Design versions of HTS three-phase cables with the minimized value of AC losses

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Abstract. Design versions of HTS three-phase cables consisting of 2G HTS tapes have been investigated by the numerical simulation method with the aim of AC losses minimization. Two design versions of cables with the coaxial and extended rectangular cross-section shape are considered – the non-sectioned and sectioned one. In the latter each cable phase consists of sections connected in parallel. The optimal dimensions of sections and order of their alteration are chosen by appropriate calculations. The model used takes into account the current distribution between the sections and its non-uniformity within each single HTS tape as well. The following characteristics are varied: design version, dimension, positioning of extra copper layer in a cable, design of HTS tapes themselves and their mutual position. The dependence of AC losses on the latter two characteristics is considered in details, and the examples of cable designs optimized by the total set of characteristics for the medium class of voltages (10 – 60 kV) are given. At the critical current $J_C=5.1$ kA per phase and current amplitudes lower than $0.85J_C$, the level of total AC losses does not exceed the natural cryostat heat losses.

1. Introduction

In [1], within the framework of the program of investigations aimed to minimization of AC losses in HTS-cables, there had been performed an optimization of coaxial three-phase cable designs by the variation of the cable geometry, mutual positions of HTS tapes layers and extra copper layers as well [2-7]. We also have investigated and used an opportunity to diminish AC losses by the minimization of gaps between the HTS tapes in each of their layers. It has been shown that, due to optimal choosing of these parameters, there is an opportunity to decrease AC losses in 2 - 3 times. We also considered
the sectioning of cables allowing decreasing of losses by an order of magnitude and even more. In this paper, we investigate another opportunity of AC losses decreasing consisting in the lowering of distance between the superconducting layers positioned in HTS tapes themselves. As it was made before, the investigations were performed by the numerical simulation using the software described in [8, 9].

2. Cable design versions

The general view of the coaxial cable cross-section is shown in Fig. 1(a), and cable design versions described in details are given in Table 1. In Fig. 1(b) are shown the configurations of HTS tapes used as basic current-carrying elements of cables. All the cable designs considered here have one and the same mutual phases position, HTS tapes layers groups (2 or 3 layers per phase), insulation and extra copper layers. Extra copper (completing copper layers of HTS tapes themselves) is introduced to prevent the superconductor overheating in a short-circuit event (within a time interval of ca. 120 ms between the start of the event and the actuation of protective circuit-breakers). The extra copper cross-section area (ca. 122 mm² per phase) is chosen by averaging, but the exact value may be found only for specific characteristics of the given electric power network and its fault current limiting devices. The first three positions in Table 1 are occupied by cables Ph3R"x" whose designs were obtained by the optimization described in [1]. They differ by the rated insulation layers thickness ("x") – respectively, 2, 4 and 6 mm. In process of optimization, actually chosen insulation thicknesses were varied in order to ensure compact positioning of tapes in layers (certainly, by the increasing of the thickness with respect to the rated value). To the same end, the number of tapes in certain cable phases was increased (resulting in the phase critical current relative to the established rated value of 5.1 kA).

Since the cable critical current is determined by its weakest phase, this increasing must be interpreted as a compelled excessive consumption of the superconducting material allowed to diminish the AC losses value. In the first three cable designs of Table 1 is used standard HTS tapes configuration 1 (see

![Figure 1](image_url)

**Figure 1.** (a) The view of the cross-section shape of coaxial cables, given in Table 1: 1 - groups of HTS tapes layers, 2 - insulation layers, 3 – extra copper layers; (b) variants of the HTS material configuration in tapes: δ– is the HTS material thickness. The arrows show the orientation of tapes in cable phases. Configuration 1 – is one of the standard designs of SuperPower tapes [10, 11]. Configuration 2 – designs of tapes, considered here. 1- copper layer (for SuperPower tapes δ= 40 μm, for SuperOx tapes δ= 60 μm); 2 – silver layer (δ= 2 μm); 3 – superconducting layer(for SuperPower tapes δ=1 μm, for SuperOx tapes δ=1,5 μm); 4 – hastelloy substrate for SuperPower tapes δ=50 μm, for SuperOx tapes δ=60 μm. The critical current of SuperPower tapes is 85 А, of SuperOx tapes - 127А, the width of both tapes is 4 mm.
Table 1. Coaxial cables with the polygonal cross-section shape

(Designations of Table 1: d, D – are the internal and external cable diameters (D is given without the external cable insulation thickness) [mm], dₗ – is the superconducting layer diameter of HTS tapes (i.e., diameter of the circle inscribed into a polygon), Jₜₚₚ – is the phase critical current [kA]. The general cable structure (from internal to external layers) is described as follows: Aₙ, Bᵢ, Cᵢ – are the phases of a layer (i is the layer number in a phase), Cu “xx” – is the extra copper layer thickness [mm], ins “xx” – is the insulation layer thickness [mm].)

