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Current distribution in parallel tapes of superconducting transformer windings

***Abstract**. The main problem of the construction of superconducting transformer with windings made of high-T_C superconductor coated tapes is the high cost of superconducting materials. Superconducting winding transporting AC current generates power losses. Their amount must remain at extremely low level allowing to cover cryogenic cooling expenditures and increased price of HTS windings. Authors consider the possibility of the replacement of expensive continuously transposed cable (CTC, Roebel cable) by discrete transposition interconnector.*

***Streszczenie.** Podstawowym problemem budowy transformatora z uzwojeniami z nadprzewodnika wysokotemperaturowego jest wysoki koszt materiału nawojowego. W uzwojeniu nadprzewodnikowym wiodącym prąd zmienny pojawiają się straty. Ich ilość musi zostać zminimalizowana do poziomu uzasadniającego zastosowanie chłodzenia kriogenicznego i taśm nadprzewodnikowych. Autorzy rozważają możliwość zastąpienia kabla CTC przez prosty transpozycjoner taśm. (**Rozpływ prądów w równoległych taśmach uzwojeń transformatorów nadprzewodnikowych**)*

Keywords: superconducting transformer, HTS tape transposition.
Słowa kluczowe: transformator nadprzewodnikowy, transpozycja taśm HTS.

Introduction

Electric energy produced in a power plant is transformed three to five times on the way to a wall socket. Despite transformer high efficiency, these devices are responsible for 5-10% of total power losses in distribution network [1]. Main part of these losses is generated in windings made of copper wires. Usage of superconductors can bring meaningful improvement in transformer efficiency.

The commercialization of high temperature superconductor (HTS, critical temperature T_c > 25 K) coated conductors (HTS CC, second generation HTS, 2G HTS) has opened a new era. 2G HTS tape is coated with a thin layer of $YBa_2Cu_3O_7$ (YBCO) superconductor (Fig. 1).

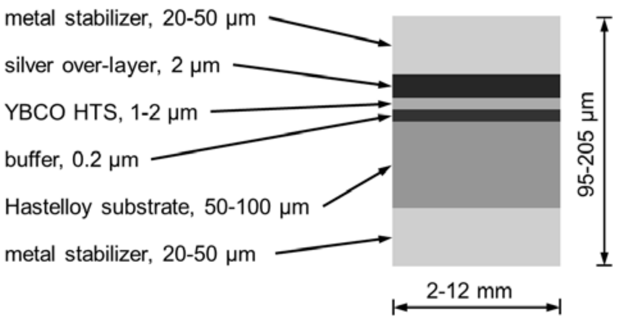

Fig. 1. Cross-section of 2G HTS tape (anisotropic scale) [2]

Winding made of superconducting wire transporting AC current generates energy losses. Their amount must remain at a very low level comparing to the losses of conventional copper winding. It allows to cover cryogenic cooling expenditures and increased cost of HTS windings [2].

The critical current of 12 mm wide 2G HTS tape is around 300 A (DC, at 77 K, at magnetic self-field). Winding of a high power transformer must be made of a number of parallel tapes (Fig. 2a). These superconducting wires are connected electrically at their ends. Loops are formed in which alternating magnetic stray field induces over-critical currents comparable to Inter-Strand Coupling Currents (ISCC). This phenomenon results in additional energy losses even at no-load state. Moreover, under the load, energy losses of the parallel stack are several times greater than it would occur in the magnetically and electrically isolated lines.

Solution to this problem is known since over a hundred years. The lowest power losses are generated in continuously transposed cable (CTC, Roebel cable) – interlaced stack with full strand transposition (Fig. 2b).

High-T_C superconductor CTC can be made of sophisticatedly cut and assembled tapes. This very expensive material is sold in limited quantities at the present time [3].

The paper describes the possibility to reduce the winding cost by means of partial transposition of standard 2G superconducting tapes (Fig. 2c).

