ENERGY STORAGE TECHNOLOGIES FOR INTEGRATION WITH FACTS CONTROLLERS: PERSPECTIVES AND PROSPECTS

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Abstract—*Flexible A.C. Transmission systems (FACTS) are now well established technologies in power system applications. Many such large scale installations are functioning around the world. In last decade many Energy Storage technologies have matured to a stage wherein they can be used for multi megawatt applications. This paper explores the possibilities of integrating various energy storage options with these controllers. An overview of energy storage options along with their characteristics and utility are described. Possible benefits of integration in terms of improvement of transient stability, frequency regulation etc. is explained.*

Keywords—Flexible A.C. Transmission; Energy Storage; Ultracapacitors; SMES

1. INTRODUCTION

Even after more than a century of invention of electrical energy, a perennial problem remains; and that is at any point of time the power produced and utilized must match. There is a slight margin for operation but that is too low. Blackout on 30 and 31 July 2012 in northern India is a testimony to this. While the semiconductor revolution took decision making capabilities of computers to nanosecond levels; the power system largely remained bottlenecked by slow operating mechanical devices. Even today the Indian power system is crippled by traditional and slow operating mechanical systems for operation and control of power systems. If the slow acting mechanical systems can be replaced by fast operating power electronics based FACTS controllers; existing transmission network can be utilized to carry more power with incremental expenditure, without having to spend too much on additional infrastructure [1]. Power Grid Corporation of India limited (PGCIL) is the National body which is responsible for proper operation of the National Grid has realized this long back and they have installed and invested in FACTS controllers. To start with, series controller TCSC has been installed at few locations in India in 2004. There is a plan to install many more FACTS controllers in near future. Recently in June 2016, Siemens has received order for India's largest STATCOM. It has a 2000 MVAR range on a 400kV system which is likely to cost approximately €78 million.

FACTS controllers which utilize Voltage Source Converters (VSCs) have a unique advantage that they have a D.C. link wherein transaction of power in D.C. terms is possible [2]. This opens a whole lot of options for Energy storage options like Batteries, Ultracapacitors, Superconducting Magnetic storage etc. These energy storage devices when connected to FACTS controllers not only reduce the rating of the controller but also add lot of value in terms of extended control capability of the FACTS controllers. In section 2 various types of Energy storage systems are described with reference to their applicability in various power system problems. Section 3 reviews various topologies and methods of integration of the energy storage systems with FACTS controllers. Section 4 describes comparison of different controllers with energy storage followed by conclusion in section 5.

2. ENERGY STORAGE SYSTEMS

There are many options available today for energy storage applications.

A. Batteries

Many Electrochemical Battery options are available today. These are Lead Acid batteries, Lithium Ion (Li-ion) and Sodium Sulfur (Na-S) batteries. Based on how much energy you need and how long you need, any of the options can be selected. There are many 1MW plus deployments in the world. Major restricting factor in large scale use of Batteries are due to challenges like Number of Charge/discharge cycles available, energy density, power density, charging circuits and cost. Recently lot of research is ongoing on various chemistries of batteries, especially the flow batteries. TABLE I demonstrates the different battery types being used around the globe and their percentage. Clearly the most prevalent one is the Lithium ion battery as most of the applications across the globe using Battery energy storage are related to short discharges of 2 Hours for frequency regulation and as UPS.

TABLE I: TYPES OF BATTERIES & USAGE

Battery Type	% Use
Lead-acid Battery	13
Lithium Iron Phosphate Battery	18
Lithium Polymer Battery	3
Lithium-ion Battery	46
Nickel-cadmium Battery	1
Sodium-ion Battery	2
Sodium-nickel-chloride Battery	5
Sodium-sulfur Battery	6
Valve Regulated Lead-acid Battery	2
Zinc Bromine Flow Battery	4
Zinc Iron Flow Battery	1

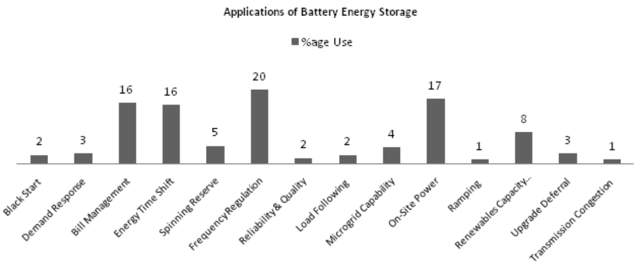

Fig.1. Usage of Battery Energy storage for different applications

Fig. 1 above demonstrates the different purposes for which battery energy storage has been put to use. It is clear from this figure that batteries are used predominantly for power back up and frequency regulation [5]

B. *Ultra capacitors*

Though the ultra-capacitor or super-capacitor technology was introduced almost five decades ago, it has found renewed interest in last decade owing to reduction of cost and improvement of energy density of these devices. Compared to batteries ultracapcitors have less energy density but higher power density, also they are virtually unaffected by number of charge/discharge cycles. This makes them ideal for application where rapid discharge is required for a short period. Fig. 2 shows some of the current applications of ultra capacitors. Clearly South Korea is leading in the applications. Rated power per kW varies from 28kW to 2340kW and primarily they are used for Voltage support and electrical energy time shift.

