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Over-Voltage Suppression in a Fault Current Limiter by a ZnO Varistor

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***Abstract*—A Superconducting Fault Current Limiter (SCFCL) of the transformer type with a ZnO varistor (Metal Oxide Varistor) in parallel was investigated to determine the effects of the ZnO varistor as an over-voltage suppressor for the SCFCL. A SCFCL of the transformer type, which has an adjustable trigger current level, has been studied. A small model of this type of SCFCL was designed and built with NbTi superconductors. Since a fault current is reduced by its inductive component, a large over-voltage is observed at the beginning of the current limiting event. It is important to suppress the over-voltage to avoid any damages to the power system apparatus. Experimental results on the fault current limiting operation of the SCFCL with ZnO varistor in parallel are shown. It was confirmed that the surge voltage that appears at the terminal of the SCFCL can be successfully suppressed by ZnO varistor. Current limiting and recovery characteristics of the SCFCL with a ZnO varistor are investigated and discussed. The trigger current level of the SCFCL is not affected by the ZnO varistor. The recovery time is a little longer with the ZnO varistor than that without it. Energy dissipation in the ZnO varistor and the SCFCL is discussed.**

***Index Terms*—Over-voltage suppression, superconducting fault current limiter, ZnO varistor.**

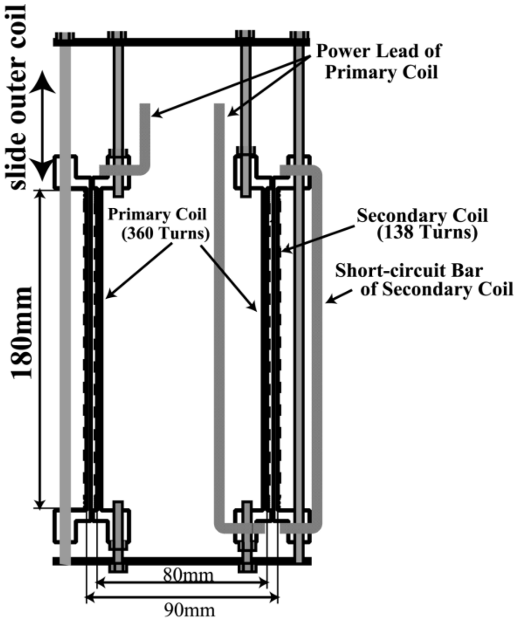

Fig. 1. Schematic configuration of the proposed SCFCL.

I. INTRODUCTION

SUPERCONDUCTING fault current limiters (SCFCLs) are expected to improve reliability and stability of power systems. Many studies have been performed with various types of SCFCLs [1]-[4]. The operating characteristics of SCFCL's have been investigated.

The important specifications of the SCFCL as a power system component are the trigger current level, the limiting impedance and the recovery time. From this point of view, we have proposed an SCFCL of the transformer type with an adjustable trigger current level. A prototype single-phase unit has been designed and built [5]. The fault current is limited by the inductance of the primary coil. Therefore, the amount of energy dissipation in the secondary superconducting wire is small in the prototype SCFCL. The recovery time (the required zero-current time for successful recovery from current limiting mode to waiting mode) is rather short, 450 ms at most [6], [7]. As the next step, a three-phase SCFCL of the proposed type was designed and built [8]. Experimental studies on the power system characteristics of the SCFCL were carried out using artificial transmission lines and a generator [9].

One of the serious problems that has to be solved is an over-voltage that appears across the SCFCL at the beginning of current limiting. It may seriously damage the rest of the power system components. In this paper, the operating characteristics of the SCFCL with a parallel ZnO varistor (which is usually used as an arrester), are studied by use of a trial model. The performance of the ZnO varistor to suppress the over-voltage was investigated by experimental and simulation studies.

