Non-Inductive Variable Reactor Design and Computer Simulation of Rectifier Type Superconducting Fault Current Limiter

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***Abstract*—A rectifier type superconducting fault current limiter with noninductive reactor has been proposed by the authors. The concept behind this SFCL is that the high impedance generated during superconducting to normal state of the trigger coil limits the fault current. In the hybrid bridge circuit of the SFCL, two superconducting coils: a trigger coil and a limiting coil are connected in anti-parallel. Both the coils are magnetically coupled with each other and could have the same value of self inductance so that they can share the line current equally. At fault time when the trigger coil current reaches a certain level, the trigger coil changes from superconducting state to normal state. This super to normal transition of the trigger coil changes the current ratio of the coils and therefore the flux inside the reactor is no longer zero. So, the equivalent impedance of both the coils is increased and limits the fault current. We have carried out computer simulation using PSCAD/EMTDC and observed the results. Both the simulation and preliminary experiment shows good results. The advantage of using hybrid bridge circuit is that the SFCL can also be used as circuit breaker.**

***Index Terms*—Bridge rectifier, fault current limiter, noninductive reactor, superconductor, super-to-normal transition, trigger coil.**

I. Introduction

MANY circuits and configurations for superconducting fault current limiter (SFCL) have been proposed and studied today, some known as rectifier types [1], [2]. The rectifier type SFCL is compatible with the semiconductor switchgear, and free from the quench phenomenon. Experimental tests with a large inductance coil revealed that unwanted limiting operation occurred with abrupt increases of current-demand [3]. One solution to avoid this problem is applying variable reactor to the DC coil, which is the key element of rectifier type SFCL. To implement variable reactor, some configurations are proposed [4]–[6], tested [7]–[9], and designed [10]. This reactor has low inductance when normal operation (wintind mode) and high inductance when the current through the reactor exceed certain value due to the fault. Low inductance value of the reactor allow to follow the current increase due to poor current limiting performance. In the case of the fault, the increased inductance of the reactor brings out current limiting faculty.

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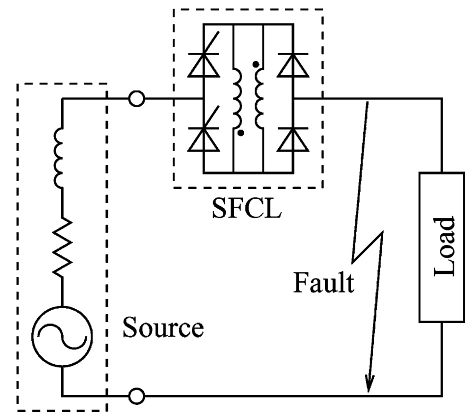

Fig. 1. Basic circuit diagram of noninductive DC rectifier type SFCL in a single phase circuit, where the source are indicated as an ideal voltage source and source impedance.

Non-inductive reactor is made of two superconducting coils. A trigger coil and a limiting coil are connected in anti-parallel and are magnetically coupled well. It is used for variable reactor as shown in Fig. 1. The power source is indicated as an ideal voltage source with a source impedance. The fault point has set at most severe position that is just the load-side terminal. In the normal mode operation, both coils are in superconducting state and noninductive reactor shows its leakage inductance, which is relatively small. In the limiting mode, the trigger coil becomes normal-conducting state due to the current through the coil reaching its critical current. The self-inductance of the limiting coil acts as a reactor as the common rectifier type SFCL. A small-scale experiment was performed using the superconducting transformer with four wound windings, where a single hybrid bridge circuit was used for both the coils [9]. The experimental results confirmed that the SFCL works in current limiting mode after quenches of the trigger coil. It was also confirmed that the SFCL can work as a half-cycle circuit breaker as well as current-limiter. In the fault test, the current limiting ratio was poor because the trigger coil used in the experiment had very high critical current capacity. The current limiting ratio could be adjusted by the proper selection (the critical current) of the trigger coil.

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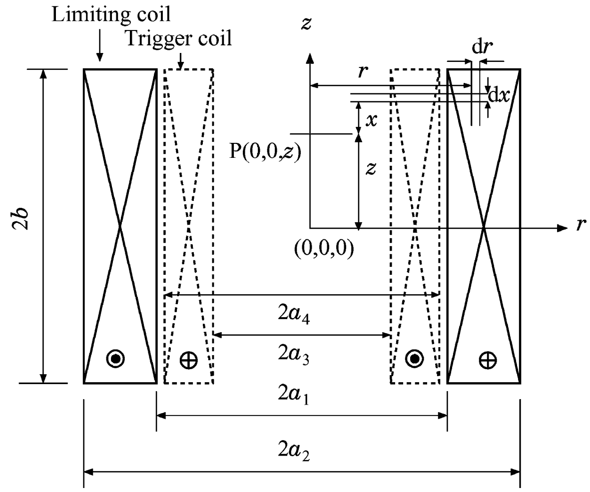

Fig. 2. Coil design 1: two coils are separately fabricated and placed them co-axially so that their magnetic field would oppose each other.

