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Influence of polymer coating on SFCL recovery under load

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Abstract

This paper is a study of recovery under load process of superconducting fault current limiter (SFCL). SFCL consists of five parallel-connected high-temperature superconductor (HTS) tapes additionally stabilized by stainless tape. Previously, HTS was heated by current pulse to simulate a short circuit in a power grid. During the cooling period, the current amplitude decreased to 23% or less of HTS critical current value, which is the simulation of network re-switching. When HTS with a polymer coating is cooled, temperature gradient on thermal insulation layer occurs, that prevents a boiling crisis and improves the heat sink into liquid nitrogen. Two samples are coated with a 30 μm and 50 μm polylactide (PLA) layers, reference sample has no polymer coating on it. Samples with a polymer coating show 3-5 times faster cooling than the reference one.

Keywords: HTS, polylactide, polymer coating, recovery under load, SFCL

1. INTRODUCTION

Utilizing of SFCL in power grids allows to decrease short-circuit currents drastically, enhancing the reliability of the power system and reducing deterioration of electrical equipment. Nowadays, work on SFCL is active engaged around the world, several dozens of devices have been developed and put into trial operation. [1]. Operation of resistive-type SFCL is based on the properties of superconductor: when a current is below critical value, the resistance is equal to zero and the device has no influence on the power grid. In a case of a short circuit, the current exceeds a critical value; SFCL is transited to a resistive state, the current is limited to a nominal value. Then the short circuit ends, HTS cools down and returns into a superconducting state. During a cooldown, SFCL is usually disconnected from network by a circuit breaker.

As a rule, unstable fault occurs on overhead power lines and self-eliminates within a short time. The cause of such faults may be the overlap of the insulation or lashing of the wires. In order to speed up the network re-switching, automatic circuit reclosers (ACRs) are usually used. The widespread implementation of SFCL in power grids requires aligned operation with the relay protection. HTS cooling time should be less than the ARC response time.

Recovery under load allows simplifying SFCL inclusion into the grid. In this case, after short circuit ends, SFCL remains in the network, and the current flowing through it is several times less than HTS critical current value. SFCL with recovery under load capability does not require additional switchgear and inductors; installation footprint also reduces up to 2 times. HTS cools down under the condition of constant heat generation, which imposes stricter requirements on its design.

Most SFCLs are cooled by liquid nitrogen. Process of heat exchange in liquid nitrogen is described in detail in [2, 3]. Dependence of the heat flow and temperature difference between the cooled surface and liquid nitrogen is highly nonlinear. When the temperature difference is above 30 K, boiling mode changes from bubble to film and heat flow drops by more than an order.

During a short circuit limitation, HTS is heated to room temperature or even higher. Evaporated nitrogen forms continuous gas layer around HTS that makes cooling even more difficult.

Application of a thermal insulating coating to surface of HTS allows accelerating the cooling process. Temperature gradient inside the thermal insulation layer is up to 100 K: liquid nitrogen contacts with a colder surface, film boiling is replaced by bubble boiling, and the heat transfer increases significantly.

Cooling process of HTS with teflon and kapton thermal insulating coatings is described in [4, 5], cooling time is reduced by 30-50% compared to bare conductors.

2. EXPERIMENTAL DETAILS

2.1. Samples

Three samples of conductors made of 2nd generation HTS tapes (S-Innovation, Russia) are investigated. The average critical current of HTS tape at 77 K is about 550 A, width - 12 mm, substrate thickness - 100 μm, substrate material - Hastelloy C276, superconductor - $GdBa2Cu3O7$. HTS tapes are sequentially covered with layers of silver (1 μm), copper (1,5 μm), and Pb-Sn solder (5 μm).

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TABLE I
HTS SAMPLES PROPERTIES.

Sample number	Resistance per unit length at 300 K (mOhm/m)	Critical current at 77 K (A)	Polymer coating thickness (μm)
1	23.2	2591	20-40
2	23.4	2605	40-60
3	23	2607	-

Manufacturing of 2nd generation HTS tape is described in detail in [6].

