

# 1선 지락 사고 시 3 권선 변압기에 적용된 초전도 한류기의 동작 특성 분석

## Analysis of Transient Characteristics of a SFCL Applied Into Third-winding Transformer in a Single Line-to-ground Fault

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**Abstract** - Coercion transformer is commonly used in the electrical grid which in three phase of distribution system. The accident of the electrical grid is divided into a single, a double, a third line-to-ground faults and a double, a third line-to-line faults. A single line-to-ground fault accounts for nearly 75[%] among them. In this research, when a Superconducting Fault Current Limiters (SFCL) was applied to the three phase power system, operation in a single line-to-ground fault and limiting characteristics of fault current according to turns ratio of third winding were analyzed. When a single line-to-ground fault happened, secondary winding's circuit was open. Then third winding's circuit with a SFCL was closed. So fault current was limited by diverted circuit. At this time, we could find out that size of the limited fault current could be changed according to third winding rate. We confirmed that limiting operation of the fault current was carried out within one-period. These results will be utilized in adjusting the size of the SFCL.

**Key Words** : Third-winding, SCR, SFCL, Superconducting element, Line-to-ground fault

### 1. Introduction

The domestic maximum power demand is 7,477 million kW, which has increased 7.0[%] over last year in Korea. It is forecasted that the power demand will increase by 3.1[%] annually on average until 2024, to 107,437 million kW. As a result of steadily increasing the power demand, the sizes of power transmission and distribution systems are expanding. Consequently, the system impedance is decreasing while the fault current size is increasing [1-2]. The 154kV power systems have replaced circuit breakers with higher-grade circuit breakers because the fault current exceeded the breaking capacity of the existing circuit breakers. Recently, the fault current of the 345kV power systems, which play the central role in South Korea, also exceeded the breaking capacity of circuit breakers [2-8]. They were replaced with higher-grade breakers as with the 154kV systems, but because they cannot endure the fault current either, the bus separation system has been adopted [4-8]. The bus separation system, however, decreases the coherence between

systems when operated for a long time. This damages stability and destroys the active and reactive power transmission flexibility, which leads to low supply reliability [5-8]. In addition, many methods for reducing the fault current have been presented, such as replacement of circuit breakers and installation of serial reactors and high-impedance transformers. However, these measures change the operation and transient characteristics of the system and decrease the reliability of the power supply. Therefore, fault current reduction measures that are more systematic and effective than the conventional methods are urgently needed. In this paper, a SFCL is proposed, which is a new-concept protection device for fault current reduction. The SFCL supplies power to the lines with no loss because it operates with no impedance at normal times. When a fault occurs, however, it generates random impedance and limits the fault current to the breaking capacity of the circuit breaker, or lower. Furthermore, after the fault current is limited, the impedance returns to zero, thus solving the conventional problem of the power fuse. For this simulation, a small-scale power distribution system was built to analyze the operation characteristics when an SFCL is applied to an actual system. To improve the reliability, a third-winding transformer was used. In a power system, single, double, and triple line-to-ground faults as well as double and triple line-to-line faults occur. The most dangerous fault among them is the triple

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line-to-line fault. However, the single line-to-ground fault has the highest frequency (75%) [1-7]. Thus, in this paper, the fault current limit of the SFCL fused with a third-winding transformer, and the voltage characteristics of the superconducting device, were analyzed.

## 2. Maintain

### 2.1 Construction of the simulation test

Fig. 1 shows the circuit diagram for the fault simulation of the third-winding transformer combined with an SFCL. The third-winding transformer was used for the Y-Y wiring connection of the three-phase power supply ( $V_P, V_S, V_T$ ) indicating the power plants and the loads indicating the customers (R-Load, S-Load, T-Load). Power was supplied to each phase through SW-R1, SW-S1, and SW-T1 and faults were generated with the switches SW-R2, SW-S2 and SW-T2. A CT for detecting the fault current was installed in the secondary winding and an SCR switching control system was installed. A superconducting element, which is a limiter device was installed in the third-winding. Superconducting element are largely divided into the resistance and induction types. The resistance type is small and simple in structure. The superconducting element that was produced for this experiment was a meander-line-type fault current limiter using a 2-inch-diameter YBCO film and Al<sub>2</sub>O<sub>3</sub>. The critical temperature of the superconducting element was 87-88[K]. In addition, to prevent degradation by water in air at the normal temperature, 0.1 [ $\mu\text{m}$ ] gold was deposited on the YBCO film [7].

