Thermal-hydraulic models for HTS power-transmission cables: status and needs

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Abstract **— An overview of the main peculiarities of the models currently available in literature for the thermal-hydraulic analysis of HTS power transmission cables, mainly in normal operating conditions, is performed. From the analysis the lack of a general model, capable to address for the different possible cable designs the thermal-hydraulic transients, with capability to catch both the behavior of the solid components of the cable and of the coolant, is evident. The main needs, in terms of ingredients that such general thermal-hydraulic model should not miss, are highlighted.**

Keywords — HTS, power cables, thermal-hydraulic modeling, numerical tools

I. INTRODUCTION

In the framework of the European Green Deal [1] call for "supplying clean, affordable, and secure energy", the path towards a clean energy transition is set with the boost of smart energy systems, providing high efficiency in the generation, transportation, and consumption of electricity and higher environmental sustainability [2]. High-temperature superconducting (HTS) AC and DC transmission cables (SCTC) and lines (SCTL), bringing a clear size advantage and low total electrical losses for high-capacity transmission, have the potential to address the need for more sustainable and efficient transmission, compared to solutions based on standard conductors [3]. The sustainability advantages of the HTS lines in terms of limiting the environmental (health and visual) impact and the destruction or alteration of the natural landscape, are clear, and several utilities around the world has already demonstrated their technical feasibility. Furthermore, easier and faster installation is expected for SCTCs [4–9]. As pointed out in [3], the global design of SCTLs includes a pressurized coolant and refrigeration or compression stations along the line, as the gas pipelines. However, their typical transverse of few tens of centimeters dimensions is smaller than that of gas pipelines, and the operating temperature is different (typically 15 K to 70 K, according to the kind of HTS material considered). No long SCTLs are currently in operation, and the maximum length of prototype cables is 3 km [10].

Before moving to a commercial era for SCTL, the experimental tests of SCTLs should be accompanied by the parallel evolution of numerical tools capable to capture the main features of such cables. Once validated against experimental data and at their maturity, the numerical tools could become an asset to flexibly design solutions with a high level of credibility. The same trajectory of numerical tool development has been followed within the framework of the superconducting cables for fusion machine [11].

The aim of this work is to present a review of the numerical tools and models available for the thermal-hydraulic analysis of AC and DC SCTLs, and to point out the design needs that are still not covered by available models.

II. GENERAL STRUCTURE OF HTS TRANSMISSION CABLES

The design of an HTS cable is the result of the trade-off between electrical efficiency, losses in the cryostat (thermal losses, pressure losses, …) and the use of superconductive material, with the aim of containing the system cost.

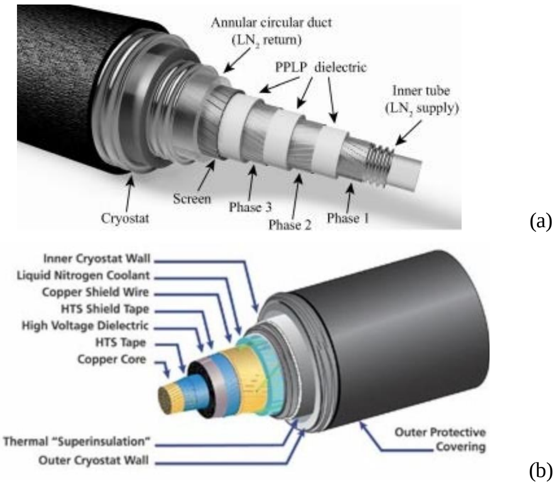

Figure 1. (a) Typical single-core three-phases HTS cable for power transmission design in counterflow from [21].(b) Typical single-phase cable, with single-path for the coolant. (courtesy of Nexans).

The structure of a typical HTS AC single-core cables is shown in Figure 1a and b. The three-phases (Figure 1a) or single phase (Figure 1b), made by several HTS layers, are concentrically wound around either a copper core ("former") or the coolant tube. An electrical insulator is interposed among the layers. In case of a single phase, a magnetic shielding is also present. An external conduit, inserted into the cryostat, provides a buffer zone, which can be filled with layers of low emissivity insulation material, to increase the level of thermal insulation. A concentric (Figure 1a) or a separate return line for the coolant can be present. Cooling is accomplished through cryogenic liquid such as: helium in gaseous phase (GHe) at 2 bar [12-14], or liquid nitrogen (LN_2) [15-17], in the 65 K-77 K temperature window. While a multicore structure for AC cables could also be envisaged, the single core structure is adopted by DC cables.

III. THERMAL-HYDRAULIC MODELS FOR SCTCS

The development aimed at reducing costs and increasing the safety, stability and reliability of systems adopting the different types of cable is essential for intensive penetration into power grids. The numerical modeling in support of such development, however, is still lagging far behind: a robust model for such cables should couple comprehensive thermal-hydraulic and electrical transient models, with material properties dependent on the operating conditions of the cables.

Limiting the present review to the published thermal-hydraulic models, many simplified 1D models are currently available for the STSCs. The cables are modeled drastically simplifying with a single variable representative of the cable properties throughout the cross section since the cable longitudinal dimension is 3 to 5 orders of magnitude larger than the transverse ones. In [18] and [19] for instance two different simplified steady-state approaches are adopted to compute pressure gradient and temperature profile in the nitrogen coolant. In [16] a more sophisticated 1D model is presented, where the conductor and shield temperature can be computed solving 1D heat conduction equations by Finite Difference technique. The solids can release heat to the coolant by suitable convective heat transfer sink terms, whereby the global pressure drop is evaluated. A radial steady-state conduction equation to evaluate the HTS cable temperature is coupled to a 1D longitudinal treatment in [17] and in [20]. Even more simplified than that, the model in [21] just considers steady-state thermal conduction in the radial direction, coupled to a steady-state enthalpy balance in the longitudinal direction.

