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Superconducting cables and their benefits for DC railway network

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Objective – Today, the increase in rail traffic while ensuring continuity of service presents a major challenge for the Société Nationale des Chemins de fer Français (SNCF). To tackle this challenge, particularly in ultra-dense areas such as in Paris, France, the SNCF has recently initiated numerous electrification projects. One aspect of these projects aims at reducing the line losses in order to decrease the voltage drop on the 1.5 kV railway network. Amongst the possible technological choices, high temperature superconductor (HTS) cables have been evaluated as a promising solution. In this paper, the focus is on the benefits of unipolar HTS cables on a direct current (DC) railway network under load.

Originality – Using co-simulation, a FE model of the HTS cable is coupled to a lumped-parameter circuit model of the railway network. The latter is particularly suited for transient simulations considering the train motion. The development of such a model was deemed essential to properly study the superconducting cable and to assess accurately its impact on the power system during train accelerations.

Findings – Based on a case study representing a fraction of the Parisian railway network, it is shown that the insertion of a superconducting cable can result in a reduction of electrical losses by 35% compared to a conventional cable. Additionally, a reduction of 8% in the total electrical consumption of the traction network can be achieved.

Keywords – Co-simulation, DC power transmission, Electromagnetic modeling, Energy consumption, Finite element modeling, Railway electrification, Superconducting cables.

1. Introduction

The French railway infrastructure and architecture must evolve in order to face the increase of energy consumption while respecting the reduction of CO₂ emissions following the ever more restrictive environmental reforms [1]. In that regard, several solutions have already been considered and tested [2], [3]. In order to avoid significant modifications of the infrastructure and at the same time to remedy the voltage drop by reducing the electrical losses along the line in a restricted environment, an interesting technological solution proposes the installation of a superconducting electrical cable. The idea is to take advantage of new developments in commercial high-temperature superconducting (HTS) tapes, known as second generation or 2G, which offer high current density without steady-state losses and better mechanical strength. For example, a typical commercially available 2G superconducting tape has an average engineer current density of about 300 A/mm² at liquid nitrogen (77 K), which is 300 times higher than the 1 A/mm² of a copper conductor according to DIN43671. The objective of this work was to develop numerical tools to design and study in detail the benefits of HTS cables in a railway traction network. Indeed, this work focuses on: 1) the quantitative evaluation of the advantages of using a superconducting cable compared to a conventional technology (energy consumption and voltage drop reduction), 2) the estimation of the impact of the superconducting cable on three major components of the railway network that are the substation (SS), the traction lines and the train.

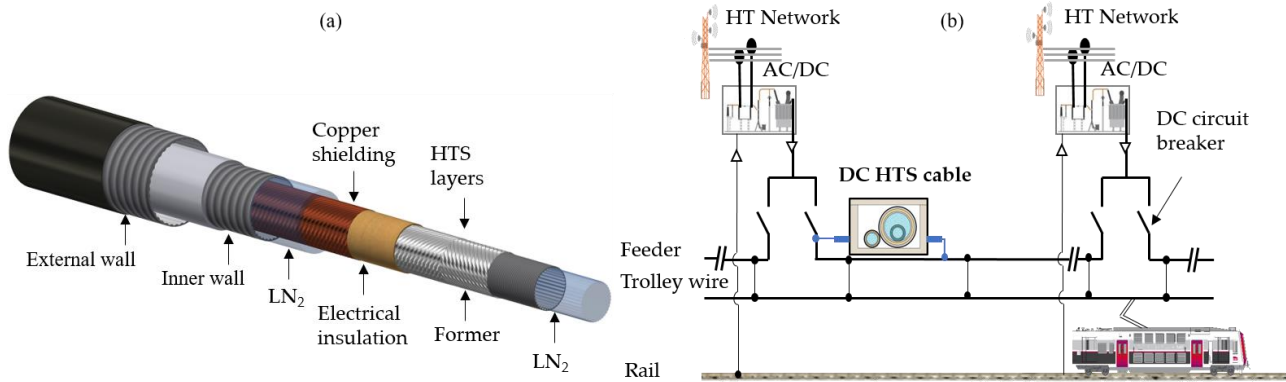


Figure 1: (a) 3D view of a coaxial superconducting cable, (b) Typical diagram of the insertion of a unipolar HTS cable on the railway network.

