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Design, fabrication and cryogenic testing of 0.6 MJ SMES coil

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Our centre has taken up a project of development of superconducting magnetic energy storage (SMES) technology to have better power quality for its accelerator program. In the first phase, a prototype cryostable coil has been designed, fabricated and commissioned in a standard bath cryostat. The various parameters of the magnet coil have been determined in order to maximize stored energy taking into consideration the constraints like geometry, maximum current limit etc. Winding tension (Pre-stress) of 13.6 MPa is maintained to keep radial stress compressive in all possible scenarios (i.e. during cool-down, excitation, etc.). Mylar is used for turn to turn insulation while 1 mm thick glass epoxy based picket fences (G-10) are placed symmetrically azimuthally for layer to layer insulation as well as to ensure passage of liquid helium inside the winding.

Cryostability of the conductor implies more copper to superconductor ratio and is desired as far as stability of the coil is concerned. Cryostability, however may degrade when helium vapor is trapped in between two layers. Therefore, quench behavior of the magnet along with protection system has also been studied and implemented. This paper describes issues related to design study, fabrication and also cryogenic test results of the coil.

1. Introduction

A rising demand for a high quality power supply has resulted in a growing interest in superconducting magnetic energy storage (SMES). Variable Energy Cyclotron Centre, Kolkata has taken up initiative to design and develop SMES system in the 11th 5 years plan. Our centre is developing a liquid helium (LHe) bath-cooled NbTi SMES system that can mitigate peak power of 0.1 MW with stored energy of 0.6 MJ. The primary objective of this pilot project is to develop expertise in superconducting coil technology and related Power Conditioning System (PCS), and study of issues related to high magnetic field transients and reliable operation.

Various parameters of the magnet coil have been optimized to maximize the stored energy taking into consideration the geometrical constraints of the existing facility in the centre. Detailed quench study has been performed and a unique protection scheme of modular type dump resistors and three channel Quench Detection Circuit (QDC) have been developed accordingly. The paper outlines issues related to coil design, thermal and magneto-structural stress, quench protection scheme for safe and reliable transient as well as hold mode operation necessary as an SMES coil and cryogenic test result. Eddy current induced force on helium vessel that could limit fast field transient has also been investigated.

2. Description of SMES system

The main part of the system is a superconducting coil, which stores energy in the form of a magnetic field generated by DC current flowing through the coil and the power conditioning system. The superconducting coil is contained in a standard magnet dewar (SMD-20, Oxford Instruments make) and is liquid helium bath-cooled.

The basic topology of the Power Conditioning System (PCS) conceived is as shown in Fig. 1.

The major components of the PCS consists of step down transformer, rectifier and DC–DC chopper for charging/discharging of the SMES coil, a voltage source inverter (VSI) for mitigating the power line sag, deriving energy from the DC/DC-chopper-SMES coil assembly, passive filters for suppressing unwanted harmonics, injection transformer and digital signal processing (DSP) based control and instrumentation for voltage sag detection and mitigation. The fabrication of the various sub-assemblies of the PCS is currently under progress.

3. Magnet coil

Many coil configurations can be designed depending on the size and application. The typical configuration is a solenoid or a toroid. A solenoid type cryostable coil cooled by pool boiling helium is designed with passive shielding arrangement.

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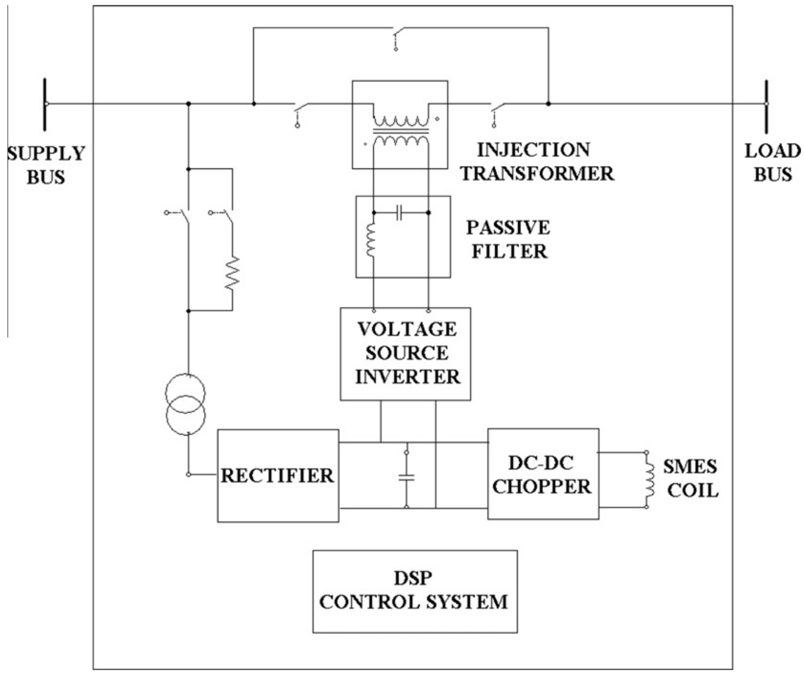

