Investigation and comparison of AC losses on Stabilizer-free and Copper Stabilizer HTS tapes

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Abstract

This paper presents the measurement and simulation of Alternating Current (AC) losses on the Stabilizer-free and Copper Stabilizer High Temperature Superconducting (HTS) Tapes: SuperPower SF12100 and SCS12050. The AC loss measurement utilised electrical method to obtain overall losses with AC transport currents. The 2D *H*-formulation by COMSOL Multiphysics has been used to simulate the real geometry and multi-layer HTS tapes. Ferromagnetic AC losses of substrate have been assumed to be ignored as the substrates of SF12100 and SCS12050 are non-magnetic. Hysteresis AC losses in the superconducting layer, and eddy-current AC losses in copper stabilizer, silver overlayer and substrate were concerned in this investigation. The measured AC losses were compared to the AC losses from simulation, with 3 cases of different AC frequency 10, 100, and 1000 Hz. The eddy-current AC losses of copper stabilizer at frequency 1000 Hz were determined from both experiment and simulation. The estimation of AC losses with frequency at 10000 Hz was also carried out using simulation method. Finally, the frequency dependence of AC losses from Stabilizer-free Tape and Copper Stabilizer Tape were compared and analysed.

Keywords: AC loss, Stabilizer-free, Copper stabilizer, High Temperature Superconducting (HTS) Tape, Non-magnetic substrate, Eddy-current.

1. Introduction

The electromagnetic behavior of superconductors significantly affects the operation performance of superconducting electrical applications [1-3]. For Direct Current (DC) systems, theoretically, superconductors demonstrate the electrically lossless characteristics in most conditions [4]. However, for Alternating Current (AC) systems, superconductors suffer AC losses in the presence of AC currents and AC magnetic fields. AC loss is an inevitable and crucial issue in AC superconducting systems, particularly in large AC systems such as AC power transmission systems and large-scale superconducting motors for wind turbines and potential aircrafts [4, 5]. AC losses could decrease overall efficiency and create massive problems in cryogenic systems [4, 5].

Second Generation (2G) High Temperature Superconducting (HTS) tapes are the suitable candidates for various superconducting power applications [6]. For manufacture processes of 2G HTS tapes, there are two typical types: Surround Copper Stabilizer (SCS) Tape and Stabilizer-free (SF) Tape [7]. SCS Tapes are widely used in high-voltage applications, as the copper stabilizer protects the conductor where overcurrent capability in SCS wire could be tailored [7]. SF Tapes do not utilise copper stabilizer but do have silver overlayer [7]. SF also has thicker Hastelloy substrates, which are non-magnetic and have high resistivity. Generally SF Tapes are suitable for power grid protection devices like Superconducting Fault Current Limiter (SFCL) [7]. Therefore, AC losses investigation on SCS Tape and SF Tapes is necessary for the researches on high-voltage applications and grid protection devices.

The AC loss feature of SCS Tape and SF Tapes is different from those researches of tapes with magnetic substrate [8, 9]. Non-magnetic Hastelloy substrates with its high resistivity lead to both lower ferromagnetic AC losses and lower eddy

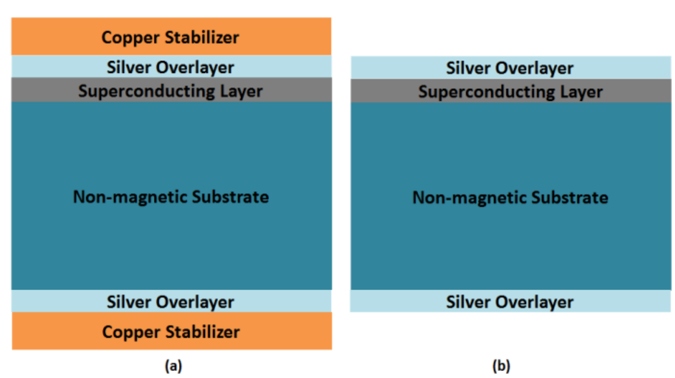

Figure 1. Cross-section of (a) Surround Copper Stabilizer (SCS) Tape, (b) Stabilizer-free (SF) Tape.