II. EXPERIMENT OF OVER-VOLTAGE SUPPRESSION BY A ZnO VARISTOR

A. Prototype SCFCL

The prototype SCFCL unit for three-phase operation was designed and built. It contains three transformer type SCFCLs in one cryostat. We used only one of the SFCFL for this study. The SCFCL consists of two superconducting coils (NbTi wire for AC use) coupled co-axially. The inner (primary) coil will be connected to a power line as shown in Fig. 1. The outer

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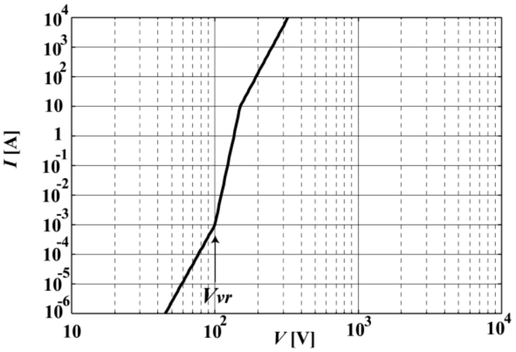


Fig. 2. Voltage-current characteristic model of typical ZnO varistor.

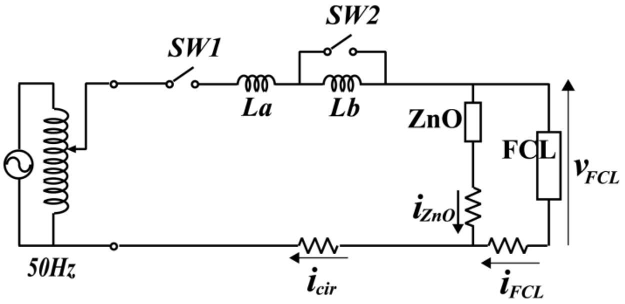


Fig. 3. Experimental circuit for over-voltage suppression across the SCFCL by use of ZnO varistor.

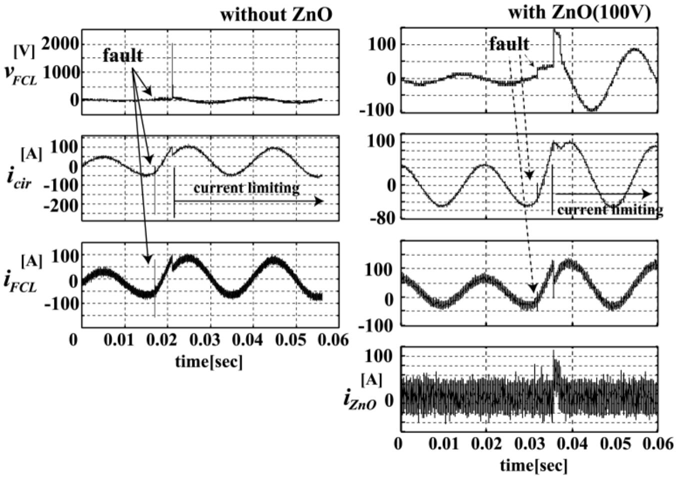


Fig. 4. Experimental result of current limiting operation with and without ZnO varistor. (Varistor voltage = 100 V.)

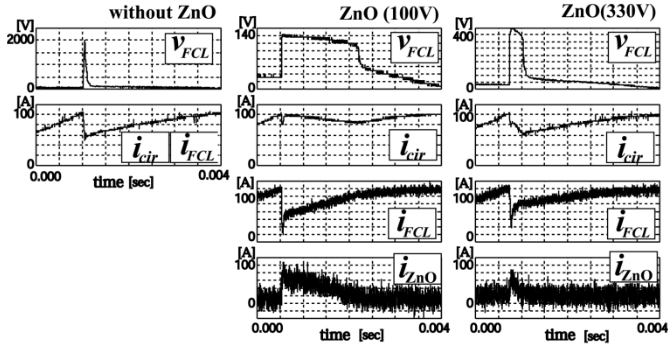


Fig. 5. Experimental result of current limiting operation with and without ZnO varistor. (Enlarged in time: Varistor voltage = 100 V and 330 V.)

(secondary) coil is short-circuited. The secondary coil can be slid a small distance in order to adjust the trigger current level [10]. The primary coil inductance $\boldsymbol{L}_1$, that is the limiting inductance, is 3.82 mH, the secondary coil inductance $\boldsymbol{L}_2$ is 0.69 mH and the mutual inductance $\boldsymbol{M}$ is 1.43 mH. The coils were designed so that the super-normal transition occurs only at the secondary wire, when the fault current flowing through the SCFCL reaches the trigger current level. The fault current is limited by the reactance of the primary coil. The over-voltage appeared across the primary coil because of the sudden change (less than sub-milliseconds) of the reactance of the SCFCL.

