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Simulations and experimental analyses of the active superconducting fault current limiter

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Abstract

This paper presents the operation principle of a new type active superconducting fault current limiter (SFCL). The SFCL is composed of an air-core superconducting transformer, a PWM converter and a superconducting magnet. The primary winding of the air-core superconducting transformer is in series with AC main circuit, and the second winding is connected with the superconducting magnet through a PWM converter. In normal (no fault) operating state, the flux in air core is compensated to zero, so the SFCL has no influence on main circuit. In the case of short circuit, by controlling the amplitude and phase angle of the second winding's current, the limiting impedance which is in series with the AC main circuit can be regulated and the fault current will be limited to a certain level. Using MATLAB SIMULINK, the simplified model of the active SFCL is created, and simulations validate this SFCL can suppress the fault current effectively. In addition, the current-limiting experiment is done with a small conventional transformer. Experimental results correspond well with simulation results.

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Keywords: Fault current; Active superconducting fault current limiter; PWM converter; Controllable current source

1. Introduction

With the growth of demand for electric power transmission, the existing circuit breakers have had the possibility that their cut-off ratings can be exceeded by the fault current any times. The increase of the fault current has imposed a severe burden on the related machinery in the grid, and the stability of power system is also damaged. Application of the FCL [1] in electric power system can not only suppress the amplitude of the short circuit current but also enhance the stability of power system.

In fact, the FCL is basically variable impedance which is in series with a circuit breaker. In the case of short circuit, the impedance rises to a value where the fault current is correspondingly reduced to a lower level, at which the circuit breaker can handle. Many kinds of fault current limiters have been put forward in accordance with the development of power electronics, magnet technologies and superconducting materials [2–5]. Superconducting fault current limiters with features of compactness and low cost have been expected as new power devices in the future electric network.

A new type active SFCL is presented, which can not only be used in the AC power system, but also in the DC system. It is an extensive concept for active DC-SFCL [6,7]. The operation principle of this SFCL is similar with the fault current limiter based on flux compensation [8]. Furthermore, this paper introduces the new concept that controlling the amplitude and the phase of the second winding's current, which can finally increase the limiting capacity of SFCL. The circuit structure and operation principle of the SFCL have been introduced. Simulations and

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experimental results can validate this type FCL is favorable for power system.

2. Theoretical analyses

2.1. The circuit structure and operation principle

The circuit structure of the active SFCL is shown in Fig. 1, which is composed of an air-core superconducting transformer, a PWM converter and a superconducting magnet. The primary winding of the air-core superconducting transformer is in series with AC main circuit, and the second winding is connected with the superconducting magnet through a PWM converter. The air-core superconducting transformer has some advantages such as absence of iron losses and magnetic saturation, and it has greater possibility of reduction in size and weight than the conventional and the iron-core superconducting transformer [9].

The current in AC main circuit (I_1), the second winding's current (I_2), and the mains voltage (U_s) will be detected in real time. According to the amplitude of the detected current, normal or fault state can be judged. Once detecting the fault, let DSP be the core of control circuit and control the PWM converter which will respond within five milliseconds to change the amplitude and phase angle of I_2.

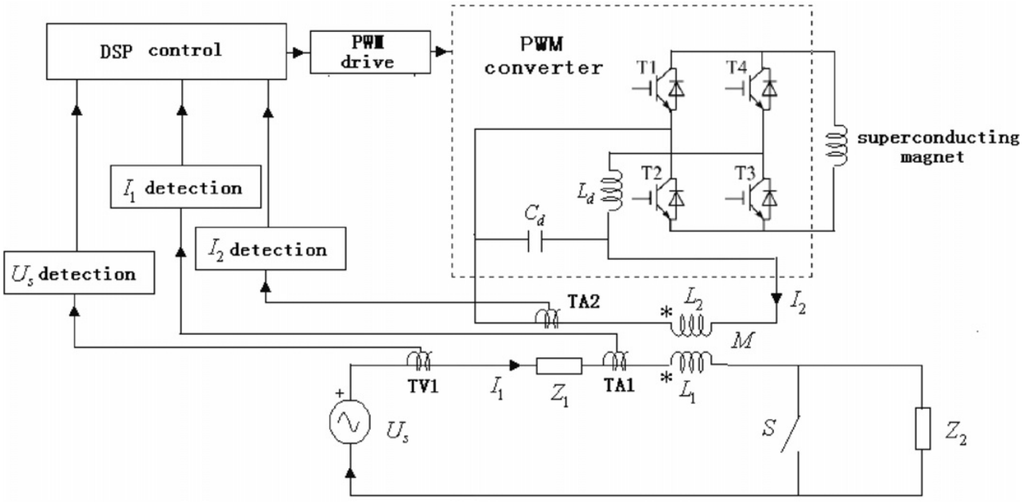
In normal (no fault) state, the converter works as a rectifier and the energy transfers from the AC side to the DC side, thus the superconducting magnet is charged. The second winding's current will up to a certain value where the flux in air-core is compensated to zero, and the SFCL has no influence on main circuit. In the case of short circuit, the limiting impedance which is in series with the AC main circuit can be regulated by changing the amplitude and phase angle of I_2, and the fault current will be suppressed. From the viewpoint of energy transferring, now the converter works as an inverter and the superconducting magnet provides energy to the AC side. The voltage of the primary winding will increase accordingly, which can compensate the descent of the voltage induced by short circuit. Superconducting magnet which is used for storing and providing energy has some advantages, such as low losses, high energy conversion efficiency and rapid response speed, as a result of increasing the working efficiency of the SFCL.

Besides, the losses of this type SFCL come from three parts: superconducting transformer, superconducting magnet, and power transistors. The adoption of superconductors is favorable for reducing losses.

2.2. The equivalent circuit

By neglecting losses of the air-core superconducting transformer, the voltage equation of the transformer is expressed as follows:

$$\begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \end{bmatrix} = j\omega \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ -\dot{I}_2 \end{bmatrix} \tag{1}$$



U_s : AC voltage source

Z_1 : Circuit impedance

Z_2 : Load impedance

L_1, L_2 : Self-inductance of two windings

M : Mutual inductance of two windings

Fig. 1. The circuit structure of the active SFCL.