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Superconducting Power Cable Application in DC Electric Railway Systems

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***Abstract*—A superconducting power cable is a prospective application of high-temperature superconductors. Although power cables using Bi2223 or YBCO wires have been developed in the world so far mainly for utility grid application, we focus attention on railway application of a superconducting power cable. We have studied how to introduce superconducting power cables effectively and economically to a DC electric railway. Numerical analysis models based on the MATLAB-Simulink are constructed for a DC electric feeder system of singe- and double-track railways. Tractive force and train resistance characteristics are modeled there. Energy saving by the superconducting power cable is investigated with the influences of the number of substations, the train operation interval, etc. taken into account. The results show that the superconducting power cables can improve regeneration rate and system energy saving, and reduce the substation capacity very effectively. It will be also an advantage that if the transportation capacity of a railway line needs to be increased, the introduction of superconducting cables could achieve it without changing the existing substations along the line.**

***Index Terms*— railway, regeneration, substation, superconducting power cable.**

I. INTRODUCTION

POWER CABLES using high-temperature superconductors have been developed in the U.S.A., Japan, Korea, China, and Europe since the 1990s [1-3]. Grid-connected demonstrations and system reliability evaluation tests of superconducting power cables of several hundred meters have been carried out. For example, in Japan, a 250 m, 66 kV, 200 MVA class, three-core superconducting power cable using Bi2223 wires has been fabricated and its grid-connected tests will be carried out within 2012 [4]. A 50 m, 275 kV, 3 kA, single-core superconducting power cable using YBCO wires has been also fabricated and will be tested within 2012 [5]. Most of the superconducting power cable projects involved AC cables. Recently, DC superconducting power cables have attracted attention and now there are some projects for DC superconducting power cables [6-8]. Most of superconducting power cable projects have so far been made for utility grid application, and recently their industrial applications also attract attention. We focus attention on railway application of a superconducting power cable [9-12].

Electric railway is an energy efficient and environmentally-friendly transportation system. However, on the electric railway there is still an increasing demand to improve energy efficiency with the growing concern for environmental issues [13]. Another typical issue is how to respond to increasing number of passengers or to speed-up of trains while the existing substations are still used, for example, because of a limited space for the substations. We have studied the feasibility of applying superconducting power cables to DC electric railway systems. Superconducting technology would be effective for novel design and efficient operation of next-generation DC electric railway systems, especially for their substantial energy saving and an efficient use of substations along the line.

In DC electric railways the most common voltages are 600 V, 750 V, 1500 V, and 3 kV, which are much lower than the voltages of AC electric railways (15 kV, 25 kV, etc.). In Japan, DC electric railway systems are widely used including in metropolitan areas. However, they have some problems such as relatively low voltage, regeneration cancelation, energy losses, etc. A regenerative brake is an electric brake, and it transforms kinetic energy to electric energy using propulsion motors in a regenerative mode. Advantages of the regenerative brake are energy saving, reduced wheel wear, improved riding comfort, reduced temperature rise in tunnels, etc. However, when a powering train does not exist near a braking train or the operation conditions are not met, the regeneration is canceled [14,15]. Introduction of a superconducting power cable can be a solution to the above mentioned issues.

This paper reports the results of numerical analyses using MATLAB-Simulink-based models for a DC electric feeder system of singe- and double-track railways. The models take into account tractive force and train resistance characteristics. From the analysis results such as currents and voltages in a modeled electric circuit, energy saving by the superconducting power cable is evaluated, and the regeneration rate and the required substation capacity are calculated. Influences of the number of substations, the train operation interval, etc. are also examined.

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II. ANALYSIS MODEL AND METHOD

A. *Model Line*

In numerical analysis of power feeding systems a model line shown in Fig. 1 was assumed. The total length of the line is 26.5 km. There are 24 stations and five substations (SS) along the line. Cases of four substations and three substations were also analyzed. Electric current flows from the substations through the feeder to a train and returns through the rail to the substations. A superconducting power cable is placed parallel to the feeder and connected to all the substations as shown in Fig. 1. The length of the superconducting cable is 22.2 km. Key parameters of the model line are summarized in Table I.

The analysis model line with substations, trains and superconducting cables was built as an electric circuit. MATLAB-Simulink was used to analyze the model [11,12].

