Review of the State of the Art Superconducting Magnetic Energy Storage (SMES) in Renewable/Distributed Energy Systems

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Abstract

This paper considers the applications of SMES technology in the context of Distributed Generation networks. Firstly, the concept of Distributed generation is detailed, together with the associated challenges and current solutions. This is followed by an introduction into energy storage technologies and in particular, to SMES. The operating principle of SMES is explained and details are given on the current status of superconductor materials used, coil geometries and cooling techniques. A brief outline of some past or ongoing major SMES projects is given and then the main applications in the context of Distributed Generation are discussed. Finally, a series of challenges posed to SMES technology is exposed, together with possible opportunities for development. The paper ends with a conclusion and the list of references.

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Introduction

Driven by the goal of reducing the CO_2 emissions by 80% relative to the 1990 levels by 2050 [1], the UK renewable energy generation capacity has increased 7.5 fold in the past 15 years [2]. Between 2014 and 2015, additional generation capacity consisting of 1254 MW of wind farms and 3763 MW of solar farms has been installed in the UK, leading to a total amount of 83.6 TWh of renewable electricity produced in 2015, which consists of 24.6% of the entire electricity consumption for the same year [1].

Renewable generation is present in various types and sizes, ranging from a few solar panels fitted on buildings' roofs or small wind turbines with capacities of under 50 kW, up to GW-scale wind or solar farms and hydroelectric plants. While larger generation systems are connected straight to the transmission lines, as they are typically at considerable distances from consumers (such as offshore wind turbines), smaller renewable systems can be placed close to consumers and connected to the distribution network, thus creating the concept of **Distributed Generation(DG)** [3]. While there is no exact definition on the upper generation limit of a DG system, its concept envisions a new type of electricity network as part of the idea of Distributed Energy Resources (DER), which also involves responsive loads and energy storage. Unlike conventional electricity networks which consist of large power plants situated in isolated locations, with attached transmission lines to move the electricity to the distribution centres, and from here further to the consumers through distribution lines, DER imply a series of smaller renewable energy systems (such as wind turbines, solar panels, hydro turbines, geothermal pumps), situated in the proximity of consumers. These renewable generation systems are coupled with energy storage installations to increase the availability of energy over generation shortfalls. By applying this idea in the context of increasing penetration of renewable generation, further investments in improving the outdated transmission network, which is experiencing an increasing stress caused by a higher consumption (predicted to increase by 37% by 2040 [4]), can be deferred or even avoided. In turn, new possibilities of providing energy to isolated establishments can arise, improving the energy security and quality.

DG challenges and solutions

An increase in renewable generation capacity represents a viable solution for the future of energy security but it also brings a series of challenges from the technical, regulatory and commercial points of view. Wind and solar power generation can be reasonably accurately predicted, but their highly variable outputs cannot provide a consistent base load and certainly cannot follow an irregular demand pattern. To ensure a constant energy availability, either a non-renewable generation form (such as Diesel generators or gas turbines) or sufficient energy storage have to be included in the DG grid. Moreover, the quick variation in wind/solar output can lead to transient voltage fluctuations and harmonic distorsion, which can affect the power quality. More stable solutions such as hydroelectric power or geothermal reservoirs can significantly improve the energy situation in a DG, however these are highly dependent on the geographical location [3].

As a solution for the technical issues present in DG, a range of power electronic devices combined with real time monitoring of the micro-grid load can be used. Distributed Flexible AC transmission systems (D-FACTS) are used in Distribution lines (DL) to improve the system performance by injecting voltage into the line in the event of a voltage drop [5]. Coupled with additional energy storage capacity, D-FACTS can also maintain the voltage magnitude during a sag or outage. However, these systems are generally used to control reactive power in particular, having a much lower real power rating. Various technologies such as large scale secondary batteries, compressed air storage (CAES) or pumped hydro energy storage (PHES) have emerged in the energy sector becoming actively used to mitigate the electricity network issues [6]. Depending on the characteristics of the storage system, the applications are: peak shifting and load levelling, power quality improvement, supply-demand decoupling, oscillations damping, voltage and frequency regulation [7].

