

Superconducting Magnetic Energy Storage: Status and Perspective

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Abstract — The SMES (Superconducting Magnetic Energy Storage) is one of the very few direct electric energy storage systems. Its energy density is limited by mechanical considerations to a rather low value on the order of ten kJ/kg, but its power density can be extremely high. This makes SMES particularly interesting for high-power and short-time applications (pulse power sources). A SMES releases its energy very quickly and with an excellent efficiency of energy transfer conversion (greater than 95 %). The heart of a SMES is its superconducting magnet, which must fulfill requirements such as low stray field and mechanical design suitable to contain the large Lorentz forces. The by far most used conductor for magnet windings remains NbTi, because of its lower cost compared to the available first generation of high- T_c conductors. Operation at higher temperatures can bring advantages such as lower investment and running costs for the cryocooler and a much enhanced stability against perturbations for the magnet. The second generation of high T_c conductor should be more attractive both in terms of cost, performance and possible operating temperature, among other things. First studies on SMES appeared in 1970, with first demonstrations and experiences on the grid in the seventies and eighties. The three main applications of SMES are UPS (Uninterruptible Power Supply), FACTS (Flexible AC Transmission System) and pulse power sources for dedicated applications. Some SMESs throughout the world are briefly characterized and the 800 kJ DGA-CNRS-Nexans high- T_c SMES now developed is described.

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I. INTRODUCTION

Superconducting magnet with shorted input terminals stores energy in the magnetic flux density (B) created by the flow of persistent direct current: the current remains constant due to the absence of resistance in the superconductor. File and Mills performed measurements of the persistent current decay and determined decay time constants on the order of 10^5 years [1]. The stored energy (W_{mag}) is given by the self inductance (L) of the coil and by its current (I):

$$W_{mag} = \frac{1}{2} L I^2 = \frac{1}{2 \mu_0} \iiint_{Space} B^2 dx dy dz \quad (1)$$

When the short is opened, the stored energy is transferred in part or totally to a load by lowering the current of the coil via negative voltage (positive voltage charges the magnet). The Superconducting Magnetic Energy Storage (SMES) is thus a current source [2, 3]. It is the “dual” of a capacitor, which is a voltage source.

The SMES system consists of four main components or subsystems shown schematically in Figure 1:

- Superconducting magnet with its supporting structure.
- Cryogenic system (cryostat, vacuum pumps, cryocooler, *etc.*).
- Power conditioning system (interface between the superconducting magnet and the load or electric grid).
- Control system (electronics, cryogenics, magnet protection, *etc.*)

A rectifier/inverter, a power electronic circuit, is typically part of the power conditioning system, as required to convert the direct current (DC) of the superconducting coil to alternating current (AC) and *vice versa* since the very large majority of the grids operate in AC.

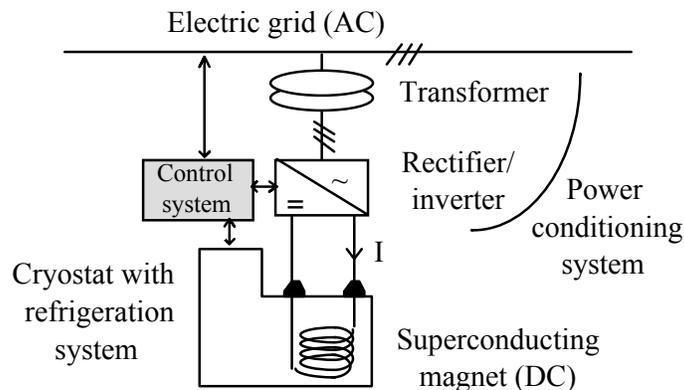


Fig. 1. Schematic drawing of SMES connected to electric AC grid.

II. SMES LIMITATIONS

SMES is an emerging energy storage technology, which has to be compared with other alternatives. For an energy storage device, two quantities are important: the energy and the power. The energy is given by the product of the mean power and the discharging time. The diagrams, which compare different energy storage systems, generally plot the discharging time versus power. These two quantities depend on the application. To protect a sensitive electric load from voltage sags, the discharging time must be short (milliseconds to seconds). For load levelling in a power grid the discharging time should be large (hours to weeks).

