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# Energy Storage Technology for Performance Enhancement of Power Systems

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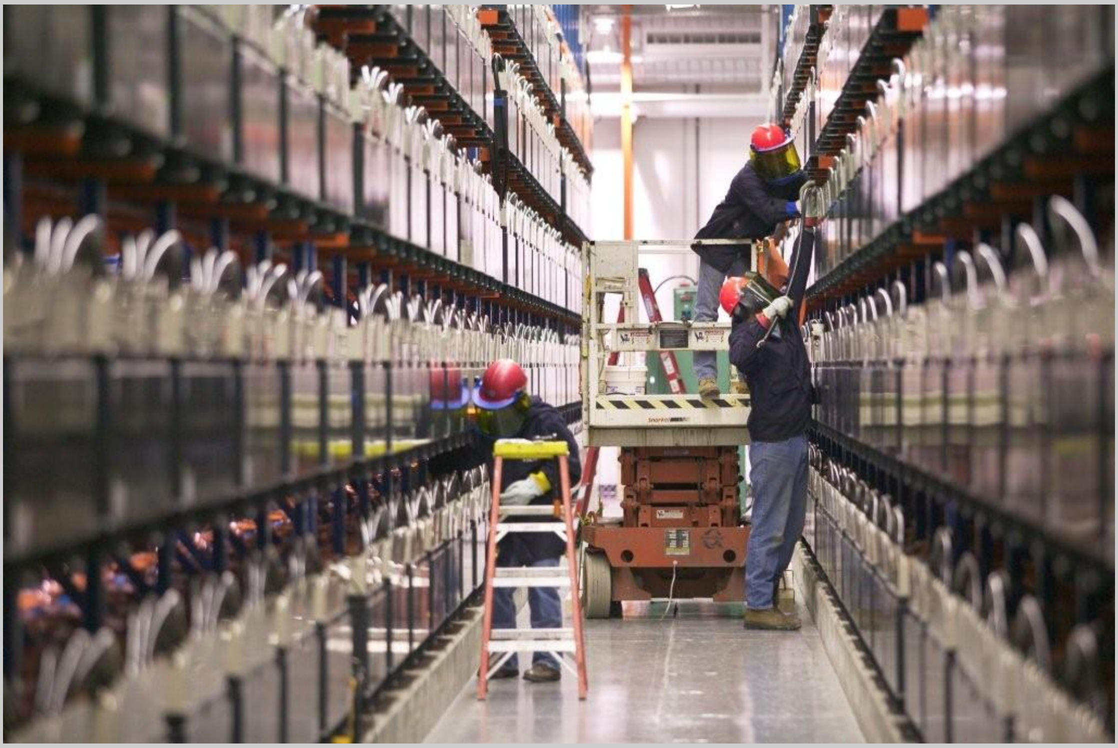

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## Abstract

The use of electronic loads is increasing very fast. The gap between demand and the short generation is also increasing very fast. These have made the power quality, reliability and stability a critical issue. Further, there is continuous thrust on optimal utilization of the non-conventional energy resources due to price rise of oil and environmental issues, in addition to the fact that the central power station with improved quality of power has made it necessary to use the energy storage technology. This paper focuses on the state and qualitative aspects associated with the different energy storage technologies and to enhance the system performance by envisaging properly designed energy storage devices for application in the power system at different stages.
**Keywords:** Supercapacitors, Energy Storage Technology, Long Term Storage, Medium Term Storage, Short Term Storage, Reliability, Power Quality.

## 1. Introduction

Nowadays the power system is in a process of undergoing from regulated market to the deregulated one, centralized to more localized systems that are situated nearer to the load centers. The reasons behind are; increased concern for environment, utilization of renewable energy technologies, flexibility of operation, lower initial investment costs, lower time of project completion, electricity market liberalization, developments in DG technology, constraints on the construction of new transmission lines and increased customer concern for highly reliable electricity etc. [1] .

A study has forecasted that the total world energy consumption would increase by 50% from 2005 to 2030. [2]. Further, the rapid increase in electronic loads has made power quality a critical issue because they are potential source of harmonics. The power generation, transmission & distribution system must be able to supply uninterrupted power reliably while maintaining the power quality throughout. The constraints like the generation capacity and slower response of alternators to system disturbances, affect the stability and overall performance of system adversely. Thus, there is a strong need of energy storage capability to maintain power quality of the grid along non-conventional energy resources units [1].

