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Energy Storage Technologies, Applications and Modeling Considerations of SMES in Power System

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ABSTRACT: The electrical energy storage systems serve many applications to the power system like economically meeting peak loads, quickly providing spinning reserve, improving power quality and stability, and maintaining reliability and security. The rapidly increasing integration of renewable energy sources into the grid is driving greater attention towards electrical energy storage systems which are capable of stabilizing the output from renewable energy sources. The application of electrical energy storage systems will also defer the installation of new transmission lines. With the development of advanced energy storage technologies, the electrical energy storage systems are making the future power system more reliable, efficient and economical. This paper presents various energy storage technologies currently used, their applications and the role they are going to play in the future power system. Superconducting magnetic energy storage (SMES) is known to be a very good energy storage device. A detailed modeling consideration for simulation of a SMES system which has the potential to bring real power storage characteristic to the utility transmission and distribution systems is also provided.

KEYWORDS: Energy storage, Renewable energy sources, Electrical power and energy systems, Superconducting Magnetic Energy Storage (SMES), Superconducting coils, Power conditioning system (PCS).

I. INTRODUCTION

Electrical energy storage systems (EESS) store the electrical energy in the kinetic, potential, electrochemical or electromagnetic form which can be transferred back to the electrical energy when required. The conversion of electrical energy to different forms and back to electrical energy is done with power conversion/conditioning systems (PCS). EESS can store the inexpensive energy during off-peak periods and be used to meet the loads during peak periods when the energy is expensive, which will improve the economic operation of the power system. Compared to conventional generators, the energy storage systems have a faster ramping rate which can quickly respond to the load fluctuations. Therefore, the energy storage systems can be a perfect spinning reserve source which provides a fast load following and reduces the need for spinning reserve sources from conventional generation plants. Electrical energy storages were initially treated only for load levelling applications. Now, they are more seen as a tool to improve the power system quality and stability, to ensure a reliable and secure power supply to loads, and to black start the power system. Poor power quality exists with variations in voltage magnitude and frequency. Electrical energy storages can help in maintaining power quality by providing necessary voltage and frequency support to the power grid. A variety of storage technologies are in the market but the most viable are battery energy storage systems (BESS), pumped storage hydroelectric systems, and superconducting magnetic energy storage (SMES) systems. Some of the disadvantages of BESS include limited life cycle, voltage and current limitations, and potential environmental hazards. Again, some of the disadvantages of pumped hydroelectric are large unit sizes, topographic and environmental limitations. SMES is a large superconducting coil capable of storing electric energy in the magnetic field generated by dc current flowing through it. The dc current flowing through a superconducting wire in a large magnet creates the magnetic field. Generally, it consists of the superconducting coil, the cryogenic system, and the Power Conversion/Conditioning System (PCS) with control and protection functions [3]. The total efficiency of a SMES system can be very high since it does not require energy conversion from electrical to mechanical or chemical energy. The real power as well as the reactive power can be absorbed by or released from the SMES coil according to system power requirements. 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, power quality improvement, automatic generation control, uninterruptible power supplies, etc. The one major advantage of the SMES coil is that it can discharge large amounts of power for a small period of time. Also, unlimited number of charging and

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discharging cycles can be carried out. In SMES systems, it is the power conditioning system (PCS) that handles the power transfer between the superconducting coil and the ac system. Comparing with other storage technologies, the SMES technology has a unique advantage in two types of applications: Power system transmission control and stabilization, and power quality improvement. In order to achieve the best system configuration possible, the design of the SMES system needs to take into account many factors. This paper intends to provide detailed model considerations of the SMES system for the SMES related power system computer simulation.

II. OVERVIEW OF ENERGY STORAGE TECHNOLOGIES

There are different energy storage technologies of which some are already in use and some are yet to be implemented. Different energy storage technologies serve different applications depending on the amount of energy to be stored, the rate at which it is to be transferred, and the response time. The following energy storage technologies are with the high priority in the energy storage applications. The comparison of these technologies is summarized in TABLE I. Besides, there are several other energy storage technologies, such as hydrogen energy storage, thermal storage, and fuel cells.

A. Pumped Hydro Storage:

The pumped hydro storage is the conventional and most widely used energy storage technology. In this storage, the electrical energy is stored as the potential energy by pumping water to a higher reservoir during off peak periods. This energy can be converted back to the electrical energy by allowing the water to flow from higher to lower reservoir and driving the hydro turbines. The pumped hydro storage is the largest one in terms of capacity. The efficiency of the pumped hydro storage plant is about 70%–80% which varies depending on the plant size, the type of turbine, the penstock diameter, the height between the reservoirs and the level of generation. The usage of pumped storage plants is limited to rural areas because of the large area the system constitutes for setting up the reservoirs [1].