### 2.2 Current and voltage characteristics in the single line-to-ground fault

The winding rate was set so that the third-winding transformer combined with a superconducting element would operate as a coercion transformer. The third-winding rate was increased to 1, 2 and 3 and a 160 voltage was applied to each phase. Power was supplied through SW-R1. And a single line-to-ground fault was generated through SW-R2. When CT detects the fault current, the SCR control system is activated, and SCR-A (contact a) and B (contact b) perform the switching operation. The turn-on operation of SCR-B is carried out simultaneously with the activation of the SCR control system. However, the turn-off operation of SCR-A is carried out when the current is zero or close to zero. In other words, SCR-A carries out turn-on simultaneously with the occurrence of a fault, but the SCR-B connected to the neutral line carries out turn-off after the half-period when the current becomes zero. Therefore, the line into which the fault current flows is changed within the half-period, and the superconducting element is quenched simultaneously with the turn-off operation of SCR-A, thus restricting the fault current after the half-period.

#### 2.2.1 The case of $N_P : N_S : N_T = 3 : 2 : 1$

Fig. 2 shows the voltage and current characteristics when the winding ratio of the third-winding transformer is  $N_P : N_S : N_T = 3 : 2 : 1$  in the event of a single line-to-ground fault. Fig. 2(a) shows the voltage and current characteristics of fault phase R. In the event of a fault, the fault current of 87.7[A] was detected by CT, and the SCR control system carried out switching operation. SCR-B carried out turn-on immediately after the fault, and changed the line of the fault current. Accordingly, the fault current of 177.3[A] which was flowing in the secondary winding, was divided into 149.6 and 28.8[A] which flowed to the neutral line and the third winding, respectively. After the half-period, when the current flowing through the neutral line became zero, SCR-A carried out turn-off, and the fault current flowed into the third winding. As a result, the limiter a superconducting element was quenched, and the voltage of 112[V]. was excited. Due to the quenching of the superconducting element, a random impedance occurred, and the fault current was limited to 41.2[A] within one cycle of fault occurrence. Figs. 2(b) and (c) show the voltage and current characteristics of the S and T phases, which are normal phases. Although a slight fault current occurred as an effect of the R phase due to the use of the third-winding transformer, the normal operation was restored within a half-cycle of fault occurrence.

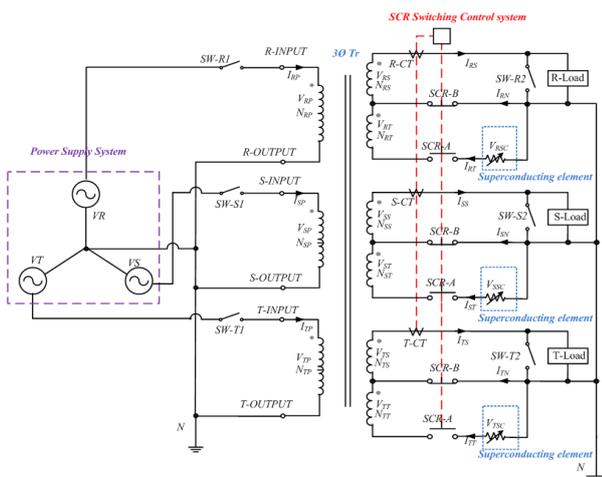


그림 1 3권선 변압기에 용합된 초전도 한류기의 모의실험 회로

Fig. 1 Circuit diagram for the fault simulation of the third-winding transformer combined with an SFCL.

