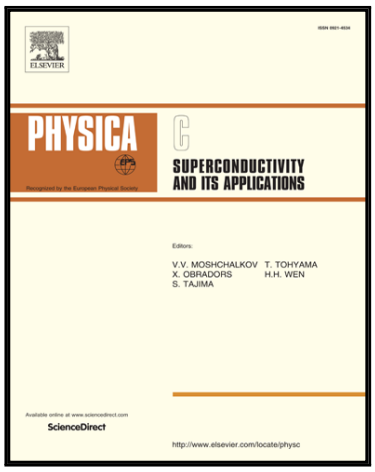
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Numerical Analysis on 10MJ Solenoidal High Temperature Superconducting Magnetic Energy Storage System to Evaluate Magnetic Flux and Lorentz Force Distribution

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Highlights

- Solenoidal geometry has been used for energy storage.
- 2-D Axisymmetric Model has been used to model the superconducting coil.
- Superconducting magnet is required to be cooled at 14K using cryocoolers.
- Operating currents significantly affect the length of the superconductor.
- Magnetic field and Lorentz forces have been evaluated.

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Abstract

Due to fast response and high energy density characteristics, Superconducting Magnetic Energy Storage (SMES) can work efficiently while stabilizing the power grid. The challenges like voltage fluctuations, load shifting and seasonal load demands can be accomplished through HTS magnet as this device has a great potential to supply power for a time span varies from few seconds to hours. Solenoidal configuration has been widely employed (over toroidal) in the development of SMES prototypes as it is simpler to manufacture and allows an easier handling of the mechanical stresses imposed on the structure due to Lorentz forces. A micro-SMES of capacity 10MJ can be employed to mitigate the challenges like load leveling, dynamic stability, transient stability, voltage stability, frequency regulation, transmission capability enhancement, power quality improvement, automatic generation control, uninterruptible power supplies, etc.

In this work, solenoidal configuration has been engaged in the development of 10MJ SMES Magnet using 2G (SuperPower, YBCO having Tc=90K @0T) High Temperature Superconducting (HTS) tape. The superconducting tape has been cooled at 14K using conduction cooling. The effect of maximum operating current (3250A, 2600A, 1950A and 1300A) on the inductance, maximum storable energy and length of superconductor has also been evaluated for a constant deliverable energy of 10MJ. A numerical analysis is done on 10MJ HTS SMES where perpendicular field of 3T has been considered. The effect of aspect ratio (solenoidal height to bore diameter ratio) on the normal component of the magnetic field has also been assessed. Lorentz forces (N/m^3) have been evaluated in the superconducting domain. It has been concluded that it would be beneficial to operate at higher currents (i.e. more current through single tape) as it can reduce the total length of the superconductor. The perpendicular component of magnetic flux for the analysis is found to 2.96T which is less than 3T.

Keywords: YBCO superconductors, HTS SMES, Lorentz force, Solenoidal Magnet, Superconducting Magnetic Energy Storage.

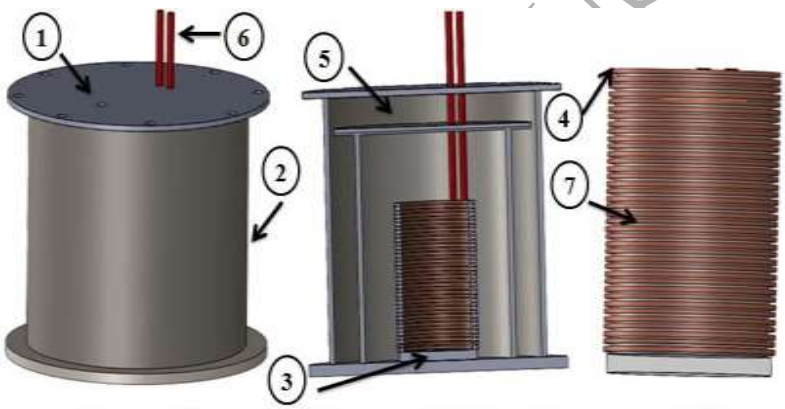
1 Introduction

Real time energy/power storage is one of the promising technologies for suitable power quality and for increasing the availability of renewable sources. Several energy storage technologies like mechanical (Compressed Air Energy Storage, Flywheel Energy Storage, Pumped Storage Hydropower etc.), electrical (Capacitor, Supercapacitor, Magnetic energy storage etc.), electrochemical (batteries), thermal and chemical energy storage exist, each offering specific performances which varies according to the applications. Among these, SMES (superconducting magnetic energy storage) is a real time energy/power storage device which offers important advantages including fast response time from stand-by to full power, high deliverable power, a virtually infinite number of charge/discharge cycles without degradation and high roundtrip efficiency[1][2]. Various superconducting materials like Low Temperature Superconductors (LTS) [3]–[5], 1st generation High Temperature Superconductors [6]–[8] and 2nd generation High Temperature Superconductors [9]–[12] have been incorporated till today in the development of

Superconducting Magnetic Energy Storage systems . However, it has been noticed that the 2nd generation HTS tapes are more efficient than other superconducting materials due to their higher current carrying capabilities.

