

# FACTS CONTROLLERS IMPLEMENTATION IN ENERGY STORAGE SYSTEMS FOR ADVANCED POWER ELECTRONIC APPLICATIONS – A SOLUTION

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## ABSTRACT

The production of electric energy is basic pillar for normal functioning of every modern society. The consumers demand for electric power varies cyclically during day and night, as well as within the week and the seasons. Potential performance benefits produced by advanced energy storage applications are improved system reliability, transient and dynamic stability, enhanced power quality, transmission capacity enhancement and area protection, reliability of the supply, etc... Some of the major disadvantages in electric power supply system have been flickering and deviations in power supply which make some of the electronic equipments and domestic devices highly sensitive to it. To avoid such problems we need to find out devices that can provide a backup during the time of voltage sags and such deviations. The paper concentrates on performance benefits of adding energy storage to power electronic compensators for utility applications. The paper concerns on analysis of various energy storage devices. This paper gives the solution for above disadvantages by using energy storage systems with FACTS (Flexible AC Transmission Systems) devices.

STATCOMs are widely used to enhance power system stability. They can exchange reactive power with the power system, but they have limited ability to exchange real power because they don't include energy storage devices. STATCOMs coupled with energy storage devices such as batteries have been introduced to improve their ability to exchange real power. However, batteries have a limitation in their maximum deliverable power because of the slow chemical process required to release their energy. The trend now is to use super capacitor energy storage systems "SCESS" as energy storage for STATCOMS. Super capacitors have lower energy storage but higher power exchanging capability compared to batteries. This paper presents the analysis, design, and control of a super capacitor energy storage system (SCESS) for a STATCOM. A peak current mode controller is used to control the SCESS system. Simulation results of the SCESS system are presented which indicate excellent performance of the proposed SCESS system

**Keywords:** Power Quality, transient and dynamic stability, Reliability of supply, Voltage sags and voltage swells, FACTS devices.

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## INTRODUCTION

The power system should have 15-20% of reserve power available to be able to meet any customer demand. If there is no or insufficient reserve capacity and the load level exceeds the

power generation level, a decline in voltage at the consumer side will appear which would upset the normal operation of the users' machines and electrical devices or even cause them to fail. For this reason it is essential for the normal functioning and development of each social community to have reliable national and local electric power systems with capacities exceeding the actual energy demand by at least 15% according to work done by Yurek (1999). Unfortunately, however, only rich and advanced modern countries possess such high-grade energy systems. The power systems of most countries in the world have capacities that only just meet their energy demands, and in some cases are simply inadequate. This hunger for electricity is very often a limiting factor for the economic and social development of a country. The electric energy needs of the population, industry, agriculture, transport, etc. increase every year, and the claims for high-quality electric power become ever more demanding in relation to the increasing automation and computerization of the national economy.

## BACKGROUND OF ENERGY STORAGE SYSTEMS



Fig1: Example of energy storage system

Energy storage is accomplished by devices or physical media that store energy to perform useful operation at a later time. A device that stores energy is sometimes called an accumulator. **Storage** is an essential unit that stores unstable electric energy during wind and the unstable energy to electric power system again in necessary moment. If there is no such energy storage unit, any kinds of serious problems like sudden blackout occurs because of unstable sunlight-dependent electricity supply. This Storage takes an important part in the electricity storage systems for households, the medium-size system for industrial/commercial use, and the extra-large system for power plants and substations like Frequency Regulations.

## ENERGY STORAGE COMPONENTS

Every energy storage facility is comprised of three primary components

1. Storage Medium
2. Power Conversion System (PCS)
3. Balance of Plant (BOP)

### 1. Storage Medium

The storage medium is the 'energy reservoir' that retains the potential energy within a storage device. It ranges from mechanical (PHES), chemical (BES) and electrical (SMES) potential energy.

## **2. Power Conversion System (PCS)**

It is necessary to convert from alternating current (AC) to direct current (DC) and vice versa, for all storage devices except mechanical storage devices e.g. PHES and CAES. Consequently, a PCS is required that acts as a rectifier while the energy device is charged (AC to DC) and as an inverter when the device is discharged (DC to AC). The PCS also conditions the power during conversion to ensure that no damage is done to the storage device. The customization of the PCS for individual storage systems has been identified as one of the primary sources of improvement for energy storage facilities, as each storage device operates differently during charging, standing and discharging. The PCS usually costs from 33% to 50% of the entire storage facility. Development of PCSs has been slow due to the limited growth in distributed energy resources e.g. small scale power generation technologies ranging from 3 to 10,000 kW.

## **3. Balance of Plant (BOP)**

- Control the environment of the storage facility.
- Provide the electrical connection between the PCS and the power grid.
- It is the most variable cost component within an energy storage device due to the various requirements for each facility. The BOP “typically includes electrical interconnections, surge protection devices, a support rack for the storage medium, the facility shelter and environmental control systems”.

## **TECHNOLOGIES OF ENERGY STORAGE SYSTEMS**

Electrical energy in an ac system cannot be stored electrically. However, energy can be stored by converting the ac electricity and storing it electromagnetically, electrochemically, kinetically, or as potential energy. Each energy storage technology usually includes a power conversion unit to convert the energy from one form to another. It has been established that the different forms of motion e.g. mechanical, thermal, electromagnetic, gravitational, chemical, etc. are converted into one another following definite quantitative ratio. To allow measurement of the various forms of motion by a unified measuring unit, the term energy has been introduced. The electrical energy is determined from the product of the voltage and the quantity of charge that passes through an electrical device (load). The work done per unit time is called power. Electrical power is determined from the product of voltage and current. The different energy storage systems are:

- i) Superconducting magnet energy storage systems (SMES)
- ii) Flywheel Energy Storage Systems (FESS)
- iii) Super Capacitor Energy Storage systems (SCES)
- iv) Battery Energy Storage Systems (BESS)
- v) Pumped Hydro Energy Storage Systems (PHESS)
- vi) Regenerative fuel cell storage systems
- vii) Compressed air energy storage systems (CAES)

### **i). Superconducting Magnetic Energy Storage Systems (SMES)**

The SMES recharges within minutes and can repeat the charge/discharge sequence thousands of times without any degradation of the magnet. Recharge time can be accelerated to meet specific requirements, depending on system capacity.

This is an energy storage device with a lot of promise in effectiveness in terms of capacity and efficiency. SMES units use liquid helium to keep the coil of niobium-titanium at 4.2K, the temperature required for its material to become superconducting.

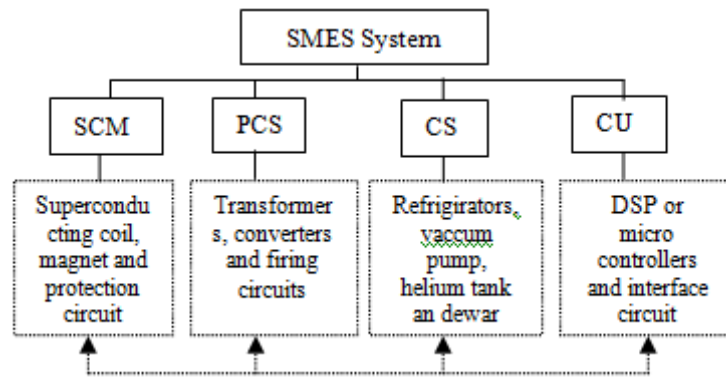


fig2: Block diagram of SMES system

### Operation

An SMES unit is a device that stores energy in the magnetic field generated by the dc current flowing through a superconducting coil. In general, an SMES system consists of four parts, which are the superconducting coil with the magnet (SCM), the power conditioning system (PCS), the cryogenic system (CS), and the control unit (CU), as shown in fig3.

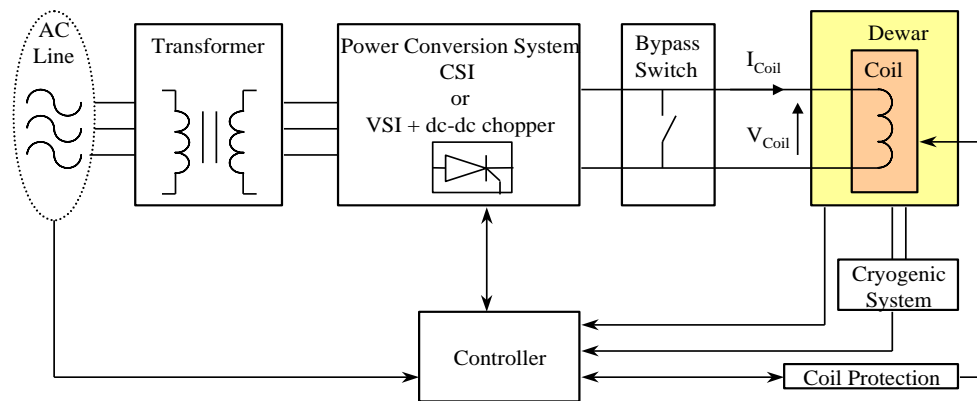


Fig3: Super conducting magnetic energy storage system

An SMES unit consists of a large superconducting coil at the cryogenic temperature. This temperature is maintained by a cryostat or Dewar that contains helium or nitrogen liquid vessels. A power conversion/ conditioning system (PCS) connects the SMES unit to an ac power system, and it is used to charge/discharge the coil. Two types of power conversion systems are commonly used. One option uses a current source converter (CSC) to both interface to the ac system and charge/discharge the coil. The second option uses a voltage source converter (VSC) to interface to the ac system and a dc–dc chopper to charge/discharge the coil. The VSC and dc–dc chopper share a common dc bus. The modes of charge/discharge/standby are obtained by controlling the voltage across the SMES coil. The SMES coil is charged or discharged by applying a positive or negative voltage across the superconducting coil. The inductively stored energy (in joules) which is shown below.

$$E = \frac{1}{2} LI^2$$

$$P = \frac{dE}{dT} = LI \frac{dI}{dT}$$

## Performance Characteristics

SMES' efficiency and fast response capability (MW/millisecond) have been, and can be further exploited in applications at all levels of electric power systems. Some of them are:

- Frequency support (spinning reserve) during loss of generation.
- Enhancing transient and dynamic stability.
- Dynamic voltage support (VAR compensation).
- Improving power quality.
- Increasing transmission line capacity, thus enhancing overall security and of reliability Power systems.
- It has efficiency greater than or equal to 90%.

