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SMES Technology, SMES and Facts System, Applications, Advantages and Technical Limitations

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Abstract: This paper introduces with the SMES Technology, its working principle, requirements and applications, Implementation of SMES in FACTS. Addition of Power electronic based flexible ac transmission (FACTS) Systems to power transmission and distribution systems at strategic locations improves the system performance. These devices can be used to control power flow on a transmission line by injecting a series voltage into the line or they can also support the voltage at a bus through shunt voltage injection. A SMES coil could instead be incorporated onto the DC bus. Interfacing the coil to the ac system through a current source inverter results in a device that injects a controlled current with the ability to regulate ac voltage or power flow under normal conditions and supply when the power supply is off-line. Some of the SMES applications are elucidated in this paper. Advantages over other technologies and technical limitations associated with the SMES Technology are discussed in this paper.

Key words: Superconducting Magnetic Energy Storage (SMES) % Power Conditioning System (PCS) % Flexible AC transmission system (FACTS) % Integrated Power System (IPS) % Current source inverter (CSC) % Voltage source inverter (VSC)

INTRODUCTION

The concept of Superconducting Magnetic Energy Storage (SMES) was developed in the early 1970's. Its concept was simple; circulate a DC current in a superconducting coil and store energy in its magnetic field with essentially zero losses. However, implementing this concept efficiently and economically has proven to be quite challenging. ENERGY STORED IN SMES COILS: - Calculation of stored energy. The magnetic energy stored by a coil carrying a current I is given by one half of the inductance of the coil times the square of the current [1].

$$E= (1/2).L.I^2$$

Where
E = energy measured in joules
L = inductance measured in Henries I = current measured in amperes

Now let's consider a cylindrical coil with conductors of a rectangular cross section. The mean radius of coil is R. Width and depth of the conductor are a and b, f is called form function which is different for different shapes of coil. L_1 (xi) and L_2 (delta) are two parameters to characterize the dimensions of the coil. We can therefore write the magnetic energy stored in such a cylindrical coil as shown below. This energy is a function of coil dimensions, number of turns and carrying current [2-6].

$E= (1/2).\, f (L_1, L_2).R.N^2.I^2$ Where E = energy measured in joules I = current measured in amperes

$f (L_1, L_2)$ = form function, joules per ampere-meter N = number of turns of coil

Technology Description: A SMES system stores energy in the magnetic field created by the flow of direct current in a coil of superconducting material. To maintain the coil

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in its low-temperature Superconducting (LTS) state, it is immersed in liquid helium contained in a vacuum-insulated cryostat. Superconducting Magnetic Energy Storage (SMES) systems store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature. A typical SMES system includes three parts: superconducting coil, power conditioning system and cryogenically cooled refrigerator. Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely [7-9].

The stored energy can be released back to the network by discharging the coil. The power conditioning system uses an inverter/rectifier to transform alternating current (AC) power to direct current or convert DC back to AC power. The inverter/rectifier accounts for about 2-3% energy loss in each direction. SMES looses the least amount of electricity in the energy storage process compared to other methods of storing energy. SMES systems are highly efficient; the round-trip efficiency is greater than 95% Due to the energy requirements of refrigeration and the high cost of superconducting wire, SMES is currently used for short duration energy storage. Therefore, SMES is most commonly devoted to improving power quality. If SMES were to be used for utilities it would be a diurnal storage device, charged from baseload power at night and meeting peak loads during the day [10-18].

The requirements for the SMES System are:

- Commercial SMES products utilize LTS material.
- Since the SMES coil is a DC device, a power converter system is required at the coil/grid interface.
- The power converter system uses standard solid-state DC-AC converters as well as other filtering and control circuitry.
- In addition to the superconducting coil and the power converter system, the only other major elements comprising a SMES plant are the cryogenic refrigerator systems (including cryostat).
- SMES technology has been under development around the world for many years.

Difficulty in Adding SMES Coil to AC System: One of the difficulties in adding a SMES coil to an ac system is the power converter interface needed to properly synchronize with the ac system and transfer energy in and out of the coil. The power conditioning for a SMES coil has the added difficulty in that a wide range of voltages may be necessary in addition to a wide range of currents. The voltage will need to reverse, although the current can stay unidirectional. Most power conversion options do better if either voltage or current has a somewhat smaller range of variation. Many power conversion options for SMES coils have been considered over the years, generally with the power conversion dedicated solely to the SMES coil. Power electronic based flexible ac transmission (FACTS) or Custom Power devices are added to power transmission and distribution systems at strategic locations to improve system performance. One class of these devices uses temporary energy storage on a dc bus in the form of a capacitor. These devices can be used to control power flow on a transmission line by injecting a series voltage into the line or they can also support the voltage at a bus through shunt voltage injection. The addition of more substantial energy storage, such as a battery or capacitor bank makes these devices capable of maintaining voltage magnitude during a voltage sag or brief outage. An example of this is the dynamic voltage restorer (DVR). A SMES coil could instead be incorporated onto the DC bus. Interfacing the coil to the ac system through a current source inverter yields a device that injects a controlled current with the ability to regulate ac voltage or power flow under normal conditions and to supply energy when the power supply is off-line. If a dc/dc boost converter is used to interface to the coil, a voltage source inverter could be used to inject a voltage into the ac system instead. The energy storage elements presently used on the dc bus of FACTS or Custom Power device, usually a capacitor will still be used to absorb the ripple from the converter and handle fast transient changes. The size of the capacitor can be reduced though.

