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Use of Superconducting Power Cables for Fault Current Analysis

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***Abstract*: -- A superconducting power cable is an application of high-temperature superconductors. Even though superconducting power cables have been developed worldwide for the grid application here the focus is on railway application. Introducing superconducting power cables effectively and economically to a DC electric railway is suggested. The aim is to upgrade the feeder of the overhead contact line system using superconducting power cables. The fault current of dc electric railway feeding systems using superconducting power cables is analyzed. MATLAB Simulink electric circuit models based on a model railway line are constructed for numerical analysis of short-circuits and grounding faults. Influence of introducing superconducting power cables under different fault conditions is analyzed.**

I. INTRODUCTION

Power cables using high-temperature superconductors have been developed in the U.S.A., Japan, Korea, China, and Europe since the 1990s. 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. 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.Recently, DC superconducting power cables have attracted attention and now there are some projects for DC superconducting power cables. Most of superconducting power cable projects have 0 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. 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. 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 cancelled. Introduction of a superconducting power cable can be a solution to the above-mentioned issues. The result of numerical analysis using MATLAB-Simulink-based model for a DC electric feeder system of single- and double-track railways will be studied. The models consider tractive force and train resistance characteristics. From the analysis results such as currents and voltages in a modelled 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. Electric railway is widely utilized all over the world for its high energy efficiency and low pollution. Compared to AC electrocution, the DC electric feeding system has a lower voltage, which means smaller space requests and simpler railcars, thus it is suitable for urban railways with dense train traffic. Meanwhile, the low voltage causes a large current, which leads to relatively high voltage drops and energy losses along the feeding system. Then more substations are needed along the line to share the loads and reduce the losses. Furthermore, another issue is regeneration cancelation. Regeneration power is produced by a regenerative brake, which is an electric brake. The regenerated energy can be transmitted via the feeder to the accelerating trains so as to improve energy efficiency, reduce wheel wear, etc. However, if there are no accelerating trains near a regenerating train or the operation conditions are not met, the regeneration is canceled. Under these circumstances, introducing superconducting power cables is now considered as a solution to these problems. It is a solution to suppress the voltage fluctuation along the feeder by laying superconducting power cables along the railway and connecting them to the conventional DC feeding system. This allows trains to function their regenerative brakes more,thus improving energy efficiency. Moreover, the superconducting power cables could also prevent electrical loads from concentrating on a single substation. With fewer loads, each substation can be designed with less capacity, which leads to lower cost for the design of the DC electric feeding system. On the other hand, introducing superconducting power cables has its own defects that it may introduce much higher fault current when a short-circuit fault or a grounding fault occurs. Compared to feeder lines, the superconducting cables connect the substations with negligible resistance, which makes it much easier for fault current to flow from other substations to the fault point, and consequently multiply the value of fault current. In order to protect the superconducting cables, it is important to figure out the precise value of the fault current within the whole system.

II. POWER CABLES TO DC ELECTRIC RAILWAY SYSTEMS

After the first high-temperature superconductor (HTS) was discovered in 1986, researches and developments of HTS materials and their applications have been performed. Power cables using HTS materials have been developed and tested in the U. S. A., Japan, Korea, China, Europe, etc. Most of the superconducting power cable projects are based on AC application. However, DC superconducting power cables have recently drawn attention in the fields of electric power systems and industry applications including railways. As introduced in section I, the DC electric railway feeding system has some drawbacks and the superconducting power cables are considered to be a solution to the problems.

Application of superconducting power cables to DC electric railway systems has been investigated by both experiments and simulations. In Japan, the Railway Technical Research Institute has designed, developed, and tested prototype DC superconducting power cables and peripheral equipment for cooling, etc. The highest critical current of the DC superconducting cables that the RTRI developed was 10 kA class at 77 K. According to the results of various tests and demonstration, the performance and reliability of the developed DC superconducting power cable systems has been successfully verified.

