Progress in Superconducting Materials for Powerful Energy Storage Systems

Essia Hannachi, Zayneb Trabelsi, and Yassine Slimani

Abstract With the increasing demand for energy worldwide, many scientists have devoted their research work to developing new materials that can serve as powerful energy storage systems. Thus, the number of publications focusing on this topic keeps increasing with the rise of projects and funding. Superconductor materials are being envisaged for Superconducting Magnetic Energy Storage (SMES). It is among the most important energy storage systems particularly used in applications allowing to give stability to the electrical grids. SMES is an electrical energy storage technology which can provide a concrete answer to serious problems related to the electrical cut causing a lot of damage. It features high power, strong power conversion efficiency and instant response times. It is capable to deliver a great amount of electricity in milliseconds when the electrical system fails and improve the quality of the electrical network. All these characteristics render them strong competitors in marketing, particularly with the arising and quickly upward energy storage market pushed by renewables, carbon emissions focus, smart grids, and transportation electrification. This chapter of the book reviews the progression in superconducting magnetic storage energy and covers all core concepts of SMES, including its working concept, design limitations, evolution, different types, advantages over other storage methods as well as its drawbacks, applications, potential solutions, and the future perspectives.

Keywords SMES system · Stored energy · Power efficiency · Superconducting coil · Mechanical limits · Quench protection

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1 Introduction

Global electricity consumption has known an abundantly increase, propelled by technological progress and stable global economic growth, pushed by technological progress and steady global economic evolution. As stated by to the latest evaluation of global energy demand by the International Energy Agency (IEA), the demand of global energy is set to rise by 4.6% in 2021 [1]. Nearly 70% of the expected increase in global energy demand is in the markets. Emerging and developing economies, where demand is expected to rise to 3.4% above 2019 levels. A device that can store electrical energy and able to use it later when required is called an "energy storage system". There are various energy storage technologies based on their composition materials and formation like thermal energy storage, electrostatic energy storage, and magnetic energy storage [2]. According to the above-mentioned statistics and the proliferation of applications requiring electricity alongside the growing need for grid stability, SMES has a role to play. This system is among the most important technology that can store energy through the flowing a current in a superconducting coil without resistive losses. The energy is then stored in act direct current (DC) electricity form which is a source of a DC magnetic field. The conductor operates to carry current at extremely cold temperatures where it features a superconducting state and therefore has virtually no loss in resistance since it generates the magnetic field. Niobium–titanium (NbTi) alloys, that operate at liquid helium temperatures (2–4 K), are the most exploited for storage. The use of superconductors with higher critical temperatures (e.g., 60–70 K) needs more investigation and advancement. Today's total cooling and superconducting technology defines and builds the components of an SMES device. The integrated module seems to be feasible for certain utility applications at a cost competitive with other technologies. SMES is the sole technology based on superconductivity appropriate to electrical utilities that is commercially available today [3]. Compared to others energy storage energy, SMES have different advantages: (i) high cyclic productivity, (ii) quick response time (few milliseconds) i.e. SMES possesses direct electrical power conversion (over 95%), whereas the other different energy storage systems include electrical–mechanical conversion or electrical-chemical conversion, which is very slow. (iii) Inherent recharge and discharge capacity-contrasting to batteries, SMES could recharge and discharge absolutely for an unrestricted number of times [4]. Nevertheless, the SMES system is not free from ingrained drawbacks such as weak volumetric and gravitational energy density, physical fatigue, and high cost. Due to its great efficiency and extremely low response time, the SMES systems has strong potential in diverse applications. This makes them very attractive and are of primary interest to a large number of researchers seeking to develop these systems and overcome the problems they encounter.

This chapter book provides the basic operation of SMES emphasizing their exceptional characteristics, related to its energy production, that are valuable to powerful energy storage. Advances so far in several SMES have also been described. The challenge of these systems and future perspectives have also reviewed.

2 Operation Concept of Superconducting Magnetic Energy Storage System (SMES)

2.1 General Description

SMES systems store electrical energy directly within a magnetic field without the need to mechanical or chemical conversion [5]. In such device, a flow of direct DC is produced in superconducting coils, that show no resistance to the flow of current [6] and will create a magnetic field where electrical energy will be stored. Therefore, the core of SMES consists of the superconducting magnet, which should meet certain exigencies like a poor stray field and a suitable mechanical conception to sustain the large Lorentz forces. A schematic drawing of a typical superconducting magnet is given in Fig. 1 in which a current flow through a closed-circuit coil. The working principle of SMES is that when a DC voltage is exerted through the terminals of the coil, the energy will be stored. The current in the coil will peruse to circulate even after the voltage source is eliminated. This is in fact due to the prior cooling of the superconducting coil to a temperature under its critical superconductivity temperature allowing the coil to have no resistance [7]. Thus, when the electrical energy will pass through the cable surrounding the coil. The latter will not undergo any resistance and therefore will not heat up, which will allow energy not to be lost and will be stored by the magnetic field generated by its inherent current. The total energy coupled to the magnetic field is then written as follows [8]:

$$E = \int_{\tau_\infty} \frac{B^2}{2\mu_0} d\tau \tag{1}$$

where B represents the magnetic flux density and τ_∞ denotes the infinite space.

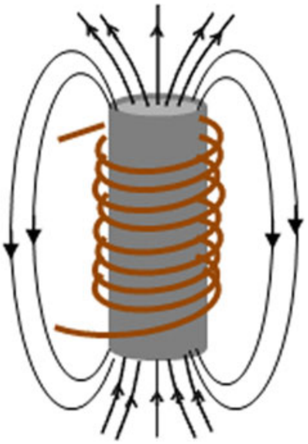

Fig. 1 Storing energy in magnetic form in a short-circuited superconducting winding

Over a medium of huge magnetic fields, the integral can be limited without causing a significant error. When the coil is in its superconducting state, no resistance is observed which allow to create a short circuit at its terminals. Thus, the indefinitely storage of the magnetic energy is possible as no decay of the current takes place. As another option, if the terminals are linked through a weak resistance contact, a quite dissipation will be occurred, and the energy can be stored for long periods of time.

To avoid energy losses, superconducting materials, such as the cheapest Niobium-Titanium alloy, are used for the cables surrounding the coil [9]. The energy stored in DC can be subsequently transformed into alternating current (AC) and delivered to the electrical network by discharging the coil. Such transformation will be done through the use of a power converter module [9]. SMES can go from full charged state to full discharge state very quickly and back, because the efficiency of SMES is ultrahigh compared to normal coils. In general, SMES has a very fast self-discharge due to self-cooling by the coolant liquid. Among the most important characteristics of this system, we cite [7, 9, 10]: a power density of 4000 W/L, a discharge in less than 1 min, the cycle efficiency of its charges/discharges is between 95 and 98%, a lifetime of more than 30 years, an energy storage efficiency over 97% anda high discharge rate around 10–15%.

Figure 2 illustrates the general components of SMES. It mainly involves three main components: (1) a low-temperature/high-temperature superconducting coil magnet which will be cooled by a cryostat to a temperature under its critical superconducting temperature. (2) a cryogenic refrigerator; here liquid helium at 4.2 K (−268.95 °C) or super fluid Helium at 1.8 K (−271.35 °C) will generally be used to cool the system

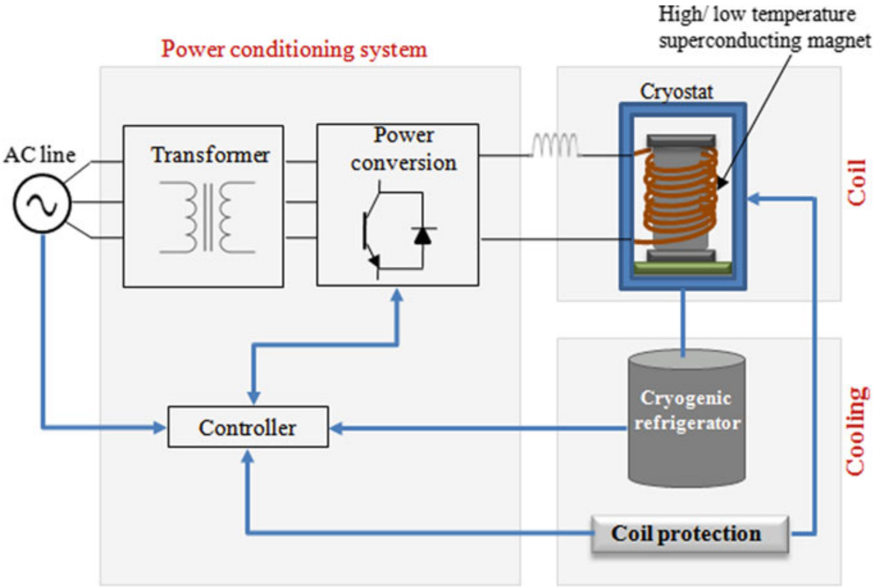

Fig. 2 Basic components of an SMES system

and (3) a driving circuit that will ensure the DC–AC conversion and vice versa. A control system is also introduced in order to regulate the energy exchanges between the electricity network and the SMES and therefore ensures the stability and fluidity of exchanges. Superconducting coil magnet and coolant are serving for storing the energy. While the driving circuit is employed for removing the power from SMES.