SMES Applications: SMES has branched out from its application origins in the early 1970s to include power quality for utility, industrial, commercial and military applications. It has also shown promise as a power supply for pulsed loads such as electric guns and electromagnetic aircraft launchers as well as for vital loads when power distribution systems are temporarily down. On application, superconducting magnetic energy storage (SMES) coils can be used in many ways.

- They can be used to damp dynamic swings on the ac system by absorbing or They can also be used for load leveling by charging them when excess generation is available and discharging them during high demand periods.
- Small SMES coils can act as an uninterruptible power supply to help loads ride through short outages and voltage sags.
- SMES Coils are also used for the Utility Applications.

[An Example of SMES application is illustrated in brief in the section 4.1].

Vital Loads: Consider an example of a Naval Ship. It is sometimes necessary that vital loads on a ship be started at a time when the required power is not available. A vital load would be defined as any load that is essential to the operation of the ship or the survival of the crew. This could include blowers, pumps or any number of systems in a submarine or ship that are needed to successfully operate the vessel. If there is a temporary power outage it could be imperative that these systems start operating or continue operation. The SMES unit could store energy for these vital loads. When numerous systems need to be brought up simultaneously quite often the power system cannot handle the start up transients. The PCS could be used to soft start the motors and eliminate startup transients that could degrade power quality and shut down sensitive equipment. In the case where power is not immediately available the PCS could run loads at a fraction of full power until auxiliary generators are brought on line.

SMES Coil with Facts System: An SMES Coil is implemented on the DC side of the FACTS Device. Because FACTS devices are usually employed to generate and control reactive power, the SMES coil serves as an energy storage element in support of that function. The FACTS devices mentioned above have been the subject of this modification. Interfacing a SMES coil to the dc side of a FACTS device requires selection of an appropriate converter topology for the FACTS device. There are two possibilities for this: a current source inverter (CSC) or a voltage source inverter (VSC). The CSC requires a stiff direct current source, whereas the voltage source inverter needs a stiff voltage. Because the SMES coil obviously behaves as an inductor, there is a generally compatible topology between a CSC and a SMES coil. The SMES coil has a somewhat larger energy storage capacity than the typical CSC's dc link inductor. With this energy storage, a CSC can provide real power to ride through sags and brief interruptions. It can also provide real power for damping of some of the slower transients on the lines. A VSC can also process the real power to ride through sags and brief interruptions. It can also provide real power for damping of transients. It can respond more quickly and therefore can address somewhat faster transients than the CSC. Consequently, a VSC is capable of pulse width modulation that produces an output current and voltage with less harmonic content than a typical CSC output current. A CSC is generally only capable of slow pulse width modulation. In other words, the VSC current requires less subsequent filtering and can serve systems less tolerant of current harmonics. Unfortunately for this application, the VSC requires a stiff voltage source. This means that a dc/dc boost converter is necessary to convert the stiff current behavior of the SMES coil to a stiff voltage on which the VSC depends.

The topology that is chosen must be able to regulate the dc link voltage while controlling the dc and ac system and losses. It must follow variations in load as commanded. Therefore, a VSC-based FACTS device as an interface may be more capable to do these tasks and may be compatible with the utility, but has more components and a corresponding cost disadvantage.

For FACTS devices, the switch chosen is a Silicon Controlled Rectifier (SCR) or Thyristor for the largest devices or the Gate Turn Off Thyristor (GTO) if the requirements are small enough to permit their use. Each has its disadvantages: the SCR is a latching device that requires either appropriate conditions within the power circuit to turn the SCR off or additional circuitry for that purpose. An advantage of using the FACTS/SMES combination for real power is that the FACTS device has a higher Q rating than P and the SMES coil will affect only the P rating. P and Q sum orthogonally, so the effect on overall current of combining the SMES and FACTS device is less when both are used together, as shown in Figure 1, than if both were used separately.

