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Winding design and Performance analysis of a flux-coupling type SFCL

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Abstract —Superconducting fault current limiter (SFCL) is an efficient way to solve the short-circuit problems in modern power system. A Flux-coupling type SFCL (FC-SFCL) based on disconnecting coupling windings for current-limiting has been proposed. For its low steady impedance at normal state and higher limiting one after fault, FC-SFCL is considered as a potential scheme to limit fault current. It contains a pair of high temperature superconducting (HTS) coupling coils wound on an iron-core with air gap. Raising coupling coefficient of the HTS coils and reducing the losses are essential issues to improve its performance, which are mainly affected by iron-core structure and winding processes of HTS coils. In this paper, the electromagnetic design of a 10 kV / 500 A FC-SFCL prototype is carried out based on genetic algorithm, and its magnetic field distributions are analyzed, along with the performances of current-limiting capacity, response time, losses of the prototype. The results show the FC-SFCL prototype with electromagnetic parameters meets the design requirements and it has a good operation characteristics.

1. Operating principles and equivalent circuit

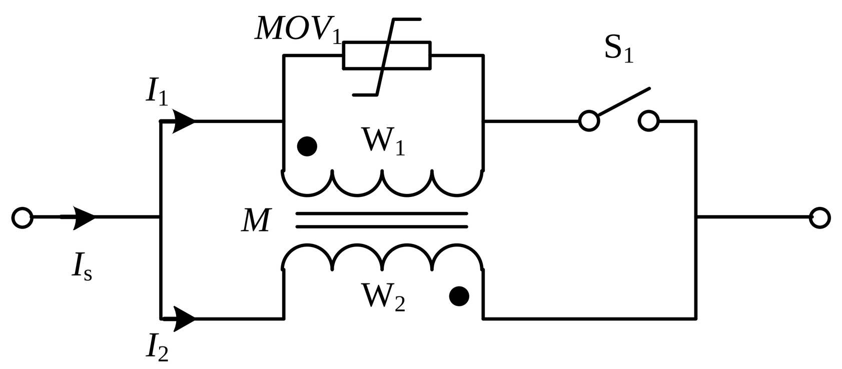

Fig. 1. The basic structure of the FC-SFCL.

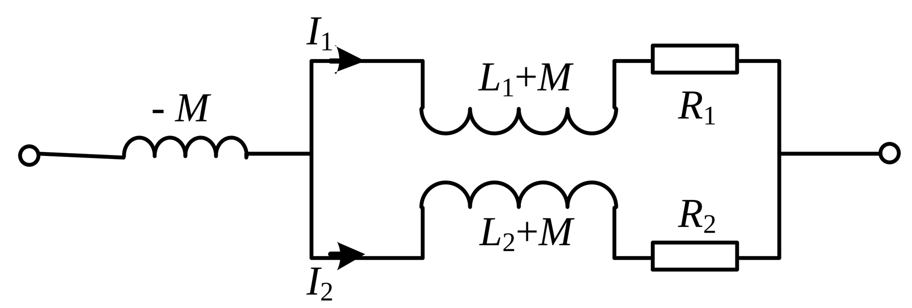

Fig. 2. Equivalent circuit of the FC-SFCL.

The FC-SFCL consists of a current-limiting unit, a metal oxide varistor (MOV), and a switch S_1. The current-limiting unit is made of two HTS windings W_1 and W_2 carrying current in reverse directions. The MOV can protect W_1 from over-voltage, especially at the time of operation of S_1.

When fault happens, S_1 is controlled to be opened rapidly and the coupling of the unit is cancelled out, where W_1 is out of the circuit and the fault current can be limited by W_2.

It has three operating conditions:

normal condition (the system operates normally with S_1 closed),

fault condition (fault happens before opening S_1) and

limiting condition (after opening S_1, the limiter acts).