India has announced its targets to create smarts grids at generation and distribution level. SMES has enormous capability to be a significant component of the smart grids as it can store large amount of energy (from kiloJoules to GigaJoules) and deliver the same whenever required for a time ranging from milliseconds to hours at the user end. In the present study, it has been proposed to install SMES device at the distribution level where a power of 1MW for 10seconds is available to overcome power interruptions. Possible applications of proposed 10MW SMES include load leveling during peak loads, dynamic stability at the user and generation level, transient stability at the user end, voltage stability, power quality improvement, uninterruptible power supplies, etc.

Also, SMES can be employed as an effective alternative while stabilizing the unsteady power source such as sunlight and wind power, as it has much longer lifecycle than the contending technologies like secondary batteries or condensers that deteriorate via charging and discharging [13]. One of the major advantage of the SMES coil is that it consists high power densities thus can deliver power from few seconds to hours effectively. It has been found that SMES technology have been successfully developed by Korea Electro-Technological Research Institute, (KERI) Korea [14]–[16], Kyushu Electric Power (KEP), Japan [17][18] and China Electric Power Research Institute (CEPRI) China [19]–[21].



1. Cryocooler Port; 2. Shell; 3. Supporting Structure; 4. HTS Coil;
5. Vacuum; 6. Current Leads; 7. Non-Metallic Spacers

Figure 1 Schematic of Solenoidal Magnet [22]

SMES is a DC device consisting mainly four major units; a superconducting coil, power conversion/conditioning unit, currents leads to transmit power and cryogenic cooling system. The development of HTS SMES involves inclusive studies of power systems, superconductors, cryogenics and vacuum technology. SMES system will demonstrate its effectiveness only when the each sub-system works optimally. Cryogenic system is needed to be installed in order to keep the temperature of the high temperature superconductor below its critical values. The schematic of solenoidal magnet is shown in Figure 1where HTS coil is wounded on a pancake and arranged axially one over another to form a solenoidal magnet. Two types of geometrical combinations have been employed in the development of SMES till today; solenoidal and toroidal. It has been found that the solenoidal arrangement is simpler to manufacture and allows an easier handling of the mechanical stresses imposed on the structure due to Lorentz forces[23]. Moreover, for isotropic superconductors, the solenoid allows minimum wire consumption and signifies the most cost effective solution[24][25]. During charging and discharging, SMES magnet experiences cyclic loads caused by large Lorentz forces and such forces may cause structural instability of the HTS coil by imposing large stresses and strains in the superconducting tape. With the increase in the energy storage capacity and magnetic flux density (B), the magnitude of such forces is found to amplify immensely [19][26]–[28]. Therefore it is

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required to consider the Lorentz force distribution while designing the HTS SMES as these can create mechanical instabilities to the SMES structure and may cause failure.

2 Design of 10MJ Solenoidal Magnet

The superconducting domain is having 2nd Generation (2G) HTS tapes manufactured by SuperPower whose properties are tabulated in Table 1[29]. 2G HTS tapes have been incorporated in the design of 10MJ SMES as they have higher critical currents than 1G tapes[15] which implies more current can be transported through each tape. The width of the tape is 12.2mm including Kapton film for the insulation. The thickness of SC tape is 0.36mm with having 0.05mm of copper stabilizer on the both sides. The critical current of this Superconducting (SC) tape is 323A at 77K self field. It has been found that the critical current of this tape is very high at 0K temperature. It is very expensive to achieve 0K temperature cryogenically therefore in the present study, 14K temperature has been selected from the literature[30] and this temperature can be achieved by installing GM cryocoolers that can attain this temperature for the cooling of the magnet through conduction cooling [31]. However, even in order to keep 14K temperature of the system, various insulations has to be chosen which are capable of protecting the device from heat-in-leaks that may occur due to conduction, convection or radiative mode of heat transfer. The HTS SMES is designed to be cooled at 14K through conduction cooling in order to transport more current through a single tape as the critical currents are significantly affected by the operating temperatures and the perpendicular magnetic field. This implies at 14K more current can be circulated through the coil with minimum consumption of the superconductor which will reduce the cost of the device to a significant level. Figure 2shows the critical current dependence on perpendicular magnetic flux density at 14K for the SC tape [30]. It can be observed from the plot that the critical current of the SC tape is found to decrease with increase in perpendicular magnetic flux density at 14K. To quantify the ratio of the critical currents (14K/77K) for different perpendicular magnetic fields, in the present work, an attempt has been made to fit this curve with polynomial fit *Equation 1* and the coefficients of this fit are given in Table 2 along with the standard errors done in estimating the coefficients.