Although the attainable magnetic flux density limits the energy per unit volume given by Equation (1) ($B^2/2\mu_0$), the real limit of the energy stored in a SMES is mechanical. The virial theorem [4] gives a relation between the minimum mass of the mechanical structure, M_{\min} , and the stored energy, W_{mag} . For a solenoid this relation is:

$$\frac{W_{mag}}{M_{min}} = \frac{\sigma}{d} \quad (2)$$

where σ is the working stress and d the structural material density. The relation defines the minimum mass of the mechanical structure in pure tension to support the radial electromagnetic forces. Force-balanced coils [5] minimize the working stress and thus the mass of the structure. The virial minimum can be then approached with these topologies, but they remain complex for the winding. Even “force-free” configurations were proposed [6], but these are only possible for infinite structures while the virial theorem definitely gives the minimum for real finite structures.

Assuming a reasonable working stress of 100 MPa, the virial theorem gives for a magnet with steel structure the value of stored energy per unit mass (mass specific energy) of 12.5 kJ/kg (3.5 Wh/kg). The CMS (Compact Muon Solenoid) [7] magnet of the LHC collider almost reaches this value for its cold mass (2.6 GJ/225 tons or 11 kJ/kg). The working stress of 100 MPa may be increased somewhat, but the mass specific energy will still be limited to the order of 10 kJ/kg. Some high-strength composite materials offer interesting perspectives for the future, because their stress density ratio is very high. High-strength aluminium alloys are also excellent candidates: they have approximately 1/3 of the steel density. The mechanical design of a SMES is of extreme importance; the magnet conductor must be designed to withstand high stresses and deformations without degradation of superconducting properties.

Two approaches have been proposed to contain the large Lorentz forces: earth- (warm) and self-supported (cold) SMES. In the first approach, the forces are transmitted to the external rock. The magnet is supposed to be installed in an underground cavern or in reinforced surface trenches. In the self-supporting design, the cold structure of the magnet itself supports the Lorentz forces. This option is cheaper than the earth-supported solution for stored energy up to GWh [3].

Overall, SMES shows a relatively low energy density. Batteries present higher values but the majority of the power condensers show lower values. Figure 2 shows the power and energy per unit mass for SMES and two more mature technologies: capacitors and batteries. For SMES, the grey zone indicates the presently attained values. The black zone covers theoretically possible ranges, which require more research and development.

The energy stored in the superconducting magnet can be released in a very short time. The power per unit mass does not have a theoretical limit and can be extremely high (100 MW/kg). The product of the magnet current (I_0) by the maximum allowable voltage (V_{max}) across it gives the power of the magnet ($I_0 V_{max}$). High powers thus require large currents and an excellent electric isolation for high voltages.

During the discharge (and the charging) some energy is lost due to the ac losses in the superconducting coil and to eddy current losses in the cryostat. These two contributions can be kept to a very low level (some low % of the stored energy) thanks to a suitable design of a low-ac-loss superconducting conductor and of the cryostat. Therefore, SMESs show excellent energy conversion efficiencies, greater than 95 %. This value is very high compared to other storage systems (batteries 70 to 90 %, pumped hydro up to 70 %). This inherently high energy efficiency is due to the absence of energy conversion to and from another form, mechanical or chemical. For the same reason, capacitors also show high energy conversion factor of 90 to 95 %). Charging of the magnet cannot be nearly so rapid as its discharge. This difference is

due to the fact that the operating margins decrease during the charging while they increase during the discharge. The number of charge-discharge cycles can be very high since it is mainly limited by the mechanical fatigue of the support structure. A SMES may be then used for repetitive and rapid bidirectional exchanges of power with the load.

