Single-Phase Resistive Superconductor Electrical Current Limiter

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***Abstract*—This paper presents the analysis, design, construction and ac test results of low voltage single-phase resistive superconductor electrical current limiters. Two different types of resistive superconductor current limiter are presented: the first one is built with three concentric, cylindrical and helicoidal coils connected in parallel and the second one is built with two superposed cylindrical helicoidal coils connected in series and in opposite magnetic polarities. Both are built using the GEC Alstom CuNi matrix superconductor type C wire for ac applications, wound on G-10 tubes and the final assembly is mechanically arranged and immersed in a cryostat filled with liquid helium at 4K. The superconductor material in this wire is the NbTi alloy.**

***Index Terms*—Current limiter, electrical protection, superconductor, switching.**

I. INTRODUCTION

AS THE electrical distribution system of a modern industrial plant is expanding continuously, the short-circuit at some point may exceed the maximum short-circuit rating of the switchgear installed in the plant. The cost of a new switchgear can be so high that the installation of a resistive superconductor electrical current limiter (RSCL), to quickly limit the fault current to a value that can be safely interrupted by that underrated switchgear, become economically attractive [1]. When the electrical current increases due to a short-circuit or excessive load condition a quench occurs and the superconductor transits from the superconducting state to the conducting state (quench), in a very short time interval, less than 1 ms which is less than 1/16 of the 60 Hz ac current cycle, introducing its electrical resistance in the circuit, increasing the circuit impedance and limiting the electrical current to the desired value.

Many papers have been reported the developments on this type of electrical equipment, among them [2] and [3] can be mentioned. In this paper it is presented additional details of single-phase RSCL design. It is also shown the construction and tests of two types of single-phase RSCL using the Alstom, type C, NbTi wire, cooled at 4K by liquid helium, which dc and ac physical characteristics at 4K are presented in the Fig. 1.

II. RSCL ELECTROMAGNETIC DESIGN

For each electric current value there is a correspondent value of the magnetic flux density at the surface of the superconductor wire at 4K, for which it transits from the superconducting state to the conducting state. The RSCL is designed so that the quench occurs at the desired current limit value I_l which is adequate to the electrical power system. This value of limit current defines the value of the electrical resistance that the RSCL must present when it is in the conducting state, named here RSCL electrical resistance.

The number of coils of the RSCL depends on the current limiter rated current that is the current which is normally circulating in the RSCL when it is in the superconducting state. This current must be divided among different coils during the steady-state operation, if necessary, to prevent the RSCL wire to transit to the conducting state, at the usual flux density provided by the carrying current in each coil of the current limiter. The number of coils (N_c) and the number of turns per coil as well as the coil diameter and height must be also so that the self-inductance of each coil and the mutual inductance between coils assume very low values.

The superconductor wire length is calculated using the RSCL electrical resistance, the superconductor wire section and its electrical resistivity. It is possible to connect coils in series and/or parallel or both. When designing the RSCL it is necessary also to have in mind that the cryostat must be adequate to cool the RSCL active part. With a set of values mentioned before (number of coils, number of turns per coil, coil diameter, coil height, and the electrical resistance to be introduced in the circuit) it is now necessary to calculate the magnetic flux density (B) on the surface of the most internal turn in each coil, as shown in the Fig. 2, for the coil 1, that is responsible for the exact value of the quench magnetic flux density at the desired limit current in each current limiter coil.

For this it is calculated the value of B at four points around the wire and the largest value is chosen as the B value at the wire surface. It is also necessary to calculate the self-inductance of each coil and the mutual inductances between coils in order to minimize them.

In [4] it was presented a mathematical method, based on the Biot–Savart law, to calculate the magnetic flux density in the surface of the superconductor wire, according to the Fig. 2, to determine if, for a given excitation state of each coil of the RSCL (current in the coil), this coil will stay in the superconducting state or will transit to the conducting state.