Before decoupling

$$Z_c = \frac{R_1R_2 + R_1X + n^2R_2X + (1-k^2)n^2X^2}{R_1 + R_2 + (n^2 + 2kn + 1)X}$$

$$Z_c = \frac{1-k}{2}X$$

After decoupling

$$Z_{dc} = X$$

2. Winding design and simulation analysis

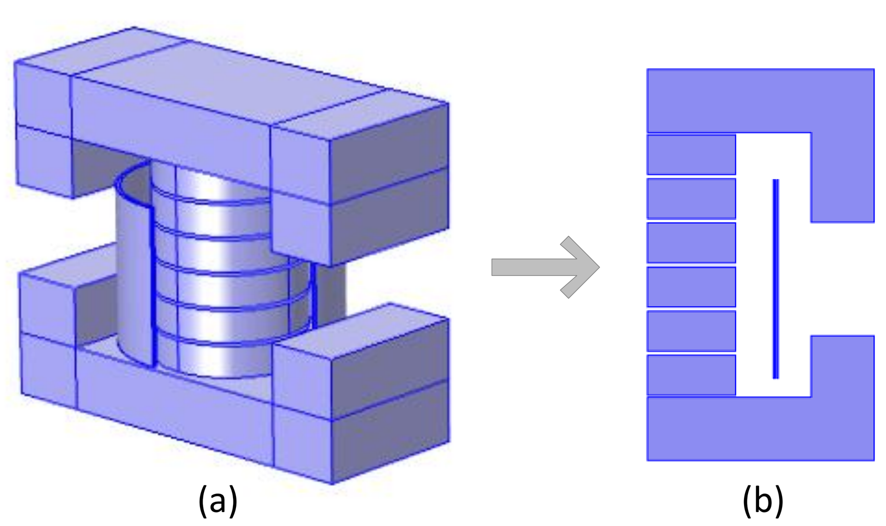

Fig. 3. The FE model for the SFCL. (a) 3D whole model. (b) 2D simplified model.

Iron core made of **30Q120** is used for the magnet to reduce the total length of tape and increase its inductance. Large fault current may result in the extreme saturation of the core after decoupling, causing the attenuation of the limiter's current-limiting capability. It's necessary to calculate the magnet's inductance value and attain 7.5 mH of inductance after decoupling during faults. A two-dimension axisymmetric model is applied to obtain the accurate parameters

The initial values of variables can be are given out by using experience formula method based on the operating capacity of the SFCL. The experience formulas are usually used to guide the design of electrical equipment with iron core. We adopt the minimum length of tape under this condition as optimum object and use the inductance of more than 7.5 mH and maximum magnetic flux density of less than 2.0 T as the criterion. The optimization of the SFCL based on **genetic algorithm** is executed by using *Matlab with Comsol*.

This current-limiting magnet is designed to cut the fault current in half, and the pulse current can arrive to 5 kA ac_{rms}, whose inductance of one winding is **no less than 7.5 mH**. A 2G Super Power SCS 4050 4-mm wide YBCO tape is used to fabricate the magnet. The operational temperature is set **at 65 K** by using sub-cooled liquid nitrogen. The average critical current under at 65 K of this kind of tape is 308 A.

Table. I Specifications of FC-SFCL Prototype.

	Items	Be optimized	Value
Iron core	Radiu of core column (mm)	Yes	300
	Height of the yokes (mm)	No	200
	Height of the iron core window (mm)	No	840
	Width of the iron core window (mm)	No	220
	Length (mm) and number of air gaps on core column	Yes	81/7
	Length of air gap on yokes (mm)	Yes	360
	Weight of silicon steel (t)	--	4.5
Current-limiting unit	Turns number of one winding	Yes	50
	Number of tapes in parallel	--	18
	IR/OR (mm/mm) of inner winding	Constraint	420/425
	IR/OR (mm/mm) of outer winding	Constraint	430/435
	Height of the windings (mm)	Constraint	630
	Total length of tapes (km)	--	4.8

