論 文
55A-6-6

하이브리드형 초전도 한류기의 동작 특성

Operating Characteristics of Hybrid Type Superconducting Fault Current Limiter

趙 鏞 善* · 崔 孝 祥† · 南 肯 賢* · 林 成 勳**
(Yong-Sun Cho · Hyo-Sang Choi · Gueng-Hyun Nam · Sung-Hun Lim)

Abstract - We investigated the operating characteristics of the hybrid-type superconducting fault current limiter (SFCL) according to the inductance of secondary windings. The hybrid type SFCL consists of a transformer that has a primary winding and a secondary winding with serially connected $YBa_2Cu_3O_7$ (YBCO) films. The resistive-type SFCL has difficulty when it comes to raising the capacity of the SFCL due to slight differences of critical current densities between units and structure of the SFCL. The hybrid-type SFCL with closed-loop is able to achieve capacity increase through the electrical isolation and reduction of the inductance of the secondary winding with a superconducting element of the same critical current. On the other hand, the current limiting characteristics were nearly identical in the hybrid-type SFCL with open-loop compared to closed-loop, but quench time was longer than the hybrid-type SFCL with closed-loop. We confirmed that the capacity of the SFCL was increased effectively by the reduced inductance of the secondary winding. In addition, the power burden of the system also could be lowered by reducing the inductance of secondary winding.

Key Words : Capacity Increase Method, Hybrid-Type Superconducting Fault Current Limiter, Inductance, Power Burden

1. INTRODUCTION

Power systems have currently increased the fault current levels to exceed breaker interruption ratings. Stresses of protective equipments on the power system have been raised by the increase of fault current levels. Therefore, the cut-off capacity of the breaker must also be raised. It is also demanded that the equipment should suppress the fault currents with reliability and rapidity. Under these situations, the appearance of the superconducting fault current limiter (SFCL) suggests a positive alternative for reduction of the fault currents. SFCLs can limit the fault current within a very short response time (less than 6m sec). There are various kinds of SFCLs: resistive, inductive, flux-lock, hybrid type, and so on. The resistive type SFCL using the intrinsic zero-impedance characteristic of the superconductor has a simple structure. It could be made to be quite compact by using thin films. The simultaneous quench between superconducting elements is important for the capacity increase in serial and parallel connections. The unbalanced quench of the resistive-type SFCL at serial and parallel connections between superconducting elements occurs by slight difference in their critical current density. The slight difference is unavoidable because of the inhomogeneity generated in the manufacturing process. To increase the capacity of SFCLs, the serial and parallel connections between superconducting elements are necessary.

As another type of SFCL, we tested the characteristics of the hybrid-type SFCL using a transformer with primary and secondary windings. In order to increase the capacity of the SFCL, we fabricated the transformers with closed-loop and open-loop, and investigated the effects by the inductance increase of the secondary winding.

2. EXPERIMENTAL

2.1 Structure of hybrid-type SFCL

Figure 1 shows the basic structure of the hybrid-type SFCL. The hybrid-type SFCL consists of a transformer, which has primary and secondary windings with a superconducting element connected in series. Because the resistance of the superconducting element connected in the secondary winding is zero, the line current on the power system flows without I2R losses before the fault

† 교신저자, 正會員 : 朝鮮大 工大 電氣工學科 助教授 · 工博
E-mail : hyosang@chosun.ac.kr
* 學生會員 : 朝鮮大 工大 電氣工學科 碩士課程
** 正 會 員 : 崇實大 工大 電氣工學科 專任講師
接受日字 : 2006年 4月 10日
最終完了 : 2006年 5月 10日

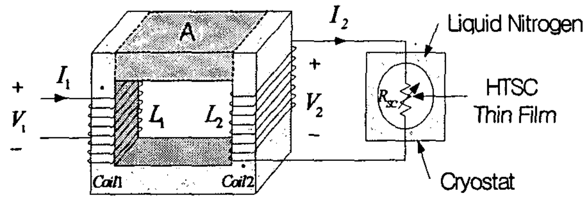

Fig. 1. Conceptive diagram of hybrid-type SFCL.

occurs.

When the fault occurs by the current I_2 controlled from the coil wound in the secondary winding, the superconducting element was quenched, and the fault current was limited.

