AC Loss Analysis on HTS CrossConductor (CroCo) Cables for Power Transmission

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Abstract — **This paper demonstrates the alternating current (AC) loss analysis on HTS CrossConductor (CroCo) cables, which could be potentially used for electrical power transmission. The modeling of HTS CroCo cables and AC loss calculation were based on H-formulation model using FEM package COMSOL Multiphysics. The AC loss calculations have been carried out for isolated single-phase CroCo cable and three-phase CroCo cables respectively.**

Keywords- CroCo; cable; AC loss; power transmission

I. Introduction

In recent years, second generation high-temperature superconductor (HTS) rare-earth barium-copper-oxide (REBCO) tapes have been widely used for high-current cables, such as round core cable [1], Roebel cable [2], and twisted stacked-tape cable [3]. CrossConductor (CroCo) cable is one of the twisted stacked-tape cables, and has the capability to achieve a high current density [4]. CroCo cable offers good mechanical performance because it can relax stresses from twisting and bending process, and increase the possibility for construction of long-length cables [4]. The cable has been initially used for magnet applications, but the compact design makes it a possible solution for AC power transmission. Nevertheless, AC loss is a big issue of superconducting power cables that cuts off the overall efficiency and challenges the cryogenic system.

There are some literatures on design and measurement of twisted stacked-tape cables [3, 5], and there is an overview on CroCo cable [4]. However, an AC investigation on CroCo cable is missing. This paper shows the modeling and AC loss analysis on isolated single-phase and three-phase CroCo cables. The AC loss angular dependence of a particular phase in three-phase CroCo cables was studied.

II. Modeling of CroCo Cables

A. H-formulation

In order to calculated the AC loss of CroCo cables, the ***H***-formulation of Maxwell's equations was chosen as the suitable method. ***H***-formulation consists of Faraday's Law, Ampere's Law, Ohm's Law, Constitutive Law, and *E-J* power Law [6]. By combining these equations, the general form of partial differential equation (PDE) for variables ***H*** is [7, 8]:

$$\frac{\partial(\mu_0\mu_r \boldsymbol{H})}{\partial t} + \nabla\times(\rho\nabla\times\boldsymbol{H}) = 0 \quad (1)$$

Equation (1) can be performed and solved in COMSOL Multiphysics [9, 10].

B. Modeling of CroCo cable

As shown in Fig. 1, the single-phase CroCo cable model investigated here comprised 10 4-mm tapes and 22 6-mm tapes (32 tapes in total). To realize better precision, we used the real dimensions of typical superconducting tapes, with a superconducting layer 1 μm thick. The gap between each HTS tape was 0.3 mm. The distance between each phase (cable boundary to boundary) was 5 mm. The power index for the E-J power law was set to be 25. Other simulation parameters are listed in Table 1. An anisotropic ***B***-dependent critical current model [11, 12], was implanted into our modeling:

$$J_c(B) = \frac{J_{c0}}{\left(1+\frac{\sqrt{(k\boldsymbol{B}_{para})^2+\boldsymbol{B}_{perp}^{\ 2}}}{\boldsymbol{B}_c}\right)^b} \quad (2)$$

where k = 0.25, b = 0.6, B_c = 0.035, and J_{c0} = 4.75 × 10^{10} A/m^2. A static model to compute the critical current with Equation (2) estimated the total critical current of single-phase CroCo cable 3889 A.

As we applied power frequency 50 Hz for all the calculations, it was reasonable to ignore the eddy current AC losses in the metal layers [13]. The ferromagnetic AC losses were neglected, as the substrates of proposed HTS tapes for CroCo cables are non-magnetic. Therefore, for the simulation, the hysteresis losses in the superconducting layer dominate total AC losses. The AC loss of the domain was calculated using the power density integration of (***E·J***) [14]:

$$Q = \frac{2}{T}\int_{0.5T}^{T}\int_{\Omega} \boldsymbol{E}\cdot\boldsymbol{J}\ \ d\Omega dt \quad (3)$$

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

III. Results and Discussion

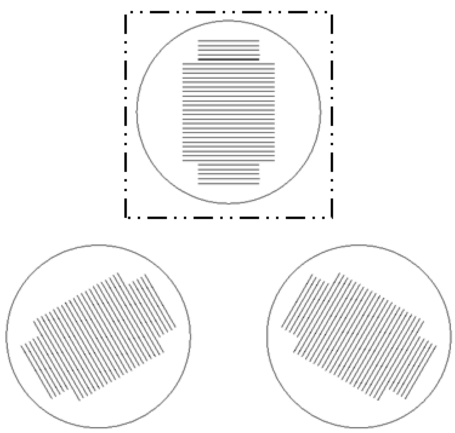

Figure 1. Configuration of three-phase CroCo cables.