One of the storage systems that has a promising role in various grid applications is the superconducting magnetic energy storage (SMES). Besides the capacitor, it is the only device capable of storing electricity without the need of conversion to another form of energy (such as electrochemical in batteries, mechanical in flywheels or CAES). Compared to other storage systems, SMES systems have relatively low gravimetric (record of 13.4 kJ/kg achieved using low temperature superconductors [8]) and volumetric energy densities, but their advantage comes to the large power density (up to 2kW/kg; 4kW/L [9]) and very short response time (on the order of milliseconds), with a better cycling ability. Moreover, real and reactive output power can be separately controlled by coupling distributed SMES (DSMES) systems with appropriate power conditioning systems (PCS), an example being D-FACTS in DG. The main advantages over power electronics are the high reliability as no moving parts are involved, very quick response time (only limited by the power electronics in conditioning systems), very high efficiency and a very high lifetime (virtually unlimited)[10].

SMES overview

A SMES system stores energy in the magnetic field created by the DC current which passes through a superconducting coil in short circuit [11]. The system can only work if the coil is maintained below the critical temperature of the superconductor (T_c), hence it is necessary to include a cryogenic system in the operation of SMES. As the electrical resistance of the coil becomes 0Ω, there are no ohmic losses, meaning that a high operating efficiency (over 95%) can be achieved [7]. The main source of inefficiency comes from the refrigeration system which keeps the cryogen below T_c, thus to minimize this, the coil has to be properly insulated so no heat is exchanged with the surrounding environment. Other losses appear in the power electronics from the Power Conditioning System (PCS).

A SMES system consists of 4 main sub-systems:

- **the superconducting coil** kept under vacuum in a thermally insulated environment by using a Dewar;
- **the refrigeration system** along with the vacuum pump - which are functioning continuously to keep the temperature under T_c;
- **the power conditioning system**, which consists of a series of power electronic devices: transistors, capacitors and inductors for regulating the electricity exchange between the SMES and the grid;
- **the control system**, which continuously monitors the essential parameters such as temperature, pressure, current, coil strain, adjusting the operation of the cryogenic system accordingly.

Besides these 4 main sub-systems, it is essential that a SMES system has a protection which prevents damage in the superconductor in the event of a sudden quench [12]. The amount of energy that can be stored in a SMES system is given by the formula:

$$E = \frac{1}{2}LI^2$$

where L is the coil inductance and I is the current circulating through the coil. The higher the inductance and the current circulating through the coil, the more energy can be stored.

Superconductor wires for SMES

The superconducting coil consists of multiple windings of superconducting wire/tape. This can be manufactured using various superconducting materials arranged in thin wires and enclosed within a matrix of Cu, Al or even Ag alloys for improved strength and quench protection (sink for the current in case the temperature of the system exceeds T_c and the superconducting properties are lost). Superconducting materials are characterised by three essential parameters: the critical temperature T_c, the critical magnetic field B_c and the critical current density j_c [13]. There is a direct dependency between these three parameters, with lower working temperatures enabling higher current densities and magnetic fields to be achieved.

Depending on their critical temperature, superconducting materials can be classified in low temperature (LTS), medium temperature (MTS) and high temperature materials (HTS). LTS have a critical temperature of under 20 K [9], the most commonly used being NbTi, Nb_3Sn and Nb_3Al, with transition temperatures between 10 and 18K[14]. The figures below represent cross sections of different types of superconducting wires.