2.2 Superconducting Coils

Superconducting coil is the core of any SMES. It is composed of several superconducting wire/tape windings. This is done by employing diverse superconducting materials arranged in thin wires. To provide better strength and protection against quenches, a matrix of Cu, Al or Ag alloys is used. Instead of normal coils, it significantly lessens the energy desirable for the production of a magnetic field. Rarely is additional power from externally sources needed to preserve current in such coils for an extended period of time. All one has to do is compensate for the negligible power losses in the resistive busbars and transferring devices connected in series with the coils and in the contacts links. Power build-up continues before the trial campaign and power extraction from the coils after the campaign is completed for an extended period of time which essentially makes it possible to reduce the power of the power supply, i.e., AC/DC converter. This one provides the current increment and decrement of files according to a specific program and its stability at a specific level. Protecting the coil in the local transition from the superconducting state to the normal state (quench) is actually the major challenge in designing a superconducting coil power supply system. This will be shown in detail below in the following subsections. Generally, in the superconducting coils, there exists a ferromagnetic core that promotes the energy storage capacity of SMES due to its ability to store, at low current density, a massive amount of energy. For elevated gain the core configuration is “closed core (CC)”. The configuration of (CC) lodges the volume both outside and inside the coil. This layout avoids the leakage of the flux. For rendering the leakage trivial, the novel modified configuration of CC is “pot core (PC)”. In PC configuration, the cross-sectional area lengthways the flux line or a flux path is maintained invariable, so that the flux leakage from the core is minimal.

Since the superconducting coil is the main component of a SMES system, the maximum stored energy is affected by three main factors: (i) the size and the shape of the coil; the stored energy amount increases while increasing the size of the coil, (ii) the characteristics of the conductor, that define the maximum current and (iii) the mechanical structure.

2.2.1 Superconducting Coil Design for SMES

Overall, the design of the superconducting coil is directed towards specific goals. This element must minimize the amount of superconducting material, provide a

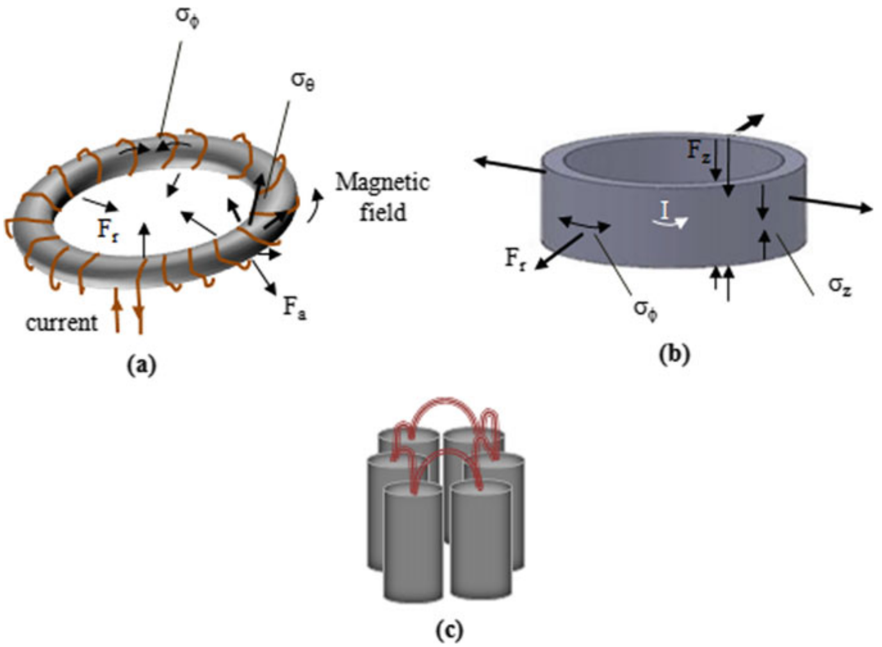

Fig. 3 Toroidal (**a**) and solenoidal (**b**) topologies with generated stresses. **c** schematic illustration of hexagonal arrangement

rigid platform for electromagnetic forces, and ensure good cooling. In this design, the magnet must be well protected against quenches which should be avoided as much as possible. There are two recognized topologies of the superconducting coil: the solenoid and the toroid. Superconducting windings generally consist of assembled modular elements. If these modules are flat, they are called pancakes. As shown in Fig. 3a, b, two different configurations are possible: solenoid if these pancakes are stacked or toroid if they are spaced at a regular angle. The solenoid shape consists of linearly stacked pancake coils in which electromagnetic forces are easier to manipulate compared to in a toroid that is subjected to additional radial forces. Solenoid design can store higher energy, but a stray field can be induced outside the cryostat yielding to adverse effects on the environment. Such an unwanted field is very limited in case of toroid shape since the perpendicular component of the magnetic field is reduced hence the AC current is lowered. However, it stores only approximately 1/2 of the energy that can be stored by the solenoid. In general, the presence of a such field requires a very large active shielding and therefore greater amounts of superconductor.

It has been shown that a hexagonal arrangement of solenoids, as illustrated in Fig. 3c, helps in minimizing the induced stray fields appreciably [11]. This topology is advantageous by its modular conception with elemental solenoid which optimize the energy per unit conductor volume with a diameter to height ratio of 5. For small dimensions and if the shielding is not taken into consideration, the solenoid is more adopted due to its cost effectiveness since it is simpler to manufacture, uses a smaller amount of superconducting material and allows easier processing of the electromagnetic stress [12, 13]. It has been proven that; a thin solenoid coil is found to be a relevant shape for energy storage [14].

However, in the case of large dimensions, the toroidal shape is more desired for two reasons: (i) they have the possibility of being built in parts in the form of small modules which will subsequently be easily and directly assembled in the land, (ii) this design can reduce the external magnetic forces and hence the dimensions of the mechanical structure. In fact, a great size of SMES leads to an increase in mechanical forces. The toroidal form is also given preference whenever second generation HTS or anisotropic superconductor such as YBCO are considered [14, 15]. Indeed, if a solenoidal coil is used in such a case, a significant radial component is generated on the conductor thus causing a remarkable degradation of the quality of the wire. Thus, the choice of the coil shape is strongly related to the used superconducting material, the size and power of the device to be manufactured, the generated electromagnetic constraints and the cost. We note that there are other coil designs that are envisioned for SMES such as dipoles, tilted toroidal coil, bunch of solenoids, etc. Although these topologies are complex and difficult to achieve, they are interesting and offer relevant solutions for certain problems. For instance, Tilted Toroidal Coils, Force Balanced Coils and Stress Balanced Coils have been applied for large scale applications and they showed satisfactory results.

2.2.2 Conductor Characteristics

The magnetic conductor used in SMES systems has to meet certain requirements [16]. It must mainly withstand stresses and strains without losing their superconducting properties, be cheap, operate at a temperature as high as possible and exhibit elevated engineering critical current density in high magnetic field. Beside the appropriate superconducting section that the conductor must have, it must include a sufficient quantity of stabilizing material in order to protect itself well from quenches and to provide adequate mechanical resistance. In addition, a very low AC loss is also required. This can be achieved using low AC loss conductors in which the conductor filaments must be surrounded by resistive barrier. Since the magnetic field shows a linear trend with the total current per unit length, a reduced mass of conductor that operates with substantially high current density or vice versa (i.e., large mass and reduced current density) can generate the desired high magnetic field. From a practical point of view, this field must be of the order of several Tesla to provide volume energy densities suitable for SMES. Due to these strong magnetic fields, the conductor must withstand the stress distribution caused by the presence of large Lorentz forces in the coil.

Until now, the NbTi conductors are the most used for the SMES since they meet all the requirements except for the operating temperature which is very low requiring cryogenics with liquid helium. This process remains costly in terms of investment and operating cost. The progressive advances in large cryocoolers aim to reduce the electrical refrigeration load and extend the maintenance cycle. Another improvement is to introduce HTS conductors. The cooling process of these materials can be done using liquid nitrogen near to its boiling temperature of 77 K which can significantly reduce losses as well as the quantity of energy input needed for refrigeration hence the cryogenic operating cost. If such high operating temperature are considered, high voltage protection can be provided by using thicker electric insulation. This must be optimized while keeping the temperature difference between the conductor and the coolant low.