The determination of the magnetic flux density at each point is done considering the contribution of all turns of all the coils,

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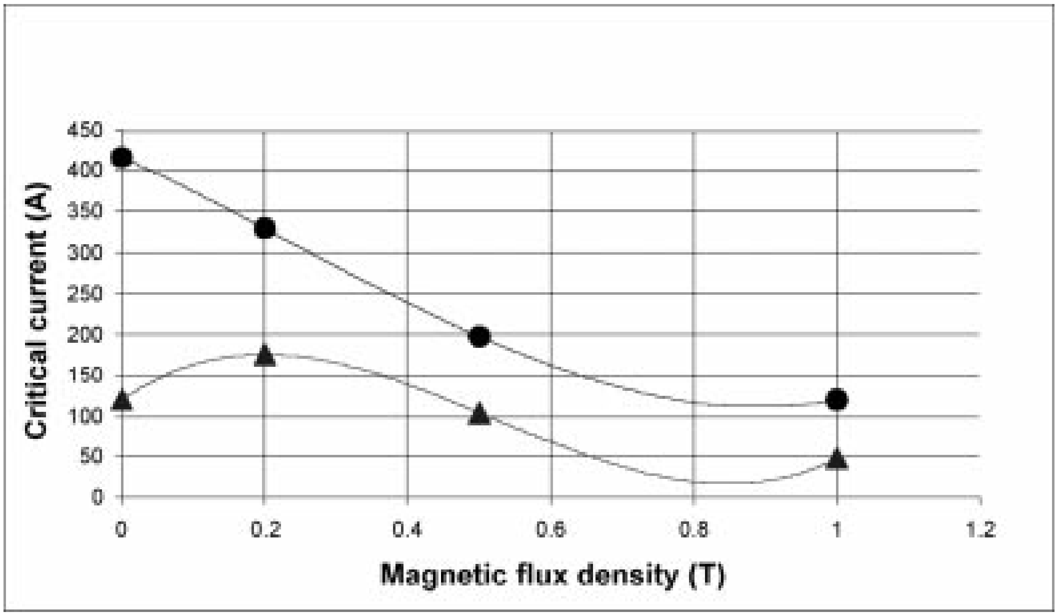

Fig. 1. Characteristic dc (●) and ac (60 Hz) (▲) of the Alsthom type C wire.

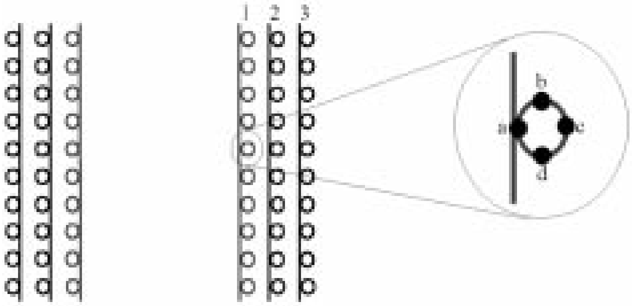

Fig. 2. Place of the turn where B is calculated in the coil 1.

considering its respective magnetic polarity, according to the Fig. 3 and in (1).

In [4] it was also shown how to calculate the self-inductance of each coil and the mutual inductance between coils. The inductance values are dependent on the voids between turns for each coil. It is important to clarify that as the coils are of cylindrical and helicoidal form with voids between turns the process presented in [4], in spite of to be a cumbersome calculation, it is very accurate and necessary for this design. It was implemented a computer program to perform the calculations involved.

