1. Paweł SURDACKI, 2. Łukasz WOŹNIAK

Politechnika Lubelska, Katedra Elektrotechniki i Elektrotechnologii

doi:10.15199/48.2023.06.30

Influence of HTS tape parameters on limiting the inrush current in superconducting transformers

Abstract*. The paper presents a computer model of superconducting tapes, SCS12050 with a copper stabiliser layer and SF12050 without a stabiliser, taking into account their electrical and thermal parameters. The obtained waveforms of cooling and heating power, temperature and currents flowing in individual layers of both types of tape were compared. A computer model of this device developed in the PSpice environment was used to calculate the inrush current of a 21 MVA, 70/10.5 kV HTS superconducting HTS transformer. The first three unidirectional current pulses generated during connecting an unloaded transformer to the network were analysed. The values of the pulse duration (γ angle), the temperature increase of the primary winding as well as the mean and effective values of the inrush current for the first three pulses in the windings with both types of HTS 2G tape were calculated. The conducted analysis allowed to determine the influence of the parameters of the tapes under consideration on the effective limitation of the transformer inrush current to the supply network and the possibility of their use in the construction of superconducting transformer windings.*

Streszczenie. *W artykule przedstawiono model komputerowy taśm nadprzewodnikowych: SCS12050 ze stabilizatorem miedzianym oraz SF12050 bez stabilizatora z uwzględnieniem ich parametrów elektrycznych i termicznych. Porównano otrzymane przebiegi mocy chłodzenia i grzania, temperatury oraz prądów płynących w poszczególnych warstwach obu rodzajów taśm. Model komputerowy opracowany w środowisku PSpice posłużył do obliczenia prądu właczania transformatora nadprzewodnikowego HTS o mocy 21 MVA, 70/10,5 kV. Analizie poddano pierwsze trzy jednokierunkowe impulsy prądowe generowane podczas załączania nieobciążonego transformatora do sieci. Obliczono wartości czasu trwania impulsu (kąt γ), przyrostu temperatury uzwojenia pierwotnego oraz wartości średnie i skuteczne prądu włączania dla pierwszych trzech impulsów w uzwojeniach wykonanych z obu typów taśmy HTS 2G. Przeprowadzona analiza pozwoliła na określenie wpływu parametrów rozpatrywanych taśm na skuteczne ograniczanie prądu właczania transformatora do sieci zasilającej oraz możliwości ich wykorzystania w budowie uzwojeń transformatorów nadprzewodnikowych. (****Wpływ parametrów taśm HTS na ograniczanie prądu włączania w transformatorach nadprzewodnikowych****)*

Keywords: HTS winding, superconducting transformer, inrush current
Słowa kluczowe: uzwojenia HTS, transformator nadprzewodnikowy, prąd włączania

Introduction

The use of very thin tapes of high-temperature superconductor (HTS) in the construction of transformers makes the radial dimensions of the windings and the length of the magnetic core yoke in such a transformer smaller than in its conventional counterpart of the same power. In the design of superconducting transformers, parameters such as the permissible current density, resistivity in the resistive (non-superconducting) state, mechanical strength as well as stresses and dynamic forces in the winding are important. A significant calculation difficulty is the considerable temperature non-linearity of resistivity and the variability of the critical parameters of the superconductor during the transformer connection to the network. These factors make it difficult to design and manufacture a superconducting transformer with the required electrical and thermal parameters to effectively limit the switch-on current values [1, 5, 6].

Design and parameters of HTS 2G high-temperature superconducting tapes

Second-generation high-temperature YBCO superconducting tapes (HTS 2G) with a layered structure operate at a higher critical current than first-generation filamentary conductor and are cheaper because they contain less silver. They are characterized by higher mechanical strength and lower AC losses than copper wires. In the superconducting state, these tapes conduct currents of hundreds of amperes with very small losses, while after the superconductor goes into the resistive state, they have a relatively high resistance value, which can limit the current level [2, 3].