Three samples of five HTS tapes and 80 μm AISI304 stainless steel tape connected in parallel are prepared. Massive copper contacts are soldered to each end of samples (See Fig. 1.). Length of samples is 76 cm (50 cm except contact and termination area), width is 40 mm. For all three samples, critical current at 77 K in the self-field is measured.

For better adhesion, surface of the samples is machined and degreased. Two samples are covered by polylactide (PLA) film. PLA layer thickness is 20 - 40 μm for first sample and 40 - 60 μm for the second, the third sample is reference. Samples properties are presented in Table I.

2.2. Test circuit

In order to measure the recovery time of HTS conductors, a test circuit, based on a powerful step-down transformer, is prepared (See Fig. 2). The primary winding voltage is 380 V, 50 Hz. The secondary winding voltage is selected from 7, 10, 13 or 16 V, by S1 - S4 switches, which corresponds to voltage drop on the 50 cm long samples of 14, 20, 26 or 32 V/m.

In order to simulate a short circuit pulse, one of S1 - S4 switches is selected, after which K1 and K2 switches are closed simultaneously. Current flowing through the sample is determined by active and reactive resistance of connecting buses, test sample and transformer windings, since these values are quite small, prospective current can reach 7 kA (12,5 кA without HTS sample). The transformer internal resistance is not a constant figure and changes when primary winding switches. After 100 ms (or 400 ms)

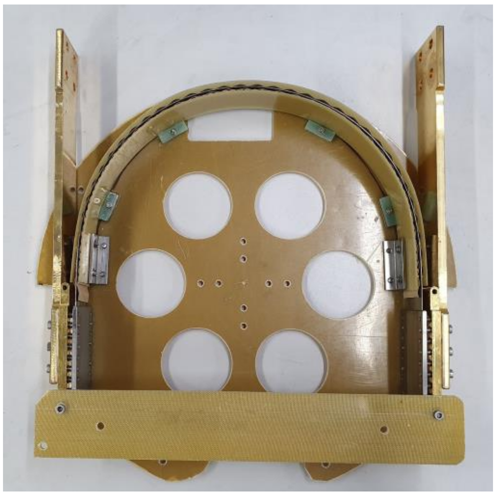

Fig. 1. The sample.

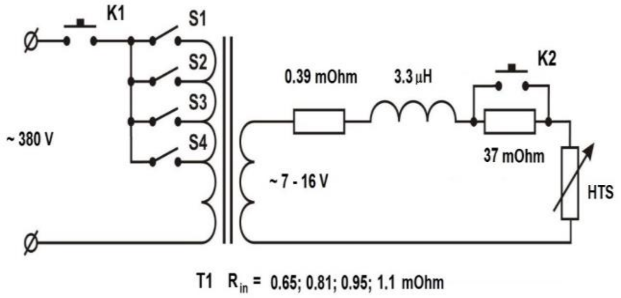

Fig. 2. Test circuit.

from the pulse starts, K2 switch opens, and 37 mOhm non-inductive resistor switches into the circuit, current through the sample is limited to the 185 - 415 A RMS (10 - 23% of HTS critical current), depending on transformer voltage. Several seconds later, recovery of superconducting state occurs (or does not occur). If necessary, for single pulse tests, K2 switch can be hold on in closed state.

Digital timers set duration of K1 and K2 closed time with a 10 ms accuracy. Multi-channel measuring system records digitally the current, measured by current transformer, and voltage on the sample during the pulse test Time dependences of resistance and power are calculated numerically by currents and voltages with percentile filter smoothing.

3. RESULTS

Typical current and voltage time dependencies are presented in Fig. 3. During the first 100 ms (or 400 ms) of pulse, current limitation occurs, heating of HTS is close to adiabatic. Limited prospective current is up to 7 кA, after 100 ms the current drops to 2 kA RMS or less. Next stage is the recovery under load: sample cools, voltage drops gradually, and current increases slightly due to sample resistance decrease. After several seconds, sample returns to superconducting state. Due to sample inductance, a small reactive voltage is observed after the end of recovery process.