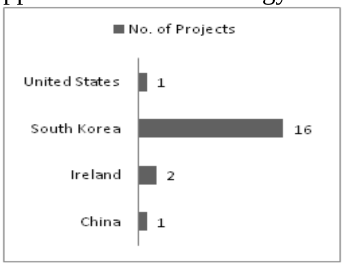

Fig.2. No. of Ultra capacitor projects around the globe

In South Korea, the applications are for Metro project and they have achieved 20% energy saving using the ultra capacitor banks. In most of the applications Maxwell has supplied the capacitors.

C. *Compressed Air Energy Storage (CAES)*

Another well known method of energy storage is Compressed air Energy storage. This large scale energy storage, it is capital intensive but provides many possibilities from back up supply to integration of renewable. Discharge amount time can run into tens of hours. The technology is quite mature and the power ranges from 1MW to 330MW for actual applications in the world. Fig. 3 shows number of major applications around the globe.

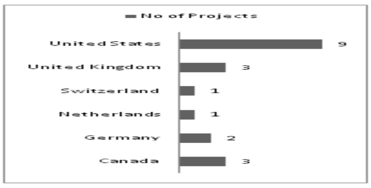

Fig.3. No. of CAES projects around the globe.

D. *Flywheels*

Flywheels are one of the methods to store energy in electromechanical form. Here the electrical energy is used to spin large inertia materials to store energy. As and when the energy is required, it can be extracted by reducing flywheel speed by appropriate mechanism. Flywheels are used primarily for frequency regulation and spinning reserve. There are many flywheel sites around the world. Table II below depicts the number and size of some projects.

TABLE II: FLYWHEEL USAGE PROFILE

Country	Max Rating kW	Purpose
France	100	Electric Bill Management
Ireland	240	Electric Energy Time Shift
Japan	200	Frequency Regulation
Mexico	390	Resiliency
UK	400000	On-Site Power
USA	50000	Spinning Reserve Frequency Regulation

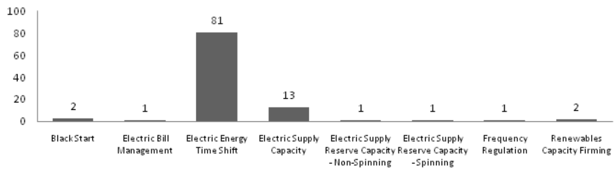

Fig.4. Application profile of Pumped Hydro Storage Systems (Y-Axis shows percentage of units)

There are many applications of SMES around the world ranging from 1MW to 10MW. As on date primarily the SMES applications are restricted to utility level for power quality applications. ABB in association with leading universities is working on a 20kW , 2MJ SMES. SMES has a very promising future as it has a very fast discharge rate and can assist power systems in dynamic conditions.[12]

E. *Thermal Storage*

Thermal storage involves various kinds of technologies as listed in table III below. It is mostly used for peak shaving, electrical bill management and as storage with solar power plants.

TABLE III: TYPES OF THERMAL STORAGE

Technology Type	No	Max Rating kW
Chilled Water Thermal	21	90000
Concrete Thermal	1	100
Heat Thermal Storage	21	50000
Hydrogen Storage	13	6000
Ice Thermal Storage	115	25600
Molten Salt Thermal	41	280000

F. *Pumped Hydro Storage*

Pumped hydro storage system is one technology which is used almost in every major power system around the world. Out of the entire energy storage systems 95% share is of this technology. Primary reason for this is the matured technology and large unit sizes. As on date units ranging from 4kW to 4GW are operational around the world. Fig. 4 below shows the application percentage of pumped hydro storage systems. Clearly the major use is for peak shaving or time shift. [5]

G. Superconducting Magnetic Energy Storage (SMES)

As against Electrochemical capacitors the Superconducting Magnetic Energy Storage (SMES) stores energy in the form of magnetism. A superconducting coil is used which is kept under the superconducting transition temperature. Similar to ultra capacitors the SMES is also power dense but energy density is less. However SMES is more energy dense than ultra capacitors.