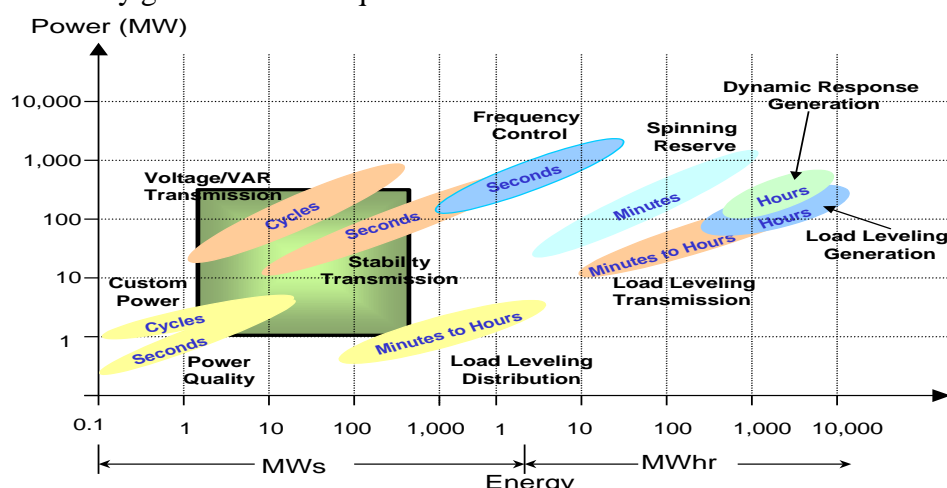


Fig 4: Energy-power characteristics for potential SMES applications for generation, transmission, and distribution.

## Applications of SMES

- An advantage of SMES is that power is available almost instantaneously, and very high power output is provided for a brief period of time. There is no loss of power, and are no moving parts.
- Already dramatically used in such applications as high-speed, magnetic-levitated trains, superconductors are also being developed for use in microelectronics and communications.

## Cost

SMES cost approximately \$300/kW to \$509/kW. It is worth noting that it is difficult to compare the cost of SMES to other storage devices due to its scales and purpose. Superconductor is expected to decline by almost 30% which could make SMES an even more attractive option for network improvements.

## Advantages

The most important advantage of SMES is that the time delay during charge and discharge is quite short. Power is available almost instantaneously and very high power output can be provided for a brief period of time.

## Disadvantages

The most significant drawback of SMES is its sensitivity to temperature. As discussed the coil must be maintained at an extremely low temperature in order to behave like a superconductor.

## Future

Immediate focus will be in developing small SMES devices in the range of 1 MW to 10 MW for the power quality market which has foreseeable commercial potential. A lot of work is being carried out to reduce the capital and operating costs of high-temperature SMES devices, as it is expected to be the commercial superconductor of choice once manufacturing processes are more mature, primarily due to cheaper cooling. There is a lot of market potential for SMES due to its unique application characteristics, primarily in transmission upgrades and industrial power quality. However, one of the greatest concerns for SMES is its reliability over a long period of time.

## ii). Flywheel Energy Storage Systems (FESS)

A flywheel is an electromechanical device that couples a motor generator with a rotating mass to store energy for short durations.

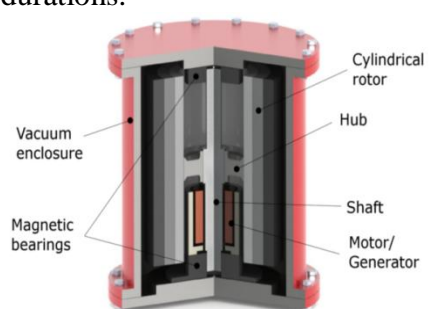


Fig5: Example of cylindrical flywheel rotor

**Flywheel energy storage (FES) System** is a device which works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy; adding energy to the system correspondingly results in an increase in the speed of the flywheel.

## Operation

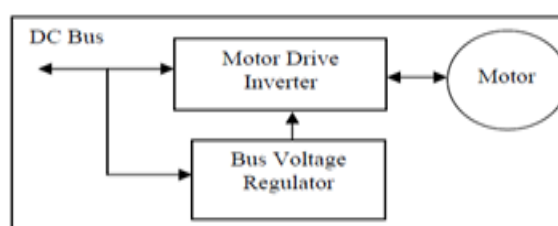


Fig 6: Flywheel Electrical Interface

The FES devices store energy in the form of kinetic energy in the high-speed rotors. The main function of a flywheel is to smoothen out variations in the speed of a shaft caused by torque fluctuations. Flywheel absorbs mechanical energy by increasing its angular velocity and delivers the stored energy by decreasing its velocity. In most cases, a power converter is used to drive the electric machine to provide a wider operating range. Stored energy depends on the moment of inertia of rotor and square of rotational velocity of the flywheel. Moment of inertia (J) depends on the radius, mass, and height (length) of the rotor. The rotor can be modelled as a rotating hollow cylinder. The kinetic energy T stored is given by



$$T = \frac{1}{2} J \omega^2$$

Where J is polar moment of inertia about axis of rotation and  $\omega$  is the angular velocity. The energy storage capability of flywheels can be improved either by increasing the moment of inertia of flywheel or by turning it at higher rotational velocities, or both. Fig.6 shows the flywheel electrical interface.

### Performance Characteristics

- Flywheels can respond to many power quality issues such as frequency deviation, temporary interruptions, voltage sags, and voltage swells.
- FESS constitutes short term storage systems, which are generally sufficient to improve the power quality compared to other ways of storing electricity, FES systems have long lifetimes (ranges from in excess of  $10^5$ , up to  $10^7$ , cycles of use), high energy densities (100-130 Wh/kg, or 360-500 kJ/kg), and large maximum power outputs.

### Applications

Flywheels have an extremely fast dynamic response, a long life, require little maintenance, and are environmentally friendly. They have a predicted lifetime of approximately 20 years or tens of thousands of cycles. As the storage medium used in flywheels is mechanical, the unit can be discharged repeatedly and fully without any damage to the device. Consequently, flywheels are used for power quality enhancements such as Uninterruptable Power Supply (UPS), capturing waste energy that is very useful in electric vehicle applications and finally, to damper frequency variation, making FES very useful to smooth the irregular electrical output from wind turbines. And also used in Rail vehicles, rail electrification etc.

### Cost

At present, FES systems cost between \$200/kWh to \$300/kWh for low-speed flywheels, and \$25,000/kWh for high-speed flywheels. However, FES have a longer lifespan, require lower maintenance, have a faster charge/discharge, take up less space and have fewer environmental risks.

### Advantages

- Flywheels are not as adversely affected by temperature changes, can operate at a much wider temperature range, and are not subject to many of the common failures of chemical rechargeable batteries.
- Another advantage of flywheels is that by a simple measurement of the rotation speed it is possible to know the exact amount of energy stored.

### Disadvantages

As flywheels are optimized for power or storage capacities, the needs of one application can often make the design poorly suited for the other. Consequently, low-speed flywheels may be able to provide high power capacities but only for very short time period, and high-speed flywheels the opposite. Also, as flywheels are kept in a vacuum during operation, it is difficult to transfer heat out of the system, so a cooling system is usually integrated with the FES device. Finally, FES devices also suffer from the idling losses: when flywheels are spinning on standby, energy is lost due to external forces such as friction or magnetic forces. As a result, flywheels need to be pushed to maintain its speed. However, these idling losses are usually less than 2%.

## Future

Low maintenance costs and the ability to survive in harsh conditions are the core strengths for the future of flywheels. Flywheels currently represent 20% of the \$1 billion energy storage market for UPS. Due to its size and cycling capabilities, FES could establish even more within this market if consumers see beyond the larger initial investment. As flywheels require a preference between optimisation of power or storage capacity, it is unlikely to be considered a viable option as a sole storage provider for power generation applications.

## iii). Super Capacitor Energy Storage Systems (SCES)

Electrical double-layer capacitors (EDLC) are, together with pseudo capacitors, part of a new type of electrochemical capacitors called super capacitors, also known as ultra capacitors.

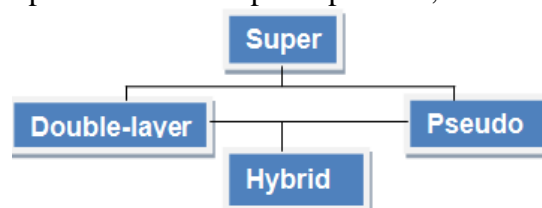


Fig7: Super Capacitor Energy Storage Systems

Double-layer capacitance and pseudo capacitance both contribute to the total capacitance value of a super capacitor. However, the ratio of the two can be very different, depending on the design of the electrodes. The pseudo capacitance may be 100 times the double-layer capacitance with the same surface of the electrode. Super capacitors have the highest capacitance values per unit volume.