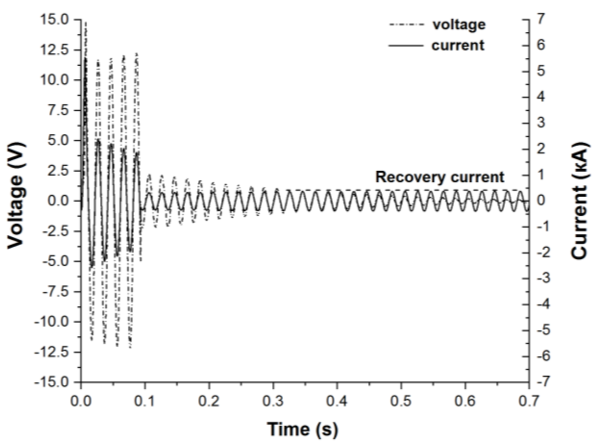

Fig. 3. Current and voltage on HTS during recovery under load test.

Temperature of HTS can be determined from its resistance. For this case, before a start of the pulse tests it is necessary to obtain temperature dependence of reference sample resistance. The sample assembled on a massive aluminum mandrel is cooled by a liquid nitrogen portioned supply in thermal insulated chamber. For convenience, temperature dependence of resistance of HTS was normalized to room temperature value (See Fig. 4).

Reference sample passed pulse tests (single pulse without recovery measurements) at different voltages. To avoid overheating above the melting point of solder, pulse duration at 32 V/m voltage is reduced to 260 ms, all other pulses are 400 ms each. Multiple pulse test has no influence to critical current of sample.

Resistance of HTS is determined from measured voltage and current, sample temperature is determined from known temperature dependence. Time dependences of HTS temperature at the 14, 20, 26, and 32 V/m voltages presented in Fig. 5, a percentile filter utilized for 50 Hz pulsations smoothing.

During the current limitation, samples with and without polymer coating heated up almost the same, since the conditions is close to adiabatic, and contribution of polymer coating to HTS heat capacity is minimal.

With a 100 ms current pulse duration, HTS heated up to a 140 - 250 K, depending on applied voltage.

Effective values of recovery current (at the moment, when sample returns to superconducting state) and temperature of samples at the beginning of recovery process are presented in table II.

TABLE II
RECOVERY CURRENT AND TEMPERATURE OF THE SAMPLE 3 AT VARIOUS VOLTAGES.

Voltage, (V/m)	Recovery current (A_{RMS})	HTS temperature (K)	
		100 ms pulse	400 ms pulse
14	185	140	
20	260	170	295
26	340	210	
32	415	250	

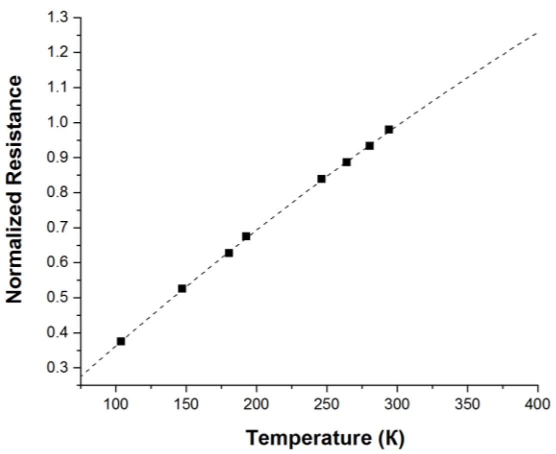

Fig. 4. Normalized temperature dependence of HTS resistance.

