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Energy Storage System Technologies for Advanced Electrical Power Applications

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Abstract: While energy storage technologies do not represent energy sources, they provide valuable added benefits to improve stability, power quality, and reliability of supply. Battery technologies have improved significantly in order to meet the challenges of practical electric vehicles and utility applications. Flywheel technologies are now used in advanced nonpolluting uninterruptible power supplies. Advanced capacitors are being considered as energy storage for power quality applications. Superconducting energy storage systems are still in their prototype stages but receiving attention for utility applications. The latest technology developments, some performance analysis, and cost considerations are addressed. This paper concentrates on the performance benefits of adding energy storage to power electronic compensators for utility applications.

Keywords: flexible ac transmission systems (FACTS), flywheel energy storage, high voltage dc transmission (HVDC), hyper capacitor, ultra capacitor.

I. Introduction

Electric power systems are experiencing dramatic changes in operational requirements as a result of deregulation. Continuing electric load growth and higher regional power transfers in a largely interconnected network lead to complex and less secure power system operation.

Power generation and transmission facilities have not been able to grow to meet these new demands as a result of economic, environmental, technical, and governmental regulation constraints. At the same time, the growth of electronic loads has made the quality of power supply a critical issue. Power system engineers facing these challenges seek solutions to allow them to operate the system in a more flexible, controllable manner. When power system disturbances occur, synchronous generators are not always able to respond rapidly enough to keep the system stable. If high-speed real or reactive power control is available, load shedding or generator dropping may be avoided during the disturbance. High speed reactive power control is possible through the use of flexible ac transmission systems (FACTS) devices. In a few cases, these devices are also able to provide some measure of high speed real power control through power circulation within the converter, with the real power coming from the same line or in some cases from adjacent lines leaving the same substation. However, a better solution would be to have the ability to rapidly vary real power without impacting the system through power circulation. This is where energy storage technology can play a very important role in maintaining system reliability and power quality. The ideal solution is to have means to rapidly damp oscillations, respond to sudden changes in load, supply load during transmission or distribution interruptions, correct load voltage profiles with rapid reactive power control, and still allow the generators to balance with the system load at their normal speed. Custom power devices use power converters to perform either current interruption or voltage regulation functions for power distribution systems.

Recent developments and advances in energy storage and power electronics technologies are making the application of energy storage technologies a viable solution for modern power applications. Viable storage technologies include batteries, flywheels, ultra capacitors, and superconducting energy storage systems. Although several of these technologies were initially envisioned for large-scale load-leveling applications, energy storage is now seen more as a tool to enhance system stability, aid power transfer, and improve power quality in power systems.

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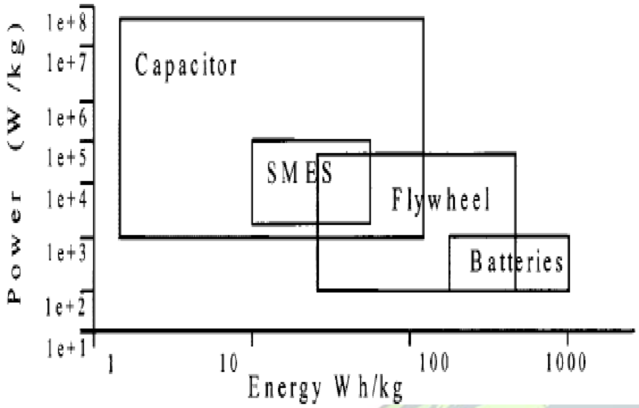

Fig 1. Specific power versus specific energy ranges for near-to-midterm technology.

II. Energy Storage Systems For Transmission And Distribution Applications

The power/energy ranges for near-to-midterm technologies are projected in Fig. 1. Integration of these four possible energy storage technologies with flexible ac transmission systems (FACTS) and custom power devices are among the possible power applications utilizing energy storage. The possible benefits include: transmission enhancement, power oscillation damping, dynamic voltage stability, tie line control, short-term spinning reserve, load leveling, under-frequency load shedding reduction, circuit break reclosing, sub synchronous resonance damping, and power quality improvement.

