PSpice modeling of the inrush and fault currents in a 21 MVA HTS transformer

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Outline of presentation

Introduction

Currently used superconducting tapes HTS 2G in the resistive (nonsuperconductive) state have high resistivity. It is therefore possible to build superconducting transformers that limit the current in transient states such as short-circuits or connecting the transformer to the network. Resistance of windings increases after exceeding the critical current density of the superconductor to a value that allows to limit the short-circuit currents.

The main advantages of a transformer with superconducting windings include:

- lower losses in the windings,
- reduction of the size and weight of the transformer,
- no oil in the transformer cooling system,
- limitation of short-circuit and inrush current.

Reducing the short-circuit current in a superconducting transformer is the most important benefit of replacing a copper winding with a superconducting transformer, providing protection and significantly reducing the consumption of circuit breakers and other power supplies.

Introduction

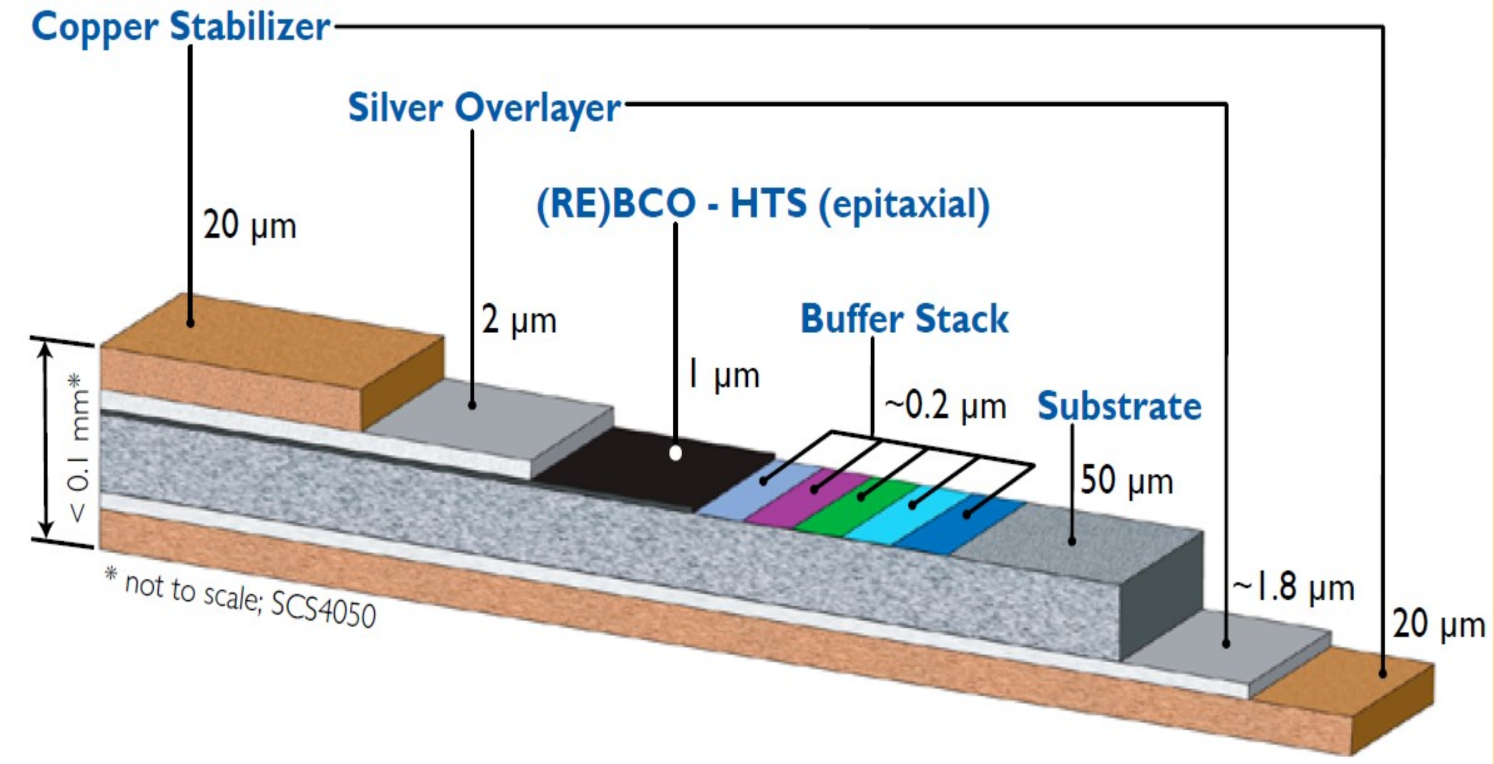
A properly designed and constructed superconducting transformer reduces the first peak short-circuit current in less than 5 ms, protecting the transformer and other equipment from dynamic and thermal damage.

When the transformer is connected to the mains, a transient state occurs that causes the current of the transformer to exceed the rated current many times over. Large pulse amplitudes and long pulse decay times lead to a deterioration in the quality of electrical energy. The current of connecting the unloaded transformer to the mains poses a threat to the winding insulation, the deterioration of which may cause short-circuits and damage to the transforme.

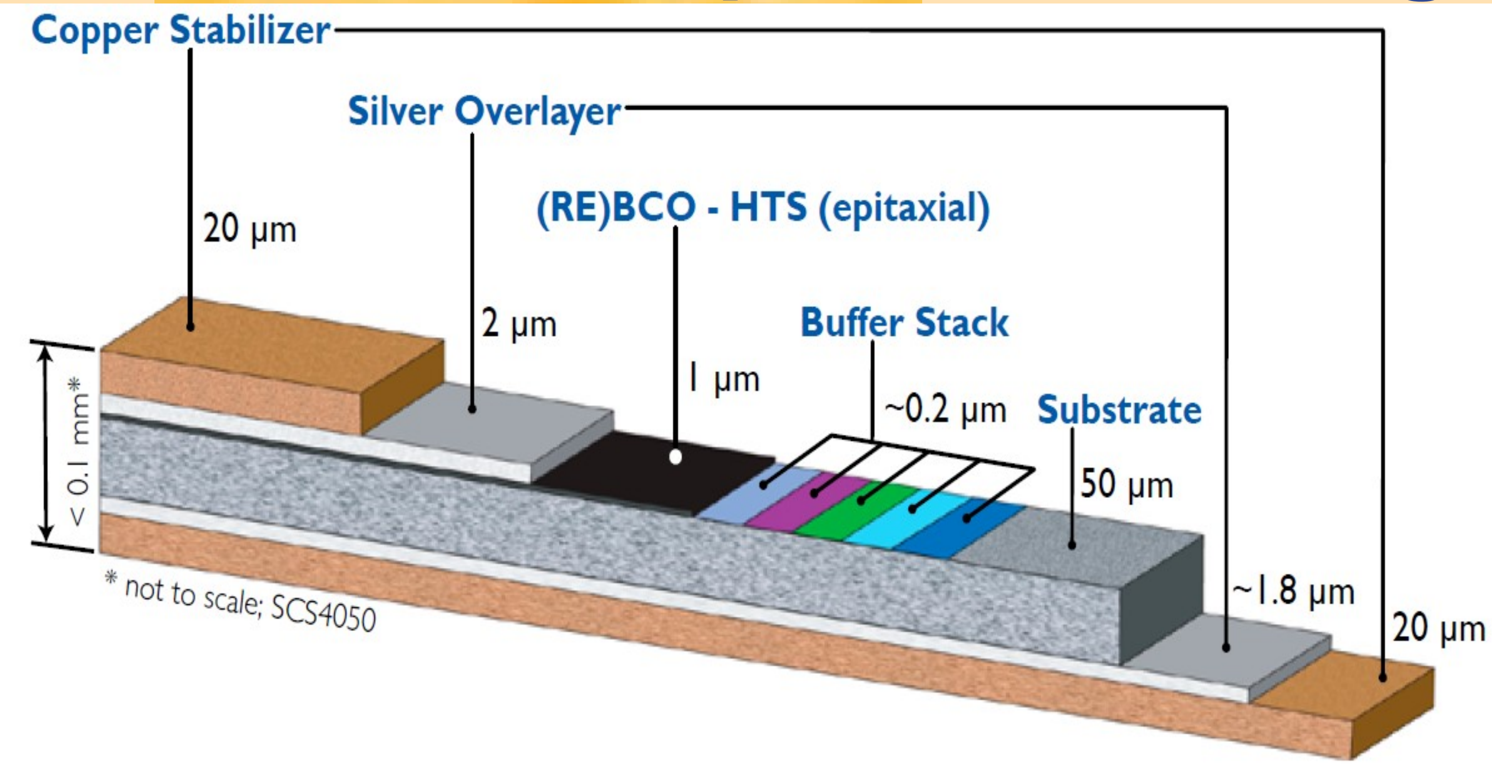
This current may be particularly dangerous in the case of a superconducting transformer, causing uncontrolled transition of the windings to the resistive state, which may lead to damage to the windings made of 2G layered tape made of HTS YBCO. Since the examination of the superconducting transformer physical model during its inrush to the network, as well as during short circuits could lead to its destruction, it is necessary to model this process. It will permit a comprehensive research allowing for an optimal selection of solutions and design parameters of a superconducting transformer

