Practical Forecasting of AC Losses in Multi-Layer 2G-HTS Cold Dielectric Conductors

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Abstract—With the recent progresses on the designing and manufacturing of lightweight superconducting cables with high engineering current density, the need for a reliable, fast, and accurate computational model forecasting the alternating current (AC) losses of cold-dielectric conductors is pivotal for power grid investors and operators. However, validating such models is not an easy task. This is due to the low availability of experimental data for large scale power cables, and likewise, because of the large computational burden which underlies the total number of second generation high temperature superconducting (2G-HTS) tapes in the modelling of realistic power cables. Thus, aiming to overcome these challenges, we present a detailed two-dimensional H-model capable to reproduce the experimentally measured AC-losses of multi-layer power cables made of tens of 2G-HTS tapes. Two cable designs with very high critical currents (1.7 kA and 3.2 kA) have been considered. These are composed of five and six concentric layers wound over a cylindrical former consisting of 50 and 67 2G-HTS tapes, respectively. In both situations a remarkable resemblance between the simulations and experiments has been found, offering a unique view of the local electrodynamics of the wound tapes where the mechanisms of shielding, magnetization, and transport currents coexist within the hysteric process.

Index Terms—Power cables, COMSOL, electromagnetic profiles, H-formulation, AC losses.

I. INTRODUCTION

AFTER the advent of the second generation of high temperature superconducting (2G-HTS) tapes, a greater interest on the development of power distribution and transmission cables under direct (DC) and alternating (AC) current conditions has been seen [1], [2], [3], [4]. Depending on the amount of current being transmitted [5], [6], [7], [8], [9], [10], DC systems offer a further reduction in electrical losses. However, most existing power grids are predominantly AC, meaning that any DC cable would require additional expenses in power conversion, which is not justifiable unless the cable is in excess of 100 miles [11]. Also, civil engineering aspects such as the use of right of way come into play when considering the actual deployment of power cables. In fact, despite HTS cables could be perceived as a more expensive upfront alternative, the reality is that the need to buy or develop new rights of way for the upgrading of an already robust but saturated grid, simply denotes the interest of investors towards the use of conventional conductor technologies. This opens a significant market window for compact HTS cables utilizing multilayer structures of 2G-HTS tapes, resulting in the lightening of the cryogenic load [11], [12], [13] and, the reduction of associated costs through the lowered use of Cu and expensive dielectric materials in the cold dielectric design [1], [2], [3], [4]. Simultaneously, these novel cables increase the transport current carrying capabilities of the grid, whilst reducing the need of substantial investments on transformers, alongside reducing the cross-sectional area of the cable for enabling the use of existing right of way.

With numerous HTS cables installed around the globe [2], [3], [4], our recent work has focused in the forefront cables developed by SuperOx and the Russian Scientific and Research Institute of the Cable Industry (VNIIKP), where a range of multilayer cable prototypes have been manufactured for both DC and single to three-phase AC systems [12], [14], [15], [16], [17], [18], [19]. Cold dielectric designs have been of particular interest where the outer layers serve as AC magnetic shields, whilst maintaining compact structure and high current capacity. For benchmarking, our numerical results reproduce and validate the experimental observations made in two of their most recent designs for single-phase power cables (see Fig. 2), namely:

1) A total of 50 SuperOx tapes of 4 mm width each are distributed in five concentric layers (Fig. 1 left-pane), following the design parameters shown in Table I. The manufacturing and initial experimental testing of this
TABLE I

| $N_i$ | $W_i$ | $R_i$ [mm] | $\Gamma_i$ [mm] | $N_T$ | $\langle J_c \rangle$ [A] |
|-------|-------|------------|-----------------|-------|--------------------------|
| Cable Core |
| 1st   | 4     | 11.3       | +200            | 8     | 72.8                     |
| 2nd   | 4     | 12.2       | +109            | 8     | 72.8                     |
| 3rd   | 4     | 13         | +61             | 8     | 72.8                     |
| Cable ‘Shield’ |
| 1st   | 4     | 18.4       | -330            | 13    | 91.8                     |
| 2nd   | 4     | 19.6       | +110            | 13    | 91.8                     |

$N_i$ stands for the number of layers, $R_i$ for inner diameter, and $N_T$ the number of tapes per layer. $\langle J_c \rangle$ corresponds to the averaged critical current per unit tape per layer, where $W_i$ refers to the width of the tape, and $\Gamma_i$ is the twist pitch length with positive or negative winding direction.