A. Superconducting Magnetic Energy Storage (SMES)

Although superconductivity was discovered in 1911, it was not until the 1970s that SMES was first proposed as an energy storage technology for power systems [1]. SMES systems have attracted the attention of both electric utilities and the military due to their fast response and high efficiency (a charge–discharge efficiency over 95%). Possible applications include load leveling, dynamic stability, transient stability, voltage stability, frequency regulation, transmission capability enhancement, and power quality improvement.

An SMES unit is a device that stores energy in the magnetic field generated by the dc current flowing through a superconducting coil. The inductively stored energy (E in joules) and the rated power (in watts) are commonly given specifications for SMES devices, and they can be expressed as follows:

$$E = \frac{1}{2} LI^2, \quad P = dE/dt = LI\, dI/dt = VI$$

Where L is the inductance of the coil, I is the dc current flowing through the coil, and V is the voltage across the coil. Since energy is stored as circulating current, energy can be drawn from an SMES unit with almost instantaneous response with energy stored or delivered over periods ranging from a fraction of a second to several hours.

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 components of an SMES system are shown in Fig. 2.

The modes of charge/discharge/standby are obtained by controlling the voltage across the SMES coil (Vcoil) .The SMES coil is charged or discharged by applying a positive or negative voltage (Vcoil), across the superconducting coil. The SMES system enters a standby mode operation when the average (Vcoil) is zero, resulting in a constant average coil current, (Icoil).

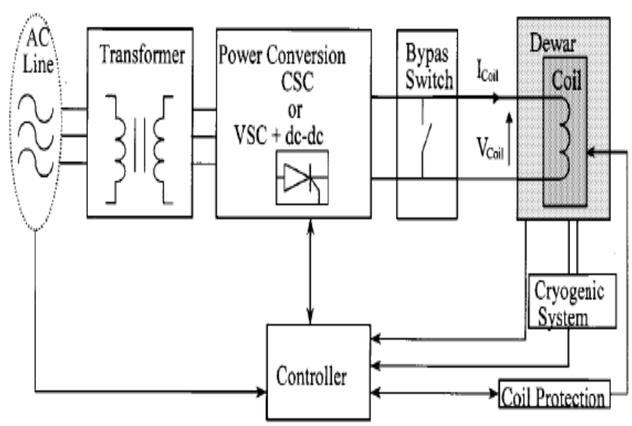

Fig 2. Components of a typical SMES system

Several factors are taken into account in the design of the coil to achieve the best possible performance of an SMES system at the least cost [3], [4]. These factors may include coil configuration, energy capability, structure, and operating temperature. A compromise is made between each

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factor considering the parameters of energy/mass ratio, Lorentz forces, stray magnetic field, and minimizing the losses for a reliable, stable, and economic SMES system. The coil can be configured as a solenoid or a toroid. The solenoid type (as shown in Fig. 3 [5]) has been used widely due to its simplicity and cost effectiveness, though the toroid-coil designs were also incorporated by a number of small-scale SMES projects. Coil inductance (L) or PCS maximum voltage (Vmax) and current ratings (Imax) determine the maximum energy/power that can be drawn or injected by an SMES coil. The ratings of these parameters depend on the application type of SMES. The operating temperature used for a superconducting device is a compromise between cost and the operational requirements. Low temperature superconductor devices (LTS) are available now, while high temperature superconductor devices are currently in the development stage.

SMES's efficiency and fast response capability (mill watts/ millisecond) have been, and can be further exploited in applications at all levels of electric power systems. The potential utility applications have been studied since the 1970s [6]. SMES systems have been considered for the following: 1) load leveling; 2) frequency support (spinning reserve) during loss of generation; 3) enhancing transient and dynamic stability; 4) dynamic voltage support (VAR compensation); 5) improving power quality; and 6) increasing transmission line capacity, thus enhancing overall reliability of power systems. Further development continues in power conversion systems and control schemes [7], evaluation of design and cost factors [8], and analyses for various SMES system applications. The energy–power characteristics for potential SMES applications for generation, transmission, and distribution are depicted in Fig. 4. The square area in the figure represents the applications that are currently economical. Therefore, the SMES technology has a unique advantage in two types of application: power system transmission control and stabilization and power quality.

