Definition of Critical Currents in Superconducting Magnetic Energy Storage Systems

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Abstract. Superconducting magnetic energy storage (SMES) systems are expected to be very prospective and flexible energy storage elements of future electric grid interconnectors based on renewable power sources. Superconducting storage elements may be characterized by such important parameters as a very fast response on variation of the energy generation conditions and consumption as well as a very high efficiency reaching 95%. In practice the quality of the power generated in renewable power systems depends strongly on fast variations in such natural factors as solar radiation or the wind velocity and abrupt change in the load. The SMES device is one of the best choices to overcome the corresponding fluctuation of a generated power. The basis of future SMES systems is assumed to be a coil set wound with high temperature superconducting tape. One of the problems to be solved in such a case is definition of the coil critical current. It is well known that the critical current density depends on the induced magnetic field intensity. The main difficulty in theoretical prediction of these characteristics is essential non-uniform current density distribution in the superconducting tapes. In this paper we propose a new method of the SMES coils description using a solution of an integral equation based on the critical state theory of 2-nd type superconductors and magnetic field laws.

Keywords: Magnetic field, superconductivity, critical current, renewable energy sources, energy storage, integral equations.

Introduction

Wind and solar energy sources are widely used nowadays in electrical energy production all over the world. The main reasons for their growth are their renewable nature and pollution-free characteristics. Main trends in modern economics imply a fast development of corresponding technologies in nearest future. Basic components of this branch of power engineering are the solar and the wind energy utilization. An important drawback of these energy resources is their instability especially in the case when they are used in local electrical grids. Sometimes the generated power may exceed capabilities of energy transfer system connecting power plant with the energy consumer while in other time periods, such as night time in solar power plants, the energy production degrades strongly. To ensure a stable energy production they require energy storage systems capable to compensate lack of energy in the periods when the energy production is affected by objective reasons. Different energy storage systems are used in such cases [1-2]. There are two contradictive requirements to such systems. One of them is capability to store maximum possible energy per unit volume of the storage system. The second one is a possibility to generate as high power as possible. Usually, chemical batteries are used in such storage system. However, their slow reaction on variable conditions of power generation and consumption requires installing additional elements capable to overcome this drawback. Superconducting magnetic energy storage (SMES) coils having fast response, high charge and discharge efficiency may be regarded as a good solution in such a situation [3-8].

Quick development of superconducting technologies nowadays brought a new solution for building SMES systems. Recently several research groups report about new achievements in creating and investigating SMES coils made of 2-nd generation high temperature superconductors (2G HTS) [9-11]. Such solution ensures relatively cheap and simple production and exploitation of the SMES device. The main specific feature of the 2G HTS conductors is their shape. Industrially produced 2G superconductors are thin tapes with the width of 4 or 12 mm, the thickness of about 0.1 mm and the superconducting layer of about 1 micrometer thickness. In the real situation the current is distributed non-uniformly over the tape width and its description requires detailed analysis of the magnetic field distribution together with specific properties of the 2-nd type superconductors with strong pinning effect.

When the SMES based on 2-nd generation HTS coil system is developed, the maximum possible transport current is estimated by the parameters of superconducting band provided by the superconductor manufacturer. This information usually takes into account properties of a superconducting sample immersed in external magnetic field. But in practice, when the conductor is used in multi-turn windings, the magnetic field distributions and consequently the critical currents may differ strongly from the preliminary defined experimental values. A purpose of this work is a considering a new method of the current density distribution modelling in NTS 2G coils.

