The Mechanical Design Optimization of a High Field HTS Solenoid

S. L. Lalitha, *Member, IEEE*, and R. C. Gupta

Abstract—**This paper describes the conceptual design optimization of a large aperture, high field (24 T at 4 K) solenoid for a 1.7 MJ superconducting magnetic energy storage device. The magnet is designed to be built entirely of second generation (2G) high temperature superconductor tape with excellent electrical and mechanical properties at the cryogenic temperatures. The critical parameters that govern the magnet performance are examined in detail through a multiphysics approach using ANSYS software. The analysis results formed the basis for the performance specification as well as the construction of the magnet.**

Index Terms—**Finite-element analysis, high temperature superconductor (HTS) magnet, solenoid, superconducting magnetic energy storage (SMES).**

I. Introduction

HTS SOLENOID capable of generating a central field of 24 T at 4 K, was designed and built at Brookhaven National Laboratory for a prototype superconducting magnetic energy storage (SMES) device with a storage capacity of 1.7 MJ [1]. The SMES technology is a promising solution for the effective integration of renewable energy sources such as solar power, wind and wave into future power grids.

This paper focuses on the electro-magnetic and mechanical design analysis of the magnet assembly. The primary goals are to ensure that the mechanical stress and strain generated within the magnet are below the acceptable limits of the mechanical strength of the HTS tape, and that the support structure can safely contain the Lorentz forces and minimize the motion of the HTS tape in the coils. A detailed parametric analysis of several initial geometries was performed to meet the original target specification of a 2.5 MJ HTS magnet. These analysis results formed a baseline for the further design optimization of a 1.7 MJ magnet.

II. Magnet and Materials

A. Conceptual Details of the Magnet Assembly

The prototype magnet consists of two co-axially nested solenoids with a mechanical support structure made of

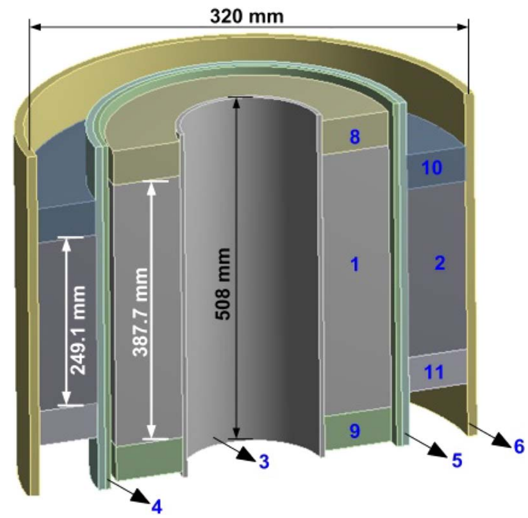

Fig. 1. Cut-away view of the conceptual design geometry of 1.7 MJ HTS magnet. The main components are (1) inner solenoid, (2) outer solenoid, (3) and (5) bore tube for the inner and outer solenoid, (4) and (6) outer tube for the inner and outer solenoid, and (8) and (9) end plates for the inner solenoid and (10) and (11) outer solenoid.

304 grade stainless steel (Fig. 1). The support structure of each solenoid includes a bore tube, outer tube and a pair of support plates. Table I lists the relevant parameters of the final magnet geometry.

Each solenoid consists of a series of identical single pancake coils (SPC). Each SPC is paired with an adjacent SPC into a double pancake coil (DPC) by a splice joint on the inner surface of the coils [2]. The bore tube serves as an initial alignment structure for the pancake coil assembly. Each coil stack is axially restrained by support plates fitted at the top and bottom ends and finally secured inside the outer tube. The other components of the solenoid assembly, not shown in Fig. 1, are (1) mylar spacers to provide electrical insulation between the SPCs, (2) copper discs to facilitate good thermal conduction between adjacent DPC units and (3) a fiberglass over-band to provide extra reinforcement and a uniform support surface to the outer tubes, and to electrically insulate the coil stack from the outer tube.