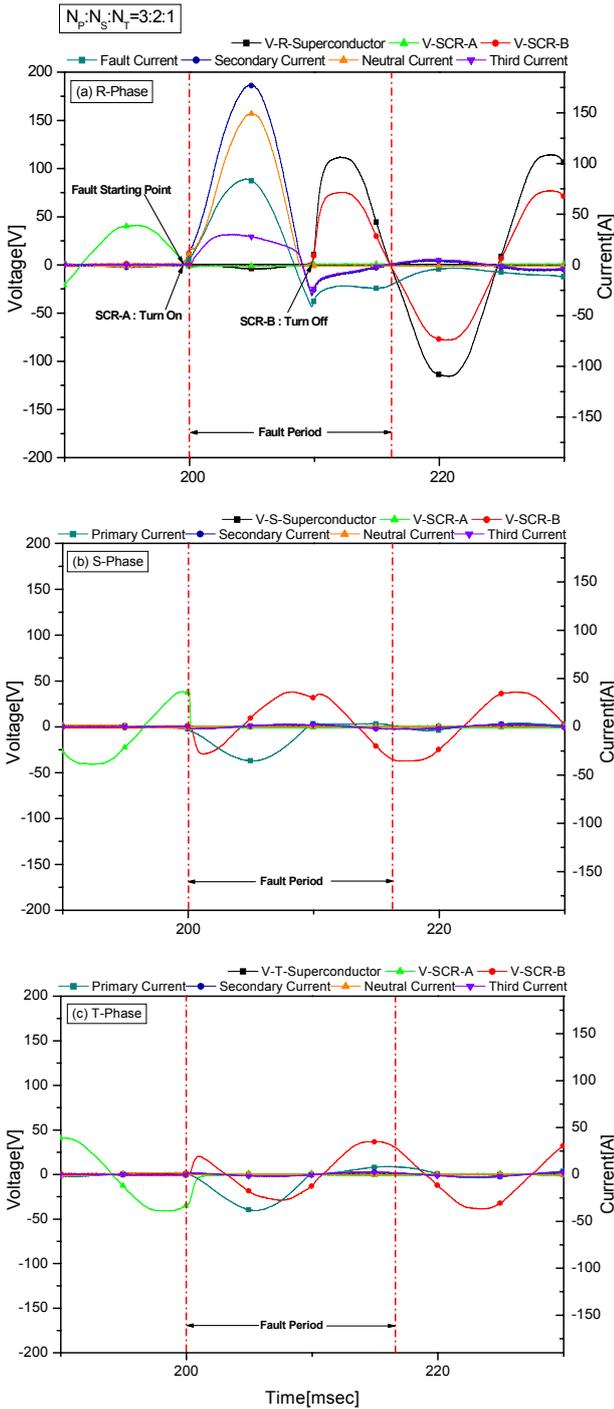


그림 2  $N_p : N_s : N_T = 3 : 2 : 1$  일 때 전압 및 전류 특성  
 Fig. 2 Voltage and current characteristics at  $N_p : N_s : N_T = 3 : 2 : 1$ . (a) R-Phase, (b) S-Phase, (c) T-Phase

2.2.2 The case of  $N_p : N_s : N_T = 3 : 2 : 2$

Fig. 3 shows the voltage and current characteristics when the winding ratio of the third-winding transformer is  $N_p : N_s : N_T = 3 : 2 : 2$  in the event of a single line-to-ground fault. Fig. 3(a) shows the voltage and current characteristics of fault phase R. As mentioned earlier, the fault current of 84.5[A] was detected by CT,