2.2.3 Mechanical Structure

Good mechanical design is a major key to have better performance of SMES systems. It is admitted that the maximum energy stored by a superconducting magnet is restricted by the strength of the mechanical structure (see Sect. 3.3). In order to contain the Lorentz forces causing significant stresses, it is essential to consider a vigorous structure. For this purpose, two techniques are envisioned. The first is to bury the magnet system in the ground. Thus, the rocks and the reinforcements will withstand all the efforts. In this case a rigid infrastructure is required. In the second technique, the magnet will support the forces via its cold structure. The support material may be a glass fiber reinforced epoxy that fits with cryogenic. The second method is widely used for SMES systems reaching an energy of the order of GJ. It appears to be a more economical technique.

2.3 Cryogenic Refrigerator

The temperature of the superconducting SMES coil should be kept low enough to maintain a superconducting state without any loss. A Cryogenic refrigerator is therefore indispensable. It contains compressor, cryostat, coolant, vacuum, enclosures, etc. Energy cannot be stored in a normal conductor because of the small resistance nature of the conductor. This resistance can be eliminated from the conductor by lowering its temperature. For this reason, coolant is used in the SMES system. On the basis of the coolant, SMES are subdivided into two sets. High Temperature (HTS) and Low Temperature (LTS) Superconductors. HTS are cooled at liquid nitrogen (LN_2) temperature of 77 K while LTS is generally cooled using liquid helium (LHe) at 4.2 K. As LN_2 is lower priced than LHe, so now all commercial SMES used currently LN_2 as a coolant. Also, LN_2 is higher operational temperature with supreme cooling effectiveness [17]. The current flowing in the coil is directly dependent on the coolant, and the power of cooling is proportionate to the operating temperature T and the room temperature T_{room} as $T/(T_{room} - T)$. The productivity of SMES directly depends on the accuracy and performance of the used coolant [18].

The maximum energy stored in the SMES is [19]:

$$E_{max} = \frac{1}{2}LI^2 = \frac{1}{2}NB_{sat}IS \tag{2}$$

in which L represents the inductance, I is the current flowing in the coil, N denotes the number of turns, S is the coil section and B the magnetic field. Based to (Eq. 2) the stored energy caused by ferromagnetic core is directly proportional to the induction of the coil and core.

2.4 Driving Circuit

The SMES also contains a protection system, which serves to shield the superconductor from damage, that may occur because of abrupt quench [20]. Figure 4 illustrates the equivalent electrical circuit of the SMES system. The main components of the SMES are transformer (converter), inverter, two DC connection capacitor, four switches and one varistor.

The transformer delivers DC power to charge the SMES, and the switches define the charging and discharging situations. SMES is being charged once switching Sw1 and Sw4 are shut and Sw2, Sw3 are unlocked. While during the discharging, Sw2 and Sw3 are locked whereas Sw1 and Sw4 are unlocked. The double DC link capacitors are intended for redressing at the output and input side. The varistor is used for overvoltage protection in SMES. The inverter is employed to supply power to the AC load [21, 22]. In this entire assembly the losses of power are within the transformer and switches, as all the settings are operating at extremely low temperature, so the resistance characteristic of the switches and transformer is lower than the normal value and the power loss is much less compared to normal operation.

As mentioned above by (Eq. 2), the maximum energy E_{max} is proportionate to the saturated magnetic field B_{sat}. The magnetic field strength and the proficiency of the superconducting coil depend on the quality factor Q that is expressed as follows:

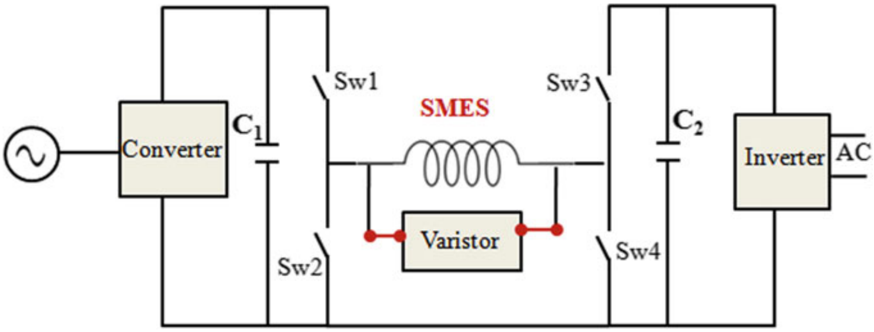

Fig. 4 Electric circuit of SMES

$$Q = 5 \times 10^3 \left(\frac{(E_{max})^2}{B_{max}} \right)^{0.33} \times \frac{1}{\left\{ \left(\frac{r}{a} - 1 \right) \left[\frac{r}{a} - \left(\frac{r^2}{a^2} - 1 \right)^{0.5} \right]^2 \right\}^{1/3}} \quad (3)$$

a and r denoted the minor and the major radius of the coil, respectively, and B_{max} is the maximum magnetic field. To avoid normal phase spread, which can drive an arc accident, the stored energy must be rapidly eliminated from the coils.

The power discharge time is specified in order to protect the error coil partition. Nevertheless, voltage reinforcement is necessary when the discharge time is very short. The current flowing throughout the coil can be rapidly minimized by introducing a discharge resistor in the circuit. It is firstly connected with the coil in series mode, whereas in normal functioning mode it is bypassed by a circuit breaker (CB). The protection signal renders the contacts of CB open, inserting a resistor into the circuit. The constant time is dependent on the inductance of the coil and the active resistance of the discharge resistor. More details on superconducting coil power supply system were given in Ref. [23].

2.5 Thermal Design and Protection

When designing a coil for SMES, the temperature should be assumed to be uniform and fixed. In practice, heat loss can be caused in several ways, raison for which the coil cannot be ideally protected. These losses can come from the radiation of the external surface of the cryostat, from the conduction across the mechanical support of the coil and from the current wires which are used for the electrical connection. On the other hand, losses by Joule effect can be created by the superconducting connection wires. The superconducting coil in turn generates operating heat when the conductor gets very close to its critical current. Thus, the design of the thermal system must meet two important criteria: a sufficiently low coil temperature, and a uniform and stable operating temperature.

On the other hand, a sudden extinction due to unexpected events must be taken into account. Passive or active protection of the coil against quenches is then necessary. The device must be equipped with a quench detection system.

2.5.1 LTS Magnet

Heat dissipation in LTS magnets is almost zero until transition. However, the specific heat of these materials at a very low temperature of around 4.2 K is highly inferior to at room temperature. Thus, the thermal inertia (the resistance of the material to the change of temperature when a disturbance of its thermal equilibrium occurs) is low and a quench can occur even following a small event (cosmic ray, vibration, etc.). To increase thermal inertia, a significant amount of conductive material such as copper alloys must be incorporated into LTS wires. This can ensure reliable operation with stable temperature.

LTS coils can provide intrinsic protection against quenches [24]. Indeed, because the thermal conductivity is excellent, the coil limits the temperature gradient in the conductor. In addition, the low thermal inertia favors a massive extinction of the coil, and the dissipation of the stored energy will take place throughout the volume of the coil. Thus, just a small rise in the average temperature is reported. However, the design constraints alongside to the giant size of the system make this intrinsic protection more difficult [25].

2.5.2 HTS Magnet

Unlike LTS magnets, dissipation in HTS magnets is not negligible and must be taken into consideration during design. If the cooling system cannot absorb these heat flows, the temperature will gradually increase, and the heat dissipation will slowly develop. This has the effect of causing a slow thermal runaway. Since the operating temperature is higher than for LTS, the temperature stability problem is more manageable. Indeed, in these materials the low thermal inertia does not cause a problem because the transition is not rigid and small events can be sustained.

In HTS magnets, the specific heat is high, and its propagation is very slow on the order of a few centimeters per second [26]. Heat dissipation will then take place in very limited volumes called hot spots. High mechanical stresses and strains can be generated in hot spots due to thermal expansion and the superconducting signature can be lost at very high temperature. Thus, protection against quenches for these HTS magnets is a major issue [27, 28] and active protection is required to reduce the maximum temperature of hot spots.

Two classic routes of active protection are considered [16]. The first is to avoid the creation of hot spots. To do this, the conductor must be heated at the start of a quench in order to promote dissipation of the energy stored over the entire volume of the coil. This method requires reinforcement by heating elements which must be in good thermal contact with the winding and having sufficient heating power which ensures rapid and uniform temperature growth. The second method consists of dissipation of the stored energy in an external load. In this case, the magnet must be discharged as soon as a quench occurs which requires a rapid discharge as well as a high discharge voltage.

2.6 Summary of the Main SMES Design Criteria

When designing an SMES system, the superconducting coil structure must have the best performance depending on the application for which the SMES will be used. The general objective, apart from the minimization of the production cost and the maximization of the discharge speed etc., is to abase the losses over the charges/discharges of the system.