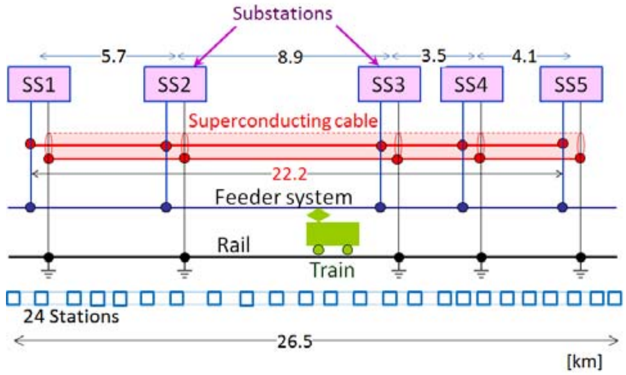

Fig. 1. Analysis model line.

TABLE I
MODEL LINE PARAMETERS

Total length	26.5 km
Number of stations	24
Number of substations	5, 4, 3
No-load output voltage of substations	1590 V
Superconducting cable length	22.2 km

B. *Train Operation*

Fig. 2 shows a set of train operation curves assumed in the analysis for a train operation interval of five minutes. Each curve indicates a trajectory of an operated train. Locations of twenty-four stations and five substations are also shown. A periodic operation of trains with a period of five minutes was assumed in the analysis, and therefore the analysis for five minutes is enough for evaluation of the system. In the analysis two track conditions were considered; one was a single-track case and the other was a double-track case. The single-track case included the case where the route was a double track but their electric circuits were independent of each other.

C. *Tractive Force and Power Characteristics*

Tractive effort characteristics of a train have three regions as shown in Fig. 3: constant tractive force, constant power, and characteristic regions [12,14-16]. In the analysis the tractive force curve shown in Fig. 3 was used.

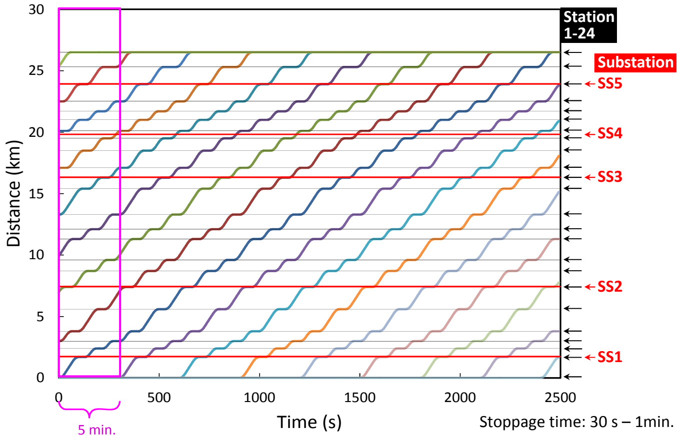

Fig. 2. Train operation curves (5 min. interval case).

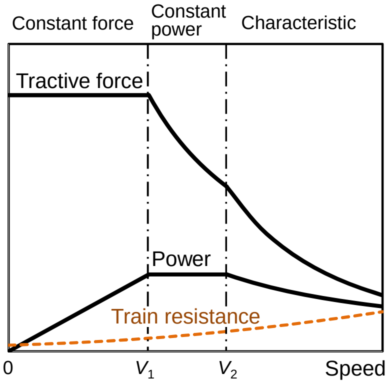

Fig. 3. Tractive force, train power, and train resistance.

A train resistance is assumed to be as follows:

$$9.8\left[(1.32+0.0164v)W+\{0.028+0.0078(n-1)\}v^{2}\right]\ \text{(N)} \qquad (1)$$

where v is the speed (km/h), W is the train weight (t), and n is the number of cars. The train resistance curve is also shown in Fig. 3. Fig. 4 shows the curves of tractive and braking forces of a train running from one station to an adjacent station with and without the train resistance taken into account. At higher speeds a tractive force decreases a little and a braking force increases when the train resistance is taken into account. In the present line conditions a coasting operation period is short, so the train resistance is ignored during the coasting operation for simplification of the analysis model.