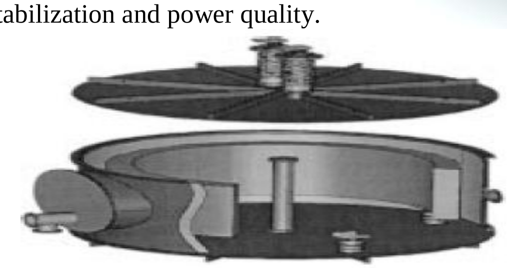

Fig 3. Solenoid configuration

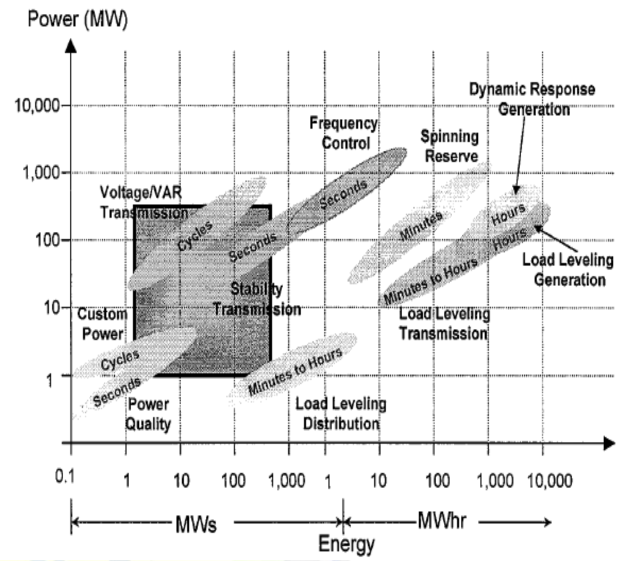

Fig 4. Energy–power characteristics of potential SMES applications

B. *Battery Energy Storage Systems (BESS)*

Batteries are one of the most cost-effective energy storage technologies available, with energy stored electrochemically. A battery system is made up of a set of low-voltage/power battery modules connected in parallel and series to achieve a desired electrical characteristic. Batteries are "charged" when they undergo an internal chemical reaction under a potential applied to the terminals. They deliver the absorbed energy, or "discharge," when they reverse the chemical reaction. Key factors of batteries for storage applications include: high energy density, high energy capability, round trip efficiency, cycling capability, life span, and initial cost [9].

There are a number of battery technologies under consideration for large-scale energy storage. Lead-acid batteries represent an established, mature technology. Lead-acid batteries can be designed for bulk energy storage or for rapid charge/discharge. Improvements in energy density and charging characteristics are still an active research area, with different additives under consideration. Lead-acid batteries still represent a low-cost option for most applications requiring large storage capabilities, with the low energy density and limited cycle life as the chief disadvantages. 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.

Due to the chemical kinetics involved, batteries cannot operate at high power levels for long time periods. In addition, rapid, deep discharges may lead to early replacement of the battery, since heating resulting in this kind of operation reduces battery lifetime. There are also environmental concerns related to battery storage due to toxic gas generation during battery charge/discharge. The disposal of hazardous materials presents some battery disposal problems. The disposal problem varies with battery technology. For example, the recycling/disposal of lead acid batteries is well established for automotive batteries.