The first step is to design a system so that the volume density of stored energy is maximum. A configuration for which the magnetic field inside the system is at all points as close as possible to its maximum value is then required. This value will be determined by the currents circulating in the superconducting materials.

Afterwards, the amount of superconductor to be used should be minimized as much as possible. This is imposed by the problem of the relatively high cost of superconducting materials compared to conventional copper conductors. It is advisable to carefully choose the superconductor to be used, ensuring the correct functioning of the system and minimizing the manufacturing costs. Looking for a favorable material by taking into account its cost, performance, manufacturing complication and accuracy remains a key challenge in the conception of SMES systems and it strongly related to the application features.

The last condition is to minimize as much as possible the electromagnetic pollution of the surrounding space caused by the system. Indeed, during the charges and discharges of the system, the variation of the induction will induce losses by eddy currents in the surrounding metal parts as well as losses in the cryostat. In addition, with the increasing requirements in terms of electromagnetic compatibility between the various devices, the minimization of magnetic leakage fields is today a key point in the design of SMES.

3 Fundamentals of SMES

3.1 Stored Energy

Biot-Savart's law postulates that an electric current flowing through a wire induces a magnetic field. The magnetic energy E_{mag} of a circuit is given by the following relation:

$$E_{mag} = \frac{1}{2}\iiint\limits_{space} BH dxdydz \tag{4}$$

where B is the magnetic flux density and H represents the magnetic field. A simplification of Eq. (4) is given by:

$$E_{mag} = \frac{1}{2}\iiint\limits_{space} \frac{B^2}{\mu_0\mu_r} dxdydz \tag{5}$$

with μ_0 is the vacuum permeability, μ_r is the relative permeability. Equation (5) can be interpreted as follow:

- The confinement of the magnetic field in a restricted volume (with the aim of limiting electromagnetic pollution for example) causes a decrease in the energy storage capacity since the integration is done over the entire volume.
- Generally, the energy is stored in the media for which μ_r is minimal. The use of magnetic materials does not bring improvement in the energy storage capacity, especially with their heavy mass.

It then turns out to be more adequate to analyze the energy storage in terms of inductance L which defines a coil. The stored energy can be written in terms of the current I and the inductance L as follows:

$$E_{mag} = \frac{1}{2} L I^2 \tag{6}$$

Noting that relation of Eq. (6) highlights the similarities with energy storage in capacitors defined by

$$E_{cap} = \frac{1}{2} C V^2 \tag{7}$$

where C and V denote the capacity the voltage, respectively. SMES and capacitors are the only energy storage technologies that can power an electrical circuit without resorting to energy conversion.

By relying on the first approximation of a superconducting winding which considers the material as purely inductive, the relation between the voltage of the circuit U and the inductance L will be given by the relation which follows:

$$U = L \frac{dI}{dt} \tag{8}$$

3.2 Relation Between Nominal Current and Inductance

For a winding with homogeneous current density J, the distribution of the magnetic field and consequently the stored energy are independent of the turns number and of the conductor section chosen for the winding. On the other hand, they depend on the value of J and on the geometry of the windings. For further explanation, let's take two windings having a 10 by 1 cm cross section, the first consists of 1 by 1 cm square conductor with 10 turns and the second is made of 1000 turns of 1 by 1 mm square conductor. These two windings have the same total magnetic energy and the same value of J, but they have different inductances and nominal currents. According to Eq. (6) and for a given energy, the inductance undergoes an evolution inversely proportional to the square of the nominal current. To protect a superconducting magnet during sudden extinction, rapid discharge is required. Thus, an adequate choice of the rated current must be taken into consideration to provide such a discharge. The voltage across a superconducting magnet, considered as a perfect inductance, is given by Eq. (8). From Eqs. (5) and (8), it is apparent that a faster discharge of the magnet can be obtained if its rated current is higher, or in other words its inductance is lower. However, achieving a high current source remains difficult.

3.3 Mechanical Constraints

Any portion of a conductor of length dl, which transports a current I and subjected to a magnetic field B, is then subjected to a Laplace force $\overrightarrow{F}_L$ (see Eq. (9)); whose volume density in a winding is defined by the vector product of the current density J and the local field B as expressed by Eq. (10).

$$d\overrightarrow{F}_L = I\overrightarrow{dl} \wedge \overrightarrow{B} \tag{9}$$

$$\frac{d\overrightarrow{F}_L}{dV} = \overrightarrow{J} \wedge \overrightarrow{B} \tag{10}$$

The conductor must then be able to withstand these forces induced by the magnetic flux. By relying on the fact that the Laplace force is zero if the magnetic flux density and the circulating current are oriented in the same direction, it is convenient to create coils without force, thus avoiding the problem of mechanical structure. To achieve this, a well-suited geometry of the coil must be taken into consideration.

3.3.1 The Virial Theorem

A system that induces a magnetic field is necessarily subjected to mechanical stresses. The virial law can govern the maximum energy density in an SMES system from a mechanical point of view. From this theorem, a theoretical determination of the minimum amount of material needed for storing a given energy is possible. The Lorentz force, created in a magnet following the interaction between the operating current and the magnetic field, will produce a tensile stress on the conductor. The stress present in the body of a non-ferromagnetic system and the energy stored within it are related by the following relation [19, 29]:

$$\int_{Body} Tr(T_\sigma)dV = \int_{space} \frac{B^2}{2\mu_0}dV = E_{mag} \tag{11}$$

with $Tr(T_\sigma)$ is the trace of the stress tensor. It is clear that the magnetic energy stored by the system and the integral of the stress on its body are proportional. This equation needs to have a more simplified form to understand its physical meaning. Therefore, the new equation can be established by considering that the absolute value of the stress is equal to σ and by neglecting the components of compression and tension of the stress tensor. Equation (11) is then rewritten as:

$$\sigma(V_T - V_C) = E_{mag} \tag{12}$$

where V_T represents the volume of the body in tension while V_C is its volume when it is in compression. Equation (12) means that the majority of the body of an energy storing system is in traction. In addition, it shows that the stress of a body with a given volume is proportional to the system energy.

Considering a hypothetical geometry in which only one tensile stress is present, the optimal energy per volume ratio is given by

$$\sigma = \frac{E}{V_{optim}} \tag{13}$$

This relation allows to estimate the absolute limit of the energy stored by an inductive storage system [19].

Let us denote by ρ the density of the system body, Eq. (12) can be written in the following form:

$$\frac{\sigma}{\rho} = \frac{E_{mag}}{M_T - M_C} \tag{14}$$

where M_T is the mass of the body in tension and M_C is its mass when it is in compression. Note that the stress distribution is affected by the topology of the system. This dependence allows to write this relation:

$$k\frac{\sigma}{\rho} = \frac{E_{mag}}{M_{total}} \tag{15}$$

where k is a positive coefficient such that $k < 1$ and M_{total} denotes the total mass of the body. In the ideal case, where the entire body is uniformly subjected to a tensile stress equal to σ, k reaches its limit called virial limit, i.e., $k = 1$. According to Eq. (15) the maximum specific energy depends on three parameters: (i) the system geometry, (ii) the maximum admissible stress and (iii) the average density of the body.

The analytical calculation of the value of *k* for some topologies was then possible. For example, it has been shown that *k* ranged from 1/3 for longer thin solenoids to 1/1.62 for very shorter thin solenoids [19, 30]. Another study on a thin-walled toroid shows that *k* is less than or equal to 1/3 [31]. From these results, a solenoid is then more suitable compared to a toroid to achieve a highly specific energy. Furthermore, a study carried out on a comparison between thick-walled and thin-walled solenoids shows that *k* is lower if the walls are thicker because the stress is no longer uniform in this case [30].

3.3.2 Mechanical Limits

According to the virial law, an important factor must be taken into account in the SMES conception which is the mechanical stability. The conductive material, the insulating materials and the mechanical support must be sufficiently resistant to the tensile stress which takes place within the magnet. Thus, the mechanical support material should be chosen with care during the winding process. As a consequence of the virial law given by (Eq. 13), optimum coil design should meet to two characteristics:

- The coil should be designed to keep the volume subjected to compressive stress to a minimum as much as possible. This comes down to the fact that energy is only actually stored by the winding sections subjected to tensile stress.
- The conductor should work as close to its mechanical limits as possible and its resistance should be extremely high. In the case of a uniform conductor, the tensile stress to which it is subjected must also be uniform. Otherwise, a reinforcement can be added.

3.3.3 Nature of the Stored Energy in SMES Systems

According to the virial theorem, the generated magnetic field induces a stress inside the system body. A question on the nature of the energy stored by the system (magnetic or elastic) is then asked. Since the body of a coil under tension is stiff and relying on the fact that the elastic energy stored by a system under elastic stress is inversely proportional to the stiffness of the material, the elastic energy stored by the coil is very low. Therefore, the elastic energy in the coil is insignificant in comparison with the magnetic energy.