2. Design and modeling of DC superconducting cable and electrical network

2.1 Design and modeling of DC superconducting cables

As shown in Figure 1 (a), the cable is made of several layers of tape wrapped around a former that allows the flow of liquid nitrogen. It consists of 24 superconducting tapes arranged in two layers, providing a current capacity of 4.4 kA. To ensure electrical insulation, the cable is covered with a thin layer of Kraft paper. For a 1.5 kV DC railway system, the insulation thickness is a few millimeters. Atop the insulation lies a layer called the "screen," which consists of copper bands connected to the ground at both ends. The whole assembly is then housed within a flexible cryostat, facilitating the circulation of liquid nitrogen in its liquid state. Such a unipolar HTS cable can be then inserted into the railway network as shown in Figure 1 (b). The algorithm developed for sizing the system, taking into account cryogenic aspects, can be found in [4]. This algorithm is used to estimate the thermal losses of the HTS cable, terminations and to define the components of the cooling system. In the same section, the finite element (FE) model, developed to calculate the dynamic losses of the superconducting cables, will be detailed. This model implements the **T-A** formulation of the Maxwell equations [5]. This model takes into consideration the highly nonlinear behavior of the resistance of the superconductor via the power law $E(J)$ relating the electric field along the superconductor E to its current density J . Details of the physics of the superconductor are considered via the Kim-Anderson relation [6]. This relation expresses the dependence of the critical current density of the superconducting tape J_c with respect to the magnetic flux density \mathbf{B} and its orientation (angle θ).

2.2 Modeling of an electrical traction network

In this section, the DC railway network model is presented, with its main components: substations, trains and line impedance management are considered. The substation model contains a transformer, whose primary windings are supplied with a line-to-ground voltage of 20 kV, generating a power of 6.6 MW on load. In addition, a double diode Graetz bridge at 1.5 kV and a continuous rated current of 4.4 kA. An inductance choke at the substation outlet is introduced to smooth the current variation (di/dt) due to the transients induced by the train acceleration and deceleration. The calculation of the electrical power of the trains is obtained from the calculation of the sum of the traction force necessary to ensure its movement and the electrical power of the auxiliaries (lighting, air conditioning, etc.). The management of the line impedance is calculated at each time step according to the position of the train during its mission [7].

3. Energy efficiency assessment and discussion

In this section we will examine the impact of the superconducting cable on the railway network. This section will focus on assessing the performance of the cable when trains run at constant speeds along the traction line. Three separate case studies will be examined to better understand the effects of the superconducting cable on the railway network:

- A conventional railway network without superconducting cable (referred to as "conventional").
- A railway network with a unipolar superconducting cable, referred to as "UniHTSC." This cable connects the substation 1 to the p_{HTS} injection point of the overhead line, with the current being returned through the rails.
- A railway network with a bipolar superconducting cable, referred to as "BiHTSC." This cable connects the substation 1 to the overhead traction line at p_{HTS} and also guarantees the return of power to substation 1.

We would like to clarify that in the cases of UniHTSC and BiHTSC, the cable is installed in parallel with the overhead

traction lines. In addition, we set a distance of 10 km between the two substations SS1 and SS2. In order to ascertain the most suitable cable length that would enhance the overall efficiency of the railway network and the HTS cable, we considered varying the cable length between 0.1 km and 5 km. The length of the cable should be greater than 0.1 km and lesser than half the distance between point SS1 and SS2. During normal operation, the cable is rated at 4.4 kA and 1.5 kV. However, it can handle up to 6.75 kA in overload mode.

The relationship between the overall system energy consumption for the superconducting cable and the overall system energy consumption for the conventional cable as a percentage η and the relative energy consumption of the traction line (TL) as a percentage δ are presented for the three case studies: conventional, UniHTSC, and BiHTSC. δ is an indicator of the electrical impact of the superconducting cable on the traction line. The whole system is defined as the traction line in the case of the conventional cable and the traction line considering:

- the superconducting cable, with the losses of the cryostat equal to 1.5 W/m, and the hydraulic losses, and the electrical losses calculated using the T-A formulation.
- the terminations, with the Joule losses and the conduction losses assumed equal. Their sum is 150 W/kA.