| Cable type | Phase | dₗ of layers | Number of tapes in layers | Jₜₚₚ |
|------------|-------|--------------|---------------------------|------|
| Ph3R2      |       |              |                           |      |
| d = 23     |       |              |                           |      |
| D = 41.16  |       |              |                           |      |
|            | A     | 26.08; 26.28; 26.48 | 20; 20; 20 | 5.1  |
|            | B     | 32.48; 32.68; 32.88 | 25; 25; 25 | 6.375|
|            | C     | 38.88; 39.08    | 30; 30             | 5.1  |
| Ph3R4      | Cu₁.₅-A₁₂-A₃₂-ins 5.4-Cu₀.₅-B₁₂-B₂₃-Cu₀.₅-ins 4-C₁₂-C₂₂-Cu₀.₈ | A 26.08; 26.28; 26.48 | 20; 20; 20 | 5.1  |
| d = 23     | B     | 38.48; 38.68    | 30; 30             | 5.1  |
| D = 49.76  | C     | 47.88; 48.08    | 37; 37             | 6.29 |
| Ph3R6      | Cu₁.₅-A₁₂-A₃₂-ins 6-Cu₀.₅-B₁₂-B₂₃-Cu₀.₅-ins 6-C₁₂-C₂₂-Cu₀.₇ | A 26.08; 26.28; 26.48 | 20; 20; 20 | 5.1  |
| d = 23     | B     | 39.68; 39.88    | 30; 30             | 5.1  |
| D = 54.76  | C     | 53.08; 53.28    | 40; 40             | 6.8  |
| Ph3R2-V1   | Cu₁.₅-A₁₂-A₃₂-ins 2.3-Cu₀.₆-B₁₂-B₂₃-Cu₀.₆-ins 2.3-C₁₂-C₂₂-Cu₁.₀ | A 26.16; 26.35; 26.36 | 20; 20; 20 | 5.1  |
| d = 23     | B     | 32.56; 32.73; 32.74 | 25; 25; 25 | 6.375|
| D = 41.16  | C     | 38.96; 38.97    | 30; 30             | 5.1  |
| Ph3R4-V1   | Cu₁.₅-A₁₂-A₃₂-ins 5.4-Cu₀.₅-B₁₂-B₂₃-Cu₀.₅-ins 4-C₁₂-C₂₂-Cu₀.₈ | A 26.16; 26.35; 26.36 | 20; 20; 20 | 5.1  |
| d = 23     | B     | 38.56; 38.57    | 30; 30             | 5.1  |
| D = 49.76  | C     | 48.06; 48.07    | 37; 37             | 6.29 |
| Ph3R6-V1   | Cu₁.₅-A₁₂-A₃₂-ins 6-Cu₀.₅-B₁₂-B₂₃-Cu₀.₅-ins 6-C₁₂-C₂₂-Cu₀.₇ | A 26.16; 26.35; 26.36 | 20; 20; 20 | 5.1  |
| d = 23     | B     | 39.76; 39.77    | 30; 30             | 5.1  |
| D = 26.58  | C     | 53.17; 53.18    | 40; 40             | 6.8  |
| Ph3R2-V2   | Cu₁.₅-A₁₂-A₃₂-ins 2.3-Cu₀.₆-B₁₂-B₂₃-Cu₀.₆-ins 2.3-C₁₂-C₂₂-Cu₁.₀ | A 26.31; 26.32 | 20; 20 (SuperOx) | 5.1  |
| d = 23     | B     | 32.60; 32.61    | 25; 25 (SuperOx)   | 6.375|
| D = 41.15  | C     | 38.96; 38.97    | 30; 30             | 5.1  |
| Ph3R4-V2   | Cu₁.₅-A₁₂-A₃₂-ins 5.4-Cu₀.₅-B₁₂-B₂₃-Cu₀.₅-ins 4-C₁₂-C₂₂-Cu₀.₈ | A 26.31; 26.32 | 20; 20 (SuperOx) | 5.1  |
| d = 23     | B     | 38.56; 38.57    | 30; 30             | 5.1  |
| D = 49.76  | C     | 48.06; 48.07    | 37; 37             | 6.29 |
| Ph3R6-V2   | Cu₁.₅-A₁₂-A₃₂-ins 6-Cu₀.₅-B₁₂-B₂₃-Cu₀.₅-ins 6-C₁₂-C₂₂-Cu₀.₇ | A 26.31; 26.32 | 20; 20 (SuperOx) | 5.1  |
| d = 23     | B     | 39.76; 39.77    | 30; 30             | 5.1  |
| D = 54.76  | C     | 53.17; 53.18    | 40; 40             | 6.8  |

Fig. 1b). In this paper were calculated the characteristics of cables denoted as Ph3R"x"-Vi. These cables differ from their counterparts only by the replacement of tapes with configuration 1 by ones with 2. That’s why comparison of the results obtained here with those of [1] allows estimation of
effects, exclusively caused by decreasing the distance between the superconducting layers of HTS tapes.