The SMES coil provides a real power contribution to the system in a location that may be strategically important in the overall operation of the system. Each of the FACTS and Custom Power devices described earlier in this paper are primarily reactive power devices. They contribute little if any real power and, for the most part, draw on the utility to provide for their losses. The UPFC circulates real power internally, but does not supply any.

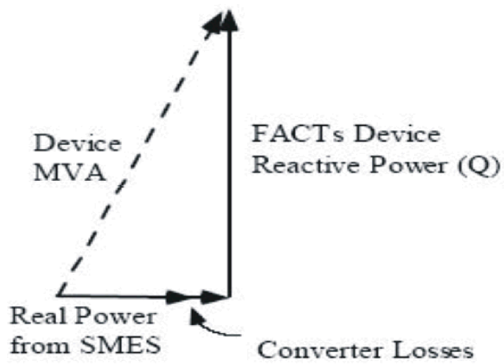

Fig. 1: Orthogonal Addition of Fuel Cell Real Power P and FACTS Device's Reactive Power Q.

Only the DVR actually stores real power to any extent. Providing a real power capability, probably close to an important or remote load (the typical placement for a small SMES coil at present), may have strategic importance. Also, a small, rapidly responding source of real power from a SMES coil when needed can be of significance for power quality support. In adding a SMES coil to the DC bus, there is a gain of another degree of control over the FACTS or custom power device because the SMES coil can regulate the voltage level of the dc bus with its dc-dc converter. Bus capacitors provide energy storage to support the dc bus voltage, making the dc bus voltage directly related to the setting of the voltage control on the dc-dc converter. Freeing the converter on the FACTS of Custom Power device from controlling the dc bus voltage, provides an additional degree of freedom for controlling the input to the ac system. The SMES coil and its converter provide a nearby and responsive means of moving energy in and out of the capacitor. Because energy also enters (and exits) to the ac line, dc bus regulation must be done in concert with the switching action of FACTS or custom power device.

Advantages over Other Technologies: There are several reasons for using superconducting magnetic energy storage instead of other energy storage methods.

- 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.
- Thus if a customer's demand is immediate, SMES is a viable option.
- Another advantage is that the loss of power is lessthan other storage methods because electric currents encounter almost no resistance.
- Additionally the main parts in a SMES are motionless, which results in high reliability.

Technical Limitations: The energy content of current SMES systems is usually quite small. Methods to increase the energy stored in SMES often resort to large-scale storage units. As with other superconducting applications, cryogenics are a necessity. A robust mechanical structure is usually required to contain the very large Lorentz forces generated by and on the magnet coils. The dominant cost for SMES is the superconductor, followed by the cooling system and the rest of the mechanical structure.

- Mechanical support-Needed because of Lorentz forces.
- Size-To achieve commercially useful levels of storage, around 1 GWh (3.6 TJ), a SMES installation would need a loop of around 100 miles (160 km). It would require access to a significant amount of land to house the installation.
- Manufacturing-There is some manufacturing issues around SMES. The first is the fabrication of bulk cable suitable to carry the current.
- Infrastructure-The second problem is the infrastructure required for an installation. Until room-temperature superconductors are found, the 100 mile (160 km) loop of wire would have to be contained within a vacuum flask of liquid nitrogen. This in turn would require stable support, most commonly envisioned by burying the installation.
- Critical current-Unfortunately the super conducting properties of most materials break down as current increases, at a level known as the critical current. Current materials struggle, therefore, to carry sufficient current to make a commercial storage facility economically viable.
- Critical magnetic field-Related to critical current, there is a similar limitation to superconductivity linked to the magnetic field induced in the wire and this too is a factor at commercial storage levels
- Possible Adverse Health effects-The biggest concern with SMES, beyond possible accidents such as a break in the containment of liquid nitrogen, is the very large magnetic fields that would be created by a

commercial installation, which would dwarf the magnetic field of the Earth.

- Obstacle-The controls for a SMES PCS have some inherent difficulties, such as the large inductance of the superconducting coil which provides the system with a virtual current source. There are several issues that arise from this system characteristic.

CONCLUSION

A SMES system stores energy in the magnetic field created by the flow of direct current in a coil of superconducting material. SMES coils can damp dynamic swings on the ac system. SMES coils can level the load and even act as an uninterruptible power supply. FACTS devices can control power flow on a transmission line by injecting a series voltage into the line or they can also support the voltage at a bus through shunt voltage injection. A FACTS device has a higher Q rating than P and the SMES coil will affect only the P rating. P and Q sum orthogonally, so the effect on overall current of combining the SMES and FACTS device is less when both are used together than if both were used separately. Using a SMES coil and a FACTS device together provides both real and reactive power in a location that may be strategically significant for improving power quality and for controlling the flow of both real and reactive power within a utility system.

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