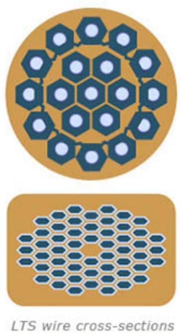

Figure 1: LTS section [15]

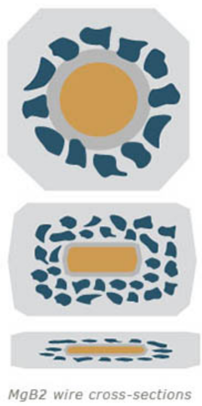

Figure 2: MgB_2 section [15]

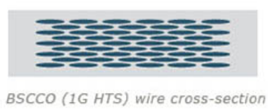

Figure 3: 1G HTS section [15]

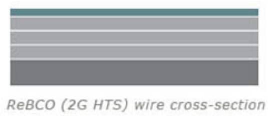

Figure 4: 2G HTS section [15]

Among the higher critical temperature compounds used in superconducting wire manufacturing are Magnesium diboride (MgB_2: T_c=39 K, considered a medium temperature superconductor and generally used at the optimal temperature of 20K), Rare Earth Barium Copper Oxide (ReBCO) compounds with Yttrium, Gadolinium, Samarium or Neodymium, having T_c of over 90K [15], as well as Bismuth Strontium Calcium Copper Oxide (BSCCO 2212: T_c=95 K and 2223 : T_c=108 K) [9]. Depending on their behaviour in magnetic field in the T_c region, HTS superconductors can either be Type I (BSCCO-abrupt transition to repelling magnetic fields below T_c, cannot sustain high magnetic fields in the superconducting region) and Type II (ReBCO-exhibit a region of mixed behaviour around T_c, can sustain much higher magnetic fields without quenching) [14]. They can be manufactured either in as wires (applicable for all LTS, MgB_2 and BSCCO) or multi-layer tapes of structural layers sandwiching a deposited layer of powdered superconductor (for ReBCO materials) [16].

Finding an optimal material by considering its cost, performance, manufacturing complexity and reliability is still a key challenge in the design of SMES systems and it highly depends on the nature of the application. Another essential driver is the maturity of superconductor technology; currently, the most common superconductor materials used in SMES are LTS (specifically NbTi and Nb_3Sn), with applications of up to 100 MJ in the US [9]. However they require temperatures lower than 4.2K and have a much lower maximum current density and magnetic field compared cu other superconductors such as BSCCO or YBCO at the same temperature [13].

To decrease the cost of cooling in a SMES system, the operating temperature of the superconducting coil must be as close to room temperature as possible. This requires the use of MTS and HTS, superconductors with potential of sustaining higher fields and current densities at higher temperatures. Because of this, a HTS SMES can be cooled using liquid nitrogen close to its boiling temperature of 77K, thus decreasing the amount of energy input necessary for refrigeration and the cost of the cryogen. However, even if the operating costs are higher, the cost per kAm (kilo-Ampere-metre) are much higher in the case of HTS. Promising results were obtained from MgB_2 coils operating at 20K, with magnetic fields of 2-5 T and current densities of up to 200A/mm^2 [17, 18]. MgB_2 wires are currently priced between $10 and $25/kAm (for 20K, 1T applications), but it is expected that their price will decrease below the $5/kAm mark by 2020-2025 [12, 19]. The main challenges in the implementation of MgB_2 superconductors in SMES applications are the increase of the current density to a level similar to NbTi (an option is C or SiC doping [19]) and finding an economic way of manufacturing long lengths of wire. SiC fibres coated in MgB_2 have shown the potential of sustaining high magnetic fields of up to 55T, which opens up the posibilities for coated superconducting wires applications in SMES [19]. Other superconducting materials which attracted interest lately are the layered rare-earth metal oxypnictides (ie LnOFeAs, with a critical temperature of 26 K and the combination with other rare-earth elements even exceeding 50K)[20].

An interesting study focusing on the design and optimization for the lowest quantity of superconducting material for a 2.5 MJ SMES has compared the performance of YBCO and BSCCO-2223 superconductors at an operating temperature of 20K. The results have shown that a higher operating current has been achieved by using YBCO, while also minimizing the cable length and decreasing the physical size of the coil and the magnetization loss [21]. The YBCO also exhibits a higher critical tensile strength, but it comes at a much higher cost (over $100/kAm)[20].

