Design optimization of high-voltage HTS three-phase cables with screened phases

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Abstract. Design versions of HTS cables with the screened phases ensuring the AC losses minimization have been investigated by the numerical simulation methods. The following methods of optimization have been proposed: sectioning of phases, using of HTS tapes with the modified configuration and variation of the phase diameter. At the critical current of a phase of 5.1 kA and its rated current of 4 kA, these methods allow lowering of AC losses level to 0.45 – 0.017 W/m what is much lower than natural heat fluxes into a cryostat. The designs proposed are compared with ones of the optimized tri-axial cables what allows a reasonable choosing of a cable type vs. a given electric power system design.

Introduction
Reduction of AC losses in superconducting AC cables by their design optimization is a very important task which determines the efficiency of using HTS materials in electric power engineering [1-3]. In this paper are investigated by the numerical simulation methods design versions of HTS cables with screened phases optimal for high voltage applications where the high electric insulation thickness is required. The comparative analysis of the characteristics of these cables with those of tri-axial ones is performed as well. The software used is based upon our previously developed inductively coupled current circuit’s technique [4, 5]. The calculation technique assumes splitting the cable cross-section area into elements whose cross-section area is much lower than one of the cable components. The current distribution in these elements is calculated by the integration of the following system of differential equations:

\[ \sum_{n=1}^{N} L_{nk} \frac{dJ_n}{dt} - U^i = 0, \] (1)

where \( L_{nk} \) is the mutual inductance of elements \( n \) and \( k \), \( J_n \) is the current of element \( n \); \( U^i \) is the voltage across the cable phase \( i \) (the phase to which belongs element \( k \)), \( N \) is the total number of cable elements. This system is completed by the equations describing the current variation in phases:

\[ \sum_i \frac{dJ_i}{dt} = \frac{dJ^i}{dt}, \] (1a)

where the summation is performed over the elements belonging to phase \( i \). Therefore, the total quantity of the system equations becomes equal to \( k+m \), where \( m \) is the number of phases. For equations corresponding to the screen elements the value of \( U^i \) is set to be equal to 0. Respectively, equations in a form of (1a) rare not used for them, and total currents in screens are not set as arguments, but calculated as functions. For elements corresponding to the non-superconducting cable components are used the
equations in a form of (1) with the additional resistive term equal to $R_k^*J_k$, where $R_k$ is the active resistance of an element. When integrating the system, based upon the current distribution pattern obtained, are calculated all the cable electric characteristics including hysteresis losses in the HTS material and eddy current losses in non-superconducting cable components. The method used, unlike the traditional finite elements method, is not limited by problem of the results convergence and allows detailed calculations of AC losses in cables having the complicated structure.

The latter unlike the commonly used finite elements method is not restricted by the results convergence problem at a large number of design elements and allows detailed calculation of AC losses in HTS cables with complicated structure.

For all the HTS cables considered here the rated critical current phases is taken one and same and equals to 5.1 kA. The current-carrying elements of the cables are 2G HTS tapes manufactured by SuperPower (SP) [6, 7] and SuperOX (SOX) [8] and having a modified configuration (Fig. 1). Apart from HTS tapes, there is an extra copper in a cable, what is a frequently used but questionable technique of cable protection in a short-circuit mode. The amount of extra copper depends on the characteristics of HTS transmission line as a whole and conditions of its operation. Here we take the extra copper cross-section area to be equal to the averaged value - 120 mm$^2$ per phase and each screen.

As it can be seen from Fig. 1, the HTS tapes modification consists in the transfer of copper layer from the silver coating side to that one of the substrate. When positioning of these modified HTS tapes in two layers they are oriented face-to-face with their silver coating sides. Therefore, the distance between the superconducting materials in layers drops up to 4 µm (as compared with 84 µm for ordinary configuration tapes). As shown in [9], this reduction can diminish the hysteresis losses by an order of magnitude. However, the efficiency of this technique lowers when a large number of layers is required for positioning the necessary quantity of tapes on a phase perimeter. To avoid this, in some designs in the internal layers of a phase are used SOX tapes having 1.5 times higher critical current as that one of SP tapes with the same width. Another important opportunity of AC losses decreasing is the dense positioning of tapes in layers. Our calculations show the gaps between the tapes to be no higher than 3-5% of their width. At greater values of them, there is a rapid growing of AC losses caused by the increasing of the time-dependent magnetic field component perpendicular to the surface of tapes on their edges [10]. This requirement makes necessary an enlargement of tapes number in external layers as compared with the rated one since their perimeter increases. We follow this requirement in all our designs, despite of the increasing of the superconductor consumption. Moreover, for cables with screened phases we fulfill an additional requirement that the screen critical current should exceed the phase critical current at least by 10%. This is to ensure a reliable phase magnetic field screening at currents close to the critical values. The origin consists in that the tapes saturation by a current is non-
uniform, and the current density becomes critical on the tapes edges earlier than anywhere else, and there can be a formation of specific gaps through which a partial magnetic field penetration may occur.