C. *Advanced Capacitors*

Capacitors store electric energy by accumulating positive and negative charges (often on parallel plates) separated by an insulating dielectric. The capacitance, C represents the relationship between the stored charge, , and the voltage between the plates, , as shown in (1). The capacitance depends on the permittivity of the dielectric, , the area of the plates, , and the distance between the plates, , as shown in (2). Equation (3) shows that the energy stored on the capacitor depends on the capacitance and on the square of the voltage

$$q = CV \quad (1)$$

$$C = \varepsilon A / d \quad (2)$$

$$E = ½ CV^2 \quad (3)$$

$$dv = i^* dt/Ctot + i^* Rtot \quad (4)$$

The amount of energy a capacitor is capable of storing can be increased by either increasing the capacitance or the voltage stored on the capacitor. The stored voltage is limited by the voltage-withstand-strength of the dielectric (which impacts the distance between the plates). Capacitance can be increased by increasing the area of the plates, increasing the permittivity, or decreasing the distance between the plates. As with batteries, the turnaround efficiency when charging/discharging capacitors is also an important consideration, as is response time. The effective series resistance (ESR) of the capacitor has a significant impact on both. The total voltage change when charging or discharging capacitors as shown in (4). Note that Ctot and Rtot are the result from a combined series/parallel configuration of capacitor cells to increase the total capacitance and the voltage level. The product Rtot, Ctot determines the response time of the capacitor for charging or discharging.

Ceramic hyper capacitors have both a fairly high voltage-withstand (about 1 kV) and a high dielectric strength, making them good candidates for future storage applications. At present, they are largely used in low power applications. In addition, hyper capacitors have low effective-series-resistance values. Cryogenic operation appears to offer significant performance improvements. The combination of higher voltage-withstand and low effective-series-resistance will make it easier to use hyper capacitors in high power applications with simpler configurations possible.

Ultra capacitors (also known as super capacitors) are double layer capacitors that increase energy storage capability due to a large increase in surface area through use of a porous electrolyte (they still have relatively low permittivity and voltage-withstand capabilities) [8]. Several different combinations of electrode and electrolyte materials have been used in ultra capacitors, with different combinations resulting in varying capacitance, energy density, cycle-life, and cost characteristics. At present, ultra capacitors are most applicable for high peak-power, low-energy situations. Capable of floating at full charge for ten years, an ultra capacitor can provide extended power availability during voltage sags and momentary interruptions. Ultra capacitors can be stored completely discharged, installed easily, are compact in size, and can operate effectively in diverse (hot, cold, and moist) environments. Ultra capacitors are now available commercially at lower power levels.

D. *Flywheel Energy Storage (FES)*

Flywheels can be used to store energy for power systems when the flywheel is coupled to an electric machine. 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 the rotor and the square of the rotational velocity of the flywheel, as shown in (5). The moment of inertia I depends on the radius, mass, and height (length) of the rotor, as shown in (6). Energy is transferred to the flywheel when the machine operates as a motor (the flywheel accelerates), charging the energy storage device. The flywheel is discharged when the electric machine regenerates through the drive (slowing the flywheel)

$$E = ½ Iw^2 \quad (5)$$

$$I = r^2mh/2 \quad (6)$$

The energy storage capability of flywheels can be improved either by increasing the moment of inertia of the flywheel or by turning it at higher rotational velocities, or both. Some designs utilize hollow cylinders for the rotor allowing the mass to be concentrated at the outer radius of

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the flywheel, improving storage capability with a smaller weight increase. Two strategies have been utilized in the development of flywheels for power applications. One option is to increase the inertia by using a steel mass with a large radius, with rotational velocities up to approximately 10 000 rpm. A fairly standard motor and power electronic drive can be used as the power conversion interface for this type of flywheel. Several flywheels utilizing this type of design are available commercially as uninterruptible power supplies (UPSs). This design results in relatively large, heavy flywheel systems. Rotational energy losses will also limit the long-term storage ability of this type of flywheel.

The second design strategy is to produce flywheels with a lightweight rotor turning at very high rotational velocities (up to 100000 rpm). This approach results in compact, lightweight energy storage devices. Modular designs are possible, with a large number of small flywheels possible as an alternative to a few large flywheels . However, rotational losses due to drag from air and bearing losses result in significant self-discharge, which poses problems for long-term energy storage. High-velocity flywheels are therefore operated in vacuum vessels to eliminate air resistance.

The use of magnetic bearings helps improve the problems with bearing losses. Several projects are developing superconducting magnetic bearings for high-velocity flywheels. The near elimination of rotational losses will provide flywheels with high charge/discharge efficiency. The peak power transfer ratings depend on the power ratings in the power electronic converter and the electric machine.