## Operation

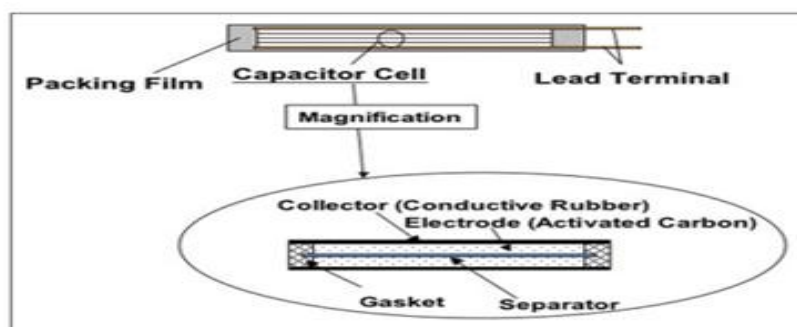


Fig8: Components of SCES

Capacitors consists of two parallel plates that are separated by a dielectric insulator, see Figure 5-15. The plates hold opposite charges which induces an electric field, in which energy can be stored. The energy within a capacitor is given by,

$$E = \frac{1}{2} CV^2$$

Where E is the energy stored within the capacitor (in Joules), V is the voltage applied, and C is the capacitance found from

$$C = \frac{A}{d} \epsilon_r \epsilon_0$$



where  $A$  is the area of the parallel plates,  $d$  is the distance between the two plates,  $\epsilon_r$  is the relative permittivity or dielectric constant, and  $\epsilon_0$  is the permittivity of free space ( $8.854 \times 10^{-12}$  F/m). Therefore, to increase the energy stored within a capacitor, the voltage or capacitance must be increased. Super capacitors are created by using thin film polymers for the dielectric layer and carbon nano tube electrodes. They can be connected in series or in parallel. SCES systems usually have energy densities of  $20 \text{ MJ/m}^3$  to  $70 \text{ MJ/m}^3$ , with an efficiency of 95%.

### Why can we use super capacitors for energy storage?

- Super capacitors are unique electrical storage devices that can store much more energy than conventional capacitors, and offer higher power density than batteries.
- Batteries are widely used for energy storage in industrial and consumer electronics devices because of their high energy density, but are limited in their power density. With its limited power the battery often cannot supply the required power while still retaining its open circuit voltage. When high power is required in battery operated devices (i.e. in pulse applications), the combination of the super capacitor connected in parallel to the battery gives the advantages of both, enhancing the performance of the battery and extending its life, exploiting the batteries to its maximum potential. The super capacitor connected to the battery in parallel produces a voltage damping effect - low impedance super capacitors can be charged in seconds with a low current during standby times between high current pulses. Adding the super capacitor to the battery in parallel decreases the voltage drop, leading to:
  - Better energy and power management
  - Battery life and operational range extension
  - Superior energy density in the battery

### Applications

Although the energy density is smaller, SCES is a very attractive option for some applications such as hybrid cars, cellular phones, and load levelling tasks. SCES is primarily used where pulsed power is needed in the millisecond to second time range, with discharge times up to one minute.

### Cost

SCES costs approximately \$12,960/kWh to \$28,000/kWh. Therefore, large scale applications are not economical using SCES.

### Advantages

- Long life time
- Little degradation over hundreds of thousands of cycles
- Enhances pulse current handling by parallel connection with an electro-chemical battery
- Reduces voltage drop compared to battery operated device with no Super Capacitor
- Much slower ageing and degradation compared to batteries
- Meets environmental standards
- Improved safety

### Disadvantages

- Low energy density
- Serial connections are needed to obtain higher voltages

- SCES has a very low energy storage density leading to very high capital costs for large scale applications. Also, they are heavier and bulkier than conventional batteries

### **Future**

Despite the small energy storage densities on offer, the exceptional life and cycling capabilities, fast response and good power capacity (up to 1 MW) of super capacitors means that they will always be useful for specific applications. However, it is unlikely that SCES will be used as a sole energy storage device. One long-term possibility involves combining SCES with a battery based storage system. SCES could smooth power fluctuations, and the battery provides the storage capacity necessary for longer interruptions. However, other technologies (such as flow batteries) are more likely to be developed for such applications. As a result, the future of SCES is likely to remain within specific areas that require a lot of power, very fast, for very short periods.

### **iv). Battery Energy Storage Systems (BESS)**

Batteries are one of the most cost-effective energy storage technologies available, with energy stored electrochemically. Key factors in battery for storage applications include: high energy density, high energy capability, round trip efficiency, cycling capability, life span, and initial cost. Battery technologies under consideration for large-scale energy storage. Lead-acid batteries can be designed for bulk energy storage or for rapid charge/discharge. Mobile applications are favoring sealed lead-acid battery technologies for safety and ease of maintenance. Valve regulated lead-acid (VRLA) batteries have better cost and performance characteristics for stationary applications.



*Photo Source: UP Networks*

fig9: Battery Energy Storage System

Lead-acid batteries have been used in a few commercial and large-scale energy management applications.

The largest one is a 40 MWh system in Chino, California, built in 1988. The table below lists and compares the lead-acid storage systems that are larger than 1MWh.



Fig10: Example of Energy Storage System

These operate in the same way as conventional batteries, except on a large scale i.e. two electrodes are immersed in an electrolyte, which allows a chemical reaction to take place so current can be produced when required.

There are three important types of large-scale BES. These are

- i. Lead-Acid (LA)
- ii. Nickel-Cadmium (NiCd)
- iii. Sodium-Sulphur (NaS)

### Lead Acid (LA) battery

This is the most common energy storage device in use at present. Its success is due to its maturity (research has been ongoing for an estimated 140 years), relatively low cost, long lifespan, fast response, and low self discharge rate. These batteries are can be used for both short-term applications (seconds) and long-term applications (up to 8 hours). There are two types of lead-acid (LA) batteries; flooded lead-acid (FLA) and valve regulated lead-acid (VRLA). FLA batteries are made up of two electrodes that are constructed using lead plates which are immersed in a mixture of water (65%) and sulphuric acid (35%). VRLA batteries have the same operating principle as FLA batteries, but they are sealed with a pressure regulating valve. This eliminates air from entering the cells and also prevents venting of the hydrogen. VRLA batteries have lower maintenance costs, weigh less and occupy less space. However, these advantages are coupled with higher initial costs and shorter lifetime.

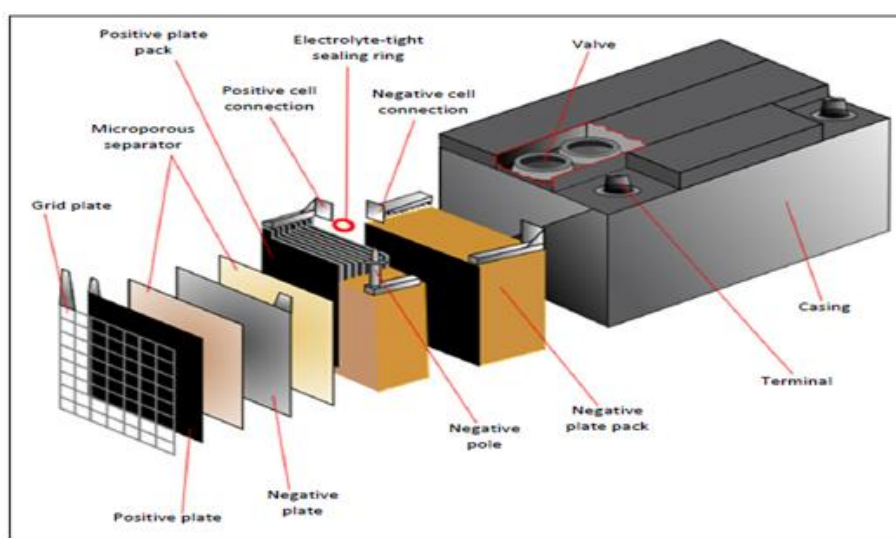


Fig11: Structure of Lead Acid (LA) battery

LA batteries can respond within milliseconds at full power. The average DC-DC efficiency of a LA battery is 75% to 85% during normal operation, with a life of approximately 5 years or 250-1,000 charge/discharge cycles, depending on the depth-of-discharge

### **Applications**

FLA batteries have 2 primary applications:

- Starting and ignition, short bursts of strong power e.g. car engine batteries
- Deep cycle, low steady power over a long time

VRLA batteries are very popular for backup power, standby power supplies in telecommunications and also for UPS systems.

### **Cost**

Costs for LA battery technology have been stated as \$200/kW - \$300/kW, but also in the region of \$580/kW.

### **Disadvantages**

LA batteries are extremely sensitive to their environments. The typical operating temperature for a LA battery is roughly 27°C, but a change in temperature of 5°C or more can cut the life of the battery by 50%. However, if the temperature exceeds this, the cycle life of the battery will also be reduced. Finally, a typical charge-to-discharge ratio of a LA battery is 5:1. At faster rates of charge, the cell will be damaged.

### **Future**

Due to the low cost and maturity of the LA battery it will probably always be useful for specific applications. The international Advanced Lead-Acid Battery Consortium is also developing a technique to significantly improve storage capacity and also recharge the battery in only a few minutes, instead of the current hours. However, the requirements of new large-scale storage devices would significantly limit the life of a LA battery. Consequently, a lot of research has been directed towards other areas. Therefore, it is unlikely that LA batteries will be competing for future large-scale multi MW applications.

### **ii. Nickel Cadmium (NiCd) battery**

A Nicd battery is made up of a positive with nickel oxy hydroxide as the active material and a negative electrode composed of metallic cadmium. These are separated by a nylon divider. The electrolyte, which undergoes no significant changes during operation, is aqueous potassium hydroxide. During discharge, the nickel oxy hydroxide combines with water and produces nickel hydroxide and a hydroxide ion. Cadmium hydroxide is produced at the negative electrode. To charge the battery the process can be reversed. However, during charging, oxygen can be produced at the positive electrode and hydrogen can be produced at the negative electrode. As a result some venting and water addition is required, but much less than required for a LA battery. There are two NiCd battery designs: sealed (Figure 12-a) and vented (Figure 12-b). Sealed NiCd batteries are the common, everyday rechargeable batteries used in a remote control, lamp etc. No gases are released from these batteries, unless a fault occurs. Vented NiCd batteries have the same operating principles as sealed ones, but gas is released if overcharging or rapid discharging occurs. The oxygen and hydrogen are released through a low-pressure release valve making the battery safer, lighter, more economical, and more robust than sealed NiCd batteries.