Second-generation high-temperature superconducting tapes consist of several layers. The superconducting layer is about 1-2 µm thick and makes up about 5 % of the thickness of the entire 2G wire. Moreover, the YBCO tape, apart from the superconducting layer, consists of the following layers: a stabilizer layer, a buffer layer and a substrate layer. The base layer, which determines the electrical and mechanical parameters, consists of a non-magnetic Hastelloy alloy (Ni – 57.00 %, Mo – 16.00 %, Cr – 15.50 %, Fe – 5.50 %, W – 4.00 %, Co – 2.50 %). The thickness of this layer is approximately 50 µm. The optional stabilizer layer, which determines the thermal and mechanical parameters of the tape, is located on the top and bottom of the tape and has a thickness of about 20 µm. In addition, the second generation superconducting tape consists of a 2 µm silver layer, a 1 µm YBCO superconductor layer, a 30 nm LaMnO3 (LMO) buffer layer, a 30 nm homoepitaxial MgO layer and a 10 nm MgO substrate layer [1, 4, 7, 8].

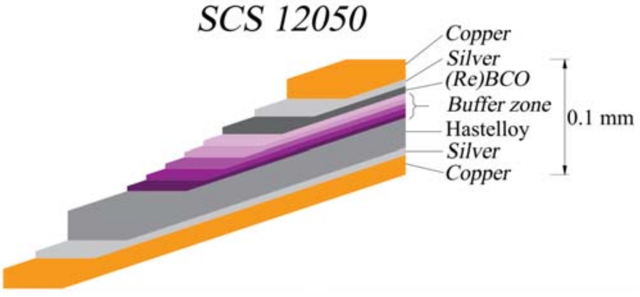

Fig.1. Structure of the second generation SuperPower SCS12050 superconducting tape with a copper stabiliser layer [1, 7-10]

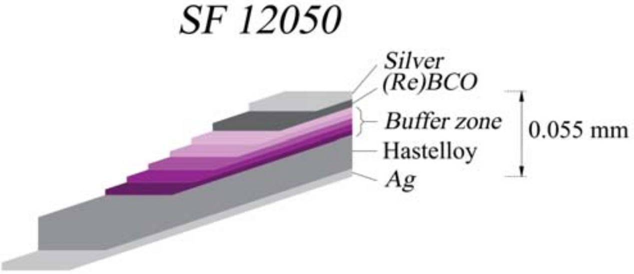

Fig.2. Structure of the second generation SuperPower SF12050 superconducting tape without a copper stabiliser [1, 7-10]

The study analyses the transient states of a superconducting transformer with windings made of two types of tapes: with a copper SCS12050 stabilizer (Fig. 1) and without the SF12050 stabilizer (Fig. 2). Their basic parameters are listed in tab. 1. Tapes without stabilizer at the same critical temperature T_c have ten times greater resistance than tapes with stabilizer [9, 10].

Table 1. Parameters of HTS 2G tapes, SCS 12050 and SF 12050 types [1, 7-10]

Tapes type	SCS 12050	SF 12050
Producer	Super Power	Super Power
Width [mm]	12	12
Thickness [mm]	0.06	0.1
Tape strength [MPa]	550	350
Critical tape current [A]	300	300
Critical current density [A/mm2]	220	450
Min. bending diameter [mm]	11	11
Tape length [m]	200	200
Tape substrate resistivity (77 K) [μΩcm]	125	125
Equivalent tape resistance (77 K) [Ω/m]	0.00362	0.105

Computer model of HTS 2G tapes SCS12050 and SF12050

The subject of the research are the parameters of the 2G SCS12050 and SF12050 tapes used to wind the windings of the superconducting transformer, determining the current limitation when connecting this device to the network. The tape equivalent diagram shown in Fig. 3 consists of resistances connected in parallel. They represent the resistances of the Hastelloy, silver, YBCO superconductor layers for both types of tapes and, additionally, for the SCS12050 tape, the resistance of the copper layer. The computer model of the HTS 2G YBCO tape realized in the PSpice software presents the block diagram shown in Fig. 4. ABM (analog behavioral modelling) blocks were used to make the model. In block ABM "1" calculated using the formula in PSpice (I(V/a))**2/V(YBCO) and in block ABM "2" calculated using the formula in PSpice (Fc*V(LN)), the heating and cooling powers of HTS tapes were defined, respectively. In the ABM block "3" described by the formula ((I(V/a))**2/V(YBCO)), the relative temperature was calculated taking into account the heating and cooling of the HTS tapes. The Cth hierarchical block calculates the heat capacity of the SCS and SF type superconducting tape. The YBCO hierarchical block takes into account the transition of the superconductor layer to the resistive state written with the Rhyner's power law [11, 12, 13, 14].