The AC losses power in a cable $P_c$ is the sum of hysteresis losses in superconducting layers of HTS tapes $P_h$ and eddy current losses in its non-superconducting components $P_e$. The highest contribution in $P_e$ make the losses in extra copper layers since their cross-section area is much greater than one of copper and silver layers of HTS tapes themselves. To minimize $P_e$, extra copper layers are preferably positioned in the zones unaffected by the time-dependent magnetic field. In particular, in cables with screened phases they are positioned on internal perimeters of phases and on external perimeters of screens.

**Comparative analysis of design versions of HTS cables.**

The cables design versions with screened phases are given in Table 1. In the first three positions there are cables with the insulation thickness of 23 mm typical for high voltage cables. Each of phases is a single structure surrounded by a superconducting screen (Fig. 2, cable Ph3R23 – Sh). In cable Ph3RS23 – Sh each of its phases is divided into 2 screened sections. AC losses in any HTS cables with the same design are directly proportional to the square of the critical current. Therefore, the division into 2 sections should decrease AC losses approximately in 2 times. For cable Ph3RS23 – Sh an additional effect is reached due to the replacement of two layers of tapes in a phase by one. The external cable diameter $D_c$ is calculated for the case of positioning the six structures in one cryostat, but, in principle, there is an opportunity of positioning in two cryostats. This version is equivalent to the replacement of Ph3R23 – Sh by two cables connected in parallel having approximately the same dimensions as the original cable but the total losses of this design are significantly lower. The amplitude of the time-dependent magnetic field on the surfaces of superconducting layers decreases with the increasing of their diameters what diminishes AC losses as well. This effect is demonstrated for cable Ph3RV23 – Sh, having the increased phase diameter allowing positioning of HTS tapes in one layer.

In the next three positions of Table 1 are given the same design versions of cables with screened phases but having the insulation thickness of 6 mm. This value may be considered as a transient one from average voltage class cables to high voltage ones. The results obtained for these cables are compared with those of tri-axial cables (Fig. 3, Table 2). In tri-axial cables the phases (or sections of phases for the sectioned design) are positioned coaxially. They do not generate magnetic field components perpendicular to the surface of tapes. Additionally, due to the interaction of phase’s fields there is no magnetic field outside the cable. The absence of screens allows a significant lowering of tapes consumption and overall cable dimensions. However, the requirement of the dense positioning of in layers should be fulfilled. Generally, this requires, in turn, increasing of the tapes number in external

![Diagram](image-url)
phases of a cable, moreover, the material consumption grows with the insulation thickness, and there is a deterioration of phases cooling conditions as well. Therefore, using of tri-axial cables at the insulation materials existing nowadays is restricted by the average class of voltages. The decreasing of AC losses with the increasing of the HTS layer diameter takes place in tri-axial cables as well. That’s why, for a more complete comparison, we also consider cable Ph3RV6, in which the tapes layer diameter of the internal phase is increased up to that one of the phase of cable Ph3RV6-Sh.

The results of the total AC losses power calculation are given in Fig. 4. Generally, for all the cables operating amplitudes of phase currents are chosen within the range of 70 – 80 % of the phase critical current. Within this range, AC losses in all the cables designs are much lower than the natural heat flux losses into a cryostat of ca. 3 W/m. However, the difference of the losses value between the design versions considered are greater than an order of magnitude. This shows great opportunities for further total AC losses lowering up to the values at which there will be no essential difference between the losses levels of AC and DC cables.

The sectioning of cable Ph3R23-Sh lowers AC losses in 3.5 times (due to decreasing of phase critical current and replacement of two layers in a phase by one). But this is reached by the increasing of HTS tapes consumption in 1.5 times and cable diameter by 40%. In this situation, the design version of cable Ph3RV23-Sh is much more preferable since, due to having only one layer of tapes and increasing of layer diameter, AC losses reduce in 13 times, and the tapes consumption increasing is only 23% at the total AC losses lowering up to the values at which there will be no essential difference between the losses levels of AC and DC cables.