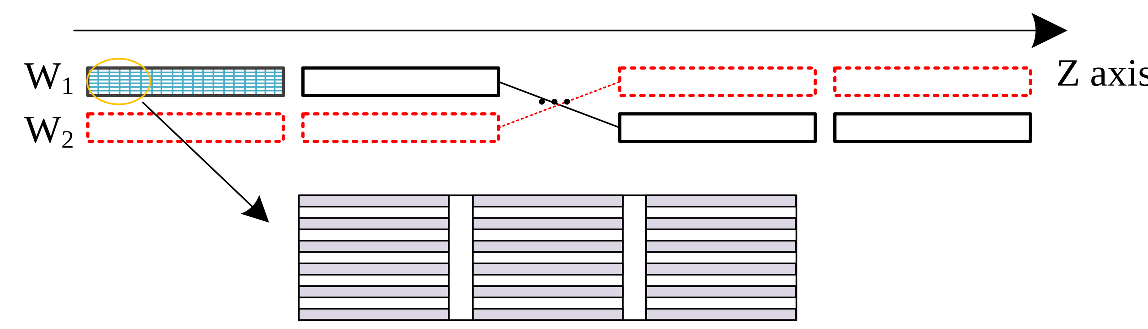

Fig. 4. The structure for the limiter's windings.

The 2D axisymmetric FE detailed model base on the optimized parameters is established in *Comsol Multiphysics*. The superconducting windings of the SFCL is made of two intersecting sub-modules which adopt the nonintersecting type structure. Each HTS winding is made of **18 tapes in parallel**, with 3 tapes arrayed in the axial direction and 6 tapes arranged along the radial direction. It can be approximated that the center plane cut section of the layer is exactly the cross-section of the tape. The insulation thickness between each layer is 0.25mm.

$$\nabla \times E = \begin{bmatrix} -\dfrac{\partial E_\phi}{\partial z} \\ \dfrac{1}{r}\dfrac{\partial (rE_\phi)}{\partial r} \end{bmatrix} = -\mu_0 \begin{bmatrix} \mu_r \dfrac{\partial H_r}{\partial t} \\ \mu_r \dfrac{\partial H_z}{\partial t} \end{bmatrix} - \mu_0 \begin{bmatrix} H_r \dfrac{\partial \mu_r}{\partial t} \\ H_z \dfrac{\partial \mu_r}{\partial t} \end{bmatrix}$$

Superconducting layer and air, μ_r =1;

Magnetic substrate (Ni-5%W) or hard magnetic material, μ_r **varies with the magnetic field *H***. The derivative of μ_r with respect to t is **no longer negligible**.

The method of detailed modeling local tapes and sub-regional calculation is used to improve the speed of calculation.

Magnetic field mf and PDEs are fully coupled and solved at the same time. To impose an explicit transport current in each superconducting conductor, integral constraints are used.

Iron losses

$$P_{cv} = K \cdot f^{\alpha} \cdot B_m^{\beta}$$

B_m --the peak magnetic flux amplitude;
P_{cv} --is the time average power loss density;
f -- the frequency of sinusoidal excitation;
K, α, and β --constants relating to the material.

