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Effect of Self-field and Loosening of Stacked Superconducting Tapes on Critical Current of a Single Pancake Coil

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Abstract: ***Research on superconducting systems is getting pace due to the increasing demand of efficient machines to fulfill the need of the society. Applications like motors, transformers and magnetic energy storage systems involve the pancake coils tightly bounded with the superconducting tapes. Moreover, all such devices are sensitive to the number of turns and operating current. Critical current of the superconducting tape is most important parameter while designing such machines as if operating current exceeds this value it will turn to a normal conductor. Critical current of the tape is further depending upon the operating temperature, external and self-field. In this work, effect of both self-field and degree of tightness or looseness on the critical current of the tape has been studied. The results showed that the critical current of the tape is significantly affected by both self-field and the inter-distance among the adjacent tapes.***

Keywords: ***Superconducting tape, critical current, pancake coils, Superconductivity, High temperature superconductors.***

I. INTRODUCTION

High temperature superconducting tapes are widely employed in various applications including high voltage power transmission, generators, motors, energy storage, and transformers etc. These superconducting systems can be implemented in various engineering fields like electric power transmission, power grid stabilization, ship propulsion, Maglev trains propulsion, electric aircrafts, solar and wind energy storage systems. Coated conductors can be used as long cables, single pancake coils and double pancake coils having circular or race-track configuration [1]–[10]. Coated conductors are used due to their capability to handle large currents (helpful in power transmission cables) and magnetic fields (energy storage systems like SMES). A tape can be used as single tape or in a stack of tapes forming Roebel configuration which is widely employed in various studies [6][10]–[14]. Pancake coils are used in various applications including motor winding [15]–[17], magnets (solenoidal or toroidal) [3][18]–[20] where these are piled up on top of the other to generate the required field. In order to retain the superconducting nature of the tape, it has to be cooled below critical temperature which limits the amount of current (termed as critical current of the tape) that can carry through the tape. It has been found that this current is significantly affected due to the presence of either external magnetic fields or self-fields [6][14][21]–[23]. Thus, it becomes essential to evaluate the critical current (I_c) dependency on the magnetic field as estimation of I_c can directly affect the design and optimization of the superconducting systems. Though, almost all superconducting tape manufacturers have defined the I_c characteristics with 0 T self-filed. Also, there is lack of information on the effect of external field to the I_c of the tape. Moreover, the effect of neighboring tapes or coils has not been considered in the general information catalogue as the I_c can vary depending on the temperature and type of engineering applications. Researchers have done studies where they have considered the effect of self-field for estimating the critical current of the superconducting tape [14][21][22]. Most of these studies consider cables with low aspect ratios or having small circular cross-sectional area. Few studies have been performed where cable consisting superconducting tapes with high aspect ratios where critical current of Roebel cables (used in transformer windings) have been estimated [14][22]. These models have provided fair results however, they need comparative and iterative processes to evaluate the I_c and there is a need to consider uniform current distribution within each superconductor. A more accurate way to estimate critical current of the tape wounded as a coil or cable is to incorporate the critical current dependency of the superconducting tape or coil on the local flux density J_c (***B***). Kim model [24] is usually used to describe the critical current density dependency on the local magnetic flux density J_c (***B***). This model is also employed to estimate the AC losses among superconducting devices using various formulations [25]–[28]. In order to model the resistivity of the superconducting material, generally *E-J* power law is used. The numerical model has been solved for AC losses where Kim model is integrated with *E-J* power law and the importance of local flux density has been considered.

In this work, the same DC model as developed by Grilli and Zermeno et al. [22] using Comsol has been incorporated in order to estimate the critical current with greater accuracy of the superconducting systems such as electric aircraft propulsion motors, superconducting magnetic energy storage devices, power transmission cables etc. The model has been developed where single pancake coil having 108 turns and the critical current of the tape is 330 A at 77 K [29].

The developed model is having an additional variable *P* which is designed to be uniform in each domain to ensure the non-linear *E-J* power law relationship.