Table 1 Specifications of HTS tape

Articles		Values
Bare Conductor	Width	12.1mm
	Thickness	0.15mm
	Cu Plating thickness	0.05mm
Insulation	Polyamide film	25mm, 30% over rapped
Conductor including insulation	Width	12.2mm
	Thickness	0.38mm
Critical Current	77K, Self field	323A

$$I_c\ Ratio(14K/77K) = \phi_1 + \phi_2 B + \phi_3 B^2 + \phi_4 B^3 + \phi_5 B^4 \quad (1)$$

Where B is the perpendicular magnetic flux density evaluated in Tesla (T), ϕ_1, ϕ_2, ϕ_3, ϕ_4 and ϕ_5 are the correlation coefficients whose values are available in Table 2. This develop correlation can be used to evaluate the I_c of HTS tape (manufactured by SuperPower-specifications given in Table 1) at 14K for a range of perpendicular magnetic flux density (0T to 8T).

It has been found that the single HTS tape can carry 650A of current if the perpendicular magnetic flux limits to 3T. In order to ensure the protection of the system, the load factor of 68% is to be considered in this study as in the literature researchers [32][33]–[35] have used load factor between 65-70%. As the delivering power is 1MW this implies that the coil cannot be discharged below I_{min} if the deliverable power P has to be ensured. Therefore, more than one tape is required to maintain the current greater than 1kA.Also, in order to lower the inductance of the coil, a

current of 3250A is chosen for this study and to achieve such a large current five superconducting tapes are staked one over the other. It has been noticed that with the drop in maximum operating current from 3250A (5 tapes) to 1950A (3 tapes), the maximum energy is found to increase drastically as shown in Table 3.Figure 3 shows the effect of maximum current flowing through the coil on the length of the superconductor and it can be noticed that with decrease in current, the length of the superconductor is found to increase. Also, it can be observed that at higher aspect ratio, more length is required to deliver same amount of energy.

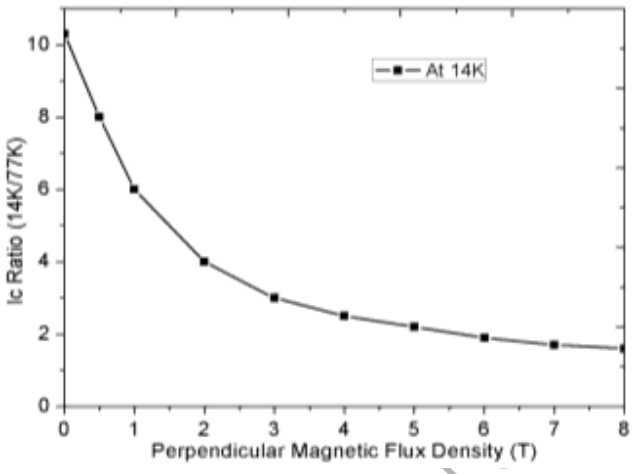


Figure 2 Critical current Vs normal magnetic flux at 14K.

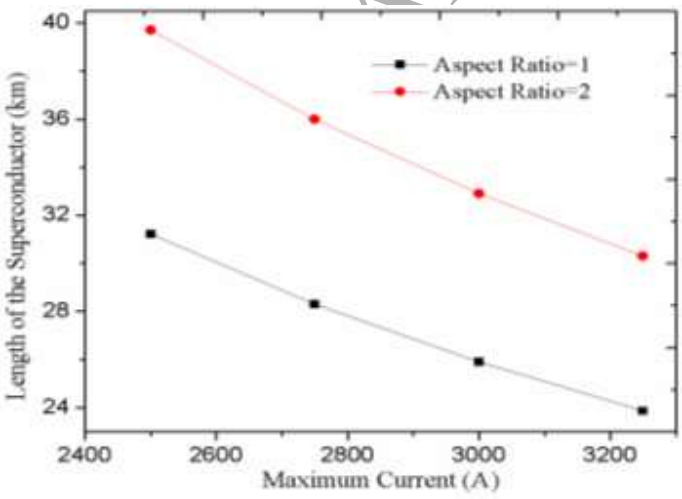


Figure 3 Length of Superconductor vs Maximum Current

Table 2Correlation Coefficients for Polynomial fit

Coefficients	Values	Standard Error
ϕ_1	10.30866	0.07595
ϕ_2	-5.50355	0.16249
ϕ_3	1.51155	0.08952
ϕ_4	-0.1916	0.01723