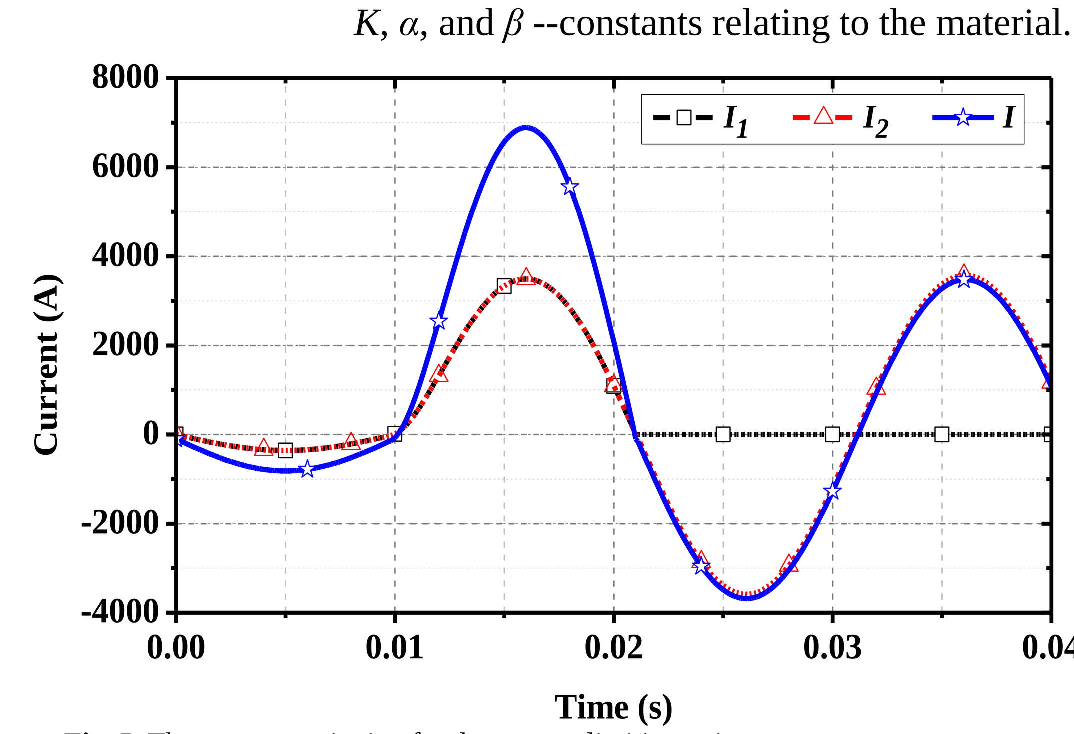

Fig. 5. The current excitation for the current-limiting unit.

3. Performance estimation

A. Current-limiting Characteristic

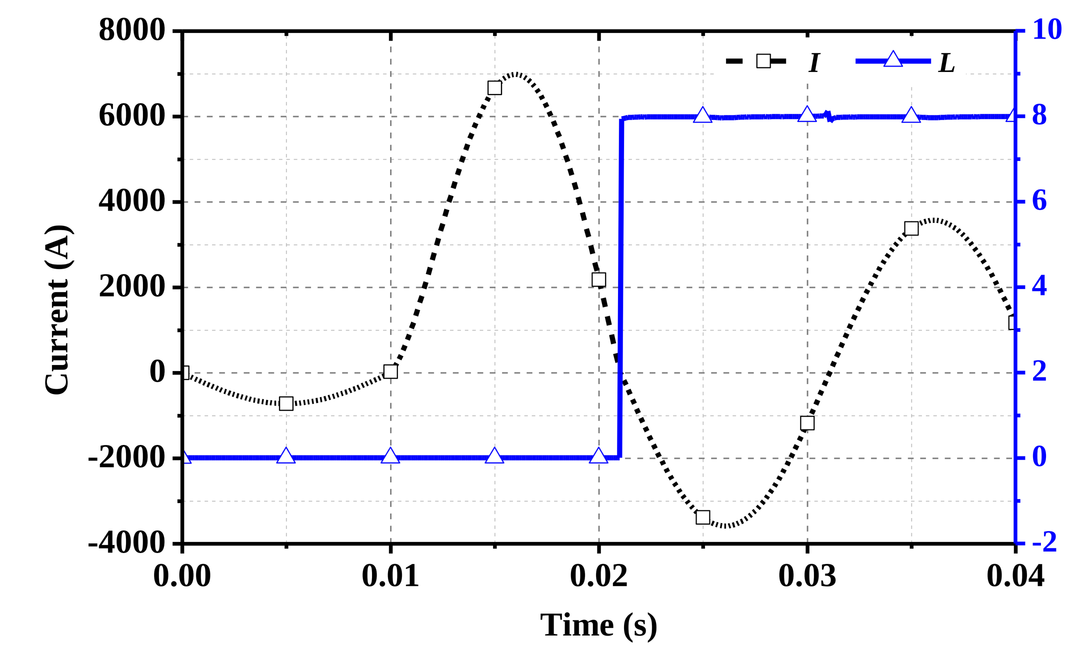

Fig. 6. The dynamic equivalent inductance of the current-limiting unit.

