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Parametric Study of AC Current Lead for the Termination of HTS Power Cable

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Abstract-- **High Temperature Superconductor (HTS) transmission cable can carry more than 2 to 5 times higher electricity and also obtain substantially lower transmission losses than conventional cables. Liquid nitrogen is to be used to cool the HTS power cable and its cost is much cheaper than the liquid helium used for the cooling of metal superconducting wire. In Korea the HTS power cable development project has been ongoing since July, 2001 with the basic specifications of 22.9kV, 50MVA and cold dielectric type as the first 3-year stage. The cryogenic system of the HTS cable is composed of HTS cable cryostat, termination and refrigeration system. Termination of HTS cable is a connecting part between copper electrical cable at room temperature and HTS cable at liquid nitrogen temperature. In order to design the termination cryostat, it is required that the conduction heat leak and Joule heating on the current lead be reduced, the cryostat be insulated electrically and good vacuum insulation be maintained during long time operation. Heat loads calculations on the copper current lead have been performed by analytical and numerical method and the feasibility study for the other candidate materials has also been executed.**

1. INTRODUCTION

HTS transmission cables carry 2 to 5 times more power than normal cables of the same size. Since they can be installed in the existing underground pipes, the construction cost can be reduced. So they are expected to be optimal means to satisfy a huge amount of power demands in the near future.

HTS cables should be cooled down up to liquid nitrogen temperature in order to operate. The cryogenic system of HTS cable is composed of HTS cable cryostat, termination and refrigeration system. Refrigeration system generates and circulates the liquid nitrogen. Termination of HTS cable transmits the power from the copper electrical cable at room temperature to the HTS cable at liquid nitrogen temperature through current leads [1].

Current lead is the main heat load on the cryogenic environment through both Joule heating generated by the transporting current and conduction from the room temperature. The other heat loads entering the liquid nitrogen chamber are radiation from the vacuum insulated cryostat and conduction between vacuum cryostat and liquid nitrogen chamber through supports. Since the heat loads through current lead are the major parts of the total heat loads generated in the termination cryostat, reducing the heat loads on the current leads plays an important role for the optimal design of the current leads [2],[3]. In this paper, the effect of AC on the design of the current leads of the termination of the HTS transmission cable system.

2. HEAT TRANSFER MECHANISM IN DC CURRENT LEAD

Copper is selected as a material of the current lead. The optimal design of the DC current lead can be performed based on the following one-dimensional equation showing the steady state heat transfer equation within the current lead carrying transporting current [4],[5]:

$$\frac{d}{dx}\left[k(T)A\frac{dT}{dx}\right]-fC_p(T)\dot{m}\frac{dT}{dx}+\frac{\rho(T)I^2}{A}=0 \qquad (1)$$

Where x is the axial distance along the lead, x is zero at the cold end. k(T), A, and ρ(T) are, respectively, the lead thermal conductivity (W/m K), cross section (m^2) and electrical resistivity (Ω m). $\dot{m}$ and $C_p(T)$ are nitrogen mass flow rate (kg/s) and specific heat (J/kg K), respectively. Also, f and I are cooling efficiency and direct current (A), respectively.

The first term of (1) represents axial conduction along the current lead. The second term represents convection by cold vapor rising from boiling nitrogen through the lead. The last term represents the Joule heating dissipated by the electrical resistance of the copper conductor.

3. AC CURRENT LEAD

3.1. Current Density Profile in AC Current Lead

When AC flows in a conductor the phenomenon of skin-effect has to be considered. Its own alternating magnetic field makes the current to concentrate on the surface layers. The magnitude of the current density falls off exponentially from the surface. When the magnitude falls to 1/e of its surface value, the distance from the surface is called as skin depth [6] and expressed by (2).

$$\delta\ (Skin\ \ Depth) = \sqrt{\frac{2\rho}{\mu\omega}} \qquad (2)$$

Where μ is permeability (H/m) representing the easiness of the magnetic field formation in the material, and ω is frequency (rad/s) of the current.

When AC flows in a circular cross-sectioned current lead, the current density profile can be obtained from the magnetic field using Ampere's law and Faraday's law and expressed by the Bessel function. The current density profiles with the radius in the current lead for various ratios of radius to skin depth are expressed in Fig. 1. The abscissa is the non-dimensional value of radius, where zero means the center and one means the surface. Also the ordinate is the non-dimensional value of current density, where zero means no current and one means the current density at the surface. As shown in Fig. 1, when the radius of the lead becomes bigger than the skin depth, the difference of current density at the surface and the center increases [6].