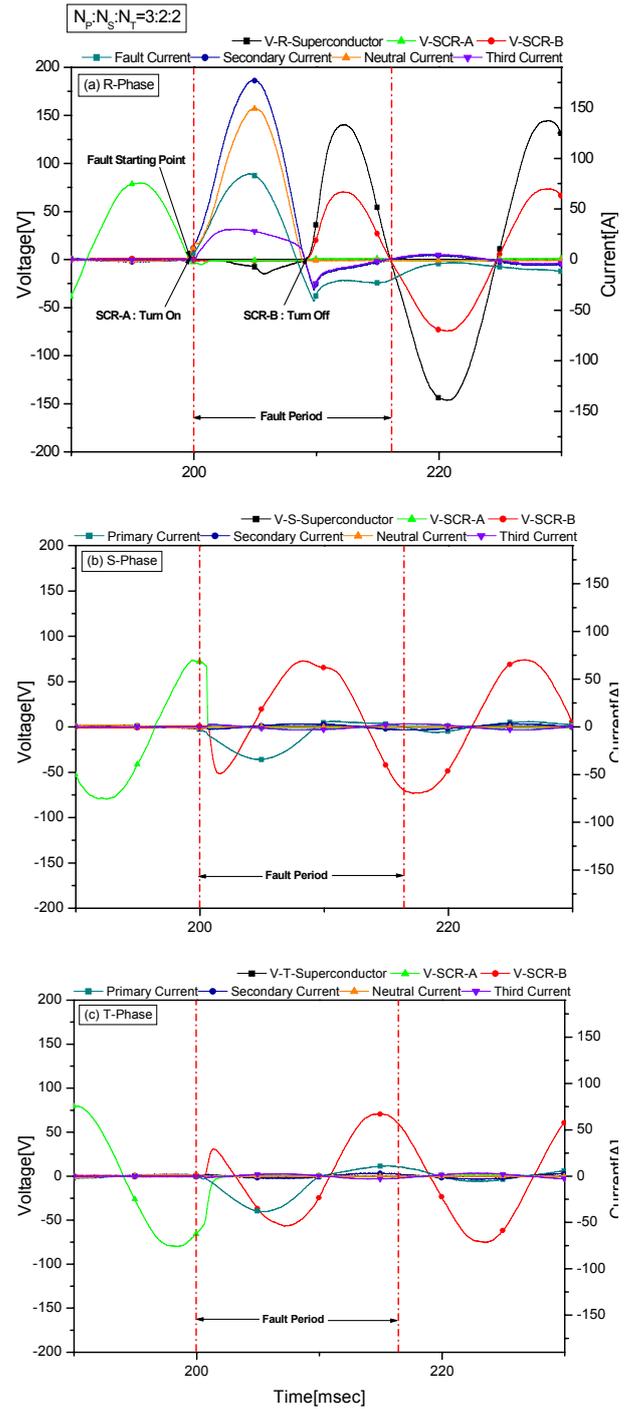


그림 3  $N_p : N_s : N_T = 3 : 2 : 2$  일 때 전압 및 전류 특성  
 Fig. 3 Voltage and current characteristics at  $N_p : N_s : N_T = 3 : 2 : 2$ . (a) R-Phase, (b) S-Phase, (c) T-Phase

and SCR carried out switching operation. SCR-B carried out turn-on simultaneously with the fault occurrence. Accordingly, the fault current of 176.8[A] which was flowing in the secondary winding, was divided into 156 and 33.5[A] which flowed to the neutral line and the third-winding, respectively. Likewise, when the current flowing through the neutral line became zero, in other

