ARTICLE IN PRESS

Physica C xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Current limiting performance test of 3-phase tri-axial transformer-type SFCL with re-wound structure at 3-line-to-ground fault in lab-scale transmission system

Yasuyuki Shirai [a,*], Sho Noda [a], Kenta Yamabe [a], Keisuke Hattori [b], Jumpei Baba [b], Shinichi Kobayashi [c], Kenichi Sato [c]

[a] Graduate School of Energy Science, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan
[b] The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[c] Sumitomo Electric Industries, Shimaya, Konohana-ku, Osaka 554-0024, Japan

ARTICLE INFO

Article history:
Accepted 19 March 2012
Available online xxxx

Keywords:
Fault current limiter
3-line-to-ground fault
HTC superconductor

ABSTRACT

We have proposed a transformer-type SFCL of a re-wound structure, which can produce a limiting reactance (L-limiting) for smaller fault current and, for larger one, additively give a limiting resistance (L + R limiting). The single-phase proposed model SFCL had been tested and shown good limiting characteristics and excellent recovery performance. A 3-phase tri-axial SFCL of the proposed type had been designed and made using BSCCO2223. This paper describes demonstration tests of the model SFCL carried out using a lab-scale one-machine infinite bus transmission model system. The experimental results on the current limiting performance of the SFCL at the 3-line-to-ground (3LG) fault were shown and discussed. The peak fault current 560 A without SFCL was reduced to 230 A with SFCL immediately. The 3-phase SFCL successfully worked without large inter-phase interaction. The SFCL recovered to the stand-by mode under a typical Circuit Breaker (CB) operation sequence.

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1. Introduction

Superconducting Fault Current Limiter (SFCL) is expected to be introduced to a power system not only for reducing a large fault current but also for improving power system flexibility and stability. Recently many research projects were undergone worldwide mainly in resistive limiting type [1–3]. Focusing on an SFCL using HTC wires, a bi-filar winding coil is one of the solutions to get a large resistance [1]. However, the energy dissipation and temperature rise during the current limiting operation are key issues for recovery characteristics, especially for a recovery under load operation [2].

In typical fault current profile, the first peak may become several times larger than the following fault current. An SFCL should be designed to reduce the first peak of the fault current at the most severe fault below a certain allowable value and, at the same time, to reduce the temperature rise during the limiting operation for quick recovery. Under these considerations, we have proposed a new design type of SFCL, which produces reactive limiting impedance for smaller fault current and additively resistive component for larger one. The aim of the proposed SFCL is to limit the large fault current, namely the first peak, by its resistance and reactance, and to limit the smaller fault current, namely the continuous fault current followed by the transient state, mainly by its reactance component. Thus, the energy dissipation in the SFCL during the fault current limiting operation is reduced and the recovery characteristics is improved. A single-phase SFCL of the proposed type was designed and made using BSCCO2223 wire [4]. The demonstration tests were performed. The test results proved the excellent limiting performance and recovery characteristics at the single-line-to-ground (1LG) fault in the small demo system [5]. In the next step, a 3-phase tri-axial SFCL of the proposed type was designed and made [6].

This paper describes demonstration tests, which were carried out using the model 3-phase tri-axial SFCL installed in a lab-scale one-machine infinite bus transmission model system. The experimental results on the current limiting performance of the SFCL at the 3-line-to-ground (3LG) fault were shown and discussed.

2. 3-Phase tri-axial fault current limiter

2.1. Concept

Proposed 3-phase coaxial SFCL, which consists of three transformer type SFCLs with different diameters, are set together coaxially (see image in Fig. 1). Each phase SFCL has two co-axially wound superconducting coils. The primary coil is wound on a bobbin as solenoid shape, and then re-wound on another bobbin of smaller diameter to minimize/cancel the resultant magnetic flux

* Corresponding author. Tel./fax: +81 75 753 3328.
E-mail address: shirai@energy.kyoto-u.ac.jp (Y. Shirai).