3.4 Parameters Affecting SMES Technology

Power exchange between the storage system and the grid is controlled by a set of solid-state power converters (PCS). Additional processes as cooling and control are required for proper functioning of the system. It is to note that, such system is affected by some parameters ensuring its better functioning. The main ones are (i) the maximum power P or the charge–discharge rate; (ii) the number of cycles N performed during the lifetime; (iii) the system response time t_r, and (iv) the duration of the power delivery, Δt.

Rapid discharges cause AC losses which can cause quenches if they exceed the available cooling power. Necessarily, a minimum amount of energy E_m always have to exist in the storage device. Thus, the rated energy E is expressed by:

$$E = E_m + P\Delta t \tag{16}$$

and the storage system efficiency in one cycle is given by:

$$\eta = \frac{P\Delta t}{\frac{P\Delta t}{\eta_s \eta_c} + P_{loss}\Delta t_{loss} + P_{sup}\Delta t_{cycle}} \tag{17}$$

where η_c is the converters efficiency while η_s is the storage device round trip efficiency. P_{sup} denotes the power needed for supplied services and P_{loss} is the power loss over the idling phase.

According to this equation, supplied and idling losses must be low to provide long-term storage efficiency. On another side, this efficiency can reduce if the SMES operates with minimized input/output power during long cycles. Some solutions were then proposed to reduce these losses such as the use of cables composed by transposed conductors, optimization of the cooling system and cryostat for the reduction of eddy losses, etc.

Alongside losses, the maximum power of SMES have other limitations related to current and voltage. It is well known that the product of the maximum current of an SMES by the maximum voltage that it can withstand defines its maximum power. In an SMES, the maximum operating current is related to the design of the coil which in turn is limited by mechanical stress. On another side, the voltage imposed by the load impedance must not exceed the breakdown voltage of the insulating layers which protect the conductive parts. However, high voltage isolation complicates the coil cooling process, and, in this case, a more powerful cooling system is required. To have a high power SMES, the energy density must be low especially when operating temperatures below 50 K are considered.

Likewise, the leakage magnetic field must necessarily be reduced, especially in the case of a solenoid-shaped magnet. In the case of a toroid, the leakage field is self-constrained by the magnet. Such a field causes serious dangers both for engineers handling and for electronic devices. SMES systems must meet safety and health regulations. An accurate calculation of the leakage field must then be provided.

4 Development of Superconducting Magnetic Energy Storage System (SMES)

4.1 LTS Based SMES

The first SEMS, designed in 1963, was based on a low-temperature superconducting material (LTS). At that time, this design has faced some structural complications. Indeed, this type of system is designed for an energy storage of more than 5000 MWh [32]. The coils are then so large. Thus, to provide a strong mechanical structure which can withstand giant electromagnetic forces, the use of underground rocks has been proposed. Since then, research has focused mainly on the study of design and cost analysis. The charging and discharging of LTS-SMES was first demonstrated in 1971. This gain allowed the design and development of SEMS for useful applications achieved in 1979. The SEMS system design was intended to suppress the low-frequency oscillations of the American Western Power System by Los Alamos National Laboratory (LANL) in the USA, and was first installed commercially in 1981. Subsequently, American Super Conductor (ASC) began developing and marketing various SMES for various commercial uses which led to global research to enhance SMES quality at reasonable cost. To effectively compete with the other energy storage systems (EES), SMES must be cost-effective (initial costs and lower lifetime costs). Compared to the other ESS, SMES displays high cyclic productivity exceeding 90%, high power density, rapid response time and indefinite discharging and charging cycles. SMES has been developed worldwide at three levels: small scale (kJ), medium scale (MJ) and large scale (GJ). Japan has developed numerous MJ and KJ class LTS-SMES only for voltage flabbiness and immediate voltage stability respectively [33, 34]. China also developed MJ and KJ class SMES to enhance the stability of the voltage [35–37] and energy fluctuation compensation [38, 39]. Korea developed SMES to improve the quality and the stability of the power system [40, 41] and to regulate the synchronization of smart micro power grid [5, 42]. India developed LTS-SMES. For example, the Indian Institute of Technology Kharagpur has fabricated an SMES/UPS with a capacity of 0.5 MJ, that is able to deliver few kilowatts of power for breaks of few seconds. The Variable Cyclotron Centre (VECC) in India designed 0.6 MJ SMES for the purpose of voltage compensation [43]. Other countries such as Australia, Germany and France have manufactured SMES principally for voltage stabilization and pulse energy source for sensitive load [43].

4.2 HTS Based SMES

The discovery, in 1986, of high-temperature superconductors (HTS) led to a main advance in SMES devices, letting the construction of magnets able to support high critical currents densities and fields, at higher operating temperatures. Thus, making these materials into practical conductors was the major goal. Since the critical transition temperatures in HTS surpass 90 K, it became possible to work SMES components at temperature range of 20–30 K, with a much wider temperature margin compared with LTS cases. To reduce the refrigeration load during operation, SMES technology has introduced HTS, mainly BSCCO and REBCO tapes. Thanks to the exceptional high field properties possessed by HTS, the capacities of SMES has greatly improved giving rise to GJ class SMES using second generation YBCO.

4.2.1 First-Generation (1G) HTS for SMES

The primary HTS based SMES based on projects utilized first-generation (1G) materials, consist essentially of bismuth-based superconductors, with two structures: Bi-2212 and Bi-2223. Bi-2212 is a very versatile material and have the advantage to be fabricated into wires, bulks, and rods. Round wires devoid of anisotropic features like LTS materials are also possible with Bi-2212. The first practical use of this material dates back to 1990. At that time, its current-carrying capacity was very low in an external field, reason for that it not widely exploited in HTS magnet. However, the advancement on this material in the last years make it more desired for high field magnet applications, especially SMES devices, than NbTi and Nb_3Sn [44]. Bi-2223 was another kind of HTS which has been made into practically used wires. Relying on the powder-in-tube process, it has been successfully made into tapes with high aspect ratio. The disadvantage of this material over LTS and Bi-2212 is its anisotropic character which makes the design of the magnet some difficult because of the propagation of the fields in different directions. These two HTS magnets have experienced different uses for SMES. One of the first SMES (5 kJ) using BSCCO-2223 conductors was built in 1997 by American Superconductor. The solenoid shape was adopted for this magnet and the system was capable to operate at 25 K [45]. A 150 kJ SMES based on Bi-2223 bands was developed by ACCEL Instruments and supported by the German Ministry of Education and Research. This system can operate at 20 K relying on a cryostat free of cryogen. It may be used as an uninterruptible power supply and furnish a power of 20 kVA [46]. In France, the National Center for Scientific Research has developed an SMES unit using Bi-2212 wires which operates at 20 K and have the potential to store 814 kJ of energy [47]. This system has been designed to offer wide pulsed power for rail gun applications. Other SMES has been also developed like a 600 kJ SMES based on Bi-2223 conceived by the Electrical Research Institute in Korea [5] and the 1 MJ SMES Bi-2212 proposed by Chubu Electric Power Corporation [48].

4.2.2 Second-Generation (2G) HTS for SMES

Recently, researchers introduced the second generation (2G) HTS to improve the skills of SMES systems. These materials are rare earth element copper ReBaCuO (Re = Y, Sm, Gd). They have a multilayered structure completely different from all other superconductors. Compared with 1G HTS, the 2G materials can maintain higher critical currents in analogous external magnetic fields, thus enhancing the SMES systems quality. As the 2G HTS tape manufacturing technologies are not yet mature, a few small size units have been made including a 4 kJ YBCO magnet [49] and a 93 J GdBCO unit [50]. Concept designs for larger 2G HTS SMES modules have been suggested in many publications, ranging from a 90 kJ YBCO module to improve photoelectric transient performance [51], a 5 MJ YBCO module to compensate for voltage drop [52] and up to a 2.4 GJ toroidal YBCO module to compensate for fluctuation load [53]. Recently Japan and China have designed kJ SMES for the stabilization of the power fluctuation of micro grid and wind generator. China developed, through the National Natural Science Foundation, 100 kJ SMES with a conduction cooling system to function at 20 k to dampen the power fluctuation of a small 25 MW grid [54]. A conduction-cooled HTS hybrid magnet is developed for a 150 kJ SMES system. This system is composed by twin pancake coils using 1G BSCCO at the top and the bottom and 2G YBCO tapes at the middle part to enhance the technical functioning and cost efficiency [55]. Contrariwise, a collaboration between China Electric Power Research Institute, University of Cambridge and University of Bath allowed the design of 6 kJ SMES with BSCCO 1G coils sited in middle, and YBCO 2G coils sited in the top and the bottom sections of solenoid coil. Such arrangement allowed the passage of high operating current and dealing with high vertically magnetic field at the top and bottom parts of the solenoid [56]. The operating temperature of this system ranges between 65 and 77 K relying on subcooled liquid nitrogen and it has been proven to deliver better quality energy and dampen power oscillations in a very short period. On other side, a hybrid energy storage system has been developed with YBCO tapes based SMES combined with batteries [57]. In this structure, the batteries have the role of regulating the low frequency components and increasing their lifetime. While the SMES is used in order to compensate the high frequency fluctuations thanks to their ultra-fast response. This kind of system finds potential applications in electric vehicles and renewable energies. The design of a 60 kJ SMES using YBCO bands and its simulation for a 10 kW wave energy converter provided a remarkable increase in battery life [58, 59]. A prototype of a 2 kJ SMES-battery hybrid system is also proposed for a micro-grid use and subsequently for renewable energy integration [57].

