Analysis of FCL effect caused by superconducting DC cables for railway systems

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Abstract. DC superconducting cable that is expected for railway system has been developed in the world, since the introduction effects were expected to energy saving. However, behaviour under unsteady states such as a short circuit accident are not entirely clear, and appropriate method of protection has not been established. Therefore, simulation model of the superconducting cable under direct current system was built and analyzed. Analysis result suggests the superconducting cable has the effect of Fault Current Limited (FCL) and critical current rise was effective method for temperature-rise suppression under unsteady states. Trade-off between cable temperature rise and overcurrent was confirmed.

1. Background

For energy saving effect, the research and development of DC superconducting cables have been advanced in the world. For example, the superconducting cables for the DC railway system have been developed in Japan[1]. By the connecting between substations with DC superconducting cables, the expected effect was not only energy saving by improving utilization rate of regenerative energy but also cost improvement by electric-load leveling among substations.

However, some problems caused by different behaviour from the conventional system must be considered. One of the most important problems is a behaviour under the unsteady states such as a short

circuit accident. By the connecting between substations with substantially zero resistance cables, it is expected that Short-circuit current increases in proportion to the number of substations. In the case of over-current mode, the behaviours of superconducting cables are not entirely clear. As protection method, SFCL and cable protection layer are adopted. Therefore, the initial cost increases, it hinders the superconducting cables.

In this study, the analysis model was built in order to clarify the behaviour of the superconducting cable in the unsteady state.

2. Approach

Thermal and electric simulation models for the superconducting layers and the protective layers were built and evaluated from experiments with various current tests of a high temperature superconducting (HTS) tape. And then, the case that superconducting cables installed in DC railway systems was discussed in greater depth and detail using these correct models.
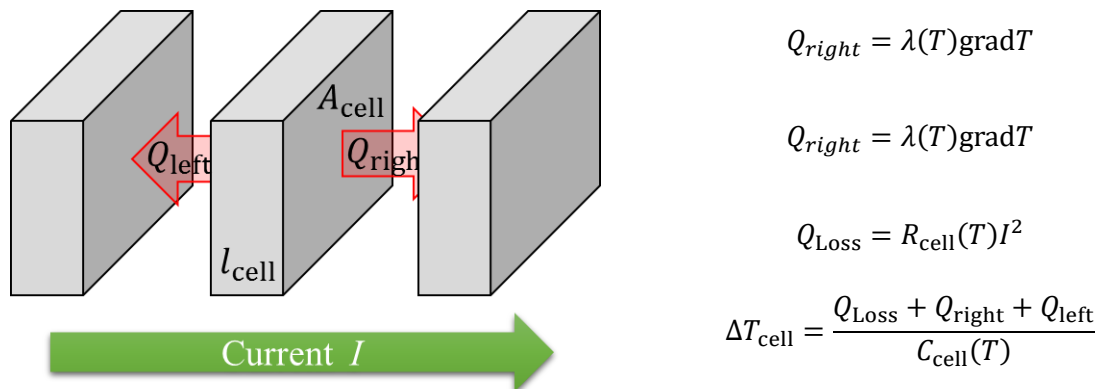
3. Modelling of a HTS tape near the Superconducting to Normal(S/N) transition

