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SMES-PCC COMPUTER PROGRAM DEVELOPMENT FOR STUDYING AND DESIGNING THE SUPERCONDUCTING MAGNETS FOR ENERGY STORAGE PURPOSE

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ABSTRACT

The superconducting magnetic energy storage (SMES) is an excellent energy storage system for its efficiency and fast response. After the invention of high-temperature superconductors (HTS), it has become more interesting for commercial usages. In this paper, the principle of the SMES system has been explained. After that, SMES-PCC computer program has been demonstrated and its function and utility in calculating the inductance, energy and some other parameters required for the designing of the SMES coils have also been discussed. This program can also be used to observe the characteristics of the parameters. Calculations have been shown for a specific design of superconducting magnet made of BSCCO tape conductor for a SMES system. A case study for geometric optimization of solenoid coil has also been presented, showing that the size ratio in the solenoid arrangement plays the most influential role in determining the amount of energy stored in the system.

Keywords: Storage systems; principle; inductance calculation; characteristics

INTRODUCTION

Superconductivity is a phenomenon shown by certain metals and alloys where the electrical resistance completely disappears when the metal is cooled at a particular temperature, called the transition temperature or cryogenic temperature. After the discovery of Superconductivity back in 1913 by H. K. Onnes, there have been many efforts led to utilize the characteristics in the power development sectors. But the main reason for not implementing such devices that constitutes the phenomenon of superconductivity was the extremely low temperature and the related expenses of keeping at that temperature. But for the last few decades, there have been many developments in this particular field. Many new materials that can exhibit superconductivity with a high transition temperature (Tc) have been introduced and they have successfully increased the applications of superconductivity with less expenditure than before.

Superconducting magnetic energy storage (SMES) is one of the applications of superconductivity. SMES stores energy in the form of a magnetic field produced by DC current flowing through a coil made of superconducting material. Discovery of high-Tc materials as well as the development of other equipment makes SMES a better option in energy storage facilities [1-3]. The advantages of SMES is due to the fact that the critical current Ic does not exceed in the superconducting wire, there is no mechanical motion of the wire, there is no energy loss (even standby losses) of the stored energy as dc current circulates without dissipation in the zero resistance environment of a superconductor. The essential parts of a SMES system [4,11] consist of superconducting coil with the magnet (SCM), power conditioning system (PCS), cryogenic system (CS) and control unit (CU). Of them the superconducting magnet coil or inductor is the most important for technical as well as electrical parameters to be considered. As it is well known, the storage energy depends on fixed operating current (of course below the critical current) and the inductance of the magnet coil, the possible way of increasing energy storage is the increasing inductance. In order to calculate the inductance of a coil (say, for Solenoid arrangement) easily and efficiently, we have developed a computer program called SMES-PCC.

PRINCIPLE OF SMES

When we pass DC current in a normal wire the energy would be dissipated due to the resistance of the wire. But when we pass the flow of DC current in a wire made of the material that possesses superconducting behavior, a magnetic field generates due to the flow under proper condition. This means that the energy will be stored in the form of a magnetic field in a persistent mode and will remain the same until utilized. A very stable DC current will also exist in a closed circuit due to the zero resistance environment of a superconductor. This principle works on a superconducting coil storing electrical energy in the form of magnetic field and the stored energy will be inductive. For more information, the readers are referred to see Ref. [5] and references therein. Now the question is how SMES work? The procedure would be to store excess energy that is generated during off-peak periods when the load is low and later to deliver it during peak-load periods. SMES may be able to store all the energy generated by a large power plant during hours of operation and then to discharge or deliver it into the power grid as well as to the residential customers when needed during peak consumption.

The energy stored in a closed circuit can be written in the form,

$$E = \frac{1}{2} LI^2 \qquad \text{--------------} \ \mathbf{(1)}$$

Where, L and I are the coil inductance and current ratings determine the maximum energy that can be drawn or injected by a SMES coil.