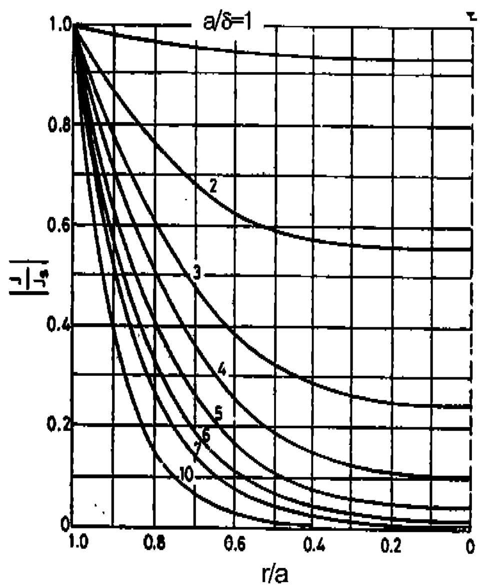

Fig. 1. Fall-off current density with radius in solid cylinder, for various ratios of radius to depth of penetration, expressed as the modulus of J/J_s

The current density distribution in a circular cross-sectioned AC and DC current lead is calculated with various areas and compared in Fig. 2. The area of the second lead is one fifth of the first one. As shown in Fig. 2 (a), the average current density of AC current lead is much higher than that of DC current lead. Also the AC current density at the surface is twice that of DC current lead. However, for the smaller area current lead the differences between current densities of AC and DC current leads became minimal. This means that because the ratio of radius to the skin depth decrease the current density distribution became flat as shown in Fig. 1.

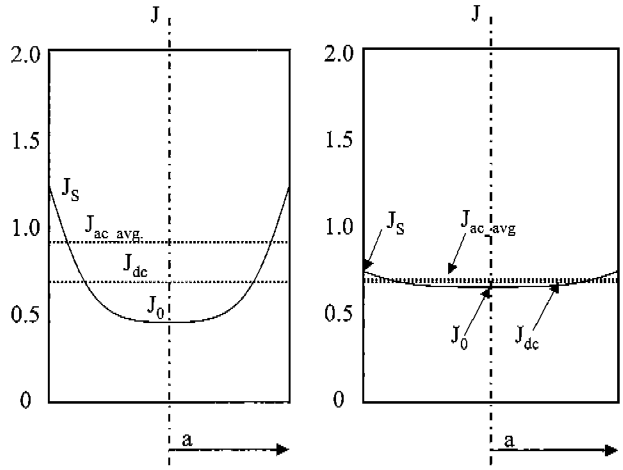

Fig. 2. Current density distribution in a circular cross-section area: (a) a=25mm, I=1260A, L=1000mm, T=20℃, ρ=2.0 x 10^{-8} Ω m, μ=4π x 10^{-7}, f=60Hz; (b) a=11.18mm(5ea), I=1260A, L=1000mm, T=20℃, ρ=2.0 x 10^{-8} Ω m, μ=4π x 10^{-7}, f=60Hz

When the same currents of 1260 A flow in the AC and DC current leads with same area, the variation of resistance, average current density and Joule heating are calculated at each current lead and the results are summarized in Table I. As the radius of AC current lead decreases Joule heating also decreases and converges to the DC values. Here the resistance of AC current was defined in section 3.2.

TABLE I

COMPARISON RESULTS OF THE CURRENT LEAD WITH VARIOUS RADIUS FOR TWO DIFFERENT TYPES OF CURRENTS

Current Type	DC	AC		
I (A)	1260	1260		
Radius (mm)	25	25	11.18 (×5)	7.906 (×10)
A (mm^2)	1963.5	1963.5	1963.4	1963.6
R (nΩ*m)	10.2	15.3	10.5	10.28
$J_{avg.}$	0.64	0.96	0.66	0.647
Q_{joule}	16.17(100)	24.26(150)	16.69(103)	16.3(101)

3.2. Resistance of AC Current Lead

The governing heat transfer equation for the AC current lead was obtained based on the heat transfer equation of DC current lead, as mentioned in (1), accounting for the resistance ratio of AC to DC current lead, such as:

$$\frac{d}{dx}\left(k(T)A(x)\frac{dT}{dx}\right)+\Theta\cdot\frac{\rho(T)I^2}{A(x)}=0 \qquad (3)$$

Here the resistance ratio, Θ, is expressed by R_{ad}/R_{dc}, and divided into three approximate relations as a function of the ratio of radius to the skin depth depending on the range of the ratio, as follows:

$$a)\ a/2\delta < 1.15$$
$$\Rightarrow \Theta = 1+\frac{1}{48}\left(\frac{a}{\delta}\right)^4$$
$$b)\ 1.15 \le a/2\delta \le 2.34 \qquad (4)$$
$$\Rightarrow \Theta = 0.174\left(\frac{a}{\delta}\right)^2-0.28\left(\frac{a}{\delta}\right)+1.13$$
$$c)\ a/2\delta > 2.34$$
$$\Rightarrow \Theta = \frac{a}{2\delta}+\frac{1}{4}$$