The advancements in custom power devices are now viably leading the use of advanced energy storage technologies like supercapacitors, flywheels and superconducting energy storage systems for transmission and distribution to enhance the system performance.

## 2. Basic Need of Energy Storage Technologies

The energy storage devices/equipments are used basically for three purposes viz; energy stabilization, ride through capability and dispatchability.

The energy stabilization permits the DG to run at a constant stable output level with the help of the energy storage devices, even if the load fluctuates rapidly. A DG unit can successfully serve a load which has capacity greater than the highest needle peaks. Power quality problems may get developed because the DG unit may not be able to respond quickly as the load changes. However, if the storage unit is connected in parallel with the load then, in case of unscheduled demand, the storage unit can supply the energy. Further, at the time of valley the storage unit would be charged by the DG/Grid. This permits the DG unit to run on smooth steady state schedule. [3]

The ride through capability is the capability of energy storage device which provides the proper amounts of energy to loads , when the DG unit is unavailable, for example during the night time the solar supply system or when the DG unit of any type is being maintained or repaired. The DG owner who needs power has two options during such periods. The first one, use another backup or use the utility grid. The second way is to meet out the needs with energy stored when the source is unavailable. The second option is often preferred because another DG unit might not be any better, and the grid may not be available as an economical option. [3]

Dispatchability permits the DG owner to commit in advance, for certain time, regardless of how much power the DG unit is producing at that time. The dispatchable energy is always more worthy than non dispatchable energy due to its inherent characteristic of availability and commit-ability. The energy sources like photo voltaic or wind energy systems, the power production depends upon availability of the resources like sunlight or wind respectively. This makes the nature of power available to loads intermittent, thus making them non-dispatchable sources. However, the energy storage systems with non-dispatchable energy can be deployed as dispatchable energy source. This only needs a proper design of the energy storage system, looking into the load curve.

## 3. Energy Storage Technologies – The State of Art

Energy Storage Technology (EST) used in conjunction with DG / Grid can be divided into two groups. The First one is that stores energy as electrical energy and the second one is that which stores it in some other form (e.g. electro-chemical storage, thermal storage, hydraulic storage, pressure storage, mechanical storage, electro-magnetic storage, electro-static storage etc.), which can be converted into electrical energy when needed.

The storage technologies are broadly described below.

## *3.1. Battery Storage*

Battery produces electricity by causing a chemical reaction in the presence of an electrolyte, in such a way that releases ions, which then travel through electrolyte, creating a direct current flow at relatively low voltage. Usually batteries are stacked to produce modules with higher voltages much like fuel cells. Batteries store energy by having electric flow crammed through them in the opposite direction, forcing ions in the other direction, and reversing the chemical transformation. The following are the types of batteries available; Lead Acid Batteries, Nickel-metal hydride, Lithium, Sodium-Sulfur (NaS), Alkaline and Nickel Cadmium, [3-5].

## *3.2. Solar Thermal Electric Storage (STES)*

Solar thermal electric steam power plants store energy as molten salt or super heated oil. Solar power is used to heat the salt or oil, put into large tanks, at temperatures between 600ºF - 1,100ºF. The heat from the salt or oil can be used when needed to turn the water into steam to run a steam turbine coupled with electric generator. A STES system is completely dispatchable. Most STES units store energy for about 20 hours at their rated output. They are efficient, robust, and relatively inexpensive [3].

## *3.3. Pumped Hydro Storage*

Energy storage systems deploying hydraulic power are based on the concept of potential energy utilization. During off-peak period the electric power is used to pump the water to the reservoir on high hill or mountain. While during peak period, the water is released through a pipe downhill to a hydroelectric generator. Such storage is generally used for utility to meet the peak demand. The efficiency for one cycle is between 70- 85%. One of the major problems related to such storage is that it adversely affects the ecology due to building of reservoir. The other one is that at least two water reservoirs are needed for such purpose [3, 4].