YBCO 2G superconducting tape

In superconducting tapes there is a combination of magnetic and electrical properties of the material manifested by the loss of electrical resistance in certain conditions. These tapes are in a superconducting state when their point of operation determined by temperature, current density and magnetic field strength lies below the critical surface characteristic for a given superconducting material.

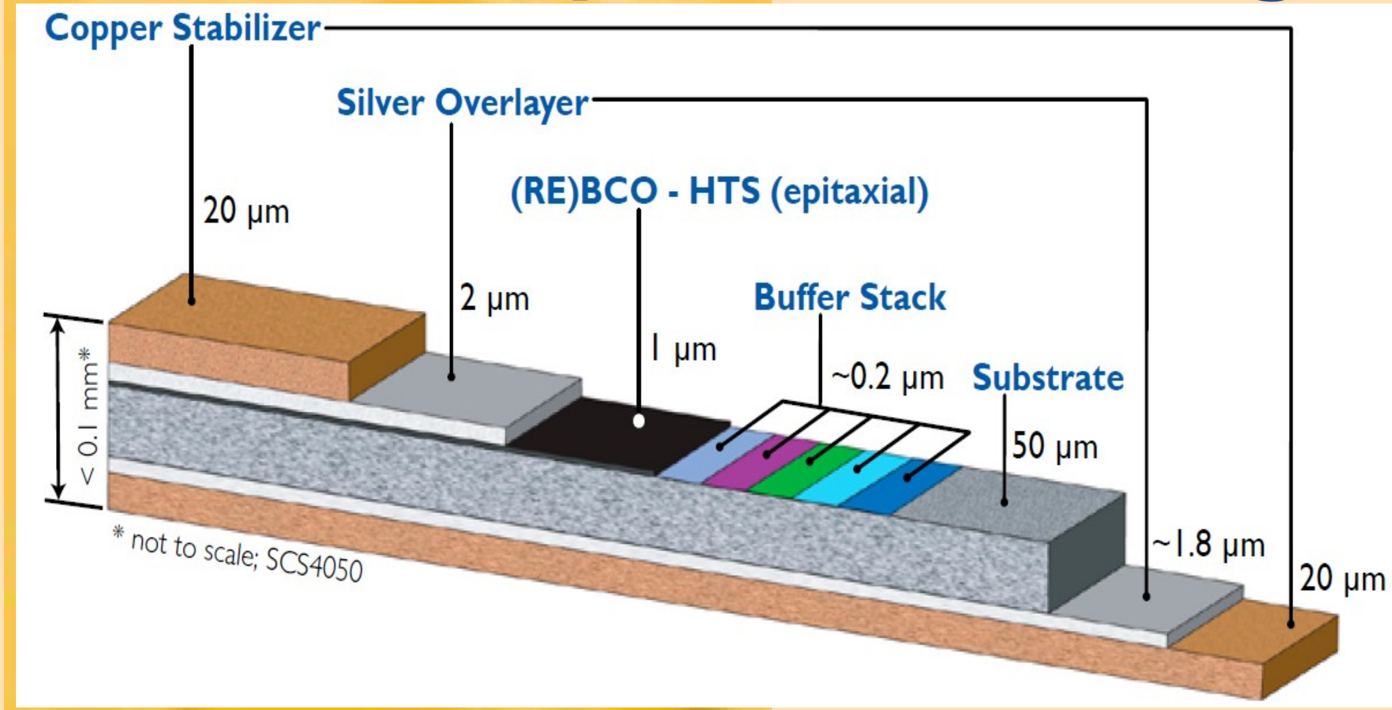


YBCO 2G superconducting tapes



HTS 2G tapes are constructed from several layers.
The substrate layer (thickness ~50 µm) is responsible for electrical and mechanical parameters, consisting of a non-magnetic Hastelloy (Ni – 57.00%, Mo – 16.00%, Cr – 15.50%, Fe – 5.50%, W – 4.00%, Co – 2.50%).
The optional Cu stabilizer layer (~20 µm) determines the thermal and mechanical properties of the tape, it is located at the top and bottom of the tape.
In addition, the 2D HTS tape consists of a 2 µm thick silver layer, 1 µm thick YBCO superconducting layer, 30 nm thick LaMnO3 buffer layer (LMO), 30 nm thick MgO homoepitaxial layer and 10 nm thick MgO substrate layer.

YBCO 2G superconducting tapes



AMSC (American Superconductors) manufactured tapes are covered with a stainless steel or copper laminate coating.

In turn, SuperPower (Fig. 1) produces tapes:
- without stabilizer (SF series) and
- with copper stabilizer (SCS series).

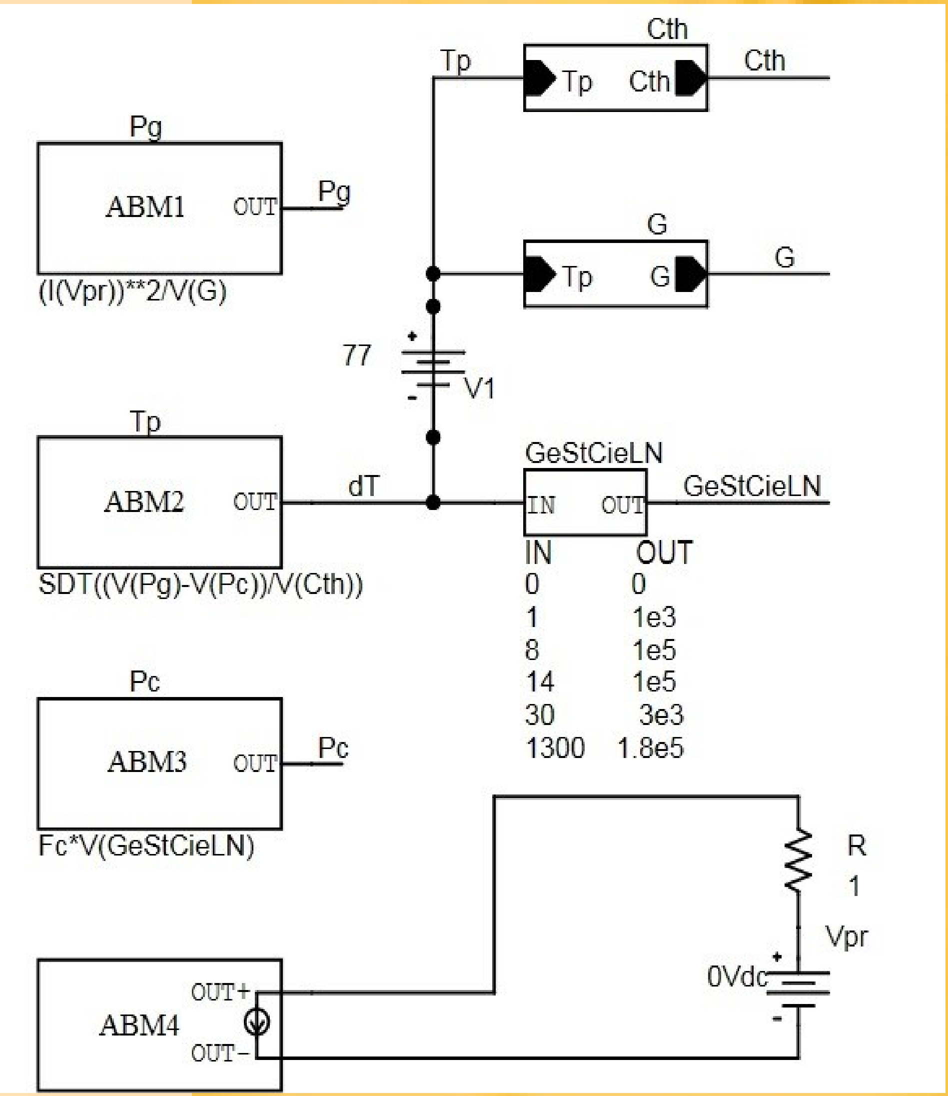
YBCO 2G superconducting tapes

TABLE I. PARAMETERS OF COMMERCIALLY AVAILABLE SECOND GENERATION TAPES OF THE SUPERPOWER ING.; SF=STABILIZER FREE; SCS=SUROUND COPPER STABILIZER [1,11-14]