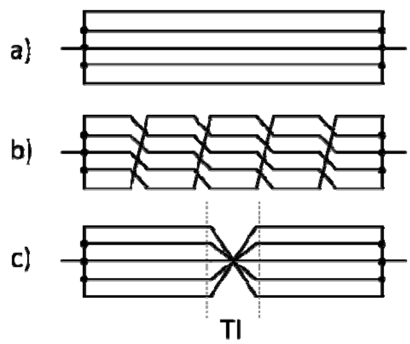

Fig. 2. Parallel wire configurations (TI – transposition interconnector)

Numerical analysis

Calculations were performed using the Finite Element Analysis software package COMSOL Multiphysics.

The computational domain is shown in Figure 3. It consists of the ferromagnetic core d_1 and diamagnets d_2, d_3, d_4. Domain d_2 represents insulation and liquid nitrogen surrounding the winding made of HTS 2G tape. Two regions of the tape are taken under consideration: HTS coating d_3 and copper stabilizer d_4.

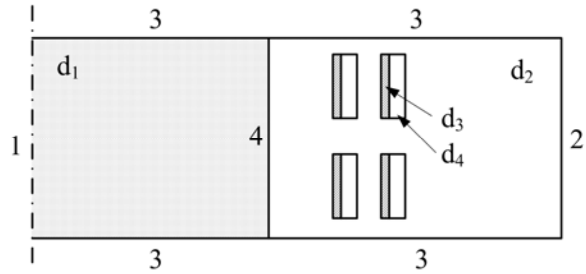

Fig. 3. Computational domain represents cross-section of the magnetic core and the winding made of HTS tapes

Boundary 1 denotes axial symmetry of the problem. Edge 2 simulates the presence of transformer secondary winding by means of axial magnetic field H_z. Boundaries 3 are set as perfect magnetic conductor, which simplifies problem to two adjacent turns of infinite solenoid.

This two-dimensional problem is governed by Faraday's, Ampere's and Gauss's equations:

$$\mu \frac{\partial \mathbf{H}}{\partial t} + \nabla \times \mathbf{E} = 0, \quad \nabla \times \mathbf{H} = \mathbf{J}, \quad \nabla \cdot \mathbf{B} = 0 . \tag{1}$$

For the superconducting layer the **E**-**J** power law representing the flux creep behavior is given by

$$E(J) = E_{\mathrm{c}} \frac{J}{|J|} \left(\frac{|J|}{J_{\mathrm{c}}} \right)^n \tag{2}$$

where: J – current density, J_c – critical current density, E_c, n – constants.

To take into account the $J_c(\mathbf{B})$ dependence, a scaled Kim-like model is used [4]

$$J_{\mathrm{c}}(B_{\mathrm{r}}, B_{\mathrm{Z}}) = \frac{J_{\mathrm{c0}}}{\left(1 + \frac{\sqrt{k^2 B_{\mathrm{Z}}^2 + B_r^2}}{B_0} \right)^{\alpha}} \tag{3}$$

where: B_r, B_z – radial and axial components of the magnetic flux density, J_{c0}, α, k, B_0 – constants.

The sinusoidal transport current $i_k(t)$ of the winding is imposed by restraining the value of integral domain probe

$$i_{\mathrm{k}}(t) = \int_k \mathbf{J} \cdot \mathrm{d}\mathbf{A}_{\mathrm{k}} \tag{4}$$

where: $\mathbf{A}_k$ – cross-sectional area of the tape.

Figure 4 depicts the dimensioning of the problem in the case of winding made of two parallel tapes.

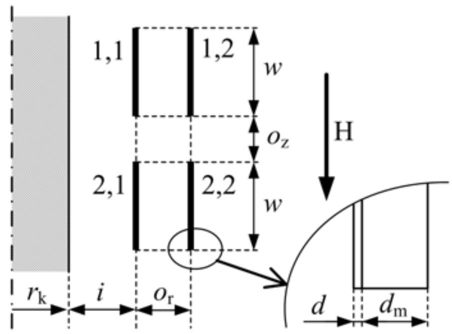

Fig. 4. Geometry dimensioning

Table 1 contains parameter values used for finite element analysis on the basis described in [5].