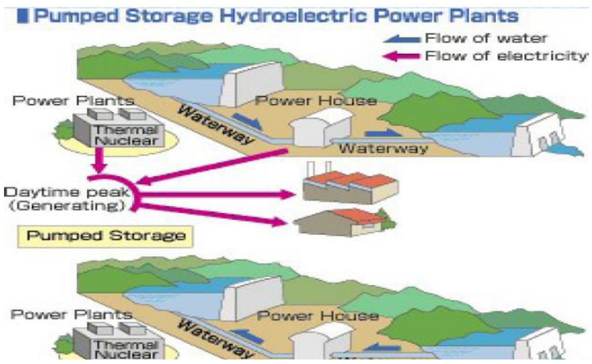

Figure 1: Pumped Hydro Storage.

B. Battery Energy Storage:

The battery is charged to store the electrical energy in the form of a chemical reaction inside the battery. The reversal of this reaction will result in the discharge of the battery producing electrical energy from the chemical reaction. Because batteries store and produce DC power, the power converters are essential for this type of storage in order to interact with the AC power grid. Because they are non-polluting, easy to install and portable, the battery energy storage is the most convenient form of storage in urban areas. A battery energy storage system is made up of several low voltage battery modules connected in series and parallel to obtain the desired electrical characteristic. There are many types of battery systems like lead-acid, Lithium-ion, Sodium sulfur and flow batteries. Among them, the Lead-acid battery is presently used in many applications due to its low cost. Although the batteries are the most convenient and practical method, their high cost and less cycle life are of great concern in their implementation. The implementation of batteries in plug-in hybrid electric vehicles is challenging the existing energy management system of power grids [1].

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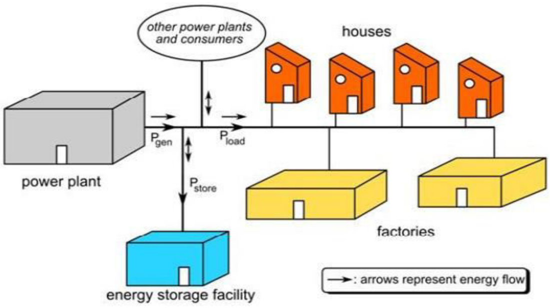

Figure 2: Battery Energy Storage.

C. Compressed Air Energy Storage (CAES):

The compressed air energy storage uses the excess power from the grid during off-peak load periods to compress air and stores it in an underground reservoir under the pressure. In case of the shortage of power, the compressed air is released and burnt with a fuel to drive the generator. Actually, this type of technology is known as hybrid energy storage as it uses fuel as well. However, for the same power output, the fuel consumption in this storage is only one third of the consumption for a regular combustion turbine. The compressed air energy storage is not widely being used presently due to the safety related issues of storing compressed air in the underground. Currently there is only one such kind of a plant in US, which is a 110 MW – 26 hour compressed air energy storage plant in Alabama, built in 1991 [1].

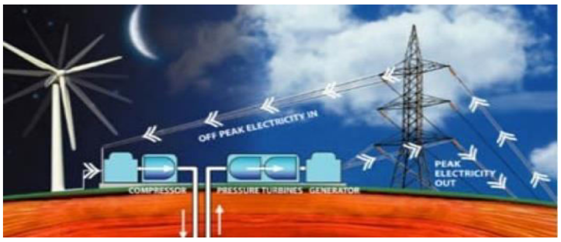

Figure 3: Compressed Air Energy Storage.

D. Flywheel Storage:

The flywheel energy storage stores the electrical energy in the form of kinetic energy of a rotor or a disc spinning around its axis on a shaft. The charging or discharging of the flywheel storage system takes place by changing the amount of kinetic energy present in the accelerating or decelerating rotor, respectively. The flywheel is coupled with an electrical machine which acts as a motor to drive the flywheel while charging and acts as a generator to discharge the stored energy by decelerating the rotor to stationary position. The amount of energy stored depends on the moment of inertia and square of the rotational speed of the rotor. Therefore, composite materials are used for the rotor to reduce its weight allowing much high speeds. The flywheel has a high-power density and high cycle life. A medium scale flywheel system is being incorporated in New York City with ten 100kW – 30 seconds flywheels for regenerative braking and start-up of subway transit cars [1].