TABLE II

| $N_i$ | $W_i$ | $R_i$ [mm] | $\Gamma_i$ [mm] | $N_T$ | $\langle J_c \rangle$ [A] |
|-------|-------|------------|-----------------|-------|--------------------------|
| Cable Core |
| 1st   | 3     | 10.32      | -56.2           | 9     | 81                       |
| 2nd   | 3     | 11.03      | -193.6          | 11    | 81                       |
| 3rd   | 3     | 12.03      | 94.3            | 11    | 81.4                     |
| 4th   | 3     | 13.06      | 40.7            | 9     | 81.7                     |
| Cable Shield |
| 1st   | 4     | 18.25      | 349.4           | 13    | 120                      |
| 2nd   | 4     | 19.06      | -317.4          | 14    | 118.6                    |

See in conjunction with the cable (i) definitions at Table I.

Cable has been reported at [14]. Notice that, on the one hand, the cable ‘core’ layers refer to the three inner layers with eight 2G-HTS tapes each, building up to $\sim 1.7 \text{kA}$ critical current. On the other hand, the two outer layers consist of 26 tapes evenly distributed, which could be eventually used as a ‘shield’ for the magnetic field created by neighboring single-phase cables, or add a further $\sim 2.3 \text{kA}$ critical current if connected in series to the ‘core’.

ii) A size wise equivalent cable (Fig. 1 right-pane), whose design involves 67 SuperOx tapes distributed across the ‘core’ and ‘shield’ layers [12], but with the core rated critical current ($\sim 3.2 \text{kA}$) nearly doubling the one for the cable design (i). In this case (see Table II), the core layers are made of 40, 3 mm width, 2G-HTS tapes distributed across 4 concentric layers, which are surrounded by a further 2 layers (the shield) with 27, 4 mm width, tapes provided by the same manufacturer.

Regarding the experimental conditions on which these cables have been tested [12], [14], which therefore act as preconditions for our computational study, it is worth mentioning that for the cable (i) the so-called ‘shield’ layers are actually connected in series with the ‘core’ layers. This means that the ‘shield’ layers are configured to be under the same transport current conditions than the ‘core’ layers, what blot out the intended purpose of magnetic shielding. However, the considered case allows to get a maximum estimation of the AC losses for these layers without the need for building a complex and costly rig with neighboring power cables, as the magnetization losses created by the called ‘shield’ layers are not expected to be greater than the sum of their own transport current losses, plus the induced magnetization losses generated by the inner ‘core’ layers [8], [10]. Simulations of the cable with the shield layers being disconnected have also been performed, i.e., without transport current, to estimate the minimum AC losses for single or isolated power cables.

Thus, under the above considerations, in this paper we present reliable numerical estimations for large scale multilayer HTS power cables, based in our comparison with the experimental data of two of the most recent prototypes for cold dielectric cables produced by VNIIKP. Thus, our numerical approach is summarized in Section II, alongside with the disclosure of the electromagnetic profiles for individual 2G-HTS tapes, where general features for the local distribution of current density and profiles of magnetic field density are informed. Further analysis of the AC losses is provided in Section III, with an in-depth analysis of the expected energy losses at each one of the individual cable layers, and how our numerical predictions contrast well with the experimental observations. Finally, the main findings of our simulations will be briefed in Section IV.

II. NUMERICAL IMPLEMENTATION AND ELECTROMAGNETIC MODELLING

Concerning the reliability and accuracy of the chosen computational model, it is to be noted that our group has extensively used the H-formulation in the past, already showing an excellent agreement between the numerical estimations and experimental measurements in a large set of power cables, either in two-dimensional (2D) or three-dimensional (3D) environments [20], [21], [22], [23], [24], [25], [26]. Conclusions from these studies have shown that the simplified 2D models can be effectively used as digital twins of warm and cold dielectric conductors, allowing the timely assessment and forecasting of their power density losses. Still, we would like to emphasize that no matter how precise the 2D approach might result, which as a matter of fact depends on how realistic the physical parameters for individual tapes are (e.g., critical current density $J_c$ at the wound tapes and in the operational conditions of the entire cable), it is safe to say that a discrepancy with the experimental results of at least $\pm 10\%$ is customarily considered as acceptable [27].