The balance energy equation for a SMES system can be written as [5, 6],

$$E_b = \frac{1}{2} LI^2(t) - P_0 t \qquad \text{--------------} \ \mathbf{(2)}$$

Where P_0 is the power provided by the SMES to protect load. The maximum power available from the SMES is represented by

$$P_{max} = \frac{P_0}{\sqrt{1-\lambda}}, \qquad \text{--------------} \ \mathbf{(3)}$$

Where 'λ' is the discharge depth defined as the ratio of the deliverable energy to the stored energy. We can calculate the value of discharge depth from the following equation [5, 6],

$$\lambda = \frac{P_0 t_p}{\frac{1}{2} L I^2} \qquad \text{--------------} \ \textbf{\textit{(4)}}$$

Where 't_p' is the load protection time.

INDUCTANCE AND THE SMES-PCC PROGRAM

In principle, the energy stored by a SMES system is related to the inductance of the superconducting coil and the current flow through it. While designing a SMES system the calculation of inductance of the coil is very important to understand how much energy can be gained from this and how to accumulate or connect the other components including the protection requirement. Basically there are two kinds of SMES magnet topologies, solenoid and toroid.

The inductance of a solenoid coil according to Wesby (1960) can be written in the form [5, 7, 10],

$$L = \pi \mu_0 \left(\frac{N^2 D_i}{16\beta}\right) \frac{(\alpha+1)^2}{1+0.9\left(\frac{\alpha+1}{4\beta}\right)+0.64\left(\frac{\alpha-1}{\alpha+1}\right)+0.84\left(\frac{\alpha-1}{2\beta}\right)} \ \ldots\ldots (5)$$

Where N is the number of turns of the solenoid; D_0 is the outer radius and D_i is the inner radius of the solenoid coil. α and β are the size ratios which are determined by the following formulas,

$$\alpha = \frac{D_0}{D_i} \quad and \quad \beta = \frac{H}{D_i}, \ \ldots\ldots\ldots\ (6)$$

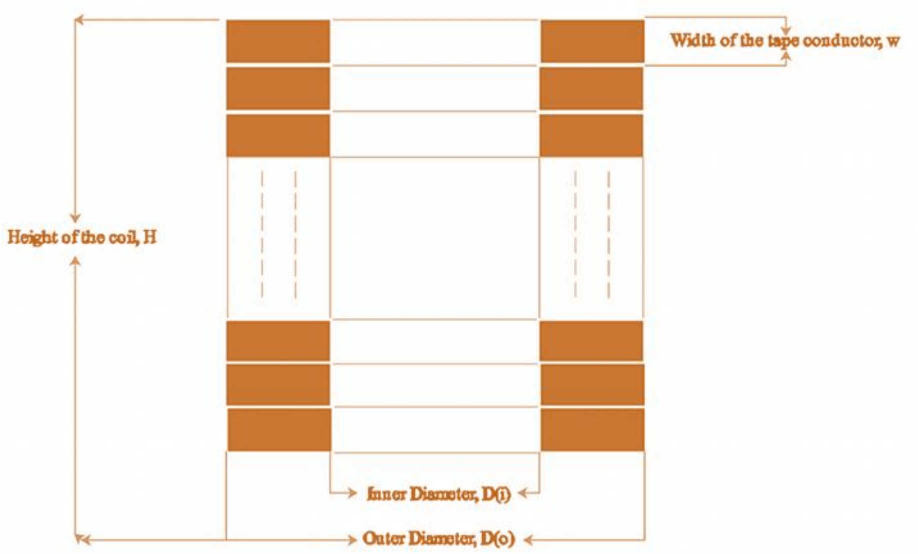


Figure 1: Construction of a SMES coil in solenoid arrangement

Where ‘H’ is the total height of the coil and

$$H = W_p\, n_p \text{ -------------------- } (7)$$

Where
n_p = the number of pancake layers and
W_p = Width of the superconducting tape

The number of turns N of the solenoid is determined by the relation

$$N = n \times n_p \qquad \ldots\ldots\ldots\ldots (8)$$

Here, n is the number of turns in each pancake and is written as

$$n = \frac{Outer\ Diameter\ (D_0) - inner\ diameter\ (D_i)}{2t} \ldots\ldots\ldots\ldots (9)$$

where ‘t’ is the thickness of the tape conductor.