## *3.4. Compressed Air Energy Storage (CAES)*

Compressed air systems use electric power to run compressors that push air into a tank at very high pressure, and then use this air under pressure in a piston or turbine to generate power on demand. CAES system stores compressed air in geologic structure such as aquifers, abandoned salt or other mines. Generally CAES has too a high fixed cost for DG applications. The smallest practical size of such storage is of the order of 10MW power and 100MW-h energy. CAES systems have high power and energy density in comparison to pumped hydro storage system [3-5].

## *3.5. Flywheel Storage*

Flywheels were the original means for energy storage in early designs of "no-break" engine-generator sets. The energy stored in flywheel is in the form of kinetic energy in the rotating mass of a rapidly spinning flywheel. The energy stored in a flywheel is given by the classical equation,

$J = (1/2) I\omega^2$,

Where, J = energy in joules or (W-s)

I = moment of inertia, ($kg\text{-}m^2$)

ω = rotational velocity, (rad/s)

Two type of such technology are in use. The first one is the high speed flywheel system having small flywheels and spinning over 50,000 rpm. Many are intended for electric vehicles and similar other applications, where size and weight are the decisive factors. The second one is the low speed flywheel system has large flywheels and usually spinning at about 7,000 rpm, the diameter might be up to a meter or more [3, 6].

## *3.6. Superconducting Magnetic Energy Storage (SMES)*

SMES systems store energy in a super conducing magnetic coil immersed in a very cold liquid such as liquid helium, contained in a highly insulated thermal bottle. Super conducting magnetic coils have zero electrical resistance, so once electric current being circulated will not diminish over time. The coils themselves are not very large. They are of approximately two feet in diameter and one foot high. Power is stored in SMES by circulating DC electric current in the coil magnetically. It is withdrawn through reversal of the process. A typical SMES unit stores about 250 kW-h of energy in a space of about a large refrigerator's size, weighting approximately 700 Pounds. The advantages of SMES are efficient, robust, very reliable and noiseless operation. It operates at microsecond speed with very good voltage regulation precision. The magnetic coil never wears out. Capacity of SMES ranges 0.3-3.0 MW, bridging time 1-60 seconds, building time only 3 weeks, efficiency 90%. The power quality conditioning by the SMES is of the highest quality. The disadvantages of SMES are; cooling requirement, expenditure involved ($2,500-$3,800 per kW-h of storage capacity, which is 20 times that of lead-acid batteries), sensitivity to temperature, very high magnetic fields (9 T or more) etc [3-5, 7].

### 3.7. Super Capacitor Energy Storage (SCES)

Super capacitor is a double layer capacitor. The energy in it is stored by charge transfer at the boundary between electrode and electrolyte. Super capacitors are constituted of two electrodes, a separator and an electrolyte. The electrodes are made-up of activated carbon, which provides a high surface area responsible for energy density of super capacitor. The two electrodes are separated by a membrane, which allows the mobility of charged ions and forbids electronic contact. The electrolyte supplies and conducts the ions from one electrode to the other. The amount of stored energy is a function of electrodes surface area, the size of the ions, and the level of the electrolyte decomposition voltage [5].

Usually super capacitors are classified into two types viz; double-layer capacitors and electrochemical capacitors. The double-layer capacitor depends on the mechanism of double layers, which is a result of the separation of charges at interface between the electrode surface of active carbon or carbon fiber and electrolytic solution. Its capacitance is proportional to the specific surface areas of electrode material. The electrochemical capacitor depends on fast Faraday Redox reaction. It includes metal oxide super-capacitors and conductive polymer super-capacitors. They all make use of the high reversible Redox reaction occurring on electrodes surface, or inside them, to produce the capacitance depending on electrode potential. Their capacitance depends mainly on the utilization of active material of electrode.

The working voltage of electrochemical capacitor is usually lower than 3 V. Based on high working voltage of electrolytic capacitor, the hybrid super-capacitor are developed by combining the anode of electrolytic capacitor and the cathode of electrochemical capacitor. It has the best features of the high specific capacitance and high energy density of electrochemical capacitor. Such capacitors can work at high voltages without the requirement of connecting many cells in series. The most important parameters of a super capacitor are designated as the capacitance (C), Equivalent Series Resistance (ESR) and Equivalent Parallel Resistance (EPR) [4, 8-13].