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This model works very well and it is easy to implement in order to estimate the critical current of the multi-turned pancake coils. The of tight and loose winding has been examined and the results showed that there is a significant variation in the I_c of the tape due to self-field and the gap between adjacent layers or turns of pancake coil.

II. MODEL DESCRIPTION

A 2D model comprising air and superconducting tapes is shown in Fig. 1 where Fig. 1 (b) shows the arrangement of 108 turns around a pancake. Only superconducting layer has been considered among the tape as most of the current is assumed to be flow through it.

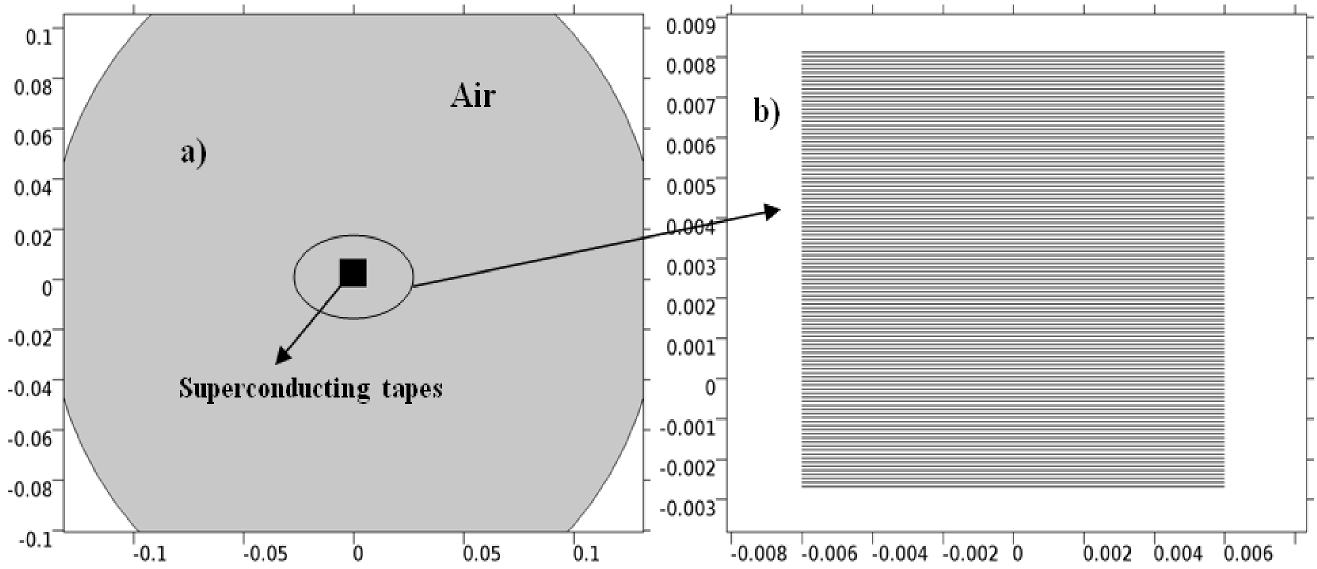

Fig. 1 Geometrical representation of the 2D model

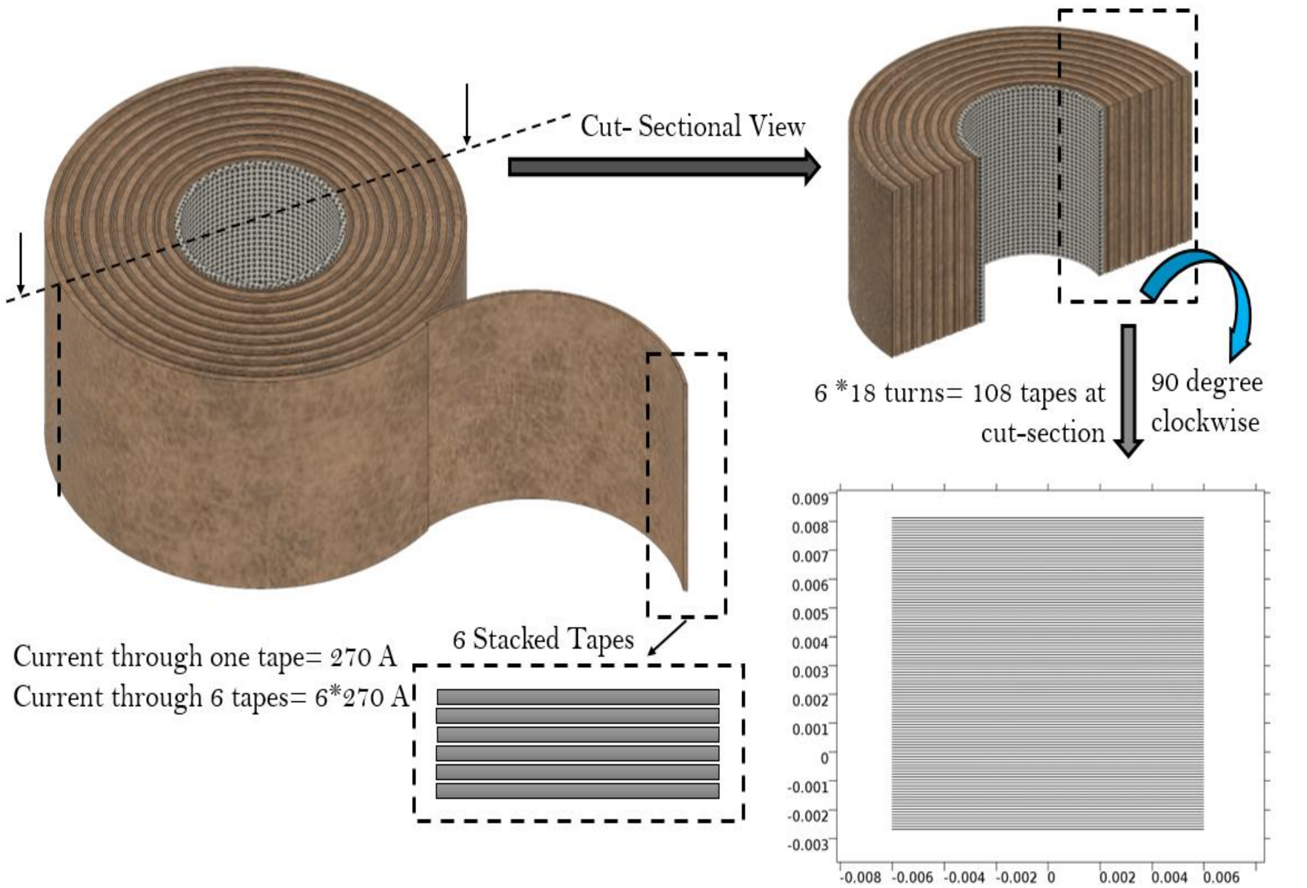

Fig. 2 Arrangement of 108 tapes (6 stacked tapes with 18 turns)

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Fig. 2 shows the detailed description of the numerical model approximation. The width and thickness of the superconducting layer is 12 mm and 1e-6 µm respectively. Table I show the modelling parameters used in the present study. Computational problem is solved using Ampere's law whose differential form is given by:

$$\nabla \times H = J$$

$$B = \nabla \times A$$

$$J = \sigma E$$

$$\rho_{HTS} = \frac{E_c}{J_c}\left|\frac{J}{J_c}\right|^{n-1}$$

To model the resistivity of superconducting layer E-J power law has been used with index, n=30. Comsol Multiphysics software package is used for the non-time dependent analysis. The developed model is having an additional variable *P* which is designed to be uniform in each domain to ensure the non-linear *E-J* power law relationship. This model works very well and it is easy to implement in order to estimate the critical current of the multi-turned pancake coils.