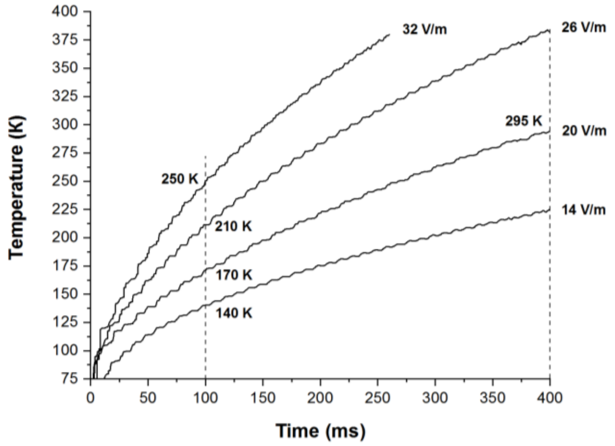

Fig. 5. Time dependences of HTS temperature during current limitation.

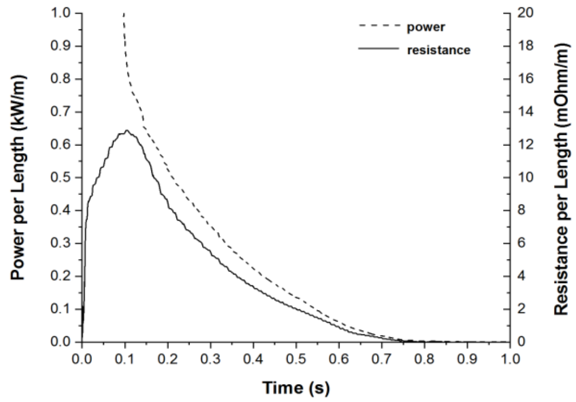

Fig. 6. Resistance and power time dependencies, 40 - 60 µm PLA coating, 20 V/m voltage, 100 ms short circuit.

4. DISCUSSION

Time dependencies of resistance and power dissipated in HTS with a 40 - 60 µm PLA coating during recover under load tests are presented in Fig. 6. Voltage drop on the sample is 20 V/m, short circuit pulse duration is 100 ms. Recovery of superconducting state is determined by zero value of power or resistance. For convenience, data on power during short circuit is excluded from charts, power and resistance values are normalized to HTS length.

Recovery under load measurements were carried out at 100 ms short circuit duration and voltages of 14, 20, 26, 32 V/m for all three samples. At the 32 V/m voltage, only samples with a polymer coating can restore their superconducting state. At the 14, 20 and 26 V/m voltages, reference sample was recovering in 3 - 5 times much slower than samples with polymer coating.

With a 400 ms short circuit duration, samples were tested only at 20 V/m voltage. Samples with a polymer coating were recovering in 2.5 times faster than the reference.

Dependences of recovery time from voltage at the sample are presented in Fig. 7. A sample with a thicker polymer coating recovers faster than a sample with a thinner coating.

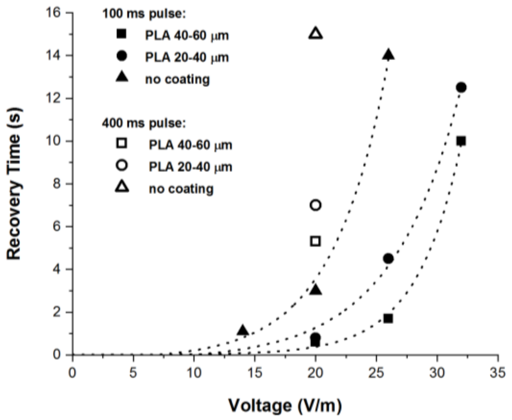

Fig. 7. Dependences of recovery time and voltage on the sample.

After recovery under load tests, all HTS conductor samples passed through cyclic short circuit test: 20 V/m, 400 ms pulse was repeated 50 times with 30 s interval. HTS temperature was up to 300 K, but no signs of critical current degradation were observed for any sample.

5. CONCLUSION

Utilizing polylactide thermal insulated coatings for SFCL can reduce recovery under load interval in 3 - 5 times. Increasing polymer coating thickness from 20 - 40 μm to 40 - 60 μm leads to reducing recovery time.

After 50 short circuit tests, no signs of critical current degradation were observed for any sample.

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