# 4. Qualitative Comparison of Various Energy Storage Technologies

In the table-4.1, the storage technologies are compared based on various parameters, their advantages, disadvantages and their applications [3-6, 6, 13-15].

Table 4.1: Qualitative Comparison of Various Storage Technologies

| **Parameters\ Storage technology** | **Batteries** | **Pumped Hydro** | **Thermal (STES)** | **CAES** | **Flywheels** | **SMES** | **Super capacitors** |
|---|---|---|---|---|---|---|---|
| Typical Range | 100W to 20MW | Up to 2.1GW | 5MW and above | 25MW to 350 MW | kW scale | 1MW to 100 MW | 1kW to 250 kW |
| Power Density ($kW/m^3$) | 106-7067 | - | 17.67 | Higher than Pumped hydro | 707-1767 | 530 | 176678 |
| Energy Density ($kW\text{-}h/m^3$) | 70.7-247 | - | 177 | Higher than Pumped hydro | 282.7-424 | 7.07 | 53 |
| Emission | Very low | No | No | No | No | No | No |
| Expected life (Years) | 07-Aug | 40-60 | 30 | 20-25 | 30 | 30 | 30 |
| Electrical Efficiency | 88-92% | 75-80% | <60% | >60% | 90-95% | 90% | >95% |
| Levelized annual cost ($/kW-h) | 25-120 | - | 15 | - | 40-80 | 200 | 85 |
| Applications | Spinning Reserve, Power quality , Transportation | Spinning Reserve, Load leveling, | Peak saving, Spinning Reserve | Peak saving, Spinning Reserve | Voltage regulation , transportation | Peak saving, Power Quality | Emergency power sources, Power Quality, Defence |
| Advantages | High energy density, High bridging time | Bridging time very high, infinite numbers of cycles, | Relatively inexpensive | Compared to pumped hydro a larger power & energy density | High efficiency, a very steep accessibility, Number of cycles $10^6$ | Storage time is very high, Independent of the number of charges & discharges, Building time of only 2 weeks. | High charge and discharge current, maintenance free ,long life, very high power & energy density |
| Disadvantages | Power density low, Hazardous to Environment, Slow charging, Limited number of cycles | Ecological problem, At least two reservoirs needed. | Very high temperature | Large Space required | A small power range | Temperature sensitive, high magnetic field, low bridging time | Less storage capacity than the one of a battery with the same physical dimensions, bridging time less. |

# 5. Application of Energy Storage Technology for Performance Improvement of Power System

From the application point of view the energy storage technology can be classified into three categories.

*(1) Short-Term Storage (STS),*

*(2) Medium-Term Storage (MTS), and*

*(3) Long-Term Storage (LTS).*

*(1)Short-Term Storage*

Short-term storage is the storage that maintains energy reserves sufficient to provide rated power from a few seconds up to a minute. The two basic applications are; for use in Uninterruptible Power Supply (UPS) and for power system stabilization.

UPS are used as storage device for sensitive equipment in the industries, which requires high levels of reliability and power quality. The fast response of the power conversion system interfaces with the storage technologies to make them well suitable to such applications as they provide power within fraction of a cycle when the grid supply fails or a voltage depression occurs.

Power system stabilization requires larger amounts of energy i.e. ranging between 1 MJ to 10MJ momentarily in order to damp voltage oscillations lasting for 5-20 cycles. Short term storages are particularly useful in remote areas or in locations where the grid is weak and prone to instability. Therefore, reinforcement of the existing network may be delayed or avoided through the use of stabilizing storage devices. The voltage support / reactive power control can also be provided continuously in addition to short-time power supply.

*(2)Medium-Term Storage (MTS)*

Medium term storage is the storage that maintains energy reserves sufficient to provide rated power from a few minutes up to a few hours. Applications for this type of storage capability include renewable energy management, customer energy management, area control / frequency regulation, and rapid reserve.

Renewable energy sources such as wind and photo- voltaic are variable and intermittent and for these reasons they are non-dispatchable and less worthy in the energy markets. Their costs can be greatly enhanced when coupled with energy storage devices that allow their operators to make firm energy commitments as per scheduled requirement.