Analytical expressions of [12, 13] show, that in a continuous superconductor with the ring cross-section shape the hysteresis losses drop with the decreasing of the ring thickness. The same is likely to expect in a cable, consisting of HTS tapes, when decreasing the distance between the HTS adjacent layers. In tapes of configuration 1, the superconducting layer is actually positioned on the tape axis of symmetry, and due to this, the distance between HTS layers weakly depends on the mutual orientation of tapes in adjacent layers. In tapes of configuration 2 the copper coating is repositioned on the substrate side. As a result, positioning the tapes of adjacent layers with the oppositely oriented silver coating reduces the distance between the HTS layers themselves to 4 μm. The transition of the copper coating part to the substrate side has been already made in some design versions of SuperPower tapes (having 20 μm of copper per each side). This design modification does not actually affect both the tapes stability against magnetic flux jumps and their mechanical characteristics. Some of our preliminary experiments showed the tape carrying AC current to remain stable and to have actually the same critical current even without copper coating. Therefore, the hypothetical design of configuration 2 may be realized in principle. However, the peculiarities of the cable manufacturing technology may require having a thin copper coating on the silver for additional mechanical and chemical protection of the superconductor’s surface. In this case the efficiency of the technique proposed is lower, and the results obtained here should be considered as ultimately possible ones.

The schematic diagrams of positioning layers of tapes in various cables are shown in Fig. 2. In phases A of cable design versions V1 there are three layers of HTS tapes (for design Ph3R2-V1 – three layers of tapes are in phase B as well). That’s why the effect of distance reduction between the layers is not totally used. In cable design V2, for these phases are used SuperOx tapes [14, 15], whose characteristics ensure the rated phase critical current when only two layers of tapes are present. This causes an additional reduction of hysteresis losses in these phases, and the general result is also improved.

Figure 2. Schematic diagrams of HTS tapes layers positioning in cable phases. The arrows show the tapes orientation according to Fig. 1(b). The dashed line is the third layer of tapes in phases B of cables Ph3R2 and Ph3R2–V1. (a) The cables Ph3Ri, SuperPower tapes, configuration 1; (b) the cables Ph3Ri-V1, SuperPower tapes, configuration 2; (c) the cables Ph3Ri-V2, all the tapes are of configuration 2, in phases A of all cables and in phase B of cable Ph3R2-V2 are the SuperOx tapes, in other phases are the SuperPower tapes.
3. Results of calculations.

AC losses in superconducting power transmission lines are the sum of hysteresis losses in superconductors and eddy current losses in other non-superconducting elements. Since in coaxial three-phase cables the external magnetic stray field is actually absent, eddy current losses consist only of losses in non-superconducting components of HTS tapes and ones in extra copper layers. The latter, having essentially greater thickness, predominate and are ca. 95% of the total eddy current losses.

In Fig. 3a are given the results of calculation of the AC losses power $P_S$ per 1 m of cable length at 50 Hz. The dimensionless current plotted on the x-axis is determined as $I = J_0/J_c$, where $J_0$ – is the current amplitude, $J_c$ – is the critical current of the weakest cable phase. Fig. 3b shows the contribution of eddy current losses in the total AC losses.

![Figure 3. (a) The total power of AC losses $P_S$ in cables with the structure given in Table 1; (b) the ratio of the eddy current losses $P_e$ power to the total power of AC losses $P_S$.](image)

AC losses in a cable do not affect essentially the economic parameters of the power system (including choosing between AC and DC cables), if they are much lower than the natural cryostat heat losses (denoted as $P_{(Cryost)}$ in Fig.3a). As it can be seen from Fig. 3a, within the actually significant range of $I \leq 0.8$, all the cables of design V2 satisfy this requirement. From Fig. 3b it follows, that in designs Ph3-V the contribution of eddy current losses is greater than in non-modified ones Ph3R. But their value does not change significantly, and the cause of it consists in an essential lowering of hysteresis losses. Hence, there is an additional opportunity of further $P_S$ decreasing by lowering the losses in extra copper layers. Since the latter have already been positioned optimally, this task can be solved either by decreasing of their thickness according to the specific power network characteristics.
or by the replacement of copper by a material having the lower electric conductivity, but, respectively, the greater specific heat capacity.

4. Conclusions
There had been proposed a technique to diminish the losses in AC HTS-cables by using HTS tapes with an asymmetrical position of the superconducting layer. It is shown that this modification enables the reduction of losses in 2 – 3.7 times, as compared with already optimized cables having the tapes with an ordinary structure. It should be especially noted that the maximum effect (decreasing in 3.7 times) takes place within the most important range of current amplitudes 0.7≤I≤0.8. The effect obtained is lower than one reached by cable sectioning. However, unlike sectioning, the modification proposed does not increase the overall cable dimensions and does not deteriorate the cooling conditions of phases. It is simpler with respect to the cable manufacturing technology. Moreover, for cables, having high critical current, and, hence, many layers of tapes in each phase, there is an opportunity to combine sectioning with the tape structure modification in each section. In this case, the losses reduction coefficient is determined both by sectioning and the technique proposed here and may be greater than an order of magnitude.

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6. References
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