The conductance of the superconductor is the reciprocal of resistance [1, 7-10].

$$G_{YBCO}=\frac{1}{\frac{E_C\cdot L}{I_C}\cdot\left(\frac{I}{I_{C0}}\cdot\frac{T_C-T}{T_C-T_0}\right)^{n_0\frac{T_0}{T}-1}} \tag{1}$$

where: G_{YBCO} – the conductance of YBCO layer, S, E_c – critical electric field intensity for HTS, 10^{-4} V/m, L – length of tape, m, I_{c0} – critical current in T_0 temperature, A, I – current, A, T – temperature of tape, K, T_0 – reference temperature, K, T_c – critical temperature, K, n_0 – exponent in T_0 temperature (for YBCO n_0 =15 ÷ 40, T_0 = 77 K), [1, 7-10].

Table LN (Fig. 4) shows the heat flux density as a function of the temperature difference ΔT between the surface of the cooled object and liquid nitrogen. In the ABM "4" block, the current flowing in the winding made of 2G SCS12050 and SF12050 tapes was calculated.

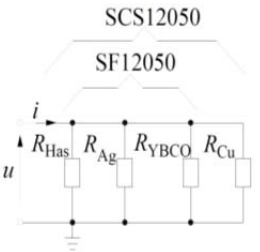

Fig. 3. Equivalent diagram of the HTS 2G superconducting tape, SF12050, SCS12050 type

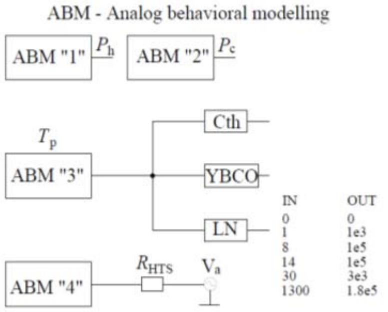

Fig. 4. Block diagram of the HTS 2G superconducting tape model, SF12050, SCS 2050 type

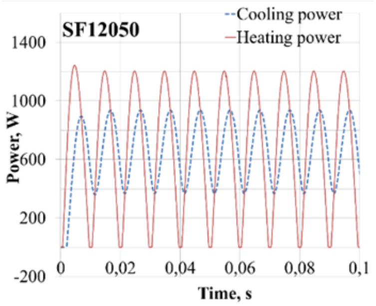

Fig. 5. The waveforms of cooling and heating power of the HTS 2G superconducting tape, SF12050 type

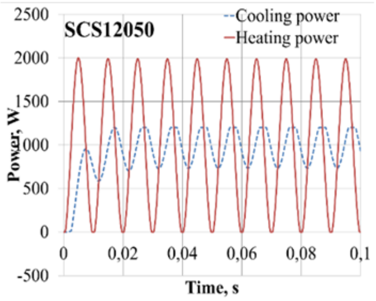

Fig. 6. The waveforms of cooling and heating power of the HTS 2G superconducting tape, SCS12050 type

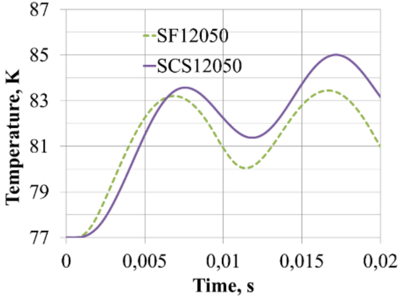

Fig. 7. The waveforms of temperature as a function of time of the HTS 2G superconducting tape, SF12050 and SCS12050 type

Using the developed computer model of winding wires made of 2G SCS12050 and SF12050 tapes, the heating power and cooling power waveforms were generated (Fig. 5, 6), as well as the temperature of the superconducting tape as a function of time (Fig. 7), the conductance of the superconductor layer (Fig. 8) and current waveforms in individual layers of the 2G SCS12050 and SF12050 tape (Fig. 9, 10).