The high power density of SMES makes it a promising candidate for pulse power sources in the military and civil fields, such as the electromagnetic launcher [8], magnetic forming (use of electromagnetic forces to form a metal) [9], and possibly other.

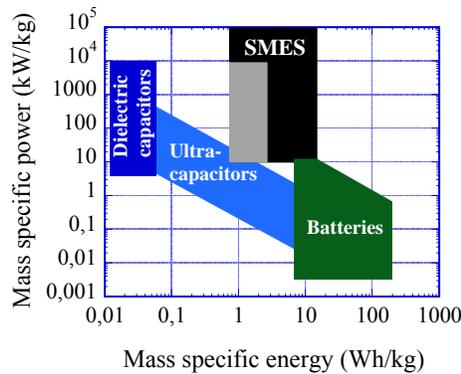


Fig. 2. Ragone plot for SMES, batteries and capacitors.

Figure 3 compares the ranges of power and discharge time for different storage technologies. Characteristic for SMES is high power, up to 100 MW, and short discharging time under several seconds.

CAES (Compressed Air Energy Storage) uses underground reservoirs (salt cavern, old hard rock mine, etc.), to pressurize large volumes of air and then to release to recover the energy. Pumped hydro storage (two water reservoirs at different elevations) and CAES are the only available technologies for very large energy storage systems.

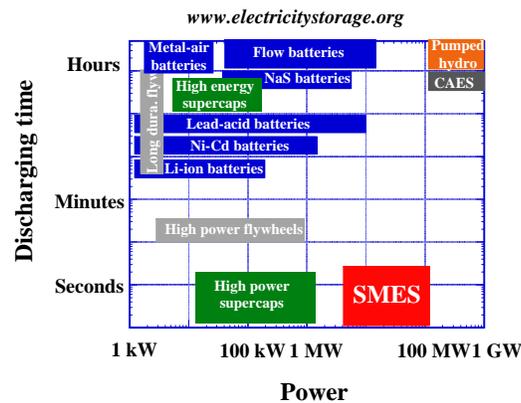


Fig. 3. Discharging time versus power for various energy-storing devices [10].

In summary the main characteristics of SMES are:

- High power density but rather low high energy density (more a power source than an energy storage device).
- Very quick response time.
- Number of charge-discharge cycle very high (infinite).
- No moving parts / low maintenance.
- Fast recharge possible.
- High energy conversion efficiency (> 95 %).

Table I characterizes three different SMESs intended for different power and energy ranges. Only the smallest was constructed and operated.

Table I. Some SMES characteristics.

	SMES plant [2]	SMES/ETM [11]	5 MVA SMES [12]
Energy	5250 MWh (18.9 TJ))	20.4 MWh (73 GJ)	7.3 MJ
Power	1000 MW	400 MW	5 MW
Magnet			
- diameter	1000 m	129 m	0.648 m (4 pole
- height	19 m	7.5 m	0.7 m configuration)
Current	200 kA	200 kA	2657 A
Superconductor	NbTi	NbTi	NbTi
Operating temperature	1.8 K	1.8 K	4 K
Status	Only design	Abandoned	Used for voltage dips

III. SUPERCONDUCTING MAGNET

A. Magnet Configuration

The superconducting magnet is the heart of any SMES. It must be designed to minimize the amount of superconducting material for a given magnetic energy, ensure proper cooling and mechanical support of the electromagnetic forces. The magnet must fulfil the specified electromagnetic signature and be protected in case of a quench. Of course, the design must prevent quenches as far as possible.

There are two main magnet topologies: solenoid and toroid. Solenoid has a simple structure and the electromagnetic forces are easier to handle than in a toroid. A toroid is, indeed, submitted to a net large radial force towards the central axis, in addition to the transverse and longitudinal forces. The quench of a toroidal coil is problematic since it creates an imbalance in the force distribution. The main advantage of a toroid is its natural low stray field since the field is contained only within the magnet bore. Its disadvantage is that it stores only about $\frac{1}{2}$ of the energy per unit conductor stored by the solenoid. Nevertheless, the conductor quantity per unit stored energy becomes nearly the same when compared to an actively shielded solenoid. Active shielding uses compensated coils around the main magnet in order to cancel the magnetic field outside. A hexagonal arrangement of solenoids, such as shown in Figure 4, can be used to reduce the stray field of solenoids [13]. Moreover this

topology offers a modular design with elementary “small” solenoids. The energy per unit conductor volume is optimized in a solenoid with a diameter to height ratio of 5.