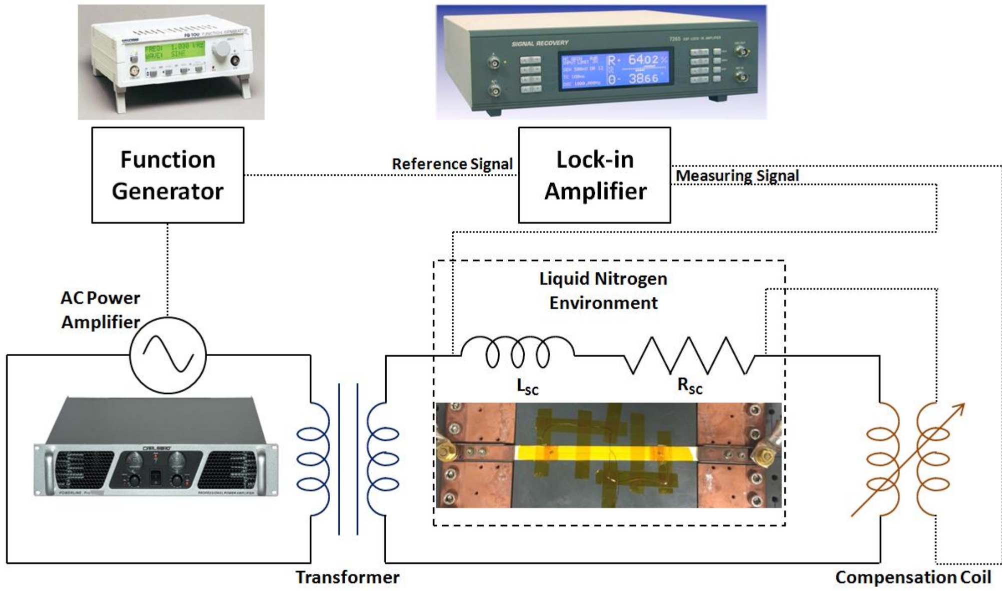

Figure 2. Experimental schematic of AC loss measurement using electrical method.

current AC losses [10].

There were some previous works on Superconducting SFCL experiments and conceptual designs which used the tapes with non-magnetic substrate [10, 11]. However, according to the best of our search on literatures, there is no specific and detailed research on the comparison of AC losses from SCS Tape and SF Tape with systematic analysis on wide range of frequency dependence. This paper presents the measurement of a single SCS Tape and a SF Tape using electrical method, comparing with real geometry and multi-layer HTS tape simulation using FEM package of COMSOL Multiphysics. Then, the frequency dependence (up to kilo Hz) of AC losses on SCS Tape and SF Tape are analysed according to the experimental and simulation results.

2. Experiment Set-up

Figure 2 illustrates the schematic of electrical method to measure the AC losses on a SF Tape (SuperPower SF12100, 12 mm wide) or a SCS Tape (SuperPower SCS12050, 12 mm wide). Their critical current I_c were measured both approximately 300 A with self-fields.

The Function Generator (digimess® FG100) created the identical AC small signal for both the reference input of Lock-in Amplifier (Signal Recovery 7265) and the Power Amplifier (Carlsbro Powerline Pro 1200). Then, the Power Amplifier generated an AC current in the primary circuit. By using a step-down transformer, the AC current in secondary circuit was increased 16 times higher of primary circuit. In the secondary side, the HTS tape was immersed into liquid nitrogen at 77 K, with the measuring technique of "8" glyph potential leads which could effectively reduces the measuring noises [12]. The length between two soldering points for voltage measuring leads was 90 mm.

