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Analysis on heat loss characteristics of a 10 kV HTS power substation ☆

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ABSTRACT

A 10 kV High Temperature Superconducting power substation (10 kV HTS substation), supported by Chinese State 863 projects, was developed and has been running to supply power for several factories for more than two years at an industrial park of Baiyin, Gansu province in Northwest China. The system of the 10 kV HTS substation compositions, including a HTS cable, a HTS transformer, a SFCL, and a SMES, are introduced. The SMES works at liquid helium temperature and the other three apparatus operates under liquid nitrogen condition. There are mainly four types of heat losses existing in each HTS apparatus of the 10 kV HTS substation, including AC loss, Joule heat loss, conductive heat, and leak-in heat from cryostat. A small quantity of AC loss still exists due to the harmonic component of the current when it carries DC for HTS apparatus. The principle and basis for analysis of the heat losses are introduced and the total heat loss of each apparatus are calculated or estimated, which agree well with the test result. The analysis and result presented are of importance for the design of the refrigeration system.

1. Introduction

The renewable energy has been developing rapidly worldwide for the urgency of exhaustion of the fossil energy and protection of environment. How to solve the problems of massive accommodation of renewable energy in the future power grid, to improve the transmission efficiency to reduce transmission losses, and to construct a more robust power grid by using new technologies and/or new methods have become a serious issue, which is also the focus concern of both electrical managers and engineers worldwide. Several new technologies are believed to have the potential of improving the efficiency and robustness of the power grid [1,2].

Superconducting power technology has many advantages compared with that of conventional counterparts. It is considered to be a competitive candidate for the future power grid: the superconducting cable would achieve large capacity transmission; the superconducting transformer could increase the efficiency while decrease the bulk of transformer; the superconducting fault current limiter (SFCL) provides a new option for the grid to enhance the security and stability; the superconducting magnetic energy storage system (SMES) may play an important role to improve the quality of electrical energy in the future grid for the renewable energy grid [3–7].

In the past decade, several demonstration projects have been developed and still many programs are under development. Typical projects includes a 5/10 MVA HTS transformer, a 138 kV/600 m HTS cable and a 138 kV/900 A SFCL in USA; a 500 m/22.9 kV HTS cable in Korea; a 15 MVA class SFCL in Italy; a 66 kV/1.75 kA HTS cable and a 2 GJ Class YBCO SMES in Japan, and so on [8–14].

A 75 m /10.5 kV/1.5 kA three-phase AC HTS cable (75 m HTS cable), a three phase 630 kVA/10.5 kV/400 V HTS transformer (10 kV HTS transformer), a three phase 10.5 kV/1.5 kA SFCL (10 kV SFCL), and a 1 MJ/0.5 MVA SMES (1 MJ SMES) were successfully developed and demonstrated by the Institute of Electrical Engineering, Chinese Academy of Sciences [15–18]. After finishing demonstrations for each superconducting apparatus, these HTS power equipment were integrated into a 10 kV HTS substation.

The 10 kV HTS substation, located at an industrial park of Baiyin, Gansu province in Northwest China, supplies power for several factories with rated voltage 10 kV.

It is of importance for 10 kV HTS substation to analyze the thermo-hydraulic characteristic and get the main heat loss sources to develop the cooling system, which is based upon the heat loss

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result. The structure and its cryogenic performance of each HTS apparatus are mainly analyzed and discussed.

2. The heat loss analysis of the 10 kV HTS substation

There are mainly four types of heat losses in each apparatus:

AC loss, which is caused by the AC transmission current and magnetic field, occupies a certain proportion of heat loss when the HTS apparatus carries AC current. The AC loss still exists at DC working condition due to the harmonic components of the current. AC loss contributions can be divided into three categories of hysteretic loss, coupling loss, and eddy current loss.

Joule heat loss, which is contributed by resistance of the current lead, transitive conduct and their joints, is a main resource for every apparatus.

The conductive heat, which is caused by current lead and inner wall of cryostat, is another heat loss source for apparatus. It is difficult to reduce the conductive heat and the joule heat of a current lead simultaneously, but it can be optimized.

The leak-in heat from cryostat, which is determined by the performance of a cryostat, affected by its structure and material, is always an important section.

2.1. AC losses

The total AC losses in HTS apparatus mainly consist of hysteresis loss, eddy current loss and coupling loss.