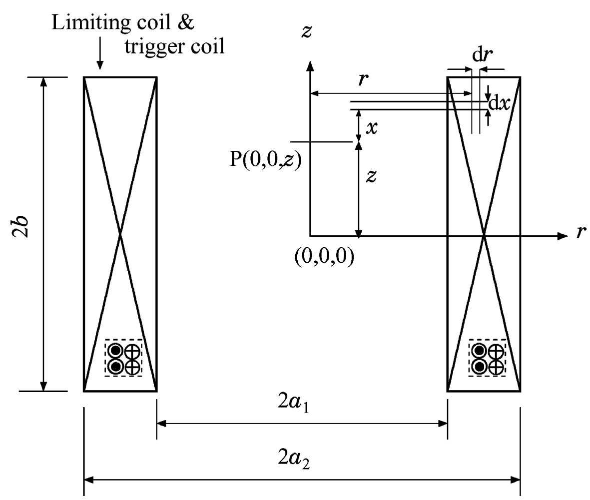

Fig. 3. Coil design 2: two coils are fabricated as single unit. The sum of anti-parallel coils current is zero.

In this paper, coil design for 6.6 kV/1 kA rated noninductive reactor and the analytical results using computer software PSCAD/EMTDC are described.

II. Coil Design for a 6.6 kV/1 kA Rated Non-Inductive Reactor

The coils of the noninductive reactor share the line current equally during normal operational time. The self inductance of each coil should be equal (to avoid the circulating current). Compact design is necessary, to reduce the leakage inductance, as well as the volume of the cryogenic system. However, the maximum flux density should not cross a limit during fault time that might quench the limiting coil. In case of Nb-Ti, the maximum flux density should not exceed a value of 8 T. For HTS bulk material, this value is lower at higher temperature. The inductor could be manufactured in two ways. The main and trigger coil are separately fabricated and could be placed coaxially as shown in Fig. 2. The other way, both the coils could be constructed as a single unit, which is a bifilar winding, as shown in the Fig. 3. The first one is easier to construct, and the temperature rise in the trigger coil does not affect the limiting coil during fault time. However the leakage inductance would be higher (because of the gap between the two coils). The latter could be made with higher coupling factor, generating less leakage inductance.

The flux density $B_z(z)$ at point P(0,0,z) along the z axis produced with the limiting coil as shown in Fig. 2 is expressed as follows,

$$B_z(z) = \mu_0 \int_{a_1}^{a_2} \mathrm{d}r \int_{-b-z}^{b-z} \frac{Nr^2 J}{4b(a_2 - a_1)(r^2 + x^2)^{\frac{3}{2}}} \mathrm{d}x \qquad (1)$$

where $2b$ is the height of the coil, a_1 is inner diameter of the limiting coil, a_2 is outer diameter of the limiting coil, N is number of turns, $(r, x+z)$ is coil fragment position, J is the current density at $(r, x+z)$.

Considering overall current density 'λj' where λ is the space factor and $\alpha = a_2/a_1, \beta = b/a_1$ and $Z = z/a_1$ the flux density at the point P is as follows,

$$B_z(z) = \mu_0 \frac{a_1 \lambda j}{2} \left\{ (Z+\beta) \ln \frac{\alpha + \sqrt{\alpha^2 + (Z+\beta)^2}}{1 + \sqrt{1 + (Z+\beta)^2}} \right. \left. - (Z+\beta) \ln \frac{\alpha + \sqrt{\alpha^2 + (Z-\beta)^2}}{1 + \sqrt{1 + (Z-\beta)^2}} \right\}. \qquad (2)$$

Flux density at the center of the coil ($z = 0$) is obtained from (2) as follows,

$$B_z(0) = \mu_0 a_1 \lambda j \beta \ln \frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}}. \qquad (3)$$

The self and leakage inductance of each coil are required to calculate. The flux linkage ϕ_{11} of the limiting coil can be express by the following equation;

$$\phi_{11} = \int_{-b}^{b} \mathrm{d}z \int_{0}^{a_2} B_z(r,x) f_l(r) 2\pi r \mathrm{d}r. \qquad (4)$$