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http://dx.doi.org/10.1016/j.physc.2012.03.039

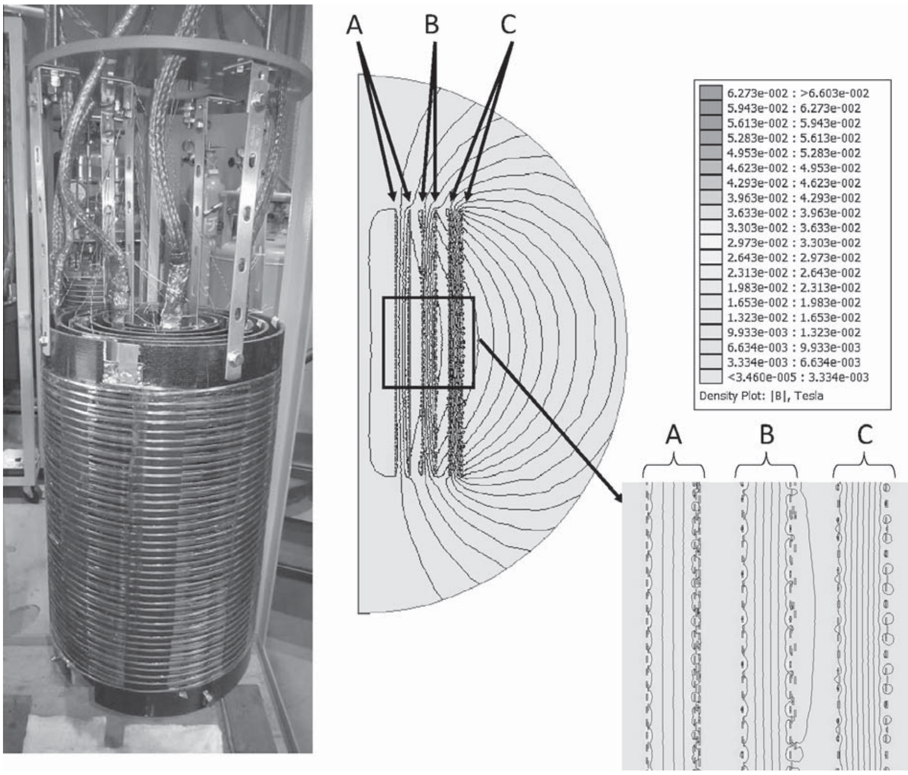

Fig. 1. Photo of the model SFCL and its magnetic flux lines during the current limiting operation.

Table 1
Specification of BSCCO wire used.

Sumitomo DI-BSCCO wire Type ACT (SCT02–2010-017)	
Materials	Silver sheathed BSCCO
Laminate materials	Copper alloy
Width	2.8 mm
Average thickness	0.31 mm
I_c (77 K, Self field)	60 A
n-Value (77 K, Self field)	14
Cross-section ratio (BSCCO:silver:copper alloy)	1:3:2
Composition ratio of copper alloy (Cu:Sn:others)	99.8:0.15:0.05

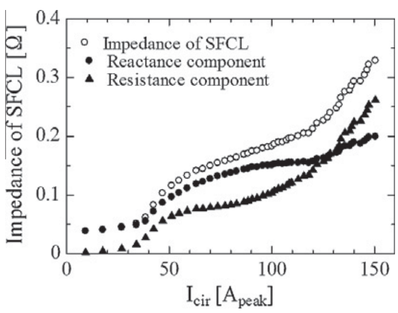

Fig. 2. Impedance of the model SFCL as a function of flowing current (peak value). (Reactance and resistance components and total impedance.)

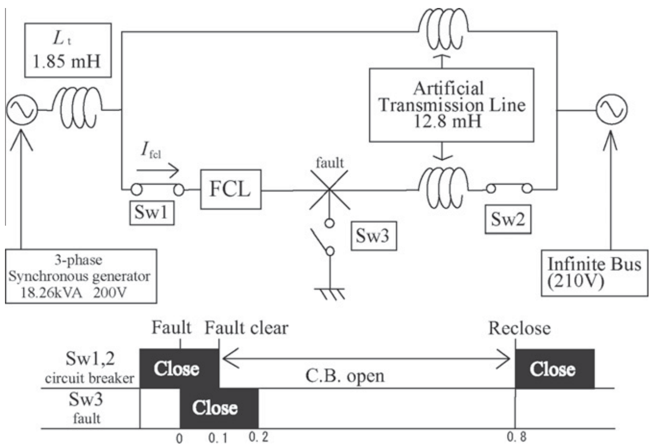

Fig. 3. Experimental system of lab-scale one machine infinite bus transmission system with SFCL and the switch sequence for the simulated 3-phase-ground fault.

inside the inner bobbin. The major magnetic flux is induced in the area between two bobbins. The terminal of the coil on the outer bobbin and that of inner one are connected in series to a line in a power system. The secondary coil is wound on the primary coils in a similar way but short-circuited and has less turns than the primary coil. When the primary coil current flows, the short-circuited secondary coil current is induced to minimize the resultant magnetic flux of the total coil system. As a result, the reactance (impedance) of the SFCL seen from the primary coil terminal becomes rather small.