Cooling systems

A refrigeration system is an essential subsystem of a SMES, as it keeps the temperature of the superconductor below T_c. For applications using LTS coils, operating temperatures of 4.2 K and lower can be sustained by submerging the coil in a pool of liquid Helium. The entire system is then encapsulated in a vacuum insulated vessel and isolated using a radiation shield [22]. Even if the cost of LTS superconductors is relatively low compared to YBCO or BSCCO, the operation costs are higher due to a higher energy input necessary for maintaining the cryogen at such low temperatures, together with the cost of the liquid Helium itself. Other cryogens include liquid Hydrogen, liquid Neon and liquid Nitrogen for applications at 20 K, 27 K and 77 K respectively. A good alternative for using cryogens are the cryo-free conduction coolers, which are generally lighter, more compact and can operate at a wider range of temperatures [23]. These systems can be Gifford-McMahon (GM), GM with Joule-Thomson circuit (GMJT), Stirling cycle (ST) or ST pulse tube (STPT). Currently, there are several companies offering cryogen-free refrigerators in compact sizes, with efficiencies of up to 10% at 20K and powers sub-100 W and over 12% at 40K and powers between 100 and 1000 W [24]. The majority of HTS SMES present demonstrators are using combinations of single or double stage GM cryocoolers, together with a series of heat dissipation discs and tubes intercalated between coils and typically made of materials with high thermal conductivity such as copper [25, 26].

SMES coil designs

The common shapes of superconducting coils are solenoid or toroidal (Figure 5). While the solenoid consists of linearly stacked pancake coils, the toroidal design supposes winding the superconductor around a supporting structure shaped as a toroid. The main advantage of the solenoid design is the higher energy that it can store, however within such a system a stray magnetic field is developed, which can have harmful effects on the environment. The same type of stray field is present in modular toroidal coils which consist of equally spaced pancake coils arranged together in a toroidal shape, however if the wire is continuously wound in a helical toroid, the coil can contain the stray field within the structure. For applications larger than 100 MJ, a toroidal coil design yields a lower capital cost [27].

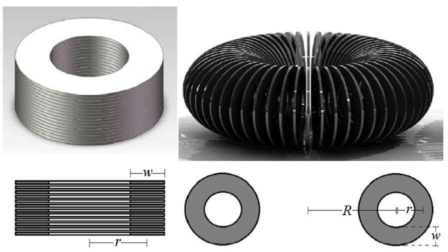

Figure 5: Solenoid and Toroid configurations [28]

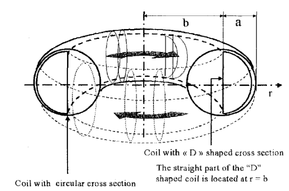

Figure 6: Double D-shaped toroid [29]

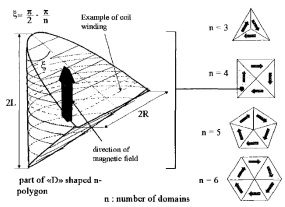

Figure 7: N polygon coils [29]

Various design adjustments of pancake coil modules can increase the amount of energy that can be stored, while keeping the amount of superconducting material as low as possible. Depending on the available space, certain solenoid designs with a high unidirectional length can be compressed by splitting the structure into multiple smaller solenoids which can be placed either vertically or horizontally to form polygons, with a relatively small energy storage loss (about 5%) [8]. In modular toroidal SMES, if some of the modular coils are build in a D shape instead of circular and intercalated between the other circular coils, the energy storage capacity would increase by 18%, but the cost and complexity would also increase [30]. By using the same D shape windings, the size of toroidal coils can be reduced by joining two semi toroidal concentric coils, as in Figure 6 [29]. For large scale applications, configurations such as Tilted Toroidal Coils [31], Force Balanced Coils [32] and Stress

Balanced Coils [27] have been tested with positive results. Other interesting coil types are the N side polygons as in Figure 7, displaying a very good stray field containment, however they are extremely difficult to manufacture, especially if using ceramic superconductors [29].