The thermal and electrical behaviours of the protective layer constructed by copper are well-known. To simulate superconducting cables, simulation model of a HTS tape near the S/N transition had to be built. A HTS tape was regarded as aggregate of continuously connected micro cells shown in figure 1 and the phenomenon of S/N transition on a HTS tape was simulated as a consequence of superposition of resistance and temperature of each cell which was electrically and thermally connected in series. The cell resistance R_{cell} was separate into three regions, superconducting region, S/N transition region, and normal region as shown in figure 2.
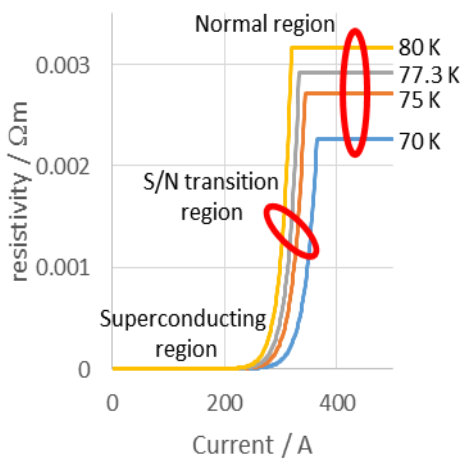
In the superconducting region, the cell resistance was 0 Ω, the energy loss was 0 as well. In the S/N transition region, the cell resistance appeared in accordance with the n value model and changed depending on cell's temperature because of temperature dependence of the measured critical current of HTS tapes. In normal region, measured resistance depending on temperature was adopted as the cells one. The unmeasurable region between the S/N transition region and the normal region was present, so the cell resistance of this region was a value where extrapolation value in the S/N transition region and that in normal region intersect. Energy loss caused by current was represented as heat, so that heat conduction of Q_{Right} and Q_{Left} occured in accordance with the temperature gradient if temperature difference in the adjacent cells existed. As a result, energizing a HTS tape, the cell temperature changed as a function of the electrical loss, heat conduction, and the heat capacity. Model of a HTS tape near the S/N transition was built by calculating repeatedly all cells every certain time. Heat capacity $C_{\mathrm{cell}}(T)$ of HTS tape was calculated from the silver and Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_y$ (BSCCO)[5]. The thermal conductivity $\lambda(T)$ of HTS tape was adopted silver.

Simulation model was evaluated from experiments with various current tests on BSCCO tapes[6]. In one example test, current under adiabatic conditions was sweep 4.5 A/s during 60 seconds was done to a BSCCO

tape with thermocouples every 30 mm. Figure 3 shows a comparison of the experimental and simulation results of a maximum temperature. In simulation, critical current value and position of tape with first fever obtained experimentally was adopted. It became apparent that simulation model can reproduce experiment data of thermal and electrical characteristics, since temperature distribution and range of normal region of simulation gave close agreement with those of experiment.

$$Q_{right} = \lambda(T)\mathrm{grad}T$$

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$$Q_{\mathrm{Loss}} = R_{\mathrm{cell}}(T)I^2$$

$$\Delta T_{\mathrm{cell}} = \frac{Q_{\mathrm{Loss}} + Q_{\mathrm{right}} + Q_{\mathrm{left}}}{C_{\mathrm{cell}}(T)}$$

Figure 1. Simulation model of HTS cables.

Figure 2. Cell resistance model.
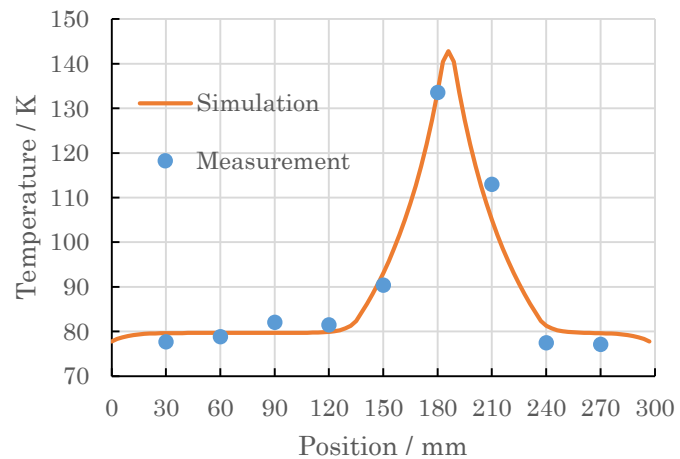
Figure 3. Comparison of the experimental and simulation results on a maximum temperature.