Both the AC currents in the primary side and secondary side were monitored by high accuracy Data Acquisition Card linked to NI SignalExpress. Currents were calculated using the voltage across the shunt resistors divided by the resistances. The compensation coil was fabricated by two co-axis coils (1st coil in high current side, and 2nd coil in measuring signal side). The secondary side of compensation coil was made by flexible litz wire (LI14, 0.04 mm^2), in order to reduce the eddy-current losses from the compensation system. Adjustable compensation coil was to compensate the the inductive component to get the minimum voltage, which enabled the Lock-in Amplifier to extract the voltage in-phase with the current of HTS tape. The transport AC losses of HTS tape can be expressed as [5]:

$$Q_{ac\_loss} = \frac{V_{rms} \cdot I_{rms}}{f} \tag{1}$$

where V_{rms} is the pure resistive voltage across two soldering points of HTS tape, I_{rms} is the AC transport current going through HTS tape, and f is the frequency of the AC current.

3. Simulation method

*3.1 **H**-formulation*

For computing the losses of HTS tape under AC current and AC magnetic field, ***H***-formulation is one of the most suitable methods for computing the hysteresis, ferromagnetic and eddy-current losses at different layers of HTS tape [4]. ***H***-formulation consists of Maxwell Ampere's Law (2), Faraday's Law (3), Constitutive Law (4), Ohm's Law (5) and *E*-*J* power Law (6) [13]:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{2}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{3}$$

$$\boldsymbol{B} = \mu_0 \mu_r \boldsymbol{H} \tag{4}$$

$$\boldsymbol{E} = \rho \boldsymbol{J} \tag{5}$$

$$E = E_0 \left(\frac{J}{J_c} \right)^n \tag{6}$$

Table 1. Parameters for the simulation of SuperPower SCS12050 Tape and SF12100 Tape

Parameters	Value
Tape width	12 mm
Superconducting layer thickness	1 μm
Upper copper stabilizer thickness (SCS12050 only)	20 μm
Lower copper stabilizer thickness (SCS12050 only)	20 μm
Upper silver overlayer thickness	2 μm
Lower silver overlayer thickness	1.8 μm
Substrate thickness (SF12050)	50 μm
Substrate thickness (SF12100)	100 μm
Silver resistivity (77 K)	2.7×10^{-9} Ω·m
Copper resistivity (77 K)	3.0×10^{-9} Ω·m
Substrate resistivity (77 K)	1.25×10^{-6} Ω·m
μ_0	$4\pi \times 10^{-7}$ H/m
n (E-J Power Law factor)	30
J_{c0}	2.5×10^{10} A/m^2
E_0	10^{-4} V/m

Where $\boldsymbol{J}$ is the current density, $\boldsymbol{H}$ is the magnetic field intensity, $\boldsymbol{B}$ is the magnetic flux density, $\boldsymbol{E}$ is the electric field, μ_0 is the permeability of free space, μ_r is the relative permeability, ρ is the resistivity. Equation (6) is the general *E-J* power law for HTS modeling, where E_0 is the characteristic electric field, J_c is the critical current density and n is the power factor. The general form of partial differential equation (PDE) which includes the equations (2), (3), (4), (5) and (6) is:

$$\frac{\partial(\mu_0 \mu_r \boldsymbol{H})}{\partial t} + \nabla \times (\rho \nabla \times \boldsymbol{H}) = 0 \quad (7)$$

This PDE was solved by COMSOL Multiphysics.

3.2 AC Loss Calculation

The simulation models were based on the real geometry of SuperPower SCS12050 and SuperPower SF12100 for the COMSOL simulation. SCS12050 has superconducting layer 1 μm, copper stabilizers 20 μm (both for upper and lower layer), upper silver overlayer 2 μm, lower silver overlayer 1.8 μm and substrate 50 μm. SF12100 has thicker substrate 100 μm but without copper stabilizers.

The critical current density in self-field was set to be 2.5×10^{10} A/m^2, which was also equivalent to the measured critical current 300 A at 77 K. Some relevant parameters are in TABLE I, e.g. the resistivity of copper is 3.0×10^{-9} Ω·m at 77 K, the resistivity of silver is 2.7×10^{-9} Ω·m at 77 K [14], and the resistivity of substrate is 1.25×10^{-6} Ω·m [7].