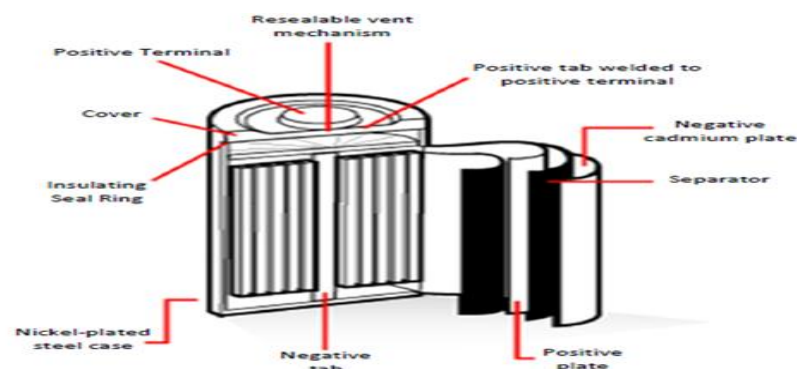


Fig12a: Structure of a sealed nickel-Cadmium battery

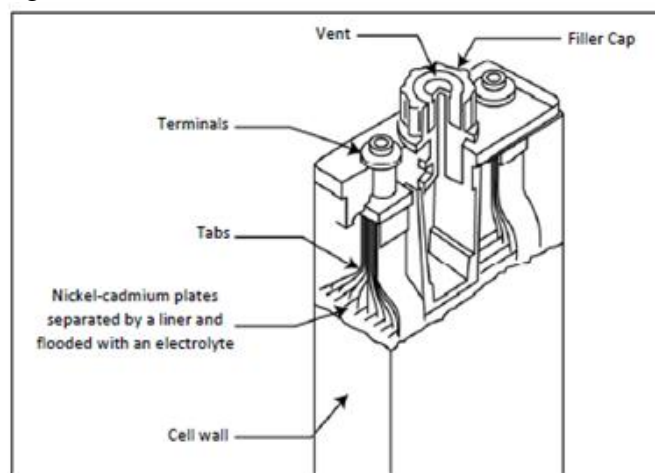


Fig12b: Structure of a vented nickel-Cadmium battery

### Applications

Sealed NiCd batteries are used commonly in commercial electronic products such as a remote control, where light weight, portability, and rechargeable power are important. Vented NiCd batteries are used in aircraft and diesel engine starters, where large energy per weight and volume are critical. NiCd batteries are ideal for protecting power quality against voltage sags and providing standby power in harsh conditions. Recently, NiCd batteries have become popular as storage for solar generation because they can withstand high temperatures. However, they do not perform well during peak shaving applications, and consequently are generally avoided for energy management systems.

### Cost

NiCd batteries cost more than LA batteries at \$600/kW. However, despite the slightly higher initial cost, NiCd batteries have much lower maintenance costs due to their environmental tolerance.

### Disadvantages

Like LA batteries, the life of NiCd batteries can be greatly reduced due to the temperature and rapid charge/discharge cycles. However, NiCd batteries suffer from 'memory' effects and also lose more energy during due to self discharge standby than LA batteries, with an estimated 2% to 5% of their charge lost per month at room temperature in comparison to 1% per month for LA batteries. Also, the environmental effects of NiCd batteries have become a



widespread concern in recent years as cadmium is a toxic material. This creates a number of problems for disposing of the batteries.

### Future

It is predicted that NiCd batteries will remain popular within their current market areas, but like LA batteries, it is unlikely that they will be used for future large-scale projects. Although just to note, a 40 MW NiCd storage facility was constructed in Alaska; comprising of 13,760 cells at a cost of \$35M. The cold temperatures experienced were the primary driving force behind the use NiCd as a storage medium. NiCd will probably remain more expensive than LA batteries, but they do provide better power delivery. However, due to the toxicity of cadmium, standards and regulations for NiCd batteries will continue to rise.

### iii. Sodium Sulphur (NaS) Battery

NaS batteries have three times the energy density of LA, a longer life span, and lower maintenance. These batteries are made up of a cylindrical electrochemical cell that contains a molten-sodium negative electrode and a molten-sulphur positive electrode. The electrolyte used is solid  $\beta$ -alumina. During discharging, sodium ions pass through the  $\beta$ -alumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulfide, see Figure 13. During charging, the reaction is reversed so that the sodium polysulfide decomposes, and the sodium ions are converted to sodium at the positive electrode. In order to keep the sodium and sulphur molten in the battery, and to obtain adequate conductivity in the electrolyte, they are housed in a thermally insulated enclosure that must keep it above 270°C, usually at 320°C to 340°C.

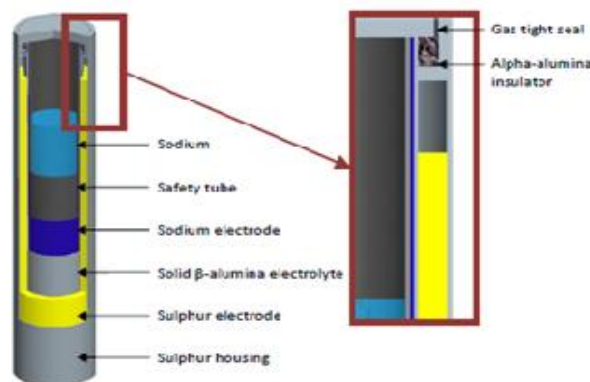


Fig13: Structure of a Sodium Sulphur (NaS) Battery

### Applications

One of the greatest characteristics of NaS batteries is its ability to provide power in a single, continuous discharge or else in shorter larger pulses (up to five times higher than the continuous rating). It is also capable of pulsing in the middle of a long-term discharge. This flexibility makes it very advantageous for numerous applications such as energy management and power quality. NaS batteries have also been used for deferring transmission upgrades.

### Cost

Currently, NaS batteries cost \$810/kW, but it is only a recently commercialised product. This cost is likely to be reduced as production increases, with some predicting reductions upwards of 33%.



### Disadvantages

The major disadvantage of NaS batteries is retaining the device at elevated temperatures above 270°C. It is not only energy consuming, but it also brings with it problems such as thermal management and safety regulations. Also, due to harsh chemical environments, the insulators can be a problem as they slowly become conducting and self-discharge the battery.

### Future

A 6MW, 8 h unit has been built by Tokyo Electric Power Company (TEPCO) and NGK Insulators, Ltd., (NGK), in Tokyo, Japan with an overall plant efficiency of 75% and is thus far proving to be a success. The materials required to create a NaS battery are inexpensive and abundant, and 99% of the battery is recyclable. The NaS battery has the potential to be used on a MW scale by combining modules. Combining this with its functionality to mitigate power disturbances, NaS batteries could be a viable option for smoothing the output from wind turbines into the power grid. American Electric Power is planning to incorporate a 6 MW NaS battery with a wind farm for a two year demonstration.

### V). Pumped Hydro Energy Storage Systems (PHESS)

Pumped hydroelectric energy storage is the most mature and largest storage technique available. It consists of two large reservoirs located at different elevations and a number of pump/turbine units (see Figure 5-1). During off-peak electrical demands, water is pumped from the lower reservoir to the higher reservoir where it is stored until it is needed. Once required (i.e. during peak electrical production) the water in the upper reservoir is released through the turbines, which are connected to generators that produce electricity. Therefore, during production a PHES facility operates similarly to a conventional hydroelectric system. The efficiency of modern pumped storage facilities is in the region of 70% - 85%. However, variable speed machines are now being used to improve this. The efficiency is limited by the efficiency of the pump/turbine unit used in the facilities

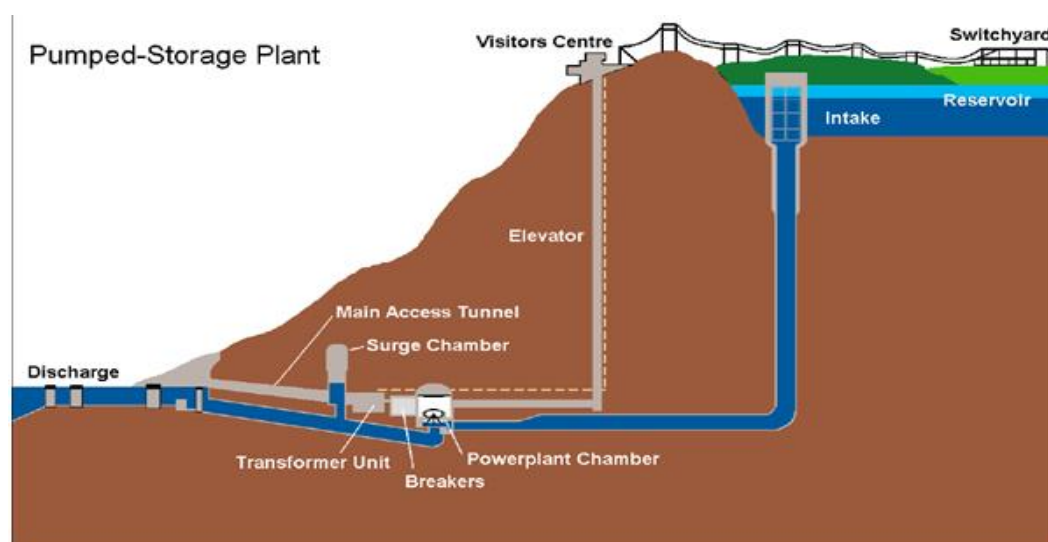


Fig14: Layout of a Pumped Hydro Energy Storage Systems (PHESS)

Until recently, PHES units have always used fresh water as the storage medium. The power capacity (kW) is a function of the flow rate and the hydraulic head, whilst the energy stored (kWh) is a function of the reservoir volume and hydraulic head. To calculate the mass power output of a PHES facility, the following relationship can be used:

$$P_c = \rho g Q H \eta_p$$

Where:

$P_c$  = power capacity in Watts (W)

$\rho$  = mass density of water in kg/m<sup>3</sup>

$g$  = acceleration due to gravity in m/s<sup>2</sup>

$Q$  = discharge through the turbines in m<sup>3</sup>/s

$H$  = effective head in m

$\eta_p$  = efficiency of the pump

And to evaluate the storage capacity of the PHES the following must be used :

$$S_c = \frac{\rho g H V \eta_T}{3.6 \times 10^9}$$

Where:

$S_c$  = storage capacity in megawatt-hours (MWh)

$V$  = volume of water that is drained and filled each day in m<sup>3</sup>

$\rho$  = mass density of water in kg/m<sup>3</sup>

$g$  = acceleration due to gravity in m/s<sup>2</sup>

$H$  = effective head in m

$\eta_T$  = efficiency of the turbine

### Applications

The recent introduction of variable speed machines, PHES systems can now be used for frequency regulation in both pumping and generation modes (this has always been available in generating mode). This allows PHES units to absorb power in a more cost-effective manner that not only makes the facility more useful, but also improves the efficiency by approximately 3% and increases the lifetime of the facility. PHES can also be used for peak generation and black starts due to its large power capacity and sufficient discharge time. Finally, PHES provides a load for base load generating facilities during off-peak production so cycling these units can be avoided, which improves their lifetime as well as their efficiency.

