Recovery Characteristics of Resistive SFCL Wound With YBCO Coated Conductor in a Power System

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Abstract—Since resistive superconducting fault current limiters (SFCLs) are inserted to a power system directly, it is necessary to recover instantly after the clearance of a fault. Most resistive SFCLs using BSCCO bulk or thick film have a recovery time of tens of seconds. An SFCL using YBCO coated conductor (CC) has a large surface area contacted to liquid nitrogen. Joule heat flux of the SFCL is smaller than that of other types when a fault occurs. Therefore, it is important for the SFCL employing CC to investigate a recovery time. In this paper, the recovery characteristics of SFCL with respect to applied voltage were analysed in a power system. All tests were performed in liquid nitrogen and sub-cooled nitrogen. From this result, the parameters for recovery time were obtained.

Index Terms—Coated conductor, recovery time, superconducting fault current limiter.

I. INTRODUCTION

DEVELOPMENT of superconducting fault current limiters (SFCLs) has been accomplished almost up to the point of commercialization [1]. In developing this machine, the fulfillment of requirements for the power system is far less fully studied than design and fabrication of the machine. Since many research groups have been developing the SFCL for distribution and transmission power grid [1]–[3], special features of the power grid to be installed should be considered in the design stage.

Fig. 1 shows schematic model of power distribution system of 22.9 kV level in Republic of Korea. Conventional power system protection has been accomplished by re-closing operation, standards of which varies with voltage level: for power distribution system, when a fault occurs, specifications require that alternate re-closing and opening of circuit breakers be performed twice in aerial line; the first opening lasts for 0.5 seconds immediately after a fault. Subsequent re-closing of circuit-breaker is intended to eliminate transient fault. On the other hand, the duration period of the second opening is 15 seconds. The second re-closing is to protect from a surge other than a transient fault. For successful application of SFCL in the existing power system, substituting existing relays and circuit breakers, SFCL should make the best of its advantages: stability of power service as well as compactness should be achieved. Stability of power service is guaranteed if surge protection is performed by fast recovery from fault duration in SFCL. Thus, design of SFCL should include fault duration and the requirement for re-closing of the circuit immediately after a fault is cleared [4]. By assuming that the entire surge current flows through the stabilizer of SFCL, fast recovery characteristics of SFCL is achieved at the expense of compactness and vice versa.

Most resistive SFCLs employing BSCCO bulk or thick film have a recovery time of tens of seconds [1]. This study is partially animated by the fact that Y$_{1}$B$_{2}$C$_{3}$O$_{y}$ coated conductor...
(CC) have been utilized for resistive SFCL. The SFCL employing CC has a large surface area contacted to liquid nitrogen. Joule heat flux of the SFCL is smaller than that of other types when a fault occurs. In considering the thermal condition, it may be useful to investigate recovery time.

This paper attempts to measure recovery time as a function of joule heating per area. The central question the authors intend to examine is, What are the parameters for determining recovery time? In exploring this question, consideration will be limited to experimental results, not calculated analysis.

II. EXPERIMENTAL SETUP

A. Non-Inductively Coil

Three coils were fabricated for short-circuit test. The coil is wound non-inductively and consists of the inner and outer layers, and they are connected in parallel. The inner and outer windings are wound along a groove on the same bobbin in the opposite winding direction to each other. Fig. 2 shows the non-inductively coil. The coils were wound with YBCO CC, called 2G wire. Two kinds of CC were wound: one is AMSC 344 wire and the other is 344S wire. The wire specifications are provided in Table I. Table II shows the specifications of the fabricated coils. The gap between layers is filled with polyimide sticky tape. The former for the coil is made of G10-FRP.

B. Short-Circuit Test for Measuring Recovery Time

Recovery time was measured by short-circuit test. Fig. 3 shows the circuit diagram for the test. A transformer was used for generating large current. A switch (S/W) made the circuit fault condition. Fault period time is 0.1 sec.

In real case of applying SFCL to the power system, the fault current is cleared after circuit breaker (CB) cuts off. In this experiment, it is very difficult to measure the recovery time exactly when the line current is cut off. Thus, load resistor of 134 Ω is used for making small nominal and remaining current of quite a few amperes.

III. TEST RESULT AND DISCUSSION

In order to find the parameters for recovery time, some experiments were performed. The experiments are focusing on the effect with respect to length of CC wire, sort of stabilizer, and cooling condition, respectively.