The $\boldsymbol{B}$-dependent critical current model was used for the COMSOL simulation, because J_c can be varied in the presence of parallel and perpendicular magnetic field [15]:

$$J_c(B) = \frac{J_0}{\left(1 + \sqrt{\frac{k^2 B_{para}{}^2 + B_{perp}{}^2}{B_0{}^2}}\right)} \quad (8)$$

where $k = 0.186$ and $B_0 = 0.426$ were used in (8), and J_0 is the critical current at self-field, 77 K.

Pointwise or Global constraint from general PDE Physics enabled transport current to be applied into the HTS tape [15]. The integration of current density $\boldsymbol{J}$ over the superconducting domain Ω equals to the magnitude of the transport current I_t:

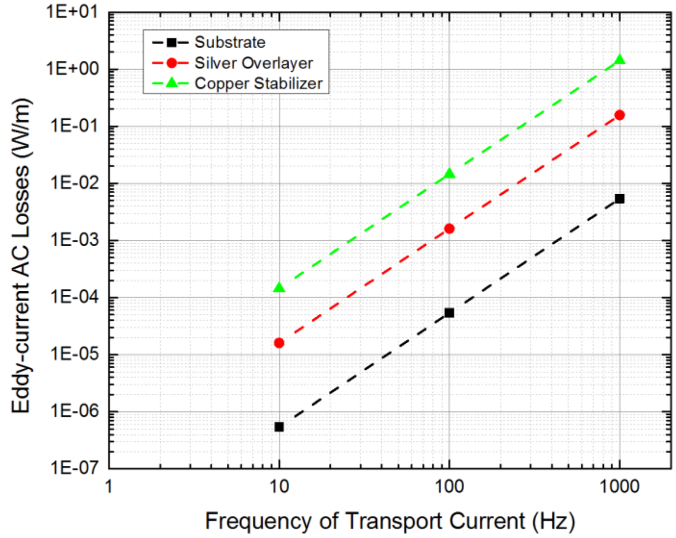

Figure 3. Simulation of the total eddy-current AC losses from copper stabilizer (2 layers), silver overlayer (2 layers) and substrate (1 layer) of SCS12050 Tape, with frequency of transport current *f* increasing from 10, 100 to 1000 Hz, at peak current 300A (100% of I_c).

$$I_t = \int_{\Omega} \boldsymbol{J} \quad d\Omega \quad (9)$$

As the substrates of SuperPower SCS12050 and SF12100 are non-magnetic, the ferromagnetic AC losses of substrate were ignored. Therefore, for the simulation, the hysteresis losses in the superconducting layer and the eddy-current losses in copper stabilizer, silver overlayer and substrate are the main factors of total AC losses. The AC loss of the domain is calculated by integrating the power density (*EJ*) over the domain and time [5]:

$$Q = \frac{2}{T} \int_{0.5T}^{T} \int_{\Omega} \boldsymbol{E} \cdot \boldsymbol{J} \quad d\Omega dt \quad (10)$$

where T is the period of cycle and Ω is the domain of interest.

4. Results and Discussion

4.1 Simulation of eddy-current AC losses in different layers of SCS Tape

Figure 3 presents the simulation of the total eddy-current losses in copper stabilizer (2 layers), silver overlayer (2 layers) and substrate (1 layer) of SCS12050 Tape, with respect to frequency of the transport current (300 A peak, 100% of I_c) which increases from 10 Hz to 1000 Hz. It can be discovered that the eddy-current AC losses of copper stabilizer substrate were approximately 10 times higher than those of silver overlayer, and over 2 orders of magnitude higher than the eddy-current AC losses from substrate. Our simulation result matched the typical eddy-current equation [4]:

$$P_{eddy} = \frac{4\mu_0{}^2}{\pi} \frac{twf^2}{\rho} I_c{}^2 h(i) \quad (11)$$

where ρ resistivity of layer material. t and w and are thickness, width. $h(i)$ is a function with normalized operation current. The simulation results are consistent with equation (11) that the eddy-current losses are inversely proportional to the resistivity of different layers and proportional to the second power of the frequency. The resistivity of copper and silver