The temperature distribution in AC current lead is obtained from (3) considering the AC resistance through the resistance ratio. Since the total heat loads generated in the AC current are the combination of Joule heating and conduction, the temperature distribution is actually the outcome of the total heat loads. In order to investigate the effect of temperature on the resistivity, skin depth, and resistance ratio, three temperature values was chosen and the AC and DC resistances are calculated based on these temperatures. And the results are as follows:

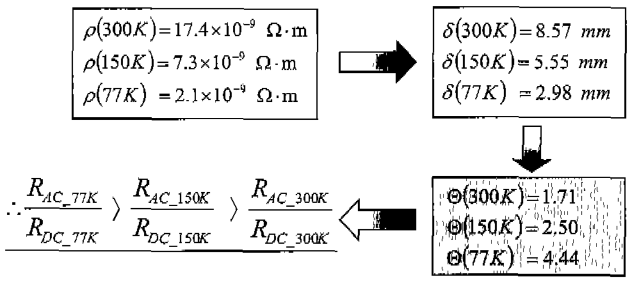

Fig. 3. comparison of resistance ratio of two current types, by calculating skin depth and electrical resistance at three different temperatures

As shown in Fig. 3, as the temperature decreases the resistivity and skin depth decrease, but the resistance ratio increase. The resistance ratio at 77 K is more than twice that at 300 K. Therefore the resistance ratio can accounted for as an important parameter in the heat transfer equation for the AC current lead especially at lower temperature.

4. Heat Load Compared with AC and DC

From the governing equations shown in (1) and (3) of DC and AC current lead the temperature distribution was obtained. The total heat loads were calculated based on the temperature of the copper current lead and the results are summarized in Table II. For DC current lead, an optimal heat load was obtained, but for AC current lead the optimal heat loads vary depending on the geometry of the lead. The difference of heat load between DC and AC becomes bigger as the length and diameter increase. This is because Joule heating due to higher AC resistance increases. More heat loads are generated on the AC current lead compared to AC current lead regardless of the geometry. As the length increases, the optimal diameter also increases to satisfy the optimal heat load condition.

TABLE II
Comparison Results of Total Heat Loads for the DC and AC Copper Current Lead

I (A)	1260			
Length [mm]	1500		3000	
Current type	DC	AC	DC	AC
Diameter [mm]	25.9	25.7	36.6	37.2
$(IL/A)_{OPT}$ [A/m]	3.59E6	3.65E6	3.59E6	3.47E6
Q_{OPT} [W]	53.4	61.0	53.4	70.3
$(Q_{AC}-Q_{DC})$ [W]	7.6		16.9	

5. Effect of Material Composition

Heat loads were calculated with brass current lead in addition to copper lead and the results are shown in Fig. 4. The AC effect on the heat load for the brass current lead showed the similar trend to the copper lead. The brass current lead generate higher heat load than copper current lead in both AC and DC current lead [7],[8].

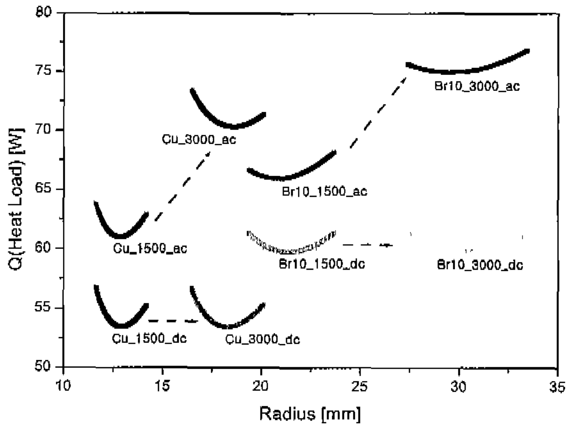

Fig. 4. Q_{DC} and Q_{AC} for copper and brass (zn10) current lead with L=1500 mm and L=3000 mm

6. CONCLUSION

The AC has been considered as an important parameter for the design of current lead for the HTS cable termination. When AC flows on the current lead the currents are mainly distributed on the edge of the current lead due to skin effect and result in the non-uniformity of the current density across the cross-section of the current lead. As area increases, the influence of skin effect became serious and therefore the heat load on the AC current lead increased.

Since the resistance of the AC current lead has been affected by the skin effect, higher heat loads were genterated in AC current lead compared to the DC current lead. When the AC of 1260 ampere were flowing in the AC current lead with radius of 25 mm and the length of 1.5 m, the heat loads were increased about 15 % compared to the DC current lead.

In order to reduce the non-uniformity of the current distribution, an AC current lead has divided into several current leads that have smaller cross-sections than the original current lead. The material properties of the current lead have also affect the AC current lead design. The brass current lead generates higher heat load than copper current lead in both AC and DC current lead. But the heat load of the brass and copper current lead for the AC case depends on the configuration of the current lead compared to DC current lead.

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