A number of numerical analysis studies also have been performed to evaluate the effects of introducing superconducting power cables. In these studies, different analysis models were built base on different model lines in various conditions. The analysis results showed that the introduction of superconducting power cables could improve the utilization of regenerative brake and the energy saving effect, even considering the heat loads of superconducting power cables and their terminals together with the cryogenic efficiency. Moreover, it could also reduce the substation capacity, and/or improve the redundancy of the substations. After introducing superconducting power cables, the loads are distributed among the substations, thus the maximum output current and power of substations decrease. Therefore, if the transportation capacity of a railway line needs to be increased, the introduction of superconducting power cables can achieve it without changing the existing substations.

Furthermore, the effect on the reduction of voltage drop was also studied Compared with other means as introduction of a new substation, an energy storage system, etc., the introduction of superconducting power cables had a similar performance on reducing the voltage drop, meanwhile had lower cost requirements and provided many other advantages. It was also shown that the combination with superconducting power cables may enhance the effect of introducing other devices such as SMES.

III. ANALYSIS METHOD

In order to study the fault current in DC electric railway feeding systems, we utilized a model railway line with superconducting power cables . An electric circuit model for transient analysis was built based on the line, which consists of substations, feeders, rails, trains, and superconducting power cables.

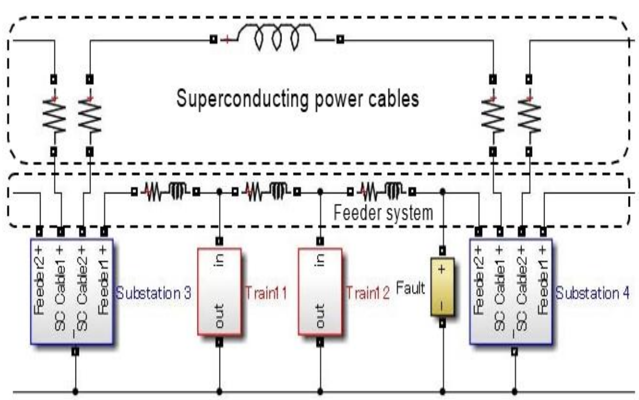

Fig. 1. Electric circuit model of DC feeding system.

The fault current on the circuit was analyzed using MATLAB-Simulink software. Fig. 1 shows the schematic view of the electric circuit model for fault current analysis. This circuit model mainly consists of five parts: substations, a feeder

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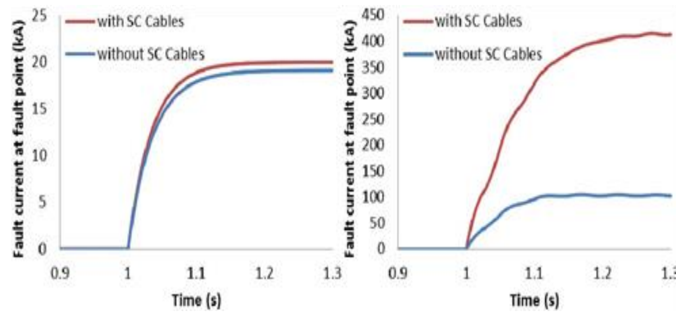
system, trains, superconducting power cables, and a fault point. In the substation model, a simplified grid model and a substation electric circuit are contained. . The substation is assumed to have two three-phase transformers in parallel, a 12-pulse rectifier, and a DC reactor.The train model is set to consume or regenerate certain amount of electric power, which depends on the preset train operation pattern. The feeder system contains feeders, trolley wires, rails, etc., and it is simplified as one lumped parameter in the model. The superconducting power cables connecting substations' output buses have zero-resistance but certain small inductances. In addition, the resistance of cable terminals cannot be ignored.

IV. ANALYSIS OF FAULT CURRENT

To study the fault current in DC electric railway feeding systems, we will utilize a model railway line with superconducting power cables. An electric circuit model for transient analysis will be build based on the line, which consists of substations, feeders, rails, trains, and superconducting power cables. The fault current on the circuit will be analyze using MATLAB-Simulink software. We will analyze fault current under various fault condition using conventional dc cables and superconducting power cables in following three cases.

