Physica C 506 (2014) 133–137

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Hysteresis losses in MgB_2 superconductors exposed to combinations of low AC and high DC magnetic fields and transport currents

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ARTICLE INFO

Article history:
Received 28 April 2014
Received in revised form 20 June 2014
Accepted 22 June 2014
Available online 30 June 2014

Keywords:
Generator field winding
Ac losses
Magnesiumdiboride

ABSTRACT

MgB_2 superconductors are considered for generator field coils for direct drive wind turbine generators. In such coils, the losses generated by AC magnetic fields may generate excessive local heating and add to the thermal load, which must be removed by the cooling system. These losses must be evaluated in the design of the generator to ensure a sufficient overall efficiency. A major loss component is the hysteresis losses in the superconductor itself. In the high DC – low AC current and magnetic field region experimental results still lack for MgB_2 conductors. In this article we reason towards a simplified theoretical treatment of the hysteresis losses based on available models in the literature with the aim of setting the basis for estimation of the allowable magnetic fields and current ripples in superconducting generator coils intended for large wind turbine direct drive generators. The resulting equations use the DC in-field critical current, the geometry of the superconductor and the magnitude of the AC magnetic field component as parameters. This simplified approach can be valuable in the design of MgB_2 DC coils in the 1–4 T range with low AC magnetic field and current ripples.

1. Introduction

MgB_2 superconductors are, for their low cost compared to the high-temperature YBCO conductors, and higher operating temperature than the low-temperature Nb_3Sn and NbTi superconductors, considered for several DC applications in the medium magnetic flux density range of 1–4 T. These applications include e.g., MRI magnets [1,2], magnets for induction heaters [3], and the field windings of wind power generators [4,5]. Under pure DC conditions the MgB_2 coils are practically loss-free (except for joints). However, the presence of a time-varying magnetic field inevitably results in energy losses. Although these losses generally are small, they add to the total heat load to be handled by the cryogenic system, and maybe more important, they result in local heating of the coil. Therefore, the coil needs to be thermally designed to withdraw the heat caused by the AC losses, or expressed alternatively; the losses need to be suppressed to a value not jeopardizing the operation of the coil.

In the design of MgB_2 superconducting generator field coils for direct drive wind turbine generators, the overall loss of the drive train must be kept within or below the range of 5–10% of the transferred power to be feasible, and local excessive heating must be prevented. Superconducting field coils may be applied to synchronous generators, where the armature is made of conventional copper conductors at ambient temperature. Thus, under normal operating conditions, the superconductor is primarily exposed to the coil's self-field and the magnetic field created by the armature. These two magnetic fields are superpositioned and include AC ripples (from the armature harmonics and from the excitation circuit of the field coil).

Here we focus on the hysteresis losses appearing under normal operation, i.e., the superconductor is exposed to a relatively low AC magnetic field superimposed on a bias DC field, as well as a low AC current superimposed on a bias DC current. Hence, flux-creep and flux-flow losses related to the instantaneous level of the current relative the critical current, which are of less importance if the coil is operated with a sufficient margin to the critical current, are not considered. Neither are eddy currents, losses during ramping of the coils and losses due to electrical faults.

Some experimental work has been done on AC losses of MgB_2, see e.g., [6–9], but measurements of AC losses due to an AC ripple on a DC magnetic field in the 1–4 T range still lack. Although results from calculations for an NbTi wind power generator design are given in Ref. [10], there is a need to establish methods for calculation of the losses in the design phase of MgB_2 based generators.

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http://dx.doi.org/10.1016/j.physc.2014.06.012
0921-4534/

The mechanism leading to AC losses in multi-filamentary superconductors is quite complicated, and there exists a wide variety of different loss equations and modelling tools covering different geometries and load cases. In this article we reason towards the use of a limited number of existing loss equations based on the critical state model to estimate the hysteresis losses for an MgB_2 coil with AC field and current components that are small compared to the DC components, as is the case in the field windings of generators for wind turbines.

2. Hysteresis loss models

2.1. Critical state model

Hysteresis losses in superconductors are commonly discussed in the framework of the critical state model [11,12] considering the vortex dynamics inside the superconductor. In the model, the magnetic flux density, $\boldsymbol{B}$, follows

$$|\nabla \times \boldsymbol{B}| = \mu_0 J_c, \tag{1}$$

where J_c is the critical current density. When an external magnetic field is increased, vortices enter into the superconductor from its surfaces. However, the vortices are hindered to move until J_c is reached (then the Lorentz-like force on the vortices equals the pinning force). As J_c is reached the vortices can move further into the superconductor, and they build up a flux distribution according to Eq. (1). Hence, the current density inside the superconductor has to be either J_c or zero (thereby the name critical state model). When the external magnetic field then is reduced, the vortices exit the superconductor from its surfaces, creating an irreversible magnetic flux pattern and leading to hysteresis losses.