Parameter	SF4050	SCS4050	SF12050	SCS12050
Minimum I_c, A	125	125	240	240
Widths, mm	4	4	12	12
Total wire thickness, mm	0.055	0.1	0.055	0.1
Standard copper stablilizer thickness, mm	n/a	0.04	n/a	0.04
Critical tensile stress, MPa		>500		>500
Critical axial tensile strain	0.45%	0.45%	0.45%	0.45%
Critical Bend Diameter in Tension, mm	11	11	11	11
Critical Bend Diameter in Compression, mm	11	11	11	11

Table I summarizes the commercial parameters of Super Power tapes. Comparing these two types of 2G superconductor tapes, it can be noted that tapes without stabilizer at the same temperature T_C have ten times higher resistance than tapes with stabilizer.

PSpice model of YBCO 2G HTS tape



consists of active blocks of the ABM user.

ABM1 - the cooling power.

ABM2 - calculates the relative temperature in relation to the temperature of liquid nitrogen,

ABM3 – SC tape heating power,
ABM4 - calculates the tape current.

An auxiliary DC voltage source (Vpr) with zero electromotive force (SEM) was used as a current sensor in the circuit.

PSpice model of YBCO 2G HTS tape

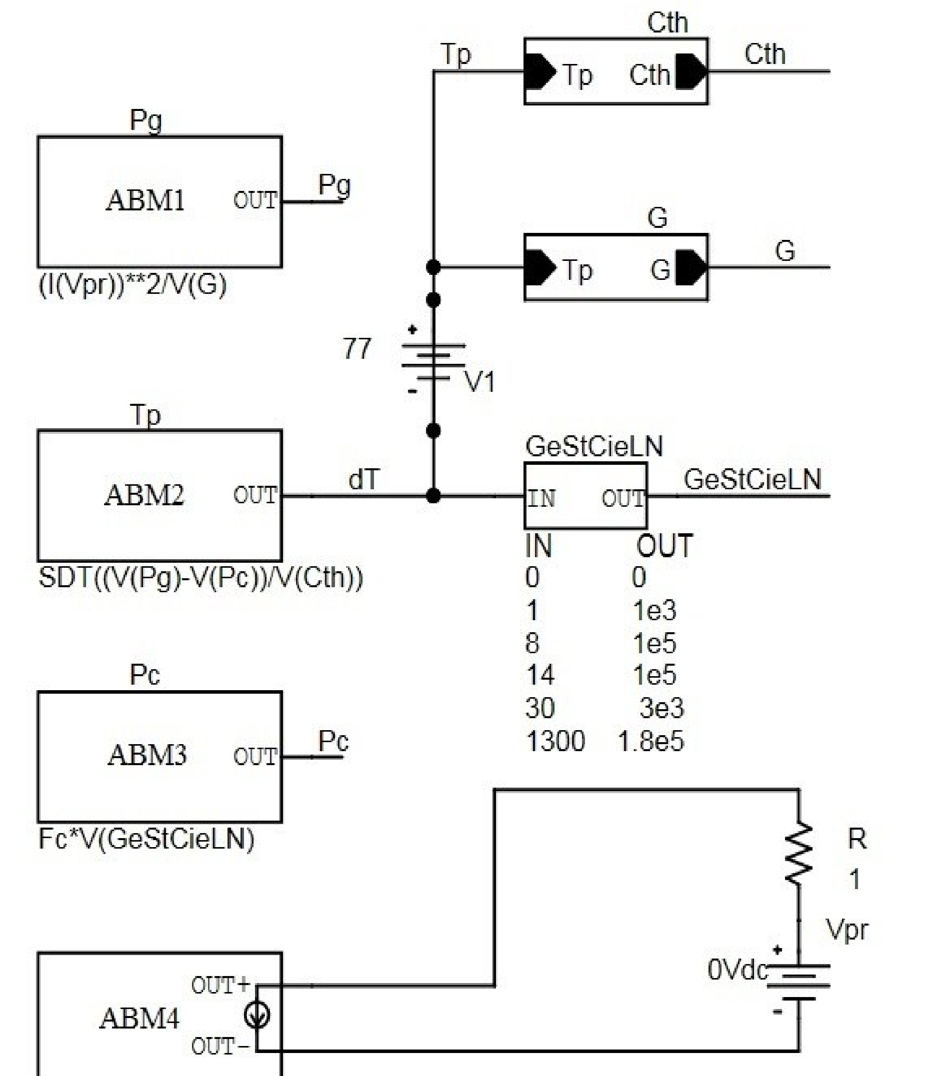


Fig. 2. Electrical diagram of YBCO 2G superconducting tape model in PSpice

In the model, tables with values of thermal power density given back to liquid nitrogen as a function of temperature (GeStCieLN) and two hierarchical blocks were used.

The first hierarchical block represents thermal capacity (C_{th}), which is a sum of thermal capacities of the following layers: copper, silver, Hastelloy and superconductor YBCO.

The second one calculates the resultant conductance of the tape (G). This block takes into account the smooth transition of the YBCO superconductor layer to the resistive state described by the Rhyner's law (1).

PSpice model of YBCO 2G HTS tape

Rhyner's law

$$\frac{E}{E_c} = \left(\frac{J}{J_c(T)}\right)^{n(T)}$$

where: E – electric field intensity, V/m,
E_c – critical electric field intensity for HTS, 10^{-4} V/m,
J – current density, A/m^2,
J_c – critical current density, A/m^2,
n – exponent depending on the temperature.

$$n(T) = n_0 \frac{T_0}{T}$$

where: T_0 – reference temperature, K,
T – temperature of tape, K,
n_0 – exponent in T_0 temperature (for YBCO $n_0 = 15 \div 40$, $T_0 = 77$ K).

$$R_{YBCO} = \frac{E_C l}{I_{C0}} \left(\frac{I}{I_{C0}} \frac{T_C - T_0}{T_C - T} \right)^{n_0 \frac{T_0}{T} - 1}$$

where: l – tape length, I_{C0} – tape critical current at reference temperature T_0, I – superconductor current, T_C – critical temperature of superconductor, T – tape temperature, n_0 – Rhyner's power-law exponent at reference temperature.

Conductance waveforms of 2G tape layers

$$G_{YBCO} = \frac{1}{R_{rez} + R_{YBCO}}$$

G_{YBCO} – conductance of YBCO layer, R_{res} – residual resistance (a certain value of resistance different from zero is necessary to carry out correct numerical calculations – in the program its value of 10^{-15} Ω is assumed).