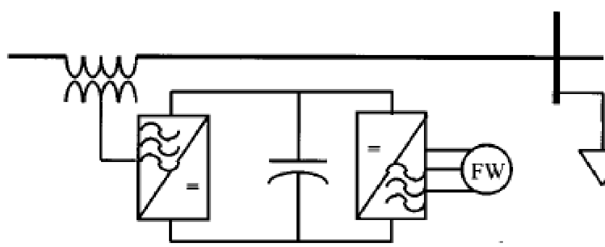

Fig 5. Flywheel energy storage coupled to a dynamic voltage Restorer

F.Other Technologies

Several other energy storage technologies have been considered and applied for utility applications, including pumped hydroelectric systems, compressed air energy storage (CAES), and flow batteries (a variation on the fuel cell now in the demonstration stage).

I. Power Systems Applications

Currently, each storage technology has advantages and disadvantages when considered for power system applications. SMES systems are environmentally friendly and can respond rapidly to changes in power demand, but battery and flywheel systems are modular and cost effective. Flywheels and capacitor technologies are still being developed and are emerging as promising storage technologies as well. The capabilities of energy storage systems in power system applications are summarized in Table 1.

Performance \ ESS	SMES	BESS	FES	Capacitor
Dynamic Stability	✓ [1,2,3,4]	✓ [47]	✓[5]	Needs to be explored
Transient Stability	✓[6,7]	✓[47,45]	✓[8]	
Voltage Support	✓[ ]	✓[47,46]	✓[9]	
Area Control/ Frequency Regulation	✓[10]	✓ [10,11]	-	
Transmission Capability Improvement	✓[11]	✓[10, 12]	-	
Power Quality Improvement	✓[8,14]	✓[13,14,15]	✓[16,17,18]	✓[ ]

Table 1. Summary of Energy Storage Systems Capabilities

Integration of Energy Storage Systems into FACTS Devices

Second generation 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. The multi-MW FACTS technologies have been introduced to the utility industry to enhance the existing transmission assets as opposed to construction of new transmission assets. Several utilities have installed such controllers in their system. The 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 (static compensator, or StatCom), series (static synchronous series compensator, or SSSC) or combined (unified power flow controller, or 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 in which they can help the power grid. The integration of an energy storage system (ESS) into FACTS devices can provide independent real and reactive power absorption/injection into/from the grid, leading to a more economical and/or flexible transmission

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controller. The addition of real power transfer capability does not necessarily result in a large increase in the MVA rating of the converter, since the real power is in quadrature with the reactive power from the converter, as shown in Fig. 6. The addition of real power capability may improve the performance of the converter enough that the total converter MVA rating could even be reduced. If a transmission line experiences significant power transfer variations in a short time notice, a FACTS/ESS combination can be installed to relieve the loaded transmission line. The enhanced performance of combined FACTS/ESS will have greater appeal to transmission service providers (Fig. 7).

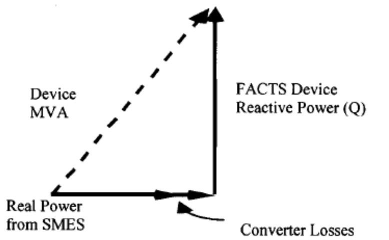

Fig 6. Device MVA rating

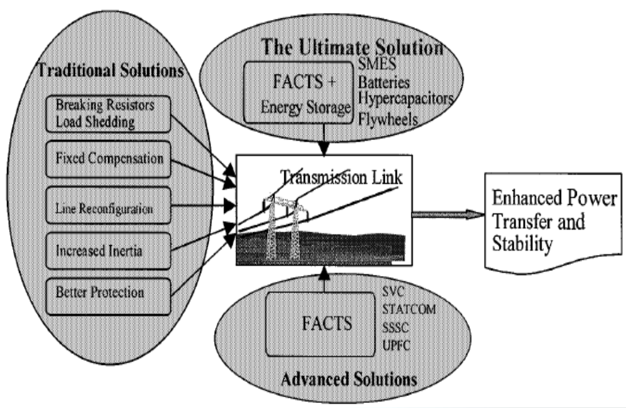

Fig 7. The ultimate solution: FACTS+ESS.