ϕ_5	0.00896	0.00107

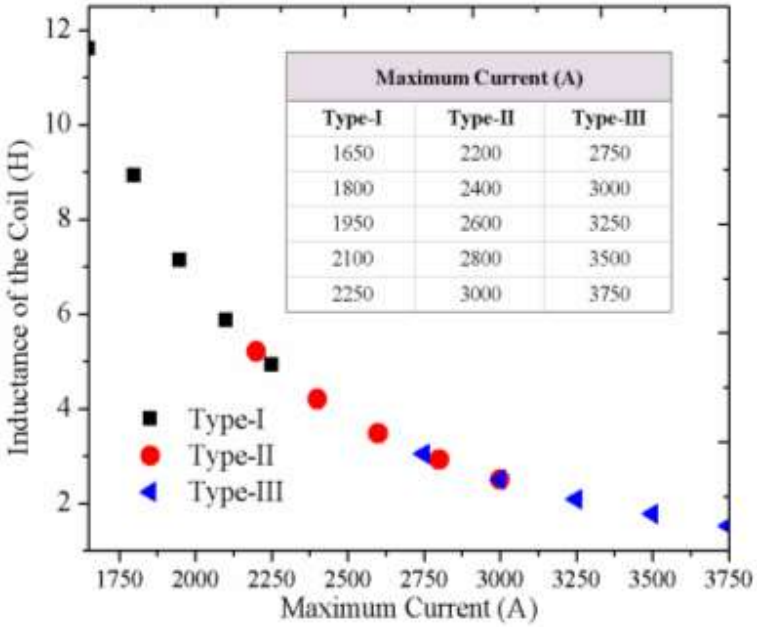


Figure 4 Coil Inductance Variation with Maximum current

This is due to the fact that there is a sudden increase in the inductance of the coil as it varies inversely with I^2_{max} (*Equation 2)*and the variation in the inductance of the coil with the maximum current flowing through it is available in Figure 4.Once the deliverable energy/power gets fixed along with the minimum current that is being required to ensure the power availability, the inductance of the coil gets affected with the change in the maximum current (*Equation 2* and *Equation 3*). Coil inductance is needs to be as minimum as possible as it affects the maximum current to reach its steady state therefore a current of 3.25kA has been chosen for the present study.

$$E_{max} = \frac{1}{2} L\, I^2{}_{max} \quad (2)$$

$$\Delta E = \frac{1}{2} L\left(I^2_{max} - I^2_{min}\right) \quad (3)$$

It has been noticed that the length of the superconducting tape is not get affected by the number of tapes stacked one over to other rather it get affected by the maximum current flowing through single tape i.e. less superconductor is required if 750A of current is passing through single tape than 550A. However, one has to take higher load factor in order to increase the maximum current and compromise with the safety of the SC tape. Also it has been noticed that higher aspect ratios will result in increasing the normal component of the magnetic field which is not required as it would affect the maximum current. Also, a solenoidal magnet having higher aspect ratios would result in to increase in the overall length of the superconductor which will further create economical issues.

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Table 3Effect of Maximum Current on E_{max} and Inductance of the Coil

I_{max} (A)	I_{min} (A)	E_{max} (MJ)	Deliverable Energy (MJ)	Inductance (H)
3250	1000	11.05	10	2.092
2600	1000	11.74	10	3.472
1950	1000	13.57	10	7.136

Table 4Design Parameters of 2D Axisymmetric Solenoidal Magnet

Item	Quantity
Operating Current	650A
Operating Temperature	14K
Number of SPCs	152
Inner diameter of solenoid	924mm
Outer diameter of solenoid	975.4mm
Distance between SPCs	0mm
Load Factor	0.68
Voltage of DC bus, V_{dc}	1 kV
Maximum Current, I_{max}	3.25kA
Minimum Current, I_{min}	1kA
Maximum Stored Energy, E_{max}	11.05MJ
Deliverable Power	10MW
Operating Time	10s
Reference Magnetic field	4.5T
Maximum parallel field	3.55T
Maximum perpendicular field	2.94T
Length of Superconductor	30.31km
Critical Tensile Strength	550MPa

3 Computational Analysis on HTS SMES

A computational analysis has been done on 10MJ SMES device, having bore diameter of 924mm and aspect ratio of 2. Since the tape width is 12.2mm thus 152 Single Pancake Coils (SPCs) are arranged in axial direction of the solenoid. The model is symmetric about *r=0* and the parameters for axisymmetric model have been enlisted in Table 4. The geometry is considered to be uniform rectangular domain as the gap among the SPCs is kept to zero. Where α is the index and for this analysis its value is 30.Faraday's Laws (*Equation 4, Equation 5 and Equation 6*) have been incorporated in order to perform time dependent analysis on 10MJ of HTS SMES using COMSOL MultiPhysics®. In order to model the superconducting behavior of the solenoidal coil Power Law (*Equation 7*) has been incorporated.

$$E = \rho(\nabla \times H - J_e) \quad (4) \quad \textit{For Air Domain}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (5) \quad \textit{Applicable for both Domains}$$

$$E = E(\nabla \times H) \quad (6) \quad \textit{For Superconducting Domain}$$

$$\boldsymbol{E} = \boldsymbol{E}_o \left(\frac{\boldsymbol{J}}{\boldsymbol{J}_c} \right)^{\alpha} \qquad (7)$$