To cope with extremely high geometric ratio of HTS coating, domains d_3 and d_4 were meshed with mapped distributed quadrilateral elements. This approach allows for the efficient decrease of problem complexity and gives possibility to evaluate power losses appropriately [6]. Remaining domains were meshed with free triangular elements.

Simulation results

Time dependent analysis of 30 ms ($1.5T$) was performed for each considered configuration. First additional half-period of 50 Hz wave allows for the suppression of transients related to zero initial conditions.

Sinusoidal transport current $i_t = I_m \sin(\omega t)$ was enforced by integral constraint covering all domains of parallel tapes belonging to a single turn. Parallel tape transposition was simulated by constraining individual tape currents.

For example, in the case of two parallel tapes (Fig. 4) the sum of tape currents $i_{1,1}+i_{1,2}$ is equal to transport current i_t. Without transposition, currents of the inner tapes must be equal $i_{1,1}=i_{2,1}$. The same applies to the outer tapes $i_{1,2}=i_{2,2}$. Situation changes when full transposition is applied: $i_{1,1}=i_{2,2}$ and $i_{1,2}=i_{2,1}$.

Table 1. Parameter values used for simulation

Parameter	Value	Description
E_c	10^{-4} V/m	critical field criterion
n	20	power law exponent
J_{c0}	28 GA/m^2	$Jc(\mathbf{B})$ model constants [4]
α	0.7	
k	0.29515	
B_0	42.65 mT	
r_k	0.3 m	magnetic core radius
i	60 mm	core-winding gap
δ	25 mm	winding-boundary 2 distance
o_r	0.2 mm	radial tape separation
o_z	0.5 mm	axial tape separation
w	12 mm	tape width
d	1 μm	YBCO layer thickness
d_m	40 μm	normal metal stabilizer thickness
I_c	300 A	critical current of single tape
p	2, 3 or 4	number of parallel tapes
f	50 Hz	frequency
I_m	$0.7 \cdot p \cdot I_c$	transport current amplitude
ρ_m	3 nΩm	normal metal resistivity
ρ_{ins}	1 Ωm	insulator resistivity
H_{zm}	$-1.9 \cdot I_m / (2w+2o_z)$	amplitude of magnetic field at boundary 2
μ_{r_core}		relative permeability of the core - soft iron model (Comsol library)

Figure 5 shows parallel tape currents in the case of no transposition of strands. Different stray field fluxes coupled with each strand and unequal strand inductances provoke the appearance of circulating current. It causes the strong imbalance of the total current values in parallel tapes. Current of the (x,2) strands exceeds critical value. Resistivity appears in full cross-section of YBCO layer during a part of the period, the current is shared between HTS and normal metal. However it is not enough to equalize parallel paths of the winding. Considering energy losses this situation is unacceptable. Peak loss value for (x,2) strand is over forty times higher than for (x,1) strand (Fig. 6).