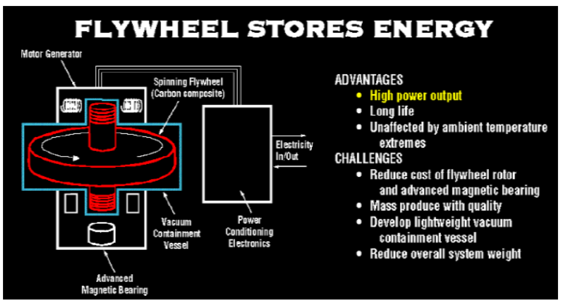

Figure 4: Flywheel Storage.

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E. Superconducting Magnetic Energy Storage (SMES):

The superconducting magnetic energy storage charges by storing the electrical energy in the form of magnetic field created by the flow of DC current through a coil made of superconducting material at very low temperatures. The DC power stored in the magnetic field can be discharged with high power output in a short interval time. The energy stored in the coil is proportional to the inductance of the coil and square of the dc current creating the magnetic field [1].

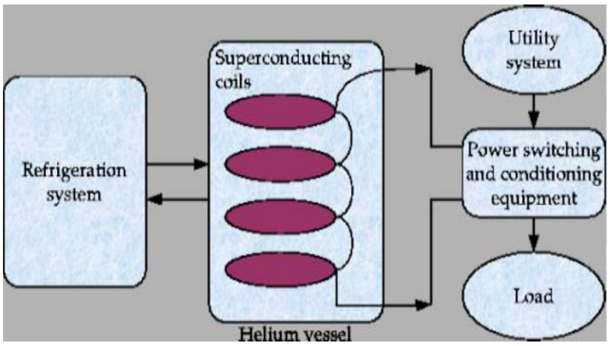

Figure 5: Superconducting Magnetic Energy Storage.

TABLE I. Comparison of Different Energy Storage Technology [1]

Storage Technology	Energy Capacity	Discharge Duration at Max Power Level	Power Level	Response Time	AC-AC Efficiency (%)	Life Time	Applications
Pumped Hydro	< 24000 MWh	12 hours	< 2000MW	30 ms	70 – 80 %	40 yrs	i) Energy arbitrage ii) Frequency regulation iii) Ancillary services
CAES	400 – 7200 MWh	4 – 24hr	100–300MW	3-15 min	85 %	30 yrs	
Fly Wheel	< 100 kWh	Minutes to 1 hour	< 100 kW	5 ms	80 – 85 %	20 yrs	i) Frequency regulation ii) Power quality iii) Fluctuation smoothing iv) Emergency bridging power
Battery	< 200 MWh	1 – 8 hours	< 30 MW	30 ms	60 – 80 %	2-10 yrs	i) Peak shaving for T&D upgrade deferral ii) Backup power iii) Small load leveling application
SMES	0.6 kWh	10 s	200 kW	5 ms	90 %	40 yrs	i) Power quality ii) Emergency bridging power

III. APPLICATIONS OF SMES IN POWER SYSTEMS

It is the fast response that makes SMES able to provide benefit to many potential utility applications. The applications of SMES are described in the following.

1) Energy storage - An SMES unit could provide the potential for energy storage of up to 5000 MWh with a high return efficiency (up to 95% for a large unit) and a rapid response time for dynamic change of energy flow (milliseconds). This aspect makes it ideal for large variations in energy requirements between daytime peak demand and off-peak back-down as well as large amounts of energy available for replacement of major unit trips. This may provide for the potential reduction of spinning reserve requirements.

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2) Load following - An SMES unit has the ability to follow system load changes almost instantaneously which provides for conventional generating units to operate at constant output.

3) System stability - An SMES unit has the capability to dampen out low frequency power oscillations and to stabilize system frequency as a result of system transients.

4) Automatic Generation Control - An SMES unit can be the controlling function in an AGC system to provide for a minimum of area control error (ACE).

5) Spinning reserve - In case a major generating unit or major transmission line is forced out of service, a certain amount of generation must be kept unloaded as "spinning reserve." An SMES unit can represent a tremendous amount of spinning reserve capacity when in the charged mode. This lowers the costs for spinning reserve requirements over comparable values and methods of maintaining spinning reserve.

6) Reactive volt-ampere (VAR) control and power factor correction - An SMES unit can increase the stability and power carrying capacity of a transmission system.

7) Black start capability - An SMES unit can provide power to start a generating unit without power from the grid. This provides for grid restoration when area failures have occurred.