B. ZnO Varistor

Metal Oxide Varistors, especially ZnO varistors, are usually introduced into power systems to suppress lightning surge voltages. The typical voltage-current characteristic is shown in Fig. 2. The varistor voltage $\boldsymbol{V}_{vr}$ is defined as the voltage at the 1 mA of current flow, that is, 100 V in this case. When the voltage across the ZnO varistor exceeds $\boldsymbol{V}_{vr}$, the resistance changes to small values drastically. Thus, the over-voltage is clipped to the varistor voltage.

C. Experimental Circuit

The experimental circuit for over-voltage suppression across the SCFCL by use of a ZnO varistor is shown in Fig. 3. Inductances $\boldsymbol{L}_a$ and $\boldsymbol{L}_b$ of reactors $\boldsymbol{a}$ and $\boldsymbol{b}$ are 2.13 mH and 6.40 mH, respectively. The AC voltage source 210 V (50 Hz) is stepped down to 100 V and applied to the test circuit. The magnetically controlled switch $\boldsymbol{SW_1}$ is closed and $\boldsymbol{SW_2}$ is open in the initial state. $\boldsymbol{SW_2}$ is closed to simulate a fault. The phase at the fault occurrence is controlled to be the same in every test case. $\boldsymbol{SW_1}$ is open for a few hundred milliseconds to allow the SCFCL to recover from current limiting mode to waiting mode. A ZnO varistor of several varistor voltages [$\boldsymbol{Vvr} = 100$ V, 200 V, 330 V, 400 V (200 V × 2), and 600 V (200 V × 3)] is installed in parallel to the SCFCL.

The current $\boldsymbol{i}_{\mathrm{ZnO}}$ through the ZnO varistor, the total circuit current $\boldsymbol{i}_{\mathrm{cir}}$, the voltage $\boldsymbol{v}_{\mathrm{FCL}}$ across the FCL and the current $\boldsymbol{i}_{\mathrm{FCL}}$ through the SCFCL are measured by a sampling oscilloscope through differential amplifiers.

III. EXPERIMENTAL RESULTS

A. Over-Voltage Suppression Test

One of the experimental results is shown in Fig. 4. Fig. 4(a) shows the voltage $\boldsymbol{v}_{\mathrm{FCL}}$ across the SCFCL, the currents $\boldsymbol{i}_{\mathrm{CIR}}$ and $\boldsymbol{i}_{FCL}$ without the ZnO varistor at the current limiting operation. $\boldsymbol{v}_{\mathrm{FCL}}$ contains a large over-voltage of 2000 V. The voltage and currents with the ZnO varistor of $\boldsymbol{V}_{vr} = 100$ V are shown in Fig. 4(b). The voltage $\boldsymbol{v}_{\mathrm{FCL}}$ is clipped to about 130 V.

Experimental results of current limiting operation with and without a ZnO varistor, which are enlarged in time, are shown in Fig. 5 (varistor voltage = 100 V and 330 V). It is confirmed that the ZnO varistor does not affect the trigger current level. The current $\boldsymbol{i}_{\mathrm{ZnO}}$ contains noise due to a measuring problem. However, it can be seen that the ZnO current only flows in a certain

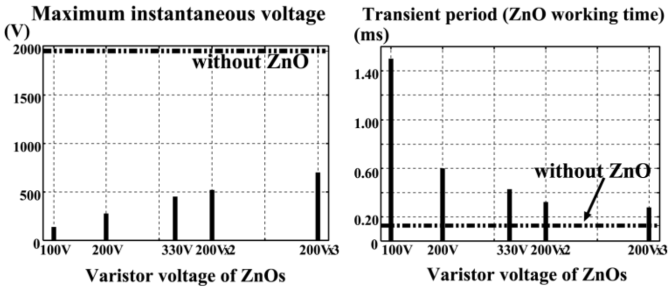


Fig. 6. Maximum instantaneous voltage and transient period for various varistor voltage of ZnO varistors.