1 Mathematical Model of the 2D HTP coil

1.1 Critical model of a superconducting material

The 2-nd type superconductors with a strong pinning can carry transport current with the engineering (average) density exceeding 100 A/mm^2. Such properties together with stability in strong magnetic fields allow to use these materials for building coils with high energy density per unit volume necessary for creating compact and powerful storage units. The relation between the magnetic flux density and the current density in superconductors is described by Kim's critical state theory [12]. This theory climes that the current density J in 2-nd type superconductors may be equal to zero or to the critical value only. Exact dependence of the critical current density on the magnetic field intensity is defined by a critical state model. The literature reports several models of this type, such as the London's - Bean's model, and different versions of the Kim's one. The most often used model for describing properties of 2G HTS tapes is an anisotropic Kim's model [13-16] with the main relation between the magnetic flux density and the critical current density of:

$$J_C = \frac{J_{C0}}{\left(1 + \frac{\sqrt{k^2 B_{=}^2 + B_{\perp}^2}}{B_0}\right)^{\alpha}} \qquad (1)$$

B_0, J_0, k, α being the material constants. $B_{=}$ and $B_{\perp}$ are respectively the parallel and perpendicular components of the magnetic field relative to the tape surface. Main parameters of this dependence are usually defined experimentally. The coefficient k is usually much less than a unit. So, the superconductivity in 2G HTS tapes is destroyed by mainly the normal component of the magnetic flux density.

1.2 An integral method of the current density modelling in 2G HTS coils

The important problem to be solved by the designer of a 2G HTS superconducting system, is the determination of distributions of the current density and magnetic field in superconducting tape windings. Different modelling methods are formulated according to the selected variable basis. One of them is the T-Ω formulation [17]. Within this approach the vector current potential *T* is combined with the scalar magnetic potential. The method is advantageous because of relatively small number of unknowns. Alternative approaches to the magnetic field modelling are: the A-V formulation [18], the T-A formulation [19] and the H formulation [20-21]. All these approaches use the finite element method to solve time dependent differential equations of electromagnetic field theory together with the critical state relation (1). Typically, a high discretization of the problem domain is required to achieve a reasonably good accuracy.

In this paper we consider alternative approach to modelling critical current and magnetic field distribution in 2G HTS coils. The magnetic field in the arbitrary point of the space may be expressed by the Biot-Savart Law:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_V \frac{\vec{J}(\vec{r}')\times(\vec{r}-\vec{r}')}{|\vec{r}-\vec{r}'|}dV \qquad (2)$$

Together with the equation (1) the last integral relation forms a non-linear integral equation for the current density *J* in a system of several superconducting tapes connected in parallel. The currents in thin superconducting layers are averaged over the whole volume of a problem domain. Such transformation is approved by specially undertaken simulations [21]. We used this mathematical formulation to find a dependence of the critical currents in superconducting structures with a set of straight current carrying tapes.

2 Results of the critical current modelling

We have applied a developed method for analysing the current density distributions in a system of the superconducting tapes industrially produced by the company Superpower [3]. The width of the chosen tape is 12 mm, the thickness is 0.15 mm (without insulation), the critical current is 240 A. The parameters of the Kim's model defined experimentally [3] are: $k = 0$; $\alpha = 1$, $J_0 = 1.11 \cdot 10^8$ A/m^2; and $B_0 = 0.12$ T.

The investigated system consists of several straight tapes connected in parallel. To validate the developed method, we applied it to the system with infinitely big number of such tapes. In this case the problem may be reduced to a solution of one-dimensional integral equation. This problem has also analytical solution described in [12]. Comparison between numerical and analytical results shown in Fig.1 demonstrates a good agreement. The distribution of the magnetic field corresponds to the case of the critical transport current in the conductor.