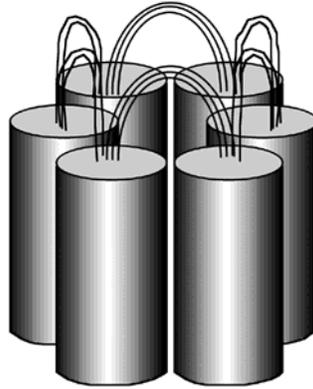


Fig. 4. schematic drawing of hexagonal arrangement of solenoids for stray field reduction [13].

B. Magnet Conductor

The superconducting conductor for the magnet winding must meet several requirements:

- High engineering (overall, *i.e.*, the superconductor and normal stabilizer matrix) current densities in large magnetic fields.
- Support of mechanical stresses/deformations.
- Low cost.
- Operating temperature as high as possible.

The conductor can be designed with a sheath for example to contain the Lorentz forces in order to reduce them on the superconducting strands themselves. The Cable-In-Conduit [14] (CICC) is an example.

At present, only NbTi conductors meet the first three requirements, but its operating temperature is unfortunately low, at or slightly above the liquid helium (LHe) temperature of 4.2 K. The LHe cryogenics does not pose any problem, but remains expensive in terms of capital investment and operational cost. The NbTi magnets benefit from steady advances in cryogenic cooling. The gradual improvements of large cryocoolers extend the maintenance cycle and reduce the refrigeration electrical load. The introduction of high-critical-temperature (HTS) current leads was another important improvement. These significantly reduce the related losses (1/10 at 4 K, 1/3 total at 300 K), a large contribution to the total loss (see also the Forum paper [ST12](#)).

When the operating temperature is further reduced below 4.2 K, *e.g.*, to 1.8 K, the superconducting volume decreases since the current density increases, but the cryogenic cost increases too. Therefore, the chosen operating temperature is a compromise between cryogenic and conductor costs.

Why HTS materials are currently used only for current leads? The reason is economical. Indeed, HTS magnets offer the possibility to operate at higher temperatures, which would reduce the cryogenic operating cost. As shown in Figure 5, Carnot efficiency increases by a factor of 5.3 at 20 K and 14.8 at 50 K when compared to 4 K operation. While a higher

operating temperature only slightly reduces the cost of the cryostat, it reduces very significantly the cost of the cryocooler, in a way similar to the Carnot efficiency improvement. However, in large systems, the cryogenic cost is only a limited (even if not very small) fraction of the total cost (see also Forum reviews [CR3](#) and [CR4](#)). Therefore, higher operating temperature cannot bring a very strong reduction of the system total cost. The resulting cost reduction not significant enough to really modify the relative SMES competitiveness.

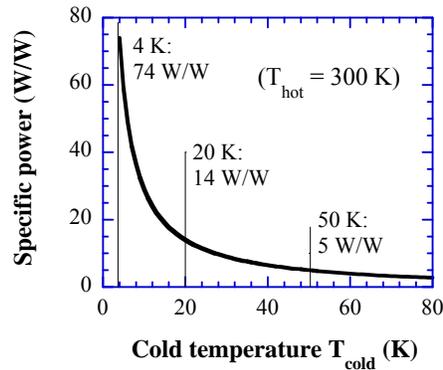


Fig. 5. Carnot specific power (minimum work to extract 1 W at T_{cold}).

In addition, the currently much higher cost of HTS conductors unfortunately also leads to a higher total cost. The cost of NbTi is about two orders of magnitude lower than that of the first generation of HTS wire (PIT, Powder-In-Tube, using BiSrCaCuO superconductor).