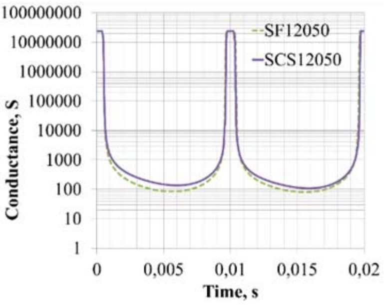

Fig. 8. The waveforms of conductance of the 2G superconductor layer, SF12050 and SCS12050 type

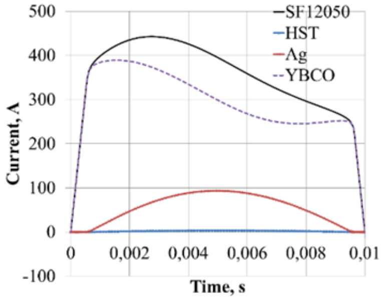

Fig. 9. Current waveforms in individual layers of the HTS 2G superconducting tape, SF12050 type

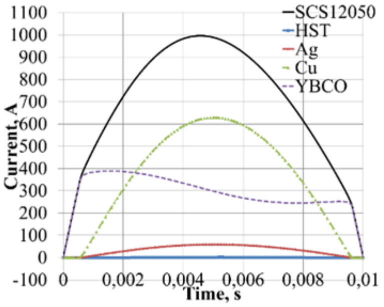

Fig. 10. Current waveform in individual layers of the HTS 2G SCS12050 superconducting tape

Winding wires made of tape without SF12050 copper stabilizer emit less heat (heating power), and thus require less cooling power compared to the SCS12050 tape. During operation, these wires reach the temperature of 83.5 K for the SF12050 tape and 85 K for the tape with a copper stabilizer, while the critical temperature of the HTS tape is equal to T_c = 93 K. The heat capacity C_{th} of the SF12050 and SCS12050 winding wire is responsible for this. The heat capacity C_{th} is the product of specific heat, material density and the volume of individual layers of the tape. The greater the heat capacity, the greater the thermal inertia and amortization of the instantaneous and local heat loss peaks in the HTS tape. The thermal conductivity of the HTS tape is an important parameter. The smaller it is, the better the heat dissipation and temperature equalization between the inside of the HTS tapes and the layers in contact with LN liquid nitrogen. The density of the heat flux received by the cooling liquid nitrogen from the HTS LN tape should be as high as possible in order to receive as much and quickly as possible the heat released in the HTS tape and transfer it for removal by the cryostat cooling system.

The copper layer conducts the largest part of the HTS tape current in the resistive state. The silver layer conducts the second, the Hastelloy layer the third and the YBCO superconductor layer the fourth largest part of the HTS tape current in the resistive state. The tape resistivity ρ depends on the presence (for SCS type tape) or non-presence of the Cu layer (SF tape). Moreover, the resistivity ρ is inversely proportional to the width of the HTS tape. The resistance of the SF12050 tape is 0.105 Ω/m and for the SCS12050 tape 0.00362 Ω/m. Both SCS and SF tapes have the same critical current value, while the tape without a copper stabilizer has twice the critical current density. The tape without a copper stabilizer has a lower strength due to the lack of a copper stabilizer and is 350 MPa.

Transient analysis – connecting the transformer to the network

In order to select the appropriate SCS12050 or SF12050 superconducting tape for use in the windings of a 21 MVA single-phase superconducting transformer, an analysis of the transient state, which is switching the transformer to the network, was carried out. For this purpose, a computer model of a 21 MVA superconducting transformer was used, developed in the PSpice program. This model has been described in greater detail and discussed in the previous works of the authors [13, 14].

The selection of the appropriate tape was considered for the moment when the zero value of the supply voltage passed through, because such initial conditions are the most unfavourable for connecting the transformer to the network. When switching on an unloaded transformer to the network, a current of about 20 - 40 times greater than the rated current of the transformer flows in its windings. The large amplitude of the transformer switching current pulses and the long decay time of its wave cause disturbances in the power grid and deterioration of the quality of electricity, as well as the appearance of higher harmonics. Switching on the transformer without load, due to the sudden appearance of high current, may result in damage to the insulation of the windings and the tap changer, as well as the entire device. Inrush current pulses often activate electrical power protection devices and cause voltage dips.