Equation (1) expresses that the line current flows in the SFCLs when a HTSC thin film is in the superconducting state, and equation (2) that the HTSC thin film is quenched when I2 exceeds its critical current density.

$$jwL_1I_1 + jwMI_2 = V_1 \sin wt \quad (1)$$

$$jwMI_1 + (jwL_2 + R_{SC})I_2 = 0 \quad (2)$$

In the equations, L_1 and L_2 are the inductance of primary and secondary windings, and R_{SC} is the resistance of the superconducting element after the quench, respectively. M is the mutual inductance between primary and secondary windings, which is $M = k\sqrt{L_1 \cdot L_2}$. The coupling coefficient (k) between primary and secondary windings here is 1.

From Equations (1) and (2), the current of primary winding (I_1) and the current flowing through a superconducting element or the current of secondary winding (I_2) are expressed as follows:

$$I_1 = \frac{jwL_2 + R_{SC}}{jwL_1R_{SC}} \cdot V_1 \sin wt \quad (3)$$

$$I_2 = \frac{-jwM}{jwL_1R_{SC}} \cdot V_1 \sin wt \quad (4)$$

The "A" region in Figure 1 can be separated for the open-loop experiment. Because the mutual inductance between primary and secondary windings decreases, in case of open-loop experiment, the current of secondary winding (I_2) is reduced as shown in Equation (4).

From Equations (3) and (4), the current ratio between I_1 and I_2 is expressed as follows

The initial limiting current (I_{ini}) of the hybrid-type

$$\frac{I_2}{I_1} = \frac{-jwM}{jwL_2 + R_{SC}} \quad (5)$$

SFCL, when the current (I_2) of the secondary winding reaches critical current of the superconducting element, can be changed from Equation (5) by inserting $R_{SC}=0$, $I_2=I_q$, and $I_1=I_{ini}$ as follows:

$$I_{ini} = \frac{jwL_2}{-jwM} \cdot I_q \quad (6)$$

From Equation (6), we confirmed that the levels of the initial limiting current could be controlled higher or lower than the critical current of the superconducting element by adjusting the inductances of the primary and secondary windings.

2.2 Experimental preparation

Figure 2 illustrates the experimental circuit of a hybrid-type SFCL according to the inductance ratio between primary and secondary windings.

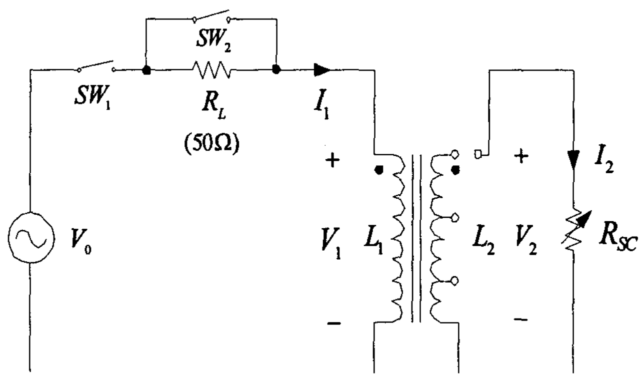

Fig. 2. Experimental circuit of a hybrid-type SFCL.

The superconducting element was fabricated using 300 nm thick $YBa_2Cu_3O_7$ thin films grown on 2 inch diameter Al_2O_3 substrates. The surface of the YBCO was coated with a 200 nm thick gold-layer that scatters the joule heat generated after quench and protects the YBCO thin film from moisture. In order to operate in the superconducting state, the YBCO thin film was immersed into a liquid nitrogen (LN_2) bath. The critical current of YBCO thin film was 22.3 A.

In Figure 2, V_0 is a source voltage of $160/\sqrt{3}$ V_{rms}. I_1 and I_2 are the currents flowing in the primary and secondary windings, respectively. The R_L of load resistance is 50 Ω. The inductance of the primary winding (L_1) was 60 mH and the inductance of the secondary winding (L_2) was adjusted to 2 mH, 11 mH, 30 mH, respectively. The short circuit accidents were simulated for five periods by SW_2, which is switch for fault condition, after switch SW_1 for normal condition was closed at 0° of fault angle. The data were recorded and analyzed from the data acquisition system (DL 750 ScopeCorder, YOKOGAWA).

3. RESULTS AND DISCUSSION

In order to analyze the operating characteristics of a hybrid-type SFCL, a transformer was designed in the both the closed-loop and the open-loop structure. The inductance ratios between the primary and the secondary windings were adjusted to 60 mH:2 mH, 60 mH:11 mH and 60 mH:30 mH, respectively. Figures 3 and 4 present the fault current limiting curves of closed-loop and open-loop hybrid-type SFCLs according to the inductance ratios between primary and secondary windings. In Figure 3, the initial limiting current levels according to the increase of inductance ratio were 6.5 A, 16.2 A and 28 A, respectively. In Figure 4, they were 6.9 A, 17 A and 29.2 A, respectively.