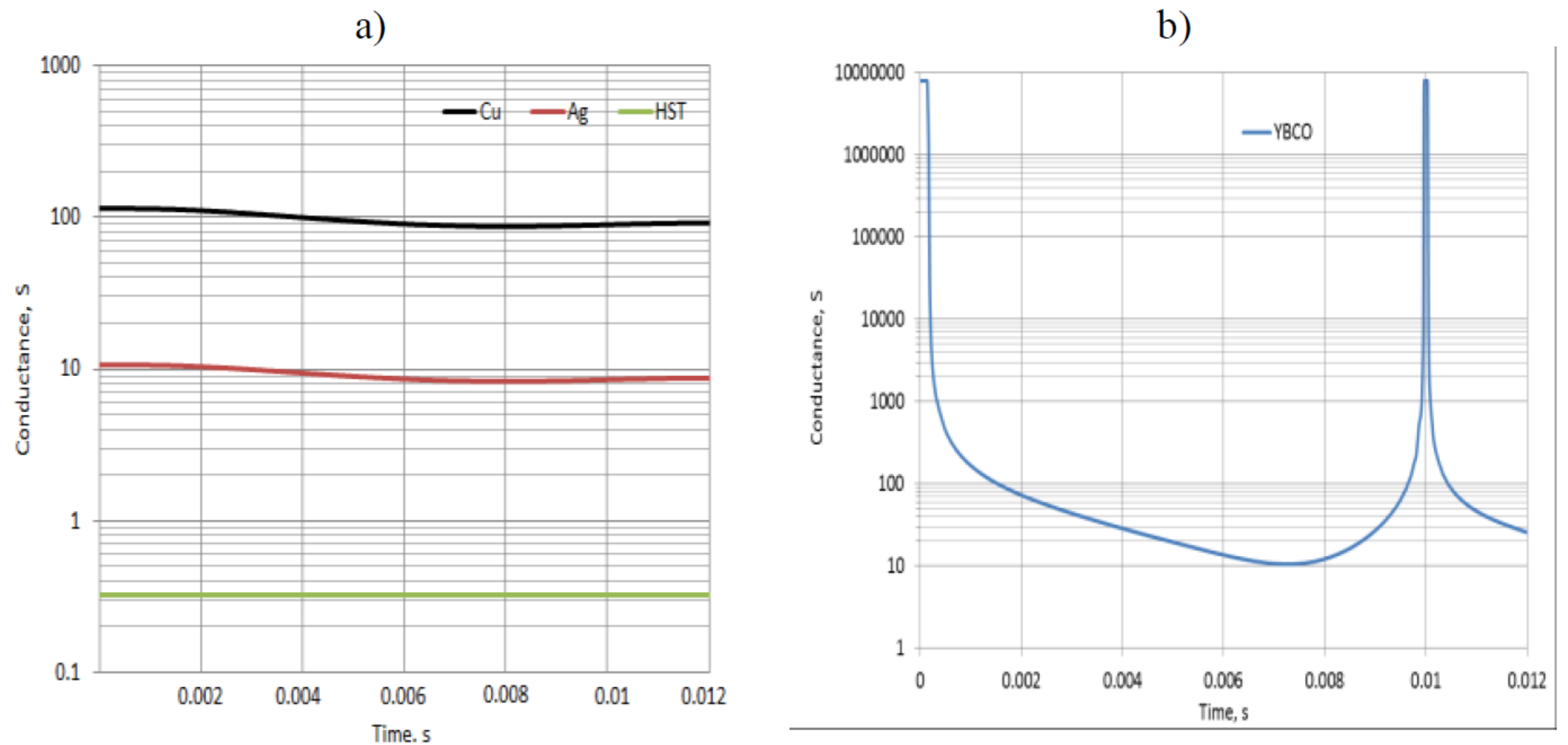


Fig. 3. Conductance of layers a) copper, silver, Hastelloy and b) superconducting layer YBCO

Current waveforms of 2G tape layers

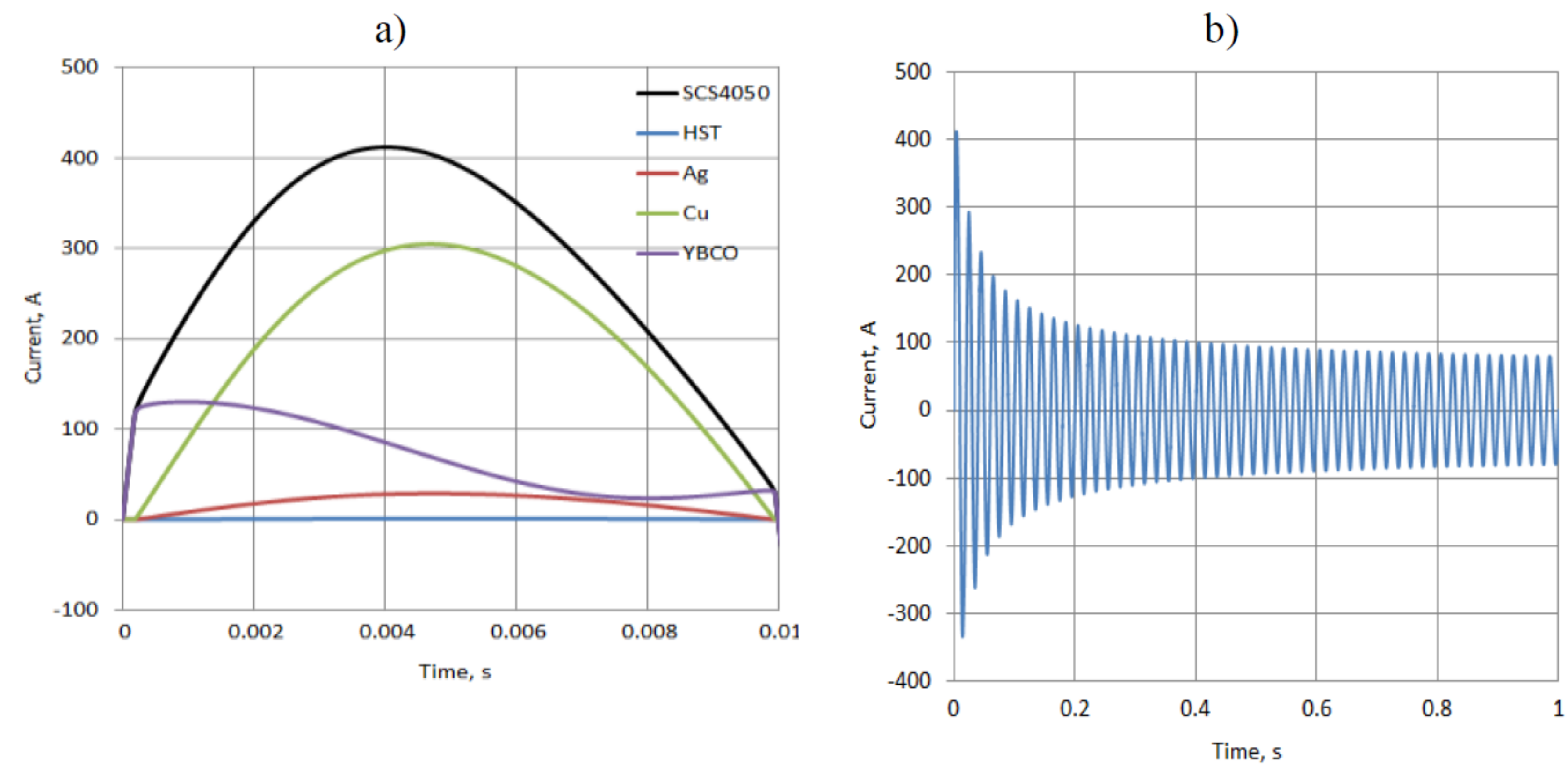


Fig. 4. Course of current of layer a) copper I_{Cu}, silver I_{Ag}, Hastelloy I_{HST}, superconductor I_{YBCO} and b) total current of superconductor tape I_{HTS}

The maximum I_{HTS} tape current is 400 A. This value is reached after the time of 4 ms.

After 30 ms, the I_{HTS} current goes to the steady state, its amplitude is about 100 A. The copper layer conducts I_C current with a maximum value of 300 A. When the tape is energized for a period of time (0-0.2 ms), the current flows only through the YBCO layer. The I_{YBCO} current amplitude during this time reaches around 100 A and then begins to decrease due to the heating of the tape. The layers of silver and Hastelloy conduct relatively small currents of the order of several amps.