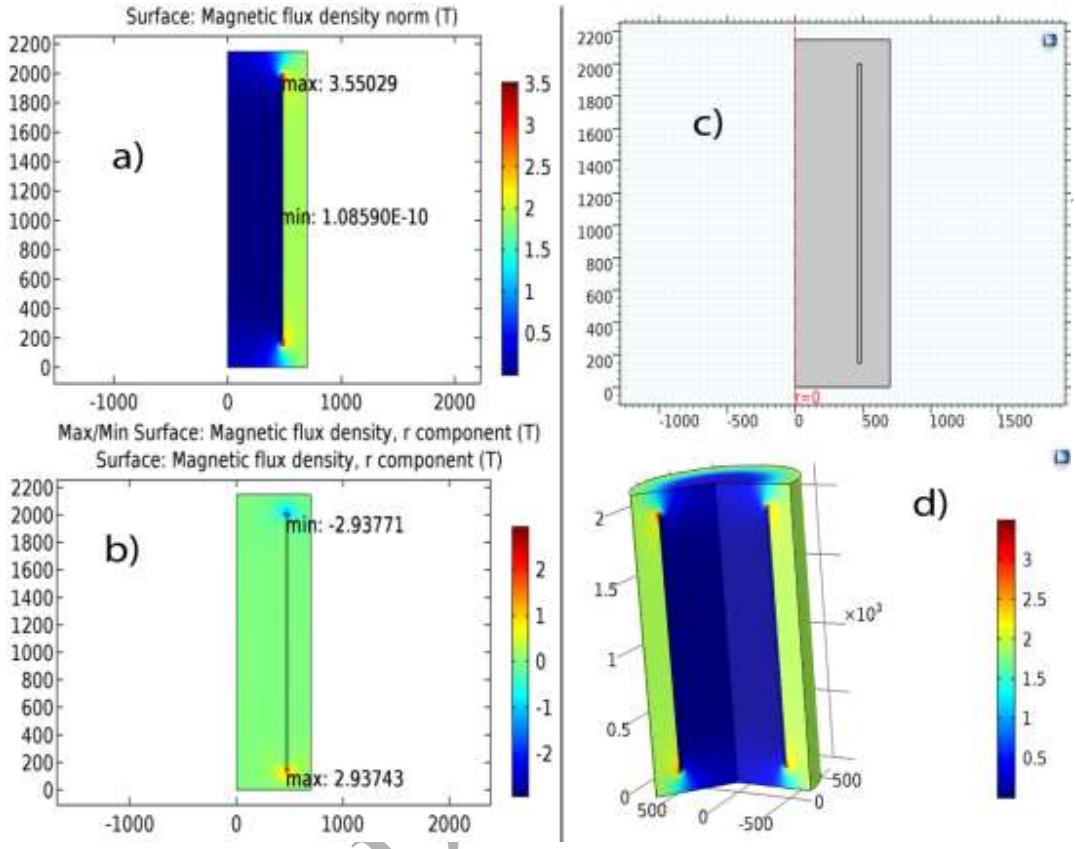


Figure 5 Magnetic Flux Density Surface Plot (a) normB (T), (b) Perpendicular B (T), (c) 2D Axisymmetric Model, (d) Magnetic Flux Density normB (T) for Revolved Geometry

A magnetic flux (normB) of 3.55T has been achieved and Figure 5 (a) shows that the maximum field is present at the solenoidal ends and minima is found at middle. Figure 5 (b) represents the surface plot for the perpendicular magnetic flux which is found to be maximum (2.94T) at the corners which means that higher forces will be generated at the both ends of the solenoidal coil. Also it can be noticed that this value is found to be lower than the designed value i.e. 3T.Figure 5 (c) represents the schematic of the axisymmetric model having coil thickness of 25.48mm and height 1848mm. Figure 5 (d) represents the magnetic flux (normB) distribution for revolved geometry and it indicates that the normB is having negligible magnitude near solenoidal axis and found to be maximum at the corners of the magnet. The time dependent analysis has been done for 1 second with having a time interval of 0.05second. The curves plotted shows the values of the parameters at different time interval.

Figure 6 indicates the magnetic flux (norm component) distribution along the axial direction and from the plots it can be seen that the magnetic is found to be maximum at the solenoidal ends which further implies that there will be large Lorentz forces present at the ends of the solenoid. Multiple lines show the magnetic flux distribution for different time steps ranges from 0 to 1second. Figure 7 shows the distribution of *Br* at (a) inner periphery, (b) outer periphery, (c) a distance 700mm from solenoidal axis. It can be noticed that the perpendicular component is found to be maximum at the solenoidal ends. Thus in order to decrease the stray fields(Br)strategies has been developed as available in literature[36]**.**