B. HTS Tape

The magnet is designed with 12 mm wide, SCS12050-AP type, 2G Rare Earth Barium Copper Oxide (REBCO) tape (manufacturer-SuperPower Inc.) suitable for high field (> 16 T) magnet applications. This material offers excellent current-carrying capacity at low temperatures and high fields,

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TABLE I
DESIGN PARAMETERS OF THE 1.7 MJ HTS MAGNET

Parameters	Unit	Value	
Operating temperature	K	4	
Design field	T	24	
Design current	A	700	
Total inductance	H	7	
Stored Energy	MJ	1.7	
Number of nested solenoids		2	
		Inner solenoid	Outer Solenoid
Number of single pancake coils (SPC)		28	18
Inner diameter (ID) of SPC	mm	101.6	223.1
Outer diameter (OD) of SPC	mm	194	302.8
Radial thickness of the fiberglass insulation	mm	1.5	2
Height (H) of the solenoid	mm	387.7	249.1
Total length of HTS tape (L)	km	3.1	3.5
Bore tube – radial thickness; height	mm	6.35;508	5.21;508
Outer shell- radial thickness: height	mm	7.75;508	6.60;508
Support plate-radial thickness; height	mm	47.75; 25.4	41.91;25.

and robust mechanical properties governed by a 50 μm thick Hastelloy substrate. The electroplated copper (Table II) surrounding the tape surface provides good electrical stability.

III. DESIGN CRITERIA

The basic assumption is that each solenoid together with its support structure forms a mechanically independent unit and that two such units can easily be put together using alignment pins. This design feature allows independent handling of the solenoid during the construction and provides convenient maintenance. The radial dimension of the whole magnet assembly was kept less than 320 mm.

Stable operation of the magnet requires that the mechanical stress and strain induced by the Lorentz forces must be less than the conductor's acceptable limits and that the support structure can safely contain the Lorentz forces and minimize the motion of the HTS tape in the coils. The stress-strain tolerance limit of the coils was set in accordance with the equivalent experimental data at 4 K of the HTS tape samples of similar geometrical specifications [3]. The tensile strength is prominently determined by Hastelloy, whereas the yield strength depends on the fraction of copper stabilizer with respect to the substrate. The tape performance is reversible below a strain limit of 0.6%. The tensile stress limit is ~650 MPa and ~500 MPa for 12 mm tape with a copper stabilizer thickness of 60 μm and 100 μm respectively [3]. The mechanical support structure parameters are designed by taking into consideration the thermal contraction and electromagnetic forces in the coil assembly. The stresses generated in the support structure must be less than 525 MPa (yield strength) at 4 K and its elastic strain limit is 0.45%.

TABLE II
MATERIAL PROPERTIES

Parameters	Unit	Value			
HTS coils					
Relative permittivity		1			
Coil type		A	B	C	D
Thickness of HTS tape	μm	120	120	160	160
Thickness of the surround copper stabilizer layer	μm	65	65	100	100
Thickness of SS ribbon	μm	25	50	25	50
Design current density @ 4 K and700 A	A/mm^2	348	296	281	246
Young's Modulus at					
297 K	GPa	106.5	117.4	89.8	100.9
4 K		112.5	125.3	95.2	107.9
Shear Modulus at					
297 K	GPa	39.9	44.1	33.5	37.7
4 K		42.5	47.5	35.8	40.7
Poisson ratio					
297 K		0.33	0.33	0.34	0.34
4 K		0.33	0.32	0.33	0.33
Co-efficient of thermal expansion	10^{-6}/K	8.34	8.59	8.28	8.49
Stainless steel support structure					
		at 297 K		At 4 K	
Young's Modulus	GPa	190		210	
Shear Modulus	GPa	74		82	
Poisson ratio		0.28		0.28	
Co-efficient of thermal expansion	10^{-6}/K	9.83			

IV. FINITE ELEMENT ANALYSIS

The magnet parameters are optimized through a multi-physics approach using ANSYS Parametric Design Language (APDL). The analysis of the magneto-thermal-structural model is performed sequentially. The axial symmetry of the solenoid geometry and the loading simplifies the three dimensional solid model to a two dimensional (2D) shell model. Taking into consideration the mirror symmetry along the radial mid-plane, only a quarter of the geometry of the magnet assembly has been considered for the design analysis.