D. *Acceleration, Power and Speed Curves*

Fig. 5 shows the acceleration and speed curves of the train that starts from the first station at 0 s. The acceleration and the deceleration are 0.97 m/s^2 (3.5 km/h/s) and the maximum speed is 25 m/s (90 km/h). If the distance between adjacent stations is so short, the speed does not reach 25 m/s.

Fig. 6 shows the distance, acceleration, power and speed curves of a train running from a station to an adjacent station. The acceleration curve is almost the same as that in Fig. 6. The train resistance lengthens the acceleration time and shortens the deceleration time.

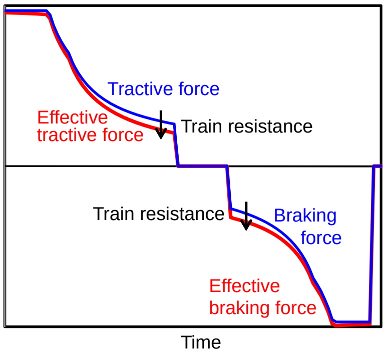

Fig. 4. Effective tractive and braking forces.

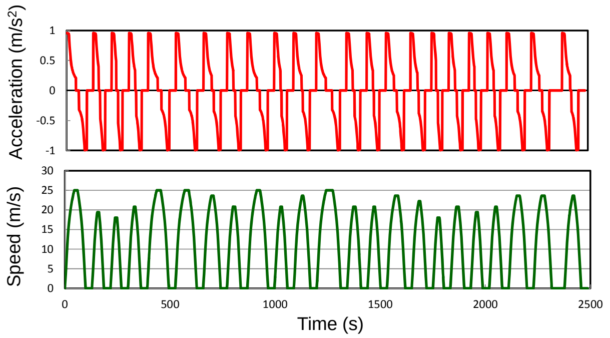

Fig. 5. Acceleration and speed curves of a train.

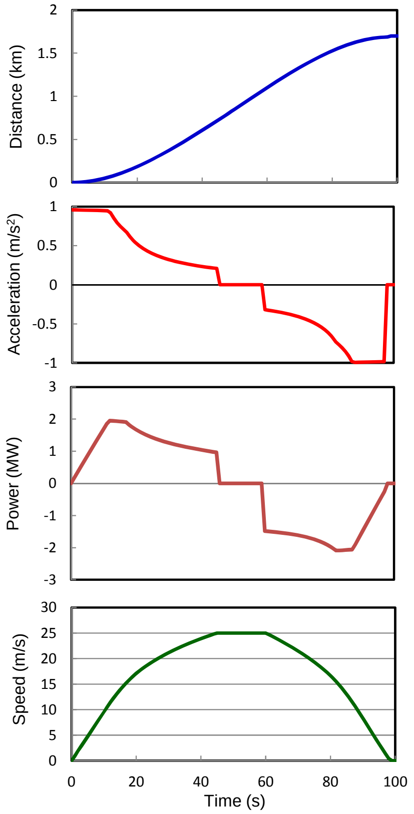

Fig. 6. Distance, acceleration, power and speed curves of a train running between two adjacent stations.

E. Analysis Conditions

Table II indicates the train operation conditions. Speeds V_1 and V_2 are shown in Fig. 3. When the voltages of braking trains become higher and reach the upper-limit of the train voltage V_{UL} (=1800 V), then the regeneration cancellation occurs. Table III indicates the assumptions of cooling component characteristics. For a superconducting cable system, the heat load along the cable of 1 kW/km, the heat load at the cable terminals of 0.25 kW/terminal, COP of the cooling system of 0.1 were assumed.

Influences of the train operation interval and the number of substations were also studied. The number of substations was three (SS1, SS3 and SS5), four (SS1, SS2, SS3 and SS5) and five (all substations). The default case has a five-minute interval and five substations.

TABLE II
TRAIN OPERATION CONDITIONS

Acceleration/Deceleration	0.97 m/s^2 (3.5 km/h/s)
Max. speed	25 m/s (90 km/h)
Max. power	2000 kW
Speed V_1	11.1 m/s (40 km/h)
Speed V_2	15.3 m/s (55 km/h)
Upper limit of train voltage V_{UL}	1800 V

TABLE III
ASSUMPTIONS OF COOLING COMPONENT CHARACTERISTICS

Heat load at cable	1 kW/km
Heat load at lead	0.25 kW/lead
COP of cooling system	0.1

III. ANALYSIS RESULTS

A. General Performance

The trains are operated to make most use of regenerative brake, and if the regeneration is not enough, then a mechanical brake is used. Without a superconducting cable the voltages of the braking trains become higher, and in some cases the voltage of a braking train reaches the upper-limit of the train voltage. It causes the regeneration cancelation. When a superconducting cable is installed, the change in the voltage is reduced and the regenerative brake is more effectively used. The regeneration cancelation occurs also when there are no powering trains that can receive the regeneration power.