Replacing the value of L in equation (1) we have the energy stored in a solenoid coil for a critical current I_c

$$E = \frac{I_c^2}{2} \left\{ \pi\mu_0 \left(\frac{N^2 D_i}{16\beta}\right) \frac{(\alpha+1)^2}{1+0.9\left(\frac{\alpha+1}{4\beta}\right)+0.64\left(\frac{\alpha-1}{\alpha+1}\right)+0.84\left(\frac{\alpha-1}{2\beta}\right)} \right\} \ldots\ldots\ldots\ldots (10)$$

Where Ic is the critical current determined by the relationship

$$I_c = J_c A_{SC} \text{ ----------------------- } (11)$$

Where,
J_c = critical current density of the superconducting tape in (A/m^2) and
A_{SC} = Area through which current flows

r_1 is the outer radius and r_2 is the inner radius which can be calculated from

$$r_1 = \frac{D_o}{2} \text{ and } r_2 = \frac{D_i}{2} \text{ ----------------------- } (12)$$

So the volume of the superconducting material is

$$V_{SC} = V_1 - V_2 = \pi r_1^2 H - \pi r_2^2 H \text{ ------------------------------- } (13)$$

Now we can discuss about the toroid arrangement of the superconducting coil for the SMES system. In Figure 2(a) we see the construction of the toroid configuration.

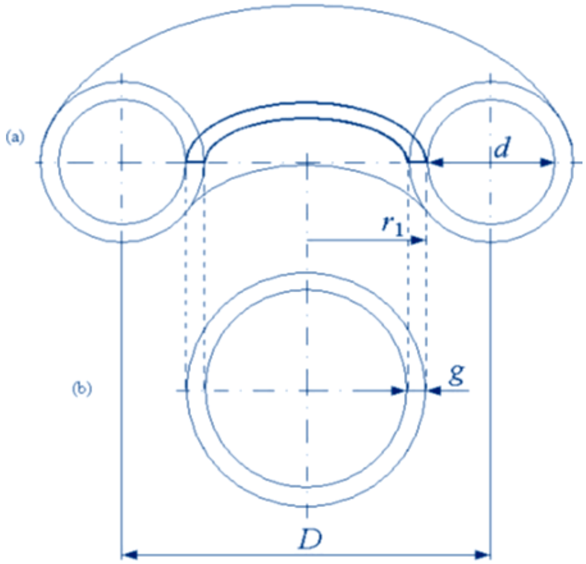


Figure 2: SMES Coil in Toroid arrangement

Here the basic dimensions are *D* (mean diameter of torus), *d* (inner diameter of winding) and *g* (thickness). For a thick torus winding (high *g*), in the exact analytical expression of inductance, is written as [6].

$$L = \frac{\mu_0}{2}\left[D^2 - \sqrt{D^2 - d^2}\right] \text{ ---------------------- (14)}$$

Where μ_0= Permeability in the vacuum.
With the equation (4.1) and (4.9) we get the expression for of toroid energy which is a function of current and inductance.

$$E = \frac{1}{2} L I_C{}^2 = \frac{\mu_0 I^2}{4}\left[D^2 - \sqrt{D^2 - d^2}\right] \text{ -------------- (16)}$$

And the volume can be written as
The volume of the superconducting material is

$$V_{SC} = \pi^2 g(D - d - g)(d + g) \text{ ---------------------------- (17)}$$

The equation for calculating the inductance as well as the energy of the SMES magnet in solenoid arrangement is very complex in nature and many derived values are required (equation 4.2 and 4.7). Also, it can be laborious to calculate the inductance for different designs and study the characteristics of several parameters when we are considering several possible cases. The possibility of occurrences of personal errors cannot be ignored. So in order to note the results pretty much easier and efficiently we have developed a new computer program called **SMES-PCC** which stands for

Superconducting magnetic energy storage parameter calculation and characteristics. This program is developed in Microsoft visual Studio 2010 and visual basic framework has been utilized. Figure 3 is showing the flowchart of the SMES-PCC program.

