Losses in Power Cables Made of 2G HTS Wires with Different Substrates

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Abstract

AC losses are an important issue in HTS power cables development especially when using low loss 2G wires. Still not so much experimental studies were performed on this subject with representative cables’ models. For cables made from 1G wires some theoretical models adequately describes losses while they does not works well enough for 2G AC losses. To study the problem, the test facility and AC loss measurement methods with 5 m HTS model cables have been developed in Russian Cable Institute. Several 5 m HTS cables made of both 1-G and 2-G wires have been produced and tested at this facility. 2-G cables have different substrates both weakly magnetic and nonmagnetic once. In this paper we present data obtained for AC loss in HTS power cable models. Theoretical analysis of losses has been done as well, including substrate losses and the losses in a superconductor. Superconducting losses dominate in cables made of 1G HTS wires, while in 2G cables magnetic substrate may dominate at low currents. Several mechanisms affected AC losses due to parallel and perpendicular magnetic fields in a cable are taken into account. Theoretical and experimental data are compared and discussed.

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Keywords: 2-G HTS power cables; AC losses.

1. Introduction

AC loss issues are very important for HTS applications such as power cables, FCL and other.

Nomenclature

\[ P_{tot} \] Total losses
\[ I_{tot} \] Total current
\[ U \] Voltage
2 G HTS tapes are considered as most prospective such applications because their high critical current density of the HTS layer reduces the surface superconductor hysteretic losses.

There are basically two leading technologies to produce 2G HTS types. The IBAD in SuperPowerInc and MOD/RABiTS™ in AMSC. 2G HTS wires produced with the MOD/RABiTS™ process have NiW substrates and have weak magnetism and therefore extra losses in a substrate.

In Russian Cable Institute were made and tested different models of cables made of both tapes (see table 1). Cables were made as two counter wound layers of tapes. As formers for cables, we used a 25 mm diameter stainless steel tubes. The tubes were insulated by Kapton™ tape. Kapton™ tape was placed between layers to insulate them. Outer insulation was made by Kapton™ tape as well.

The comparison of our former AC losses measured [1] with known theoretical models [2]-[5] showed the limitation of these models to describe AC losses in 2G HTS cables, especially for cable with ferromagnetic substrates.

The full consideration and computer simulation of AC losses is a tough task. The proper model should take into account the following: strongly nonlinear resistivity of HTS materials; hysteretic behavior of the magnetic substrate, losses in superconducting thin layer depending on transport current and corresponding magnetic field magnitude and orientation, the substrate ferromagnetism depending on magnetic fields magnitude. In recent years, the most advanced FEM models on the calculation of losses in works presented in [6] - [7]. In paper [8] we studied numerically hysteresis losses only in ferromagnetic substrates of a cable and we made comparison of calculated results with experimental ones. Here we studied numerically of total losses in cables, including losses in superconducting layers and also we made comparison of calculated results with experimental ones.

Table 1. Parameters of tape and cables

| Parameters of tape       | Number tapes in layers of cable, configuration and critical current. |
|-------------------------|--------------------------------------------------------------------|
| 1)AMSC 344B, 4.4x0.42 mm², Ic=86A | 17-17, “in-out”, Ic=2750A                                          |
| 2)SuperPower SCS 4050, 4x0.1 mm², Ic=90A | 14-14, “in-out”, Ic=2420A                                          |
| 3)SuperPower SCS 4050, 4x0.1 mm², Ic=115A | 18-18, “in-out”, Ic=3990A                                          |

2. Experiment

Experimental details of measurements tools are described in [1], [8]. Low voltage high current test facility is equipped by 5 m flexible test cryostat; power supplies set with up to 2 and 6.5 kA DC and up to 3.6 kArms AC. Computerized data acquisition system with 100-1000 and more samples per 50 Hz cycle provide high accuracy in digital measurements.

The model cables were heavily instrumented with probes and voltage taps to measure current distribution and AC losses. During tests we measured digitally instant AC currents and voltages in layers and total current with sampling rate from 400 to 1000 points per cycle. Voltages at inner and outer layers were exactly the same. These measurements were basic for all following data reduction procedures, especially for AC loss analysis. General view of the test facility is shown in Fig.1 (a).