The expressions of the ratio η and the relative consumption δ are as follows:

$$\eta / 100 = \frac{Q_{HTSC}}{Q_{Conv}} \quad (1)$$

$$\delta / 100 = (Q_{TL, Conv} - Q_{TL, HTSC}) / Q_{TL, Conv} \quad (2)$$

where Q represents the total energy of the system; $Q_{Conv} = Q_{SS1, Conv} + Q_{SS2, Conv}$ for the conventional cable and $Q_{HTSC} = Q_{SS1, HTSC} + Q_{SS2, HTSC} + Q_{cooling}$ for the superconducting cables. Q_{SS1} and Q_{SS2} depend on the traction line efficiency. Therefore, as the superconducting cable inherently dissipates less than the conventional

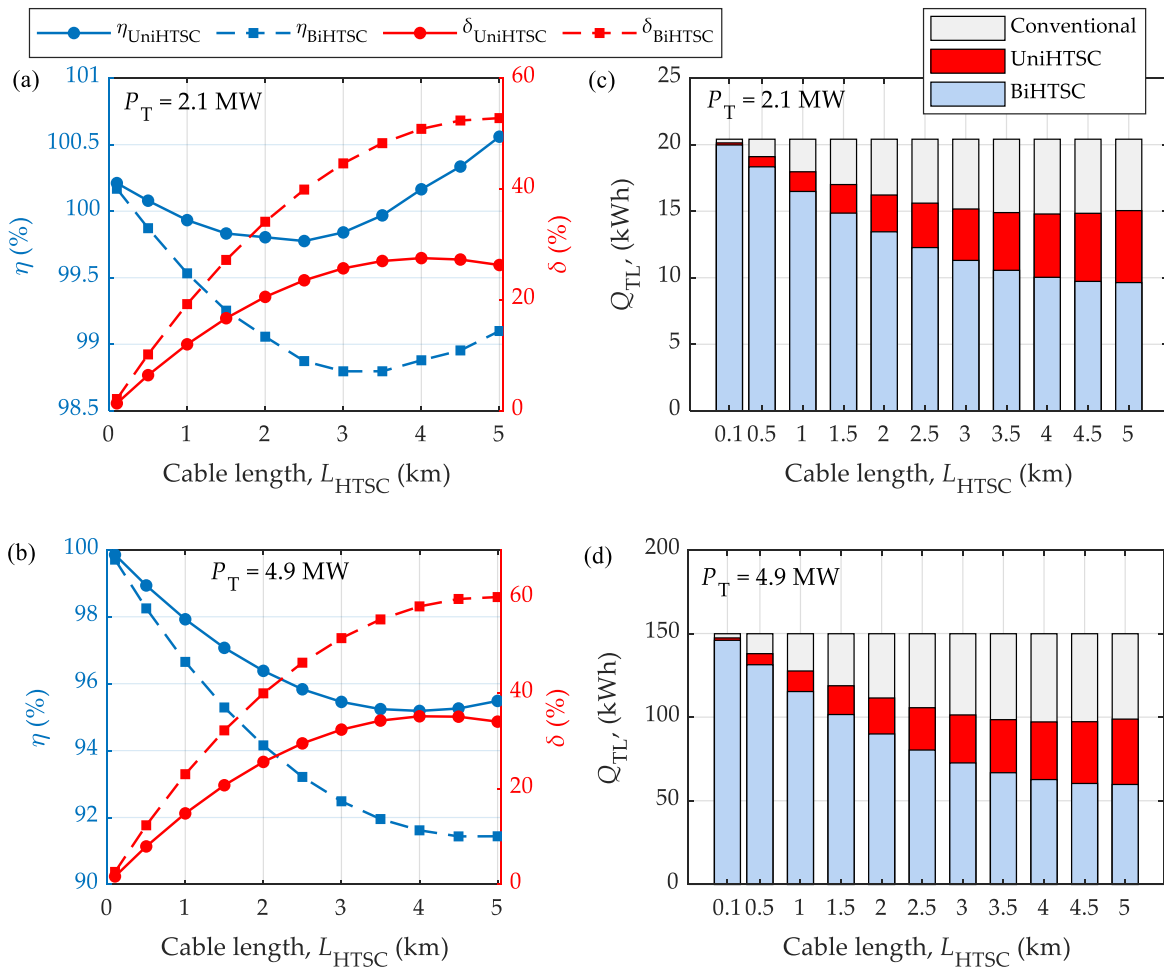


Figure 2: (a) and (b): on the left, the ratio η in percent of the energy consumption of a superconducting cable over the energy consumption of the conventional one is shown; on the right, the relative energy consumed by the traction line δ in percent as a function of the length of the superconducting cable for train powers P_T of 2.1 MW and 4.9 MW. (c) and (d) shows the energy consumed by the traction line Q_{TL}' as a function of the cable length for the same powers.

cable, $Q_{SS1,HTSC} + Q_{SS2,HTSC} < Q_{SS1,Conv} + Q_{SS2,Conv}$ in any normal operating conditions. Q_{TL} represents the energy consumed by the traction line through its circuit impedance. It is defined as follows:

$$Q_{TL} = \sum_i \int_0^t Z_i I_i^2 dt \quad (3)$$

where i is the index of an electrical branch in the traction line, Z_i is the impedance of the branch i and I_i is its current.

Figure 2 shows the evaluation of the parameters δ and η and the energy Q_{TL} as a function of the superconducting cable length for two magnitude of train electrical power P_T of 2.1 MW and 4.9 MW. Figure 2 (a) reveals a rise in δ for both UniHTSC and BiHTSC cases, indicating that less energy is needed to supply the traction line and hence less energy dissipation is achieved compared to the conventional solution. The superconducting cable is inherently less resistive than a conventional cable. However, it's worth noting that the power required by the cooling system must also be added to the overall electrical power. This power is included in the ratio η . In some cases, the installation of a superconducting cable may not result in an overall reduction in energy consumption. Indeed, the voltage drop reduction alone is not a decisive factor for the choice of the technology, as the energy budget impacting the cost of operation should be included as well. For instance, an UniHTSC having a length of 0.5 