III. RESULTS AND DISCUSSIONS

The critical current for the assumed tape is 330 A and as 108 tapes are stacked around the coil thus the critical current for all tapes should equal to 35,640 A without considering self-field effect. However, when the effect of self-field is considered its value found to equal to 29,671 ≈ 275 A for a single tape which was initially 330 A. This shows that the self-field has significant effect on the critical current. Also, the effect of the gap among the adjacent turns has been varied in order to evaluate the effect of the loosening or tightening of the SC tapes. Fig. 3 shows that with the increase in the inter-distance among tapes, the critical current is found to increase. However, the magnetic flux density is found to decrease with the inter-distance among tapes and which results in less dense fields.

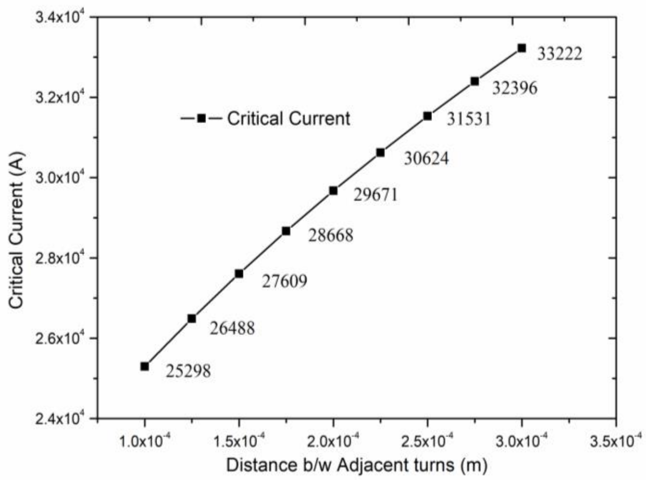

Figure 3 Critical Current vs inter-distance among tapes

Therefore, the inter-distance among the tapes is a crucial factor while tightening the coils as loosening can affect the magnetic flux density significantly. Such situations usually impact the performance of magnetic energy storage systems where higher denser fields are generally required to have higher power densities. Also, the effect of number of tapes may also affect the critical current and magnetic flux densities due to self-field however in this work that aspect has not been taken into account.

Table- I: Model Parameters

Parameters	Data
Number of turns	108
Width of the tape	12 mm
Thickness of the tape	1 µm
Inter-distance among tape	1 to 3×10^{-4} m
Index, n	30
Critical Electric field	10^{-4} V/m
Constant, k	0.29515
Magnetic field, B0	42.65 mT

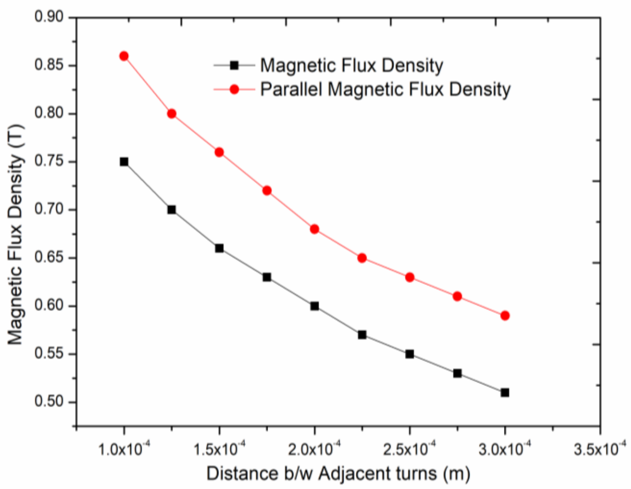

Figure 4 Magnetic flux density vs inter-distance among tapes

IV. CONCLUSION

The developed 2D model is a fair approximation for this problem where the effect of self-field and degree of looseness of windings on critical current of the superconducting tape has been studied. The model predicts that there is a significant effect of both self-field and degree of looseness of windings on the critical current thus these measures has to be taken into account before designing the pancake coils for superconducting applications.

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