Medium term storage can be used for customer peak-saving, network reinforcements, area control, frequency regulation and rapid reserve. They can reduce the amount of spinning reserve capacity, leading the generators to run with better economic loading and avoiding mechanical and thermal stresses on them.

*(3)Long-Term Storage (LTS).*

Long term storage is the storage that is able to hold energy for duration ranging from a few hours to weeks or months. This is typically bulk energy storage and is generally used to take advantage of the energy price difference between peak and off-peak periods. A typical daily cycle would include energy storage during off-peak (night time) hours and generation during peak (day time) hours.

Long term storage can also be useful in reducing daily peaks, deferral of generation capacity expansion, leveling the system load profile and reduction of cost of operation of thermal units [16].

**Table 5.1: Summary of Application of Energy Storage Systems [17]**

| Sl.No. | Category | Application/Benefit | Discharge Duration (Hours) | Type of Storage |
|---|---|---|---|---|
| 1 | Grid System<br>A | Bulk Electricity Price Arbitrage | 1-10 | LTS |
| | B | Central Generation Capacity | 4-6 | LTS |
| | C | Ancillary Services | 1-5 | MTS |
| | D | Transmission Support | 2-5 seconds | STS |
| | E | Reduce Transmission Access Requirement | 1-6 | MTS |
| | F<br>G | Transmission Congestion Relief<br>Distribution Upgrade Deferral | 2-6<br>2-6 | MTS<br>LTS |
| | H | Transmission Upgrade Deferral | 2-6 | LTS |
| 2 | End User Utility Customer | | | |
| | a | Availability Based Use / Energy Cost Management | As per required cost benefits | LTS |
| | b | Demand Charge Management | 6-11 | MTS |
| | c | End User Electric Service Reliability | 1/4 -5 | MTS |
| 3 | Renewables | | | |
| | a | Renewables Capacity Firming | 6-10 | MTS |
| | b | Renewable Contractual Time – Off Production Payments | 6-10 | MTS |

## 6. Importance of Proper Design of Energy Storage Technology Bank and Scope of Work

The existing distribution system is greatly suffering from frequent interruptions due to overloads, insufficient generation, load imbalance, poor maintenance and bad weather conditions etc. Enhanced usage of power electronics devices and computers has also led to deterioration in power quality. This not only leads to irritation to the users but also incurs a huge loss to the utilities and industries. In order to circumvent such difficulties, it is imperative to make use of suitable energy storage along with the usual supply.

In order to reliably and safely supply the uninterrupted and quality power to the customers, maintaining techno-economic viability, the judicious choice of energy storage technology is utmost important. The major contributing factors for proper design and implementation of EST for power distribution systems, both in the grid -connected mode as well as in the grid -independent mode, are as follows.

1. Identification of the problems to be addressed,
2. Specifying the energy density, power density, voltage, current and efficiency requirement,
3. Modeling of the energy storage technology for specific use,
4. Optimizing the specifications as per needs (i.e. LTS, MTS, STS),
5. Analysis of the techno-economical benefits from application of the storage technology,
6. Analysis of the return on investment to utility / customer.

There is a vast scope of work, particularly in the power deficient countries like India, where scheduled and unscheduled power outages take place and the quality of the power supply is also very poor. Some of the areas to be explored are as follows.

1. The optimal placement of storage device.
2. The optimal utilization of the non-conventional resources along with storage.
3. Reactive power planning with storage.
4. Ride trough capability of supply.
5. Dispatchability of power
6. Transient stability improvement.
7. Transmission capacity improvement.
8. Dynamic stability improvement.

## 7. Conclusions

After thorough and critical survey of the literature on the state of reported energy storage technologies, their qualitative analysis, advantages, disadvantages and applications have been compared in this paper. Various aspects for improving the power quality and reliability of weak as well as of the strong systems have been suggested by addressing to the issues like providing ride through, making non-dispatchable power into dispatchable, improving overall performance of power system etc. by deploying adequately designed energy storage systems. Among the major benefits that can be achieved are distribution upgrade deferral, transmission upgrade deferral, availability based use / energy cost management, end user electric service reliability etc. Further, with the custom power devices the real and reactive power can be handled leading to smooth control of the system stability. The authors, through this paper, are of definite opinion that performance of the existing power system can be enhanced with the implementation of energy storage technologies by means of integration with the renewable energy resources. This would also lead to positive impact on environment by virtue of reduced fuel consumption, reduced emission of gases and renewable capacity firming.