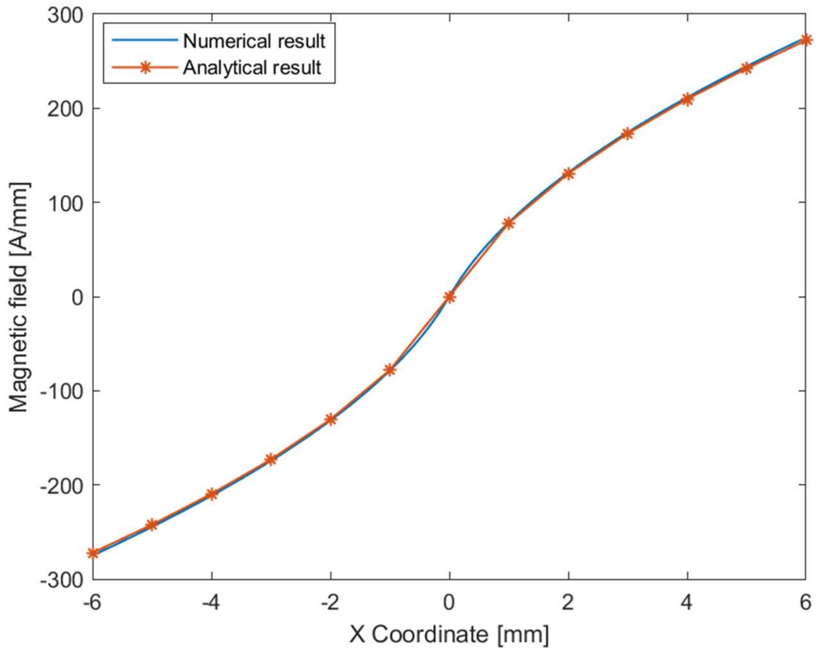

Fig. 1. Comparison of numerically derived distribution of the magnetic field intensity in the infinitely high superconducting plate with analytical results.

A similar problem is solved for a set of infinitely long superconducting tapes connected in parallel. To approximate the current density distribution in such a system, its cross section is split into a set of small rectangular elements as it is shown in Fig. 2. The current density inside each element was considered to be constant. The integral equation (1) – (2) was approximated by a set of non-linear algebraic equations by applying the collocation method. The magnetic field intensity induced by simple elements was calculated analytically.

To solve the nonlinear system of algebraic equations approximating the integral one we used a simple iterative procedure.

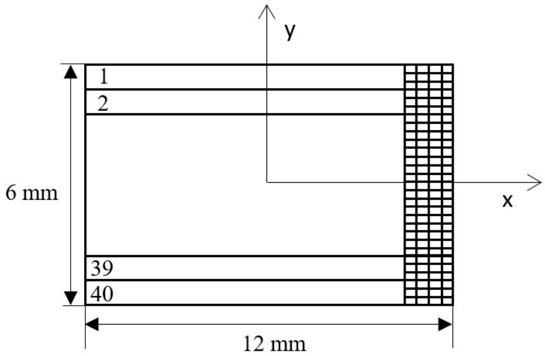

Fig. 2. A cross section of the superconducting system consisting of 40 parallel superconducting tapes of 12 mm width.

The results of calculations corresponding to the case of 40 parallel tapes are shown in Fig. 3 – Fig.4.

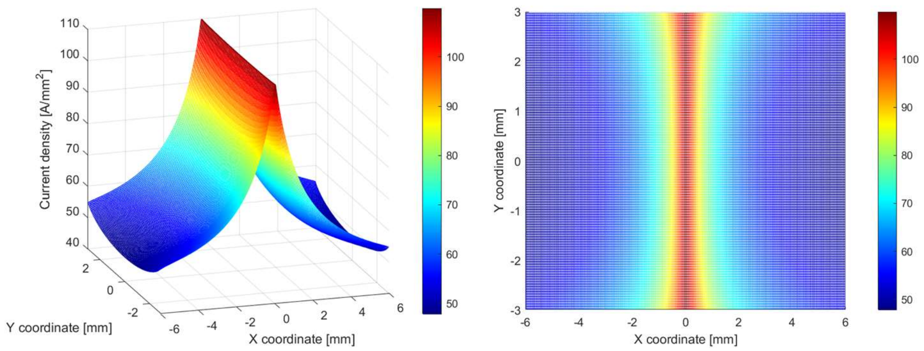

Fig. 3. A Distribution of the current density in the superconducting system consisting of 40 parallel tapes.