Using the information in Tables I and II, the computer-aided design of the single-phased cables can be drawn in a 2D-approach with 3 mm and 4 mm width 2G-HTS SuperOx tapes [28], with the critical current densities magneto angular properties, $J_c(B, \theta)$ being characterized at [29]. The twist pitch length, $\Gamma_i = \pi R_i \cot \alpha$, being $\alpha$ the pitch angle, is duly considered for the relative positioning and sizing of each one of the tapes cross-section in the 2D approach. In this sense, the cross-section of the arced tapes is defined as the arclength along half the thickness of the corresponding 2G-HTS tapes, divided by the sine of their pitch angle. Nonetheless, it is worth mentioning that three dimensional effects caused by the inter-crossing of superconducting tapes with different winding directions, such as...
flux-cutting events [30], cannot be accounted within a 2D model. However, the impact of neglecting the three-dimensional effects can be mitigated by having into consideration the experimentally measured critical current density of the wound tapes per layer, $\langle I_c \rangle$, which substitutes the self-field critical current density in the found formula for the magneto angular anisotropy of the critical current density originally introduced in [31], as it has been previously shown in the 3D modelling of Conductor on Round Core (CORC) cables [25, 26].

The 1 $\mu$m thickness of the superconducting layer is scaled by a factor of 50, improving the convergence and computing time of the model, as in previous works it has been already proven that a coherent rescaling of the self-field critical current density, allows for the proper reproduction of experimental results [20, 25]. Still, for an adequate computation of the local electrodynamics inside the superconducting layers, each of the scaled superconducting domains must be split in at least 7 sublayers, such that sufficient ‘computational resolution’ is enabled for the convergence of Maxwell equations as shown in [24]. Not such high resolution is required for any of the other components in the cable, as there is no current sharing nor eddy currents within them, i.e., behaving as electrical insulators which do not add any significant losses to the system. Still, it is necessary to incorporate its right dimensions for fidelity with the real system.

About the computational formulation, the general form of the PDE module of COMSOL Multiphysics is used, where the state variable for the magnetic field $\mathbf{H}$ can be introduced by the partial derivatives function,

$$ e_a \frac{\partial^2 \mathbf{H}}{\partial t^2} + d_a \frac{\partial \mathbf{H}}{\partial t} + \nabla \cdot \mathbf{\Gamma} = f, $$

(1)

This allows to rewrite Faraday’s law by making the mass coefficient $e_a$ and the source function $f$ equal zero, whilst the damping coefficient $d_a$ and the conservative flux function $\mathbf{\Gamma}$ are rewritten in the matrix form, with respect to time $\partial t$:

$$ \begin{bmatrix} \mu_0 & 0 \\ 0 & \mu_0 \end{bmatrix} \begin{bmatrix} \partial_z H_x, H_y \end{bmatrix}^T + \begin{bmatrix} \partial_x, \partial_y \end{bmatrix} \begin{bmatrix} 0 - E_z \\ E_z \end{bmatrix} = 0, $$

(2)

with $H_x$ and $H_y$, the main variables of the system to be computed at the different elements of the meshed domains, alongside the vacuum magnetic permeability, $\mu_0$, and electric field in the z-direction, $E_z$.

The electrical behaviour of the superconducting material is defined through the $E - J$ power law [20],

$$ E = E_0 \frac{J_z}{J_{z\text{c}}} \left( \frac{J_z}{J_{z\text{c}}} \right)^n, $$

(3)

where the standard electric field criterion, $E_0$, of 1 $\mu$V/cm has been adopted. An n-value of 34.4 is used according to the experimental measurements of the $J_{z\text{c}}(B, \theta)$ of the SuperOx tapes [29], with respect to the critical current density in the z-direction, $J_{z\text{c}}$.