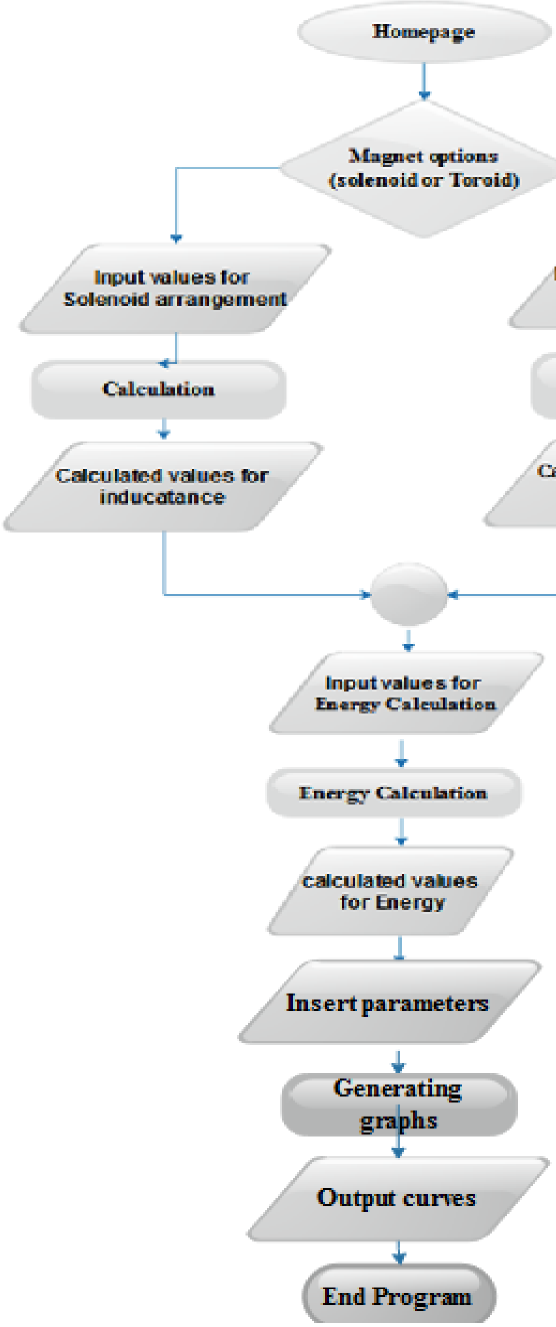


Figure 2: Flowchart of SMES-PCC Program

The program can be useful in calculation of the parameters related to the SMES magnet and it is programmed for the calculations in both geometrical options. Figure 4 is showing the 'Homepage' UI (user interface) of the SMES-PCC program.

