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Investigation on AC loss of a high temperature superconducting tri-axial cable depending on twist pitches ☆

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ABSTRACT

High temperature superconductor (HTS) cables have been intensively studied because they are more compact compared with conventional copper cables. Since it is strongly expected that the HTS cables replace conventional power lines, some HTS cables are designed, manufactured, installed in power grids and tested to demonstrate full time operation. Recently, a tri-axial cable composed of three concentric phases has been developed, because of its reduced amount of HTS tapes, small leakage field and low heat loss when compared with single phase and co-axial HTS cables. The layers inside the tri-axial cable are subject to azimuthal fields applied from inner layers and axial fields applied from outer layers with different phase from their transport currents. These out-of-phase magnetic fields should be calculated under the condition of the three phase-balanced distribution of the tri-axial cable, and thereby AC losses should be evaluated. In this paper, the AC loss in the tri-axial HTS cable consisting of one layer per phase is theoretically treated for simplicity. The AC losses in the cable are calculated as functions of the twist pitches of HTS tapes. It is found that the AC losses rapidly decrease with increasing twist pitch.

1. Introduction

High temperature superconductor (HTS) cable system is expected to replace the existing copper cable system in the near future; especially in the metropolitan where electric energy demand is increasing. In an HTS cable system, lower settlement cost and loss can be obtained, therefore several HTS cable system projects are settled into real power grids and they continue active operation [1–4], recently. Till now, three single phase and triad co-axial HTS cables have been designed and tested in various researches in terms of AC loss. Fig. 1 represents the general concept of those three types of HTS cables accompanied by their cross-sectional view. Among them, the tri-axial cable has small cross-section and maintains less HTS tape usage, when compared with the three single phase and triad co-axial cables [1,5–9]. In addition, the tri-axial cable can achieve lower AC loss and leakage field. Due to these properties, the tri-axial cables are actively researched and developed, recently.

Because the tri-axial cable layers differ in radii, all layers have different inductances and hence inherent unbalanced current distribution exists in operation. In case unbalanced currents flow through the tri-axial cable layers, leakage fields are generated outside of the cable and result in AC loss and electromagnetic noise, which reduce the electric transmission quality of the power line. Therefore, realization of the balanced three phase distribution is one of the important issues among tri-axial HTS cable researches.

Since the both sides of the cable joints can be configured as separate segments, the balanced three phase condition can be realized [5–9]. In real underground cable system, the cable joints are connected at the manholes, and distance between manholes may differ. Thereby, the tri-axial HTS cable can be researched in two segments with variable length as well we research those segments with different twist pitches.

Since HTS tapes are wound spirally, layer currents of the tri-axial cable generate axial magnetic field inside and azimuthal field outside the layers. External magnetic fields from different phases combine with the self magnetic field produced by transport current. Therefore, different phase fields generate complex magnetic fields and AC losses [6,7]. The field losses increases the load of the refrigerator in the HTS cable system, and therefore reducing the AC loss is an important issue in order to decrease the cooling cost of the tri-axial cable.

In this paper, segment twist pitch ratio of two different segments is considered as a parameter in order to solve balanced three phase distribution equations of the tri-axial cable. Using the equations, we analyze twist pitches to maintain lower AC loss. In AC loss calculation, the AC loss derivation become complex in case penetrated field exceeds the center of the slab. We use the simplest

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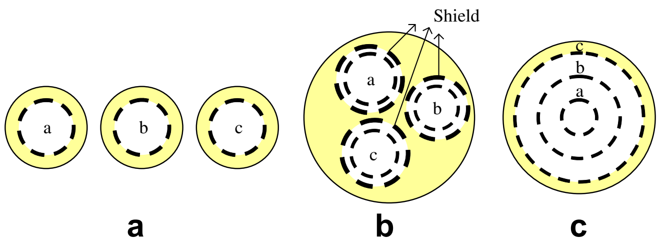

Fig. 1. Three types of three-phase cable: (a) three single phase, (b) triad co-axial cable and (c) tri-axial cable.

configuration of the tri-axial cable with one layer per each phase in order to analyze basic properties of AC loss.

2. Balanced twist pitches

In case of balanced currents and voltage drop of three phases, phase-current and voltage drop amplitudes are equal and each phase has 120° phase difference each other, as following equation shows

$$I_b = \alpha^2 I_a, \quad I_c = \alpha I_a, \quad \alpha = \exp(j2\pi/3)$$
$$V_b = \alpha^2 V_a, \quad V_c = \alpha V_a \tag{1}$$

Here, α is the operator that shifts phase 120°. We substitute the balanced current condition into the balanced voltage drop equations and obtain two complex equations. In order to derive balanced three phase distribution equations, we separate real and imaginary parts of the equations and finally get four fundamental equations.

Fig. 2 outlines the two segment model cable where we can select segment twist pitches as unknown variables of the fundamental equations. Twist pitches are totally six for two segments and they are two more compared to fundamental balanced equation number, thereby we can freely select two of the pitches. By means of that, we can make an appropriate configuration of cable pitches. In the analysis we compare 1st and 2nd segment pitches of phase-a and phase-b and use the ratio between them. Namely, phase-a and phase-b segment pitch ratios are assumed as follows.

$$L_{a2} = kL_{a1}, \; L_{b2} = kL_{b1} \tag{2}$$

Here, L_{a1} is the twist pitch in the 1st segment of phase-a and k is the proportional constant. The condition of $k = 1$ means that the segment twist pitches of the same phase are equal.