## References

1. Ribeiro F.Paulo, Johnson K.Brian,Crow L. Mariesa Arsoy A. and Liu Yilu, "Energy Storage systems for Advanced Power Applications" Proceedings of the IEEE,Vol.89,No.12,Page(s0:1744-1756, December 2001
2. Energy Information Administration U.S. Department of Energy Washington, DC 20585, "International Energy Outlook 2008", September 2008, pp.7.
3. Wills H Lee and Scott Walter G, "Distributed Generation Planning and Evaluation", Marcel Dekker Inc. New York.pp.1, 151-153,159,166-167,170,175-177, 2000.
4. Sels T, Dragu C, Van Craenenbroeck T and Belmans R, **"**Overview of New Energy Storage Systems for an Improved Power Quality and Load Managing on Distribution Level**"**, Electricity Distribution, 2001. Part 1: Contributions. CIRED. 16th International Conference and Exhibition on (IEE Conf. Publ No.482) Volume 4, 18-21 June 2001 Page(s):5 pp. vol.4
5. http://en.wikipedia.org/wiki/supercapacitor pp1to 4 last modified 13 march 2007.
6. Kusko A and Dedad J, **"**Short-term, Long-term, Energy Storage Methods for Standby Electric P Systems", Industry Applications Conference, 2-6 Oct. 2005, Fortieth IAS Annual Meeting Conference Record 2005, Volume 4, pp 2672 – 2678.
7. Pasko S, Biskup T, Buehrer C, Grzesik B, Roest-Krijgsman J, Michalak J, Stepien M and Zygmanowski M, **"**Comparison of SMES and SCES Based Power Conditioning Systems"**,** Power Electronics and Applications European Conference, 11-14 Sept. 2005,Pages(s) P1-P10.
8. Kazimierczuk M K and Cravens R C**,** "Application of Super Capacitors for Voltage Regulation in Aircraft Distributed Power Systems," Power Electronics Specialists Conference PESC '96 Record, 23-27 June 1996, 27th Annual IEEE, Volume 1, pp 835 - 841.
9. Palma L, Enjeti, P.; Aeloiza, E "An Approach to Provide Ride-Through for ASD systems with Supercapacitors," Power , 20-24 Oct. 2002 , pp 182 – 187
10. Dandan Zhang; Man Luo; Jin Li; Junjia He; "Surveying into Some Aspects of Internal Resistance of Super capacitor," Electrical Insulation and Dielectric Phenomena, 2005. CEIDP '05. 2005 Annual Report Conference on 16-19 Oct. 2005 Page(s):637 – 640.
11. Ji-Yan Zou; Li Zhang; Jin-Yan Song; "Development of the 40 V Hybrid Super-Capacitor Unit" Magnetic, IEEE Transactions on Volume 41, Issue 1, Part 2, Jan. 2005 Page(s):294 – 298

12. Yao, Y.Y.; Zhang, D.L.; Xu, D.G.; “A Study of Supercapacitors Parameters and Characteristics”, Power System Technology, 2006. PowerCon 2006. International Conference on Oct. 2006 Page(s):1– 4.

13. http://leiwww.epfl.ch P.Barrade and Prof. A Rufer, “Voltage Drop Compensation for Weak Distribution Systems: Simulation for Study and Implementation”.pp1-13.

14. http://www.mitre.org/tech/nanotech , Marin S.Halper and James C. Ellenbogen “Supercapacitors Brief Overview,” March 2006 pp.1-26.

15. California Energy Commission http://www.energy.ca.gov

16. Paul David Brown; Ph.D. thesis “Evaluation of Integration of Pumped Storage Units in an Isolated Network” University of Porto 2004, Page(s) 26-28.

17. James M.Eyer, Joseph J.Lannucci, Garth P.Corey; “Energy Storage Benefits and Market Analysis Handbook” Sandia Report No. SAND2004-6177 December 2004 Page(s) 3-4.