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Experiment study on an inductive superconducting fault current limiter using no-insulation coils

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ABSTRACT

No-insulation (NI) coil made of 2 G high temperature superconducting (HTS) tapes has been widely used in DC magnet due to its excellent performance of engineering current density, thermal stability and mechanical strength. However, there are few AC power device using NI coil at present. In this paper, the NI coil is firstly applied into inductive superconducting fault current limiter (iSFCL). A two-winding structure air-core iSFCL prototype was fabricated, composed of a primary copper winding and a secondary no-insulation winding using 2 G HTS coated conductors. Firstly, in order to testify the feasibility to use NI coil as the secondary winding, the impedance variation of the prototype at different currents and different cycles was tested. The result shows that the impedance increases rapidly with the current rises. Then the iSFCL prototype was tested in a 40 V rms/ 3.3 kA peak short circuit experiment platform, both of the fault current limiting and recovery property of the iSFCL are discussed.

1. Introduction

With the growing power grid capability and distributed power generation, the increasing fault current level has become a big challenge to nowadays power grid. At present, the superconducting fault current limiter (SFCL) is one of the most effective and reliable approaches to limit fault current. Several SFCL prototypes have been fabricated and successfully tested in real power grid operation [1–3]. Among these SFCLs, the air-core inductive superconducting fault current limiter (iSFCL) is a kind of novel SFCL structure that is studied in the past decade [4–6]. The absence of iron core significantly reduces the weight of the iSFCL device. It at least consists of two windings, a primary winding and a magnetically coupled secondary winding. The secondary winding is usually composed of short-circuit and insulated superconducting coils.

On the other aspect, the no-insulation (NI) coil, since firstly proposed in 2011 [7], has been widely used in high-field DC magnet systems [8, 9] owing to its excellent performance of engineering current density, thermal stability and mechanical strength [10–12]. However, there are few AC power device using NI coils, it might be because of its charging/discharging delay effect. While, reference [13] studied the magnetic field coupling property of NI coil, it shows that the response of the NI coil to the background magnetic field variation is instantaneous. Thus, the charging/discharging delay is avoided.

In this paper, the NI coil is firstly applied in an iSFCL prototype as the secondary winding, which is magnetically coupled with the primary winding. Compared with the insulated coils, the NI coils have better mechanical strength and more compact volume. During normal operation, the secondary winding can shield most of the alternating magnetic field (AMF) generated by the primary winding, keeping the impedance of the iSFCL at a low level. When the fault current flows into the primary winding, the AMF exceeds the shielding capability of the secondary winding, then the impedance of the iSFCL will rise rapidly and limit the fault current.

To testify the feasibility of applying NI coil in the iSFCL, a two-winding structure air-core iSFCL prototype was fabricated, with the copper winding as the primary winding and four independent NI coils as the secondary winding. Firstly, the impedance variation of the iSFCL prototype is measured at different operating currents and different cycles. Then the short circuit test was conducted in a 40 V rms/ 3.3 kA peak short circuit experiment platform, both of the fault current limiting and recovery property of the iSFCL are discussed.

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Table 1
The specifications of YBCO tape and NI coil.

Items	Specifications	Value
YBCO tape	Tape width	4.8 mm
	Total Thickness	0.25 mm
	YBCO Thickness	~1.5 μm
	Substrate Thickness	50 μm
	Ag Stabilizer Thickness	2 μm + 1 μm
	Cu Stabilizer Thickness	10 μm + 10 μm
	Stainless Steel Thickness	75 μm + 75 μm
	I_c / n-value (@77 K, Self-Field)	40 A / 28
Double pancake NI coil	I.D. / O.D.	110 mm / 113 mm
	Height	9.6 mm
	No. of turns	10
	$I_{c\text{-coil}}$ (@77 K, Self-Field)	28 A
	Time constant	1.49 s
	Equivalent turn-to-turn resistor	0.015 mΩ

Table 2
The Specifications of the iSFCL prototype.

Items	Specifications	Value
Secondary shielding winding	Height, h_s	40 mm
	I.D. / O. D., id_s / od_s	110 mm / 113 mm
	No. of NI coils	4
	Total no. of turns, N_s	40
Primary copper winding	Height, h_c	30 mm
	I.D. / O. D., id_c / od_c	115 mm / 118.5 mm
	No. of turns, N_c	50
Total	Gap between primary winding and secondary winding, *gap*	1 mm