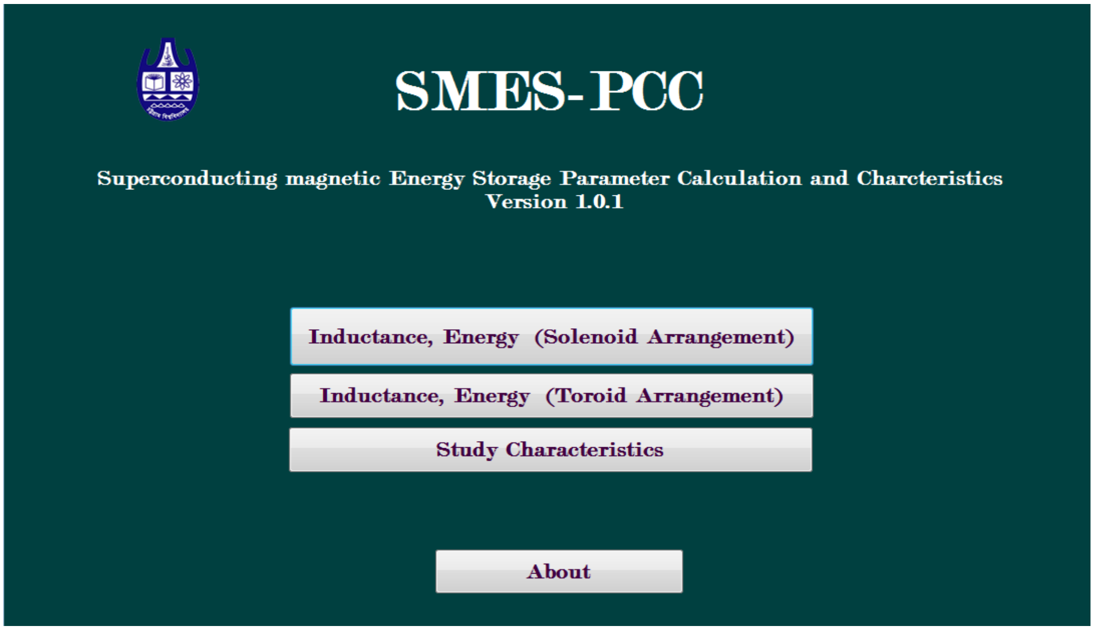


Figure 3: Homepage UI

Figure 5(a) and 5(b) are showing the inductance and other parameters calculation segment. The calculate button can provide the values if the mandatory inputs are given in the fields above it. The 'Reset Inputs' button clears the inputs after a calculation and makes the fields ready for the next inputs.

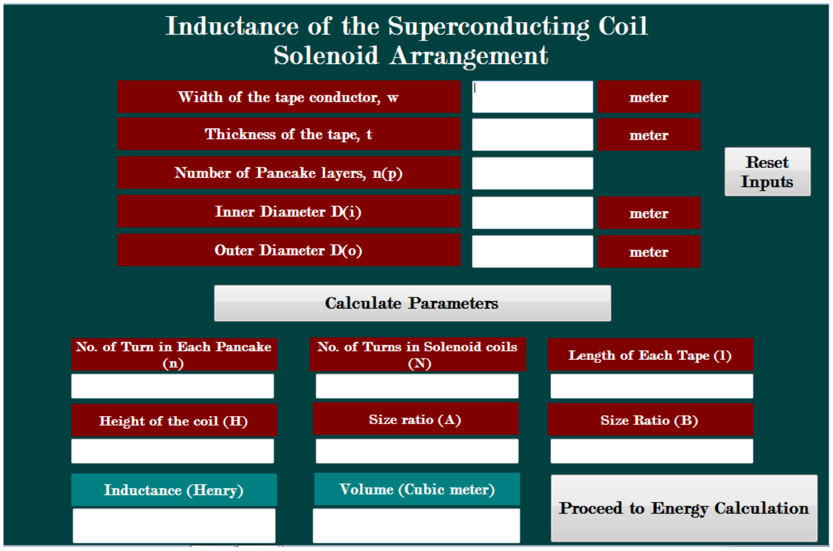


Figure 5(a): Inductance calculation (solenoid)