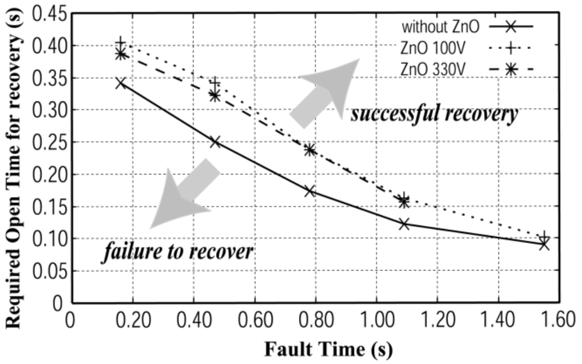


Fig. 7. Recovery time (required open time for successful recovery) versus fault time of SCFCL with and without ZnO varistor. (Varistor voltage $= 100$ V and 330 V.)

short transient period, which depends on the varistor voltage of the ZnO varistor.

B. Maximum Instantaneous Voltage and Transient Period for Varistor Voltage

The maximum instantaneous voltages and transient periods for various varistor voltages are shown in Fig. 6. The transient voltage at the current limiting operation is successfully suppressed to a certain value according to the varistor voltage of ZnO varistor. On the other hand, the transient period becomes longer as the varistor voltage become smaller. However, it has less influence on the current limiting characteristics, that is, the trigger current level and the limiting impedance of the SCFCL.

C. Recovery Time

The recovery time, which is defined as the required zero current time for recovery from the current limiting mode to the waiting mode, has already been measured and reported on for various fault times, in which the current limiting operation continues [7]. It was reported that the proposed SCFCL has a very short recovery time (less than 450 ms) and it decreases as the fault time is longer. The recovery time depends on the temperature of the normal zone of the secondary wire.

TABLE I
ENERGY DISSIPATION AT ZnO DURING THE CURRENT LIMITING OPERATION

varistor voltage(V)	dissipation energy (J)
100	11.3
200	4.5
330	4.3

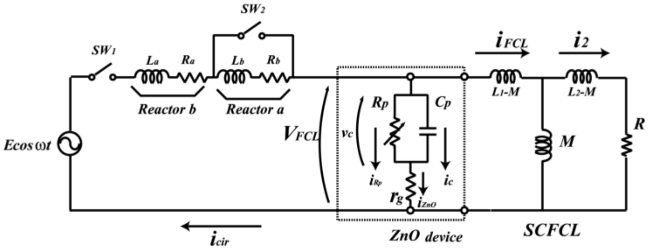


Fig. 8. Equivalent circuit for the simulation.

The recovery times were measured on the SCFCL with a ZnO varistor in parallel to study how the ZnO varistor affects them. The results are shown in Fig. 7. The recovery time becomes longer with the ZnO varistor than without it by several tens of milliseconds for the shorter fault time. For longer fault times, both recovery times decrease and are close to the same value. From these results, it can be assumed that, with the ZnO varistor, the temperature of the normal zone of the secondary wire at the beginning of the current limiting event is a little higher locally than that without the ZnO varistor. After a sufficient fault time, the temperature distribution of the normal zone along the wire is averaged and becomes a flat shape. Therefore, the recovery times with and without a ZnO varistor become close to the same value.

D. Energy Dissipation in ZnO at the Current Limiting Operation

The energy dissipated in the ZnO varistor is roughly calculated from the experimental results and listed in Table I. The energy dissipated in the ZnO varistor becomes larger for smaller varistor voltages. They are sufficiently within the rated capacity of the ZnO varistors.