### Cost

Cost ranges from \$600/kW to upwards of \$2,000/kW, depending on a number of factors such as size, location, and connection to the power grid.

### Disadvantages

Due to the design requirements of a PHES facility, the ultimate drawback is its dependence on specific geological formations. A suitable site needs two large reservoirs with a sufficient amount of hydraulic head between which are located close enough to enable the construction of a PHES system. However, as well as being rare these geological formations normally exist in remote locations such as mountains, where construction is difficult and the power grid is not present.

Finally, in order to make PHES viable it must be constructed on a large scale. Although the cost per kWh of storage is relatively economical in comparison to other techniques, this large-scale necessity results in a very high initial construction cost for the facility, therefore detracting investment in PHES e.g. Bath County storage facility in the United States which has a power capacity of 2,100 MW and cost \$1.7 billion in 1985.

## Future

Currently, a lot of work is being carried out to upgrade old PHES facilities with new equipment such as variable speed devices which can increase capacity by 15% to 20% and efficiency by approximately 3%. This is very popular as energy storage capacity is being developed without the high initial construction costs. Prospects of building new facilities are usually hindered by “high development costs, long lead times and design limitations”. However, even with these issues, there is over 7 GW of new PHES planned within the EU over the next eight years alone. In addition, new methodologies continue to locate more and more suitable PHES sites. Therefore, considering the maturity and cost of PHES, it is a very attractive option as an energy storage technology for aiding the integration of fluctuating renewable energy.

## vi). Regenerative fuel cell storage systems

A fuel cell converts stored chemical energy, in this case hydrogen, directly into electrical energy. A fuel cell consists of two electrodes that are separated by an electrolyte, see Figure 15

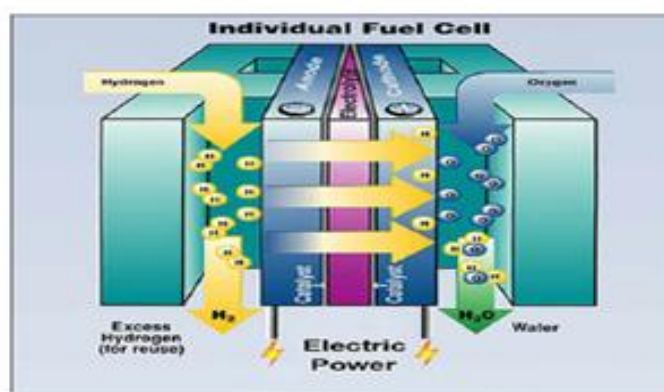


Fig15: Structure of a Regenerative fuel cell storage systems

Hydrogen is passed over the anode (negative) and oxygen is passed over the cathode (positive), causing hydrogen ions and electrons to form at the anode. The electrons flow through an external circuit to produce electricity, whilst the hydrogen ions pass from the anode to the cathode. Here the hydrogen ions combine with oxygen to produce water. The energy produced by the various types of cells depends on the operation temperature, the type of fuel cell, and the catalyst used; Fuel cells do not produce any pollutants and have no moving parts. Therefore, theoretically it should be possible to obtain a reliability of 99.9999% in ideal conditions.

## Cost

All fuel cells cost between €500/kW and €8,000/kW which is very high, but typical of an emerging technology. These costs are expected to reduce as the technology ages and commercialisation matures.

## Future

Immediate objectives for fuel cells include harnessing the waste heat more effectively to improve cogeneration efficiency and also, combining fuel cells with electrolyzers as a single unit. The advantage being lower capital costs although resulting in lower efficiency and increased corrosion. Fuel cells are a relatively new technology with high capital costs.

However, with characteristics such as no moving parts, no emissions, lightweight, versatility and reliability, this is definitely a technology with a lot of future potential.

### vii). Compressed air energy storage systems (CAES)

A CAES facility consists of a power train motor that drives a compressor (to compress the air into the cavern), a high pressure turbine (HPT), a low pressure turbine (LPT), and a generator see in fig 16.

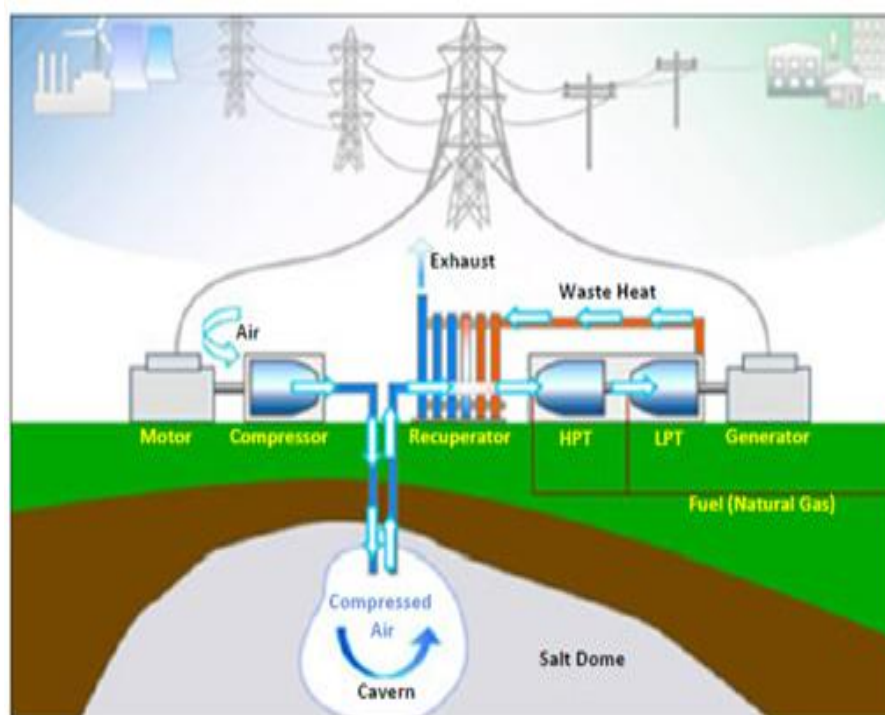


Fig16: Layout of Compressed air energy storage systems (CAES)

In conventional gas turbines (GT), 66% of the gas used is required to compress the air at the time of generation. Therefore, CAES pre-compresses the air using off-peak electrical power which is taken from the grid to drive a motor (rather than using gas from the GT plant) and stores it in large storage reservoirs. When the GT is producing electricity during peak hours, the compressed air is released from the storage facility and used in the GT cycle. As a result, instead of using expensive gas to compress the air, cheaper off-peak base load electricity is used. Although, when the air is released from the cavern it must be mixed with a small amount of gas before entering the turbine. If there was no gas added, the temperature and pressure of the air would be problematic. If the pressure using air alone was high enough to achieve a significant power output, the temperature of the air would be far too low for the materials and connections to tolerate. The amount of gas required is so small that a GT working simultaneously with CAES can produce three times more electricity than a GT operating on its own, using the same amount of natural gas.

The reservoir can be man-made, but this is expensive so CAES locations are usually decided by identifying natural geological formations that suit these facilities. These include salt caverns, hard-rock caverns, depleted gas fields or an aquifer. Salt caverns can be designed to suit specific requirements. Fresh water is pumped into the cavern and left until the salt dissolves and saturates the fresh water. The water is then returned to the surface and the

process is repeated until the required volume cavern is created. This process is expensive and can take up to two years. Hard-rock caverns are even more expensive, usually 60% higher than salt caverns. Finally, aquifers cannot store the air at high pressures and therefore have a relatively lower energy capacity. CAES uses both electrical energy and natural gas so its efficiency is difficult to quantify. It is estimated that the efficiency of the cycle based on the compression and expansion cycles is in the region of 68% to 75%. Typical plant capacities for CAES are in the region of 50 MW – 300 MW. The life of these facilities is proving to be far longer than existing gas turbines and the charge/discharge ratio is dependent on the size of the compressor used, as well as the size and pressure of the reservoir

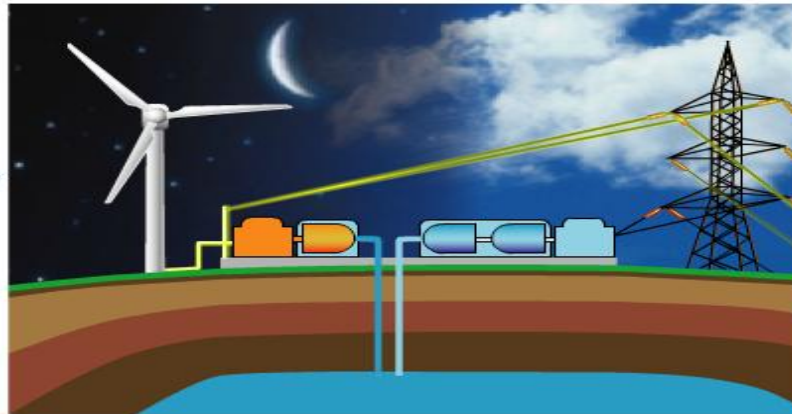


Fig17: Compressed Air Energy Storage System

### **.Applications**

CAES is the only very large scale storage technique other than PHES. CAES has a fast reaction time with plants usually able to go from 0% to 100% in less than ten minutes, 10% to 100% in approximately four minutes and from 50% to 100% in less than 15 seconds. As a result, it is ideal for acting as a large sink for bulk energy supply and demand and also, it is able to undertake frequent start-ups and shutdowns. Furthermore, traditional GT suffer a 10% efficiency reduction from a 5°C rise in ambient temperatures due a reduction in the air density. CAES use compressed air so they do not suffer from this effect. Also, traditional gas turbines suffer from excessive heat when operating on partial load, while CAES facilities do not. These flexibilities mean that CAES can be used for ancillary services such as frequency regulation, load following, and voltage control. As a result, CAES has become a serious contender in the wind power energy storage market.