The first three inrush current pulses were subjected to computer analysis. Fig. 11 shows the first three inrush current pulses in the superconducting transformer model with windings made of HTS 2G SF12050 and SCS12050 tapes. Fig. 12 shows the second inrush current pulse, which for windings made of SF12050 tape is almost 180 times smaller than in windings with a copper stabilizer and amounts to i_2 SF12050 = 9.8 A, i_2 SCS2050 = 1764 A, respectively. The value of the critical current I_c for the primary winding was shown on the waveforms. For a tape with a copper stabilizer, the first three pulses exceed the critical current $I_c < i_{1,2,3}$ SCS12050, while in the case of tape windings without a stabilizer, the value of the current does not exceed the critical current $I_c > i_2$ SF12050 during the second pulse.

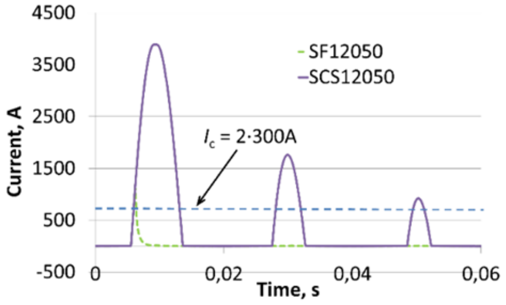

Fig. 11. The waveform of the first three inrush current pulses in the HTS 2G SF12050 and SCS12050 tape

In the simulation, the duration of the first three inrush current pulses was calculated. The obtained results for superconducting transformers with SF and SCS windings are shown in Fig. 13, giving the γ angle measure. This angle corresponds to the duration of the unidirectional current pulse.

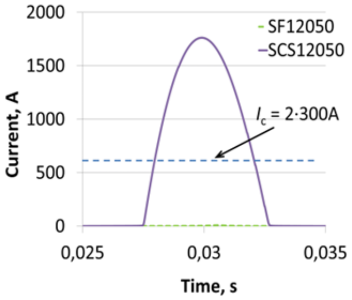

Fig. 12. The waveform of the second pulse of the inrush current in the HTS 2G SF12050 and SCS12050 tape

The temperature increase of the primary winding made of HTS 2G tapes, type SF12050 and SCS12050 for the first three pulses, is shown in Fig. 14. For the first pulse of the inrush current in the case of a tape with a copper stabilizer, the temperature increase was 33 K. However, in the case of windings made of SF12050 tape, it increased by 16 K not exceeding the critical temperature T_c = 93 K. For the remaining pulses for both tapes, the temperature rise does not exceed the critical value.

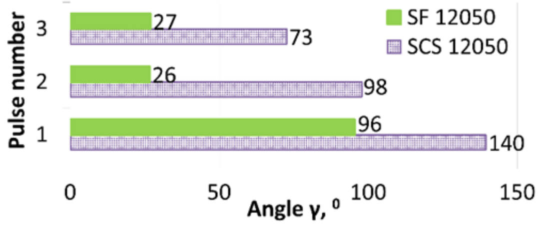

Fig. 13. The value of the angle γ for HTS 2G SF12050 and SCS12050 transformers

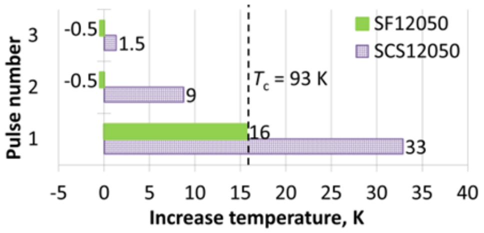

Fig. 14. Temperature increase of the HTS 2G SF12050 and SCS12050 primary winding

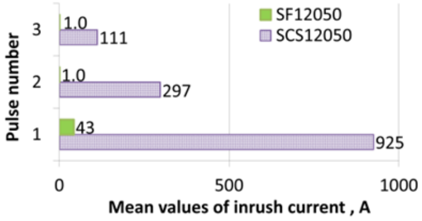

Fig. 15. Average values of the inrush current for the first three pulses

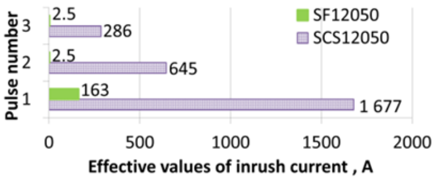

Fig. 16. Effective values of the inrush current for the first three pulses

In the computer simulation, the mean and effective values of the switch-on current for the first three pulses were also determined (Fig. 15, 16). In the case of a superconducting transformer with windings made of SCS12050 HTS tapes, during the first pulse, the average value of the switch-on current was 925 A, while the effective value was 1677 A. For the second and third pulse, the mean value of the inrush current was 297 A and 111 A, respectively, and the rms value was 645 A and 286 A.
In the case of a superconducting transformer with SF12050 tape windings without a copper stabilizer, during the first pulse, the average inrush current was 43 A, while the effective value was 163 A. For the second and third pulse, the average value of the inrush current was 1 A, and the effective value was 2.5 A.

