Developmental Challenges of SMES Technology for Applications

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Abstract. This paper reviews the current status of high temperature superconductor (HTS) based superconducting magnetic energy storage (SMES) technology as a developmental effort. Discussion centres on the major challenges in magnet optimization, loss reduction, cooling improvement, and new development of quench detection. The cryogenic operation for superconductivity in this technological application requires continued research and development, especially with a greater engineering effort that involves the end user. For the SMES-based technology to more fully mature, some suggestions are given for consideration and discussion.

1. Introduction

Superconducting magnetic energy storage (SMES) technology development has received a renewed focus worldwide, especially with the use of the high-temperature superconductors of BSCCO, MgB_2, and REBCO. The increased developmental investments are directed to applications related to both traditional electric systems and renewable energy conversion. As a short-term energy storage technology, the SMES can provide the benefits of voltage stabilization (momentary voltage spikes and sags), load fluctuation compensation, and improved power quality [1]. In principle, the SMES possesses characteristics of quick response to energy demand and high efficiency [2]. Additional potential niche application areas may include utility in aerospace propulsion [3] and pulsed power source development [4-5].

Although superconducting machines and devices are widely used in laboratories and hospitals at liquid helium temperatures (e.g. NMR and MRI), many applications using superconductors require higher operating temperatures to be more practical. In the case of the SMES, as various other applications, the use of high-temperature superconductors in these systems is not yet adequately developed to take advantage of the higher current carrying capacity under higher magnetic fields at higher operating temperatures, especially above 20 K. This paper reviews some of recent research and development efforts that have brought the SMES incrementally closer to technology maturation, and provides some future considerations for subsequent development.

2. Recent Progress in HTS SMES Development

2.1. Magnet Design Optimization

To improve the magnet performance, efforts focus in areas of coil/magnet configuration optimization, conductor choice, and magnet geometry designs.

2.1.1. Optimization of Solenoid Configuration

For a solenoid magnet, the magnet's energy storage capacity and the upper limit of the attainable magnet field depend partially on the optimization of the solenoid's aspect ratio. A computation effort was carried out [6] based on HTS ribbon conductor with the same specified conditions: a coil volume of 5000 cm^3, a current density of 211 A/mm^2, and a stress of 500 MPa. It was determined that short coils with thick windings will provide a higher stored energy, which in this case was 4237 kJ. If using this conductor with attributes of 500 MPs stress to make a coil weighing 400 kg and operating at 20 K, the specific stored energy will be more than 10 kJ/kg [6]. Development of this magnet will produce a record of storage capacity per unit mass over the most efficient and elegant NbTi coils [7].

IOP Conf. Series: Materials Science and Engineering **279** (2017) 012013 doi:10.1088/1757-899X/279/1/012013

This leads to another consideration, the optimization of the coil configuration at the end of the solenoid. Toward this end, models have analysed the transport current performance of a high-temperature superconductor coil and demonstrated that relatively large electric fields appear at the coil's edges [8]. Because of these large magnetic fields, design efforts were undertaken to modify the end coils in order to reduce the component of perpendicular field that the coils are subjected to. One means to accomplish this is to make those coils located at the end of solenoid to be separated with graded heights (i.e. reduced pancake height) [8]. This graded heights of the coils will help minimize the amount of conductor that is subjected to the large fields in these locations at the end of the solenoid magnet. Another separate design approach [9] is to make solenoidal coils with an outward step-shaped configuration near the end, i.e., thinner pancake coil with reduced difference between outside diameter and inner diameter. In essence, the design is to minimize the amount of conductor that is subjected to nearly perpendicular fields in the magnet, with the same goal as the other design [8]. For a fixed amount of tape usage in the entire magnet, this step-shaped coils can increase the critical current to about 1.4 times that with the traditional rectangular-shaped coils [9].

2.1.2. Hybrid HTS Magnet Configuration

The hybrid magnet configuration basically consists of two or more different types of conductors with different superconducting materials. Often some of the coils are wound using the same type of superconducting wire. While the use of a single type of wire is convenient, wires can be specially designed for different sections of the magnet. Consider the previous section where the magnetic field imposes more on the two ends of the solenoid. A magnet may be designed to take into consideration the field's directionality. Most companies are already offering different HTS tapes based on the given application, both in performance and size. Although tailored versions of the same HTS material may be a desired choice, the two examples below make use of different generations of HTS wire, 1G BSCCO and 2G YBCO in the magnet design and fabrication.