Nevertheless, the true limitations on the amount of energy that can be stored in a SMES system are given by its mechanical properties. Due to the formation of a high magnetic field, the structure of the coil is subject to multi directional stresses (longitudinal, radial and hoop) which lead to the strain of the structure. After the maximum level of stress is reached, the entire structure can collapse, long before the limitations on the current or magnetic field are reached. This fact gives rise to one of the fundamental issues of SMES, namely the necessity of strong infrastructure for supporting the superconducting magnet, which increase the capital costs and restrict the possible installation sites.

Applications of SMES

SMES is a relatively new technology in the energy storage sector and its development is fully dependant on the advances in superconductor performance. Hence, the majority of commercial applications are based on LTS, which is a more mature technology. Because of the capacity of quickly discharging or absorbing energy, SMES applications are mainly found in power networks for power quality improvement, low frequency damping, system stability control and Uninterruptible Power Supplies (UPS) [33]. Renewable energy systems such as wind or solar power farms have a highly varying voltage and frequency output, so coupling them with high power energy storage systems such as SMES can significantly improve the stability of the electricity network.

The first commercial application of a SMES system was developed in 1980-1981 in Los Alamos Laboratory, US. It consisted of a 30MJ NbTi unit, with a maximum power output of 10 MW [34], used for low frequency stabilization (0.35 Hz). Since then, a few other major projects have been carried out in the USA, Japan, China, Korea and several European countries and are summarized in Table 1.

Table 1: SMES projects around the world. Data taken from [33]

Superconductor Material	Storage size (MJ)	Application	Country	Year
NbTi	30	Low frequency damping	USA	1980
	100			2003
	1	UPS	Japan	2006
	20	Instantaneous Voltage drop compensation		2004
	2.9	Power System Stability	China	2006
	2	Impulse Power Source		2010
	2.6	Sensitive load protection	Italy	2006
Bi 2212	1	Voltage drop protection	Japan	2009
	0.8	Impulse Power Source	France	2005
Bi 2223	0.15	UPS	Germany	2003
YBCO	2400	Load Fluctuation Compensation	Japan	2010

Most of these projects have employed LTS superconductors and have had experimental purposes. Projects with Type I HTS superconductors have relatively low energy storage capacity, in comparison with Type II superconductors. Besides the ones outlined in the table above, there are several other ongoing projects employing MTS and HTS, one of them being the 48 GJ MgB_2 toroidal system intended for buffering power fluctuations at a rating of 200 MW for up to 4 minutes [35]. Such a high energy capacity is possible due to the low cost of MgB_2 superconductor and because the entire coil will be submerged in a liquid H_2 tank, thus creating a Hybrid energy storage system (HESS). Specific to the applications of SMES in DG, a demonstrator project has been carried by American Superconductor Corporation, which installed six D-SMES units of 3 MJ/3 MW each in Wisconsin to enhance the grid stability [36].

Possible SMES applications in distributed/renewable generation

For satisfying the power requirements of a DG, a SMES installation has to be designed for several MJ level in energy storage and with power outputs of around 1 MW [27] over a few seconds. For this size, a solenoid coil design is the most suitable and brings the lowest cost and complexity.

SMES installations can be used in DG for the following applications:

- **Voltage stabilization**: Can quickly regulate voltage sags, swells or drops [37];
- **Frequency regulation**: Frequency variations can be damped by modulating the real/reactive power [38];
- **Power quality improvement**: In the case of sudden fluctuations in power, SMES systems can quickly inject or absorb real power in the grid [38];
- **Wind and solar photovoltaics (PV) stabilization**: Numerous studies have shown that coupling SMES installations directly to wind or PV installations can vastly improve the voltage stability by either absorbing excessive power when there is extra generation, or by discharging it in the grid if the voltage is suddenly dropping [27, 37];
- **Uninterruptible Power Supply (UPS)**: Can provide protection in case of power outage for sensitive loads[39];
- **Electric Vehicles Charging stations and Vehicle to Grid (V2G) operation**
- **Bulk Energy Storage**: Certain configurations of SMES (series of Force Balanced coils [27]) can be used for storing vast amounts of energy which can be used for peak shaving, contingency or during periods of decreased generation capacity (less windy/sunny days). However, this would bring very high costs considering the present technology status.
- **D-SMES trucks**: Distributed SMES installations can be loaded on trucks and moved between certain grid points for voltage stabilization [27].