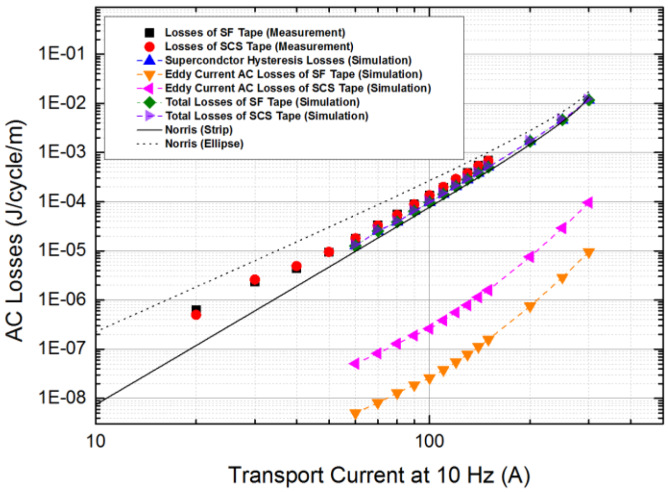

Figure 4. Measured AC losses on SCS Tape and SF Tape, COMSOL simulation of hysteresis AC losses in superconducting layer, overall eddy-current AC losses, and total losses of SCS Tape and SF Tape, with the reference of Norris's analytical solutions (Strip and Ellipse), at frequency of transport current 10 Hz.

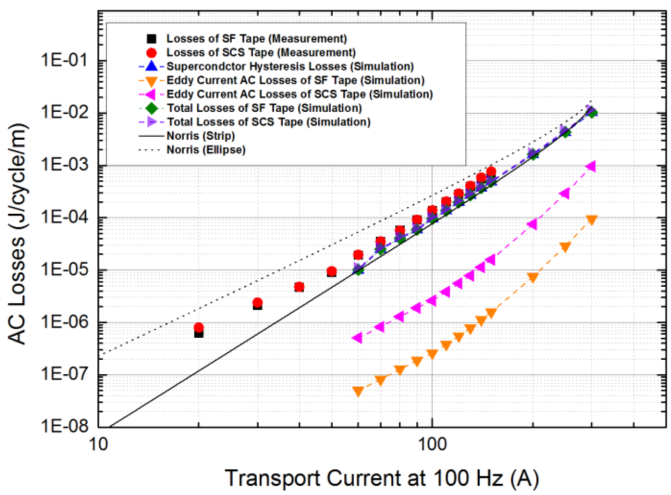

Figure 5. Measured AC losses on SCS Tape and SF Tape, COMSOL simulation of hysteresis AC losses in superconducting layer, overall eddy-current AC losses, and total losses of SCS Tape and SF Tape, with the reference of Norris's analytical solutions (Strip and Ellipse), at frequency of transport current 100 Hz.

are comparable when they are in 77 K and the total thickness of copper stabilizer is 10 times greater than the thickness of silver overlayer. That was the reason for the copper stabilizer had one order higher eddy current losses than silver overlayer, and the eddy-current losses from copper stabilizer dominated the total eddy-current losses of SCS Tape.

4.2 Comparison of SF Tape and SCS Tape with various frequency of transport current

Figure 4-6 show the comparison of experimental AC losses from SCS Tape and SF Tape, as well as the simulation of hysteresis AC losses in superconducting layer, overall eddy-current AC losses all the layers, and the total losses (superconductor hysteresis losses adding eddy-current losses) from simulation. Norris's analytical solutions for both the Strip and Ellipse cases are also shown in Figure 4-6. The frequency of transport current changed from 10, 100 to 1000 Hz. For all three cases, hysteresis AC losses in superconducting layer from simulation agreed well with