km or a length greater than 3.5 km requires more energy as a whole than a conventional cable. In such cases, the energy required for cooling causes η to be greater than 100%. For cable lengths between 1 km and 3 km, η is less than 0.3%, meaning the overall energy consumption gain from the superconducting technology is marginal and there is no significant improvement in energy consumption compared to a conventional cable. Nevertheless, it still offers a reduction in voltage drop. In the case of BiHTSC, the HTSC technology provides a larger improvement on the total system consumption for any cable lengths, making it the most compelling solution. For both UniHTSC and BiHTSC configurations, η tends to decrease as the energy required to maintain the HTSC at its nominal temperature increases at a slower rate than the electrical energy required to supply a conventional cable. Figure 2 (b) depicts that for a P_T value of 4.9 MW, the use of a superconducting cable always ensures a reduction in the energy consumption of the traction line and the overall system. As the cable length is increased, the total energy consumption decreases. For instance, using the BiHTSC results in a 3.3% and 8.6% reduction in energy consumption for a cable length of 1 km and 5 km respectively.

4. Conclusion

A FE model was created to represent the behavior of a superconducting cable associated with part of a traction network containing two substations. The model was therefore coupled to a circuit model and included the physical details of the superconductor and the movement of the trains. This work was carried out as part of the SuperRail project to assess the benefits of using superconductor technology for the Parisian railway lines, with the aim of improving efficiency and reducing voltage drops. The results showed that the use of superconducting cables has clear advantages. This technology, especially in its bipolar configuration, can allow more trains to run on the same track or increase the operating rate. In addition, the energy consumption saving of a superconducting cable becomes more important as the total power consumed on the line by the trains becomes greater and greater. For railway installations where the number of trains running has increased significantly, the installation of superconducting cables can extend the life of the existing infrastructure without the need for extensive electrical modifications or construction.

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