The second generation of HTS wire, the Coated Conductor (CC) [15, 16, 17, 18], may offer savings for SMES. They have the potential for lower costs and operation at 50-60 K is expected in the SMES magnetic flux density conditions (a few Teslas), instead of only 20 K operation of the first generation. Several hundred meters long CC sections are produced now and kilometer lengths are in sight. The CC technology advances are rapid and remarkable. The MgB₂ wires do not have the potential for a significant breakthrough, even at low conductor cost, because the operating temperature increase is not significant enough compared to NbTi (10-15 K instead of 4 K).

In the future, HTS magnets can bring advantages not only in terms of cryogenics. Operation at higher temperatures makes the magnet much more stable and less sensitive to external perturbations. This improvement is due to the large increase of specific heat with temperature (by two orders of magnitude at 50 K compared to 4 K). Furthermore, when operating at higher temperatures, the electric insulation may be thicker. That makes it possible to increase the power *via* a higher operating voltage. The admissible temperature difference between the conductor and the cold source, ΔT , can be indeed increased, because temperature margins are higher. This temperature difference is due to the AC losses during the charges and the discharges. The relation between ΔT , AC loss and insulation thickness, d_i is:

$$d_i = \lambda \Delta T / AC_{\text{loss}}, \quad (3)$$

where λ is thermal conductivity of the insulation. A potential difficulty when using high- T_c magnets could be in attaining their effective protection. Due to the very low propagation velocities of a normal zone when the temperature increases, the quench time risks to be too long, and the local temperature rise high enough to cause damage.

IV. SMES USES AND HISTORY

A. SMES in Power Grid

The idea of SMES first appeared in 1970; the motivation was to level the load in the French electricity network [19]. The energies required (thousand of MWh) led nevertheless to huge magnets (1 km in diameter, see table I) with a lot of realization difficulties. Furthermore, SMES is not the best solution in this case due to its rather low energy density. Pumped hydroelectric and compressed air units offer higher performances.

With energies of some to tens of MJ, SMES can be used in the electricity networks as a Flexible AC Transmission System (FACTS). A FACTS is a static device installed in the electric grid in order to enhance its operation in terms of controllability and power transfer capability. It is generally a power-electronics-based device. A SMES operating as a FACTS was the first superconducting application operating in a grid. In the US, the Bonneville Power Authority used a 30 MJ SMES [20] in the 1980s to damp the low-frequency power oscillations. This SMES operated in real grid conditions during about one year, with over 1200 hours of energy transfers. This represented more than 10^6 cycles for the magnet. The main operating problems concerned the power converter and above all the refrigerator. No problems occurred with the superconducting magnet and the cryostat. In addition to the refrigerator problems, alternative solutions were found to damp the oscillations and the SMES operation was stopped. This experience was the first successful and conclusive demonstration of a large SMES operation in a real power grid.

More recently, in 2000, the American Superconductor company installed six SMES units at key points in the grid in northern Wisconsin, USA, to enhance its stability [21]. This grid experienced voltage instability problems with large momentary voltage depressions, which could lead to the grid collapse. The six SMESs at different key locations in the grid injected real and reactive powers into the grid to boost the voltage and they increase the power transmission capabilities by 15 %. Each SMES could provide continuously 2.8 Mvar (5.6 Mvar during 1 s) and 2 MW during a short duration. These SMESs were packaged in standard trailers for an easy and rapid deployment. The commissioning of a 345 kV line some years later has solved the voltage instability problems so that these SMES units were disconnected.

Generally, the FACTS serve mostly for transfers of reactive power. The active power transfers, which require a superconducting magnet, are a small part. So a FACTS, which provides only reactive power such as the STACOM (D-VAR) meets most of the grid requirements. Using PWM (Pulse Width Modulated) power converters, they do not need a superconducting magnet.