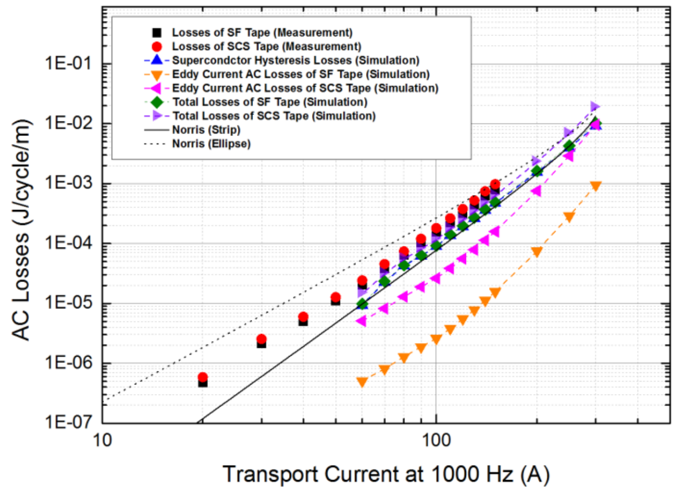

Figure 6. Measured AC losses on SCS Tape and SF Tape, COMSOL simulation of hysteresis AC losses in superconducting layer, overall eddy-current AC losses, and total losses of SCS Tape and SF Tape, with the reference of Norris's analytical solutions (Strip and Ellipse), at frequency of transport current 1000 Hz.

Norris's Strip characteristic, which were frequency independent.

In 10 Hz case (Figure 4), for both the SCS Tape and SF Tape, the simulation results demonstrate the total eddy-current AC losses were always far lower than the hysteresis AC losses in superconducting layer. Therefore, the total losses curve clearly indicates that the hysteresis AC losses dominated. The experimental results were between the two Norris's curves, and agreed with the total losses curve (simulation). The measured AC loss data points of SCS Tape and SF Tape were well matched.

For 100 Hz case (Figure 5), the circumstance of eddy-current AC losses was similar to 10 Hz case. Simulation shows that the total eddy-current AC losses were still much lower than the hysteresis AC losses in superconducting layer for both SCS Tape and SF Tape cases. The experimental results were consistent with the total losses curves from simulation with the 100 Hz case. The loss measurements of SCS Tape made a good agreement with the loss measurements of SF Tape.

For 1000 Hz case (Figure 6), the simulation results present eddy-current AC losses of copper stabilizer increased and started to affect the total losses of SCS Tape, which could be observed from the simulation: the curve for total losses of SCS Tape was slightly above the hysteresis losses of superconducting layer and became more obvious with higher transport current. On the contrary, the eddy-current AC losses of silver overlayer at 1000 Hz were still much smaller than the hysteresis losses of superconducting layers which was much less significant. The measured AC losses data points of SCS Tape were also slightly higher than the measured losses of SF Tape with 1000 Hz Transport current, which implies the eddy-current AC losses of copper stabilizer slightly affected the total AC losses of SCS Tape.

4.3 Eddy-current AC loss measurement and simulation with frequency in kilo Hertz level

To be more precise, the eddy-current AC losses of copper stabilizer could be calculated using the difference value between the total losses of SCS Tape and the total losses of SF

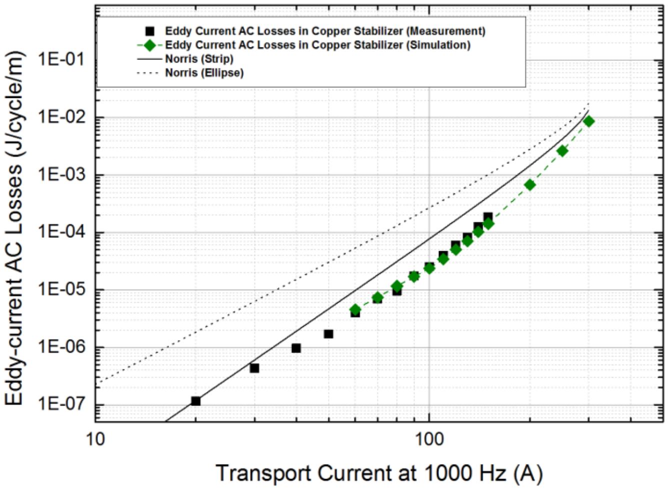

Figure 7. Comparison between measurement and simulation: eddy-current AC losses in copper stabilizer in SCS Tape, with the reference of Norris's analytical solutions (Strip and Ellipse), at frequency of transport current 1000 Hz.