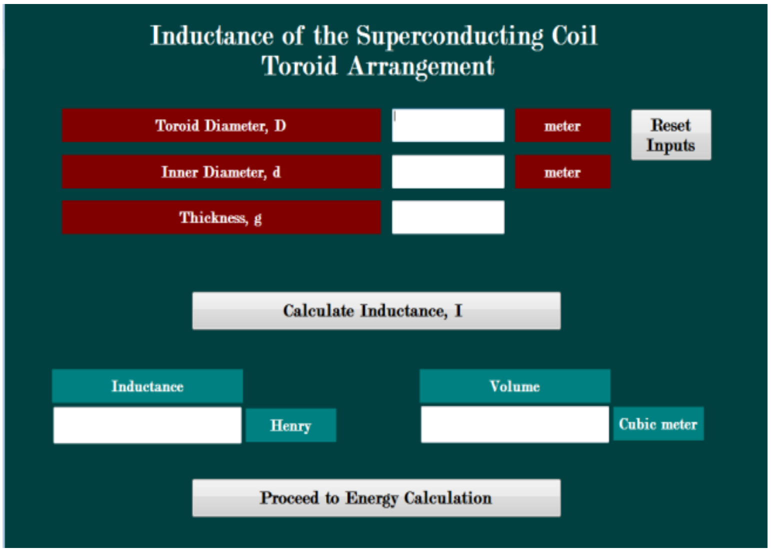
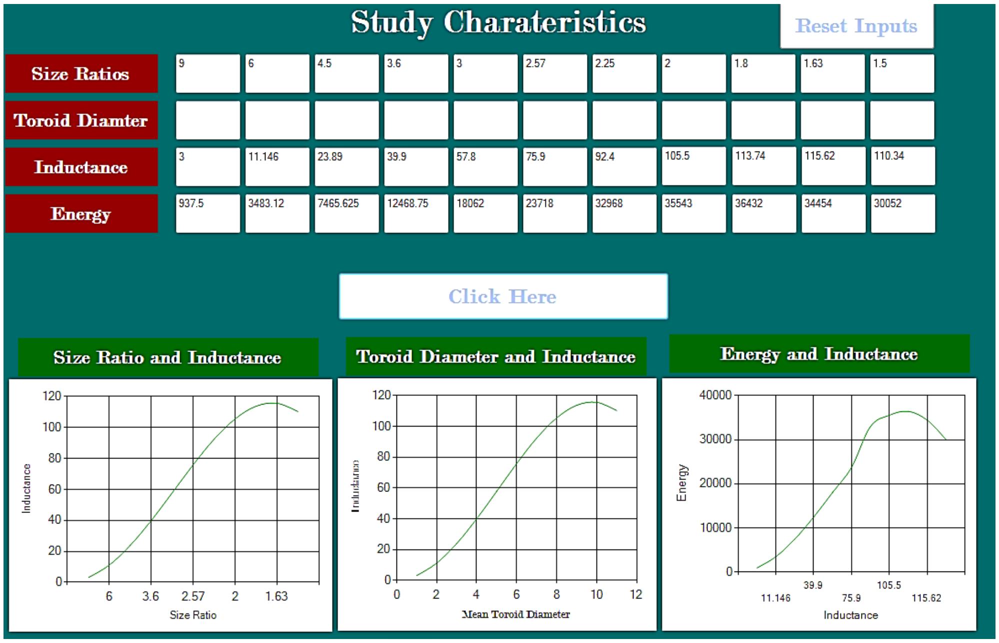


Figure 4(b): Inductance calculation (toroid)



Size Ratios	9	6	4.5	3.6	3	2.57	2.25	2	1.8	1.63	1.5
Toroid Diamter											
Inductance	3	11.146	23.89	39.9	57.8	75.9	92.4	105.5	113.74	115.62	110.34
Energy	937.5	3483.12	7465.625	12468.75	18062	23718	32968	35543	36432	34454	30052

Figure 6: Study Characteristics segment

The 'study characteristics' segment can show the relationships among the parameters when calculated values are provided. Currently this segment is limited to some specific parameters and works are going on to improve it (Figure 6).

By using the SMES-PCC program we have calculated the inductance and energy of a BSCCO coil (Bi-2223, 14 pancake layers) as well as the possible total energy from the arrangement. This design was constructed in Laboratory of Superconducting Technology in Lublin, Poland.