The steady-state impedance of the SFCL is almost equal to 0 (0.0045 mH);

The current-limiting impedance is 2.52 Ω (8.0mH).

The response time of the SFCL depends on **the decoupling time** of the current-limiting unit, namely the operation time of the auxiliary switch S_1.

For the SFCL, the vacuum type circuit breaker VBM7 for 10 kV power system can acts in 11 milliseconds.

B. Loss Estimation

During normal and fault operations, iron core works in linear zone for that the magnetic flux of the current-limiting unit counteracts each other. Ac losses, along with iron losses of iron core, **increases** in **limiting** state.

The total transient ac loss can reach its maximum value of 1988 W, and the transient maximum values of W1, W2 are 688 W, 1300 W, respectively.

Losses in the longitudinal distribution have significant non-uniformity, and losses of end are higher.

The transient iron losses are 5.63 W and 5762 W before and after decoupling, respectively.

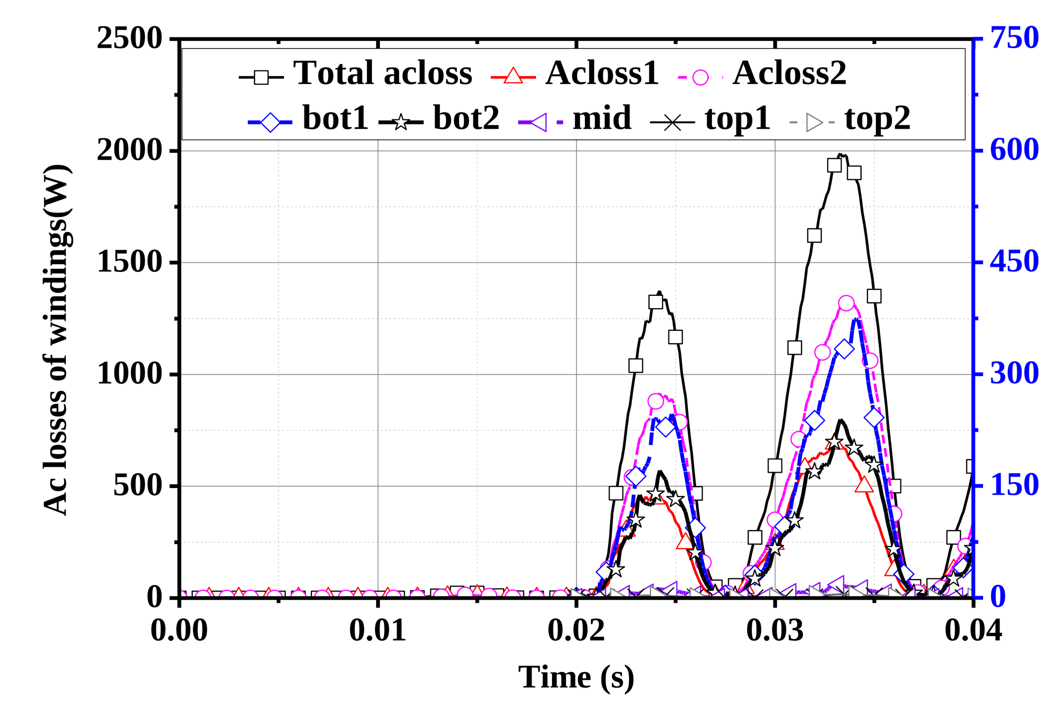

Fig. 7. Ac losses of the current-limiting unit in three states.

4. Conclusion

1) **The impedance characteristic of FC-SFCL and performances of current-limiting capacity, response time, losses of the prototype are evaluated, which indicates that the FC-SFCL has a good operation characteristics and can meet the design requirements.**
2) **It's necessary to estimate the total losses after the current-limiting's decoupling, adjust the structure of the windings according to the losses distribution, and optimize the cooling system.**
3) **There are still many works should be enriched, such as the current-limiting characteristic analysis and design scheme of current-limiting unit with quenching, and the method of fast and accurate calculation of ac losses for FC-SFCL and so on.**