A. Recovery Time in Cases of Coil 1 and 2

First of all, tests for measuring recovery time in coil 1 and 2 were performed. As it is shown in Table II, the only difference between the two coils is the length of CC wire. In a resistive SFCL, assuming that whole current flows through only the stabilizer when a fault occurs, (1) can be useful [1].

\[ E = \sqrt{\frac{C_v \cdot \Delta T \cdot \rho}{\Delta t}} \]  

(1)

where \( E \) is the electric field intensity, \( C_v \) is heat capacity of the stabilizer, \( t \) is fault period time, \( \rho \) is resistivity of stabilizer, and \( \Delta T \) is temperature increased. Since the stabilizer is fixed in coil 1 and 2, reached temperature at the moment after the fault is up to electric field intensity applied. Fig. 4 shows the recovery time as a function of reached temperature and electric field intensity.
Fig. 4. Recovery time in coil 1 and 2. (a) Recovery time as a function of maximum temperature. (b) Recovery time as a function of electric field intensity.

Fig. 5. Structure of winding.

Fig. 6. Recovery time in coil 1 and 3.

in sample 1 and 2, respectively. In Fig. 4, the result of coil 2 bears a clear resemblance to coil 1.

The most important thing in general design process of resistive SFCL is the maximum temperature reached. Determination of the temperature leads to choosing proper electric field intensity. For example, if the reached temperature is fixed to 200 K, the electric field intensity will be 7.9 V_{rms}/m and the recovery time will be 0.88 seconds.

Consequently, the recovery time depends on the maximum temperature at the end of fault based on the same condition of used wire, material of bobbin, and method of winding. In addition, since the proper electric field intensity can be chosen with respect to the temperature, it is also possible to estimate the recovery time as a function of electric field intensity [5].

In evaluating the data and discussions of this section, it is important to keep in mind that the use of these results is restricted to our exclusive experimental condition: i.e. winding structure is like as Fig. 5 and used wire is 344 type clad with Cu155 stabilizer, and operating conditions are 65 K and 1 atm. Even if these results are limited to thermal condition, the results can be applied to various rating power capacities.

B. Recovery Time in Cases of Coil 1 and Coil 3

The difference between coil 1 and 3 is the stabilizer. Recovery time is the period time from maximum temperature to steady state of 65 K. Since the heat capacity of 344 wire is different from that of 344S wire, there is a significant disparity between the coil 1 and 3.

Fig. 6 shows recovery time with respect to two different stabilizers. For analyzing the difference, it is necessary to estimate effective heat capacity because these wires are composite conductor. The exact analysis based on calculation is beyond the scope of the present paper and will be performed some other time.

In this paper, recovery time of commercial two CC wire, 344 and 344S, is experimentally measured. Fig. 6 can be applied to estimate the recovery time in any scale ratings.

C. Effect of Cooling Condition

For recovery of superconductor, cooling condition is one of dominant parts. Two tests for measuring the recovery time were performed using coil 3 under different cooling condition: one is saturated liquid nitrogen, 77 K and 1 atm, and the other is sub-cooled liquid nitrogen, 65 K and 1 atm. It is shown in Fig. 7 that the recovery time is reduced in the sub-cooled condition.

D. A Case Study on the Estimation of Recovery Time in SFCL

In Republic of Korea, a resistive SFCL rated on 13.2 kV/630 A, distribution voltage level, has been developed. Basic design
of the machine was performed [6]. In view of the recovery time, this research can be applied.

From the basic design, 13.2 kV/630 A SFCL requires 344S CC wire, clad with stainless steel stabilizer, length of 330 m except parallel wires. By fixing the maximum temperature of 300 K, the electric field intensity is 40 V/m and the recovery time is about 4.2 seconds at 65 K, 1 atm.

IV. CONCLUSION

The parameters for recovery time of SFCL in a power system have been obtained. Main results are as follows:

1) The recovery time mainly depends on the maximum temperature at the end of the fault and the material of the wire.
2) In terms of cooling condition, sub-cooled nitrogen has much shorter recovery time than saturated one.
3) It is reasonable to estimate the recovery time by using small-scale experiment.

In the future, the estimation of the recovery time in SFCL based on numerical calculation should be investigated.

REFERENCES