A. Influence of introducing superconducting power cables on fault current in different faults.

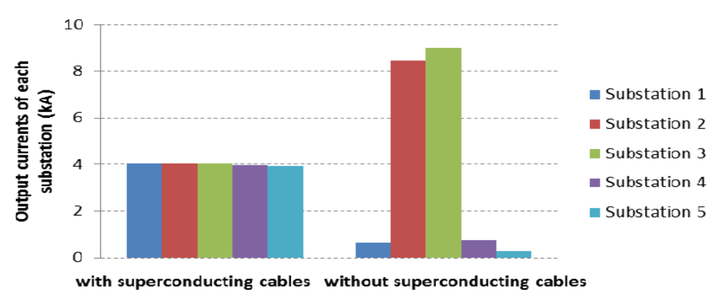
Due to the negligible resistance of superconducting cables, the substations' output buses are connected with very low resistance, which makes the fault current mainly flow through the superconducting power cables. This also means that the fault point is connected to all the substations with less impedance. However, when the fault point is far away from substations, the impedance of feeding system is introduced, thus the effect of superconducting power cables is suppressed. Consequently, the values of fault currents with and without superconducting power cables get closer when the fault point goes farther away from the substations. Even though the fault current at the fault point seems close, the output currents of each substation are different. While the fault current without superconducting power cables is mainly provided by substations, the introduction of superconducting cables distributes the fault current among the substations. The same situation is also observed in other cases.



(a) (b)

Fig. 2. Fault current at the short-circuit fault point between feeder line and rails (a) close to a substation; (b) at the middle of two adjacent substations

Different short-circuit faults and grounding faults were simulated to figure out the influence of introducing superconducting power cables on the maximum fault current in different faults without considering any protecting methods like circuit breakers and fault current limiters. As an example, the fault current at the fault point in short-circuit fault between feeder line and rails is shown in Fig. 2. When the short-circuit fault happens close to substation, the short-circuit fault current multiplies nearly 4 times and reaches an extremely high value after introducing superconducting power cables. In comparison, when the fault is far away from substations (in the middle between substation 2 and substation 3), the influence of introducing superconducting power cables on the fault current at fault point is much smaller. With more simulations based on different cases, it was verified that the influence of introducing superconducting power cables on the fault current became more significant when the fault point moved closer to the substation. And even at the same location, the influence was smaller in the fault with higher fault resistance like some kinds of grounding faults.



(a) (b)

Fig. 3. Maximum output currents of five substations in the short- circuit fault at the middle of two adjacent substations (a) with superconducting power cables; (b) without superconducting power cables.

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B. Fault current after introducing circuit protections.

The development of DC electric railway feeding system is constrained by the lack of operational experience in DC system, the small interrupting capacity of DC circuit breaker (CB), and the lack of protection schemes for system itself. In the real DC electric railway feeding systems, the fault current will never reach such high values, as there must be relay protections and circuit breakers installed to cut off the fault current and protect the system. So, the protections will be taken into consideration in this simulation. The faults that are most severe to the superconducting power cables have to be simulated to study the fault current in the electric power system with protections, and the safety of superconducting power cables.

Different short-circuit faults and grounding faults are simulated to figure out the influence of introducing superconducting power cables on the maximum fault current in different faults considering protecting methods like circuit breakers and fault current limiters. After introducing superconducting power cables, the fault current may reach an extremely high value, and the requirements for circuit breakers are strict to protect the superconducting cables and the system. Fault currents can be small, due to high impedance ground faults, or due to the position of the fault, which can happen along the line and far away from the substation. In standard heavy rail systems, the lines are divided in straight sections, and in each section, for safety reasons, only a few trains are allowed to run at the same time, in urban rail systems, instead, the network is meshed, and also the sections are meshed, many trains can be running at the same time inside the same section, resulting in higher currents and complex current profiles in normal operation.

For these reasons, using standard protection principles, such as instantaneous and time-delayed over-current protections is not sufficient. Different studies have been performed on innovative protection schemes such as superconducting fault current limiter (SFCL) etc.