Within the 2D illustration of the cable designs shown at Fig. 1, the position of each tape can be seen to be evenly distributed across their layers, alongside the magnetic profile derived from cables (i) and (ii). Due to the experimental setup of cable (i) incorporating an applied transport current within the shield, a blatant difference in the magnetic fields of both cables is shown at the same time instance, i.e., at $t = 0.025$ s, time when the transport current reach its maximum value within hysteretic (cyclic) conditions. This shows that the applied transport current causes the maximum magnetic field to be produced on the outer layer of the shield, whereas the peak magnetic field of cable (ii) is evidently on the outermost tapes of the core.

Under both scenarios, and for a moderate transport current, i.e., $I_{t} = 0.5 I_{c}$ (per tape), being $I_{c}$ the minimum average critical current allowed for the individual 2G-HTS at the corresponding cable cores, 72.8 A or 81 A for the cable designs (i) and (ii) respectively (see Tables I & II), the peak magnetic field tend towards the upper end of the spectrum with cable (i) reaching 0.05 T and cable (ii) slightly higher at 0.06 T. The space between the core and the shield shows a peak of 0.015 T when a current is applied to the shield in cable (i), whereas when this ‘shielding’ current is not added for cable (ii), the magnetic field increases about three times, i.e., with a maximum field seen of about 0.045 T.

To assist with the understanding of the complex electrodynamics exhibited by individual tapes at these fairly large cable designs, and by considering a sufficiently large representative section (with angular symmetry) of the corresponding two cables in Fig. 1, the normalized current distribution profiles $J_z/J_{z\text{c}}$ for different transport current conditions are shown in Fig. 2. Therein, it can be seen that at $t = 0.025$ s, i.e., when the transport current is at its positive peak value within the first hysteresis cycle, both of the cable configurations provide similar results within the core layers, i.e., showing the concomitant action of transport and magnetization currents as $I_{t} < I_{c}$. This shows similar features to the ones observed in HTS monofilament rounded wires [8, 9, 10], where the local dynamics of profiles of current density for multiple experimental conditions have been thoroughly discussed. Thus, as it can be seen within the innermost layer (core layer 1), the $+J_{c}$ region is about but less than half the size perceptible within the other core layers. In fact, as the tapes at this layer are barely affected by the edge fields created by the neighboring tapes (due to the symmetry of the problem), a flux free region is still noticeable at the innermost region, where only the tape edges are being slightly affected by the concurrent action of magnetization currents. However, as the core layer 1 induces a magnetic field to the other layers, for instance to the core layers 2 and 3, the flux free region is not any longer observed in those, but on the contrary this is fulfilled mostly by magnetization currents flowing in the opposite direction, i.e, with $-J_{c}$. In finer detail, for the cable design (i), due to the transport current being applied to both, the ‘core’ and ‘shield’ layers, the 2G-HTS tapes at the two outermost layers of the core shown the same kind of current profiles than the shield layers, this because the dominant mechanism is the transport current. However, for the cable design (ii), it is to be noted than the current distribution profiles at the ‘shield’ layers refers only to magnetization currents, reason why the distribution between positive an negatives profiles of current density is fully balanced.
solution for isolated tapes or monolayer compact cables. However, for multilayer cables where the occurrence of magnetization currents and therefore magnetization losses (invisible to the electrical method), become of utter relevance, the electrical method offers only an approximate but generally lower representation of the true AC losses of the power cable. Thus, until an AC loss calorimetric rig for the testing of these cables is not completed (currently undergoing at the VNIIPK facilities), a proper estimation of the AC losses in triaxial cables can be only met by benchmarking the experimental results already available with the predictions made by numerical methods.

Thus, starting with the cable design (i), where transport current was applied to the ‘shield’ layers, it is to be noticed that although the predicted AC-losses of the ‘core’ layers is the same regardless whether the ‘shield’ layers are connected in series or not to the \( I_\text{tr} \) (see the red solid line at Fig. 3), the losses calculated at the shield layers without transport current (dashed line) are lower than the experimental ones (\( \nabla \)), and in fact these are nearly the same than the ones exhibited by the core layers (\( \bigcirc \)). Nevertheless, when transport current is considered at the ‘shield’ layers as defined in the actual experimental conditions [14], we have found that for moderate current amplitudes \( (0.4 I_c - 0.6 I_c) \), the AC losses of the cable, including magnetization losses, can be about 20% over the ones estimated by the electrical method (having as relative reference \( I_\text{tr} \), i.e., about 10% over the claimed ‘acceptability’ window. However, this is not to be understood as a criticism to the scope of the experiments within the electrical method, nor to be inferred as a robustness of the numerical method, but simply as a more detailed benchmark with which the actual AC losses of multilayer cables can be informed.