## 4. Analysis model of superconducting cable

Schematic figure of the superconducting cable was shown in figure 4. First of all, the superconducting cable with complicated structures was separate in terms of thermal and electric properties into three parts, superconducting layers, protective layers and other structures. Superconducting layers responsible for conduction in steady state are constructed by HTS tapes, and protective layers intended for the protection of superconducting layers from the overcurrent under unsteady stats are constructed by copper tapes. Other structures which are former, electrically insulating papers was regarded as thermally and electrically insulated, since the analysis time was less than one hundred milliseconds.
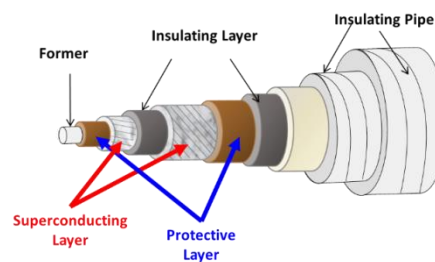
Figure 4.   Schematic figure of the superconducting cable.

5. Analysis of superconducting cable under direct current system

The behaviour of superconducting cables $I_c = 10$ kA at 77.3 K under direct current system was analyzed. The circuit model is shown in figure 5. E is voltage, R is resistance, L is inductance and subscript indicate shows the respective elements.
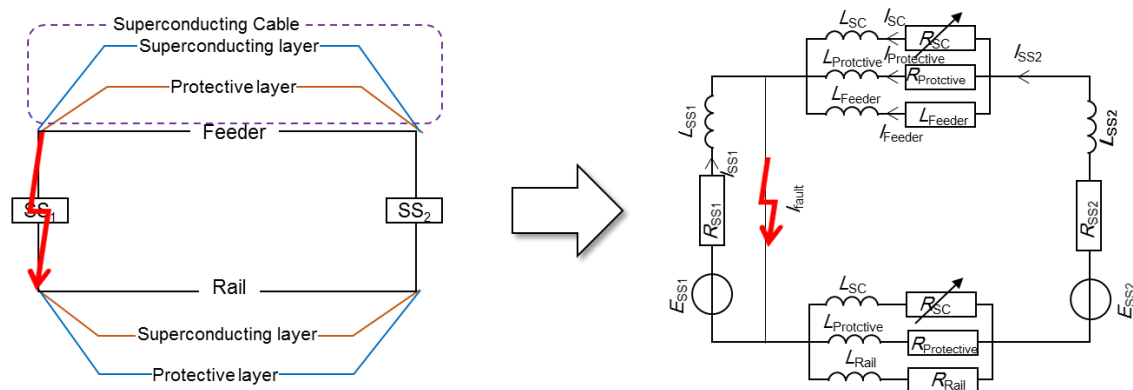
Figure 5.   Simulation model under direct current system.

Superconducting layer resistance R_{SC} was simulated as a variable resistor which assigned successively a value obtained by the HTS tape simulation. Short circuit accident as a stringent situation occurred beneath a substation, the distance between the SubStation(SS)1 and SS2 of 3 km and short circuit remove time of 100 ms. Superconducting cable in counter-flow cooling system has temperature