Fig. 4 shows the fault current under the short-circuit fault between feeder line and rails close to substation 5. This fault gave the highest fault current, which emerged in the superconducting power cable between substation 4 and substation 5 . According to the current waveform, the peak current through superconducting cables is approximately 9 kA. Furthermore, during the fault the breaker of SC4 operates first, then the feeder breaker in substation 5 operates, at last the fault is completely detached in 12 ms after the fault by the feeder breaker in substation 4 as remote operation. The safety of superconducting power cables is ensured in this case. Other serious faults were also studied, and the results showed that it is also possible to protect the superconducting power cables with proper setting in those cases. Although the rising of fault current is steep and requires the circuit breaker to cut off the current in a few milliseconds, it is still possible for today's DC high-speed vacuum circuit breakers.

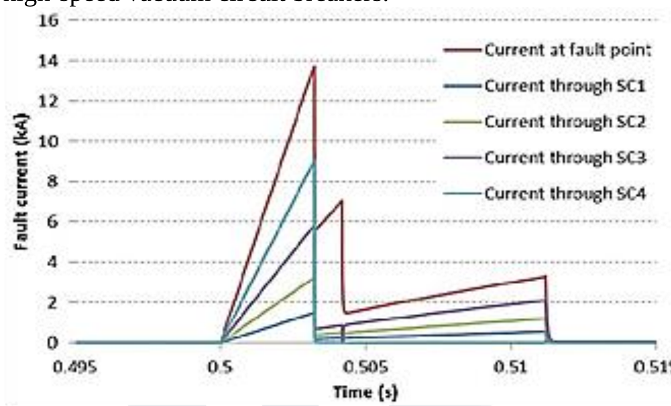

Fig. 4. Fault currents at the fault point and through the superconducting power cables (SC) in the short- circuit fault between feeder line and rails close to substation 5.

C. Potential application of a Superconducting Fault Current Limiter

After introducing superconducting power cables, the fault current may reach an extremely high value, and the requirements for circuit breakers are strict to protect the superconducting cables and the system. However, as the possibility of breaker operation failure cannot be neglected, it is necessary to develop a method to protect the superconducting power cables when the breaker operation fails. Fault current limiters are the effective solution for most of the power system failures nowadays. Superconducting fault current limiters are used as effective way of fault current limiting. Most of the problems or failures in system are due to overloading of system lines thus flashover or fire hazards. This all will occur mostly at the time of fault because fault current will be of a large value than system can withstand. By expanding system, we have to increase the fault current level also. Otherwise system will collapse soon. The better way is to use current limiters. The fault current limiters limit current at the event of fault. Superconducting fault current limiters use superconducting material for current limiting. Here a study on superconducting fault current limiters, their usage, types etc., are included. The SFCL was designed as a superconducting coil, which consists of a number of superconducting wires in parallel (Fig. 5 (b)). It was assumed to be installed to both ends of a superconducting power cable, and designed to limit the fault current with its inductance and flux-flow resistivity due to the normal conducting transition. In order to gain enough resistance, a certain length of superconductor was needed, and part of it was designed as bifilar coil to save space.

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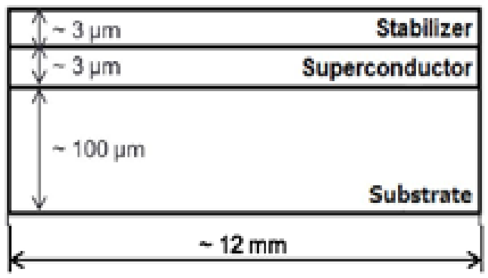
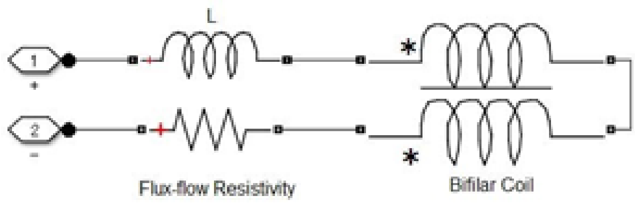