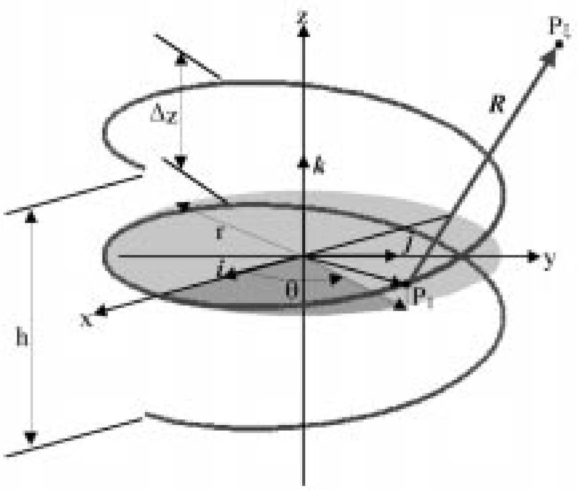

Fig. 3. Cylindrical and helicoidal coil with voids between turns.

RSCL ac power losses are calculated as well as the helium consumption using equations presented in [5]. See (1) at the bottom of the page.

$$B_x = \frac{\mu_0 i}{4\pi}\int_{\theta=-\pi N}^{\theta=+\pi N} \frac{r\cos\theta\left(z_\xi - \frac{\theta h}{2\pi N}\right) - \frac{h}{2\pi N}(y_\xi - r\,\mathrm{sen}\,\theta)}{\left[x_\xi^2 + y_\xi^2 + r^2 - 2r(x_\xi\cos\theta + y_\xi\,\mathrm{sen}\,\theta) + \left(z_\xi - \frac{\theta h}{2\pi N}\right)^2\right]^{3/2}}\,d\theta$$

$$B_y = \frac{\mu_0 i}{4\pi}\int_{\theta=-\pi N}^{\theta=+\pi N} \frac{-r\,\mathrm{sen}\,\theta\left(z_\xi - \frac{\theta h}{2\pi N}\right) + \frac{h}{2\pi N}(x_\xi - r\cos\theta)}{\left[x_\xi^2 + y_\xi^2 + r^2 - 2r(x_\xi\cos\theta + y_\xi\,\mathrm{sen}\,\theta) + \left(z_\xi - \frac{\theta h}{2\pi N}\right)^2\right]^{3/2}}\,d\theta$$

$$B_z = \frac{\mu_0 i r}{4\pi}\int_{\theta=-\pi N}^{\theta=+\pi N} \frac{r - (y_\xi\,\mathrm{sen}\,\theta + x_\xi\cos\theta)}{\left[x_\xi^2 + y_\xi^2 + r^2 - 2r(x_\xi\cos\theta + y_\xi\,\mathrm{sen}\,\theta) + \left(z_\xi - \frac{\theta h}{2\pi N}\right)^2\right]^{3/2}}\,d\theta \qquad (1)$$

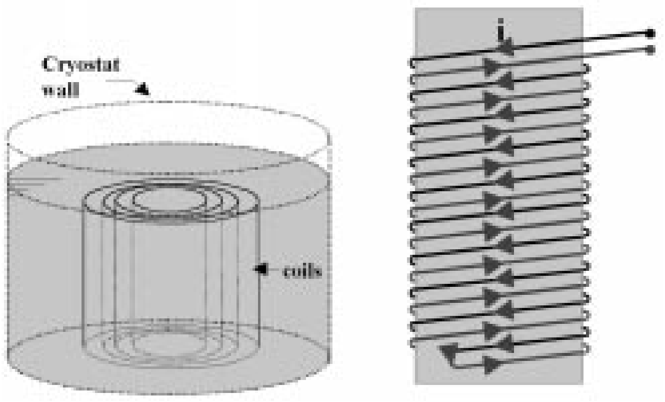

Fig. 4. Schematic diagram of a Type W (left) and Type O (right) current limiters built.