distribution of 70-75 K (for instant) in accordance with the distance from the cryocoolers[7]. So critical current is different depending on the position. Figure 6 shows analysis results of superconducting cable in DC system with short circuit. Short-circuit current is I_{fault}, current of substation 1 is I_{SS1}, current of superconducting layer is I_{SC}, current of cable protective layer is $I_{Protective}$, and current of feeder is $I_{feeder.}$ I_{SS1} was about 50 kA regardless of the number of substations, since short circuit accident had occurred beneath the substation1. However, I_{SS2} wasn't almost the same value of I_{SS1} (50 kA) and just only 20 kA. This result shows that I_{SC} was over the critical current, so that S/N transition of superconducting layer caused FCL. Time dependence of I_{fault}, I_{SC} and resistance was shown in figure 7 in case of the critical current was infinite and 10 kA. I_{fault} of the conventional (not introduction superconducting cable) system was about 60 kA, since substation 2 was lightly affected. When the critical current was infinite, I_{SC} was about 50 kA and I_{falut} was 100 kA, more specifically, I_{fault} was proportional to the number of substations. This result was the worst type of short circuit accident.
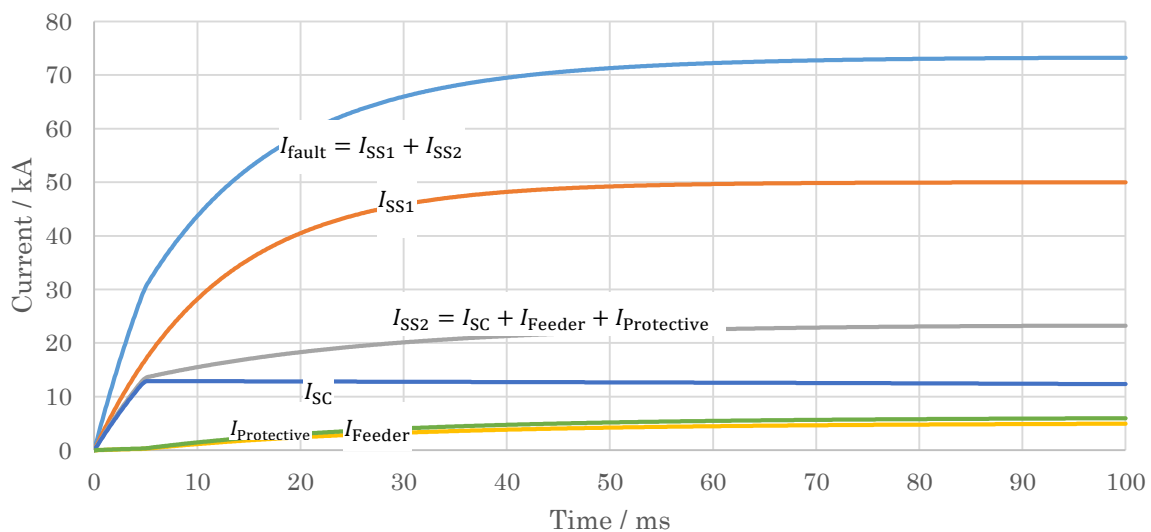

**Figure 6.** Analysis results of superconducting cable in DC system with short circuit.

However, the real superconducting cable has finite critical current, so that S/N transition appeared before 50 kA in I_{SC}. In figure 7, R_{SC} rise just after over the critical current flew, so that FCL appeared. Limited I_{SC} by FCL caused temporary decrease of R_{SC} and after that, increasing temperature, rising the resistance. much smaller than that of cable distance. In other words, S/N transition had a significant influence only on the current. From the steady state of the figure 7, the critical current depended on the position in accordance with the temperature of the position. As a result, S/N transition appeared from the maximum temperature point where critical current was minimum. After the FCL, the residuary area was kept superconducting state, since the current didn't reach critical current. The fact that temperature rise didn't occur in all area agree well with the result of I_C = 10 kA in the figure 8. Heat conduction of