Conclusions

The inrush current pulses of a superconducting transformer with tape windings without a copper stabilizer SF12050 are many times smaller than for windings made of SCS12050 tape. For windings made of SF12050 tape, duration of unidirectional current pulse is shorter than for SCS12050 tape. Smaller values of the switch-on currents and shorter duration of the pulses also result in smaller increases in the temperature of the primary winding. However, in reality, making the tape windings without the copper stabilizer SF12050 is technically unjustified, since each transition of the tape to the resistive state causes its degradation. The computer analysis carried out allows us to conclude that only the tape with a copper stabilizer SCS12050 allows for the production of transformer windings with a capacity of 21 MVA.

***Authors**: dr hab. inż. Paweł Surdacki, prof. uczelni, Politechnika Lubelska, Katedra Elektrotechniki i Elektrotechnologii, ul. Nadbystrzycka 38 A, 20-618 Lublin, E-mail: p.surdacki@pollub.pl; mgr inż. Łukasz Woźniak, Katedra Elektrotechniki i Elektrotechnologii, ul. Nadbystrzycka 38 A, 20-618 Lublin, E-mail: wozniak.lukasz1988@gmail.com;*

REFERENCES

[1] Kalsi S. S. 2011, High temperature superconductors to electric power equipment (IEEE Press, Wiley).
[2] Komarzyniec G, Energies 2021, 14, Calculating the inrush current of superconducting transformers, doi: 10.3390/en14206714.
[3] Berger A at al 2010, Comparison of the efficiency of superconducting and conventional transformers, J. Phys. Conf. Series 234 032004, doi:10.1088/1742-6596/234/3/032004.
[4] Lu J, Choi E S, Zhou H D 2008, Physical properties of Hastelloy C-276 at cryogenic temperatures, J. Appl. Phys. 103, 064908.
[5] Smith D R, Fickett F R 1995, Low-temperature properties of silver, J. Res. Natl. Inst. Stand. Technol. 100 2 pp 119-171.
[6] Matula R A 1979, Electrical resistivity of copper, gold, palladium, and silver, J. Phys. Chem. Ref. Data 8 4 pp 1147-1298.
[7] Naito T et al. 2012, Specific heat and thermal diffusivity of YBCO coated conductors, Phys. Procedia, 36 pp 1609-1613.
[8] Janowski T, Wojtasiewicz G and Jaroszyński L 2016, Transformatory nadprzewodnikowe (Warszawa: Instytut Elektrotechniki), ISBN 978-83-61956-54-9.
[9] Wilson P R, Ross J N, Brown A D 2001, Optimizing the Jiles-Atherton model of hysteresis by a genetic algorithm, IEEE Trans Magn, 37 2 pp 989-993.
[10] Du R and Robertson P 2015, Dynamic Jiles-Atherton model for determining the magnetic power loss at high frequency in permanent magnet machines, IEEE Trans Magn 51, 6, 7301210.
[11] Majka M., Kozak J., Wojtasiewicz G., Kozak S., Janowski T.: "Current limiting performance of 9 kVA superconducting transformers", Przegląd Elektrotechniczny, r. 90, nr 4, s. 70–73, 2014.
[12] Wojtasiewicz G., Majka M., Kozak J.: „Badania eksperymentalne transformatora nadprzewodnikowego 10 kVA", Przegląd Elektrotechniczny, r. 90, nr 3, s. 153–156, 2014.
[13] Surdacki P., Jaroszyński L., Woźniak Ł., 2021, Modelowanie prądu włączania transformatora nadprzewodnikowego w środowisku PSpice, Przegląd Elektrotechniczny, nr 4, 162-165, doi:10.15199/48.2021.04.29
[14] Surdacki P.; Woźniak Ł.; Influence of the HTS Winding Tape on Limiting the Transient Currents in Superconducting Transformers, Energies 2022, 15(5), 1688; https://doi.org/10.3390/en15051688