Challenges and opportunities

SMES has proven to be a promising energy storage technology that can offer unbeatable response times, power density and reliability in essential DG applications. It has, however, several disadvantages that pose challenges for research in the field of superconductors, cryogenics and power electronics.

Firstly, one of the major impediments of SMES is the high capital cost, especially if levelized to the amount of energy stored. However, a study showed that if a very high storage capacity is considered (over 1 GWh) and for an assumed lifetime of 30 years, a SMES system can be more economical than two of the lowest cost energy storage technologies on the market: Pumped Hydro and NaS batteries [40]. In this estimation, the operational costs have been assumed at 5% of the capital cost per year. This fact combined with a higher adoption of HTS SMES through demonstrators supported by subsidies and investments and a cost reduction of superconductor materials can lead to a cost levelling between SMES and other storage technologies such as secondary batteries or redox flow batteries.

Secondly, the technology for manufacturing high lengths of MTS and HTS wires is still underdeveloped. The process has to be precisely controlled so that the cross section of the wire is constant and a consistent current density can be maintained along its entire length. Alternatively, researchers are exploring ways of doping superconducting materials to increase the critical magnetic field and current at higher temperatures [20].

Integration with renewables

There is a strong drive for migration to a cleaner and more secure energy supply, but the challenges that come along cannot be ignored. SMES systems have a great potential for supporting renewable systems within distributed generation networks, however there is a lack of demonstrators which would provide a deeper insight into the long term behaviour of such systems. Subsidies and investment in such projects could provide researchers and companies with essential data sets that would enable them to investigate the technical, commercial and regulatory aspects of SMES integration, which would lead to a better understanding and development of this technology. Another renewable technology that would unlock the potential of SMES is the LH_2 fuel usage. Fuel cells can be used very efficiently to replace conventional generation in both vehicles and power systems. The LH_2 storage tanks, however, can be used for keeping SMES coils under certain HTS and MTS transition temperatures, significantly decreasing the operating cost and creating the opportunity of a hybrid system [35].

Hybrid Energy Storage Systems

Energy storage systems have different characteristics that make each one suitable in certain applications. It is clear, though, that there is no perfect energy storage technology, so a key solution for improved performance would be to associate complementary storage systems and create hybrid systems. The uniqueness of SMES is given by the high power density, low response time and high efficiency, but it lacks high energy density and it implies high costs. By coupling it with technologies with high energy densities, such as batteries, compressed air storage or pumped hydro storage, a complete hybrid system can be created and used for a wider range of applications, including demand-side energy management with power quality control, peak shaving and voltage stability [41]. Moreover, by forming hybrid systems, the cost can be significantly decreased: for the same energy storage capacity, a HESS with SMES and pumped hydro energy storage can bring savings of over 90% in comparison with a sole SMES systems with the same capacity [27]. Interesting concepts have been developed around the idea of hybrid SMES systems for use in transportation, with the role of SMES being for storing the regenerative braking energy and discharging it to provide boosts [42].

Conclusions

At the moment, the commercial market for HTS SMES is not sustainable, mainly due to strong competitor technologies such as high power batteries, flywheels and compressed air energy storage, storing significant amounts of dispatchable energy, which is more valuable for the network. However, in the context of Distributed Generation, SMES systems can provide services of essential importance such as power stability. More electric vehicles, a higher penetration of small scale renewables, the decrease in superconductor costs along with advancements in performance at high temperatures and manufacturing technologies represent the main drivers for a higher adoption of SMES units, which by 2030 would be able to compete with other storage technologies in more areas.

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