2.2. Basic analytic loss equations for AC magnetic fields

Based on the critical state model, several loss equations and calculation methods have been developed. A simple case is an AC magnetic field in parallel with a slab, infinite in two directions and with a width α in the third. Introducing the field of full penetration, B_p (the field at which the vortices reach the centre of the superconducting slab),

$$B_p = \frac{\mu_0 J_c a}{2}, \tag{2}$$

the hysteresis losses per unit length, P_l, can be expressed by Ref. [12],

$$P_l = \begin{cases} \frac{2fA}{3\mu_0 B_p} B_{ac}^3 & \text{for} \quad B_{ac} \leqslant B_p \\ \frac{2fAB_p}{3\mu_0}(3B_{ac} - 2B_p) & \text{for} \quad B_{ac} \geqslant B_p \end{cases}, \tag{3}$$

where f is the frequency, A the conductor area (considering a finite conductor approximated with the slab geometry), and B_{ac} the peak applied AC magnetic field. As can be seen, P_l is proportional to B_{ac}^3 for low applied fields and to B_{ac} for high applied fields. This field behaviour is typical for most wire geometries (with the exception for the strip geometry in perpendicular field [13]), although the factors in front vary with geometry.

Eq. (3) has been extended to include transport currents both below [14] and above [15] the critical current, I_c.

2.3. Approach for the low AC – high DC magnetic field limit

Eq. (3) has also been extended to include both AC and DC components of applied magnetic fields and transport currents [16]. Different loss equations are applied for different relationships between the AC and DC components. For convenience we introduce $b_{ac} = B_{ac}/B_p$, $i_{ac} = I_{ac}/I_c$ and $i_{dc} = I_{dc}/I_c$, where I_{ac} is the peak of the applied AC transport current and I_{dc} is the applied DC transport current. Furthermore, we are interested in small ripples corresponding to the cases where b_{ac} and i_{ac} are small compared to $1-i_{dc}$, i.e., smaller than the operating margin to the critical current. We are then left with two load cases for the hysteresis losses [14],

$$P_l = \begin{cases} \frac{2fAB_p^2}{3\mu_0}\left(b_{ac}^3 + 3b_{ac}i_{ac}^2\right) & \text{for} \quad i_{ac} \leqslant b_{ac} \leqslant 1 - i_{dc} \\ \frac{2fAB_p^2}{3\mu_0}\left(i_{ac}^3 + 3i_{ac}b_{ac}^2\right) & \text{for} \quad b_{ac} \leqslant i_{ac} \leqslant 1 - i_{dc} \end{cases}. \tag{4}$$

In these two load cases (unlike all other load cases) the losses are independent of the DC component of the current, and (like all cases) independent of the DC component of the magnetic field. However, the DC component of the magnetic field influences both I_c and B_p which will be considered later in the article.

To simplify the expressions further, we consider the operating conditions of a wind turbine generator MgB_2 coil. In the crucial high-field region (the inner part) of the coil, the DC magnetic field is of the order 3–4 T, much higher than B_p (which typically is a factor 10 or more, lower), and therefore b_{ac} is much larger than i_{ac}, and only the upper part of Eq. (4) needs to be considered. Furthermore, the second term within the parenthesis becomes small compared to the first in the interesting region of the coil and hence, one may estimate the losses accurately (or accurately enough) by only considering the magnetic field's AC component (and not the current's AC component). Interestingly, the equation remaining is identical to the upper part of Eq. (3) yielding a convenient treatment of the losses due to small ripples in high field coils.

The weak dependence of a DC current (significantly lower than the critical current) on the AC losses due to a low AC current ripple has been shown experimentally in e.g., [16,17], and the weak dependence of a DC magnetic field on low magnetic field ripple in e.g., [18,19], all those for multifilamentary BSCCO/Ag tapes, expected to behave quantitatively similar to MgB_2 wires with respect to AC losses.

2.4. Handling the wire geometry and magnetic field orientation

The quantitative behaviour above was deduced for slab geometry and with a magnetic field in parallel with the slab. The losses are however, largely dependent on the geometry and field orientation. For tape-shaped superconductors the losses due to magnetic fields perpendicular to the face of the tape are often an order of magnitude larger than the losses due to parallel or longitudinal fields [20]. Models for how to treat the different field orientations based on weighing the losses from the parallel and perpendicular fields are presented in Refs. [21–23]. However, calculating the losses from the two magnetic field components separately generally gives sufficiently accurate results. In the middle of the coil the parallel magnetic field component dominates, whereas at the coil ends the perpendicular field component dominates. Only in a small part of the coil (and not where the losses are highest) are the components of comparable magnitude. Thus, we combine the total losses P_{total} according to,

$$P_{total} = P_{para} + P_{perp}, \tag{5}$$

where P_{para} is the loss due to the parallel field component and P_{perp} is the loss due to the perpendicular field component.

To account for the shape of the superconductor we use a model for elliptical cross-sections and arbitrary aspect ratios developed by ten Haken et al. [24] and based on the critical state model. An elliptical cross-section (including circular as a special case) describes well how the superconducting filaments are arranged in many MgB_2 conductors, and the model accounts for both losses due to parallel and perpendicular magnetic fields (by setting the aspect ratio, α, above or below unity, see Fig. 1). The model can