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BREAKDOWN HAZARD OF ELECTRIC INSULATION IN SUPERCONDUCTING COIL PROTECTED WITH RESISTOR

1. Introduction

The superconducting coil loses its superconductive state if the copper cannot give the full thermal stabilization for the filaments. Then the coil resistance increases till the moment when the full magnetic field of the coil will be dissipated. The coil temperature is increasing and the considerable volume of the liquid helium is vaporizing. The high voltage occured on the resistance threatens the electric insulation of the coil. Furthermore, the considerable rise in temperature may result in the thermal faults of the insulation and even burnout of filament [1,2].

The common used protection for the superconducting coils is an electric circuit or a device (most often resistor) which dissipates the magnetic field energy outside the cryostat. So, the coil resistance is small and as a result the voltage, temperature and the liquid helium losses are rather limited.

The disadvantage of this method are overvoltages induced on the coil by means of the alternating current during the energy dissipation.This is the sele factor threating the electric insulation of the protected superconducting coil. The analysis of this hazard is given in the paper.

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2. The choice of the resistor for the superconducting coil protection system

The protection system is presented in Fig.1. When the superconducting coil loses its superconductivity the switch W opens and the magnetic field

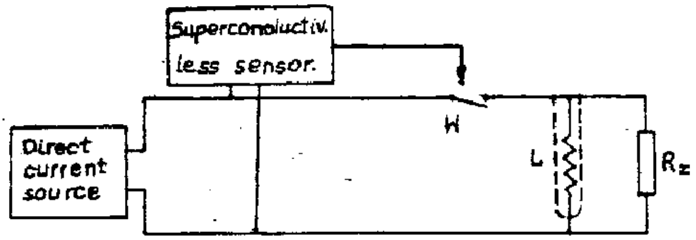

Fig.1. The superconducting coil protection system

energy is dissipated with the resistor R_z. In accordance with the literature [2,3,4].

$$R_z = \frac{j_o \cdot L}{2\left[\frac{1+\alpha}{\alpha} Z(T_k) - j_o\, t_o\right]} \qquad (1)$$

where: R_z - protection resistance, $[\Omega]$
L - superconducting coil inductance, $[H]$
j_o - current density in the copper (when the superconductive state is lost), $[Am^{-2}]$
α - copper superconductor ratio [1],
t_o - the time necessary for the detection of the loss of the superconductivity state and for the switching operation $[s]$

$$Z(T_k) = \int_{4.2K}^{T_k} \frac{C_{Cu}(T)}{\rho_{Cu}(T)}\, dT$$

where: T_k - final coil temperature, $[A^2\ sm^{-4}]$

From the formula (1) it appears, that the greater R_z the smaller final coil temperature T_k after the energy dissipation.

3. The analysis of the breakdown hazard

The analysis leaves out the voltage between the ends of the conducting region in the filament as well as the temperature in this region because they are of limited values without the practical effects on the hazard degree. The aim of the analysis is to state the voltage distrubion along the coil when the energy is dissipated on the resistor.

In the large extend, this distribution is determinated by capacitance between the winding and the earth or cryostat. Thus, the voltage distribution is temporarily nonlinear, so, there are the regions of the high voltages. These phenomena have the greatest effect on the electric insulation in this case when the coil end is connected with the earth or with the cryostat. This connection may be necessary for the reliable work of the protection system. Sometimes it may be due to the current lead fault. The analysis scheme is presented in Fig.2.

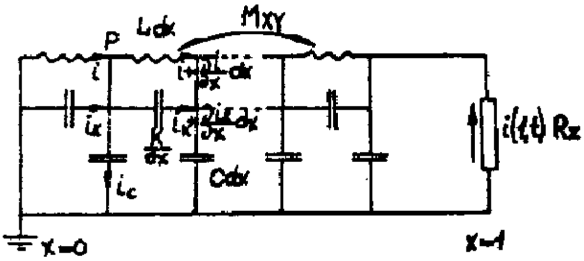

Fig.2. The scheme of the superconducting coil winding protected with a resistor (one end is joined with the earth or with the cryostat)

The Kirchoff's I^{st} and II^{nd} laws used for the element dx and for the point P give the following formula [5,6,7].

$$\frac{\partial i\ (x,t)}{\partial x} = C\ \frac{\partial u\ (x,t)}{\partial t} - K\ \frac{\partial^3\ u\ (x,t)}{\partial x^2\ \partial t} \qquad (2)$$

where: - K - the longitudial capacitance along the coil, [F]

C - the capacitance between the coil and the earth, [F]

u(x,t)-the voltage between the points x and x=0, [V]

The voltage on the inductance of the element dx is as follows [5,6,7].

$$\frac{\partial u\ (x,t)}{\partial x} = -z^2 \int_0^1 M\ (x,y)\ \frac{\partial i_y}{\partial t}\ dy \qquad (3)$$

where: z - the number of the coil turn

y - moving coordinate of the current element.