In the 1980s, a large SMES development program was carried out in United States under the Strategic Defence Initiative (SDI) [22, 23]. The main objective was a power source for the Free Electron Laser but utility applications were studied as well. The aim of SMES ETM (Engineering Test Model) was to design and build a 20-30 MWh (72-108 GJ) – 400/1000 MW magnet (see Table I, middle column). There was competition between two teams (Bechtel and Ebasco) in the design phase and they proposed rather different solutions. One used a 60 kA Al stabilized NbTi conductor with a helium bath cooling. The second was based on a 200 kA CICC. A NbTi CICC with low ac loss was developed and tested up to 303 kA under 5 T at 1.8 K, which is still a world record in term of current capacity. Abandoning the SDI resulted in the termination of this SMES project.

Reference [24] gives a review of the SMES in power systems.

B. SMES for Local Power Conditioning and Pulse Power Sources

Several SMESs have been and still are operated in uninterruptible power supplies (UPS) with power rating on the order of MW. These are used locally for critical loads requiring ultra-clean power for sensitive processing (such as semiconductor chip fabrication facilities for example) or military and research laboratory applications. The superconducting magnet replaces the batteries classically used. These SMES are mainly provided by American Superconductor [25]. They have led to a considerable amount of test experience. From 2000, this company had accumulated more than 35 unit-years of operation.

One of the first systems was installed in 1993 for an ammonia production furnace. Another 1.4 MVA/2.4 MJ SMES was installed at the Brookhaven National Laboratory (USA) to offer high quality power for a synchrotron source [26]. It provides power during voltage sags or momentary interruptions to avoid beam loss. Owens Corning's extrusion and production lines in North Carolina have been protected by SMES from voltage sags [27]. Likewise, in South Africa, a SMES has protected a paper machine against 72 dips in 11 months [28].

In Japan several SMESs have been built. One objective is the protection of sensitive load against voltage dips. In 2003 a 5 MW – 7 MJ SMES was fabricated using NbTi solenoid in a 4 pole configuration [12]. It has compensated voltage dips in a liquid crystal manufacturing factory. Another SMES system with a rating of 10 MVA was built in 2005. A national Japanese program is carried out on SMES for load fluctuation compensations. They have initiated the development of high- T_c SMES and tested a 1 MVA SMES using a Bi-2212 PIT wire, but operating at 4 K [29].

Another SMES class are pulse power sources for dedicated applications having very high power demand over short time. Examples of such applications are electromagnetic launchers and magnetic forming. One such current development is described in Section V. Pulse power SMES sources using toroidal coil magnets have been also studied in Russia [30, 31].

C. Summary

In summary several SMESs have proved their operational capabilities for short-term (seconds) power at MW scale. They are commercially available and the field test experience is very large in the US and Japan. Nevertheless, the number of sold SMES remains very low and does not increase much. The major reason is the high initial cost while in competition with more mature technologies. Moreover SMES addresses niche applications having high active power – short time demands. Table II summarizes the main applications of SMES.

Table II. Main Applications of SMES

Application	UPS	FACTS	Pulse power source
Use	Voltage-power quality and security for sensitive-critical loads.	Active (and reactive) power exchanges with the grid to improve its operation (stability, capacity enhancement, ...)	Devices with high power – short time requirements: - Electromagnetic launcher - Magnetic forming

V. SMES FOR ELECTROMAGNETIC LAUNCHERS

An electromagnetic launcher developed in France by the DGA (Délégation Générale pour l'Armement) and ISL (Institut Saint Louis) [32] requires high power pulse sources. The electromagnetic launcher 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. However, an electromagnetic launcher could also be used to launch small payloads into suborbital or orbital altitudes [33].

Due to its high power density, SMES is a very interesting energy storage device for an electromagnetic launcher. Furthermore, SMES being a current source is more suitable than the presently used capacitors, which are voltage sources. Indeed, the energy conversion efficiency has the potential to be much higher with a SMES than with capacitors. Nevertheless, considerable research and development is still required to develop a SMES fully suitable for electromagnetic launchers. For example, very-high-current conductor should be developed: the electromagnetic launchers require currents higher than 100 kA. Taking into account the severe military environment, an HTS SMES appears more suitable for the application.