Based on the behaviour of the critical current of BSCCO and YBCO tapes in external magnetic fields at 77 K [10], i.e., the I_c of BSCCO decreased more than that of YBCO in the same perpendicular magnetic field, the hybrid magnet was built with YBCO coils on the top and bottom ends and BSCCO in the middle, where the perpendicular field is much smaller than at the ends. This hybrid SMES magnet was shown to have stored energy of 1.6 kJ with operating current of 54 A at 77 K, and 6.0 kJ of 109 A at 69 K, respectively. More recently, a conduction-cooled HTS hybrid magnet was reported [11] for a 150 kJ/100 kW SMES system. In this design the BSCCO coils were placed on the two ends of the magnet with YBCO in the middle, which is a reversal to the design mentioned above [10]. For this design, the critical current of a BSCCO coil falls to about one-third of its original value, and that of a YBCO coil falls to about half of its original value.

Other hybrid magnet designs were reported to have achieved record high levels of magnetic field either with different conductors [12], or with same conductor but multiple geometries [13]. These fruitful hybrid magnet developmental efforts suggest that there is potential to be further explored in the magnet design domain to accomplish specific but challenging goals with different applications.

2.1.3. Solenoidal and Toroidal Geometry

Although the solenoidal design is the most common, it is not the only possible configuration. The practical application of SMES entails not only an issue of efficiency, but also nearby exposure to large magnetic fields, among others. A recent effort focused on the development of a toroidal configuration for a high-temperature superconducting SMES, which offered a power rating of 1 MW for a duration of 5 seconds [14]. The effort provided a comparison of the toroidal design with the solenoidal geometry, taking all major factors into account such as conductor/cable choice, sizing of the magnet bore, corresponding coil design, and ac losses using 2G HTS YBCO tape in the form of a Roebel cable. With the same requirement of stored energy being 5.6 MJ, and overall inductance of 1.25 H for the coil to be able to deliver 5 MJ energy in five seconds, both solenoid and toroid magnet design parameters were presented along with the associated field maps, showing constant stray field lines with the solenoidal geometry, and virtually fully contained field with the toroidal geometry. The total length of HTS tape for the toroid and solenoid was 59.8 km and 68.1 km, respectively.

Numerical calculations and simulations additionally showed that for the same field level, only slightly higher losses per cycle per unit length of conductor occurred for the toroid, despite the much higher transport current of 300 A for the toroid (188 A for solenoid) [14]. This suggests that the losses are dominated by the applied field. The distribution of the length of the HTS tape versus the perpendicular field, to which the HTS tape is subjected when the SMES operates at the maximum current, was calculated for both the toroid and solenoid. By combining the losses per unit length of the conductor corresponding to each level of perpendicular field with the actual length of the conductor that is exposed to that level of field, a quantitative estimate was determined. While this is not a total loss since some other factors are not included in the consideration, it does provide a loss indicator which was 76.7 kJ for the toroidal and 31.0 kJ for the solenoidal design [14]. It is important to note that the toroidal configuration in this example is designed with pancake coils aligned in the toroidal geometry leaving spacings between the coils on the outside of the donut shape. In this case, the perpendicular field on the conductor is over the outside portion of each coil for the toroid, and for the solenoid it is only at the end region of solenoid (albeit the whole coil at the ends), thus, it can be understood that greater ac losses may well be the case for toroid than solenoid. Even though there are relative lower field(s) in the toroidal geometry than in the solenoidal geometry, it is noted that the field(s) is more even across the entire length of the magnet in the toroid.

Further simulation design effort for maximum magnetic energy storage with optimization [15] for both solenoid and toroid showed that the upper limit level of stored energy in solenoidal SMES is estimated to be 2.2 times of that of toroidal SMES with the same length and type of the conductors. However, lower leakage flux density, lower tensile mechanical stresses, and lower magnetization loss--all of these are desirable characteristics—are only provided by the toroidal magnet. It has also been shown that the toroidal magnet for SMES can be further improved by making the coil as mainly racetracks rather than circular shape, and by making additional inner racetracks inside the main racetrack so that the entire coil becomes a constant field unit [16]. This constant field toroidal SMES magnet configuration is estimated to be able to provide 1.6 times more stored energy than the non-constant field counterpart. However, the complexity of the design and the difficulty of manufacturing this device poses a greater challenge at present technology readiness levels [16].

Unlike a hybrid solenoid magnet discussed above, the same toroidal geometry of a 2.5 MJ SMES by either REBCO or BSCCO conductors were also reported [17] to show that YBCO may provide advantages of smaller magnet size, less total conductor length, and smaller ac losses; but the high magnetic flux density in YBCO toroid may lead to very high mechanical stresses.