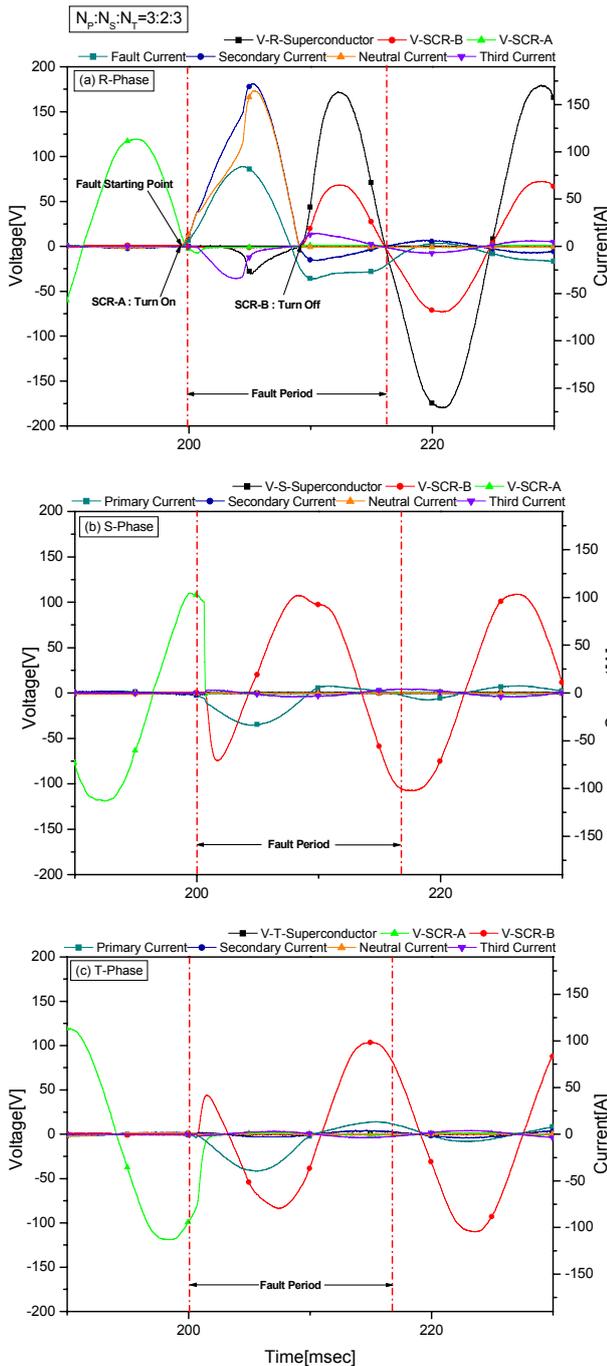


그림 4  $N_p : N_s : N_t = 3 : 2 : 3$  일 때 전압 및 전류 특성  
 Fig. 4 Voltage and current characteristics at  $N_p : N_s : N_t = 3 : 2 : 3$ . (a) R-Phase, (b) S-Phase, (c) T-Phase

words, after a half-period, the SCR-A carried out turn-off. Accordingly, as the fault current flowed only to the third-winding, the superconducting element was quenched, and the voltage of 140[V] was excited. Due to the quenching of the superconducting element, the fault current was limited to 35.1[A] within one cycle of fault occurrence. Figs. 3(b) and (c) show the voltage and current characteristics of the S and T phases, which are

normal phases. Likewise, even though the fault phase had an effect, normal operation was soon restored due to the third-winding transformer.

### 2.2.3 The case of $N_p : N_s : N_t = 3 : 2 : 3$

Fig. 4 shows the voltage and current characteristics when the winding ratio of the third-winding transformer is  $N_p : N_s : N_t = 3 : 2 : 3$  in the event of a single line-to-ground fault. Fig. 4(a) shows the voltage and current characteristics of fault phase R. The same operation was carried out as when the third-winding ratio was 1 and 2. When a fault was generated with SW-R2, the fault current of 84.5[A] was generated. It was detected by CT, and at the same time, SCR-B carried out turn-on and changed the line. Accordingly, the fault currents of 164.3 and 34[A] flowed to the third winding and the current flowing through the neutral line became zero after the half-period. At the moment when the current became zero, SCR-A carried out turn-off, and the superconducting element was quenched. With the quenching, the voltage of 172.7[V] was excited. As a result, the fault current was limited to 34.3[A] within one cycle of fault occurrence. Figs. 4(b) and (c) show the voltage and current characteristics of the S and T phases, which are normal phases. The same operation was carried out as when the third-winding ratio was 1 and 2.

### 2.2.4 Discussion

This simulation analyzed the fault current limitation and the voltage characteristics of the superconducting element according to the third-winding rate. As the third-winding rate of the third-winding transformer increased, the initial fault currents of 84.7, 83.3 and 84.5[A] occurred. Furthermore, the turn-on and turn-off switching times of SCR were shortened to 9.5, 8.7 and 8.5 [msec]. As a result, the superconducting element was quickly quenched, and the fault current was limited to 41.2, 35.1 and 34.3[A] after a half-period. The voltages that were applied to the superconducting element were 112.2, 140.0 and 172.7[V].

## 3. Conclusion

In this paper, the operation characteristics of a SFCL combined with a third-winding transformer were analyzed according to the third-winding rate in the event of a single line-to-ground fault. In the event of a single line-to-ground fault, SCR changed the line and limited the fault current by switching operation so that the fault current would flow to the winding to which a superconducting element was connected. When SCR-B carries out turn-off, the voltages induced at the

secondary and third windings were applied to the superconducting element. If turn-off was not carried out, only the voltage induced at the third winding is applied to the superconducting element. In other words, the voltage induced in the superconducting element was determined by the third winding. The simulation revealed that as the number of third windings increased, the fault current remained similar, but the turn-on and turn-off operations of the SCR were gradually shortened. Thus, the superconducting element was quickly quenched, which quickly restricted the fault current to a lower value. Consequently, the fault current was limited to within one cycle in accordance with the switching operation speed of the SCR. The simulation in this work showed that it is possible to decrease the size of the fault current and to control the operation time of the SCR as well as the quench operation of the superconducting element by increasing the third-winding rate of the SFCL.

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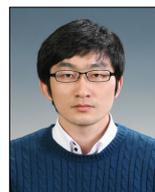
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