4.3 MgB_2 Compound for SMES

MgB_2 compound has experienced a continuous increase in the critical current density which explains the success of devices based on MgB_2 magnets of small size. It has been used several times thanks to its critical temperature which is around 39 K. For that reason, MgB_2 have also been contemplated for SMES systems which can operate at 20 K reached by the liquid hydrogen. For instance, an SMES system was developed by The High Energy Accelerator Research Organization in Japan by adopting liquid hydrogen for cryogenics [60]. It is designed to fill the electricity deficit in hospitals. Another 48GJ SMES with similar design based on MgB_2 materials was also suggested by Karlsruhe Institute of Technology [61]. On the other hand, Atomura et al. [62] proposed a design of a 100 MJ MgB_2 SMES in order to stabilize the fluctuations of renewable energies, namely wind turbines and photovoltaics. A hybrid energy storage system is considered in this design. It is a combination of a fuel cell electrolyzer (FC-H2-EL) and an MgB_2 PME with a storage capacity of 100 MJ. This SMES is part of an advanced superconducting energy conditioning system.

5 Advantages and Drawbacks of SMES

Several advantages have been attributed to SMES but the most interesting one is related to the speed of operation. SMES features a high efficiency of charging and discharging (>95%) since no conversion of the electric energy from or to different forms is associated. As a consequence, a rapid response within seconds is achieved for SMES [7] making them suitable for power quality applications [63, 64]. Power is almost instantly available and extremely high output power can be provided for an extremely short delay. Compared to other energy storage systems equivalent in terms of the amount of storage like Compressed Air Energy Storage (CAES) or Pumped Storage hydropower (PHS), this short time response constitutes an excellent advantage in the event of an accidental failure of the power grid where the SMES can react more quickly. Therefore, SMES present promising alternative in case of immediate demand. This type of system can also be used to enhance the stability of the power grid. In addition, SMES results in less power loss compared to other storing systems since electric currents experience negligible resistance. Unlike batteries, this storage system based on superconducting materials is preferred for the environment because no chemical reaction is necessary and thus have little environmental impact [65]. SMES are also able to improve the capacity and performance of the transmission line thanks to their extremely high energy recovery rate and significant dynamic range. An SMES is then a real key for non-interruptible power supplies or certain FACTS (Flexible AC Transmission System) in order to improve the operation of electrical grids. It provides clear benefits in terms of productivity, lightness and congestion; it is the smallest system that has seen commercial success, especially for energy conditioning. In this context, several SMES, especially those based on conventional superconductors, have proven their efficiency and operational capabilities for powers in the megawatt range with very short duration. They are exploited as non-interruptible source for sensitive loads or to stabilize certain electrical grids. The obtained results are generally satisfactory, but the high cost of SMES as well as the competition with other more mature technologies face the development of this system.

Economically seen, the use of low temperature (LTS) or high temperature (HTS) superconductors explains the difference in cost since the cryogenic system represents 15% of the total cost of SMES. Indeed, when the SMES was invented, the price of HTS was higher than that of LTS because technical advances in the field were not yet sufficient. But with the technical developments, research was focused on HTS technology accessible by cooling with liquid nitrogen as an alternative to the expensive liquid hydrogen. Thus, the use of HTS will reduce the refrigeration required and, consequently, the operating cost of this energy storage system [9]. However, since the costs of HTS material remain high, they cannot yet bring satisfactory reductions in the total cost of SMES and they are still far from being economically viable. For instance, when compared to the 1G HTS wire (PIT, Powder-In-Tube, using BSCCO superconductor), the cost of NbTi is more lower by approximately two orders of magnitude. Thus, HTS conductors require additional research and development. Despite of all, this does not prevent that such materials make SMES more attractive because they show a remarkable improvement in energy density with much less restrictive cryogenic conditions reaching temperatures in the order of − 253 °C [66]. Therefore, the need of cooling is the main drawback of SMES that implies permanent power consumption and high cost when LTS are used. Another limit is that high power necessarily requires relevant electrical insulation and high currents. However, the production of very high current remains difficult. Because of this disadvantage, SMES technology is currently exploited for short duration energy storage.

6 Comparison with Other Energy Storage Systems

Currently, there are different types of energy storage technologies (electrochemical, mechanical, thermal, magnetic) that are in serious competition. The SMES is an inductive device. We have chosen to compare this system with two other energy storage technologies: the flywheels that share it the same nature and the supercapacitors of a capacitive nature which appear to be the most competitive technology for SMES.

6.1 Comparison with Flywheels

The specific mass energy of the two systems, SMES and flywheel, is fundamentally limited by the virial theorem. They then have comparable specific energies. However, for the energy conversion process (from mechanical energy into electrical energy), the flywheel must be equipped with a generator whose size depends on the nominal power required. This operation is never necessary in the case of SMES because the electric energy is directly stored in a magnetic field. In addition, the flywheel must also be fitted with a reinforced housing in order to protect the system against breakage. The large sizing of these two elements, generator, and reinforced housing, are added to the mass and to the overall system volume resulting in degraded energy and power densities. The SMES, in turn, needs a cooling system as well as a conditioning system whose dimensions are also important. Nevertheless, the SMES seems safer than a flywheel.

6.2 Comparison with Supercapacitors

SMES are characterized by higher specific mass and volume energy than supercapacitor banks. In the case where the thickness of the coil is neglected and the magnetic field B is assumed to be homogeneous, the volume energy E_ν of an SMES system can be estimated by the following relation:

$$E_\nu = \frac{B^2}{2\mu_0} \tag{18}$$

From this equation, a volume specific energy of 40 MJ/m^3 can be achieved with a magnetic field B of 10 T. In addition, HTS conductors provide the opportunity to have magnetic fields that can reach 20 T at low temperatures which corresponds to a volume specific energy of MJ/m^3. The volume specific energy of supercapacitor banks, however, is around 1 MJ/m^3. It should be noted that the SMES is an inductive system whereas the high-power capacitor banks are capacitive. Thus, SMES are designated for more specific applications such as electromagnetic launchers [67]. If not, they must be equipped with a suited power conditioning system to transmit the stored energy [68].

6.3 Further Comparison

A detailed comparison of the three energy storage technologies through relevant metrics like response time, power density, round-trip efficiency and cost in terms of both power and energy is given in the following paragraph and recapitulated in Table 1 [57].

Response time: The fastest response times are attributed to SMES and supercapacitors. This is due to the fact that in these systems the stored electrical energy can be supplied directly without energy conversion. Flywheels, however, have a longer response time due to the time lost in the mechanical conversion of energy.

Table 1 Comparison between SMES, supercapacitors and flywheels

	SMES	Supercapacitors	Flywheels
Relative response time (%)	0.1–1	0.1–1	1–10
Life time (years)	20	20	20
Self discharge (% day)	10–15	2–40	20–100
Power cost (€/kW)	100–400	100–400	100–300
Energy cost (€/kW)	700–7000	300–4000	100–3500

Data were collected from Ref. [57]

Power density: Compared to flywheels and supercapacitors, SMES have a considerably high-power density which is limited by the current flowing in the magnet as well as the voltage of the winding insulation.

Lifetime: The three technologies considered have practically the same lifetime. For the SMES system, there is a slight degradation of materials for each operational cycle which makes their lifetime very long.

Round-trip efficiency: Since the losses related to the charge/discharge process of the SMES are very low, their cyclic efficiency is the highest in comparison with the other energy storage technologies. This is because most of the losses come from semiconductor switches.

It is clear that SMES systems are endowed by rapid response time, long lifetime, large power density and high cyclic efficiency allowing them to be prime candidates for power dense applications. However, this technology appears more expensive with respect to energy when compared to flywheel and supercapacitor systems.