8) Bulk energy management - An SMES unit has the ability to store large quantities of energy, and thus can act as a storage and transfer point for bulk quantities of energy based on the economics, potentially lowering the cost of electricity.

9) Transient voltage dip improvement **-** A transient voltage dip lasting for 10–20 cycles can result when a major disturbance on the power system occurs. SMES and associated converter equipment has been shown to be effective for providing voltage support which can result in increasing the power transfer limitations on the transmission system.

10) Dynamic voltage stability - Dynamic voltage instability can occur when there is a major loss of generation or heavily loaded transmission line and there is insufficient dynamic reactive power to support voltages. SMES has been shown to be effective in mitigating dynamic voltage instability by supplying real and reactive power simultaneously supplanting loss of generation or a major transmission line.

11) Tie line control - When power is scheduled between utility control areas, it is important that the actual net power matches closely with the scheduled power. Unfortunately, when generators are ramped up in one control area and down in the receiving control area to send power, the system load can change causing an error in the actual power delivered. This ACE can result in inefficient use of generation. SMES can be designed with appropriate controls to inject power to virtually eliminate this error and ensure that generation is efficiently used and power schedules are met.

12) Underfrequency load shedding reduction - When the power system suffers the loss of a major resource such as a generating plant or major importing transmission lines the system frequency will drop and continue to decline until the generating resource—load balance is restored. Because SMES can inject real power rapidly into the system, it is an effective method to offset, or reduce, under frequency load shedding because it reduces the mismatch between load and supply capability of the system disturbance [2].

13) Circuit breaker reclosing - Following clearance of a fault, circuit breakers attempt to reclose and return the affected transmission line to service. This is accomplished routinely whenever the power angle difference across the circuit breaker is within acceptable limits. However, protective relays prevent the circuit breaker from reclosing if the angle difference is too large. By briefly supplying some fraction of the power normally transmitted by the transmission line, SMES can reduce the power angle difference across a circuit breaker and allow reclosure of the circuit breaker. This allows restoration of the system power transfers quickly following outages of major transmission lines [2].

14) Power quality improvement - SMES can provide ride through capability and smooth out disturbances on power systems that would otherwise interrupt sensitive customer loads. When momentary disturbances such as transmission line flashovers or lightning strikes occur, power can be lost if the transmission line trips, or voltages can dip low. SMES

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has very fast response and can inject real power in less than one power cycle preventing important customers from losing power.

15) Backup power supply - The energy storage capacity of SMES can be used as a backup power supply for large industrial customers in case of loss of the utility main power supply. Studies have shown SMES can be sized with the appropriate energy storage and capacity to provide backup through most disturbances and be cost-effective.

16) Sub-synchronous resonance damping - Generators which are connected to transmission lines which have high levels of series compensation (series capacitors) can be exposed to a phenomenon called sub-synchronous resonance (SSR) which can result in serious damage to the generator. SMES as an active device can be designed to provide mitigation of SSR and allow higher levels of series compensation to be installed [2].

17) Electromagnetic launcher - An electromagnetic launcher requiring high power pulse sources has been developed as a railgun for military applications. A railgun can launch projectiles at velocities higher than 2000 m/s, surpassing the conventional possibilities. Due to its high-power density, SMES is a very interesting energy storage device for an electromagnetic launcher.

18) Wind generator stabilization - Wind generators have transient stability problems during network disturbances. An SMES unit based on a self-commutated inverter using IGBT.

or gate-turn OFF (GTO) thyristor is capable of controlling both the active and reactive powers simultaneously. Therefore, it can act as a good tool to stabilize the
wind generator system considerably [2].

19) Minimization of power and voltage fluctuations of wind generator - Due to random variations of wind speed, output power and voltage of wind generator fluctuate randomly. These fluctuations pose serious problems on the system, for example, lamp flicker and inaccuracy in the timing devices. Since an SMES unit is capable of controlling both the active and reactive powers simultaneously, it can act as a good tool to decrease voltage and power fluctuations of the wind generator system considerably.

In addition to direct applications and benefits from the SMES technology, the following are additional secondary benefits that could be derived.

1) Lower use of oil and gas - An SMES unit can be charged by the more efficient units in a system, thereby lessening the need for the lower efficiency units to operate during peak periods.

2) Increased efficiency and reduced maintenance of generating units - Because an SMES unit can absorb the fluctuations in demand and ramp at extremely rapid rates, generating units can be operated and maintained at their most efficient set points, thereby increasing efficiency, reducing maintenance, and extending operability.