$M(x,y)$ – mutual induction between the coil turns of x,y coordinates in accordance with the following formula [6,7]:

$$M(x,y) = M_o e^{-\lambda|x-y|} \tag{4}$$

where: M_o – self-inductance of a coil convolution, [H]

λ – the constant determined by the coil construction and its dimensions [1]

From (3), (4) and $L = \dfrac{2z^2 M_o}{\lambda}$ we obtain

$$\frac{\partial i(x,t)}{\partial t} = \frac{1}{L}\left(\frac{\partial u(x,t)}{\partial x} - \frac{1}{\lambda^2}\frac{\partial^3 u(x,t)}{\partial x^3}\right) \tag{5}$$

Next, from (2) and (5) we obtain the following formula for the coil voltage

$$\frac{\partial^4 u(x,t)}{\partial x^4} - \lambda^2 \frac{\partial^2 u(x,t)}{\partial x^2} - K L \lambda^2 \frac{\partial^4 u(x,t)}{\partial x^2 \partial t^2} + C L \lambda^2 \frac{\partial^2 u(x,t)}{\partial t^2} = 0 \tag{6}$$

The general solution of this equation (worked out by means the Laplace's transformation) for the initial conditions

$$u(x,0) = 0 \qquad \frac{\partial u(x,0)}{\partial t} = 0 \tag{7}$$

is as follows

$$u(x,s) = A_1 \sin r_1 x + A_2 \cos r_1 x + A_3 \operatorname{sh} r_2 x + A_4 \operatorname{ch} r_2 x \tag{8}$$

where: $A_{i(i=1,\dots,4)}$ – constants

$$r_1^2 = \frac{1}{2}\left[\lambda^2 + KL\lambda^2 s^2 - \sqrt{(\lambda^2 + KL\lambda^2 s^2)^2 - 4\,CL\lambda^2 s^2}\right]$$

$$r_2^2 = \frac{1}{2}\left[\lambda^2 + KL\lambda^2 s^2 + \sqrt{(\lambda^2 + KL\lambda^2 s^2)^2 - 4\,CL\lambda^2 s^2}\right]$$

whereas:

$$r_2^2 = \frac{\lambda^2 - r_1^2}{1 - \dfrac{Kr_1^2}{C}} \tag{9}$$

Because $i(x,0) = I_o$ and $u(0,t) = 0$ as well as $u(1,t) = -i(1,t)R_z$ we obtain the following formulae.

$$A_2 + A_4 = 0 \tag{10}$$

$$A_1\left[\sin r_1+\frac{R_z}{4_s}\left(r_1+\frac{r_1^3}{\lambda^2}\right)\cos r_1\right]+A_2\left[\cos r_1-\frac{R_z}{4_s}\left(r_1+\frac{r_1^3}{\lambda^2}\right)\sin r_1\right]+$$
$$+A_3\left[\mathrm{sh}r_2+\frac{R_z}{4_s}\left(r_2-\frac{r_2^3}{\lambda^2}\right)\mathrm{ch}r_2\right]+A_4\left[\mathrm{ch}r_2+\frac{R_z}{4_s}\left(r_2-\frac{r_2^3}{\lambda^2}\right)\mathrm{sh}r_2\right]=-\frac{I_oR_z}{s} \tag{11}$$

The solution of the formula (8) has to comply with the introductory equations (3) and (2) presented in the following forms

$$A_1r_1\lambda+A_2r_1^2+A_3r_2\lambda-A_4r_2^2=0 \tag{12}$$

$$A_1r_1(\lambda\cos r_1-r_1\sin r_1)-A_2r_1(\lambda\sin r_1+r_1\cos r_1)+A_3r_2(\lambda\mathrm{ch}r_2+r_2\mathrm{sh}r_2)+$$
$$+A_4r_2(\lambda\mathrm{sh}r_2+r_2\mathrm{ch}r_2)=0 \tag{13}$$

So, we may obtain the factors A_i with the following formula

$$A_i=\frac{D_i}{\Delta} \tag{14}$$

where: Δ - the determinant for the equations (10), (11), (12), (13),
D_i - the determinant obtained from Δ by the replacement the A_i factors column with free terms column.

