Simulation and Test of the Compact 2G HTS Power Cable

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Objectives

Superconducting power cables offer the advantage of lower loss, lighter weight, and smaller dimensions, in comparison with conventional cables. It is important to developed most compact cable to increase the transmission power density of a cable. The compact 1-phase 2G HTS AC power cable model has been developed and tested in Russian Cable Institute. The cable core consists of three layers of 2G HTS tapes, with eight tapes per layer and two layers of 2G HTS shield with thirteen tapes per layer. The inner diameter of HTS layer in the cable core is 11 mm. The current distribution in the co-axial multi-layered cable has been analyzed and simulated by three numerical models. First, we have developed the electric circuit model cable, and then developed two FEM models using the finite-element code ANSYS. The numerical simulation provided detailed information about the current and field distributions inside the cable and the optimal parameters of the cable have been determined. We also analyzed the sensitivity to variations of key parameters and their affect on the current distribution in a cable with small diameter. The test results including AC loss are compared with calculations.

The electric circuit scheme

$$\begin{pmatrix}\Delta I_1\\ \vdots\\ \Delta I_m\\ \Delta I_{m+1}\\ \vdots\\ \Delta I_N\end{pmatrix}=\begin{pmatrix}L_1 & \cdots & M_{1,m} & M_{1,m+1} & \cdots & M_{1,N}\\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots\\ M_{m,1} & \cdots & L_m & M_{m,m+1} & \cdots & M_{m,N}\\ M_{m+1,1} & \cdots & M_{m+1,m} & L_{m+1} & \cdots & M_{m+1,N}\\ \vdots & & \vdots & \vdots & \ddots & \vdots\\ M_{N,1} & \cdots & M_{N,m} & M_{N,m+1} & \cdots & L_N\end{pmatrix}^{-1}\cdot\begin{pmatrix}R_{add}\\ \vdots\\ R_{add}\\ R_{addSc,1}\\ \vdots\\ R_{addSc,n}\end{pmatrix}\cdot\begin{pmatrix}I_{add}\\ \vdots\\ I_{add}\\ I_{addSc,1}\\ \vdots\\ I_{addSc,n}\end{pmatrix}\cdot\Delta t,$$

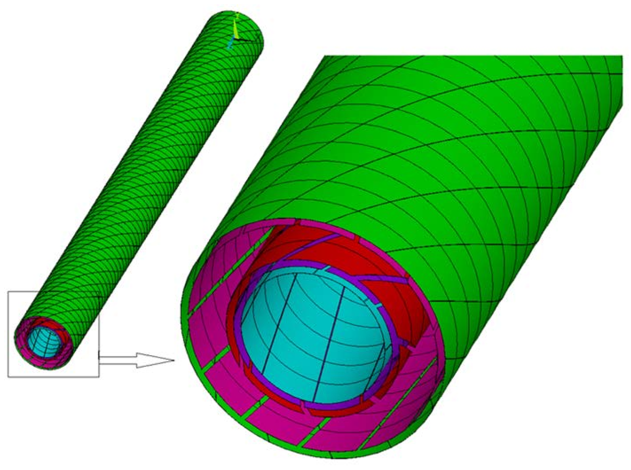
$$\sum_{i=1}^{m} I_i(t)+I_{add}=I_{total}(t) \qquad I_{m+1}(t)+I_{addSc1}=0,\ldots I_N(t)+I_{addScn}=0$$

$$F(X)=\min f(X)=\sum_{i=1}^{m-1}\sum_{j=i+1}^{m}\left|I_i(X)-I_j(X)\right|+\sum_{i=m+1}^{N-1}\sum_{j=i+1}^{N}\left|I_i(X)-I_j(X)\right|$$

