expensive in Comparison to Batteries
- Completely discharge causes Voltage Swing

IX. Qualitative Comparison of Energy Storage Technologies

Table 1 Comparison of Different Energy Storage Technologies.

Storage Device	Power	Energy	Discharge Duration	Response Time	Efficiency	Cost	Life time(Yr)	Class	Application
CAES	110-290 MW	2860 MWh	Days	4 -10 min	70%	12-85	40	Long Term	➢ Energy Arbitrage ➢ VAR Support
Hydrogen energy storage	10 MW	---------	Min/hours	-------	70 – 90 %	----	10 years	Middle Term	-----
Pumped Hydro	< 2 GW	<24000 MWh	Days	Few Seconds	80%	45-85	40	Long Term	➢ Energy Arbitrage ➢ Frequency regulation
Battery	<30 MW	<300MWh	hours	Millisecond	60 -90 %	85-4800	10 years	Middle Term	➢ Back up Power ➢ Small load levelling
Flywheel	<100kW	<100kWh	Sec/min	Millisecond	90%	170-420	30	Short Term	➢ Power Quality
SMES	3 MW	250 kWH	Sec/min	Millisecond	90%	240-600	40	Short Term	➢ Power Quality
Super capacitors	250kW	3 MWh	Sec/min	Millisecond	95%	85-480	40	Short Term	➢ Power Quality

X. Power Electronics Devices for Different Energy Storage Systems.

The energy storage systems have different power ratings, so it is essential to integrate these with some power electronics devices to modify their rating according to required output with desired waveform.
Depending upon the storage technology the main function of power converter is as follows:

- Connect Two DC Bus
- Connection between DC to AC Bus
- Connection of Current Source to DC Bus
- Isolation of Two circuits

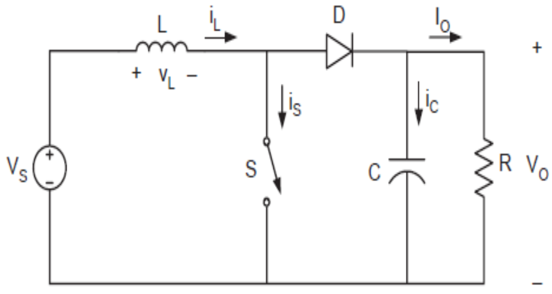
Characteristic of Power Converter are as follows:

- Small Size and Weight
- High Efficiency
- Fast Response
- Bidirectional Power Flow

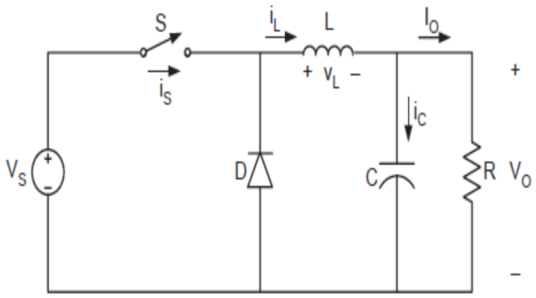
For storage technologies such as super capacitors, batteries, the main power electronics devices are boost, and buck converter. These topologies enable the connection between two electrical DC systems and minimize the fluctuation coming from storage system. The boost, and buck converter shown in fig 1. Sometimes isolation transformer is needed to isolate between primary and secondary system. This is needed

for resonant system and high frequency applications. This is shown is fig 2
Connection of DC storage system with an AC grid requires an inverter which is shown in fig 3

For the system of current source, the topology is shown in fig 4.



1 (a) Boost converter [22]



1 (b) Buck converter [22]

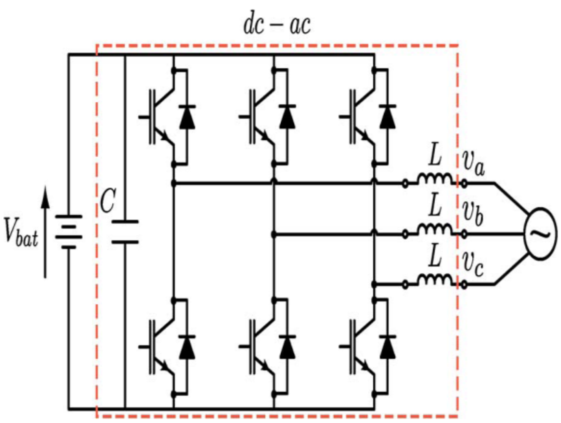


Fig 3 DC – AC Converter

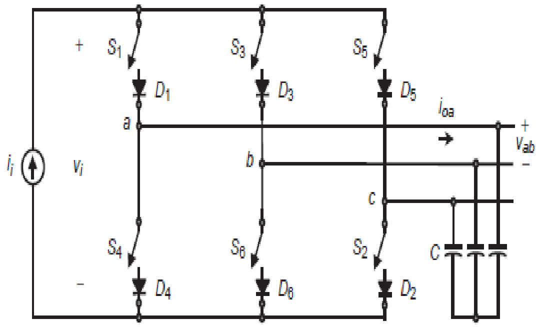


Fig 4 Inverter connected to a current source [22]

XI. Conclusion

This paper evaluates the different energy storage devices that can be integrated with power system to improve all over performance. The energy storage technology and its benefits are also stated. Different energy storages which consist of small, medium and large scale are studied. Their characteristic, merits and demerits, are also taken into consideration. The technical study of different devices is very important when contribution of renewable energy sources is increasing at a very rapid rate in all over electricity generation. It creates a lot of problem to power system, so energy storage in an attractive solution. Every energy storage technology denotes its characteristic which is suitable for a particular application. This literature provides a complete description about the latest energy storage technology. It is beneficial for the researcher to provide fundamental information which is beneficial to plan a system.

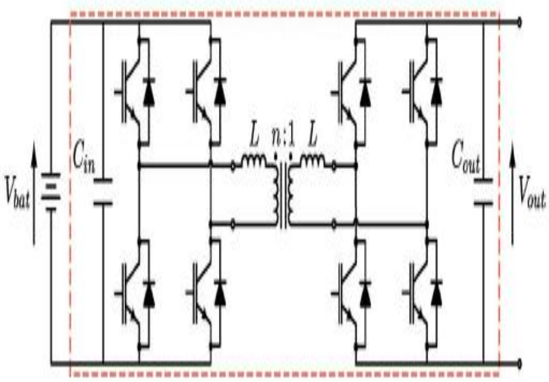


Fig 2 Isolated DC DC converter [23]

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