From the formula (14), for $\lambda\to 0$ (because the magnetic coupling between the coil turns is strong) we educe

$$u(x,s)=-I_oR_z\frac{r_2^2\,\mathrm{sh}r_2\,\sin r_1x+r_1^2\sin r_1\,\mathrm{sh}r_2\,x}{s\left[\left(\sin r_1+\frac{R_zr_1(\lambda^2+r_1^2)}{L\lambda^2s}\cos r_1\right)r_2^2\mathrm{sh}r_2+\left(\mathrm{sh}r_2+\frac{R_zr_2(\lambda^2-r_2^2)}{L\lambda^2s}\mathrm{ch}r_2\right)r_1^2\sin r_1\right]} \tag{15}$$

usually $C>K$ and $\lambda\to 0$ so, from the formula (9) we achieve $r_2^2\approx -r_1^2$ and the solution of (15) is as follows

$$u(x,s)=-I_oR_z\frac{\mathrm{sh}r_2x}{s\left[\mathrm{sh}r_2+\frac{R_zr_2(\lambda^2-r_2^2)\mathrm{ch}r_2}{4\lambda^2s}\right]} \tag{16}$$

Denoting $r_2=\sigma+j\tau$ (because the scheme consists of the active and passive elements) and using the theorem about the distribution [8]

$$u(x,t) = \frac{V(0)}{W(0)} + \sum_{-\infty}^{+\infty} \frac{V(s_k)}{s_k W'(s)\big|_{s=s_k}} e^{s_k t} \tag{17}$$

where: $s_{k(k=0,1,2,\ldots,n)}$ - solutions of the equations $W(s) = 0$ by means of the inverse transformation of the formula (15) solution we obtain

$$u(x,t) = -I_0 R_z \left\{ e^{-\frac{\sigma_0}{\sqrt{LC}}t} \frac{\mathrm{sh}\, \sigma_0 x}{\mathrm{sh}\,\sigma_0 - 2\frac{R_z}{\lambda^2}\sqrt{\frac{C}{L}}\,\sigma_0\, \mathrm{ch}\,\sigma_0} + \sum_{1}^{+\infty} \frac{B_k e^{-M_k t}}{G_k} \cdot \right.$$

$$\left. \left[e^{\sigma_k x} \cdot \sin(\tau_k x - N_k t) + e^{-\sigma_k x} \sin(\tau_k x + N_k t) \right] \right\}$$

where: $G_k = \tau_k \left(1 + \frac{K \tau_k^2}{C}\right)$

$$M_k = \sqrt[4]{\frac{P_k^2 + Q_k^2}{Z_k^2}} \cos\left(\frac{\pi - \mathrm{arc\,tg}\,\frac{Q_k}{P_k}}{2}\right)$$

$$N_k = \sqrt[4]{\frac{P_k^2 + Q_k^2}{Z_k^2}} \sin\left(\frac{\pi - \mathrm{arc\,tg}\,\frac{Q_k}{P_k}}{2}\right)$$

$$P_k \approx C\tau_k^4$$

$$Q_k \approx 4C\sigma_k \tau_k^3$$

$$Z_k \approx L\lambda^2 (C + K\tau_k^2)$$

$$\left.\begin{aligned} &\mathrm{th}^2\sigma_k - \mathrm{tg}^2\tau_k - (1 - \mathrm{th}^2\sigma_k \mathrm{tg}^2\tau_k) g_k + 2\mathrm{th}\sigma_k \mathrm{tg}\tau_k - h_k = 0 \\ &2\mathrm{th}\sigma_k \mathrm{tg}\tau_k - (1 - \mathrm{th}^2\sigma_k \mathrm{tg}\,\tau_k) h_k - 2\mathrm{th}\,\sigma_k \mathrm{tg}^2\tau_k g_k = 0 \end{aligned}\right\}$$

where:

$$g_k \approx \frac{R_z^2 C}{L\lambda^2 \tau_k^8} \left\{ \left\{ \left[\sigma_k(\lambda^2 - \sigma_k^2 + \tau_k^2) + 2\sigma_k \tau_k^2\right]^2 - \left[(\lambda^2 - \sigma_k^2 + \tau_k^2)\tau_k - 2\sigma_k^2 \tau_k\right]^2 \right\} \cdot \right.$$

$$\cdot \left[\sigma_k^2(\lambda^2 + 6\tau_k^2 - \sigma_k^2) - \tau_k^2(\lambda^2 + \tau_k^2)\right] + 2\left[\sigma_k(\lambda^2 - \sigma_k^2 + \tau_k^2) + 2\sigma_k \tau_k^2\right] \cdot$$