When the fault current flows through the primary coil, the secondary coil current exceeds the critical current of the wire and then the magnetic flux due to the primary coil appears. Thus, the SFCL reduces the fault current inductively (L limiting) in the main. If the fault current is much larger, the primary coil wire also turns to the normal state and the resistance appears additively. The SFCL reduces the fault current both resistively and inductively (R + L limiting). Since the first peak of the fault current is generally rather large and contains DC component, the large limiting impedance (R + L) is desirable. On the contrary, as the subsequent fault current is not so large, the inductance (L) limiting is desirable for the good recovery characteristic.

2.2. Model SFCL [6]

The model SFCL was designed and fabricated for installation in the 18 kV A, 220 V lab scale transmission test system described in later [6]. The rated voltage is 220 Vrms, the rated peak current is 300 A (where the limiting impedance is 1 Ω). The specification of the superconducting wire used for the model SFCL is listed in Table 1. The 3-phase coaxial SFCL has six coils, that is, two inner coils, two middle coils, and two outer coils are called A-phase, B-phase, and C-phase, respectively as shown in Fig. 1. The height of the bobbins is 500 mm and coil wound part is 400 mm. The diameters of the inner and outer coil bobbins are (110, 150 mm) for A-phase, (190, 230 mm) for B-phase and (270, 310 mm) for C-phase, respectively. The 3-phase coaxial SFCL can save its operating cost and space because the A-phase SFCL and the B-phase SFCL are set inside the C-phase SFCL.

It was designed to meet the following three demands. First, the impedance (resistance and reactance) of each phase SFCL is same in 3-phase. Second, the trigger current level for limiting of each phase SFCL is same in 3-phase. Third, each phase SFCL must work independently without interference of the other phase SFCLs. That is to say, the magnetic field out of the rewound coils must be cancelled in order to make the each other influence smaller. The magnetic flux distribution of the SFCL during the current limiting operation mode was calculated and is shown in Fig. 1. Major part of the magnetic flux lines are between the coils for each phase. The superconducting wire lengths were same in every phase, that is, 208 m for primary coil and 277 m for secondary coil.

3. Experiment in lab-scale transmission system

3.1. Impedance of the SFCL

Fig. 2 shows the measured impedance of the model SFCL (A-phase) as a function of the peak of the flowing current. Leakage reactance is about 0.04 Ω. Since the secondary coil wire turns to resistive state from around 35 A, the reactance component increases and the resistance one appears with the increase of the current. The primary coil wire is still in the superconducting state until the current of around 80 A. When the current exceeds 80 A, the resistive component additively increases due to the normal resistance of the primary coil wire.

3.2. Experimental system

Fig. 3 shows the schema of the experimental one-machine infinite bus transmission system of lab-scale. The 3-phase synchronous generator whose rated capacity and voltage are 18.26 kV A, 210 V was connected to the infinite bus through double transmis-