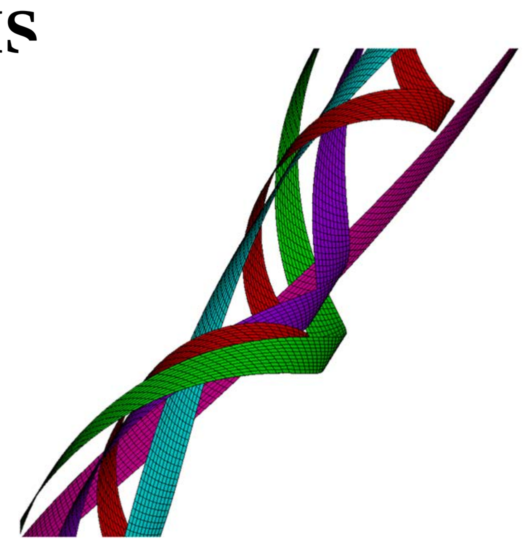
$$X=\left[r_1,\beta_1,a_1,r_2,\beta_2,a_2,\ldots,r_N,\beta_N,a_N\right]$$

Models for optimization

Complex detailed FEM 3D model using ANSIS



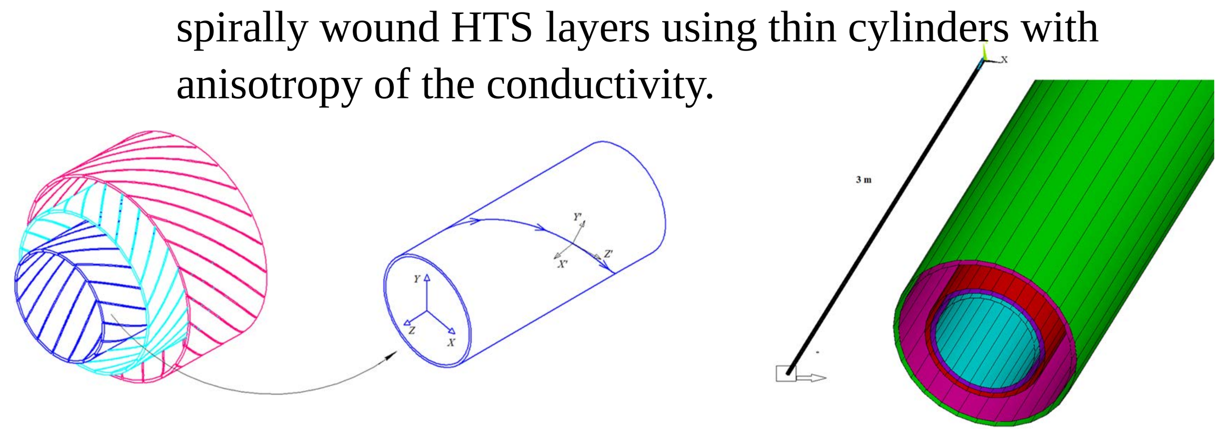
FEM of HTS power cable composed of 3-layer HTS conductor and 2-layer HTS shield.



Some tapes in layers of the cable.

FEM simulations of the HTS cable with anisotropy of the conductivity using ANSIS

For faster and simpler calculation first FEM simulate spirally wound HTS layers using thin cylinders with anisotropy of the conductivity.

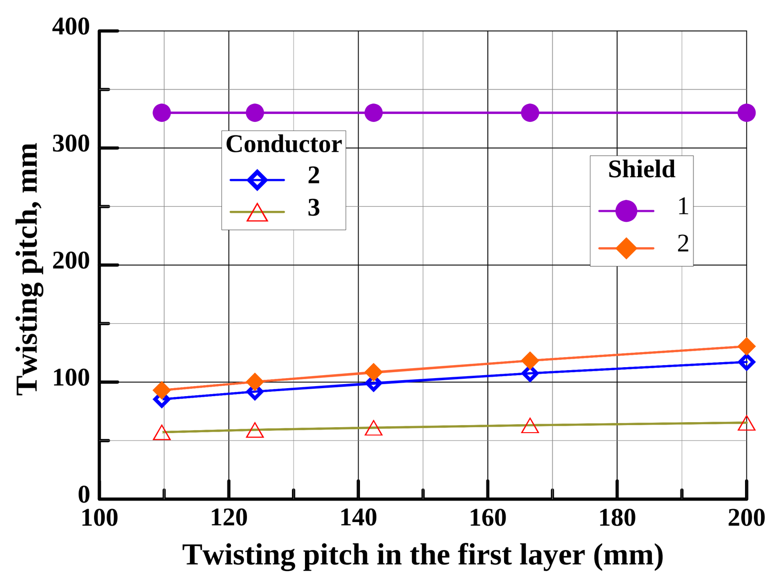


The conductivity of the anisotropic thin conductor is a tensor of order two, of which the off-diagonal elements are all zero.