The StatCom/SMES is applied to a system with two synchronous areas coupled via parallel tie lines. Dynamic oscillations of approximately 3 Hz are induced between the two areas by applying a 0.15 second three phase fault at the midpoint of one of the parallel lines. Fig. 8 shows the system dynamic response caused by the short circuit for the system with and without the StatCom/SMES.

Without a controller, the system response shown in Fig.8 (a) exhibits lightly damped oscillations in both frequency and generator rotor speed. Adding a StatCom to the system at the tie line bus stabilizes the voltage excursions but has little impact on damping the generator rotor oscillations. The reactive power injection capabilities of the StatCom enable the voltage to be rapidly controlled, but without active power capabilities, the rotor oscillations are relatively impervious to the effect of the StatCom. When an SMES coil is added to the StatCom, both the voltage and rotor oscillations are quickly damped. If the StatCom/SMES is placed close to the generator, the SMES coil acts as an energy booster for the generator and yields better damping performance.

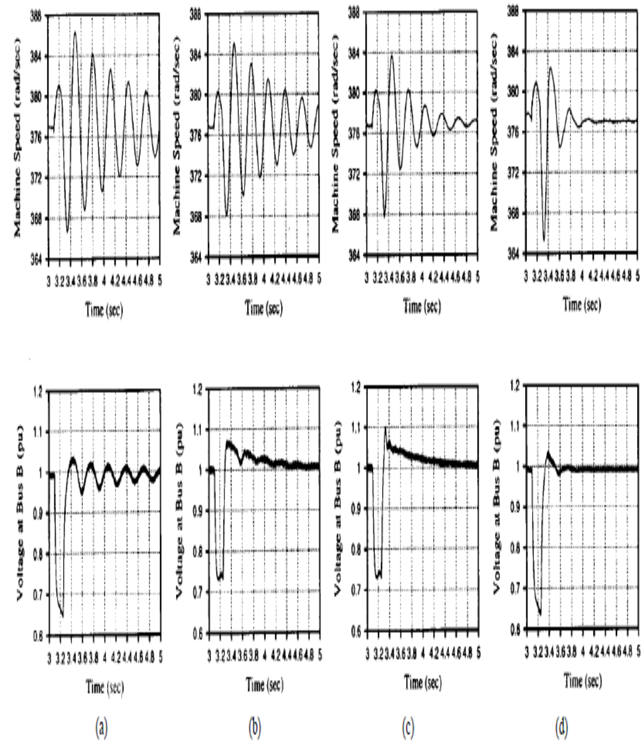

Fig 8. StatCom/SMES dynamic response to ac system oscillations. (a) No compensation. (b) StatCom only at tieline bus. (c) StatCom/SMES tieline bus. (d) StatCom/SMES at generator

B. *HVDC Transmission and Distribution Applications*

Improvements in power electronic device technologies have led to significant improvements in the flexibility of dc transmission systems through the ability to use voltage source converters [10]. Traditional direct current systems see limited use as high power, high voltage dc (HVDC) transmission systems. These HVDC systems operate at high voltage levels to reduce resistive losses. The systems use line-commutated, thyristor-based converters and have fairly simple point-to-point layouts with a single rectifier and a single inverter. More complicated multi

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terminal systems have been considered, but the complexity of a reliable control scheme allowing operation without communication during a disturbance severely limits the number of converters in the system.

Voltage source converter based dc systems allow for lower voltage dc transmission systems capable of supporting a large number of standard "off the shelf" inverters. Energy storage can be added to the dc system, providing improved response to fast load changes drawn by the inverters (see Fig. 9). The addition of energy storage to superconducting transmission systems is explored in [11], and battery storage to a dc distribution system based on voltage source converters.