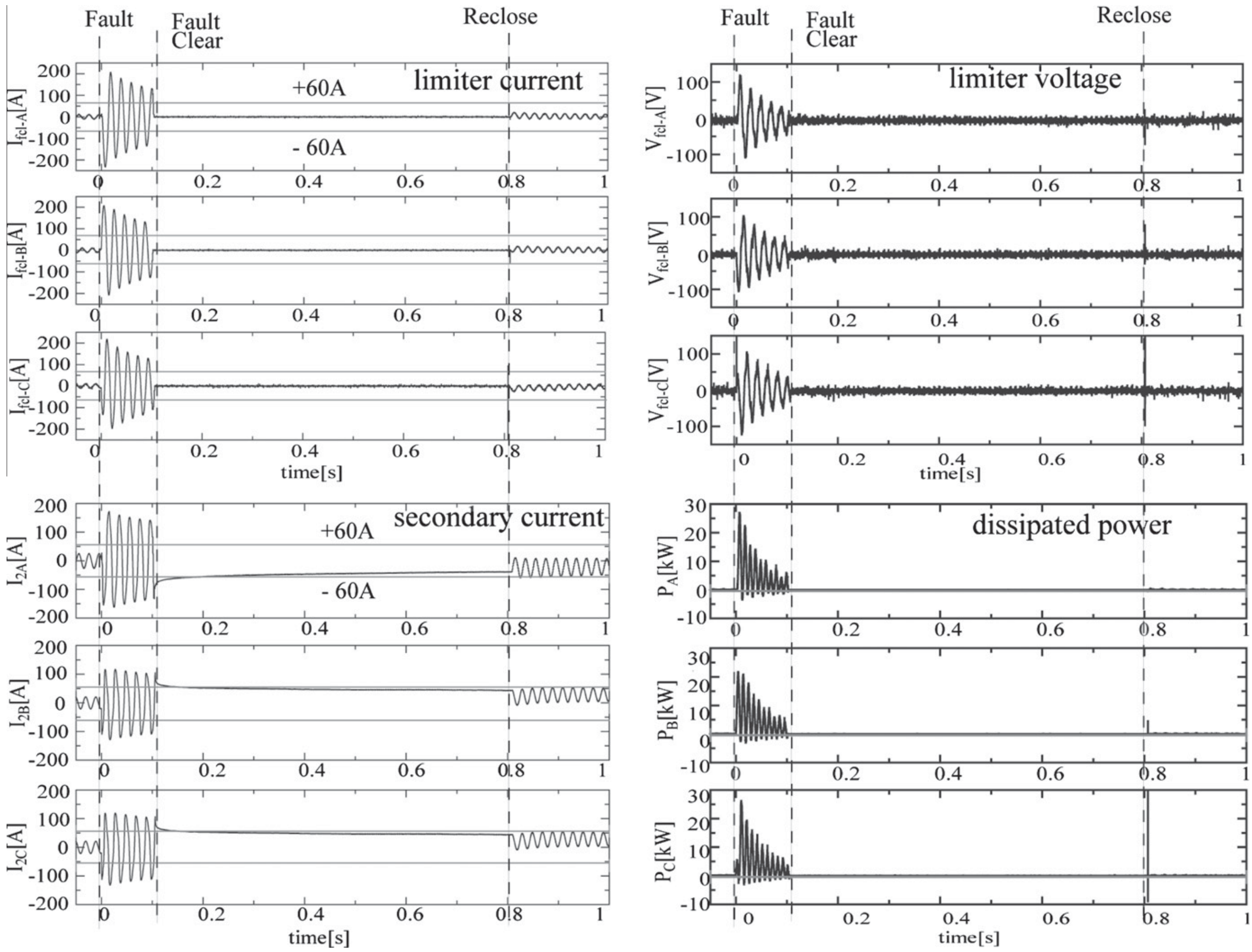

Fig. 4. Current limiting experimental result at the simulated fault with the switch sequence in Fig. 3. A-, B- and C-phase SFCL current (upper left), A-, B- and C-phase SFCL secondary coil current (lower left), A-, B- and C-phase SFCL terminal voltage (upper right), the dissipated powers in A-, B- and C-phase SFCL (lower right).

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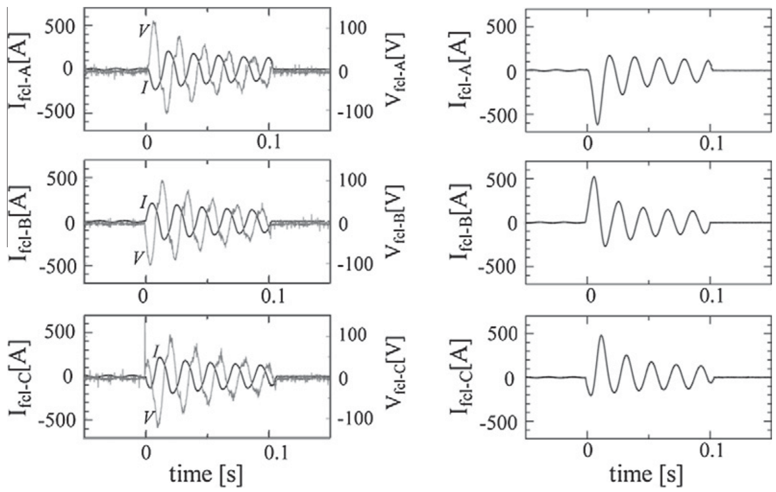