7 Challenges and Future Developments

Since the built of the 10 MVA/30 MJ Nb–Ti SMES system in 1983 whose effectiveness was confirmed by successful laboratory tests [69], a lot of other prototypes designed for power quality applications have been constructed worldwide. These systems exhibit a rated power ranging between 0.1 and 10 MW and supplied energy around 0.2–10 MJ, [70, 71]. For instance, a typical micro-SMES unit providing a storage capacity of 3 MJ (0.83 kWh) and able to deliver 3 MW of power for 1 s is commercially available today. As an advancement, these small units can be placed in a container to facilitate its deployment. They are then used in industrial operations requiring high-quality power. Another prospect in this sector is to integrate larger superconducting coils that can maintain the stability of the generation system. These new systems are expected to have outputs 10 times greater than the power supplied by the mico-SMES [72]. Thus, the development of these large systems will compete with batteries in energy storage. The future advancement of SMES system strongly depends on the maturity of superconducting materials technology in terms of their critical temperature, prices and properties. The ultimate goal is then to discover superconductors at room temperature. Although that SMES has been found to be a promising energy storage technology offering fast response time and high efficiency, it has some disadvantages mainly related to the cryogenic technology and high cost and posing challenges to research.

7.1 HTS Conductors, Cost, and Refrigeration Issue

Despite that the development of HTS materials helped to reduce the operating cost of the cryogenic refrigerator, the cost of the SMES system does not reduce significantly since the refrigeration process is only a part of the whole arrangement. Therefore, this slight reduction is not sufficient to compete with alternative technologies. However, compared to LTS which operate at about 4 K, Carnot efficiency rises by a factor of 5.3 and 14.8 when it comes to 20 and 50 K operations respectively. Over the last decade, the research on SMES based on HTS has seen an interesting progression. SMES prototypes based on Bi-2212 and Bi-2223 conductors have been developed. They showed a rated energy of about 0.6–1.0 MJ. In this study a 4.2 K operating temperature has been chosen [71, 73]. In case of special demand, such system can be carried out with operating temperature of 20 K [74]. However, as mentioned previously, the cost of the superconductor materials constitutes a real barrier to the development of SMES based1G HTS conductors that operate at about 20 K like Powder-In-Tube (PIT), using BISSCO superconductor. It remains also two orders of magnitude higher than the classical NbTi conductor cost. Additional efforts were devoted in order to reduce the cost in the near future by using 2G HTS wires, such as the Coated Conductor (CC) [75–77], that is expected to provide savings for SMES. These generation is estimated to operate at 50–60 K for SMES magnetic flux densities of a few Teslas. Currently, CC technology is showing rapid advancement and a CC with several hundred meters in length is available now and more of kilometers in length are in production. Research studying SMES based on YBCO-coated conductors with high field and high energy density are in progress [71, 73, 78]. Recently, a design of an SMES device with 100 MW/2GJ characteristics exploiting high-performance YBCO tape that operate at 20 K to 11 T have been established [78]. The challenge now is to achieve a SMES of 20 kW/3.2 MJ based on YBCO which operate at 4.2 K to 25 T. Other projects are focused on carrying out SMES with the MgB_2 compound which is less expensive than YBCO. This system is expected to operate at 20 K relying on liquid hydrogen technology [61, 79]. Nevertheless, MgB_2 have lower critical field resulting in a limited volume energy density which need larger windings and more cryogenic requirements.

In the future, additional advantages, other to those associated with cryogenics, can be reached. The high operating temperatures may bring more stability to the

HTS magnet, making it more resistant to external disturbances. Indeed, the increase in temperature causes a significant increase in specific heat. On the other hand, the high temperature causes the electrical insulation to be thicker, thus promoting an improvement in power by adopting a higher operating voltage. In addition, the allowable temperature difference between the conductor and the cold source ΔT, mainly caused by AC losses during charges and discharges, can also be increased. This difference is related to the AC loss and the thickness of the insulation d_i, by the following relation:

$$d_i = \lambda \frac{\Delta T}{AC_{loss}} \tag{19}$$

in which λ is the thermal conductivity of the insulation. The problem lies in providing good protection of the magnet at high temperature. Indeed, the high temperature favors too long quench causing remarkable damage.

If the cost of the refrigeration process is eliminated by using a room temperature (or near room temperature) superconductor material, other technical challenges toward SMES must be taken into consideration.

7.2 Protection

A superconducting magnet enable to store a great amount of energy which can be liberated in a short duration. In addition, the power is hugely high that can reach 100 MW/kg and massive magnetic field are involved. Therefore, special precaution and an excellent isolation should be available mainly in case of a coil failure or an accidental loss of coolant. In such event, the fast release of the energy will damage the coil and the surrounding system. Assumptions have been put forward to overcome this problem which mainly consist in equipping the SMES system with a superconducting cable allowing to absorb the energy after coil failure [80].

7.3 Precooling Time

Because of the extremely low operating temperature of a SMES (4.2 K), superconducting magnet takes four months, until now, to be cooled from room temperature to operating temperature. Thus, after maintenance or in case of outage and even an emergency energy release, the system needs the same period of time to be recovered. This outcome is strongly linked to the improvement of the critical temperature of superconducting materials. In other words, this time problem can be solved if the design of HTS based SMES that work at temperature is successfully completed.

7.4 Size and Infrastructure

To ensure sufficient and commercially useful energy storage of about 5 GWh (3.6 TJ) (600 m), an SMES center necessarily requires a loop of about 0.5 mile to be properly installed while respecting all the requirements. This large area of land must necessarily be confined in a vacuum flask of liquid nitrogen essential for the cooling process. Thus, a very stable support must be founded by burying the installation and kept underground [63], adding to the expense of the system. This infrastructure problem will no longer be posed if superconducting materials at room temperature are involved.

7.5 Challenge Related to Integration with Renewables and Hybrid EES

It is well known that SMES systems are characterized by a strong potential allowing the support of the renewable systems integrated in distributed production grids. However, further study of the behavior of such systems in the long term is still lacking. The study of the commercial, technical, and regulatory aspects of the application of SMES is essential because it allows to better understand and develop this technology. The use of liquid hydrogen (LH_2) fuel in renewable technologies would unleash the potential of SMES. Indeed, LH_2 storage tanks can be considered in order to maintain the SMES coils under very precise transition temperatures, which leads to a significant reduction in the operating cost and a prospect towards hybrid systems [61].

Creating hybrid EES is a key point to improve their performance and analyze the optimal operational scenario. A complete hybrid system can be created by combining an SMES with high energy density technologies as a complement (because SMES has a low energy density). The applications of this system span a wider range including shaving and voltage stability, power management and quality control [81]. This new approach has the advantage of reducing the cost of EES. For example, a hybrid ESS with an SMES and a pumped hydro energy storage brings a reduction of more than 90% in cost compared to a single SMES having the same energy storage capacity [82]. The design of these systems has already been developed and they are used in transportation to provide impulses by storing braking energy [83].

8 Applications of SMES

Load imbalance in electrical systems is inherent because of the random fluctuations in loads induced either by customers or by unstable production from renewable sources. This causes oscillations of frequencies which can cause serious damage in the event of a delay in compensation. To overcome this problem, persistent and rapid control of the generated power loads is therefore essential. SMES systems represent a potential route to minimize load imbalance and ensure the efficiency of the electrical system. The customer, in turn, can benefit from appropriated power quality and power absorption smoothing of impulse loads by using SMES. Thanks to their power deliverable, energy density and efficiency, very rapid response time, and practically high/unlimited number of cycles, SMES have found a wide range of applications. These characteristics make it well appropriated for frequency regulation, power quality control, and pulsed power supply. Noting that, until now, only SMES exhibiting small storage capacities are commercially available and they found a great success. They have been in use for several years in order to enhance industrial power performance and to give a satisfactory service for individual customers exposed to voltage fluctuations. However, large-scale applications remain in the experimental phase and require large monetary investments [84].

8.1 Frequency Regulation

The net load of a power system is defined as the difference between the power absorbed by all customers and the produced power from renewable sources. This has the effect of continuously fluctuating the net load over a time scale of tens of seconds or minutes [85]. Such fluctuations, usually in order of several tens of megawatt, will disturb the frequency and therefore cause an instability of the system. SMES system can compensate the load mismatch owing its rapid response time and its great number of cycles. It provides a reliable frequency regulation as it is capable to deliver tens of megawatts with a response time in the order of seconds. Moreover, SMES is also used as spinning reserve in order to balance the frequency. Indeed, it can reserve an additional capacity which will be used in case of need, i.e., in case of electrical network failures or if a significant grid of transmission lines is out of service.

8.2 Uninterruptible Power Supply (UPS)

Unexpected voltage disturbances can take place either as prolonged and repetitive phenomena or occasionally. Certain applications such as data centers, industrial plants, etc. are unable to support voltage disturbance for more than few milliseconds, hence they need continuously available power supplies with fast response to avoid a lot of problems that can affect customers in terms of malfunctions, lack of production, or security concerns. SMES-based UPSs can provide this compensation due to their dynamic capabilities and long-term lifecycle. They have received a much interest since they can instantly provide the necessary power requested and ensure a continuous operation of systems [86]. Military and research laboratory applications as well as other applications requiring extremely clean power for sensitive treatments have benefited greatly from these SMES-based UPS devices which are mainly provided by American Superconductor company. It reported an accumulation of more than 35 unit-years of operation.