A. Model Features

The magneto-structural analysis requires two finite element models. The electromagnetic (EM) model uses the eight node, coupled field, 2D axi-symmetric element, PLANE 53. A sufficiently large air enclosure is included in the model to practically achieve an infinite boundary condition. The thermal-structural (TS) model employs the eight node, coupled field, 2D axi-symmetric structural element, PLANE 183. The degrees of freedom are appropriately constrained at the radial as well as the axial plane. This model also takes into account the interaction along any material interface by means a pair of surface-to-surface contact elements, CONTA172 and TARGE169. Here the material interface refers to surfaces between the adjacent SPC, stainless steel or other components coming in contact with each other. A total of ninety nine pairs of contact elements are present in the model.

B. Material Properties

The material properties are assumed to be isotropic and are temperature dependent as shown in Table II. To avoid oversize meshes, smeared properties are considered for the coil windings. The weighted average contribution from different components in the pancake coil assembly such as the HTS tape, stainless steel ribbon, mylar spacers, copper discs and also the fiberglass insulation layer on the outer surface of the coil winding is estimated using the standard rule of mixtures. The contact surfaces between SPC and the structure and between the adjacent DPC units are assumed to be frictionless. A bonded contact is established between the pair of SPCs constituting a DPC unit. For the EM analysis, a relative permittivity equal to one has been assigned for all component parts.

C. Loads

The load transfer method is used and the following analysis is performed under static load conditions. The EM model considers the scenario of just energizing the cold magnet at 4 K. It computes the magnetic field and the electromagnetic force distribution in the magnet assembly. The excitation current (Table I) is kept the same in both solenoids. The TS model considers the entire magnet assembly at two different stages of operation: after cool down from room temperature (297 K) to the operating temperature (4 K) and the subsequent magnetic excitation. The temperature distribution in the magnet assembly is assumed to be uniform at 4 K. The thermal loads are evaluated first by applying a uniform thermal gradient of 293 K to all component parts. Thermal loads are then coupled with Lorentz force to generate the mechanical stress-strain distribution in the entire magnet assembly. A non-linear contact analysis is performed prior to the cool-down analysis to check the initial contact status at the material boundaries and to ensure that coupled-field loads are appropriately transferred in the structural analysis. The effect of pre-stress on the magnet assembly is not included in the TS model.

V. Parametric Study

We have arrived at the final geometrical specification of the magnet assembly through a detailed parametric analysis of its critical parameters such as the radial width and axial thickness of the coils and the support structure. The starting model contains two co-axial solenoids separated into three coil blocks with a relatively complicated support structure. In particular, the adjacent coil blocks in a solenoid are separated by a beam structure that is also attached to the bore tube and the outer tube. The purpose of having the beam structure is to keep the mechanical stress and strain on the narrow face of the HTS tape within the allowable limits. Optimization of the radial dimensions of the outer tube of the inner solenoid and bore tube of the outer solenoid was very crucial to minimize the hoop stress and hoop strain in the whole assembly.