3. FACTS CONTROLLERS & TOPOLOGIES FOR INTEGRATION

Broadly FACTS controllers are classified as variable impedance type and converter controlled type. In variable impedance type controller's large size inductor and capacitor banks are interconnected to grid via power electronics interface. This is like replacing mechanical switches with power electronics. This provides a very fast response; however fundamentally the method remains same. Examples are Thyristor Controlled Reactor (TCR), Thyristor controlled series capacitor (TCSC) etc.

In Converter based FACTS controllers, Voltage sourced based (VSC) power electronics controllers are used. They emulate operation of inductor or capacitor bank without need for actual banks. This is done by controlling the injected voltage/current phase as per requirement of power system. The VSCs have a D.C. link which provides an ideal interface for energy storage devices. These devices are Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC)[3], [4], [9]

A. Integration with STATCOM

STATCOM is a shunt compensator, ideally connected at the midpoint of a transmission line. It draws inductive/capacitive current in response to the control action required. It can control voltage at the point of connection, or exchange specified amount of VARs. Essentially there is only exchange of reactive power. When a energy storage system is connected at the D.C. link; it is possible to exchange active power as well. Major advantage of adding and energy storage device is realized when power oscillation damping is the goal. By proper control of active power through the energy storage power oscillations can be damped more effectively. Fig. 5 below shows how addition of energy storage can improve the performance of a STATCOM. It reduces the overall MVA size and increases the operating capability. Of course there is an additional cost involved of the energy storage itself.

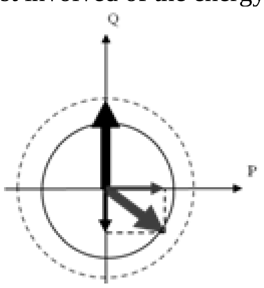

Fig.5. Effect of Energy Storage on STATCOM

When a STATCOM is used alone MVA rating required is higher as indicated by outer dotted circle in fig.5. This is because higher capacity power electronic front is needed.

B. Integration with SSSC

SSSC is connected in series with the transmission line and hence location over the length of the line is not always an issue. It injects a voltage in ninety degrees phase with line current and thus varies the effective reactance of the line. Generally, SSSC injected voltage is modulated to control power flow. It can be also used for power oscillation damping and other purposes. With the addition of an Energy storage device; SSSC can now inject voltage at any phase with line current. This increases the operating range of SSSC. Fig. 6 below indicates the difference between SSSC alone and SSSC with Energy storage [1]

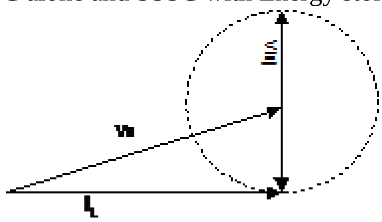

Fig 6 . Effect of Energy Storage on SSSC

C. Integration with UPFC

The unified power flow controller (UPFC) is a device with capabilities of both STATCOM and SSSC. In addition to this the UPFC is capable of injecting a voltage in series with line using its series part. This injection can be at any angle unlike the SSSC. In this way it seems that UPFC is analogous to SSSC with energy storage. However, UPFC also controls bus voltage through its STATCOM part. Addition of the energy storage increases the capability of UPFC especially during the severe disturbances. Fig. 7 below shows a general topology of integrating energy storage with all the devices. The figure shows schematic for an UPFC; however it is similar for other devices.

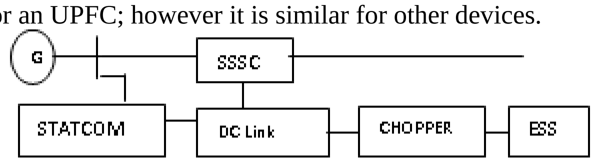

Fig 6 . General Topology for connecting an Energy storage

The D.C. Link in an UPFC can be connected to the energy storage system. The chopper shown can be various topologies based upon the type of energy storage. Power electronic interface like chopper is required to optimize the size of Energy storage.

With continuous improvement in power electronics, it is now becoming possible to apply various topologies which were earlier restricted to low power applications only. Current FACTS installations across the world do not use PWM control as high frequency switching in Multi-MW applications is not feasible. The scenario may soon change. This well open a whole new set of possibilities for the power system applications.