2.1.1. Hysteretic loss

Bi2223/Ag tape has high anisotropy in the presence of a magnetic field at 77 K. Hysteretic loss occurs when it carries AC in the HTS tape. It can be analyzed by (1) and (2) when the HTS tape operates in perpendicular and parallel magnet field respectively [20,21].

$$P_{\perp} = Kf\frac{w^2\pi}{\mu_0}B_c^2\beta_{\perp}\left(\frac{2}{\beta_{\perp}}\ln(\cos h\beta_{\perp}) - \tan h\beta_{\perp}\right) \tag{1}$$

where K is the geometry structure factor which is 1.35 for the HTS tape with stainless steel reinforced layer; B_c is the critical magnetic field decided by J_c; w is the width of the tape; $B_c = \mu_0 J_c d/\pi$, where J_c is the critical current density and d the half-thickness of the HTS tape.

$$P_{\parallel} = \begin{cases} \frac{2fcAB_p^2}{3\mu_0}(i_{ac}^3 + 3b_{ac\parallel}^2 i_{ac}) \quad (b_{ac\parallel} < i_{ac}) \\ \frac{2fcAB_p^2}{3\mu_0}(b_{ac}^3 + 3b_{ac\parallel} i_{ac}^2) \quad (i_{ac} < b_{ac\parallel} < 1) \\ \frac{2fcAB_p^2}{3\mu_0}(b_{ac\parallel} + (3 + i_{ac}^2 - 2(1 - i_{ac}^3) + \\ 6i_{ac}^2\frac{(1-i_{ac})^2}{(b_{ac\parallel}-i_{ac})} - 4i_{ac}^2\frac{(1-i_{ac})^3}{(b_{ac\parallel}-i_{ac})^2}) \quad (b_{ac\parallel} \gg 1) \\ \frac{2fcAB_p^2}{3\mu_0}(b_{ac\parallel}(3 + i_{ac}^2) - 2(1 - i_{ac}^3)) \end{cases} \tag{2}$$

where f is the current frequency; normalized current $i_{ac} = I_{ac}/I_c$, I_{ac} and I_c are the amplitude of transmission current and tape critical current respectively; normalized parallel magnetic field component $b_{ac\parallel} = B_{ac\parallel}/B_P$, B_P is the full penetration field determined by $\mu_0 J_c d$ and $B_{ac\parallel}$ is the parallel magnetic field amplitude, and the J_c here is the critical current density of the tape, cA the effective area depending on the geometrical configuration of the tape, the A is the total cross section area.

2.1.2. Coupling loss

HTS tape is a kind of multi-filament composite conductor and there are many filaments within it. The alternative magnetic field induced by AC will cause coupled field within the filaments and it will induce an electric field and then a coupled current around a loop across the normal conducting of the filaments occurs. The coupling current leads to joule heat and the coupling loss can be described by (3) below [22].

$$P_c = \eta_c\frac{AB_{ac}^2}{2\mu_0}\left[\frac{\eta_s\omega^2\tau}{1 + (\omega\tau)^2}\right] \tag{3}$$

where η_c is the filamentary core volume fraction in the composite tape and A the cross-section of the tape; B_{ac} is the ac magnetic field amplitude and η_s the shape factor of the filamentary core; $\omega = 2\pi f$, is the angular frequency; and τ the characteristic decay time constant.

2.1.3. Eddy current loss

The eddy current and the eddy loss exist in the matrix of the normal conductor of reinforcing layers, such as the stainless steel or the brass, due to the magnetic field. It can be significant under the perpendicular magnetic field. The eddy loss is given by [22]

$$P_e = \frac{2B_{ac}^2}{\mu_0}\left[\frac{\mu_0 d\omega^2 w^3}{48\rho_s}\right] \tag{4}$$

where ρ_s is the resistivity of the reinforce layer; w and d are the width and the thinness of the tape respectively.

Based upon the analysis above, the total AC loss can be got by summing the three categories:

$$P = P_{\perp} + P_{\parallel} + P_c + P_e \tag{5}$$

2.2. The Joule heat and conductive heat loss caused by the current lead

The heat loss of the current lead, including conductive heat and joule heat, contributes a part of the total loss of HTS apparatus. If the resistivity is assumed as a constant, the heat loss can be got by (6) below [23]:

$$Q = \frac{1}{2}I^2\rho\frac{L}{S} + \frac{S}{L}\int_{T_L}^{T_H}\lambda(T)dT \tag{6}$$

where the S and L are the cross section and the length of the current lead respectively and $\lambda(T)$ is the thermal conductivity of the conductor.

The working temperature of current lead for a HTS apparatus is designed to 77 K and 300 K respectively. The current lead design can be optimized as (7) [9,23].

$$\frac{LI}{S} = \sqrt{\frac{2}{\rho}\int_{T_L}^{T_H}\lambda(T)dT} \tag{7}$$

where L is the length of the current lead; I is the rated current of the current lead; T_H and T_L are the working temperature at the two ends of the current lead; ρ, λ and S are electrical resistivity, thermal conductivity and cross section of the current lead respectively.

2.3. The losses of leak-in heat

The structure of cryostat is designed to be thermal insulated with high vacuum and multilayer insulation generally. The radiation heat loss induced by the nature property of material, the conductive heat loss caused by the inner wall of cryostat, and the convective heat determined by the vacuum degree, exists in cryostat at the same time. The performance of cryostat material has great influence on its thermal property because it determines the ability of maintaining vacuum. The cryostat made of nonmetallic material has poorer thermal insulation property generally than that made of metal.