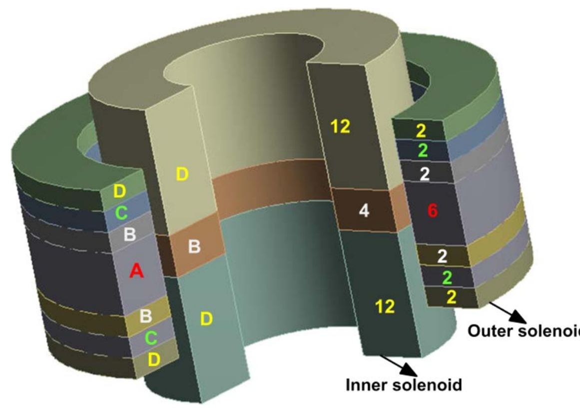

Fig. 2. Lay-out of the coils in the 1.7 MJ HTS magnet after grading the coils with a view to improve the magnet performance and mechanical stability. A, B, C, and D denotes the type of the coils based on the combination of HTS tape and co-wound stainless steel ribbon used. Refer to Table II for details. Numbers of each type coils in the solenoid are also shown.

The field strength and mechanical stability margin are further improved by carefully grading the coils in the magnet assembly (Fig. 2) and by replacing the intermediate beam structure with extra coils. This process simplifies the geometry of the 1.7 MJ magnet. The construction method is to co-wind a series of pancake coils (type A, B, C, and D as listed in Table II) using HTS tape with either 65 μm or 100 μm thick copper stabilizer and a slightly wider stainless steel ribbon with a thickness of either 25 μm or 50 μm [2]. The ribbon provides turn-to-turn electrical insulation and helps minimize the radial stress accumulation. For fixed inner and outer dimensions, each combination of HTS tape and stainless steel ribbon results in a different number of turns (N) in the coil [2]. The current density in the coil depends on N and its mechanical strength is additionally influenced by the co-wound ribbon (Table II). The coils are arranged in a sequence as shown in Fig. 2 to strike a balance between the field strength and mechanical robustness. In particular, the coils offering the highest current density and elastic modulus (type A or type B) are placed at the middle section of the solenoid to achieve the highest field strength and to withstand the higher hoop stress and strain acting on the HTS tape. Similarly, the coils with a relatively lower current density, but high mechanical strength are placed at the end-plane to withstand the maximum axial stress and strain on the narrow surface of the tape. The results of the coupled analysis of the final magnet geometry are discussed in the following.

VI. Analysis Results of 1.7 MJ Solenoid

The nested solenoids (Fig. 1) are electrically connected in series. Fig. 3(a) and (b) shows the magnetic field distribution in the solenoids at the operating current of 700 A. The middle coils in the solenoid experience the maximum axial field [Fig. 3(a)]. The axial field component produces an outward radial force which in turn causes a circumferential (hoop) stress on the HTS tape [Fig. 4(a)]. The hoop stress and hoop strain [Fig. 4(b)] are the maximum at the center of the magnet assembly (Table III) and are sufficiently below the acceptable limit of the HTS tape [3]. The end coils experience the maximum radial field component [Fig. 3(b)] and the resultant (axial) force component

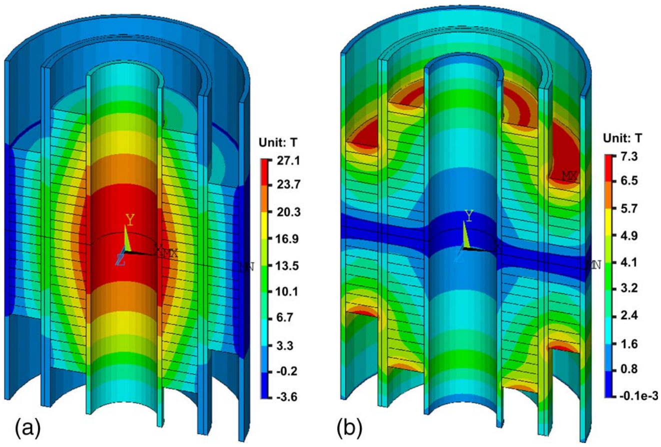

Fig. 3. (a) Axial field and (b) radial field distribution in the inner and outer solenoid at a design current of 700 A. Refer to Table III for details.