3) Deferral of new conventional capacity - An SMES unit has the ability to receive credit that would otherwise go to additional intermediate load and peak load generating units. It may also serve to reduce the calculated avoided cost [2].

4) Deferral of new transmission capacity - An SMES unit, if strategically placed, can defer the need for new transmission to high load centers by loading existing transmission systems during off-peak periods.

5) Increased availability of generating units - An SMES unit provides for the back-up of additional generating units which were previously needed only during peak periods, thus increasing the overall capacity of the system.

6) Environmentally sound - The clean and efficient storage of electricity by SMES from conventional units operating more efficiently at their set points will displace inefficient fossil-fueled units, conserve premium fuels, and reduce air pollutants. SMES may provide for some emissions credit. SMES has no emissions and its electromagnetic field is confined to an area comparable to generating technologies [2].

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IV.SMES SYSTEM ELEMENTS MODELING

As can be seen from Figure 6, a SMES system consists of several sub-systems. A large superconducting coil is the heart of a SMES system, which is contained in a cryostat or dewar consisting of a vacuum vessel and a liquid vessel that cools the coil. A cryogenic system is also used to keep the temperature well below the critical temperature of the superconductor. An ac/dc PCS is used for two purposes:

One is to convert electrical energy from dc to ac, and the other is to charge and discharge the coil. Finally, a transformer provides the connection to the power system and reduces the operating voltage to acceptable levels for the PCS.

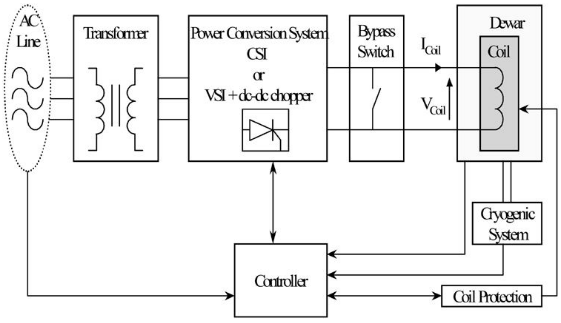

Figure 6: Typical SMES System.

For a SMES system, the inductively stored energy (E in Joule) and the rated power (P in Watt) are commonly the given specifications for SMES devices, and can be expressed as follows:

$$E = \frac{1}{2}LI^2 \qquad P = \frac{dE}{dt} = LI\frac{dI}{dt} = VI \qquad \text{------- (1)}$$

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. During SMES operation, the magnet coils have to remain in the superconducting status. A refrigerator in the cryogenic system maintains the required temperature for proper superconducting operation. Since the refrigeration load can affect the overall efficiency and cost of a SMES system, the refrigeration load that has loss components (such as, cold to warm current leads, ac current, conduction and radiation, etc) should be minimized to achieve a higher efficient and less costly SMES system [3].

V. DEVELOPING A SMES COIL MODEL

a) Modeling Assumptions:

It is assumed that the SMES coil can be accurately represented by a lumped parameter model as shown in figure 7. In this model, each double pancake is represented by self and mutual inductors, and series and ground capacitors. The inductance and capacitance values of a double pancake are obtained by lumping those of turns forming the pancake. The following additional assumptions are made:

1. The dielectric constant of the insulating material does not vary with frequency. The thermal enclosure and the tank do not carry current, and they are represented as ground plane
2. A small value of resistor represents skin effect and eddy current losses.
3. Parallel plate model is employed to calculate ground and series capacitances of each turn [3].

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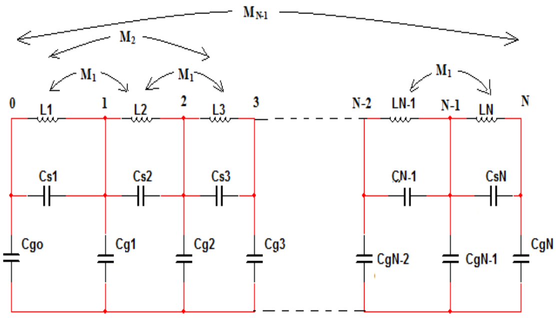

Figure 7: Schematic representation of a winding.