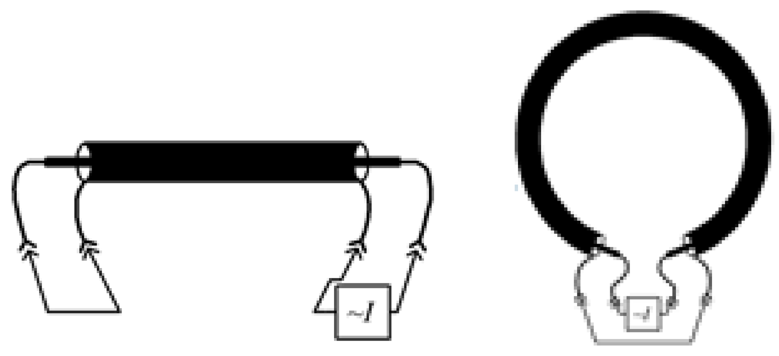
$$\sigma=\begin{bmatrix}\sigma_{x'} & 0 & 0\\ 0 & \sigma_{y'} & 0\\ 0 & 0 & \sigma_{z'}\end{bmatrix}$$

The standard test program for cable includes: DC test to determine critical currents; AC test to determine current distribution among layers at AC conditions; AC loss measurements by electrical method.

Models and DC test



Twisting pitch in three-layer conductor and two layers shield for realizing homogeneous current distribution.



Two types of connections both sides of the cable.