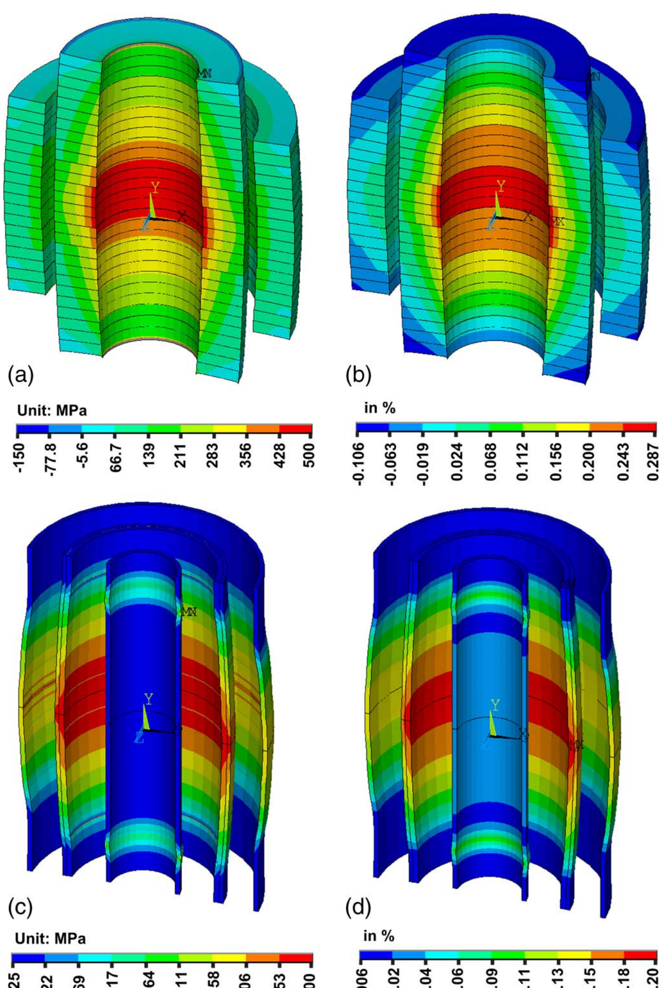

Fig. 4. Hoop stress distribution in the (a) HTS solenoid and (c) support structure. Similarly, the hoop strain distribution in the (b) HTS solenoid and (d) support structure are also shown. The end plates are not shown in the plots. Refer to Table III for details.

squeezes the coil stack towards the mid-plane. The peak axial compressive stress in the middle coils is less than 120 MPa, a guideline based on the 77 K measurements of typical HTS coils [4]. The radial stress is compressive in nature and it helps in managing the hoop stress distribution. Moreover, the tensile stress and strain generated in the support structure are well within its elastic limits [Fig. 4(c) and (d)]. It ensures that the mechanical support structure is robust under the operating environment of the magnet.

TABLE III
ANALYSIS RESULTS OF 1.7 MJ SMES MAGNET

Parameters	Unit	Peak value	
		Inner solenoid	Outer solenoid
Cumulative Lorentz force Radial ; axial	MN	15.2; -3.1	4.8; -3.6
Radial stress; Radial strain	MPa; %	-35; -0.06	-20; -0.0
Axial stress; Axial strain	MPa; %	-103;-0.19	-86; -0.15
Hoop Stress; Hoop strain	MPa; %	490; 0.41	178; 0.19
Support structure components	stress;strain (MPa; %)		
	Radial	Axial	Hoop
Outer tube (inner solenoid)	-74; -0.08	-54; -0.08	397; 0.2
Bore tube (outer solenoid	-21; -0.05	-59; -0.08	363; 0.18
Outer tube (outer solenoid)	-35; -0.04	-22; -0.04	313; 0.15

VII. CONCLUSION

The performance of the HTS solenoid and the design of the magnet support structure are optimized through a coupled field parametric analysis using ANSYS. The computed stress and strain distribution in the magnet assembly is found to be sufficiently below the allowable value of its component materials. This ensures that HTS tape performance remains reversible under the high field and high stress generated in the magnet assembly and that the magnet support structure is mechanically stable under such environments.

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