### **Cost**

The cost of CAES facilities are \$425/kW to \$450/kW. Maintenance is estimated between \$3/kWh and \$10/kWh. Costs are largely dependent on the reservoir construction. Overall, CAES facilities expect to have costs similar to or greater than conventional GT facilities. However, the energy cost is much lower for CAES systems.

### **Disadvantages**

The major disadvantage of CAES facilities is their dependence on geographical location. It is difficult to identify underground reservoirs where a power plant can be constructed, is close to the electric grid, is able to retain compressed air and is large enough for the specific application. As a result, capital costs are generally very high for CAES systems. Also, CAES still uses a fossil fuel (gas) to generate electricity. Consequently, the emissions and safety



regulations are similar to conventional gas turbines. Finally, only two CAES facilities currently exist, meaning it is still a technology of potential not experience.

### **Future**

Reservoir developments are expected in the near future due to the increased use of natural gas storage facilities. The US and Europe are more likely to investigate this technology further as they possess acceptable geology for an underground reservoir (specifically salt domes). Due to the limited operational experience, CAES has been considered too risky by many utilities. A number of CAES storage facilities have been planned for the future including:

- 25 MW CAES research facility with an aquifer reservoir in Italy.
- 3 x 100 MW CAES plants in Israel.

## **ENERGY STORAGE APPLICATIONS**

There are wide ranges of applications for energy storage devices. These include...

- i. End-use applications
- ii. Emergency back-up
- iii. Transmission and distribution stabilization
- iv. Load management

### **i. End-Use Applications**

The most common end-use application for energy storage is power quality, which primarily consists of voltage and frequency control. Transit and end-use ride-through are applications requiring short power durations and fast response times, in order to level fluctuations, prevent voltage irregularities, and provide frequency regulation. This is primarily used on sensitive processing equipment and thus the capacities required are usually less than 10 MW.

### **ii. Emergency Backup**

This is a type of uninterruptable power supply (UPS) except the units must have longer energy storage capacities. The energy storage device must be able to provide power while generation is cut altogether. Power ratings of 1 MW for durations up to one day are most common.

### **iii. Transmission and Distribution Stabilisation**

Energy storage devices are required to stabilise the system after a fault occurs on the network by absorbing or delivering power to generators when needed to keep them turning at the same speed. These faults induce phase angle, voltage, and frequency irregularities that are corrected by the storage device. Consequently, fast

Response (seconds) and high power ratings (1 MW to 10 MW) are essential.

### **iv. Load Management**

There are two different aspects to load management: load levelling and load following. Load levelling uses off-peak power to charge the energy storage device which can then be discharged during peak demand. Many international electricity markets trade on a spot market utilising half-hourly trading periods, each with a Unique cost per unit of electricity generated (€/MWh). This price can vary significantly over a 24-hour period due to the relative change in electricity demand. Therefore, energy storage devices can be charged during these off-peak hours at night and then used to generate electricity when it is the most expensive, during short peak production periods in the evening. Not only does this enable the energy storage unit to maximise its profits, but it can also reduce the cost of operating the system.



## TYPICAL STORAGE CAPACITY VERSUS DISCHARGE TIMES FOR ENERGY STORAGE TECHNOLOGIES

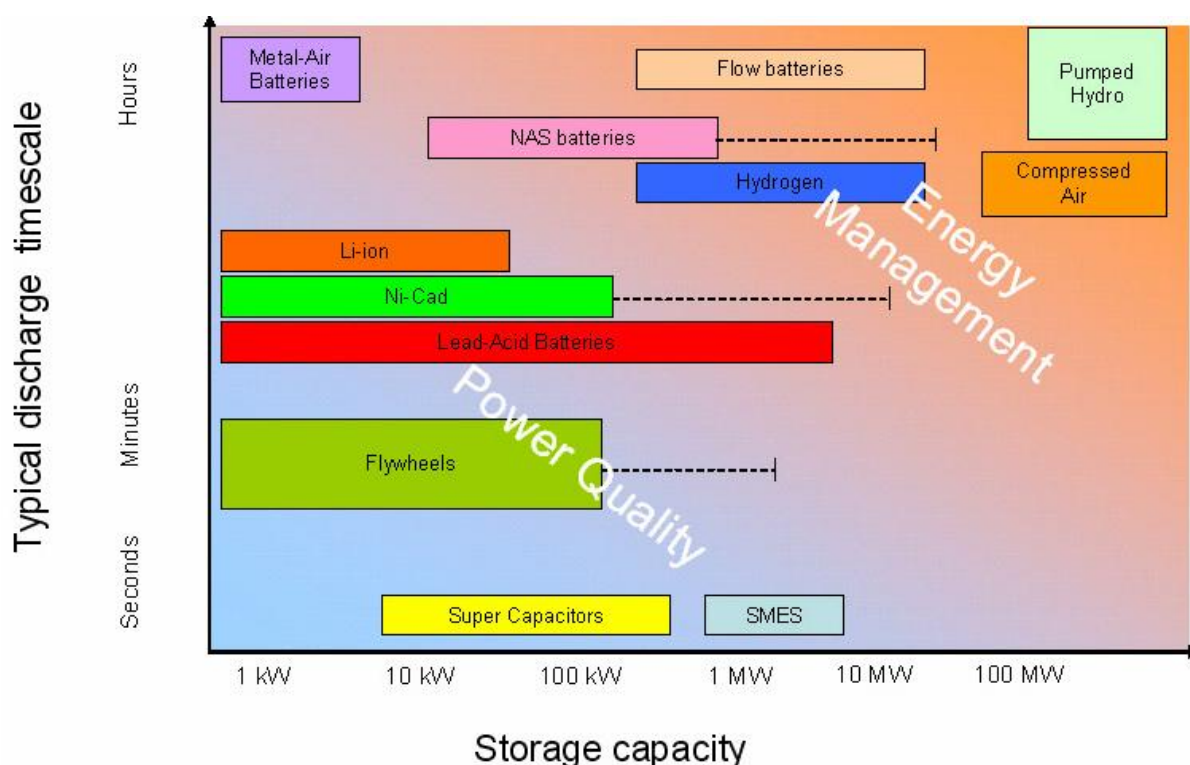


Fig18: Typical storage capacity versus discharge times for energy storage technologies

## IMPLEMENTATION OF FACTS WITH ENERGY STORAGE DEVICES

### i. Proposed FACTS Controller + Energy Storage

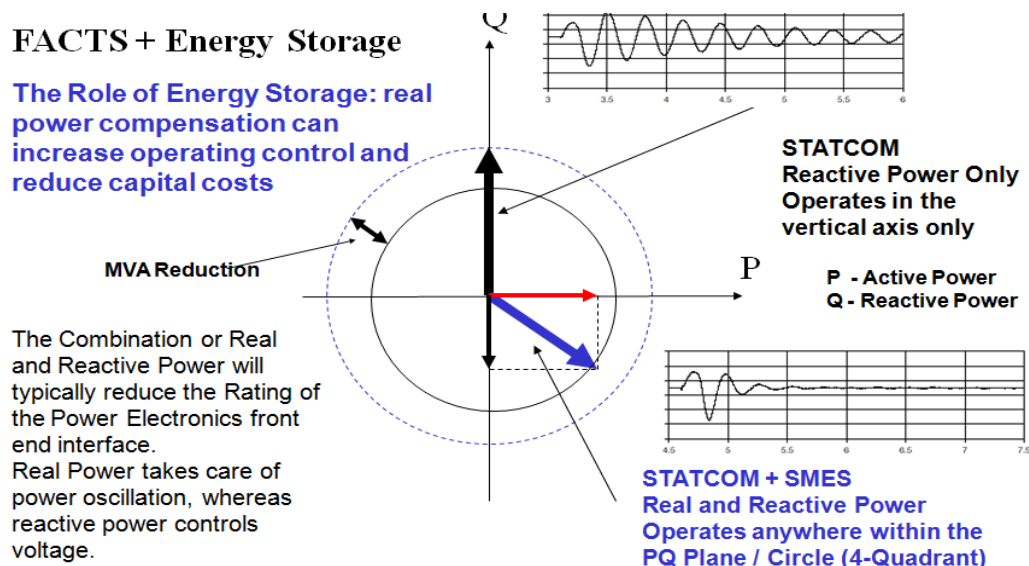


Fig19: Proposed FACTS Controller + Energy Storage

## ii. Integration of Energy Storage Systems into FACTS Devices

- FACTS controllers are power electronics based devices that can rapidly influence the transmission system parameters such as impedance, voltage, and phase to provide fast control of transmission or distribution system behavior.
- FACTS controllers that can benefit the most from energy storage are those that utilize a voltage source converter interface to the power system with a capacitor on a dc bus. This class of FACTS controllers can be connected to the transmission system in parallel (STATCOM), series (SSSC) or combined (UPFC) form, and they can utilize or redirect the available power and energy from the ac system.
- Without energy storage, FACTS devices are limited in the degree of freedom and sustained action