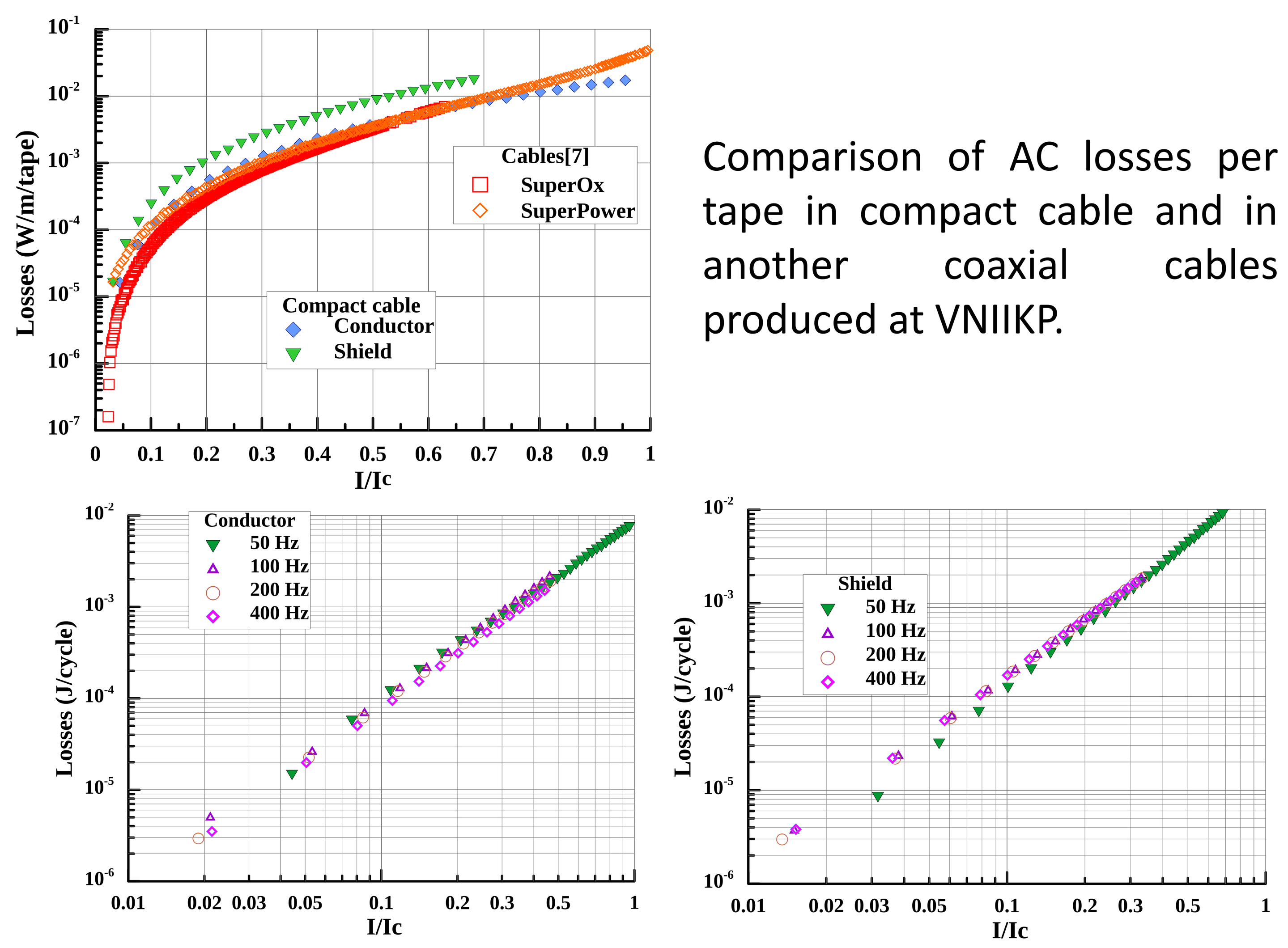
TABLE I

Parameters of the 5 m 2G HTS cable

	Inner radius, mm	Twisting pitch, mm	winding direction	Number of tapes
	Cable core			
1st layer	11.5	200	+1	8
2nd layer	12.25	109	+1	8
3rd layer	13	61	+1	8
	Cable shield			
1st layer	18.4	330	-1	12
2nd layer	19.6	110	+1	12

The critical currents (I_c), defined by the criterion of 1 µV/cm, of the cable core is 3640 A and in the shield 4590 A at 77.4 K. The sum of critical currents of all 2G HTS tapes used is 4600 A. The degradation of the critical current in the cable core is due to mechanical stress, because we used tape with a thick substrate.