On the other hand, concerning to the cable design (ii), the experimental measurements of the AC losses were reported at a layer-by-layer level [12], what allows a better insight and assessment of the numerical model, and how it can offer a better discerning of the physical mechanisms that cause the.

III. AC LOSSES

The experimental measurement of the AC-losses in large scale multilayer cables as the ones presented in Fig. 1, is a very demanding and complicate task. Up to know this has been achieved only by means of elaborate electrical transport measurements [12], [14], which are known to offer an adequate...
energy losses, and influences the electromagnetic performance of the overall cable. Our results are shown in Fig. 4, where two contrasting scenarios can be seen at first sight. On the one hand, there is a clear discrepancy between the experimental measurements obtained at the innermost layer of the cable, i.e., for the core layer 1, whilst on the other hand, their is an outstanding agreement between the experimental results and the numerically calculated AC losses for all the other five layers, including the couple of outer layers at the ‘shield’. Thus, although at first, several hypothesis on the numerical model conditioners were questioned to determine the origin of such increment in the AC losses for the innermost layer of the cable, in a close inspection of the experimental results, it can be seen that the measured AC losses at this layer is unexpectedly higher than the losses at the other ‘core’ layers. However, as discussed before for the case of the cable design (ii), the innermost layer is the one less prone to be affected by magnetization currents, i.e., with its superconducting AC losses being determined mostly by the flow of transport current, whilst for all the other layers, the AC losses is the adding result of the concomitant action between transport and magnetization currents. Therefore, from fundamental physical principles, the superconducting energy losses for the core layers 2 to 4 cannot be greater than the superconducting energy losses at the core layer 1. This results in the conclusion that the experimental measurement for the AC losses at the core layer 1 reported at [12], is picking up a further source of energy losses that is not due to the hysteresis of the superconductor. Then, bearing in mind that in the experiment all superconducting layers and the former were electrically isolated, as it was the case for the cable design (i) where such behaviour is not observed, the most likely cause for this unexpected increment in the AC losses is suspected to be a defective soldering at one of the voltage taps used over these tapes. In this sense, the above does not really compromise the readability and validness of the experimental results with the electrical method for any of the layers of the cable, but on the contrary, by benchmarking with our numerical model, it offers a good and reliable testing for the electromagnetic performance of multilayer cables within well defined levels of tolerance.

IV. CONCLUSIONS

In this article, we have proven that by adequately setting the physical parameters of 2G-HTS tapes wound in cable configurations, and by taking advantage of two-dimensional computational frameworks in the so-called H-formulation, a sufficiently accurate estimation of the AC-losses for such complex cable arrangements can be made. Moreover, and advantage of this methodology is not only its shorter computing times, if compared with equivalent 3D models, but also the possibility to access the local electrodynamics for the profiles of current density inside each one of the wound superconducting tapes, where mechanisms such as occurrence and consumption of magnetization currents can be seen by the dynamics of the transport currents in Bean-like profiles.

Our conclusions are supported on the study of two cable designs which have been experimentally tested at the VNIIPK facilities under different transport current conditions [12], [14], with which we have established a proper benchmark for the forecasting of the overall AC losses of 2G-HTS cold dielectric triaxial cables. Thus, alongside a critical analysis of the physical mechanisms involved in the hysteresis cycle of the superconducting tapes, by direct comparison between our numerical results with the experimental measurements achieved by the electrical testing method, we have concluded that an acceptable margin of difference for either very low transport currents ($I_{tr} \lesssim 0.3I_c$) or very high transport currents ($I_{tr} \gtrsim 0.7I_c$), i.e., where the impact of magnetization currents is low or overcome by the transport current losses, is of about just 10%. However, at moderate transport currents, which can be classified to be between the aforementioned boundaries, the impact of the magnetization currents is significant, what might lead to differences of up to 20% the losses measured by the electrical testing method, as the latter is unable to give accountancy for the losses created by the magnetization currents.

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