2.2. Loss Reduction in Magnet

When rapidly adding or removing electrical current from the SMES magnet, losses will be generated with these fast current level changes. It is not only due to the hysteresis and coupling losses of the superconductor, but also to the eddy current losses in the metals used to make the high-temperature superconducting wire, for example, substrates and stabilizers. A 'loss indicator' has to be developed for the magnet design effort with the information and knowledge on the loss properties of the superconducting wire/tape as conductor, cable and coil as component, and magnet as device. Some of the reported work is discussed below, although more effort to understand all the factors that contribute to the losses and to understand the interplays/interactions among those factors should come along in the near and far future.

A 28 pancake coil unit made of BSCCO conductor was simulated [18] to reveal the ac loss distribution among the coils under the condition of steady state current I_o = 80 A and a linear dynamic current I_d = 3A in 2 seconds duration. The results showed that higher ac losses occurred with pancake number 1 to 6 and 23 to 28 at the both ends of the solenoid, while 7 to 22 in the middle had smaller ac losses. When

I_d changed from 3 A to 20 A, the increased losses were mostly concentrated in pancake number 1 to 6 and 23 to 28, whereas number 7 to 22 had minimal increase in losses.

Experimental investigation of four YBCO coils [19] that were wound with YBCO with no insulation, YBCO co-wound with copper, YBCO co-wound with stainless steel, and YBCO co-wound with Kapton under varying operating current conditions from 10 A to 80 A at 150 Hz frequency, showed that ac losses for the no-insulation coil (bare wire itself) and copper co-wound coil are much lower than for those using stainless steel and Kapton materials along the conductor, and it was reasoned that lower radial resistance in the formers allows bypassed ac current through the turn-to-turn contact.

Analysis of Eddy current losses on a 2.5 MJ HTS toroidal SMES [20] with YBCO conductor illustrated that engineering effort on the thermal conduction plate and the centre ring was effective to reduce the Eddy current losses. The engineering effort includes making a slit in the bobbin to reduce the induced Eddy current in the metal based thermal conduction plate and in the centre ring, with some trade-off in the mechanical integrity of the SMES structure.

2.3. Cooling Improvement

For conduction cooling, it was reported that paraffin impregnation of copper and stainless steel laminated tapes can improve the cooling effects by increasing the contact areas between the copper-stainless steel tape and the cooling copper plate [21].

Mixed cryogen cooling techniques also showed improved thermal stability with the components of solid nitrogen-liquid nitrogen, solid nitrogen-liquid neon, and solid argon-liquid nitrogen [22], with the case of solid cryogen used alone as the baseline for comparison.

Based on cooling requirements needed by different SMES applications, a variety of cryocooling approaches are available for consideration in the design of SMES system, examples include closed re-condensing cryostat, variable operating frequency of the compressor to allow adjustment of refrigeration capacity at 4 K, 20 K, and 77 K, in order to reduce power consumption [23]. High-efficiency conduction cooling technology development was also reported recently [24].

For better cooling control and management, a promising development was reported on built-in cryogenic oscillating heat pipe (OHP) in HTS magnet [25]. The cryogen media employed in the oscillating heat pipe can be hydrogen (17-30 K), neon (26-39 K), or nitrogen (67-91 K). Moreover, a flat-plate cryogenic OHP has been developed, which is suitable for embedding in magnet windings to increase the thermal conductivity and the thermal diffusivity at the same time [26].

2.4. Quench Detection and Protection

Traditional quench detection for LTS magnet is based on small voltage signal changes caused by normal transition, but generally this approach is difficult to apply to HTS because of the very slow velocity of normal-zone propagation and relatively large voltage noise from other parts of the system compared to the local normal-zone voltage. However, an accurate and sensitive measurement of the dissipative voltage on an HTS coil was demonstrated by a new detection circuit design with two stage SMES detection scheme [27] that is able to detect a quench regardless of the coil discharge voltage in operation.