A 2D Finite Element Model has been applied in [15] for different three-phases SCTCs in normal operation, showing that a radial model for the temperature could be useful only for the HTS region.

Quite popular for the HTS cables are the Volume Element Models (VEM) [12], [20], [22] where the 3D differential equations describing the first principle of thermodynamic and heat transfer constitutive relations are discretized in space using a cell-centered finite volume scheme. Typically, the LN_2 flow is assumed uncompressible and steady, while it becomes more sophisticate when GHe is considered [13].

IV. CONCLUSIONS

The SCTCs can have different layouts and their behavior is typically characterized by a very tight operating range. As today a model able to reliably describe the solid and thermal behavior of the SCTCs and SCTLs in normal and off normal conditions, possibly capable of comparing different cable layouts and different coolants, is not available to the best of our knowledge. The comprehensive model should be able to cope with a radial (either lumped or continuous) description of the HTS layers, a lumped description of the former, of the insulation and of the cryostat, a detailed 1D longitudinal transient description of the coolant (including mass, momentum and energy conservation), the main heat transfer mechanisms (conduction, convection and radiation from the cryostat), and also the possibility to account for vaporization in case a cryogenic fluid in the liquid phase is targeted.

REFERENCES

[1] "A European Green Deal," *European Commission - European Commission*. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed Mar. 14, 2021).

[2] V. E. Sytnikov *et al.*, "The Test Results of AC and DC HTS Cables in Russia," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, pp. 1–4, Apr. 2016.

[3] H. Thomas *et al.*, "Superconducting transmission lines – Sustainable electric energy transfer with higher public acceptance?" *Renew. Sustain. Energy Rev.*, vol. 55, pp. 59–72, Mar. 2016.

[4] "High Temperature Superconductors (HTS) Cables - ENTSO-E." https://www.entsoe.eu/Technopedia/techsheets/high-temperature-superconductors-hts-cables (accessed Mar. 14, 2021).

[5] S. Yamaguchi *et al.*, "Construction and 1st Experiment of the 500-meter and 1000-meter DC Superconducting Power Cable in Ishikari," *Phys. Procedia*, vol. 81, pp. 182–186, 2016.

[6] M. Stemmle *et al.*, "Ampacity project - worldwide first superconducting cable and fault current limiter installation in a German city center," 22nd International Conference on Electricity Distribution, pp. 0742–0742, Jan. 2013.

[7] L. Xiao *et al.*, "Development of a 10 kA HTS DC Power Cable," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, pp. 5800404–5800404, Jun. 2012.

[8] V. E. Sytnikov *et al.*, "HTS DC Cable Line Project: On-Going Activities in Russia," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, pp. 5401904–5401904, Jun. 2013.

[9] J. F. Maguire *et al.*, "Development and Demonstration of a HTS Power Cable to Operate in the Long Island Power Authority Transmission Grid," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 2034–2037, Jun. 2007.

[10] C. Lee *et al.*, "Thermo-Hydraulic Analysis on Long Three-Phase Coaxial HTS Power Cable of Several Kilometers," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019.

[11] R. Zanino *et al.*, "Multiscale Approach and Role of Validation in the Thermal-Hydraulic Modeling of the ITER Superconducting Magnets," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, pp. 4900607–4900607, Jun. 2013.

[12] C. L. Buiar *et al.*, "Thermodynamic Analysis Applied to Superconducting DC Cable Model.", 14th Brazilian Congress of Thermal Sciences and Engineering, p. 8, 2012.

[13] N. G. Suttell *et al.* "Modeling and optimization of gaseous helium (GHe) cooled high temperature superconducting (HTS) DC cables for high power density transmission," *Appl. Therm. Eng.*, vol. 143, pp. 922–934, Oct. 2018.

[14] L. Graber *et al.*, "Thermal Network Model for HTS Cable Systems and Components Cooled by Helium Gas," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 1–5, Jun. 2016.

[15] S.-J. Lee *et al.* "Analysis of the Temperature Characteristics of Three-Phase Coaxial Superconducting Power Cable according to a Liquid Nitrogen Circulation Method for Real-Grid Application in Korea," *Energies*, vol. 12, no. 9, p. 1740, May 2019.

[16] Y. Sato, *et al.*, "Temperature and Pressure Simulation of a High-Temperature Superconducting Cable Cooled by Subcooled LN_2 With Fault Current," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, pp. 1–5, Jun. 2015.

[17] W. T. B. de Sousa *et al.*, "Investigation of a Concentric Three-Phase HTS Cable Connected to an SFCL Device," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, pp. 1–5, Jun. 2018.

[18] O. Maruyama *et al.*, "Numerical Analysis of Heat Transfer and Fluid Characteristics of Flowing Liquid Nitrogen in HTS Cable," *Phys. Procedia*, vol. 58, pp. 330–333, 2014.

[19] G. Angeli *et al.*, "Development of Superconducting Devices for Power Grids in Italy: Update About the SFCL Project and Launching of the Research Activity on HTS Cables," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–6, Jun. 2017.

[20] E. Shabagin *et al.*, "Modelling of 3D temperature profiles and pressure drop in concentric three-phase HTS power cables," *Cryogenics*, vol. 81, pp. 24–32, Jan. 2017.

[21] D. Kottonau, *et al.*, "Design Comparisons of Concentric Three-Phase HTS Cables," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 6, pp. 1–8, Sep. 2019.

[22] D. I. Doukas *et al.*, "Volume Element Method for Thermal Analysis of Superconducting DC Transmission Cable," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–8, Jun. 2017.