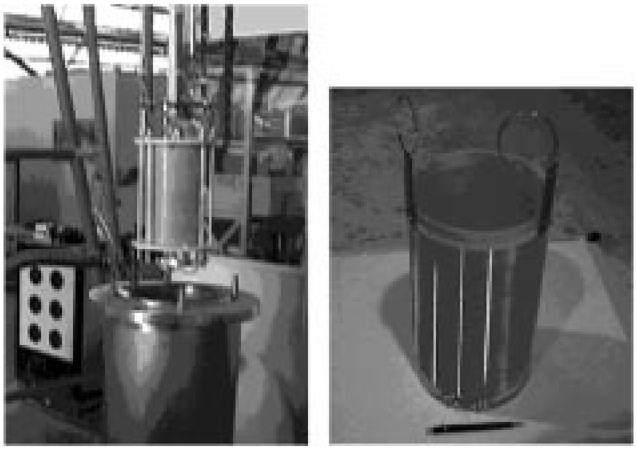

Fig. 5. RSCL built: Type W (left) and type O (right)—Details of the cryostat, electrical junctions and connections.

III. THE RSCL DESIGNED AND BUILT

After some iterations the RSCL is designed. At this time it has: the number of coils (N_c), the number of turns per coil ($N_1, N_2, N_3, \ldots$), the diameter of the coils ($D_1, D_2, D_3, \ldots$), the height of the coils ($h_1, h_2, h_3, \ldots$), the voids between turns for each coil ($d_1, d_2, d_3, \ldots$), very low values of the RSCL self and mutual inductances and also the value of the magnetic flux density on the external wire surface to cause the quench at the exact current for which the RSCL was designed. The RSCL is constituted by N_c cylindrical coils wound around a glass fabric with epoxy resin system (NEMA grade G-10) tubes. Two different single-phase RSCL were designed, built and tested in this project: The first one, named type W, whose active part is built with 3 parallel concentric one-layer cylindrical and helicoidal coils with voids between turns wound on 3 G-10 concentric tubes, and the second one, named type O is built with 2 series superposed, one-layer cylindrical and helicoidal coils with voids between turns, in opposite electrical polarities wound on just one G-10 tube as shown in the Figs. 4 and 5 whose design data can be seen in Tables I and II. Care must be taken in respect to the voltage level of the RSCL to avoid internal electrical discharges between coils and between coils and the cryostat. The mechanical forces exerted by the coils against the coil support flanges of the cryostat also have to be calculated for the adequate flange mechanical calculation.

TABLE I
TYPE W RSCL DATA

	Coil a	Coil b	Coil c
Number of turns	86	74	66
Internal radius (mm)	67.0	77.5	87.5
Coil lenght (mm)	258.0	111.0	264.0
Superconductor wire lenght (m)	36.34	36.15	36.39
Helix step (mm/turn)	3.0	1.5	4.0
Void between turns (mm)	2.494	0.993	3.492
Self-inductance (mH)	0.4254	0.7295	0.3996
Mutual inductance (mH) - ab/bc/ca	0.3767	0.3720	0.2885
Equivalent inductance (μH)	63.040		
Resistance at 4K (Ω)	28.3450	28.1974	28.3842
Equivalent resistance (Ω)	9.4362		
Transition sequence	3	2	1
Coil polarization	+1	-1	+1
Transition current (A) - Limit		434.0	
Power losses at 60 Hz, 272 A (W)		2.8	
Helium volume evaporated (l/hour)		4.0	

TABLE II
TYPE O RSCL DATA

	Coil a	Coil b
Number of turns	86	86
Internal radius (mm)	87.5	87.5
Coil lenght (mm)	260.0	260.0
Superconductor wire lenght (m)	47.42	47.42
Helix step (mm/turn)	3.0	3.0
Void between turns (mm)	2.517	2.517
Self-inductance (mH)	0.6784	0.6784
Mutual inductance (mH) - ab	0.6594	
Equivalent inductance (μH)	37.978	
Resistance at 4K (Ω)	36.9851	36.9851
Equivalent resistance (Ω)	73.970	
Coil polarization	+1	-1
Transition current (A) - Limit	176.0	176.0
Power losses at 60 Hz, 272 A (W)	2.5	
Helium volume evaporated (l/hour)	3.6	