Fig. 1. Overall SMES system perspective.

Table 1
Coil specification.

Parameters	Values
Coil type	Solenoid
Operating current (A)	800
Inductance (H)	1.87
Stored energy (MJ)	0.6
Peak coil field (T)	6.6
Coil inner diameter (mm)	132.5
Coil outer diameter (mm)	416
Height (mm)	790
No of layers	36
No of turns/layer	154
Cable length (km)	5
Winding tension (MPa)	13.6
Number of joints	2

Table 2
Conductor (NbTi/cu) Specification.

Parameters	Values
Conductor dimension (mm)	2.97 × 4.79
Number of strands	1
Diameter of strand (mm)	1.29
Number of filaments	500
Diameter of filament (μm)	40
Filament twist pitch (mm)	<12.7
Overall Cu to Sc ratio	20
Critical current (at 5.5 T)	1080 A
RRR	~150
Insulation	Mylar and glass epoxy

The coil parameters have been optimized in order to maximize stored energy considering the constraints like coil outer diameter (to contain inside existing magnet dewar), maximum current limit (critical characteristics with 30% margin), hoop stress at inside layer (in median plane), etc. for a given length and type of conductor. The critical current margin (30%) corresponds to a temperature margin (T_{cs}–T_{op}) of 0.7 K for the coil operating at maximum field level up to 7 T. This temperature margin has been kept considering different operational scenarios such as flexibility of operating temperature from 4.2 to 4.4 K and any other small disturbances that might occur in the coil. When fully charged margin ensures superconducting operation of the magnet. The maximum operating current is found to be 800 A with the corresponding stored energy of 0.6 MJ. The design specification of the coil is as shown in Table 1.

A mylar tape of 100 μm thick and 3 mm width is used to provide insulation between turns. The coil consists of 36 layers, and a gap was placed with 1 mm thick spacers between two layers for cooling channel and interlayer insulation. The conductor used is NbTi alloy with following specification as in Table 2.

Several authors [1,2] have considered various aspects of stress analysis problem in thick superconducting solenoid. When the cool-down process undergoes from room temperature down to 4.2 K, various parts of the coil experiences differential thermal stress. As the coil consists of copper, superconductor and insulation materials, the equivalent modulus of elasticity of the coil is considered. Several analysis were performed to determine a minimum winding pre-tension (13.6 MPa in present design) that ensure the conductor remained compressed (i.e. radial stress is negative) against the bobbin when both cool-down and magnetic load are applied. Several studies have also been done in order to reduce conductor hoop stress at inner turns varying bobbin thickness. An acceptable bobbin thickness of 5 mm is chosen considering both hoop stress and structural load point of view. For solenoid type coil, dominant stress term is circumferential tension or hoop stress that becomes maximum in the median plane ($y = 0$) [3]. The stress presented in Figs. 2 and 3 indicate hoop stress and radial stress distribution respectively at the median plane (A–B) in the coil.

The steady state heat load of the magnet cryostat without excitation is measured to be around 1.5 W at 4.2 K. Photograph of the coil during assembly inside cryostat is as shown in Fig. 4.

The fringe magnetic field developed outside the cryostat is very significant (~1200 G) and ferromagnetic shielding (mild steel) has been incorporated around the cryostat to reduce it to a value less than 100 G. The measured fringe magnetic fields at 1 m away from magnet dewar in different vertical positions is found to be maximum 85 G at full excitation of the coil.