Heating and cooling power of 2G tape

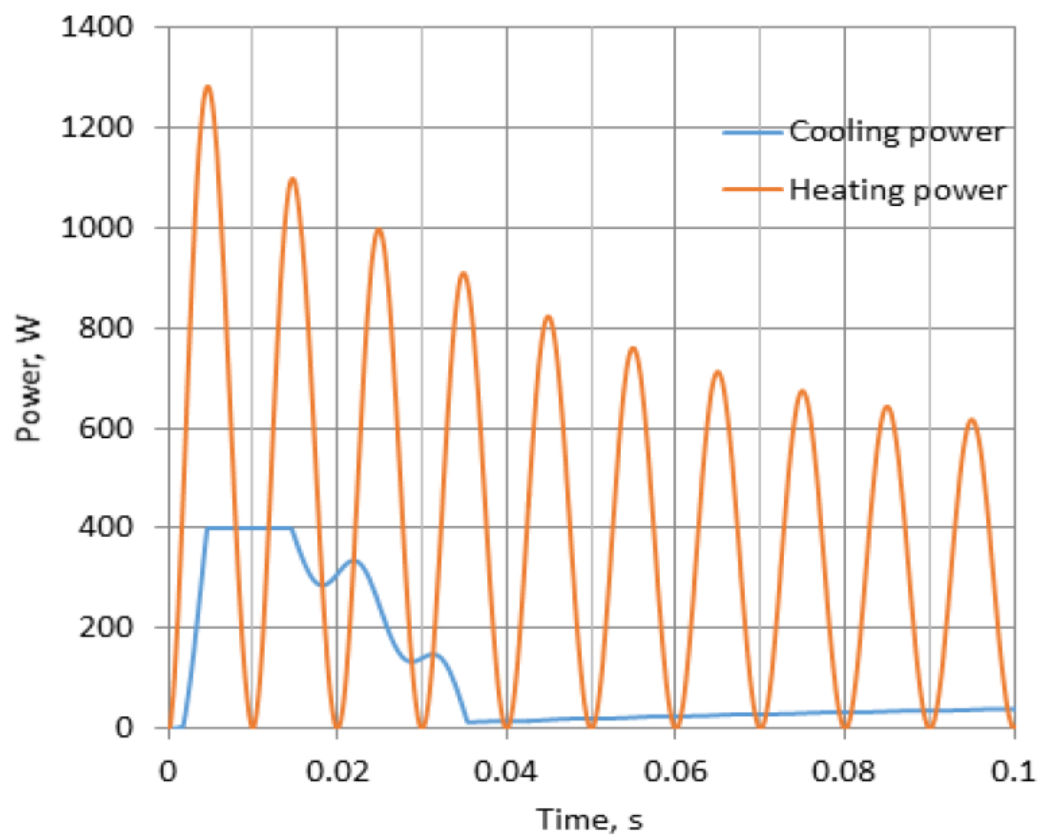
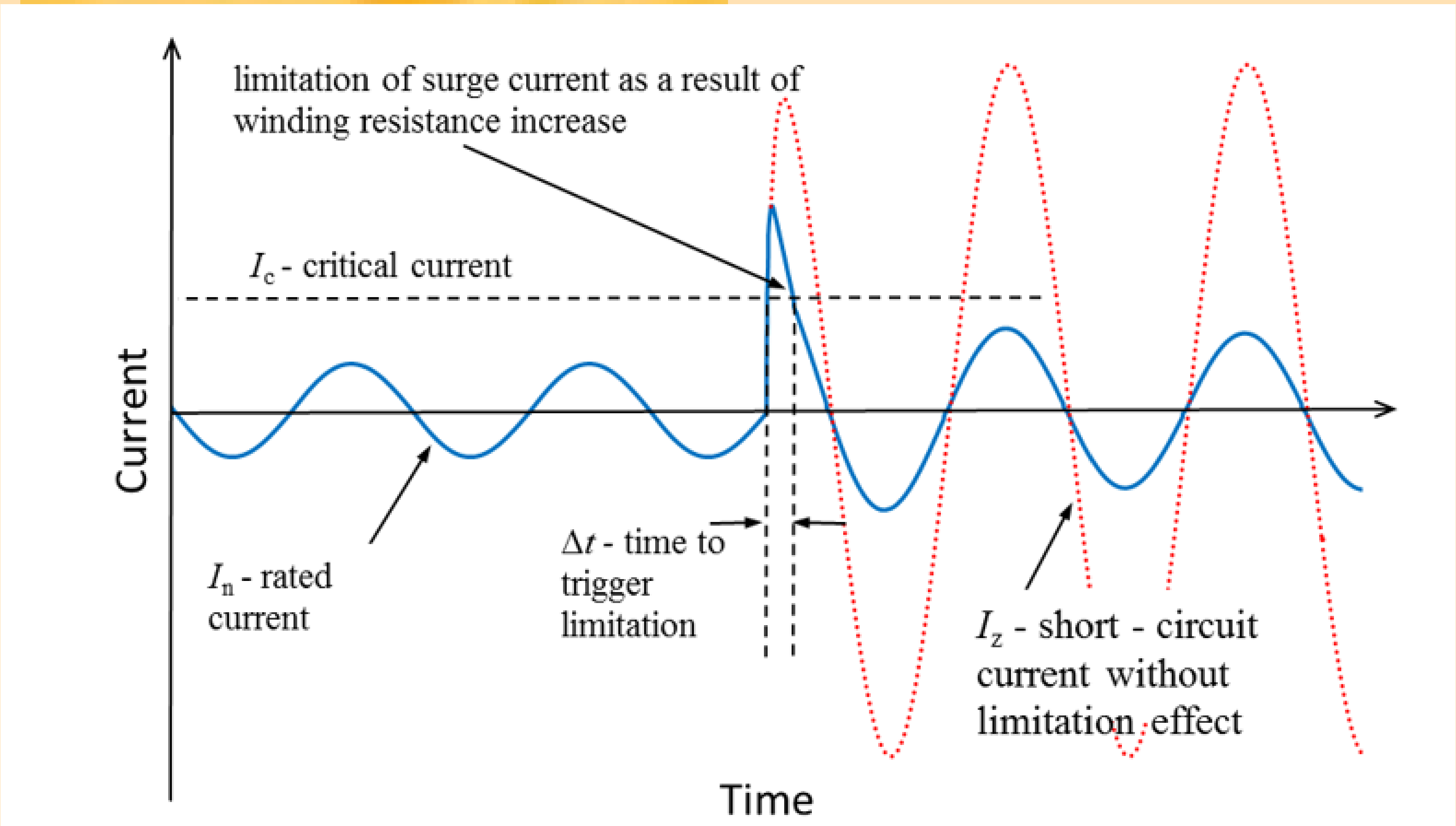


Fig. 5. Heating and cooling power of the SCS4050 tape

The maximum cooling power of the superconducting tape is 400 W. The heating power of the tape reaches 1.3 kW and then decreases to about 0.62 kW.

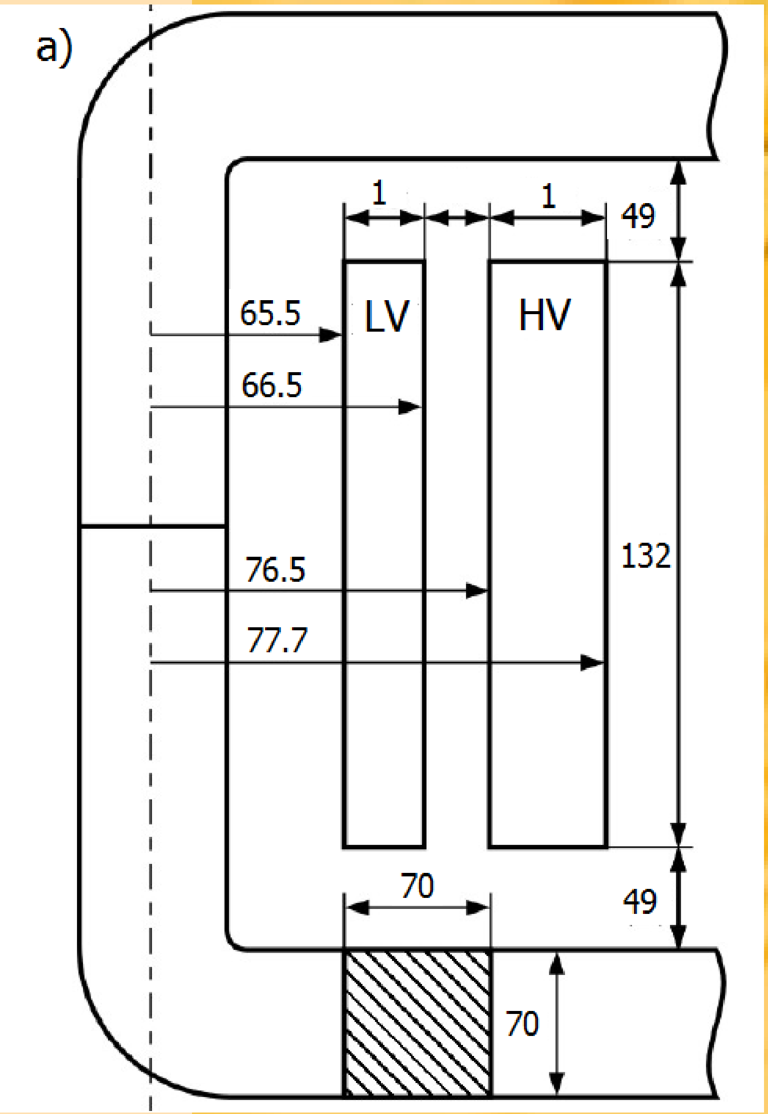
Limiting the short-circuit current in SC transformer