IV. RSCL DYNAMIC MATHEMATICAL SIMULATION

To improve the electromagnetic design a dynamic simulation of the RSCL operation can be done. Fig. 6 presents a schematic diagram of a 3 coils RSCL. This electrical system can be extended to a N_c coils RSCL and (2) can be written:

$$\boldsymbol{e} = \boldsymbol{r}\boldsymbol{i} + \boldsymbol{L}\frac{d}{dt}\boldsymbol{i} \tag{2}$$

In (2) $\boldsymbol{e}$ is the voltage between RSCL terminals, $\boldsymbol{r}$ is a diagonal matrix of the coil electrical resistances, $\boldsymbol{L}$ is the matrix of the self-inductance of the coils and of the mutual inductances between coils and $p_1, p_2, \ldots, p_n$ are the polarities (-1) and $(+1)$ of each coil, as seen in (3). An iterative calculation using the ac characteristic curve of the superconductor wire (Fig. 1) to verify the quench occurrence in any coil at each time step of the state equation obtained from (2) numerical solution can be described by the following algorithm: 1. Input data: voltage vector (e), coil resistance matrix (r), coil inductance matrix (L), starting current (i_0), initial time (t_0), final time (t_f) and time of the fault (t_c); 2. Starting the routine of a 4th order Runge–Kutta method for the numerical solution of the state equation obtained

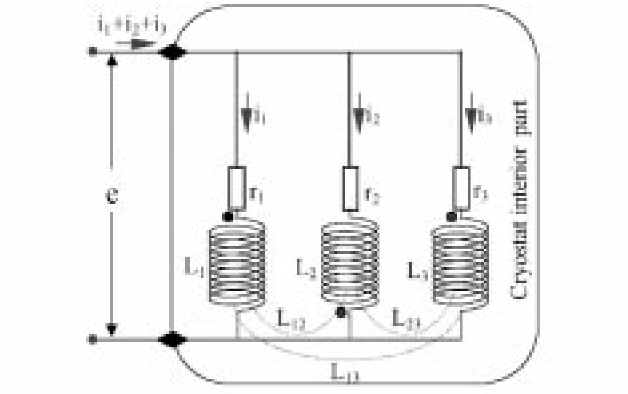

Fig. 6. Equivalent circuit for a 3 coils current limiter.

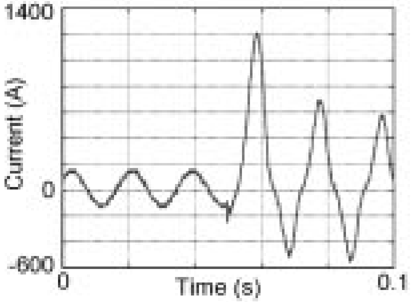

Fig. 7. Short-circuit current to be limited in the ac RSCL test.

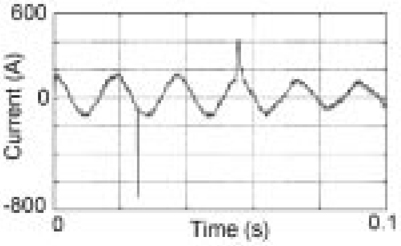

Fig. 8. Short-circuit current limited by the type W RSCL.

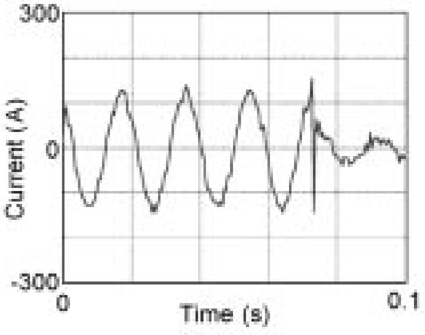

Fig. 9. Short-circuit current limited by the type O RSCL.