$$\left. \left[(\lambda^2 - \sigma_k^2 + \tau_k^2)\tau_k - 2\sigma_k^2 \tau_k\right]\left[\lambda^2 - 2(\sigma_k^2 - \tau_k^2)\right] 2\sigma_k \tau_k \right\}$$

$$h_k \approx \frac{R_z^2 \cdot C}{L\lambda^2 \tau_k^8} \left\{ 2\left[\sigma_k(\lambda^2 - \sigma_k^2 + \tau_k^2) + 2\sigma_k \tau_k^2\right]\left[-\tau_k^6(\lambda^2 + \tau_k^2)\right] - \right.$$

$$\left. - \left\{\left[\sigma_k(\lambda^2 - \sigma_k^2 + \tau_k^2) + 2\sigma_k \tau_k^2\right] - \tau_k^6\right\}(\lambda^2 + 2\tau_k^2) 2\sigma_k \tau_k \right\}$$

The formula (18) enables us to determine the voltage distribution along the coil winding if its end is connected to the eart' or to the cryostat It makes possible to state the breakdown hazard of the turn to turn and interlayer electric insulation when it is protected with a resistor.

For the coil insulated from the earth and cryostat, the breakdown hazard is less (because the voltage distribution is close to the linear shape).

4. Summary

The breakdown hazard analysis for the electric insulation of the real solenoid superconducting coil has been carried out. This solenoid, containing the canal of the rectangular cross-section, is used for the investigations of mixture separation and slurries filtrations. The coil height is of 314 mm, outer diameter of 163 mm and inner diameter of 198 mm. The coil consists of 24 layers. It is wound with superconductor of 0,6 mm diameter: its α ratio is of 1,9. The electric insulation of the wire is the polyester lacquer of 22 μm thickness. The polyester film of 45 μm thickness gives the interlayer electric insulation. The coil inductance is of 9,3 H; the current of 70 A creates the magnetic induction of 3,2 T.

We assume, that the maximum temperature in the coil after the lost of the superconductive state is not greater than 60 K if the current is of 70 A. For the literature value of Z(80) = 2,35 . 10^{16} $A^2 sm^{-4}$ [3] at the moment t_0=0, the formula (1) gives the R_z value of 18,25 Ω.

The capacitance between the coil and cryostat is of 12,65.10^{-9}F and the longitudinal capacitance is of 0,7.10^{-9} F. The factor λ is of 0,4 [10].

The voltage distribution, according to the formula (18), calculated with a computer is presented in Fig.3. The greatest breakdown hazard of the turn to turn electric insulation exists in the coil end region (where are the greatest voltage gradients). The maximum voltage between the adjoining turns in the coil end region is of 0,37 V. According (18) the maximum voltage between the layers a x = 0 and x = 0,917 co-ordinates as we as between the layers at x = 1 and x = 0,083 co-ordinates is of 341,3 ·
The polyester film of 100 μm thickness used as an electric insulation be

ween the winding and the core may be effected by a voltage of 1277,5 V.

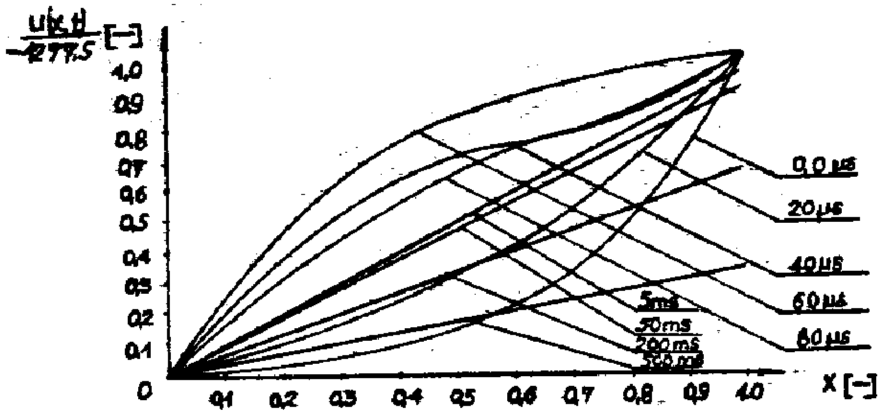

Fig.3. The voltage distribution for the superconducting coil winding protected with the resister of 18,25 Ω (one end is connected with the cryostat)

The polyester film electric strength for the temperature 4,2 K is about of 230 kV mm^{-1} [11]. So, the voltages determined above do not are hazard for the analysed electric insulations.

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