Similarly for the flux linkage ϕ_{22} of the trigger coil is

$$\phi_{22} = \int_{-b}^{b} \mathrm{d}z \int_{0}^{a_4} B_z(r,x) f_t(r) 2\pi r \mathrm{d}r \qquad (5)$$

where $f_l(r)$ is the number of turns in per unit length of the limiting coil that can be expressed as

$$f_l(r) = \begin{cases} \frac{N_l}{2b} & \text{if } 0 \le r < a_1 \\ \frac{N_l(a_2 - r)}{b(r - a_1)} & \text{if } a_1 \le r \le a_2 \\ 0 & \text{if } a_2 < r \end{cases} \qquad (6)$$

where N_l is turn number of limiting coil. Similarly for trigger coil $f_t(r)$ can be written as

$$f_t(r) = \begin{cases} \frac{N_t}{2b} & \text{if } 0 \le r < a_3 \\ \frac{N_t(a_2 - r)}{b(r - a_1)} & \text{if } a_3 \le r \le a_4 \\ 0 & \text{if } a_4 < r \end{cases} \qquad (7)$$

where N_t is turn number of trigger coil.

TABLE I
DESIGNED SINGLE COIL PARAMETERS, WHERE ITS CURRENT IS 1 kA

r_d mm	d_d mm	$2b$ mm	N	L_d mH	B_0 T	J_e A/mm
195	10	100	300	48.0	0.937	300
190	20	100	310	47.3	0.992	155
100	20	150	210	6.54	1.06	70
140	20	150	300	23.2	1.19	100
130	20	140	280	18.6	1.19	100
130	25	200	240	11.0	0.92	48
140	15	200	300	20.1	1.10	100
150	20	224	360	29.9	1.21	80.4
160	30	200	240	15.2	0.8	40
180	20	180	224	17.5	0.7	62.2
175	40	50	200	15.9	0.71	100
250	60	350	200	15.1	0.41	9.52
280	80	350	200	17.6	0.38	7.14

The flux linkage ϕ_{12} of the limiting coil induced by the trigger coil can be expressed by the following equation,

$$\phi_{12} = \int_{-b}^{b} \mathrm{d}z \int_{0}^{a_4} B_z(r,x) f_t(r) 2\pi r \mathrm{d}r \tag{8}$$

Similarly

$$\phi_{21} = \int_{-b}^{b} \mathrm{d}z \int_{0}^{a_2} B_z(r,x) f_l(r) 2\pi r \mathrm{d}r \tag{9}$$

Assuming the limiting and trigger coil current are equal to unity, the self inductance of the limiting coil (L_1) and trigger coil (L_2) and their mutual inductance (M) can be calculated by the following equations. $L_1 = \phi_{11}, L_2 = \phi_{22}$ and $M = \sqrt{M_{12}M_{21}} = \sqrt{\phi_{12}\phi_{21}}$. As the magnetic field of each coil is anti-parallel, the conditions to get zero field at the center point can be calculated.

The impedance of this SFCL is not zero in the normal operational condition because there are always some magnetic flux in the space in between the two coils, which caused the leakage inductance. If the coils are fabricated as a single unit (bifilar winding) as shown in Fig. 3, a lower leakage inductance can be achieved, but has difficulty of the insulation between two coils. In such a case, the same thickness of the winding are shared by the two coils. Equal turns per unit cross section of the windings is necessary for main and trigger coil to produce equal inductance. At normal condition, the coil current $i = i_1 - i_2 = 0$ so the (3) gives zero flux density for the design shown in Fig. 3. At fault time, after super-to-normal transition of the trigger coil $(i_2 = 0)$, the flux density along z axis increases with the increase of current though the main coil. Based on the above equations, the possible design parameter sets of a winding are calculated in Table I for a 6.6 kV, 1 kA class SFCL considering $i_1 = 1$ kA and $i_2 = 0$. For Nb-Ti, the flux density of 1.0 T or less is a reasonable value at the center point of the coil, where r_d is the average radius such as $(a_1 + a_2)/2$ or $(a_3 + a_4)/2$, d_d is the thickness of the coil such as $a_2 - a_1$ or $a_4 - a_3$, L_d is self inductance of the coil, J_e is over all current density. If the limited fault current goes up to 3 or 4 times of the rated 1 kA, the flux density also increases 3 to 4 times but still remain below its critical value around 8 T. The last two parameter sets of the Table I represent feasible designs using HTS superconducting tape where low electric field intensity is required.