During a short-circuit, the current is limited by the impedance of the short-circuit loop. The most important element is the short-circuit reactance of the transformer.

When superconducting windings goes to the resistive state, the increase in the resistance of windings, largely dependent on the resistance of normal metal layers, causes that the impedance of the transformer increases many times in comparison with its impedance in the superconducting state

Structure of the SC transformer



Cross-section of 10 kVA transformer.

TABLE III. PARAMETERS OF THE 10 KVA SUPERCONDUCTING TRANSFORMER [2, 4]

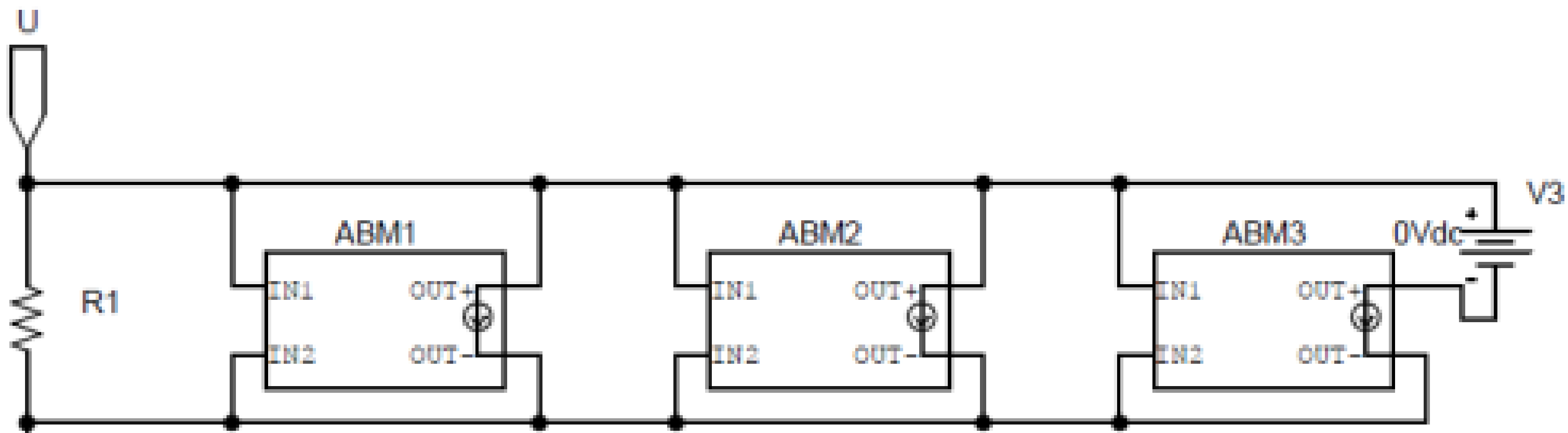
Parameter	Value
Number of phases	1
Rated power	10 kVA
Frequency	50 Hz
HV/LV winding voltage	230 V/115 V
HV/LV winding current	44 A/88 A
Core flux density	1.6 T
Relative short-circuit voltage	5%
Number of HV/LV winding turns	132/66
Number of HV/LV winding strands	1/1

TABLE II. PARAMETERS OF THE MAGNETIC CORE MODEL

Parameter	Description	Value
LEVEL	Model level	2
AREA	Core cross-section area	49 cm^2
PACK	Core packing factor	0.95
PATH	Average length of magnetic flux path	76.3 cm
GAP	Core air gap	10 mm (case #1) 1 mm (case #2)
MS	Saturation magnetisation	1.52 MA/m
A	Shape parameter of the normal magnetisation curve	10 A/m
C	Reversible energy loss parameter	0.01
K	Irreversible energy loss parameter	110 A/m

Computer model of SC tape

Equivalent circuit of superconducting tape.



R1 - (1.24e-6*L1/GrubHst/Szer) Hastelloy

ABM1 - (V(U)-V(O))*GrubAg*Szer/L1/1.59e-8/((V(Tp) -293)*3.8e-3+1) Ag

ABM2 - (V(U)-V(O))*GrubCu*Szer/L1/1.68e-8/((V(Tp) -293)*3.86e-3+1) Cu

ABM3 - IF(V(Tp)>=Tc-0.01, (V(U)-V(O))*KY/L1/0.85,

(V(U)-V(O))*KY/L1/1e-15/((ABS(I(V3))/Ico*(Tc-77)/(Tc-V(Tp)))**(N*77/V(Tp)-1)+1)) YBCO

It consists of four resistances connected in parallel: R1, ABM1, ABM2 and ABM3.
These ones represent Hastelloy, Ag, Cu and YBCO layers, respectively.
The resistance of substrate was considered as temperature independent.
For resistivity of other normal metals, simple linear functions of temperature were used.

Equivalent circuit of the SC transformer in PSpice

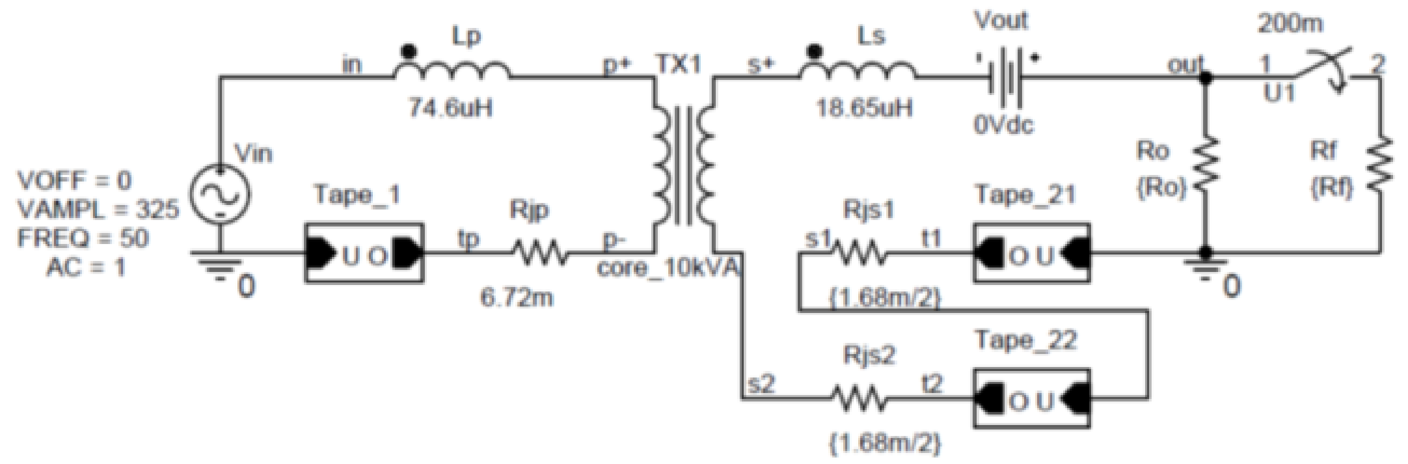


Fig. 9 Equivalent circuit of the superconducting transformer in PSpice

1. subsystem - semi-ideal transformer with a magnetic core described by Jiles-Atherton model. Full magnetic coupling of lossless windings and a ferromagnetic core model with parameters from the magnetization curve of ET114-27 steel sheets (Table IV). Jiles-Atherton model takes into account hysteretic energy loss in the core.