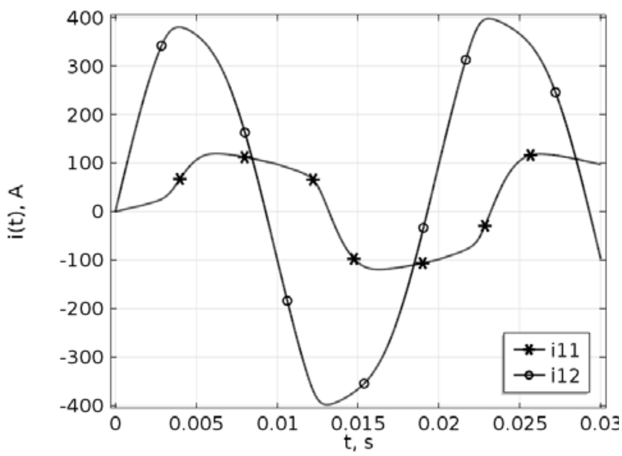

Fig. 5. Currents in two parallel tapes without transposition

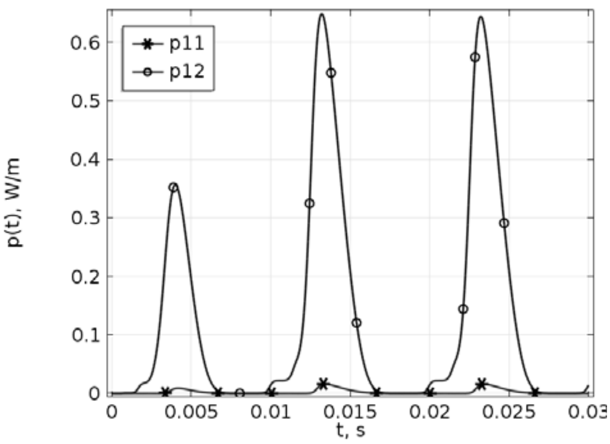

Fig. 6. Instantaneous power losses in parallel strands without transposition

Figure 7 depicts currents in the case of full transposition of tapes. Obviously, currents of parallel strands are perfectly balanced and they reach expected amplitude of $0.7 \cdot I_c$. Peak power losses in parallel strands with full transposition are similar (Fig. 8). Difference in loss waveforms is caused by the stronger stray field penetrating strand (1,2) situated closer to the secondary winding.

Such a behavior natural for CTC, may be achieved with a discreet transposition interconnector TI (Fig. 2c). Each winding of the transformer may be divided into halves. Electrically and geometrically identical pairs must be connected by the transposition interconnector. This may be easily done for windings made of a few parallel tapes.

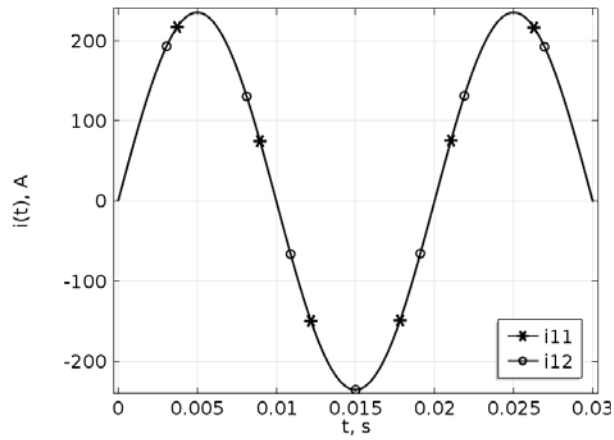

Fig. 7. Currents in two parallel tapes in the case of full transposition

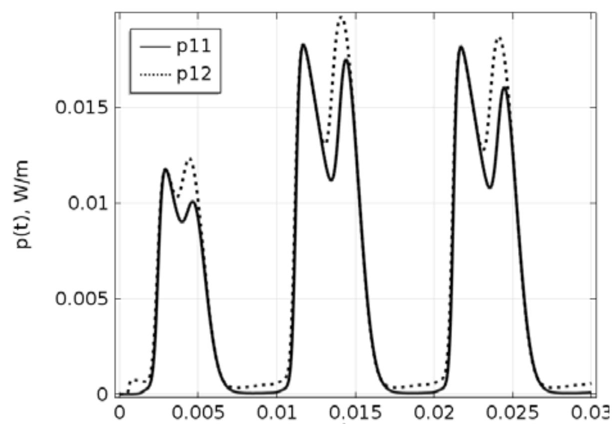

Fig. 8. Instantaneous power losses in two parallel strands with full transposition

Figure 9 shows currents of three parallel tapes with the partial transposition of strands. It can be clearly seen that the partial transposition equalized currents in outer strands only. Middle wire coupled with the lower aggregate amount of stray flux has much smaller contribution to the current transport.