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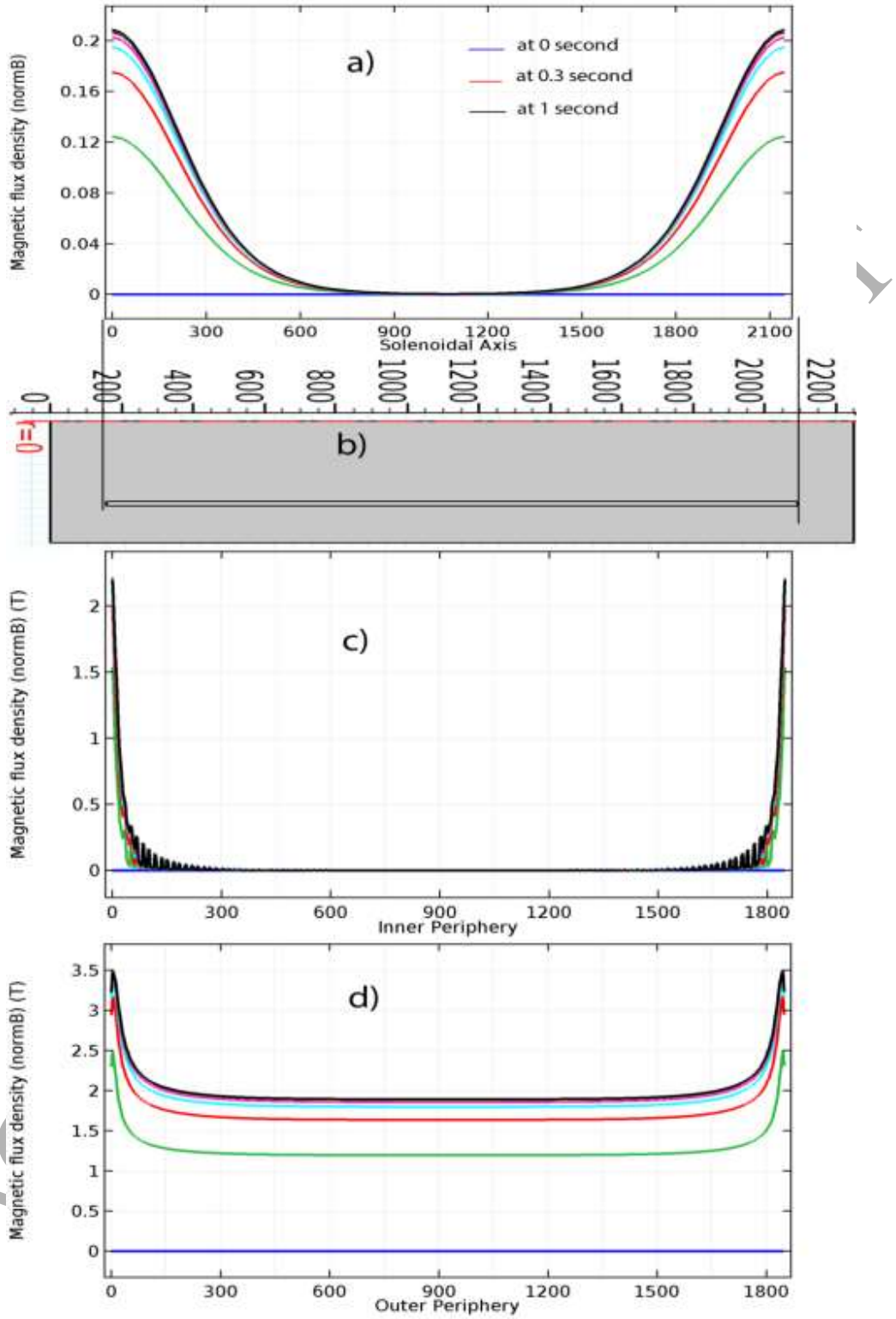


Figure 6Magnetic Flux Density (normB)Distribution (Axial) at various time interval (a) At Solenoidal Axis, (b) Solenoidal geometry revolved 90^{o} in clockwise direction (c) At Inner Periphery (r=462mm), (d) At Outer Periphery (487.48mm)