the cell was practically negligible, since the order of cross-sectional area was

These results suggest that short current in superconducting cable under direct current system is suppressed by S/N transition.
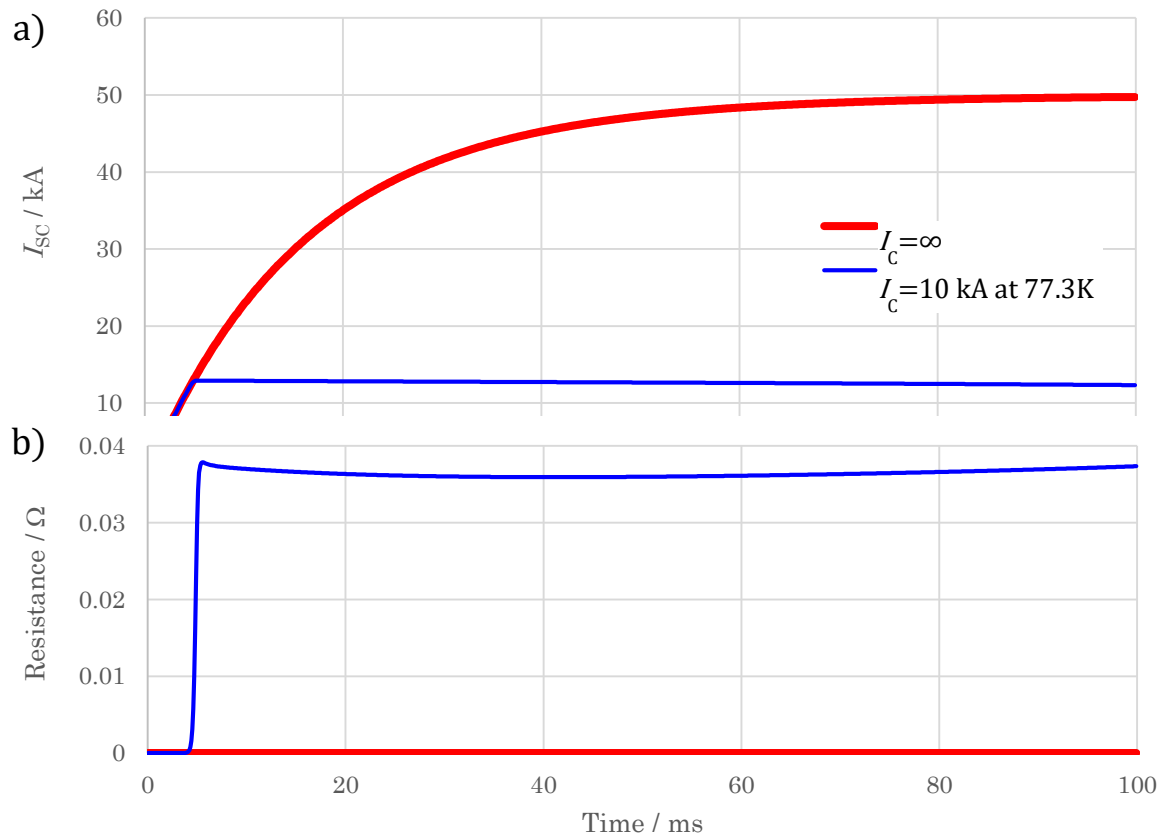
Figure 7.   Time dependence of a) I_{fault}, I_{SC} and b) resistance of superconducting layer.
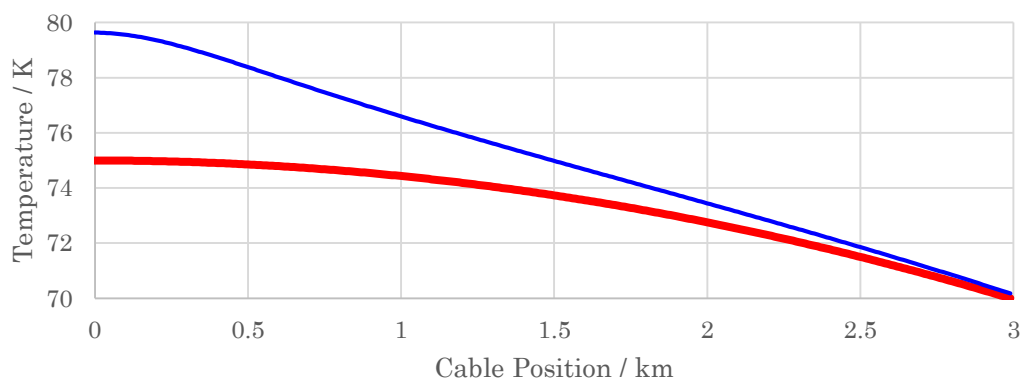

Figure 8.   Temperature distribution of superconducting layer on 100 ms.