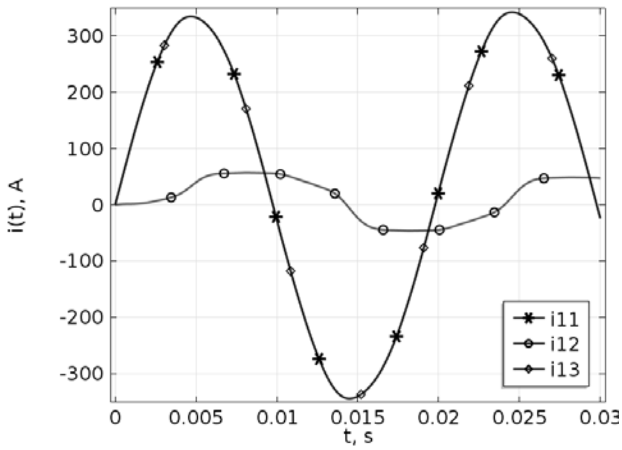

Fig. 9. Currents in three parallel tapes with partial transposition

This situation may be improved by the adjustment of strand gaps (isolation thickness). If the distance between first and middle wire be doubled (Fig. 10), the aggregate stray flux coupled with each transposed pair of strands will be approximately the same.

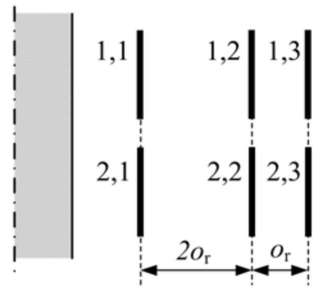

Fig. 10. Modified strand configuration

Currents in three parallel tapes with the partial transposition and modified strand configuration mentioned above are shown in Figure 11.

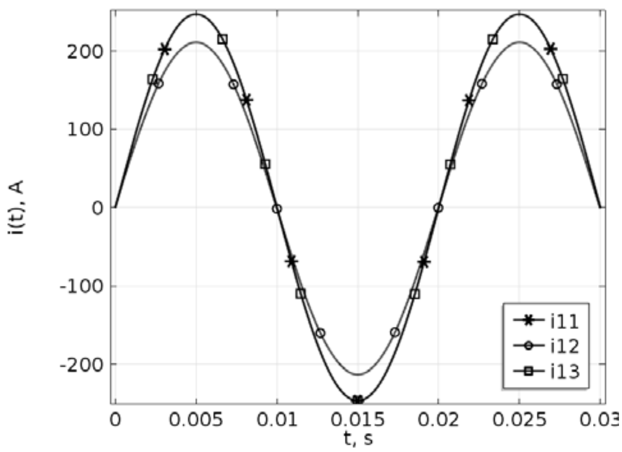

Fig. 11. Currents in three parallel tapes with partial transposition and strand shift

Current distribution has been distinctly improved. However, each parallel turn has a little different inductance and that is why the gap width needs further adjustment.

Figure 12 depicts currents waveforms in three parallel tapes with the partial transposition and the $2.2 \cdot o_r$ gap between first and second strand.

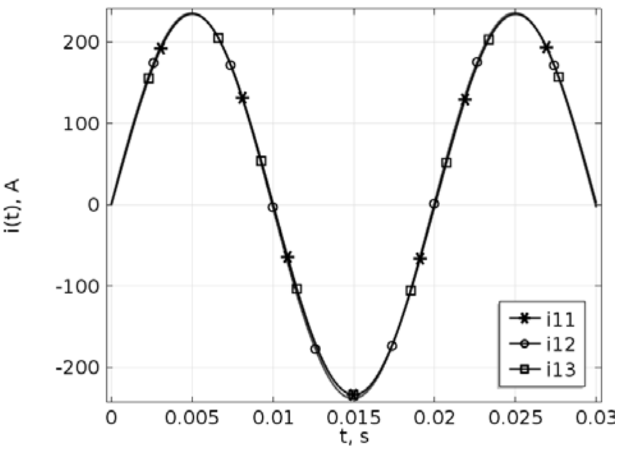

Fig. 12. Currents in three parallel tapes with partial transposition and optimized strand shift

This manipulation seems to be quite effective because aggregate energy losses for each pair of transposed wires $p_{11}+p_{23}$, $p_{13}+p_{21}$ and $p_{12}+p_{22}$ are comparable (Fig. 13).