For AC loss evaluation we used digital integration of $V \cdot I$ product. By the classical definition the losses in the system with current $I$ and voltage $V$ are the integral of instant power per time. Thus, total losses in our cable may be evaluated as:

$$P_{tot}(t) = \frac{1}{T} \int_0^T V(t) \cdot I_{tot}(t) dt,$$  \hspace{1cm} (1)
This expression was our basis to evaluate AC losses in our cable via digital measurements of currents and voltages. Some typical results of measurements current $I$ and voltage $V$ are shown in Fig. 1 (b).

In Fig. 2 measured AC loss per unit length are plotted against the amplitude of transport current for AMSC and SP cables listed in the Table 1.

3. AC Loss Calculation

The calculation of AC losses in HTS cables is based on solving Maxwell equations by finite element methods. There are both 2 D and 3 D model [8]. In our model we calculate the losses separately in the substrate and HTS layers. In order to simulate the losses in HTS layers, we can use a 2-D model; in substrates we can use 3-D model.

2 D analyze was made for two models: tape-on-tape cross-section and tape-on-gap cross-section shown in Fig. 3(a). In 2D model the average ac loss calculated at the tape-on-tape cross-section and that calculated at the tape-on-gap cross-section gives the approximate average ac loss in a real HTS cable. In a real HTS cable, where each tape is spirally wound, the relative position between the inner-layer tape and outer-layer tape varies along the cable axis. 3D model used for numerical calculations is shown in Fig. 3(b).

Fig. 1. (a) General view of the facility for testing 5 m HTS cables; (b) Results of measurements current $I$ and voltage $V$.

Fig. 2. Measured AC losses vs. normalize current in different cables made of 2G HTS wires.
The calculation losses in HTS layers is based on the electromagnetic transient analysis, where the nonlinear resistivity of the HTS material is simulated in terms of a power law $\rho(J) = E_c J_c J / J_c^{n-1}$. Due to the nonlinear resistivity the large iteration number is required in each solution step. The high aspect ratio (width/thickness) of 2G HTS tapes implies a large number of mesh nodes in the geometry of model. This lead to unacceptably long computation times. Therefore we did calculate losses in HTS layers only in 2D model. For the critical current density in HTS layers the following dependence $J_c(B)=J_c(1+((B_x^2+B_y^2)^{0.5})/0.36)^{1.2}$ [2] has been used.

It is known that the magnetism of the substrate can affect AC loss by two ways: the hysteretic behavior of the magnetic substrate generates hysteretic loss in the substrate itself; a high permeability of the substrate can vary the magnetic field distribution around an HTS conductor to increase the magnetic field component normal to its superconductor layer, which dominates ac loss in the superconductor layer [5].

By the transient analysis, we can simulate the magnetic material as a linear paramagnetic material. Paramagnetic model are presented in paper [4].

In Fig. 4 the measured and calculated AC losses per unit length of the SP1 and AMSC cables are plotted against the amplitude of transport current. Calculations were made for uniform current distribution among layers. Cables losses calculated by Norris model are presented in Fig. 4(a) and 4(b). The Norris model does not take account variation of magnetic field distribution around the HTS conductor due to small gaps between tapes in the cable. Small gaps between tapes increase superconductor hysteretic losses.

In Fig. 2(b) one can see that at currents $< 0.3I_c$ substrate losses are dominating in the cable with NiW substrate. In addition to gap losses vary the magnetic field distribution around the HTS conductor in cable with weakly magnetic substrate to increase superconductor hysteretic losses. The measured and calculated loss curves coincide well for both type of cable.

4. Conclusions

The test facility developed permits to perform accurate measurements of AC loss in HTS power cables models. Models of HTS cable with different substrate was developed produced and AC loss measured.
The numerical 2D and 3D models were developed to calculate losses in a 2G HTS superconducting cable made from 2G wires. Numerical calculations coincide well with measured AC losses in models of HTS cables.

Small gaps between tapes in the cable increase superconductor hysteretic losses. Substrate losses in cables made of 2G wires with weakly magnetic substrate contribute much at currents < 0.3Ic. At higher currents superconductor hysteretic losses are dominating. Variation of magnetic field distribution around an HTS layers in a cable with weakly magnetic substrate increases superconductor hysteretic losses.

Fig. 4. Measured and calculated AC losses vs. total current in cables (a) SP-1; (b) AMSC.

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