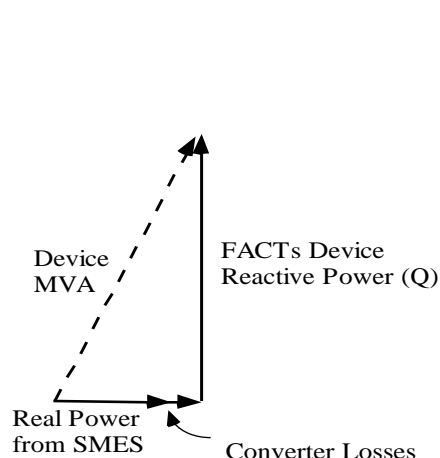


Fig20: Device MVA rating of Energy Storage

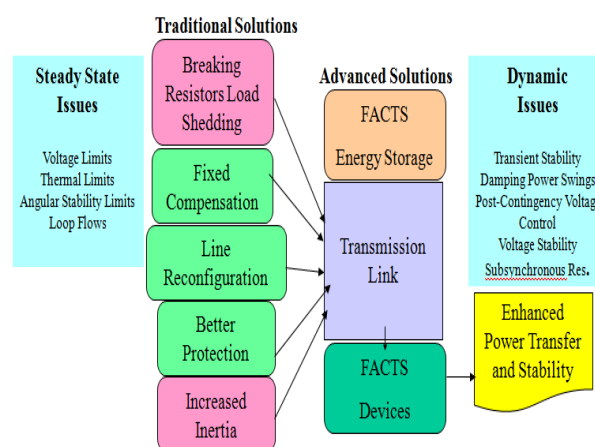


Fig21: Integration of Energy Storage into FACTS Devices

into FACTS Devices

System

## iii. Integration of Energy Storage Systems

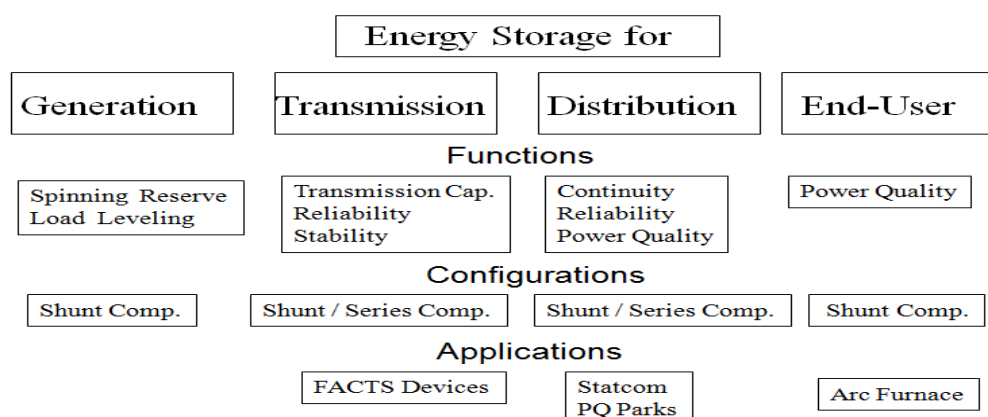


Fig22: Block diagram of Integration of Energy Storage Systems

### iii. a. STATCOM with SCESS:

A MATLAB/SIMULINK simulation model was built for the SCESS system. It consists of the power circuit and the control circuit. The power circuit (Figure 23) consists of the super capacitor, the inductor, the boost and buck IGBTs, the dc link capacitor, the dc load, and the switched on/off dc source. The DC load and the DC source represent a simplification of the STATCOM. The DC load is used to discharge the DC link capacitor while the DC source is used to charge it. The power circuit parameters are:

Super capacitor:  $C = 0.5$  F, and  $V(0) = 300$  V.

Inductor:  $L = 0.075$  H, and  $R = 0.001$  ohm.

DC link capacitor:  $C = 800$  uF, and  $R = 0.01$  ohm.

DC load:  $R_L = 120$  ohm.

DC source:  $V = 610$  V, and  $R_S = 0.01$  ohm.

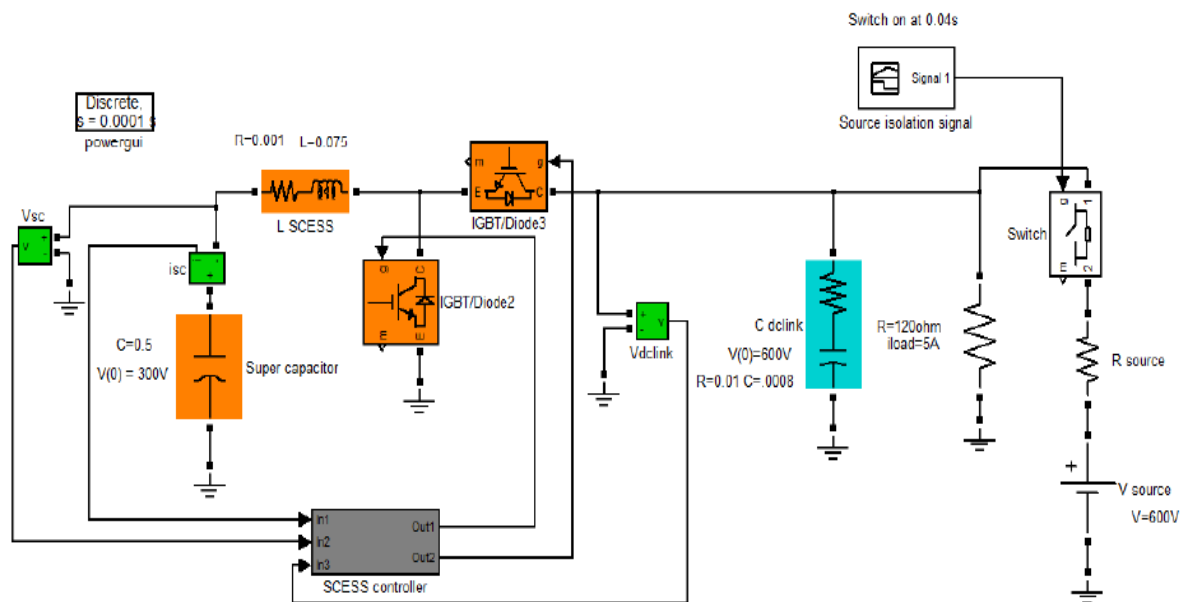


Fig23: Super capacitor, Boost transistor, Buck transistor and DC link simulation model in MATLAB

The SCESS system was tested by disconnecting the main DC source at the dc link for 1 second. The dc source is disconnected at  $t=0$  and reconnected at  $t=1$  s. While the DC source is disconnected, the dc link capacitor shall starts discharging its stored energy to the resistor. As a result, the super capacitor shall provide its energy to the dc link to maintain the dc link voltage fixed. The energy discharged into the resistor represents the energy transferred STATCOM to the load at the AC side. The objective of test is to check if the SCESS system has the ability to maintain the dc link voltage fixed at the pre-set value. Therefore this test is an indication of the proposed SCESS capability.

The simulation was run first with without SCESS system, and then with the SCESS system. The DC link voltage profile while the SCESS system is not active is shown in fig27. The dc link voltage dropped to zero after 0.4 seconds.

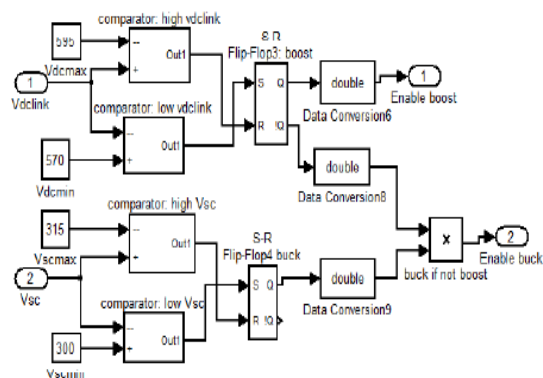


Fig24: Buck boost logic circuit model in MATLAB

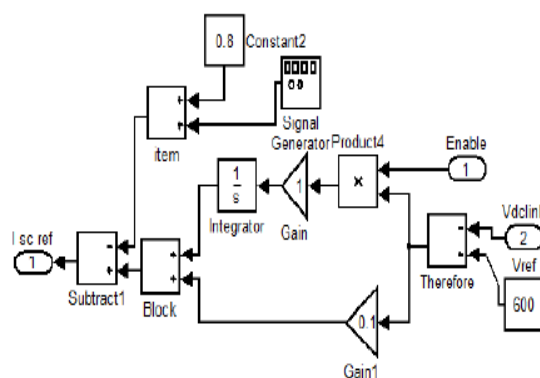


Fig25: DC link voltage controller

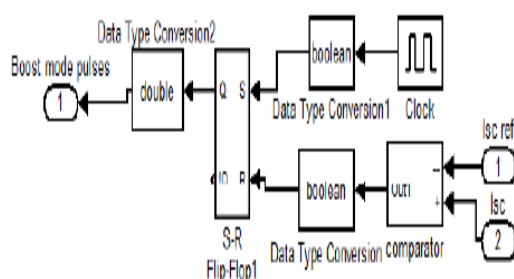


Fig26: Boost controller model in MATLAB (seconds) without

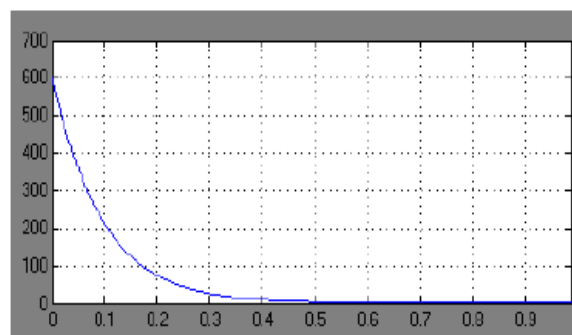


Fig27: DC link voltage (V) versus time (seconds) without SCESS

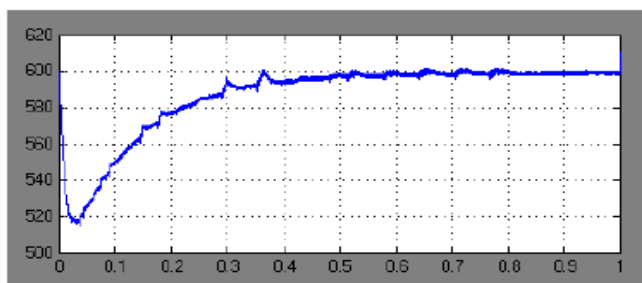


Fig28: DC link voltage (V) versus time (seconds)