Considering total cable length is fixed, we can change lengths of two segments. Making the comparison between two segment lengths and total cable length we set $s_1 = L_1/L$, $s_2 = L_2/L = 1 - s_1$. Here, L is the total cable length, L_1 and L_2 are 1st segment and 2nd segment lengths, respectively.

We substitute the ratios mentioned above into the balanced three phase equations and finally obtain the following twist pitch equations.

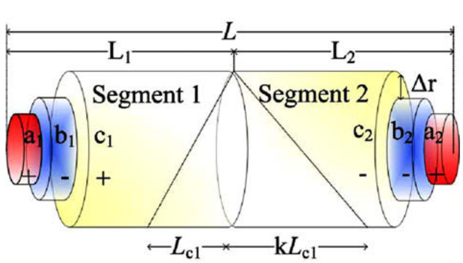

Fig. 2. The structure of the tri-axial cable.

$$L_{a1} = f_1 g_a, \quad L_{a2} = f_2 g_a$$
$$L_{b1} = -f_1 g_b, \quad L_{b2} = -f_2 g_b$$
$$L_{c1} = -f_{c1} g_c, \quad L_{c2} = f_{c2} g_c$$

$$f_1 = \frac{\sqrt{1 - s_1 + s_1 k^2}}{k}, \quad f_2 = kf_1, \quad f_{c1} = f_1\sqrt{\frac{s_1}{1-s_1}}, \quad f_{c2} = f_{c1}\frac{1-s_1}{s_1},$$
$$g_a = \frac{2\pi r_a}{2u_2 \log u_3}\sqrt{\log u_2 + \sqrt{(\log u_2)^2 + (2u_2 \log u_3)^2}},$$
$$g_b = \frac{2\pi r_a}{2u_2 \log u_3}\sqrt{-\log u_2 + \sqrt{(\log u_2)^2 + (2u_2 \log u_3)^2}},$$
$$g_c = 2\pi r_a u_2 u_3\sqrt{\log u_2 + 2\log u_3 + \sqrt{(\log u_2)^2 + (2u_2 \log u_3)^2}},$$
$$u_2 = \frac{r_b + \Delta r}{r_a}, \; u_3 = \frac{r_c + \Delta r}{r_b} \tag{3}$$

Here, r_a, r_b, r_c corresponds radii of phases-a, b and c, respectively, and Δr defines the gap width between them. Among the equations, the minus sign of the pitch indicates the opposite twist direction than others. Typically, if twist pitch becomes shorter, the AC loss increases. In order to reduce AC loss, we need to investigate the cable parameters that lengthen the twist pitches. But, the parameters r, radii of all phases, and Δr, the gap width between them, are determined according to the voltage class. Therefore, we can freely change the parameters k, segment twist pitch ratio, and s_1, segment ratio. As Eq. (3) shows, four functions f_1, f_2, f_{c1}, f_{c2} are functions of k and s_1, and are proportional parts of twist pitches L_{a1} and L_{b1}, L_{a2} and L_{b2}, L_{c1} and L_{c2}, respectively. Using k and s_1, twist pitch proper-

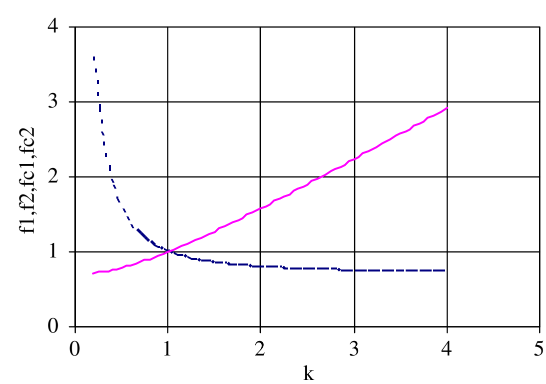

Fig. 3. f_1, f_2, f_{c1} and f_{c2} functions vs. segment twist pitch ratio for ($s_1 = 0.5$).

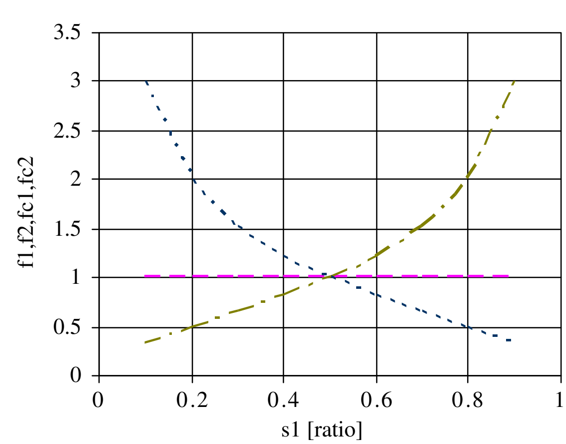

Fig. 4. f_1, f_2, f_{c1} and f_{c2} functions vs. segment ratio for $k = 1$.