Design tools and optimization for DC HTS cables for the future railway network in France

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Abstract—The use of High Temperature Superconducting (HTS) cables in power systems increases transmission capacity while reducing the volume of the installation. In addition, when transmission currents exceed a few kA, HTS DC cables significantly reduce power losses, rights-of-way and total system mass. This summary describes the various studies to be carried out in order to correctly dimension DC HTS cables for the new railway network envisaged by the French company SNCF, which has to take into account the ultra-urban needs. The process used to design DC cables for different operating current values between 5 kA and 20 kA at 1 750 V using commercial (RE)BaCuO tapes is presented. In this design stage, the dependence of the critical current density $J_c(B, \theta, T)$ of the superconducting tapes, the thermal properties of the materials used, and the different cooling modes as a function of the cable length were taken into account. Finally, we are discussing a cryogenic solution to protect the cable in case of short-circuit or overload.

Keywords—Superconducting cable, magnetic field, analytical calculation, direct current, cryogenics, thermal and hydraulic modelling.

I. INTRODUCTION

Direct Current (DC) electrical networks represent a considerable part of rail electrification in France and worldwide [1]. The transport of electrical energy in urban areas is limited by the space required for transformers and other static converters to transform electrical energy. Moreover, to reduce line losses, electrical energy is transported at high voltage, which requires a transformer substation close to where the energy is used, and the installation of a substation in a densely populated area imposes constraints. On the other hand, the new environmental reforms impose a high consumption of electrical energy [2], which implies that the moderate rail network has to adapt to these conditions.

In order to meet these constraints, recent developments in High Temperature Superconducting (HTS) tapes make it possible to develop cables carrying a high current density without losses [3]. Thus, the installation of a superconducting cable in an urban environment makes it possible to move substations to the periphery [4], where space constraints are less important, and to transport electrical energy directly in the form in which it will be used. Superconducting cables also have the advantage that they can be dimensioned to limit the current in case of failure: e.g. short-circuit, overload [5].

An iterative process has been developed for the complete sizing of DC superconducting cables, whose results are limited to minimizing the total number of tapes [6].

In this paper, we present a new sizing method that minimizes both the number of tapes per layer and per pole, as well as the overall cable losses. Our algorithm determines the number of tapes per layer and per pole, while ensuring that the cable is protected in the event of a fault. The performance of the latter does not stop at the dimensioning of the superconducting tapes, it is also able to compare different types of cooling. Different design steps are discussed, and in particular the choice of the cryogenic line among which are the following configurations: Separate Pipes (SP), Concentric Pipes (CP), Concentric Pipes with Separate Return (CPSR) and concentric pipe with double cooling system at each end of the cable (CPDS). Our design tool will allow not only to size the superconducting cable but also to estimate the cooling system and the required volume of the Liquid Nitrogen (LN_2) tank upstream of the installation. This volume is directly related to the targeted autonomy in LN_2, i.e. the time between two fillings, by considering hydraulic losses, thermal losses, contact resistances, AC losses, cooling system losses.

II. DIMENSIONING PROCESS

In DC rail applications, two superconducting cable topologies can be considered [7]. A superconducting cable with a positive pole is injected at one point of the line and the return current flows through the rail, or a superconducting cable with concentric positive and negative poles that supplies the forward and return current.

A method for the design of DC superconducting cables is proposed below. The first part consists of identifying the critical current that must be higher than the transmission current by considering the different cable designs. For this, a 3D analytical model has been proposed for the calculation of the magnetic field in the cable. The second part consists of a steady state thermal and hydraulic study to keep the LN_2 temperature below 78 K with a pressure above 3 bars [8]. The last part aims to determine the thickness of the copper to ensure the continuity of current in the cable when a fault occurs. All the parts mentioned below are coupled together through an iterative process that will be detailed in the final version.

A. Electromagnetic study

According to the topology of the cable, the DC HTS cable under consideration consists of one or two concentric poles. Each pole has a number of layers. A layer consists of N tapes and the radius of each layer is directly related to the number of tapes on top of it. We want to calculate the magnetic field distribution produced by n rings of N tapes of each pole. Here we consider that the current density J is uniformly distributed between the tapes and constant in each of the superconducting parts. To simplify the complexity of the geometry related to the twisting of the tapes, we treat the REBCO layer as an infinitely thin shell [9]. To avoid a vector problem with three variables in space, the magnetic scalar potential (V_m) has been chosen as the state variable. In addition. The analytical model is based on solving the Laplace equation by the separation of variables method, first, we solve the Laplacian of V_m equal to zero, then, we use the Neumann outer boundary condition and the transition conditions to determine the value of V_m.

To determine the critical current, we estimate the radial and tangential components of the magnetic field applied on each tape without considering the field of the tape itself. For each simulation, we calculate the value and the application angle of the magnetic field generated by the current flowing through the cable. From these values and the tape manufacturer's data [10], [11], we obtain the critical current for the chosen operating temperature of the LN_2 in contact with the tapes. Finally, we check if the critical current value is higher than the transport current. We take into account the inhomogeneities over the wire length by choosing a security margin of 20 % between the operating current and the critical current.