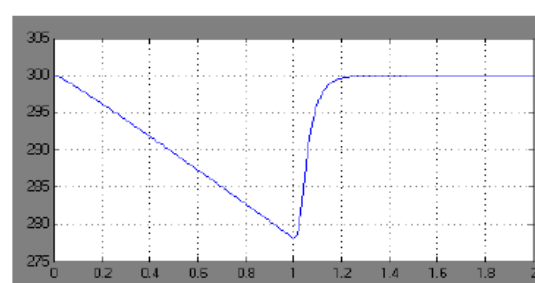


Fig29: Super capacitor voltage (V) versus time (seconds) With SCESS

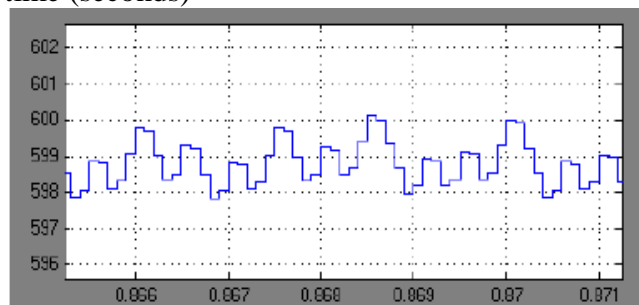


Fig30: DC link voltage ripple (V) versus time (seconds)

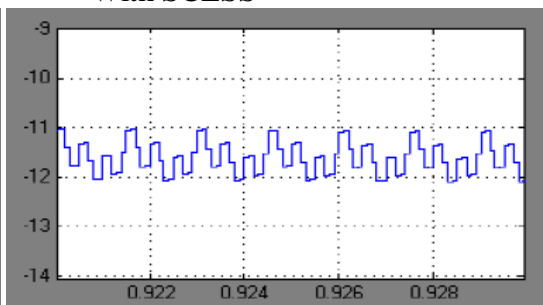


Fig31: Super capacitor current (A) versus time (seconds) during SCESS boost mode

### iii. b. FACTS with BESS

The principal benefit of the STATCOM for transient stability enhancement is direct through rapid bus voltage control. In particular, the STATCOM may be used to enhance power transfer during low-voltage conditions, which typically predominate during faults, decreasing the acceleration of local generators. An additional benefit is the reduction of the demagnetizing effects of faults on local generation.

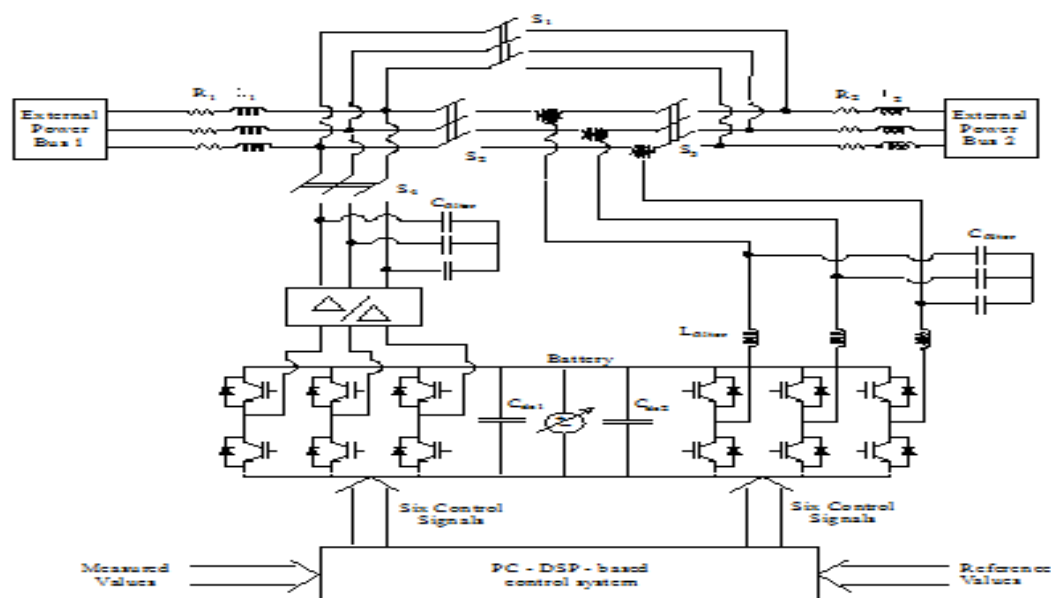
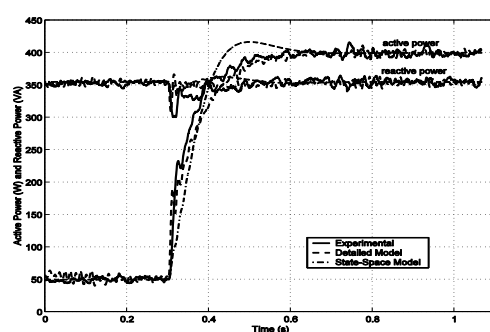
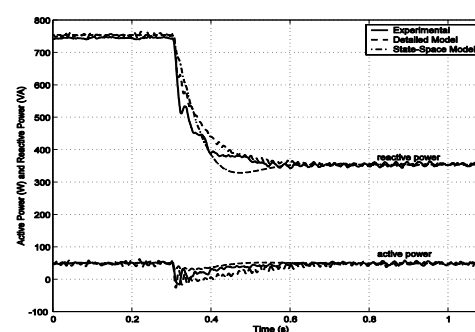


Fig32: FACTS with BESS

The active and Reactive power responses are as shown below.



(a) Active power from 50W to 400 W



(b) Reactive power from 755Var to 355Var

Fig33: Predicted and experimental response of the BESS

The STATCOM is connected in a circuit which is commonly used with energy storage systems to improve the system performances.

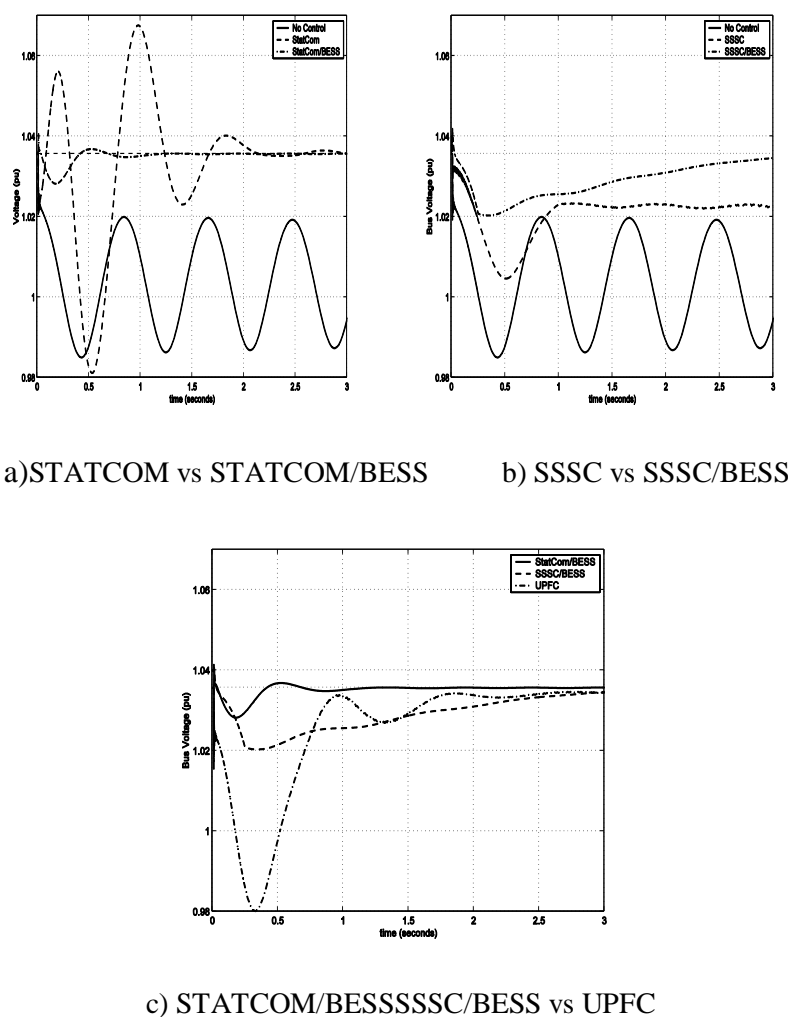


Fig34: Active power flow between areas

## V.CONCLUSION

In the changing system of power production more storage systems will be needed in the future. The more renewable energy power plants with fluctuating supply of solar radiation or wind are connected with the grid, the more additional conventional power plants or storage systems are needed to guarantee a balancing of demand and supply of power. FACTS (Flexible AC Transmission Systems) devices which handle both real and reactive power to achieve improved transmission system performance are multi-MW proven electronic devices now being introduced in the utility industry. In this environment, energy storage is a logical addition to the expanding family of FACTS devices. Potential performance benefits produced by advanced energy storage applications improved system reliability, dynamic stability, enhanced power quality, transmission capacity enhancement, area protection, etc..

Energy storage devices can facilitate this process, allowing the utility maximum utilization of utility resources. The new power electronics controller devices will enable increased utilization of transmission and distribution systems with increased reliability. This increased reliance will result in increased investment in devices that make this asset more productive. Energy storage technology fits very well within the new environment by enhancing the potential application of FACTS, Custom Power and Power Quality devices. As deregulation



takes place, generation and transmission resources will be utilized at higher efficiency rates leading to tighter and moment-by-moment control of the spare capacities.

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