Table 1:Input values for the Calculation of inductance and energy of a BSCCO coil [9]

Type of Configuration	**Quantity**
No. of pancake layers (n_p)	14
No. of turns in each pancake (n)	161
No. of turns of the solenoid coil (N)	2258
Length of each tape (l)	1621 meter
Inner diameter (D_i)	0.21 meter
Outer diameter (D_0)	0.31 meter
Height of the coil (H)	0.191 meter
Width of the tape (W)	0.0041 meter
Thickness (t)	0.00031 meter

Table 2: Calculated Results for inductance and stored energy at different temperatures and critical currents [9] by using SMES-PCC program.

Temperature	**Critical Current I_c**	**Inductance L**	**Energy E**
77 K	25	0.90 henry	0.28 KJ
64 K	50	0.90 henry	1.12 KJ
35 K	180	0.90 henry	14.63 KJ
13 K	264	0.90 henry	31.37 KJ

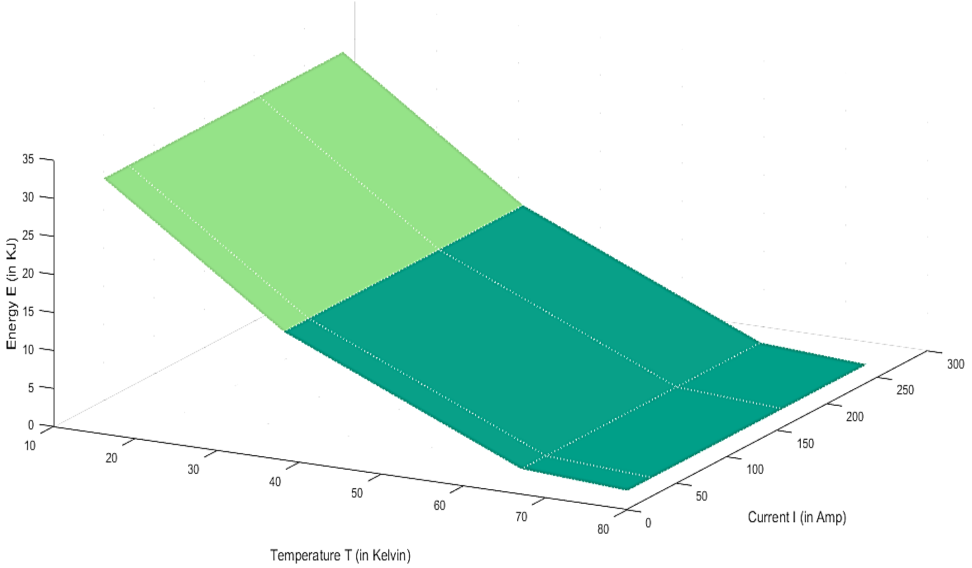


Figure 5: Relationship among critical current, temperature and stored energy

With this particular model (Table 1) keeping the inner diameter of the solenoid constant, we have found the possible energy that can be stored for different outer diameters with the SMES-PCC program and MATLAB.(Table 3)

Table 3: Calculated results obtained from SMES-PCC program for energy at different temperatures while keeping the inner diameter constant.

No. of turns in each pancake n	No. of turns of the solenoid coil (N)	Length of each tape l_p (m)	Inner diameter D(i) (m)	Outer diameter D(o) (m)	Size Ratio α	Size ratio β	Inductance L	Energy E (at 77k, 25amp)	Energy E (at 65k, 50amp)	Energy E (at 35k, 180amp)	Energy E (at 13k, 264amp)
80	1129	82	0.3	0.35	1.1	0.19	0.579	180.79	723.75	9379.8	20176.99
161	2258	177.34		0.4	1.33		2.33	728.125	2912.5	37746	81195.84
241	3387	285.02		0.45	1.5		5.3	1665.625	6662.5	86346	185739.8
322	4516	405.36		0.5	1.6		9.71	3034.375	12137.5	157302	338374.1
403	5645	538		0.55	1.83		15.5	4843.75	19375	251100	540144
483	6774	684		0.6	2		23	7187.5	28750	372600	801504
564	7903	842.4		0.65	2.16		32.221	10062.5	40250	521640	1122106
645	9032	1013.4		0.7	2.33		43.31	13534.38	54137.5	701622	1509267
725	10161	1197.1		0.75	2.5		56.43	17634.38	70537.5	914166	1966473
806	11290	1393.45		0.8	2.66		71.73	22406.25	89625	1161540	2498602
887	12419	1602.4		0.85	2.83		89.35	27906.25	111625	1446660	3111926
967	13548	1824.15		0.9	3		109.43	34196.88	136787.5	1772766	3813417
1048	14677	2058.5		0.95	3.16		132.12	41350	165625	2146500	4617360
1129	15806	2305		1	3.33		157.56	49218.75	196875	2551500	5488560
1209	16935	2565.21		1.05	3.5		185.91	58093.75	232375	3005100	6464304