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TABLE I. PARAMETERS FOR THE SIMULATION OF CROCO CABLE

Parameters	Value
Number of 4 mm tapes	10
Number of 6 mm tapes	22
Total number of HTS tapes	32
Cable Diameter	12 mm
Tape thickness	1 μm
Gap	0.3 mm
μ_0	$4\pi\times10^{-7}$ H/m
n (power index for E-J power law)	25
J_{c0}	4.75×10^{10} A/m^2
E_0	10^{-4} V/m
B_C	35 mT
b	0.6
k	0.25

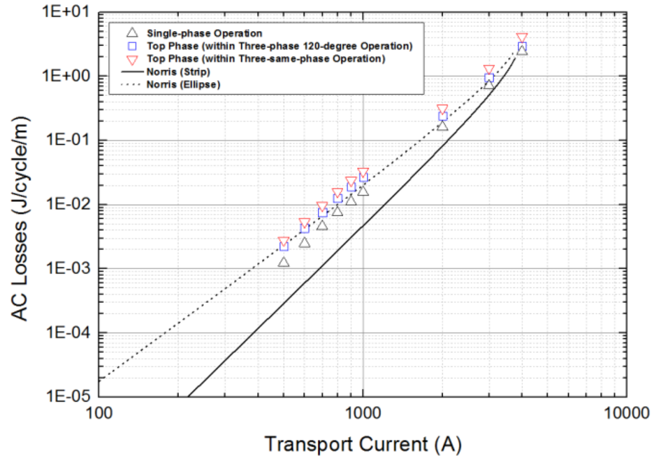

Figure 2. Comparison: AC loss of an isolated single-phase CroCo cable, AC loss of one phase CroCo cable within three-phase system (each phase difference 120 deg), and AC loss of one CroCo cable within three-same-phase system, with the Norris's analytical solutions (strip and ellipse).

Fig. 2 shows the comparison of the AC loss of an isolated single-phase CroCo cable, of one phase CroCo cable within three-phase system (each phase difference 120 deg), and of one phase CroCo cable within three-same-phase system, with the reference of Norris's analytical solutions (strip and ellipse). It can be seen that AC loss curve of isolated single-phase was slightly lower and tracing Norris ellipse. The AC loss curve of the phase with 120 degree phase difference was slightly over Norris ellipse, but always lower than the AC loss curve with three-same-phase. That was due the stronger magnetic field interaction of three-same-phase with respect to the three-phase with 120 degree difference.

Fig. 3 illustrates the AC loss angular dependence for the top phase in three-phase CroCo cables, with overall transport current 1000 A. By changing θ from 0 to 90 degree, the AC loss decreased approximately 15%.

IV. CONCLUSION

The modeling and AC loss calculation of isolated single-phase cable and three-phase CroCo cables have been performed by ***H***-formulation model using FEM package COMSOL Multiphysics. Results revealed that the AC loss of one phase in typical three-phase CroCo cables was greater than that from isolated single phase and Norris ellipse, but smaller than that from three-same-phase CroCo cables. The AC loss angular dependence was not significant when rotating the top phase in three-phase CroCo cables.

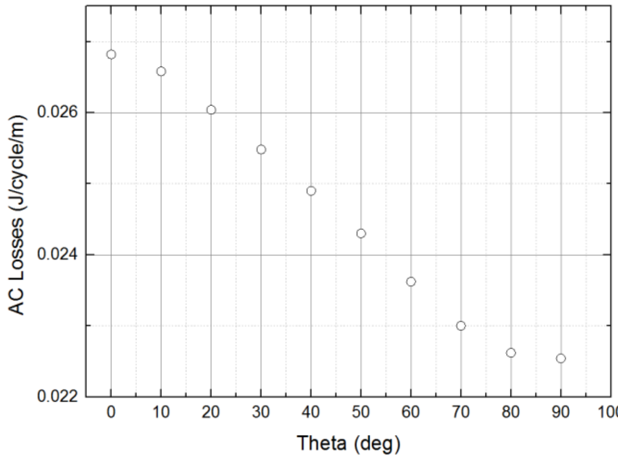

Figure 3. AC loss angular dependence for top phase of three-phase CroCo cables, with overall transport current 1000 A.

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