The initial limiting current levels between the closed-loop and the open-loop were similar. However, the limiting peak value in the first cycle of the line current

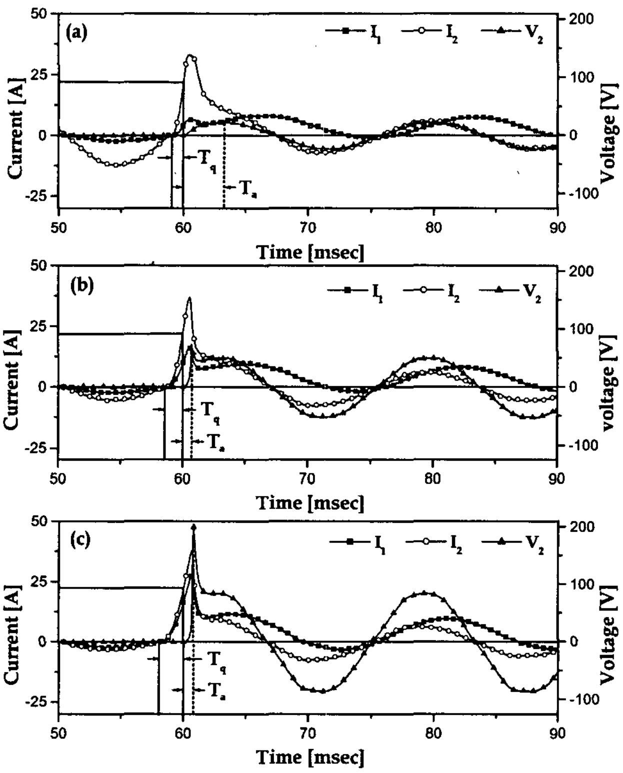

Fig. 3. Fault current limiting characteristics of closed-loop circuit according to the inductance ratios between primary and secondary windings: (a) 60 mH:2 mH, (b) 60 mH:11 mH, (c) 60 mH:30 mH.

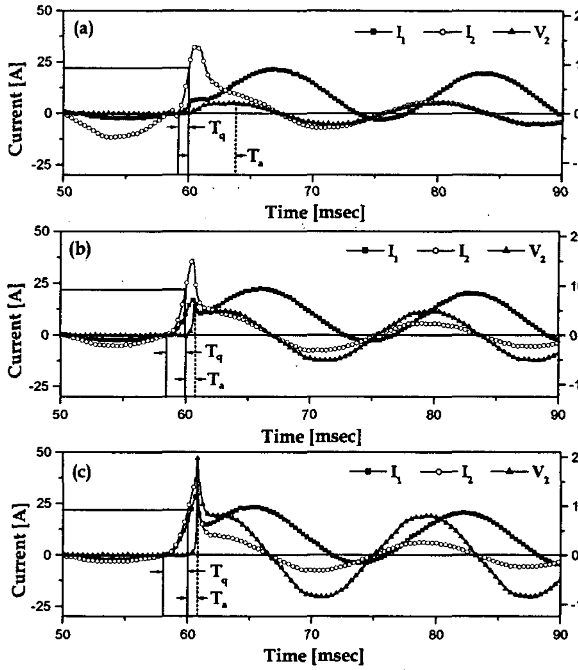

Fig. 4. Fault current limiting characteristics of open-loop circuit according to the inductance ratios between primary and secondary windings: (a) 60 mH:2 mH, (b) 60 mH:11 mH, (c) 60 mH:30 mH.

(I_1) during the fault condition indicated 8.2, 9.7 and 11.8 A in the closed-loop, and 21.5 A, 22.5 A and 23.5 A in the open-loop, respectively. We confirmed that such difference of limiting current levels happened because the mutual inductance of iron core between the primary and the secondary windings in the open-loop structure noticeably reduced more than in the closed-loop structure.

In Figures 3 and 4, the peak current (I_2) flowing into a superconducting element was similar as 33 A, 36.5 A and 37 A in the closed-loop, and as 32.5 A, 36.6 A and 37.6 A in the open-loop, respectively. However, the quench time (T_q), which is defined as the time interval from fault starting point to the critical current value (25 A), increased gradually according to the increase of inductance ratio as 0.84, 1.43 and 1.79 msec in the closed-loop, respectively. The T_q of the open-loop structure was 1.81, 3.21 and 3.7 msec, respectively. The delay of T_q occurred due to the increase of the inductance in the secondary winding.