TABLE IV. PARAMETERS OF THE MAGNETIC CORE MODEL

Parameter	Description	Value
LEVEL	Model level	2
AREA	Core cross-section area	49 cm^2
PACK	Core packing factor	0.95
PATH	Average length of magnetic flux path	76.3 cm
GAP	Core air gap	0.1 mm (case #1)
		0.23 mm (case #2)
MS	Saturation magnetisation	1.52 MA/m
A	Shape parameter of the normal magnetisation curve	10 A/m
C	Reversible energy loss parameter	0.01
K	Irreversible energy loss parameter	10 A/m (case #1)
		110 A/m (case #2)

Equivalent circuit of the SC transformer in PSpice

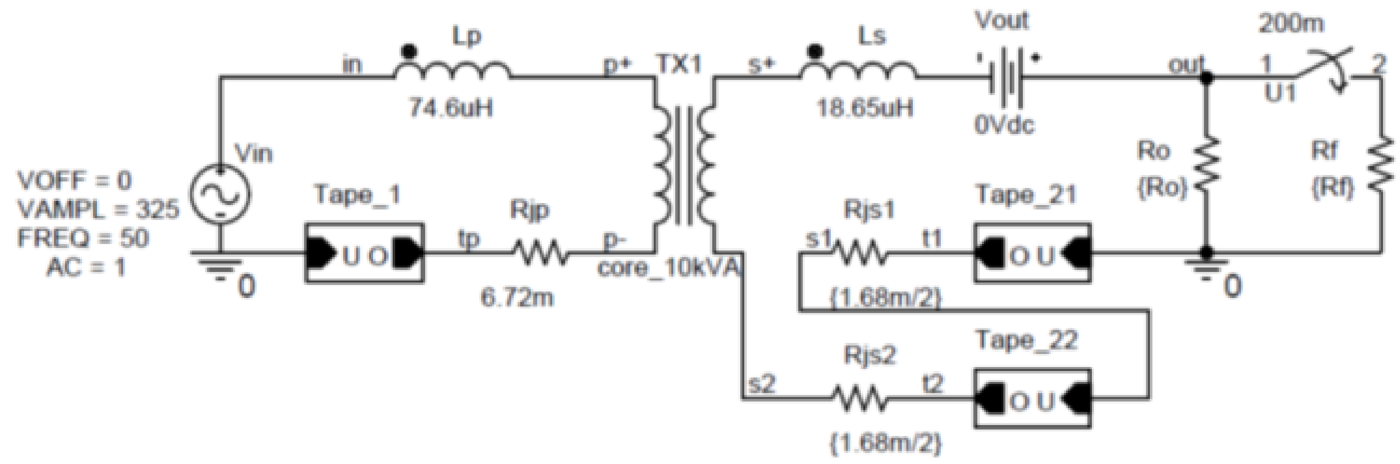


Fig. 9 Equivalent circuit of the superconducting transformer in PSpice

2. subsystem - consists of the lossy and inductive components:

Tape$_1$ - non-linear superconducting tape sub-circuit,

R_{jp} - additional resistance (normal metal parts and connections),

L_p - leakage inductance of the primary winding,

Tape$_2$ - superconducting tape sub-circuit,

R_{js} - additional resistance, L_s - leakage inductance of the secondary winding,

R_c - resistance representing eddy-current loss in the magnetic core.

R_o - transformer load, which value was set accordingly to the test type (idle, nominal load, short-circuit test).

Equivalent circuit of the SC transformer in PSpice

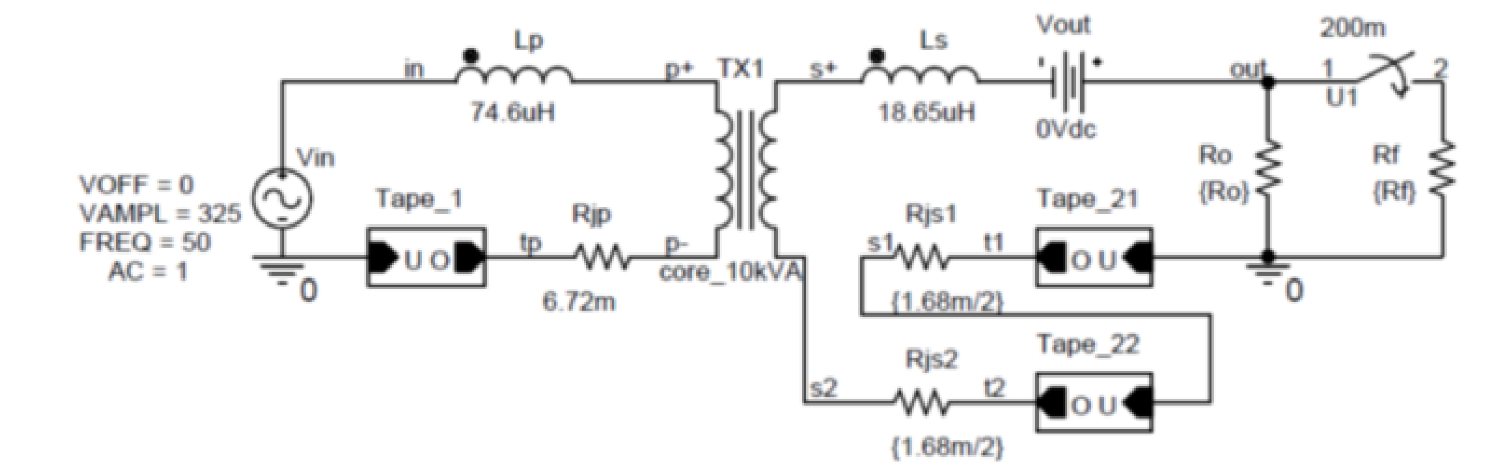


Fig. 9 Equivalent circuit of the superconducting transformer in PSpice

3. subsystem - thermal subsystem calculating temperature of the windings was also prepared and tested.

This module calculates thermal capacity of superconducting tape, Joule heating and heat dissipation to liquid nitrogen bath.

However, it is not shown here because described below experiments and simulations generated winding currents lower than the tape critical value I_C.

Joule heating was insignificant and temperature of superconducting windings was approximately equal to the coolant temperature (77 K).

Primary winding short-circuit current simulation using a computer model of a 10 kVA superconducting transformer