B. Hydraulic and thermal design (normal operation)

1) Hydraulic study

The main parameter concerning the thermal cooling of the cable is the LN_2 flow rate $\dot{m}$. The mass flow rate, in addition to being limited by the capacity of the station, is constrained by the pressure drops in the pipe. Indeed, the circulation of a fluid in a long pipe induces strong pressure drops that can bring the LN_2 below the minimum pressure to maintain its liquid state and decrease both cooling and dielectric performances [13]. The main calculations are made using Bernoulli's theorem applied in each pipe. The pressure drops in the pipes are obtained by considering regular pressure drops [14] and using the Blasius correlation in order to estimate the coefficient of friction [15]. Fig. 1 shows a HTS cable with a typical cryogenic line configuration using Separate Pipes.

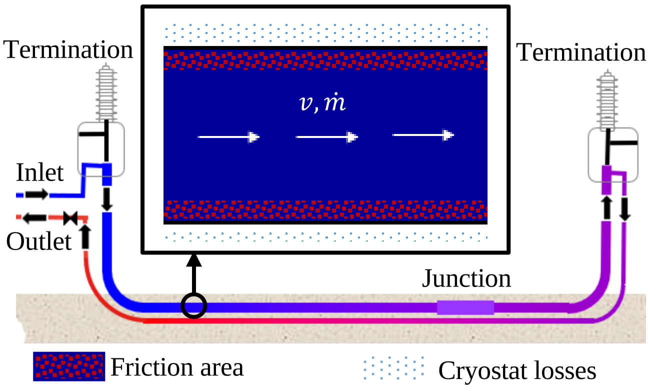

Fig. 1. Schematic illustration of a cryogenic line with Separate Pipes.

2) Thermal study

In the section, we determine the temperature of the tapes in steady state along the cable length. For the thermal design, it is assumed that the only losses in the system are those of the cryogenic line and are proportional to its outer surface area [16]. It is also assumed that the LN_2 temperature in a single pipe only varies with the length of the cable while the heat transfer between the layers is only in the radial direction. The temperature of LN_2 of each pipe along the cable length is then obtained by integration. As an example, Fig. 2 shows the temperature distribution along a two-layer cable of 10 kA and 500 m for SP, CP and CPSR, with a mass flow rate of 0.3 kg/s. The selection of the proper cooling system can easily be made by considering the cost of the required pump, from the mass flow rate and the pressure drop.

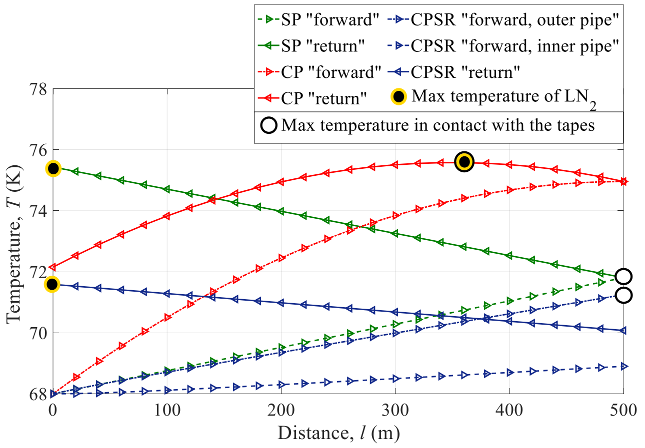

Fig. 2. Temperature distribution a two-layer cable of 10 kA and 500 m for SP, CP and CPSR, with a mass flow rate of 0.3 kg/s.

C. Copper thickness design (in case of a fault)

In this section, the worst case of failure is taken into account to determine the copper cross-section. It means that the inductance and resistance of the traction line are considered and a free short circuit is assumed on the HTS cable. An electrical model [5] coupled to a thermal nodal [17] model has been used to study the temperature of the different layers of superconducting tapes as well as in LN_2. The objective of this part is to design and determine the ideal copper thickness to ensure the fault current flow before the circuit breaker opens, while maintaining the nitrogen in a liquid state.

For cables in concentric pipes, the liquid nitrogen in the outer pipe is in direct contact with the superconducting tapes. When a fault occurs, the current starts to penetrate the copper layer and the temperature of the tapes rises rapidly and reaches about 10 K in a few milliseconds. It may change the LN_2 to a gaseous state. The presence of the latter decreases the heat exchange in the cable and may also cause a dielectric breakdown of the cable in some cases. For this reason, a new layer is necessary to decrease the temperature gradient between the nitrogen and the superconducting tape in case of a fault. This solution will be well discussed and detailed in the final article.

III. CONCLUSION

In this paper, we propose a method based on electromagnetic calculations combined with hydraulic and thermal dimensioning to determine the best cooling configuration and to entirely design an HTS DC cable. The developed algorithm is also used to size the HTS cable to protect it in case of a failure. The algorithm, equations and all assumptions will be clearly detailed and discussed in the final article including several examples.

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