Fig. 5. Fault current with SFCL (left) and without SFCL (right) and SFCL terminal voltage (grey: left) during the fault.

sion lines (simulated by 12.8 mH air–gap reactors) and the reactor *Lt* (0.37 mH). The magnetically controlled switches (Sw1 and Sw2) simulated the Circuit Breaker (CB). The model 3-phase SFCL was installed between Sw1 and the fault point. The switch operation sequence is shown in Fig. 3. The magnetically controlled switch Sw3 was closed to simulate the 3LG fault at the generator terminal and after 100 ms, the fault line was rejected by opening Sw1 and 2. At 200 ms after the initiation of the fault, the fault was cleared (Sw3 open). The Sw1 and Sw2 were re-closed at 800 ms to recover the initial operating condition.

3.3. Experimental results

Fig. 4 shows the experimental result of the SFCL current $I_{\mathrm{fcl\text{-}A,B,C}}$ (the primary coil current), the SFCL voltage $V_{\mathrm{fcl\text{-}A,B,C}}$, the secondary coil current $I_{2A,2B,2C}$ and the dissipated power $P_{A,B,C}$ in the SFCL coils throughout the fault test sequence. Subscript A, B and C denote the phase. Before the fault, both the primary and the secondary coil current were smaller than the critical current (60 A: red line), that is, both coils were in the superconducting state and then the SFCL voltage was almost zero. During the fault period of 100 ms, both the primary and the secondary coil currents in every phase exceeded the critical current. Every coil wire was in the normal (resistive) state. The fault current was limited to less than 230 A. Since the SFCL voltage and the dissipated power did not appear after the re-closure, it was confirmed that the SFCL recovered to the stand-by mode successfully.

The experimental results of the fault current and the voltage across the SFCL are shown in Fig. 5 (left). The fault currents without SFCL are shown in Fig. 5 (right). The first peak (over 500 A) of each phase without SFCL, which contained large DC components, was reduced to about 200 A with SFCL. The limiting impedance of SFCL at the first peak was evaluated to be 0.51–0.56 Ω (resistive component; 0.47–0.52 Ω, reactive component; 0.17–0.21 Ω).

It can be seen from the phase difference between voltages and currents in Fig. 5 (left) that the SFCL limited the fault current mainly by the resistive component at first and second peak, and then the resistive component gradually decreased, the fault current was limited mainly by the reactance component.

Fig. 6 shows the generator terminal voltages during the fault with and without the SFCL. The SFCL suppressed the generator voltage drop during the fault, that is, improved the stability of the system.

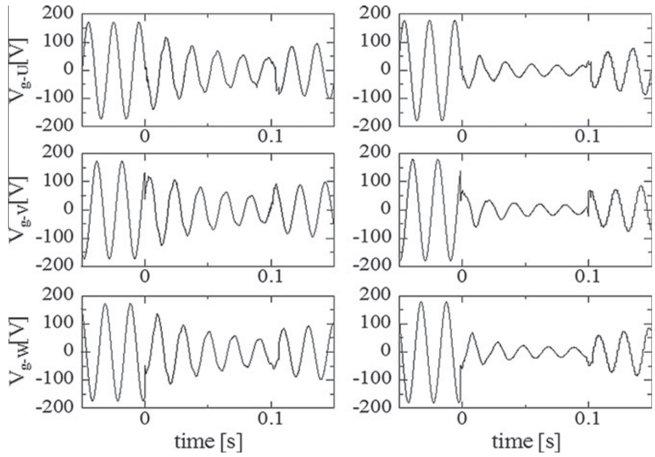

Fig. 6. Generator voltage with (left) and without SFCL (right) during the fault.

4. Conclusions

A 3-phase tri-axial SFCL of re-wound structure was designed and made using BSCCO2223 wire. The model SFCL limits the fault current mainly by its reactance, but for larger fault current, by its additional resistance.

The demonstration tests were carried out using the 3-phase SFCL installed in a lab-scale one-machine infinite bus transmission model system. The experimental results on the current limiting performance of the SFCL at the 3LG fault were shown and discussed. The 3-phase SFCL successfully worked without large inter-phase interaction. The peak fault current 560 A without SFCL was reduced to 230 A with SFCL immediately. The SFCL recovered to the stand-by mode under a typical CB operation sequence.

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