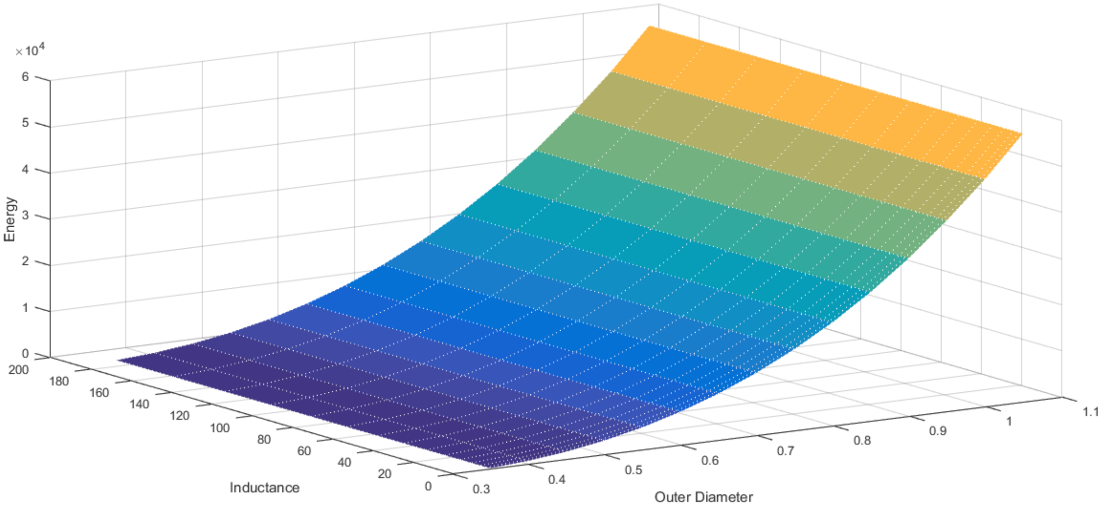


Figure 6: Outer diameter, Inductance and Energy (at 77k and Constant inner diameter)

CONCLUSION

SMES is an excellent technology in today's world even it is a good option for the people who are concerned about the environment. SMES can also reduce the cost of oil and gas by a good amount. The high capital cost is still an obstacle to the widespread availability of the SMES system but still many projects have been utilizing SMES successfully. Here, we have discussed about the principle of SMES and the terms related to it. After that, we have demonstrated the

SMES-PCC program which can be very useful in some primary calculations associated with the SMES magnet. We have calculated the energy and inductance with our program and the results were pretty much similar to others [10]. Also the calculations obtained for keeping the inner diameter as well as pancake layers constant and varying the outer diameter, we can see the rise of energy as the inductance plays the vital role here which is determined by the size ratio of the coil. Same sort of study can be done with other superconducting HTS tapes or toroid configuration. However, the program has some limitations and efforts are going on to improve it. **MATLAB-GUIDE** Package is a very promising option for further development of this type of program. We are also trying to integrate the excel file reading facility here for making this more efficient and hope that With some other softwares and packages it can be very useful for research purposes especially while studying the design optimization of the superconducting magnets. The software can be downloaded from the link provided below:

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