8.3 Flexible AC Transmission System (FACTS)

FACTS is a stationary device which can be installed in the power grid in order to improve the controllability and the power transfer capability. SMES systems are widely used as FACTS devices. The first superconducting application has been implemented in 1980 by the Bonneville Power Authority in U.S.A to attenuate the low frequency [80, 87]. This device has successfully operated over a year with 1200 h of energy transfer which corresponds to 10^6 cycles for the magnet. In this device, the refrigerator and the power converter constitute the major problems in the operation of SMES and no other problems have been encountered at the level of the cryostat or the magnet. Thereafter, SMES systems using FACTS devices will act as a system stabilizer. For instance, six SMES-based FACTS units have been installed at at different key locations in the northern Winston in 2000 to improve the stability of the electrical grid. They increased the voltage by providing reactive power in the grid. Electricity transmission capacities have also been improved by 15%. Each SME has the capacity to continuously supply 2.8 Mvar and 2 MW for a short period. Furthermore, such devices are also exploited in renewable energy technologies such as wind generator [80].

8.4 Electromagnetic Launchers

Electromagnetic launchers for military or civilian purposes, requiring pulsed energy sources, also offer other opportunities for SMES. This device is an electric weapon capable of accelerating projectiles to extremely high speeds. To benefit from a better functioning of these rockets, high power pulse sources are essential. SMES as fast releasers of stored energy with high power density provide a potential energy storage device for creating high performance electromagnetic launchers [80].

8.5 Load Leveling

The quantity of electrical energy required, whether commercially or residentially, fluctuates significantly during the day and throughout the seasons. Energy stability is determined by the difference between the amount of energy consumed and that generated. The role of the SMES system is to store energy when the power generated exceeds the demands [86, 88]. This energy will be released to compensate for power fluctuations during high demands. In this way, conventional production units can operate more conveniently and efficiently at constant output. In the event of a persistent imbalance between supply and demand, the SMES may be totally discharged.

8.6 Circuit Breaker Reclosing

Electrical networks are generally equipped with conventional circuit breakers which are used to close and put the transmission line back into service after an accidental failure. This operation is performed whenever the power angle difference across the circuit breaker reaches a certain limit. Otherwise, i.e., the power angle difference is too great exceeding the imposed limit, the protection relays prevent the circuit breakers from reclosing. In this situation, SMES systems can intervene to diminish the power angle difference across a circuit breaker. They will provide a portion of the power normally transmitted by the transmission line allowing the circuit breaker to be reset. Rapid restoration of system power is then provided during severe transmission line failures [86, 88].

8.7 Microgrid and Electrical Vehicle

The main purpose of microgrid sources is to serve energy to rural areas. The best-known sources are fuel cell (FC), solar photovoltaic (PV) systems, wind power systems and diesel generators. However, these technologies encounter certain problems related to intermittent power outputs which generate system instability. SMES appears to be an appropriate solution to confront stability problems. The results obtained depend on the reliability of the SMES used [89]. The energy stored in the superconducting coil will be exchanged through the DC-DC converter and the DC-AC inverter. To ensure a better self-switching capacity, the SMES is connected to a voltage source converter. This technique will make it possible to reduce the disturbances affecting the micro-grid. Consequently, a microgrid benefits from an improvement in the quality of the power supply and the voltage if an SMES is associated with it [46].

Electric vehicles will be the future of the transportation area. These require significant load requirements. Indeed, load fluctuations are possible in electric vehicles caused by their sudden power load. These fluctuations, in turn, will cause harmonics in the system. Intermittent powering of photovoltaic and wind power systems makes the situation more serious if the sudden power load is connected to a microgrid. Minimizing harmonics and compensating for the difference between intermittent electricity from renewable sources and electric vehicles are therefore essential. The microgrid system with SMES works much better and allows harmonics to be reduced.

In addition, the introduction of SMES can keep the charging voltage constant and dampen the circulating currents [14].

Noting that new SMES designs such as 10 kJ class SMES, high-filed HTS SMES coil or 200 kJ 2G HTS solenoidal SMES coil were recently studied [13, 90]. These new designs provide further opportunities for SMES that can be used in mitigating wind energy system fluctuations, voltage harmonics and other perspectives are offered [82, 91–93]. In China, superconducting plants have already been installed and are in operation [94]. It is expected that, in the near future, SMES will be found in space shuttles, satellite systems and also in medicine area.

9 Different SMES Scales: Some Examples

9.1 Large Scale SMES

The power scale required for an ESS to be able to balance the load in the electricity distribution grid is in the range of GW. For this reason, the SMES were not entrusted to fulfill this role. Indeed, this application requires a gigantic dimension (about 1 km in diameter) of superconducting magnets. The construction of such a magnet encounters certain problems related to the cryogenics, the mechanical structure and the quantity of the conductor to be used. The mechanical structure must be sufficiently robust so that it can withstand the weight of the magnet and the components of the large Lorentz forces: the radial component which tends to extend the coil and the axial component which is symmetric with respect to the vertical line central.

The design of a large SMES system with a capacity of 1000 MW was developed in 1987 in the United States but its construction has not been carried out until now. This SMES must meet certain specific parameters such as its size which corresponds to a diameter of 1 km and a height of 19 m. It should operate at a temperature of 1.8 K with an operating current of 200 K and a magnetic field of 5.18 T. The energy storage capacity of this system is 18.9 TJ. Further characteristics are found in [12, 95].

9.2 Medium Scale SMES

In 1987, a 400MWSMES program was initiated from the United States Defense Nuclear Agency (DNA). This SMES is designed for later use as a pulsed energy source for electron laser directed energy weapons. It is also intended for load leveling and stabilizing the electrical network. For this type of system, two different designs were proposed by two teams, Bechtel and Ebasco. In Bechtel's design, the magnet has a diameter of 129 m and a height of 7.5 m. It was planned to use an Nb–Ti Cable-in-Conduit Conductor (CICC) having very low losses in alternating current. This system should operate at 1.8 K at a current of 303 kA generating a magnetic field of 5 T. The CICC conductor is designed with a Liquid Helium flow channel, so the Liquid Helium vessel is not present in this design making cryostat construction less complicated. Such high current as the proposed one can reduce the required amount of conductor and keep the working voltage stable and not exceeding the safe limit (10–12 kV).

In Ebasco's design, a 60 kA Nb–Ti conductor was considered with Al stabilization. The coil is 134 m in diameter and 4.2 m in height with a solenoidal magnet configuration. In this design, extra effort is dedicated for mechanical support, electrical insulation and quench protection by introducing fiberglass reinforced epoxy G-10CR finger plates. More information is provided in [12, 96].

9.3 Micro Scale SMES

Small-sized micro SMES have the opportunity to be constructed and even successfully used in industries having remarkable sensitivity to semiconductors and liquid crystals. Their role is to provide protection against unexpected voltage drops for high power. Since 2011, 5 and 10 MVA [34, 71] commercial SMES manufactured by Toshiba Corporation Power System Co and Chubu Electric Power Co. are operational. A four-pole solenoidal configuration is adopted for the 5 MVA SMES to reduce the leakage magnetic field. The SMES was designed with a current of 2.66 kA at a temperature of 4.2 K and a magnetic field of 5.3 T. The compensation time is 1 s. YBCO class 1 kA wires have been proposed to join the current wires in parallel. They are able to support a voltage of 6 kV. The same company also distributed SMSE 10 MVA units. Currently, a number of these units are operational in Japan.

10 Conclusion

Through SMES, superconductivity provides an alternative to store magnetic energy and power an electrical circuit without energy conversion. These SMES have become a realizable device thanks to approved advancements in superconducting materials and cryogenics. They are therefore considered a suitable solution for several applications as they are attractive pulse/transient power sources allowing perfect frequency control and promoting transient stability in power grids. The main advantages of SMES system consist of the rapid power response and the high power and energy density with outstanding conversion efficiency. Although their specific energy is reasonable, beyond that of the batteries, the stored energy in an SMES system can be released in an extremely short time and with negligible losses. This property is not recognized for batteries. A certain number of projects dealing with the conception of SMES used as a power source for short-term duration have demonstrated the versatile and potential applications of this device which can be found in electrical energy and power systems as pulse power source, frequency regulator, power fluctuations stabilizer, etc. SMES can be revisited in smart grid projects, in particular for intermittency management. This is related to the advancement in HTS materials and conductor technologies which allow for more compact and robust SMES at lower costs. Further creativity and persistence would be required in the future to meet the SMES challenges.

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