The SMES for an electromagnetic launcher is definitely used as a power supply and stores energy only during a limited time. The SMES is used as an intermediate short-term storage. Figure 6 shows a typical operating sequence. First, a primary source of reduced power charges the SMES. The duration of this stage is mainly fixed by the power of the primary supply, even if the magnet may bring some constraints due to its AC losses. When the rated current is reached, the magnet is short-circuited by an external switch S, but very soon after the energy is transferred to the electromagnetic launcher by opening the same switch S. The superconducting magnet does not operate in persistent mode. The magnet discharge is mainly due to the current leads and the external circuit, in particular the switch S. There is no real specification in term of persistent operation for the magnet. This can even be a little resistive. Its resistance plus the external circuit resistance including the current leads divided by the magnet self inductance must be low enough compared to the inverse of the storage time (the duration of step ②). This theoretically very simple operation of a SMES for an electromagnetic launcher is another advantage. Nevertheless, it assumes that the SMES current is high enough to directly supply the railgun.

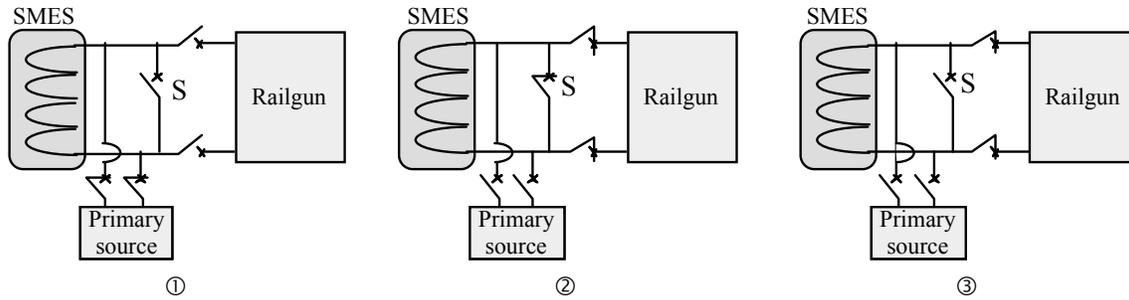


Fig. 6. Operation of a SMES supplying directly a railgun.

A SMES storing a few hundreds of kilojoules at a temperature of 20 K and with an integrated cryogenics is an intermediate development phase. Such a 800 kJ device is the goal of the collaborative project involving DGA, CNRS and Nexans, in which this author is active. It is essential to develop basic technologies for manufacturing HTS SMES [34]. The purpose is to qualify several technological solutions on a representative level and to acquire an essential operational experience feedback. The two key components to be implemented are: (1) an HTS conductor adapted to the SMES needs, and (2) cryogenics transparent to the user, *i.e.*, without cryogenic fluid handling.

The conductor, shown in Figure 7, is made of several Powder-In-Tube tapes from Nexans with the 2212 stoichiometry ($\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O} - \text{Bi-2212}$) [35]. The tapes are soldered in parallel. A stainless steel tape mechanically reinforces the conductor where the Lorentz forces are highest within the magnet. Despite an external AgMg external sheath the critical current irreversibility threshold decreases for stresses higher than 100 MPa, which is a rather low value. The number of PIT tapes in parallel (3 or 4) is dictated by the local magnetic flux density (amplitude and direction) within the magnet.

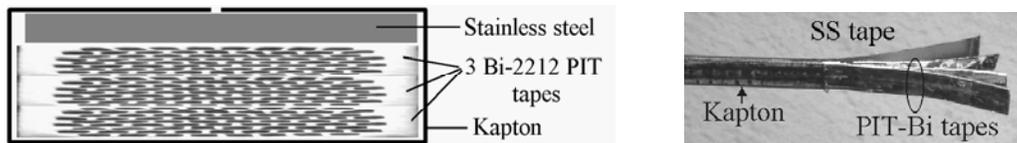


Fig. 7. The Bi-2212 PIT conductor reinforced by stainless steel for the DGA-CNRS-Nexans SMES.