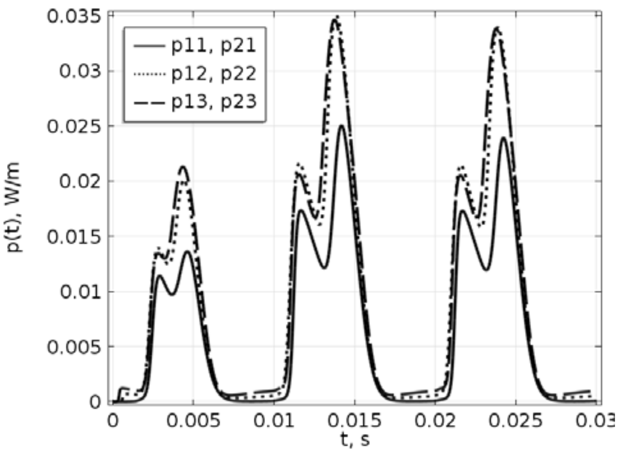

Fig. 13. Instantaneous power losses in three parallel tapes with partial transposition and optimized strand shift

Analogous modification can be made in the case of four parallel strands. This time the gap width of $3.5 \cdot o_r$ between first and second strand was required to equalize the current distribution. Figure 14 depicts power losses in this configuration.

Conclusion

CTCs made of high-T_c superconductor coated tapes are manufactured by two research companies in limited lengths at the present time. Unit price reaches 3000 USD/kA-m and it is at least four times greater than the cost of unprocessed HTS tapes.

Results of the numerical analysis show that the construction of the transformer winding with several parallel HTS tapes without continuous transposition may be possible.

The best and straightforward solution is to use two parallel strands for the full wire transposition with a simple mid-winding interconnector.

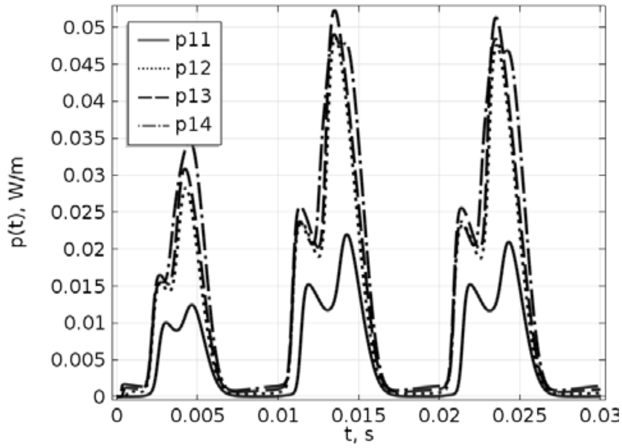

Fig. 14. Instantaneous power losses in four parallel tapes with partial transposition and optimized strand shift

It is also possible to use the strand interconnector for the windings made of three or four parallel tapes. In these cases the designs are more complicated due to inconstant insulation thickness.

Assuming relative current amplitude I_m/I_c as 0.71, one can calculate phase current of transformer winding as 300, 450 and 600 A (RMS) for two, three and four parallel 12 mm HTS tapes respectively.

Maximal power of transformer depends on the allowable phase current, line voltage of low-voltage side and winding configuration. Table 2 contains selected results of this calculation for three-phase units.

Table 2. Apparent power of three-phase HTS transformers

line voltage (low side), kV	LV winding configuration	number of parallel HTS tapes I_c=300 A		
		2	3	4
0.4	wye (star)	208 kVA	312 kVA	416 kVA
0.4	zigzag	240 kVA	360 kVA	480 kVA
6.3	wye (star)	3.3 MVA	4.9 MVA	6.5 MVA
6.3	delta	5.7 MVA	8.5 MVA	11.3 MVA

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