4. IMPACT OF FACTS AND ESS INTEGRATION

A lot of recent and old work on integration of various FACTS controllers with different types of Energy storage devices has been reported earlier in the literature. In [6],[7] impact of a UPFC-SMES combination on power oscillation damping and power swing is demonstrated. In [11] UPFC and Ultra capacitor combination is explored for damping the oscillations. In [8] STATCOM with SMES is studied for improvement of power system performance. In a recent work STATCOM with energy storage using adaptive controller is explored [10]. Even though researchers have started working on the FACTS-ESS model since almost last 20 years, yet many new articles are coming up with different control schemes and topologies. This indicates that there is still a lot of scope for research in this area, especially in India where the technology is likely to be inducted in near future.

There are varieties of applications for which the FACTS-ESS combination can be deployed apart from the power back up. These are transient stability, dynamic stability, voltage support and frequency regulation etc. It has been very well established that the FACTS controllers alone can also address these issues. Addition of energy storage enhances the performance and the FACTS controller can achieve the desired objectives in less cost and time.
FACTS-ESS are not restricted to transmission system applications but also can address issues like Voltage stability, harmonic distortion and power quality problems. Table IV highlights applications of various combinations of FACTS-ESS for different applications.

TABLE IV: APPLICATIONS OF FACTS+ESS

Combination	Volt Control	VAR comp.	Oscillation damping	Stability control	Active power support
STATCOM +ESS	Yes	Yes	Yes	Yes	Yes
STATCOM	Yes	Yes	Limited	Limited	No
SSSC + ESS	Yes	Yes	Yes	Yes	Yes
SSSC	Limited	Yes	Limited	Limited	No
UPFC+ESS	Yes	Yes	Yes	Yes	Yes

In the above table comparison shows that performance of FACTS controller is augmented with addition of energy storage. Only UPFC also has lot of control capability but does not have active power support. In case of STATCOM , oscillation damping and transient stability performance is significantly improved as compared to only STATCOM. In case of SSSC voltage support and voltage stability improvement is enhanced by addition of the energy storage.

5. CONCLUSION

A review of current status of Energy storage technologies and their applications around the world has been carried out. It is evident that many technologies like Ultracapcitors, SMES and Battery energy storage are getting matured. Even though current contribution of these technologies is around 5% of all energy storage, it is likely to grow at a rapid rate due to developments in Smart grid and increased investment in renewable.
Future FACTS installations can be evaluated with addition of energy storage. A detailed cost-benefit analysis shall surely indicate the value addition of energy storage, as with minimum power electronics provision of not only energy storage is made but also control capabilities of the current device are improved significantly.

REFERENCES

[1] Hingorani NG, Gyugyi L. "Understanding FACTS concepts and technology of flexible AC transmission systems". IEEE Press; 2000.
[2] Gyugyi L, Schauder CD, Torgerson SL, Edris A. "The unified power flow controller: a new approach to power transmission control" IEEE Trans. Power Delivery, 1995;10(2):1085–97.
[3] P. F. Ribeiro et al., "Energy storage systems for advanced power applications," Proc. IEEE, vol. 89, no. 12, 2001. pp. 1744–1756,
[4] U.S. Department of Energy, "Grid Energy Storage", December -2013
[5] DOE Global Energy Storage Databse, http://www.energystorageexchange.org
[6] Saravanan Kandasamy and Anita Rajapalan, " Dynamic control modeling and simulation of a UPFC–SMES compensator in power systems," Ain Shams Engineering Journal, vol. 6, 2015.pp. 1179-1186,
[7] Bidadfar, A. et.al, "Power swings damping improvement by control of UPFC and SMES based on direct Lyapunov method application" IEEE Power and Energy Society General Meeting ,2008, pp: 1 – 7
[8] Anju, M.; Rajasekaran, R "Co-ordination of SMES with STATCOM for mitigating SSR and damping power system oscillations in a series compensated wind power system". IEEE International Conference on Computer Communication and Informatics 2013, pp: 1 – 6
[9] Jian Xun Jin, Xiao Yuan Chen, "Study on the SMES Application Solutions for Smart Grid" Physics Procedia, Vol.36 2012, pp: 902 – 907
[10] Mebtu Beza,Massimo Bongiorno "An Adaptive Power Oscillation Damping Controller by STATCOM With Energy Storage" , IEEE Transactions On Power Systems, Vol. 30, No. 1, January 2015,pp:484-493
[11] Mahyar Zarghami et.al, "A Novel Approach to Interarea Oscillation Damping by Unified Power Flow Controllers Utilizing Ultracapacitors", 404 IEEE Transactions On Power Systems, Vol. 25 ,No.1, February, 2010 pp 404-412
[12] Mohd. Hasan Ali, Bin Wu, Roger A. Dougal, " An overview of SMES Applications in Power and Energy Systems", IEEE Transactions on sustainable energy, Vol1, No1, April 2010, pp 38-47.