6. Relationship between critical current and overcurrent

The cases of various critical current over 10 kA of superconducting cable were considered. Figure 9 shows critical current dependence at 70 K of maximum I_{SC} and cable temperature. The more critical current is increased, the more the maximum temperature is decreased. This tendency was explained by the fact that fever time was short and FCL effect happened in retard according to critical current increase.

The critical current and the maximum I_{SC} were increased almost in proportion but the overcurrent was saturated before the value reached the critical current. In fact, when the overcurrent was saturated, cable temperature wasn't changed, since the S/N transition wasn't appeared. As a result, cable temperature rise and overcurrent were trade-off.
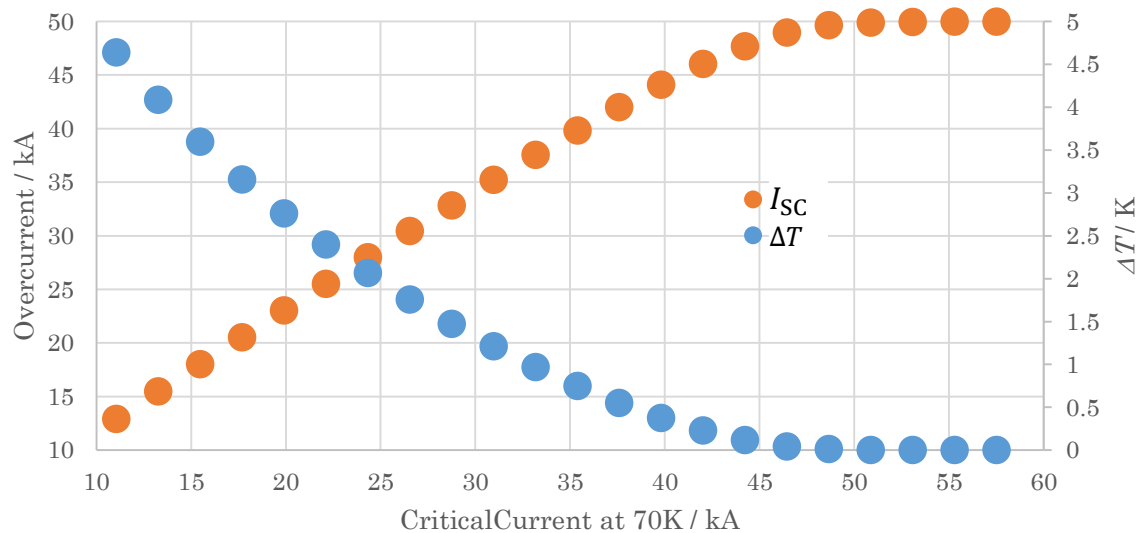
Figure 9.   Critical current dependence at 70 K of maximum I_{SC} and cable temperature.

7. Conclusion

The analysis model was built for the purpose of making clear superconducting cable behaviour under unsteady states. At first, thermal and electric simulation models for the superconducting layers were built and evaluated from experiments with various current tests of a HTS tape. Further, superconducting cable behaviours under unsteady states were analyzed by the model. Analysis result suggest that superconducting cable has the effect of FCL. Therefore, the value of FCL overcurrent was lower than that of the value of zero resistance connection overcurrent. And it was clarified that critical current rise was the effective method for temperature-rise suppression under unsteady states. However, critical current rise not only increases the cost of itself, but also increases the overcurrent. Furthermore, when the overcurrent is increased, cost of peripheral equipment which has to need to increase current capacity rises. Therefore, proper protection design has to be adopted in the superconducting cable. This analysis model plays important role.

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