The voltage (V_2) detected in both terminals of a superconducting element was also similar as 22, 73 and 204 V in the closed-loop, and as 21.2, 71.2 and 198.8 V in the open-loop, respectively. But arrival time (T_a), which is defined as the time from the quench starting-point to the peak voltage point, reduced as 3.26, 0.64 and 0.76 msec in the closed-loop when the inductance ratio increased, while the arrival time (T_a) in the open-loop was 4.47, 1.31 and 1.3 msec, respectively. We speculated that this is because of the leakage flux in the open-loop structure. If the applied voltage was equal and the arrival time (T_a) was shorter, the quenching ratio of the resistance in the superconducting element during the fault condition would increase more in the open-loop structure. At this time, the power burden of the superconducting element became higher due to the abrupt increase of joule heat generated from its quench.

4. CONCLUSIONS

We investigated the fault current limiting characteristics of a hybrid-type SFCL according to the inductance ratio between the primary and the secondary windings. The current limiting characteristics in the closed-loop structure under the same inductance ratio were similar compared to the open-loop structure. However, the fault current in the closed-loop structure could be limited more quickly than in the open-loop structure circuit. The arrival time (T_a) to the peak voltage was shorter according to the increase of the inductance ratio. Because of the resistance generated by the quench of the superconducting element, the joule heat was generated in the superconducting element. If the arrival time (T_a) of peak voltage is shorter, the increase ratio of joule heat is faster and this will operate as the power burden of a superconducting element.

참 고 문 헌

[1] W. Paul, M. Chen, M. Lakner, J. Rhyner, D. Braun, W. lanz, "Fault current limiter based on high temperature superconductors different concepts, test results, simulations, applications", Physica C, Vol. 354, No. 1-4, pp. 27-33, May 2001.

[2] Yu Jiang, Shi Dongyuan, Duan Xianzhong, Tang Yuejin and Cheng Shijie, "Comparison of superconducting fault current limiter in power system", IEEE Power Engineering Society Summer Meeting, Vol. 1, pp. 43-47, 2001.

[3] M. Yamaguchi, S. Fukui, T. Satoh, Y. Kaburaki, T. Horikawa and T. Honjo, "Performance of DC reactor type fault current limiter using high superconducting coil", IEEE Trans. Appl. Superco-nd., Vol. 9, No. 2, pp. 940-943, Jun. 1999.

[4] Sung-Hun Lim, Hyo-Sang Choi and Byoung-Sung Han, "Operational characteristics of flux-lock-type high - T/sub c/superconducting Fault Current Limiter with a Tap changer", IEEE trans. Appl. Supercond., Vol. 14, No. 1, pp. 82-86, Mar. 2004.

[5] Hyo-Sang Choi, Hye-Rim Kim and Ok-Bae Hyun, "Operating properties of superconducting fault limiters based on YBCO thin films",Cryogenic, Vol. 41, No. 3, pp. 163-167, Mar. 2001.

[6] Hyo-Sang Choi, Ok-Bae Hyun, Hye-Rim Kim and Kwon-Bae Park, "Switching properties of a hybrid type superconducting fault current limiter using YBCO stripes", IEEE trans. Appl. Supercond., Vol. 14, No. 3, Sep. 2002.

저 자 소 개

조 용 선(趙 鎔 善)
1980년 1월 15일생, 2005년 조선대학교 전기공학과 졸업, 현재 동 대학원 전기공학과 석사과정.
Tel : 062-230-7054
Fax : 062-230-7020
E-mail : cys5144@hotmail.com

최 효 상(崔 孝 祥)
1966년 2월 21일생, 1989년 전북대학교 전기공학과 졸업, 1994년 동 대학원 전기공학과 졸업(공학석사), 2000년 동 대학원 전기공학과 졸업(공학박사), ~ 2003년 한전 전력연구원 선임연구원, 현재 조선대학교 전기공학과 교수.
Tel : 062-230-7025
Fax : 062-230-7020
E-mail : hyosang@chosun.ac.kr

남 긍 현(南 肯 賢)
1979년 10월 22일생, 2005년 조선대학교 전기공학과 졸업, 현재 동 대학원 전기공학과 석사과정.
Tel : 062-230-7054
Fax : 062-230-7020
E-mail : kkoragi@hanmail.net

임 성 훈(林 成 勳)
1973년 11월 1일생, 1996년 전북대 공대 전기공학과 졸업, 1998년 동 대학원 전기공학과 졸업(공학석사), 2003년 동 대학원 전기공학과 졸업(공학박사), 현재 숭실대학교 전기공학부 교수
Tel : 02-828-7268
Fax : 02-817-7961
E-mail : superlsh73@ssu.ac.kr