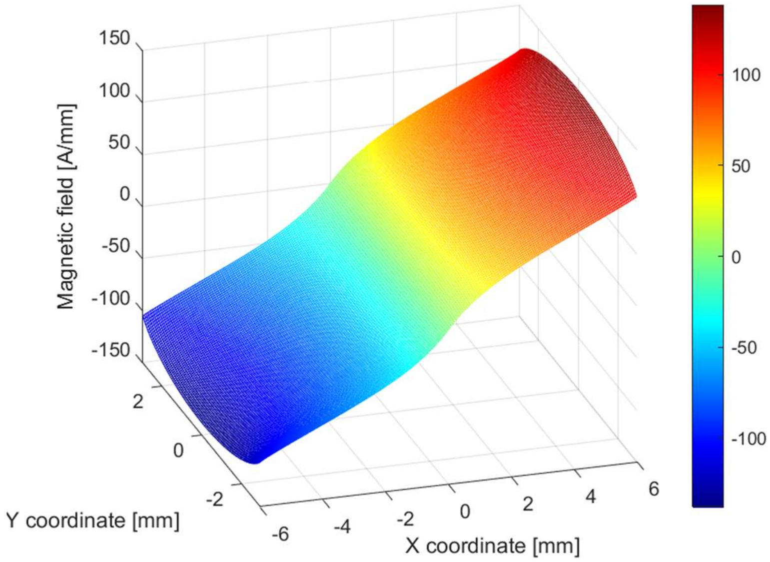

Fig. 4**.** A Distribution magnetic field intensity in the superconducting system consisting of 40 parallel tapes.

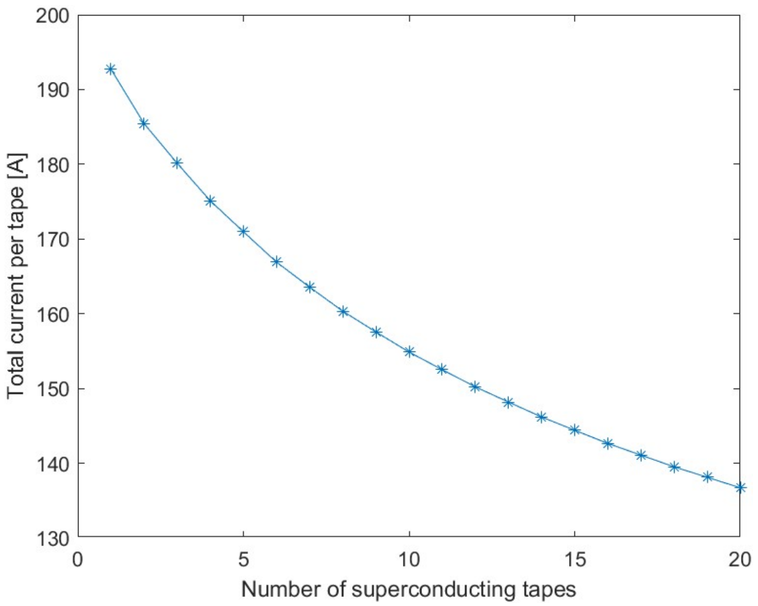

Fig. 5**.** Dependence of the effective critical current on the number of 2G HTS tapes connected in parallel.

The most important consequence of non-uniform current density distribution in superconducting tapes is degrading of their critical currents. The dependence of the current reduction on the number of parallel tapes is shown in Fig. 5. We see that the critical current degradation may reach a value of about 20-30%. This effect should be taken into account when optimizing a SMES coil structure.

The important advantage of the proposed integral approach with respect to typically used differential methods is a necessity to solve a static problem instead of time dependent ones [15-21].

Conclusions

We have demonstrated that the magnetic field intensity and the current density distributions in the 2G HTS coils may be described by solution of a non-linear integral equation based on the Biot-Savart Law and the anisotropic Kim's model of the critical state of superconductors. This approach is successfully applied for calculating critical currents in the pack of tapes and later is supposed to be used for optimization of the SMES coil shape. The derived results are verified at the case of infinitely long superconducting plate with the current for which the analytical solution is available. At this stage of the research work we considered a superconducting current lead with a certain number of tapes connected in parallel. We demonstrated that critical currents in a system of superconducting 2G HTS conductors degrades with increasing a number of tapes connected in parallel. In future we plan to apply the developed numerical technology for description of the multi-turn superconducting structures.

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