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Reduction of fault current peak in an inductive high-T_c superconducting fault current limiter

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Abstract

This paper dealt with current-limiting performances of an inductive high-T_c superconducting fault current limiter with an auxiliary coil. The fault current limiter mainly consists of the primary copper coil, secondary high-T_c superconducting rings, and auxiliary high-T_c superconducting coils, which are magnetically coupled through three-legged core. The superconducting fault current limiter as a series element in the power system is inserted to limit the fault current. The device presents fast variable-impedance features in the event of a fault condition. The fault current peak can become relatively large for certain ranges of the flux and the fault instant due to the core saturation. The auxiliary coil proposed in this paper was proven to increase the impedance of the SFCL up to more than 31% while preventing the core saturation.

Keywords: High-T_c superconducting fault current limiter; Auxiliary high-T_c superconducting coil; Power system protection

1. Introduction

The growth of demand for electric power requires replacement of existing circuit breakers or fault current interrupters. Due to efficient current-limiting performance and cost competitiveness the high-T_c superconducting (HTSC) fault current limiters have been considered as alternatives to conventional devices. The superconducting fault current limiters (SFCLs) may be classified into two kinds of devices according to working principles: the inductive type and resistive one [1–8]. The main benefit of the SFCL is to limit high fault currents within one quarter cycle before any damage can occur in the power grids. The significant requirement on SFCLs is that they have low impedance under normal (non-fault) operations and high impedance when a fault condition occurs. Most SFCLs utilize a variable-impedance based on the intrinsic transition from the superconducting to resistive state when an induced current exceeds a critical level in the superconductor.

This paper will describe how the inductive high-T_c SFCL goes into action properly according to source voltage levels and fault instants, and its new operational features by using the auxiliary superconducting rings. An inductive high-T_c SFCL proposed in this paper consists of a three-legged magnetic core, primary copper windings, secondary windings in form of the high-T_c superconducting rings, and an auxiliary HTSC ring as shown in Fig. 1. The magnetic flux links each of windings through a three-legged magnetic core. The primary copper winding is connected in series to the electrical power system for system protection. The auxiliary HTSC ring was implemented to control the system current peak during a fault.

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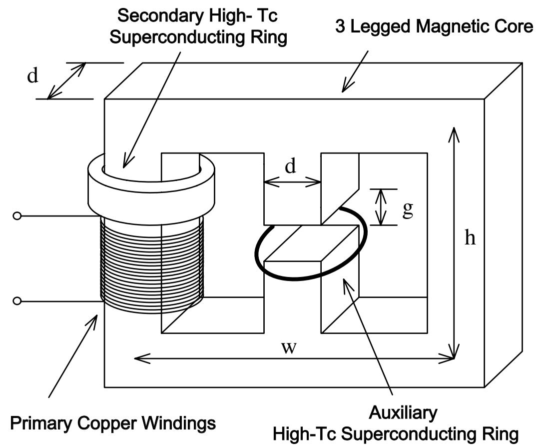

Fig. 1. Schematic of the inductive SFCL with auxiliary HTSC ring.

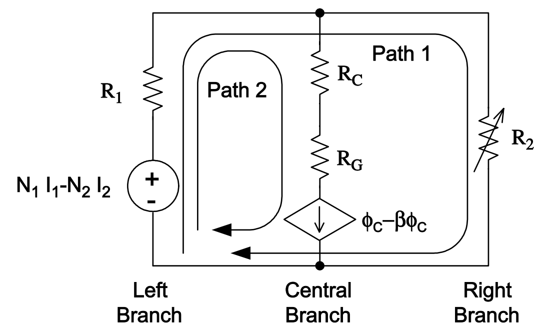

Fig. 2. Magnetic circuit for three-legged core.

2. Fault current limiter concepts

2.1. Inductive high-T_c SFCL

While the high-T_c SFCL operates under normal conditions, its impedance should be as low as possible to avoid dissipating electric power. The induced currents in the high-T_c superconducting rings nullify the magnetic flux produced by the primary windings in the magnetic core. Thus its impedance becomes very low and is predominantly dependent upon the primary winding resistance and leakage inductances. In case of a fault current, the induced currents in the high-T_c superconducting rings overstep their critical current and their flux cancellation effect may fade away. This allows the magnetizing flux to build up abruptly in the magnetic core and the impedance of the high-T_c SFCL increases significantly. Thus the fault current can be limited to a predetermined level. For simplicity, the leakage inductances and the primary winding resistance are neglected. The limited fault current can be expressed as follows:

$$I_{\text{Lim}} = U \cdot \sqrt{1/(2\pi f L_{\text{M}})^2 + 1/(a^2 R_{\text{SC}})^2} \tag{1}$$

where U is the source voltage, f is the power frequency, a is the turns ratio, R_{SC} is the resistance of the superconducting ring,

$$(L_{\text{M}}) = \frac{L_1(L_{\text{C}} + L_{\text{G}})}{2(L_{\text{C}} + L_{\text{G}}) + L_1}, \quad Z = \mu_0 \mu_{\text{r}} d^2 N_1^2,$$

$$L_1 = \frac{Z}{2w + h}, \quad L_{\text{C}} = \frac{Z}{h - g}, \quad L_{\text{G}} = \frac{Z}{\mu_0 g},$$

g is an air-gap length, N_1 is the number of turns in the primary winding, μ_0 is free space permeability, and μ_{r} is the relative permeability of the core.

2.2. Operational function of auxiliary HTSC coil

At higher short-circuited current, the core saturation under a fault condition can cause severe problems. This may result in lower impedance of the SFCL than an ideal value. To solve the saturation problem, an air-gapped magnetic core having three branches and the auxiliary high-T_c superconducting ring was newly devised in this paper.

Fig. 2 shows a magnetic circuit for the inductive SFCL. Reluctances R_1, R_2 and R_{C} represent the left, right, and central paths, respectively, in the three-legged magnetic core. The air gap is represented by the linear reluctance R_{G}. The total magnetomotive force (mmf) of the current-carrying primary and secondary windings is depicted by a source with the magnitude of $N_1 I_1 - N_2 I_2$, where I_1 is the primary current, N_1 is the number of turns of the primary coil, I_2 is the secondary current, and N_2 is the number of turns of the secondary coil. The resultant flux of the central branch is represented by a controlled source with the magnitude $\phi_{\text{C}} - \beta\phi_{\text{C}}$. The quantity ϕ_{C} is the magnetic flux passing through the central branch with the auxiliary coil made inoperative. The total flux in the central branch resulting from the flux ϕ_{C} and the opposing flux of the auxiliary coil can be computed by summing the components acting alone. The quantity β is dimensionless constant, referred to as the flux gain of the auxiliary coil. The constant β depends on the coefficient of coupling. Before the core saturation, the reluctance of the path 1 is smaller than that of the path 2. This means that most magnetic flux flow through the path 1. As the magnetic flux passing through the right branch of the path 1 reaches the knee of the saturation curve, the reluctance of the right branch (R_2) becomes larger than that of central branch (R_{C} + R_{G}). The difference between the reluctances causes the magnetic flux above the knee of the saturation curve to be transferred to the central branch. The induced current in the auxiliary superconducting ring, which is accompanied by its opposing flux, cancels out the magnetic flux above the knee of the saturation curve. Therefore, the right branch of the core remains unsaturated while the auxiliary coil nullifies the magnetic flux above the knee of the saturation curve. The auxiliary coil and a special core configuration can prevent the saturation problem.