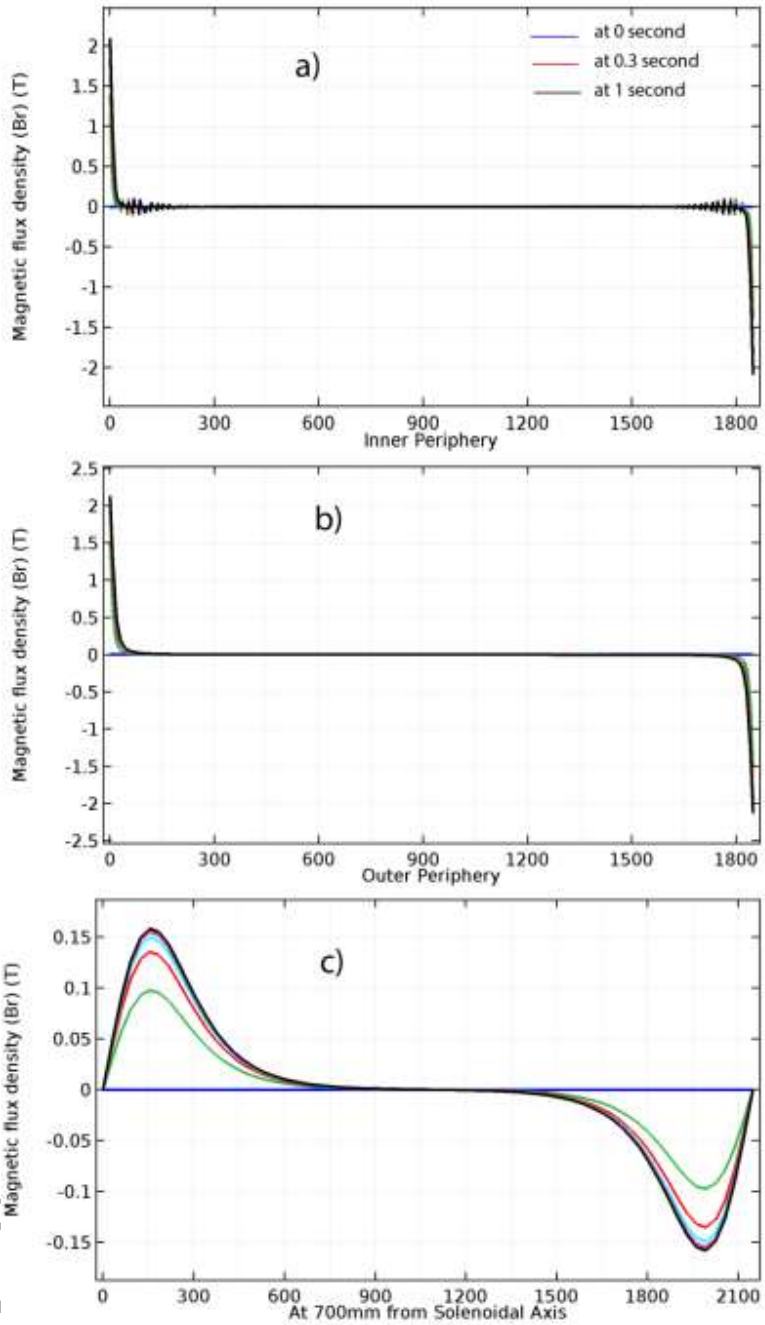


Figure 7Magnetic Flux Density (Br) Distribution (Axial) at various time interval (a) At Inner Periphery (r=462mm), (b) At Outer Periphery (487.48mm), (c) At 700mm from the solenoidal axis.

Figure 8 shows that the normB and Br is found to be higher at the solenoidal ends and it can also be found that the magnetic flux starts with lesser values and with the time it achieves its maximum. Negative sign is just represent the magnetic polarity i.e. either field is coming in or leaving out of the pole.

4 Lorentz Force Distribution

Lorentz forces developed in the coil are due to the magnetic field which is found to be maximum at the both ends of the solenoid. This will result in the excessive stresses which must be withstood by the superconducting tape. The

maximum tensile stress arising on the superconductor can be estimated by using *Equation 8* where 'r' is the ratio between the outer and inner diameter of the solenoid[37]. For the designed coil to be acceptable it is required that the calculated tensile strength should lower than the rated strength for the HTS tape otherwise other materials have to be taken into account in order to provide additional supporting structure for increasing the overall strength.

$$\sigma_{max} = \frac{1}{2} J_{max} B_{max} D_{sol} \frac{1}{r-1}\left[\frac{2r(7r^2+r+1)}{9(r+1)} - \frac{5}{12}\left(2r^2+r-\frac{3}{5}\right)\right] \quad (8)$$

$Where,\ J_{max} = Maximum\ Current\ Density, A/m^2$

$B_{max} = Maximum\ Magnetic\ Flux\ Density(T)$

$D_{sol} = Bore\ Diameter\ of\ the\ Solenoid$

Figure 9 represents the Lorentz force distribution at inner (a) and outer (b) periphery. Maximum forces can be found near the ends of the solenoidal coil as the magnetic field was found to be higher on these locations. It has been found that the calculated maximum tensile stress is found to 22.3MPa (using *Equation 8*) which is well below the critical value see Table 4. Thus the chosen design is found to secure as per mechanical point of view.