IV. SIMULATION STUDY

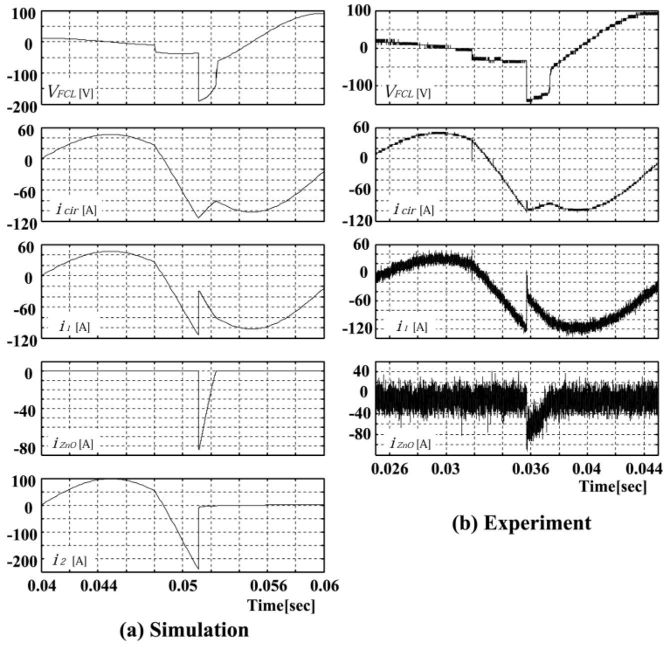
A. Equivalent Circuit

The equivalent circuit for the simulation is shown in Fig. 8. The equivalent circuit of the ZnO varistor is surrounded by a dotted square. Capacitance $\boldsymbol{C}_p$ and series resistance $\boldsymbol{r}_g$ can be neglected for a small ZnO varistor as used in the tests. The nonlinear resistance $\boldsymbol{R}_p$ is modeled as shown in Fig. 2 for varistor voltage 100 V, for example.

The resistance $\boldsymbol{R}$, which is also nonlinear one, depends on the super-normal transition of the secondary superconducting wire. The resistance $\boldsymbol{R}$ is given by use of a simple simulation based on the heat equation. This has already been reported and it was confirmed that the simulation results agree well with the experimental ones [11].

B. Simulation Result

Fig. 9(a) shows one of the simulation results of the current limiting operation with a ZnO varistor of varistor voltage 100 V. Fig. 9(b) shows corresponding experimental results. The FCL voltage and the currents agree well with the experimental results. A basic design can be performed by use of the simulation model. The current $\boldsymbol{i}_2$ of the secondary coil, which is difficult to measure directly, can be evaluated by use of this simulation.



(a) Simulation

(b) Experiment

Fig. 9. Simulation result and corresponding experimental result with ZnO varistor of varistor voltage 100 V.

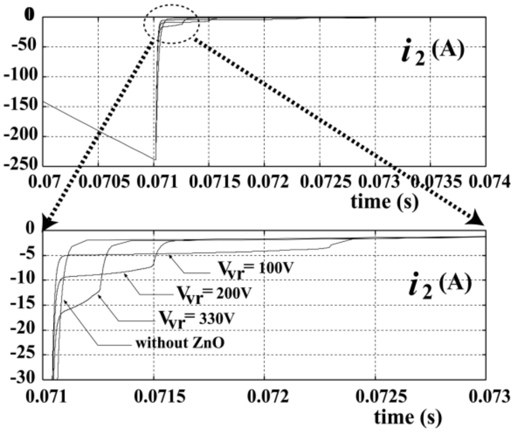


Fig. 10. Magnified wave forms of the secondary coil current at the beginning of the current limitation for various varistor voltages.

C. Secondary Coil Current at the Voltage Suppression

The magnified wave forms of the secondary coil current at the beginning of the current limitation are shown in Fig. 10 for various varistor voltages. During the transient period due to the voltage suppression by the ZnO varistor, the currents i_2 remain at certain values depending on the varistor voltage. This current may affect the temperature rise in the normal zone of the secondary wire at the beginning of the current limiting event.

V. CONCLUSION

The transformer type SCFCL with a ZnO varistor in parallel was investigated experimentally. The over-voltage across the SCFCL that appears at the beginning of the current limiting event is successfully suppressed by use of the ZnO varistor.

The trigger current level and the limiting impedance of the SCFCL were not affected by the ZnO varistor. The recovery time with the ZnO varistor is just a little longer than without it.

The simulation study on the availability of ZnO varistor is carried out according to the experimental system. The performance of ZnO varistor and the secondary coil current at the current limiting operation were confirmed by the simulation results.

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