C_{gi} = shunt capacitance. C_{si} = series capacitance.
L_i = self-inductance. M_i = mutual inductance.

b) Modeling Steps:

The most detailed mathematical model for a coil can be obtained if each turn in the coil is represented by its associated L, M, C_{adj}, C_{ax}, and C_g. But this detailed model requires much memory and computing time if the coil consists of excessive numbers of turns. N number of turns in an N_{dp} number of double pancakes in a coil can be lumped to model the coil in the level of double pancakes. For better understanding, an example coil is considered with N_{sp}= 12 single pancake (N_{dp}= 6 double pancake) where each Single Pancake (SP) consists of N=10 turns [3].

i) Forming inductance matrix:

Calculate self-inductances for each turn in a SP by applying the Miki's formula, and mutual inductances between each turn in a SP by applying the Lyle's method. Construct an $N \times N\ (10 \times 10)$ matrix block. Where N is the number of turns in SP. Diagonal elements correspond to the self-inductances and off-diagonal elements correspond to mutual inductances between each turn in a SP [7].

$$L_{turn} = \begin{bmatrix} [A]_{N\times N} & [B]_{N\times N} & [C]_{N\times N} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & [L]_{N\times N} \\ [B]_{N\times N} & [A]_{N\times N} & [B]_{N\times N} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & [K]_{N\times N} \\ [C]_{N\times N} & [B]_{N\times N} & [A]_{N\times N} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & [J]_{N\times N} \\ [D]_{N\times N} & [C]_{N\times N} & [B]_{N\times N} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & [I]_{N\times N} \\ [E]_{N\times N} & [D]_{N\times N} & [C]_{N\times N} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & [H]_{N\times N} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ [L]_{N\times N} & [K]_{N\times N} & [J]_{N\times N} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & [A]_{N\times N} \end{bmatrix}_{NN'_s\times NN_s} . \quad \text{---------------------- (2)}$$

We applied Lyle's method to calculate mutual inductances between turns in the first SP and turns in the other SPs. A series of $N \times N\ (10 \times 10)$ matrix blocks (B to L in (2)) are constructed where each $N \times N\ (10 \times 10)$ represents mutual inductances between the first SP and other SPs. These matrix blocks and the one constructed above builds a column with a size of $N * N_{sp} \times N\ (120 \times 10)$. Once the first column of L turn is formed, a lumped inductance matrix representing the double pancakes of the coil is computed as given in equations (3) – (4), [3], [7].

$$L_{db} = \begin{bmatrix} \text{sum (ABAB)} & \text{sum (CBCD)} & \cdots & \cdots & \text{sum (KJKL)} \\ \text{sum (CBCD)} & \text{sum (ABAB)} & \cdots & \cdots & \cdots \\ \text{sum (EDEF)} & \text{sum (CBCD)} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \text{sum (KJKL)} & \cdots & \cdots & \cdots & \text{sum (ABAB)} \end{bmatrix}_{2N_s \times 2N_s} \quad \text{---------------------- (3)}$$

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$$\text{sum (ABAB)} = \sum_{i=1}^{N}\sum_{j=1}^{N} A(i,j) + \sum_{i=1}^{N}\sum_{j=1}^{N} B(i,j) + \sum_{i=1}^{N}\sum_{j=1}^{N} A(i,j) + \sum_{i=1}^{N}\sum_{j=1}^{N} B(i,j)$$

-------------------------- (4)

ii) Calculating capacitances for a double pancake:

Calculate capacitances between C_{adj}, C_{ax} and C_g using equation 5. Capacitances between C_{adj} and C_{ax} are combined in such as to compute the equivalent series capacitance for a double pancake. C_g calculated for each turn within a double pancake are summed to obtain an equivalent C_g for a double pancake [3], [6].

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

------------ (5)

VI. CONCLUSION AND FUTURE ENHANCEMENT

This paper presents various energy storage techniques and their applications in the power system. It has been shown that energy storage devices not only enable the large-scale integration of renewable energy sources into the grid, but also ensures the economic generation by the application of grid energy storages. An overview and potential applications of the SMES technology in electrical power and energy systems are also provided. Since the up-to-date SMES references and applications are provided in this article, this would serve as a basic guideline to investigate further technological development and new applications of SMES, and thus benefits the readers, researchers, engineers, and academicians who deal with the research works in the area of SMES. Also, a detailed model considerations for the simulation of the SMES system is described. The model is intended to provide guidelines for a detailed SMES device simulation in the power system, as well as to provide a basis for comparison of various simulation tools, control strategies, algorithms and realization approaches. The SMES coil is modelled as sections where each section is represented with its series capacitance, shunt capacitance, self and mutual inductances to other sections. The computation of models is developed to represent the entire coil to reduce computational effort.

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