Table 1. Design versions of cables with screened phases. Symbols in the table: \( D_c \) is the external diameter of the structure described, \( D_e \) is the external diameter of a cable (without the external insulation thickness), \( d_s \) is the layer diameter HTS tapes over the superconductor [mm], \( J_c \) – phase critical current [kA], \( n \) is the total number HTS tapes in a cable. Structure description format from external to internal layers: \( F_i \) is the phase, \( S_i \) is the screen (\( i \)- layer number in a phases or screen), Cu “xx” is the extra copper thickness [mm], in “xx” is the insulation layer thickness [mm].

| Cable type            | Description and structure                                      |
|----------------------|----------------------------------------------------------------|
| Ph3R23-Sh \( D_c = 190 \) | Structure of a screened phase: Cu1.0 - \( F_1 - F_{23} \) - \( S_1 - Cu0.5 \); \( D_e = 86.1 \) |
| \( n = 378 \)        | F(Phase) Two layers of tapes SP \( n_1 = n_2 = 30 \); \( d_{S1} = 39.18 \); \( d_{S2} = 39.19 \) |
| \( J_c = 5.1 \)      | S(screen ) One layer of tapes SP: \( n = 66 \); \( d_s = 85.377 \) |
| Ph3RS23-Sh \( D_c = 266 \) | Structure of a phase section: Cu0.5- \( F_1 \) - in\( 23 \)- \( S_1 - Cu0.25 \); \( D_e = 85.9 \) |
| \( n = 576 \)        | \( F_1 \)(phase) One layer of tapes SP: \( n = 30 \); \( d_s = 39.18 \). |
| \( J_c = 5.1 \)      | \( S_i \)(screen ) One layer of tapes SP: \( n = 66 \); \( d_s = 85.19 \). |
| Ph3RV23-Sh \( D_c = 273 \) | Structure of a screened phase: Cu0.5 - \( F_1 \) - in\( 23 \)- \( S_1 - Cu0.3 \); \( D_e = 124.0 \) |
| \( n = 468 \)        | F (phase) One layer of tapes SPm: \( n = 60 \); \( d_s = 77.18 \). |
| \( J_c = 5.1 \)      | S (screen ) One layer of tapes SPm: \( n = 96 \); \( d_s = 123.19 \). |
| Ph3R6-Sh \( D_c = 120 \) | Structure of a screened phase: Cu1- \( F_1 - F_{6.5} \) - \( S_1 - S_2 - Cu0.7 \); \( D_e = 54.7 \) |

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\[ n = 420 \]
\[ J_C = 5.1 \]
Two layers of tapes SP: \( n_1 = n_2 = 30; d_{S1} = 39.76, d_{S2} = 39.77. \]

**S (screen)**

Two layers of tapes SP: \( n_1 = n_2 = 40; d_{S1} = 53.17, d_{S2} = 53.18. \]

**Ph3RS6-Sh**

Sectioned cable (6 structures in a cable)

\[ D_C = 162 \]
\[ n = 420 \]
\[ J_C = 5.1 \]

Structure of a phase section: Cu0.5- F1 - in6 - S1 - Cu0.35; \( D_{st} = 52.8 \)

**F1 (phase)**

One layer of tapes SP: \( n = 30; d_S = 39.18. \)

**S1 (screen)**

One layer of tapes SP: \( n = 40; d_S = 51.19. \)

**Ph3RV6-Sh**

Non-sectioned cable with the enlarged diameter (3 structures in a cable)

\[ D_C = 200 \]
\[ n = 384 \]
\[ J_C = 5.1 \]

Structure of a screened phase: Cu0.5- F1 - in6 - S1 - Cu0.45; \( D_{st} = 90.3 \)

**F1 (phase)**

One layer of tapes SP: \( n = 60; d_S = 77.00. \)

**S1 (screen)**

One layer of tapes SP: \( n = 68; d_S = 89.19. \)

**Figure 3.** Schematic diagrams of the tri-axial non-sectioned (a) and sectioned (b) cables. In Fig. (b) is shown only the part of cable cross-section area with the sides of polygons parallel to the Y-axis.