A new approach to current detection for HTS coil for quench event was proposed in 2011 [28] and has been in development with simulation and experimentation [29-30]. The concept is to design laminated bundled YBCO conductor that consists of four insulated parallel tapes labelled as 1, 2, 3, and 4, see Figure 1 and 2. This laminated bundled conductor is wound as Pancake Coil 1. Pancake Coils 2, however, is made similarly with four insulated parallel tapes but labelled as 2, 1, 4, and 3. Pancake Coil 1 is connected to Pancake Coil 2 by the four tapes with only the same number as 1 to 1, 2 to 2, 3 to 3, and 4 to 4. In this way, supercurrent carried by tape 1 in Coil 1 will only go to tape 1 in Coil 2, in which tape 1 is no longer in the edge position as in Coil 1, but in the position neighbouring with tape 2 and 4 as indicated by 2, 1, 4, and 3 that are defined for Coil 2. Tapes 2, 3, and 4 in Coil 1 will be also connected to corresponding 2, 3, and 4 in Coil 2 as defined as 2, 1, 4, and 3. Therefore, four tapes 1, 2, 3, 4 in Coil 1 switched their positions in Coil 2 by design as 2, 1, 4, and 3. The design for Coil 3 and 4 with the

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locations of four tapes is 3, 4, 1, and 2 for Coil 3, and 4, 3, 2, and 1 for Coil 4. Tape 1 will be connected only to tape 1 in all the coils such that supercurrent will travel at four different locations defined in each

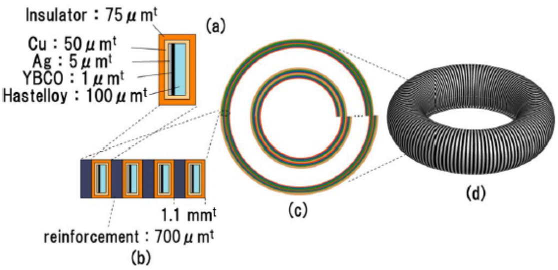

Figure 1. Schematic drawings of (a) YBCO tape, (b) laminated bundle conductor, (c) pancake coil, and (d) toroidal coil. Adapted with permission from Ref. [28], copyright 2011, IEEE.

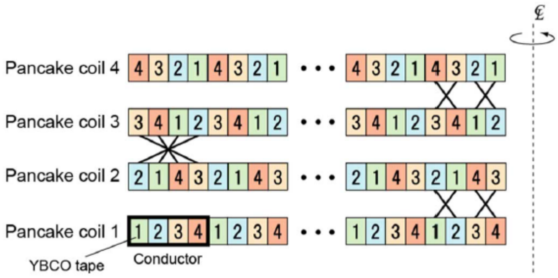

Figure 2. Schematic drawing of transposition in a unit coil. A unit coil consists of four pancake coils, each of which is wound with a laminated bundle conductor composed of four YBCO tapes. Adapted with permission from Ref. [28], copyright 2011, IEEE.

coil from 1, 2, 3, and 4 in Coil 1 and will end up in Coil 4 with 4, 3, 2, and 1. Tape 2, 3, and 4 will follow the similar pattern respectively. This supercurrent transposition will allow observation of any non-uniform current in YBCO laminated bundled conductor, and the non-uniform current occurring can be indicative of a possible quench event. This new coil design with the connection pattern established the base for current based quench detection method [28]. Experimental verification [30] of the concept showed that local normal transition (i.e. the non-uniform current occurring) on one tape could be detected with high accuracy and the associated temperature change was less than 15 K. In principle, once a local normal transition is detected by monitoring the supercurrent level in tape 1, 2, 3, and 4, measures can be taken to protect the tape/coil/magnet.

2.5. Fast Response to Power Demand and High Energy Density

In order to charge-discharge the superconducting coils as fast as possible to meet power demand, a recent paper [31] experimentally examined the effect of improved winding geometry with a quasi-turn-to-turn incomplete insulation that used a narrowed polyimide film of 3.5 mm for a 4.8 mm width YBCO conductor tape. This coil winding additionally created six times more contact area for the coil to contact with cryogen in comparison to conventional fully insulated winding in which only the top and bottom areas of the pancake are actually in contact with the cryogen. Due to this increased cooling contact margin, experimentally the coil could work under over-current conditions and generate relatively higher magnetic field linearly up to ~1.5 times its critical current.

Besides the superconducting magnet, the development of the interface between the dc magnet and the ac power system, as well as the control system made of efficient electronics, are all equally challenging undertakings. As a possible strategy, a fuzzy logic control method was demonstrated [32]. In comparison to metallic oxide semiconductor field effect transistor (MOSFET) based bridge-type chopper controlled SMES system, the SMES with the fuzzy control power electronics will have better robust performance in ideal and disturbance situations (such as in response to power demand in real world). Also communication between the controller and SMES components was shown to be more effective and faster so that shorter response time and safer operation of the SMES system may be ensured [32].