Electric power is supplied from the substations to the feeding system, and then to the trains. Some of kinetic energy of the train is recovered by regenerative brake to the power feeding system, but the rest wastes into the heat by the mechanical brake. There is also Joule loss in the components of the system. Introduction of superconducting cables would bring the reduced Joule loss and improved regenerative brake, and also reduced maintenance of mechanical brake. In addition, the reduction of the number of substations or the improvement of redundancy and reliability of the substations could be expected. On the other hand, cooling power is needed for a cryogenic system with heat load along the superconducting cable and at the cable leads.

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B. Fundamental Cases

Table IV summarizes the analysis results for the cases with a single track, five substations, and 5-min. train operation interval. Since the 5-min. periodic operation of trains was assumed, energy flow for five minutes was evaluated. The number of cable leads is ten. By introducing the superconducting cable, the regeneration power increases by 82 MJ and the regeneration rate becomes about 7% higher, although the cooling power of 74 MJ is needed. As a result, the total input power of the substations decreases by 21 MJ for five minutes. The maximum current of substations decreases drastically. It becomes about 64% of that for the conventional system without a superconducting cable.

Table V shows the results for the double-track cases. Since the number of trains and the total acceleration energy increase, the substation input and the regeneration energy become larger than those for the single-track cases. It should be noted that the regeneration rate for the superconducting single-track case is higher than that for the conventional double-type case, and also that the maximum substation current for the superconducting double-track case is smaller than that for the conventional single-type case. The introduction of superconducting cable is very effective to increase the regeneration rate and to decrease the maximum substation current. When the single track needs to be changed into the double track, the existing substations can be still used in terms of the maximum substation current by introducing a superconducting cable connecting the substations.

TABLE IV
ANALYSIS RESULTS FOR SINGLE TRACK (5 SUBSTATIONS, 5-MIN. INTERVAL)

Type	Conventional	Superconducting
Tack	single	
Acceleration energy (MJ)*	1144	
Superconducting cable	without	with
Substation input (MJ)*	582	561
feeder input (MJ)*	582	487
cooling energy (MJ)*	0	74
Regeneration energy (MJ)*	635	717
Losses (MJ)*	73	60
Max. substation current (kA)	2.1	1.3
Regeneration rate (%)	56	63

* Energies for five minutes

TABLE V
ANALYSIS RESULTS FOR DOUBLE TRACK (5 SUBSTATIONS, 5-MIN. INTERVAL)

Type	Conventional	Superconducting
Tack	double	
Acceleration energy (MJ)*	2288	
Superconducting cable	without	with
Substation input (MJ)*	1103	927
feeder input (MJ)*	1103	853
cooling energy (MJ)*	0	74
Regeneration energy (MJ)*	1317	1563
Losses (MJ)*	132	128
Max. substation current (kA)	2.8	1.8
Regeneration rate (%)	58	68

* Energies for five minutes

Table VI shows the results for the cases where more acceleration energy is needed; for example, a train has more cars. Compared with the results shown in Tables IV and V, the regeneration rate becomes slightly lower in the conventional cases. However, it becomes higher in the superconducting cases. When the transportation capacity needs to be increased by increasing the number of cars, the existing substations can be still used by introducing a superconducting cable.

TABLE VI
ANALYSIS RESULTS FOR LONGER TRAINS (5 SUBSTATIONS, 5-MIN. INTERVAL)

Tack	single		double	
Acceleration (MJ)*	1550		3100	
Superconducting cable	without	with	without	with
Substation input (MJ)*	843	732	1576	1231
Regeneration (MJ)*	840	1012	1767	2190
Max. substation current (kA)	3.1	1.9	4.0	2.5
Regeneration (%)	54	65	57	71

* Energies for five minutes

C. Influence of the Number of Substations

Fig. 7 shows the influence of the number of substations on the maximum substation current. The open symbols indicate the conventional cases without a superconducting cable. Only the 5-substation cases are shown for the conventional cases. The solid symbols indicate the cases with superconducting cables. Although the energies are not so much influenced by the number of substations, the maximum substation current becomes higher with the increasing number of substations. Even so, it is still lower in the superconducting cable system with three substations than that of the conventional system with five substations both for the single- and double-track cases. The introduction of superconducting cables would make it possible to reduce the number of substations or to improve the redundancy of the substations.