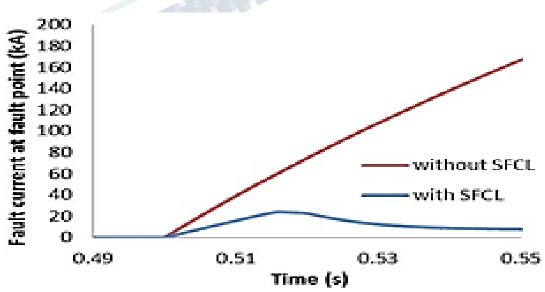
(a)



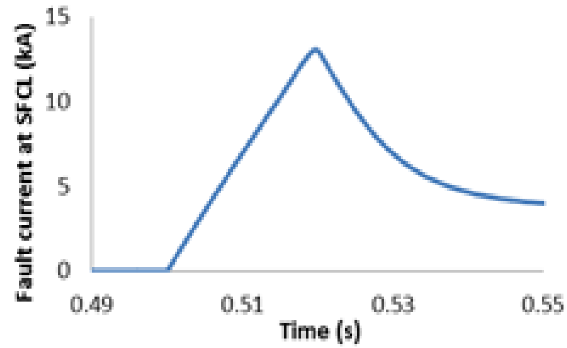
(b)

Fig. 5. (a) Schematic cross section of superconducting wire used (not to scale); (b) Electric circuit model of the superconducting fault current limiter.

After installing the SFCL model in the railway electric circuit model, several severe faults were simulated to study the effect and behavior of the SFCL during the fault. Fig. 6 shows the results in the short-circuit fault between feeder and rails close to substation 5. The fault current without considering any protecting methods has been also shown in Fig. 2. (a). After installing the SFCL, the rising of fault current is suppressed from the very beginning of the fault, and the peak value which appears in tens of milliseconds is also limited to a low level comparing with that without SFCL. Fig. 6. (b) shows the maximum current that emerges in SC4 (between substation 4 and 5). The value of the current is acceptable both to the capacity of superconducting power cables and the capability of circuit breakers. Finally, as for the SFCL itself, the equivalent resistance of SFCL is shown in Fig. 6. (c), together with the temperature of the superconductors during the fault.



(a)



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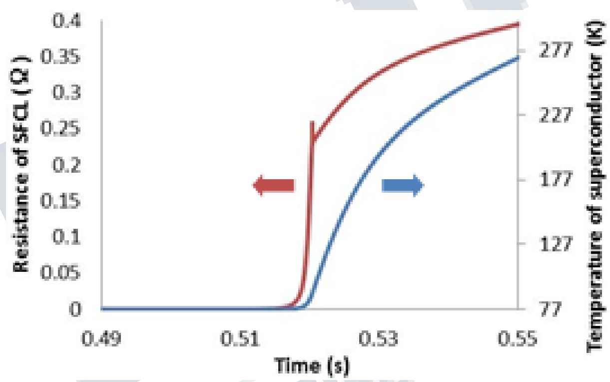

(c)

Fig. 6. (a) Fault current at the fault point with and without superconducting fault current limiter (SFCL); (b) Fault current at the SFCL; (c) Equivalent resistance of the SFCL, and temperature of superconductor.

V. CONCLUSION

We studied the fault current of DC electric railway feeding systems with superconducting power cables introduced. The MATLAB-Simulink models based on the electric circuit were utilized in the numerical analysis from the Electric circuit model shown above. The models consist of substations, a feeder system, trains, superconducting power cables, and a fault point. The simulation results showed that the introduction of superconducting power cables could lead to an increase in fault current, and the increase became more significant when the fault point got closer to a substation and the fault resistance became smaller. The superconducting power cables also showed their feature for distributing loads among the substations even during the fault. Considering the real electric system with protections, the analysis showed the feasibility for detaching the fault and protecting the system including the superconducting power cables. Undoubtedly it required proper settings and high performance protection devices. Finally, as a method to increase the reliability of the electric power system with superconducting power cables, the introduction of a superconducting fault current limiter was considered in the simulation model, and the results showed its feasibility and potential in fault current limiting.

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