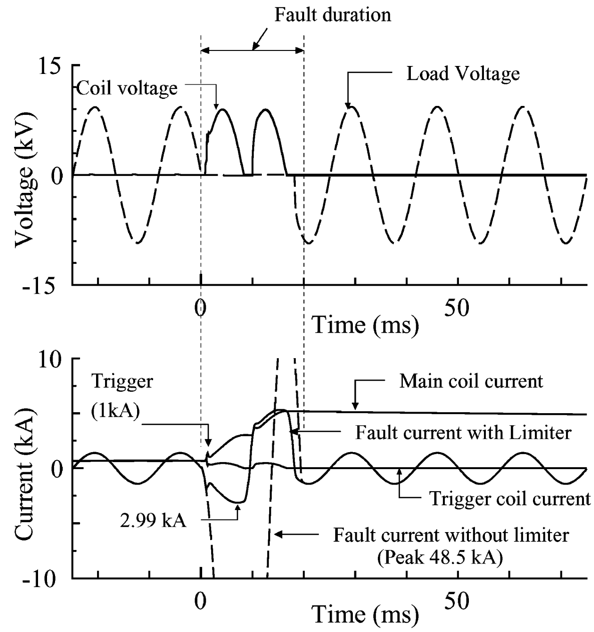

Fig. 4. Simulation result of a 6.6 kV, 1 kA system with zero crossing fault.

III. PSCAD/EMTDC ANALYSIS RESULTS OF A 6.6 kV, 1 kA CLASS SFCL

Non-inductive reactor shows only the leakage inductance during normal operation. The self inductance of the limiting coil is the maximum inductance that could be seen during current limiting mode at fault condition with the test circuit as shown in Fig. 1. We performed simulations, using EMTDC (Electro-Magnetic Transient for DC system) for a 6.6 kV, 1 kA system, with 5 percent source inductance. The inductance of each coil is assumed to be 17.5 mH $(= 1 \text{ pu})$, with a coupling factor of 0.9. The critical current of the trigger coil was set to 1.0 kA. Fig. 4 illustrates the output waveforms of the simulation. A short term (1 cycle) zero crossing fault was made. The voltage waveforms are presented in the upper curves, with current waveforms in the lower curves. Before the fault, both coil current waveforms stay on 0.7 kA. The waveforms were slightly rippled. In the first half-cycle of the fault, the peak current reached only 2.99 kA with SFCL, while it was 48.5 kA without the SFCL. The average current increase rate was 2 kA/half-cycle with 1 pu limiting inductance. When the load current reached 40% over its rated peak value, the SFCL entered limiting mode. And after one cycle, the peak current reached 3.6 times larger than rated peak value. After release of the fault, the main coil current flows through the diode leg of the bridge. The current decays slowly. In Fig. 5, the waveforms are obtained when fault is made at 90° of the current phase. This time, the fault duration is set for 1.25 cycle. The limited fault current has reached to 2.0 kA in the first half-cycle where this value is 44.5 kA without SFCL. The reason of 1/4 cycle delay to shutdown the fault is the delay of turn off the thyristor which simulate the short-circuited fault. Increasing the value of limiting inductance up to 4 pu, the fault current was less than

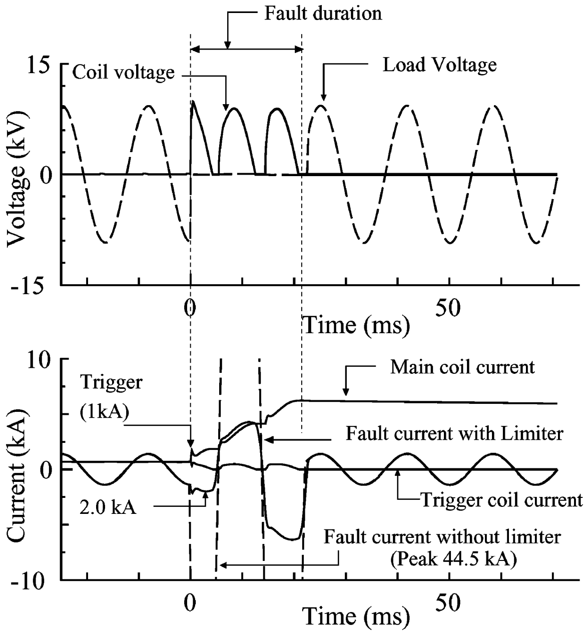

Fig. 5. Simulation result of a 6.6 kV, 1 kA system with 90° fault.

2 kA. A limiting inductance value of 1 pu, is a moderate value, with smaller cold mass for the system.

IV. Conclusion

Basic coil design for 6.6 kV/1 kA rated noninductive reactor has been carried out. Two configuration of the noninductive reactor for rectifier type SFCL has been proposed. Coaxial coil arrangement and bifilar winding arrangement were compared. Bifilar winding arrangement was superior to have high impedance ratio (normal operating mode and current limiting mode), but coaxial arrangement is selected in the point of the insulation. The total loss in the cryogenic environment should be accumulated to design cooling system. The PSCAD/EMTDC simulations have been carried out with the designed coil and the current limiting performances have been evaluated. With five percent source inductance, adequate inductance value 1 pu ($= 17.5\ \mathrm{mH}$) was obtained.

The insulation layer was considered as a lower current density of the winding. Design of the insulator and electric field analysis are expected to be performed in consecutive work.

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