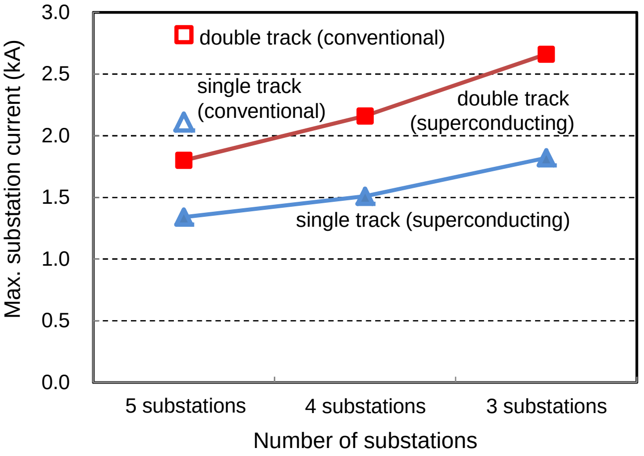

Fig. 7. Influence of the number of substations on substation current (Train operation interval: five minutes).

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D. *Influence of Train Operation Interval*

Fig. 8 shows the influence of train operation interval on the maximum substation current and the regeneration rate. A shorter interval is more effective for energy saving, but the maximum substation current and the regeneration rate are more sensitive to the train operation conditions in the conventional cases when the interval is shorter than five minutes. In the two-minute interval case, for example, there are two solid triangle symbols in Fig. 8. They were obtained on different conditions of time shift between the two directional train operation patterns. The introduction of superconducting cable has still large effect even for two-minute interval case because regenerative energy can be transmitted to a more distant accelerating train through the superconducting cable. It indicates that by introducing the superconducting cables the train operation interval can be shortened from ten minutes to three minutes without changing the current capacity of the substations.

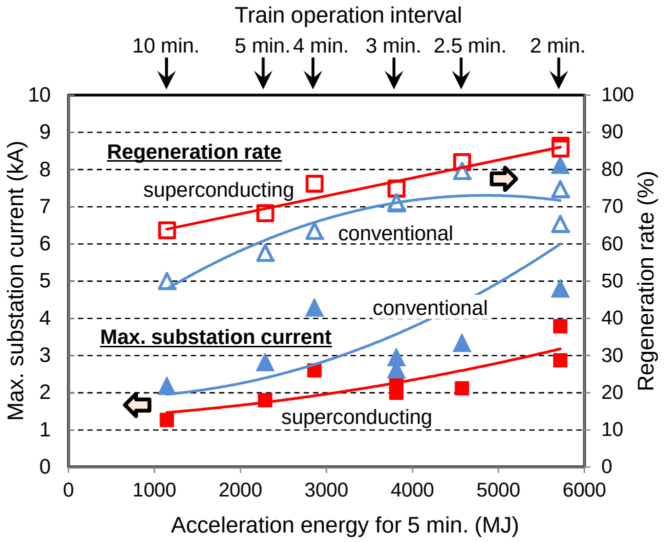

Fig. 8. Influence of train operation intervals on the maximum substation current and the regeneration rate (Double track, five substations).

IV. CONCLUSIONS

We studied the feasibility of applying superconducting power cables to DC electric feeder systems of singe- and double-track railways. The MATLAB-Simulink models based on the electric circuit models were used in the numerical analysis, taking into account the tractive force and train resistance characteristics. From the calculated voltages and currents of the circuit, the regeneration rate and energy losses were estimated. The results showed that the introduction of superconducting power cables increased the regeneration rate and improved the energy saving. It could reduce the substation capacity, and/or improve the redundancy of the substations. Therefore, if the transportation capacity of a railway line needs to be increased, the introduction of superconducting cables could achieve it without changing the existing substations.

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