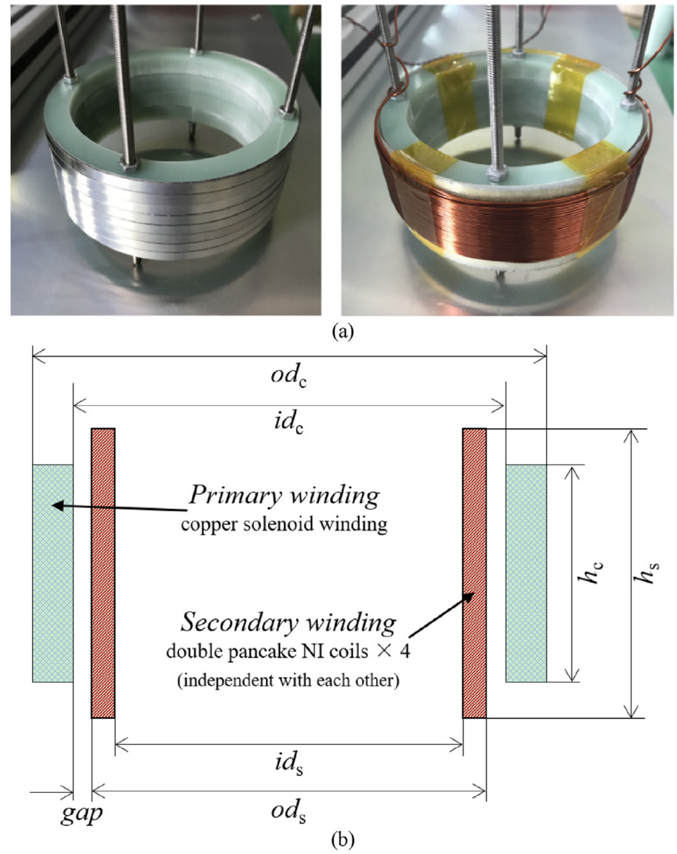

Fig. 1. (a) Photos of the iSFCL prototype. The right one is the secondary shielding winding and the left one is the whole iSFCL prototype. (b) diagrammatic sketch of the iSFCL prototype.

2. Experiment setup

2.1. Specifications of YBCO tape and NI coils

Table 1 lists the specifications of the YBCO coated conductor (SSTC Co., Ltd.) and basic electric parameters of the double pancake NI coils. Due to the maximum fault current (~3.3 kA peak) of the short circuit platform, we specifically chose the YBCO tape with small critical current (40 A) to fabricate the secondary winding of the iSFCL prototype. The comparatively small critical current ensures the impedance of the iSFCL can increase rapidly when the current exceeds the normal operation current. Otherwise, if the critical current of the tape is too large, the secondary winding can still shield part of the AMF generated by the primary winding even when the fault current comes, and the impedance of the iSFCL will still stay at a low level.

2.2. Specifications of iSFCL prototype

The photos of the iSFCL prototype are shown in Fig. 1. The secondary shielding winding of the iSFCL is composed of four double pancake NI coils. These NI coils are independent with each other and stacked up in the axial direction, as shown in the right photo of Fig. 1(a). A lap joint is made in each NI coil to make it closed-loop ('superconductor side' soldered with 'substrate side'), and the joint resistance is about 1 μΩ. A 1 mm-thick epoxy interlayer is used to cover the secondary winding and separate it from the primary copper winding. Then the copper winding is wound on the epoxy interlayer. The diagrammatic sketch of the iSFCL is shown in Fig. 1(b). The specifications of the iSFCL are listed in Table 2.

The normal operation current can be approximately calculated as follows [4],

$$I_n = \frac{I_{c-coil} \cdot n_2}{\sqrt{2} \cdot n_1}$$

where I_n is the rms value of the normal operation current, $I_{c\text{-coil}}$ is the critical current of the NI coil, n_1 is the number of the primary copper winding turns and n_2 is the number of the secondary winding turns. The calculated I_n is 15.8 A, which is an approximate value because the secondary winding is composed of four independent NI coils. It should be mentioned that during AC operation of the iSFCL prototype, part of the perpendicular magnetic field on the NI windings will be counteracted by the primary winding. Thus the actual coil critical current might be larger than its self-field critical current, which also leads to larger normal operation current.

3. Impedance variation test

In order to verify the feasibility of the iSFCL using NI coils, a current source with maximum output of 14 V rms / 800 A rms is used to test the impedance variation of the iSFCL prototype.

3.1. Impedance variation under different currents

Firstly, the impedance of the prototype under current of 10 A, 20 A, 30 A, 40 A, 50 A, 60 A rms is tested, respectively. The voltage and current waveforms (50 Hz) in two cycles are shown in Fig. 2. (I_{10} means the current of 10 A rms and U_{10} means the corresponding voltage.)

Because of the current source, the current waveform is sinusoidal in all situations. When the current ≤ 20 A, the voltage waveform is also sinusoidal. The phase difference between the current and the voltage is caused by the leakage reactance, which is calculated to be 17.2 mΩ. When the current ≥ 30 A, the voltage waveform is distorted and becomes sharper. In one cycle, when the current becomes higher and exceeds the normal operation current,