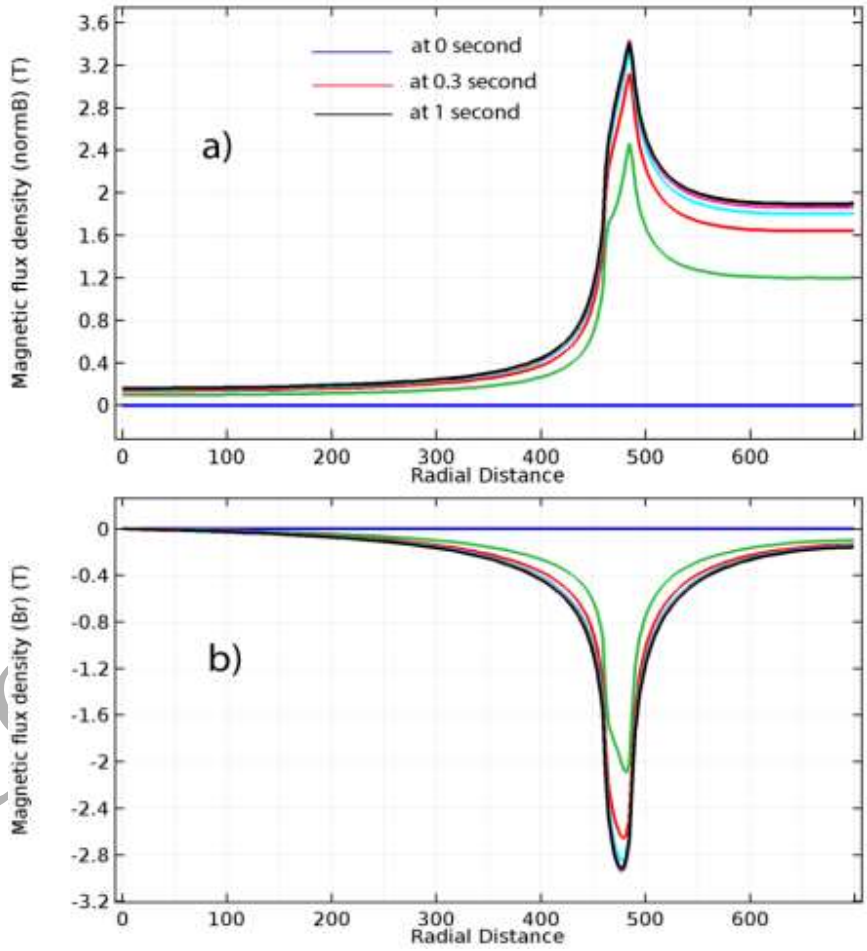


Figure 8 Magnetic Flux Density Distribution (Radial) (a) normB (z=150mm and z=1998mm), (b) Br (z=150mm and z=1998mm).

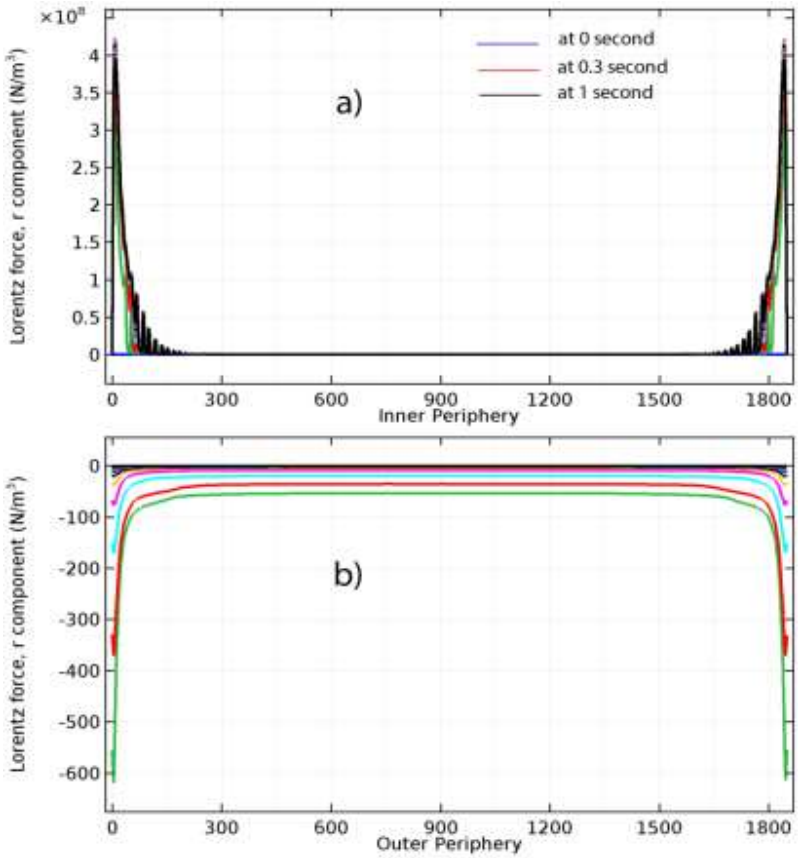


Figure 9 Lorentz Force Distribution (r-component) (a) Inner Periphery, (b) Outer Periphery.

5 Conclusions

In the present work, electromagnetic analysis on 10MJ of HTS SMES has been done using axisymmetric 2D model. It has been observed that the length of the superconductor is affected by maximum operating currents i.e. lesser SC tape is required for higher currents (i.e. 3250A needs less superconductor to store deliverable energy than 3000A, 2750A, 2500A etc.) which further reduce the total cost of the device as superconducting tape itself contribute to about 40-50% cost of the total expenditure. Therefore, it is recommended that one should use higher operating currents at relatively low aspect ratios if objective function is to minimize the length of the superconductor as higher aspect ratio will result in larger normal fields and also increase the length of the superconductor (Figure 3). In the design of 10MJ SMES, it has been found that the perpendicular magnetic flux is limited to 2.94T, thus the design is safe as the chosen field was 3T. Lorentz forces are found to very large thus special attention is needed to be pay while designing the supporting structure for the SMES.

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