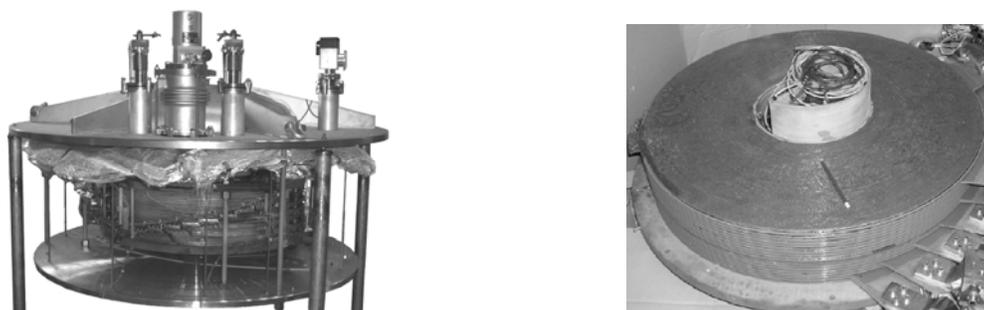
The superconducting magnet (Table III) has been designed to minimize the superconductor amount for the specified magnetic energy (800 kJ), to ensure the proper cooling and the support of the electromagnetic forces with a maximum stress of 100 MPa. Without specification for the stray field, we choose a solenoid. The coil consists of 26 superposed simple pancakes wound and bonded on copper supports coated with epoxy. Special connections between the pancakes have been designed to lower the contact resistance especially for the inner connections under field. To make the cryogenics transparent and friendly to the user, we designed thermoconductive cooling at 20 K using cryocoolers [36]. The copper supports are used to cool the conductor. They are machined with slits in order to reduce the eddy current losses during charges and especially rapid discharges. Figure 8 shows the SMES with the 26 pancake coil assembly.

Table III. Parameters of the 800 kJ DGA-CNRS-Nexans SMES.

Stored energy	814 kJ
Internal / External coil diameter - Height	300 mm / 814 mm – 222 mm
Rated current	315 A
Operating temperature	20 K
Number of pancakes	26
Max magnetic flux density (longit./transvers.)	5.2 T / 2.5 T
Max circumferential stress / axial stress	80 MPa / 24 MPa

In addition to the cryocooler for the magnet, a second cryocooler cools the HTS current leads (Bi-2212 tubes from Nexans) and the thermal shield. The cryogenic system operates in a satisfactory way and in agreement with the calculations. Approximately one week is necessary to completely cool the SMES.

Tests of the magnet were conclusive even if the energy of the theoretical design has not been reached. For the stored current, 80 % of the rated value was recorded (244 A). In resistive discharges from this current, a maximum power and energy of 175 kW and 425 kJ have been recorded. Fast discharges showed that the losses in the magnet and in its close environment are low; the rise in temperature is very limited. Presently, the SMES is disassembled to modify its configuration for further investigations.

**Fig. 8.** The assembly of 800 kJ HTS SMES with the 26 pancake magnet cooled by conduction.

VI. CONCLUSIONS

SMES is particularly suitable for power sources of short duration, because the power density is much higher than the stored energy density. It is thus an excellent solution for applications such as pulse power sources, UPS or FACTS for power grids. A number of SMES units have been installed and operated successfully during many years demonstrating their very satisfying performance. The obstacle for widespread commercialization of SMES remains the high capital cost. The deregulation of the electricity market and the requirements to enhance the power capacities of the present grids bring the opportunity for FACTs using SMES. The need for pulse power sources for emerging applications such as electric weapons also offers

good chances for SMES. Even if high- T_c materials cannot yet bring reduction of the total cost, they can make SMES more attractive for some users, especially when lower-cost high-performance coated conductors of the second generation will become available.

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