As an energy storage device, the energy density of SMES is always an important characteristic for technology development. Several papers have been published on optimization and design considerations of high-energy density SMES [4-5, 33]. To design and develop a high performance SMES with capability to deliver large amounts of energy in a short time, multiple parameter studies and detailed optimizations are needed in order to determine the best suitable topology of SMES [32] to meet those requirements. In terms of optimization, even if only a strongly constrained problem is given, a large space of solutions could still be available [4], which implies that significant effort in simulations and computations are not only highly desirable, but also should be widely employed to enhance the effectiveness and efficiency of the technology development endeavour. In a word, efforts in simulation, computation, and optimization are necessary for HTS SMES development. For example, it is very helpful and beneficial to have the knowledge and understanding that in order to reach the goal of an energy density of 20 kJ/kg (cold mass), we would need, at minimum, the conductor to sustain a hoop stress of 500 MPa with engineering current density (J_e) of 600 A/mm^2, and to fabricate a magnet that has a storage capacity of 1 MJ [5] as the core component for the HTS based SMES, among others.

3. Major Engineering and Technology Challenges

Multi-component/parameter interactions with high sensitivity in undetermined magnitude might contribute to the overall complexity of superconductivity based technology, especially with respect to applications under dynamic conditions that SMES will see. The significant progress reported in the literature contributions cited in this paper (not an exhaustive coverage) suggests more fundamental knowledge be learned and engineering expertise gained for further development of the SMES technology. Although some brief discussion is outlined in the following three sections, many real practical issues, as noted, are more complex than what a few examples can fully represent and illustrate.

3.1. Temperature-related influences

At least for now, effective management of heat flux dynamics in magnet with the best possible heat transfer techniques proves to be of help to the development of SMES technology.

3.2. Multi-component interactions

The superconductors, cables, and magnets are the key components of the SMES, and Ref. [5] provided useful information for building a SMES magnet with a targeted energy density of 20 kJ/kg. Computation and simulation applying well-defined conditions may produce reasonable and meaningful results. In reality, there could be some uncertainties introduced from the process of manufacturing of the conductors/cables, as well as the winding process of the magnet. The consistent performance of the conductors is desired in the first place, and the overall consistency of the magnet as the core component is also expected. The fabrication process to make a magnet may bring in additional variations that should be understood in terms of electric, magnetic, mechanic, and thermal interactions in the configuration of the magnet. And those variables should be well controlled in order to achieve the overall desired performance of the SMES technology. Furthermore, how the dynamic energy input and output conditions presented by real application affects the performance of the SMES magnet should be also learned. After all, a higher degree of optimization effort through extensive testing and design iterations will be essential to ensure the consistency and reliability of a matured technology.

3.3. Specific electromagnetic effects

To better contain the stray magnetic field while also increasing the energy capacity of a racetrack toroidal magnet, the effort described in [16] has shown that the individual coil unit can be made with constant field characters, resulting in 1.6 times more stored energy, see Section 2.1.3. However, due to the concerns of the complexity and difficulty related to the design and manufacturing, it was not recommended as a practical approach by the researchers. This is understandable, given the current knowledge level, engineering ability, and projected economic viability of the constant field racetrack toroidal SMES design. Nevertheless, potential in the current technology landscape still exists and should be further explored in terms of better understanding the electric and magnetic effects in other possible geometries where the magnet components may be arranged in such a way as to achieve any specific effects. This is still a relatively less developed area but with possibility of new discovery and innovation.

4. Summary/Future Considerations

There are some future considerations for the subsequent development of HTS SMES.

4.1. Simulation and computation effort

Extensive simulations and computations should be performed on the SMES system design along with experimental verification and validation. It will be important to map out the three dimensional space of the associated magnetic field for particular designs resulting from the electric current in the SMES coils. Additional developmental issues for modelling and simulation include structural and heat management parameters.

4.2. Testing effort

Conduct comprehensive and thorough testing at component and system levels. A higher degree of optimization through extensive testing and design iterations for all aspects is needed to ensure the consistency and reliability of any superconductor product. This is not simply testing the SMES functionality by itself but especially for its given use. Testing needs to be developed that will determine the utility of SMES prototypes in an electrical grid for achieving its desired purpose. This will entail a comparison to other systems that may achieve similar goals.

4.3. Collaboration

Enhance concerted/coordinated effort to develop collaborations to achieve unrealized synergies that will increase the outcome of the R&D effort, which will accelerate the pace of superconducting technology development. This must include the technology users to ensure proper development of the system.

4.4. Readiness of technology

The ultimate determining factors for a useful technology, including superconductivity, will be the higher maturity levels that can be reached and the system affordability. The superconductivity technology must offer consistent performance in applications with the necessary reliability. Again, this must all be ultimately accomplished with the system being offered at a reasonable cost.

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