from (2), 3. Calculation of $i(t)$ for the time $i(t+\Delta t)$, 4. Calculation of the magnetic flux density $B(t)$ in the point of the RSCL shown in the Fig. 2 using $i(t)$ calculated in the step 3, 5. Check in the curve of the Fig. 1 if $|i(t)| > i_c(B)$ where $i_c(B)$ is the critical current for the calculated B value in the step 4, 6. If not make the coil resistances equal to zero and go to the step 3 checking also for fault time and end time, if yes insert the wire resistance and go to the step 3 (quench reached). If the fault occurs, then, the electrical circuit topology change to comply with the fault and continue from step 3

$$\boldsymbol{e} = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ \vdots \\ e_n \end{bmatrix}_{(n\times 1)} \qquad \boldsymbol{i} = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ \vdots \\ i_n \end{bmatrix}_{(n\times 1)}$$

$$\boldsymbol{r} = \begin{bmatrix} r_1 & 0 & 0 & \cdots & 0 \\ 0 & r_2 & 0 & \cdots & 0 \\ 0 & 0 & r_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & r_n \end{bmatrix}_{(n\times n)}$$

$$\boldsymbol{L} = \begin{bmatrix} L_1 & L_{12}p_1p_2 & L_{13}p_1p_3 & \cdots & L_{1n}p_1p_n \\ L_{12}p_1p_2 & L_2 & L_{23}p_2p_3 & \cdots & L_{2n}p_2p_n \\ L_{13}p_1p_3 & L_{23}p_2p_3 & L_3 & \cdots & L_{3n}p_3p_n \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ L_{1n}p_1p_n & L_{2n}p_2p_n & L_{3n}p_3p_n & \cdots & L_n \end{bmatrix}_{(n\times n)} \tag{3}$$

This simulation helps the designer to find appropriate RSCL dimensions, coil number and turns/coil number, It helps also to find adequate value for the magnetic flux density which induces the quench at the desired current limit.

V. AC TESTS

To perform the AC test of the RSCL it was used a motor-generator group 88 kVA, 380 V, 60 Hz rated feeding a three-phase resistive load. A phase-to-phase load short-circuit was done so that the peak current in one of the phases reached 1200 A as can be seen in the Fig. 7. The type W RSCL has limited this current to 400 A, as shown in the Fig. 8 and the type O RSCL has limited the current to 170 A, as shown in the Fig. 9. These results are in complete agreement with the foreseen correspondent values of the transition current shown in the Tables I and II, respectively.

VI. COMMENTS AND CONCLUSIONS

Guidelines for design and construction of low voltage RSCL were presented. The test results has shown that the procedure to design them seems very adequate and had encouraged the authors to design and construct a high voltage larger RSCL. Details on how to settle the superconductor wire on the G-10 tube, how to build the joints connecting the superconductor wire to the conductor terminals, ac power losses calculation shall be subject of a coming paper.

REFERENCES

[1] Y. Wu and Y. Yin, “Fault-current limiter applications in medium and high-voltage power distribution systems,” *IEEE Trans. Industry Applications*, vol. 34, pp. 236–242, Jan./Feb. 1998.
[2] P. C. Michael, K. Ryu, and O. Tsukamoto, “Quench currents of ª C. superconductor in supercritical helium,” *IEEE Trans. Appl. Superconduct.*, vol. 5, no. 2, Jun. 1995.
[3] K. Teklletsadik and M. P. Saravolac, “Development of a 7.5 MVA superconducting fault current limiter,” *IEEE Trans. Appl. Superconduct.*, vol. 9, no. 2, Jun. 1999.
[4] R. P. Homrich, E. R. Filho, and D. G. Pinatti, “Helicoidal single-layer cylindrical coil self-inductance evaluation: A didactic method,” *IEEE Trans. Education*, vol. 44, no. 2, May 2001.
[5] M. N. Wilson, *Superconductor Magnets*: Claredon Press Oxford, 1983.