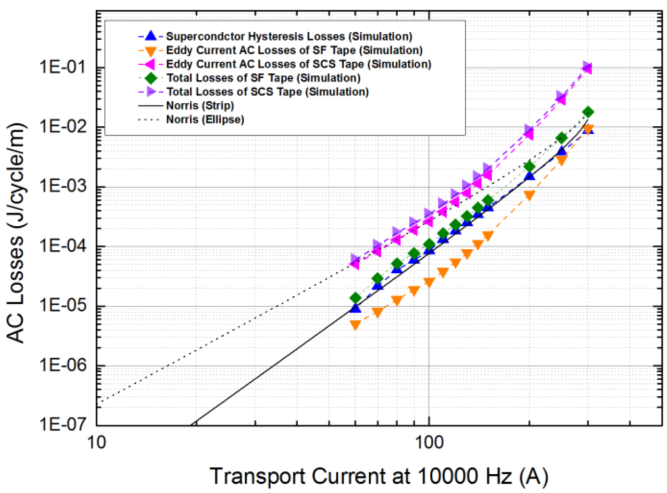

Figure 8. Simulation of hysteresis AC losses in superconducting layer, overall eddy-current AC losses, and total losses of SCS Tape and SF Tape, with the reference of Norris's analytical solutions (Strip and Ellipse), at frequency of transport current 10000 Hz.

Tape, because the only difference between SCS Tape and SF Tape was the outer layers of copper stabilizer. This method was valid both for the measurement and simulation. Figure 7 illustrates the eddy-current AC losses in copper stabilizer of SCS12050 Tape determined by above method with the AC transport current at 1000 Hz. It reveals that the eddy-current AC losses in copper stabilizer started to approach the Norris's Strip in Joule per cycle value with frequency at 1000 Hz. From Figure 7, it can be discovered that the measurement results matched the simulation results with the same magnitude of transport current.

As the limitation of measurement devices, the AC loss measurement with transport current frequency above 1000 Hz was difficult to achieve, but the estimation of total AC losses from SF Tape and SCS Tape could still be carried out using simulation. Figure 8 presents the simulation of SF Tape and SCS Tape with the AC transport current at 10000 Hz. It can be seen that the eddy-current AC losses of silver overlayer at 10000 Hz also slightly affect total AC losses of SF Tape. Furthermore, the eddy-current AC losses of copper stabilizer at 10000 Hz were greater than hysteresis AC losses in superconducting layer. From Figure 8, it can be estimated that the eddy-current AC losses of copper stabilizer occupied a great amount of the total losses of SCS Tape with frequency at 10000 Hz.

5. Conclusion

The investigation and comparison of AC losses on SCS Tape and SF Tape have been carried out, which includes the AC loss measurement using electrical method, as well as the real geometry and multi-layer HTS tape simulation using 2D ***H***-formulation by COMSOL Multiphysics. We focused on hysteresis AC losses in the superconducting layer and eddy-current AC losses in copper stabilizer, silver overlayer and substrate, because ferromagnetic AC losses of substrate have been ignored due to the substrates of Superpower SCS12050 and SF12100 are non-magnetic. Results show that hysteresis AC losses in superconducting layer were frequency independent. The eddy-current AC losses (in Watt) were proportional to the second power of the frequency. The experimental and simulation results reveal that the eddy-current AC losses almost did not affect the total AC losses for both SCS Tape and SF Tape with transport current frequency at 10 Hz and 100 Hz. However, for transport current frequency at 1000 Hz, the experiment and simulation present eddy-current AC losses started to affect the total losses for the SCS Tape, but the SF Tape still obtained negligible eddy-current AC losses when transport current frequency reached 1000 Hz. We determined the eddy-current AC losses in copper stabilizer using the difference value between the total losses of SCS Tape and the total losses of SF Tape, which was valid for both measurement and simulation, and the results show that measurement matched simulation. The estimation of AC losses with frequency at 10000 Hz was also carried out using COMSOL simulation. It could be deduced that the eddy-current AC losses in copper stabilizer should also be taken into consideration for high frequency applications over kilo Hz level.

6. Acknowledgments

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