**Table 2.** Design versions of tri-axial cables. Thickness insulation 6 mm. The symbols are the same as in Table 1.

| Non-sectioned cable | Sectioned cable, all tapes SP |
|---------------------|-------------------------------|
| **Ph3R6** | Cu1.5- A1-A2-in6-Cu0.5- B1-B2-Cu0.5- in6- C1-C2-Cu0.7 |
| \( D_C = 54.8 \) | | |
| \( n = 180 \) | Phase A Two layers of tapes SOX: \( n_1 = n_2 = 20; d_{S1} = 26.31, d_{S2} = 26.32 \) |
| \( J_C = 5.1 \) | Phase B Two layers of tapes SP: \( n_1 = n_2 = 30; d_{S1} = 39.76, d_{S2} = 39.77 \) |
| | Phase C Two layers of tapes SP: \( n_1 = n_2 = 40; d_{S1} = 53.17, d_{S2} = 53.18. \) |
| **Ph3RS6** | Cu0.4-A1-in6-B1-Cu0.3-in6-C1-Cu0.8-C2-in6-Cu0.4-B2-in6-A2-Cu0.35; \( D_{st} = 76.26 \) |
| \( D_C = 76.3 \) | | |
| \( n = 227 \) | Phase A Two sections with one layer of tapes: \( n_1 = 18, n_2 = 58; d_{S1} = 23.48, d_{S2} = 75.48 \) |
| \( J_C = 6.375 \) | Phase B Two sections with one layer of tapes: \( n_1 = 27, n_2 = 48; d_{S1} = 35.68, d_{S2} = 63.28 \) |
| | Phase C Two sections with one layer of tapes: \( n_1 = 37, n_2 = 39; d_{S1} = 48.48, d_{S2} = 50.28 \) |
In tri-axial cables Ph3R6 and Ph3RV6 the exceeding of HTS tapes number over that one required for ensuring of the rated phase critical current is insignificant. In Ph3R6 this was provided by the replacement of SP tapes by ones of SOX in phase A. In Ph3RV6 it was reached by the comparatively low insulation layer thickness. But in a sectioned cable where the number of insulation layers increased up to 4 the tapes consumption increased as well. However, tri-axial cables, as compared with their equivalents with screened phases, have actually doubled gain in tapes consumption and overall diameter. But they have a more than doubled level of losses. The increasing of the latter in tri-axial cables Ph3R6 and Ph3RS6 can be partially explained by the lower diameters of HTS tapes layers (ones of phase A).

Figure 4. AC losses power for design versions of cables given in Tables 1 and 2. $J_0 = J_0 / J_C$, where $J_0$ – current amplitude of a phase, $J_C = 5.1 \text{ kA}$ - phase rated critical current. (determined by the minimal $J_C$ of a phase), $f = 50 \text{ Hz}$. Solid lines – cables with screened phases, dashed lines – tri-axial cables.

Figure 5. Analysis of the components of AC losses power. Solid lines with light markers – cable with screened phases Ph3RV6-Sh, dashed lines with dark markers – Tri-axial cable Ph3RV6.
But the layer of phase \( A \) in cable Ph3RV6 has the same diameter as one of the phase of Ph3RV6-Sh, and the decreasing of AC losses in the tri-axial cable in 2.2 times seems to be strange at first sight. The origin of this can be found from Fig. 5. It is seen that hysteresis losses in tri-axial cable are almost twice lower than the total losses in screens and phases of cable Ph3RV6-Sh. But they are only 23% of the total losses. Other 77% are the eddy current losses totally caused by the extra copper in phase \( B \). This extra copper cannot be removed from the zone subjected to the time-dependent magnetic field.

In cable designs where the AC losses level is not optimized (e.g. having multilayer phase windings onto a low diameter at the long distance between layers, low density of tapes positioning in layers etc.) the hysteresis losses are 80 – 90% of the total value. For these cables, the problem of \( P_h \) decreasing is not essential. However, an optimization performed allows decreasing of \( P_h \) more than by an order of magnitude. That’s why, the problem of eddy current losses decreasing becomes important for optimized cables. Generally, adding of extra copper in a cable is explained by the requirement to ensure its stability against short-circuit modes. But in [11] this approach was shown to be valid for short samples only. For actual HTS lines, in the most of instances, takes place a reversed situation consisting in that extra copper not deteriorates the stability against short-circuit modes but also worsens other characteristics of the latter (e.g. surge and breaking currents). Therefore, the problem of diminishing of extra copper in a cable or its replacement by a material with the higher resistance becomes significant not only in terms of reduction of AC losses.

**Conclusion.**

Various design versions of tri-axial cables and ones with screened phases have been investigated by the numerical simulation methods with the aim of AC losses minimization. At the phase critical current of 5.1 kA and rated current amplitude 4 kA the minimized losses values are within the range 1 – 0.017 W/m what is much lower than the natural heat fluxes into cryostat (2 – 3 W/m). Moreover, the optimized designs obtained have an insignificant difference in the total losses level between AC and DC cables.

It has been shown that at the insulation thickness ca. 6 mm and lower the cables with screened phases yield in dimensional characteristics and superconductor consumption against tri-axial ones, and at a significant reduction of eddy current losses, the total losses of tri-axial designs are lower. However, with the increasing of insulation thickness this advantages diminish with the simultaneous complication of various technological problems – e.g., deterioration of cooling conditions of intermediate phases or sections, enlargement of dimensions and, hence, lower flexibility, what, in turn, hinders the transportation etc. Therefore, at the insulation thickness for high voltage range using of cables with screened phases becomes reasonable. An exact boundary between the fields of application of both these types of cables cannot be drown. It depends of the characteristics of the given electric power system under development and technologies used by the cable manufacturer. But, the enhancement of the latter and improvement of the insulation characteristics can move this boundary in favor of tri-axial cables.

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