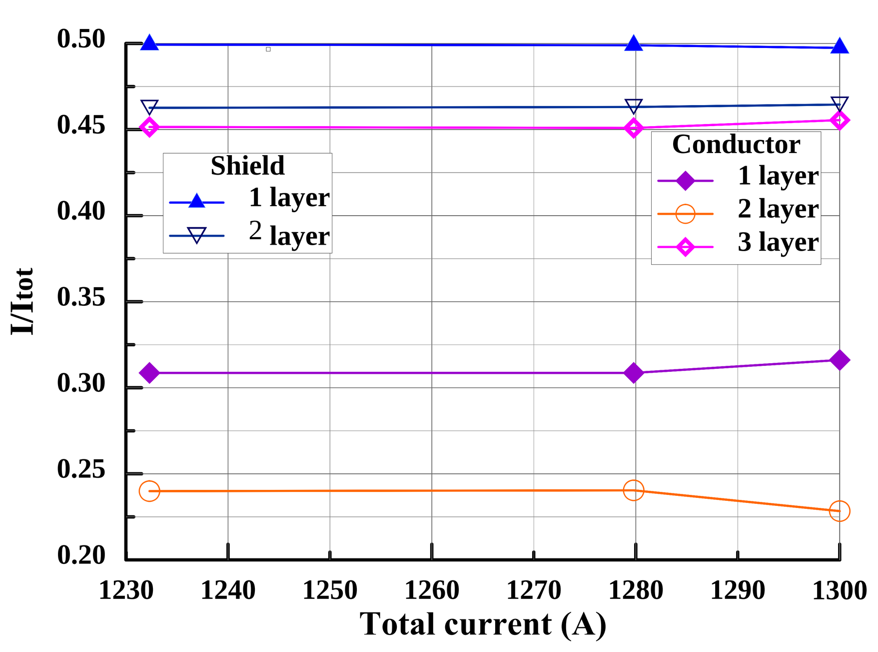
AC loss measurements



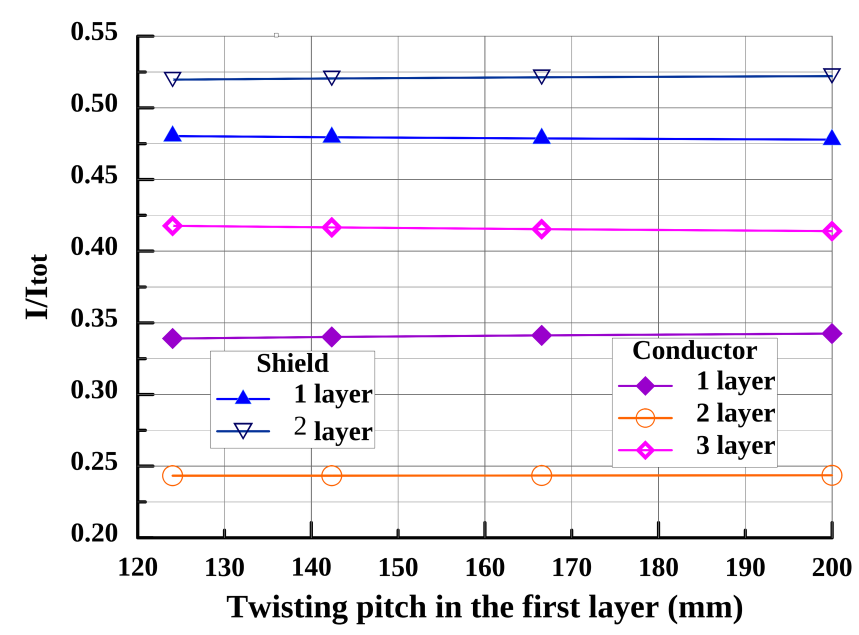
Comparison of AC losses per tape in compact cable and in another coaxial cables produced at VNIIKP.

AC Losses at the conductor and shield at different frequencies.

AC test and Discussion



Measured current distribution between layers of conductors and shield of the HTS cable.



Calculated maximal currents in layers of the cable versus total current when the diameter of the third layer deviates from the optimal diameter by 0.1 mm that is just the thickness of one HTS tape.

To use HTS tape with a smaller width.

To improve the process quality and design reliability in the optimization procedure of the compact cable it is necessary to use robust optimization in which we can use for example two-objective function, in contrast to the classical optimization, where a one-objective function $f(x)$ is used,

$$F(X)=\min(\mu(f(x)),\sigma(f(x)))$$

were $\mu(f(x))$ – mean value and $\sigma(f(x))$ – standard deviation of the objective function $f(x)$.

CONCLUSIONS

Analysis of research results shows that during design and optimization of compact coaxial HTS cables it is necessary to use 3D FEM to obtain current and magnetic field distribution inside the cable taking into a consideration spiral structure of current-carrying and shielding layers. The problem is that such FEM model takes a lot of time to perform calculations.

Simplified 3D FEM model had been created to reduce calculation time. In this model, multi-layer current carrying element and magnetic shield of HTS cable are represented as system of thin concentric cylindrical layers so calculation time is drastically reduced.

Finite difference model based on equivalent electrical scheme of the cable had been also created to verify FEM calculation results.

Design of compact coaxial HTS is complicated and requires high precision optimization and manufacture. The models developed were used during design and manufacturing process of HTS cable with small diameter. As a result of the new research methods and technical solutions to obtain optimal construction of compact cables were created.

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