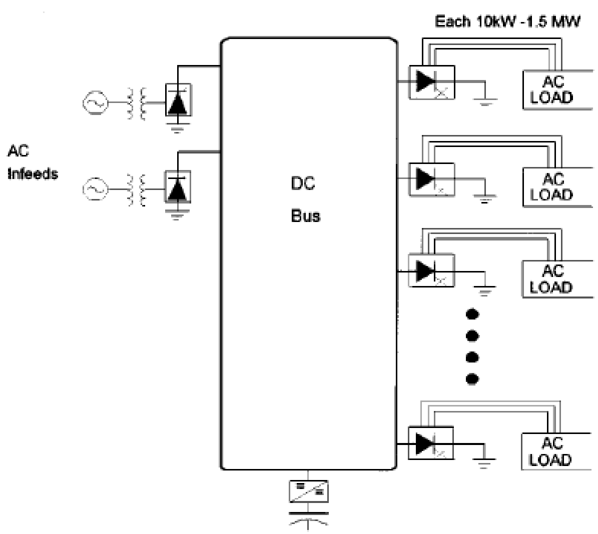

Fig 9. DC system with capacitive energy storage added to the dc system through a dc-to-dc converter.

C. *Power Quality Enhancement With Energy Storage*

Custom power devices address problems found at distribution level such as voltage sags, voltage swells, voltage transients, and momentary interruptions. The most common approaches to mitigate these problems focus on customer side solutions such as UPS systems based on battery energy storage. Alternative UPS systems based on SMES and FESs are also available. On the utility side of the meter, studies have indicated that using power line conditioners and redundant feeder systems operating in conjunction with fast acting circuit breakers and fault isolators can eliminate a majority of the load disruptions. Custom power devices are entering service to act as fast circuit breakers and perform line conditioning. The dynamic voltage restorer (DVR) is a pulse width-modulated (PWM) converter in series with the lines, having a dc link stabilized by an energy storage element, usually a large capacitance. The DVR is distinguished by having a dc energy source, often dc storage capacitors, supplying the dc link as well, as shown in Fig. 14, although ultra capacitors, FES, and SMES can all be used to allow the DVR to operate over longer/deeper voltage sags. A distribution StatCom (DStatCom) is similar to the DVR, except that the voltage source converter is connected in parallel with the line. Energy storage can also be added to the dc bus of the DStatCom.

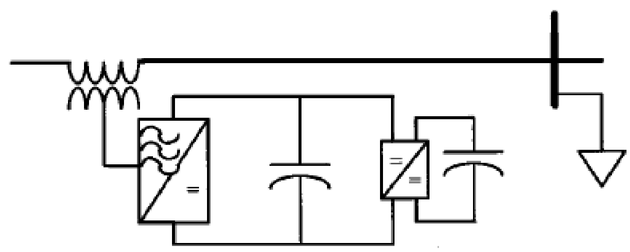

Fig 10. Dynamic voltage restorer (DVR) with capacitor storage

II. Cost Considerations

In order to establish a realistic cost estimate,Cthe following steps are suggested:

- identify the system issues to be addressed;
- select preliminary system characteristics;
- define basic energy storage, power, voltage and current requirements;
- Model system performance in response to system demands to establish effectiveness of the device;
- Optimize system specification and determine system cost;
- Determine utility financial benefits from operation;
- Compare system's cost and utility financial benefits to determine adequacy of utility's return on investment;
- Compare different energy storage systems performance and costs.

III. Conclusion

Among the potential performance benefits produced by advanced energy storage applications are improved system reliability, dynamic stability, enhanced power quality, transmission capacity enhancement, and area protection. An energy storage device can also have a positive cost and environmental impact by reducing fuel consumption and emissions through reduced line losses and reduced generation availability for frequency stabilization.

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FACTS 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.

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. 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.

This paper shows that energy storage devices can be integrated to power electronics converters to provide power system stability, enhanced transmission capability, and improved power quality. Adding energy storage to power electronics compensators not only enhances the performance of the device, but can also provide the possibility of reducing the MVA ratings requirements of the front-end power electronics conversion system. This is an important cost/benefit consideration when considering adding energy storage systems.

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