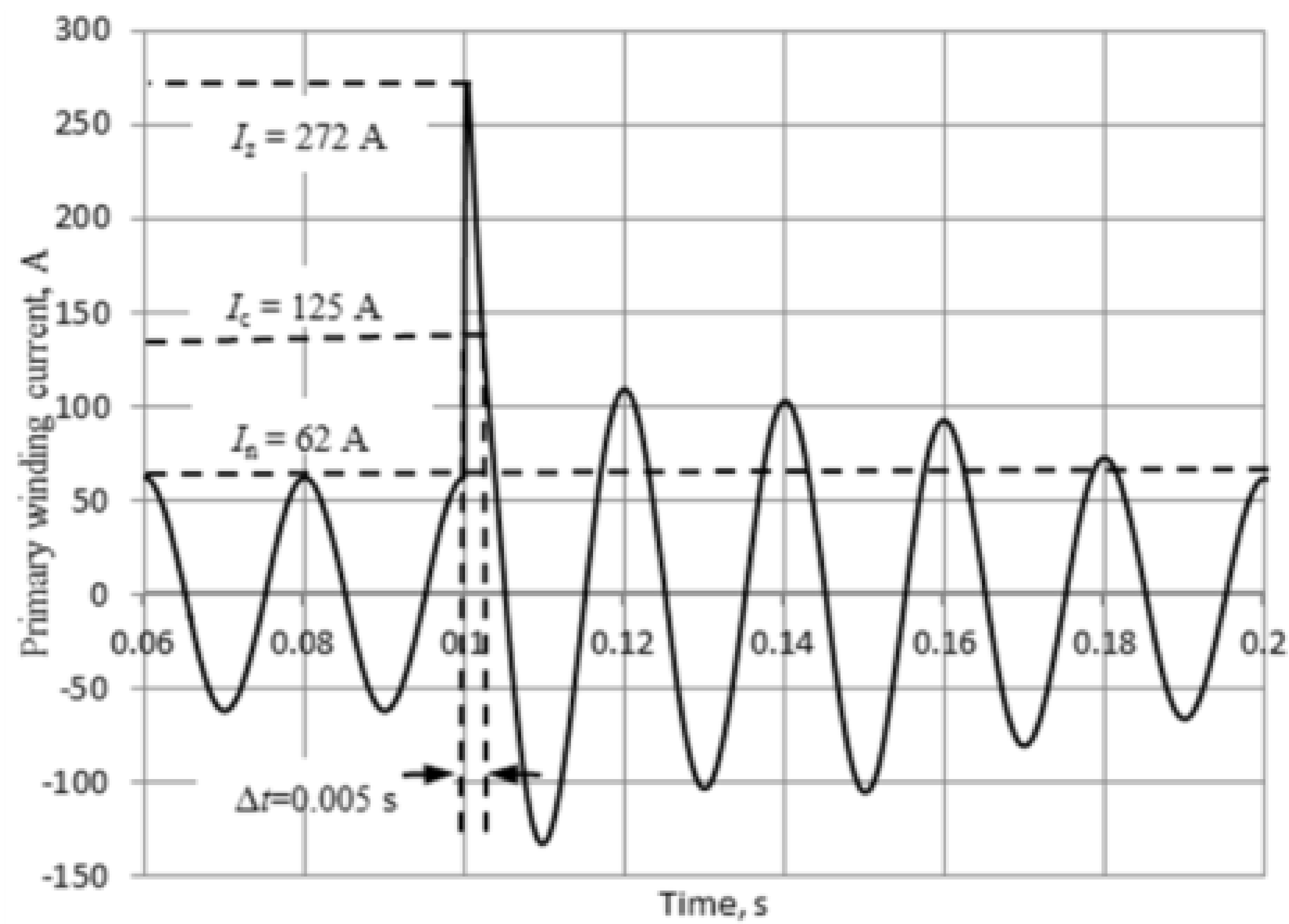


Fig. 11 Primary winding short-circuit current waveform

I_z - peak current, I_n - peak rated current,
I_c - critical current of the SCS tape.

Secondary winding short-circuit current simulation using a computer model of a 10 kVA superconducting transformer

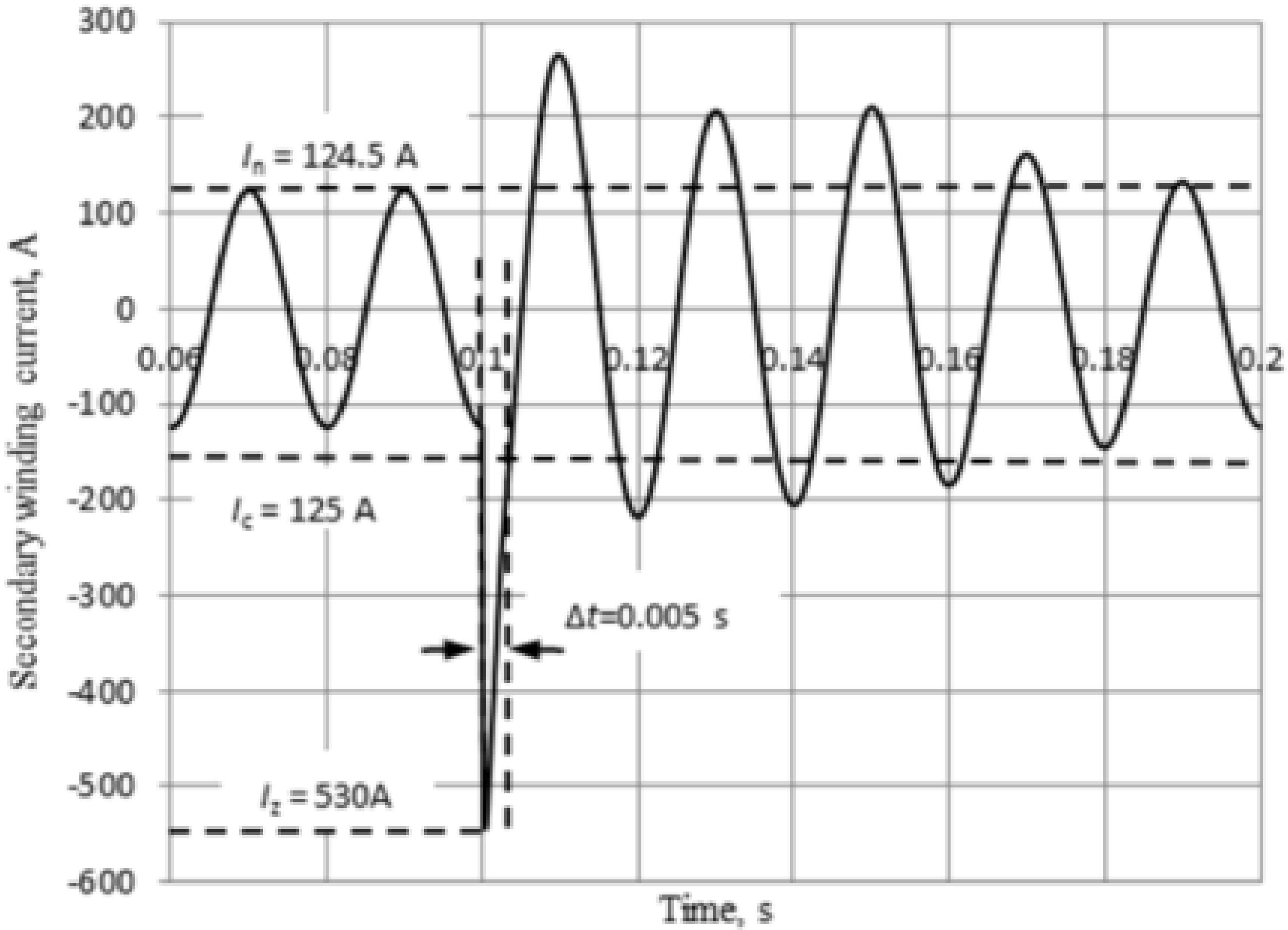


Fig. 12. Secondary winding short-circuit current waveform

Resistance waveforms during short-circuit for primary and secondary winding using a computer model of a 10 kVA SC transformer

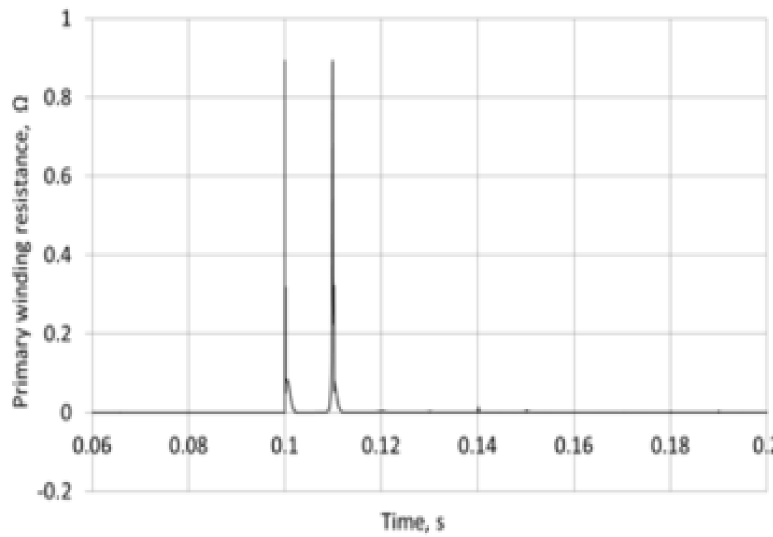


Fig. 13 Primary winding resistance waveform

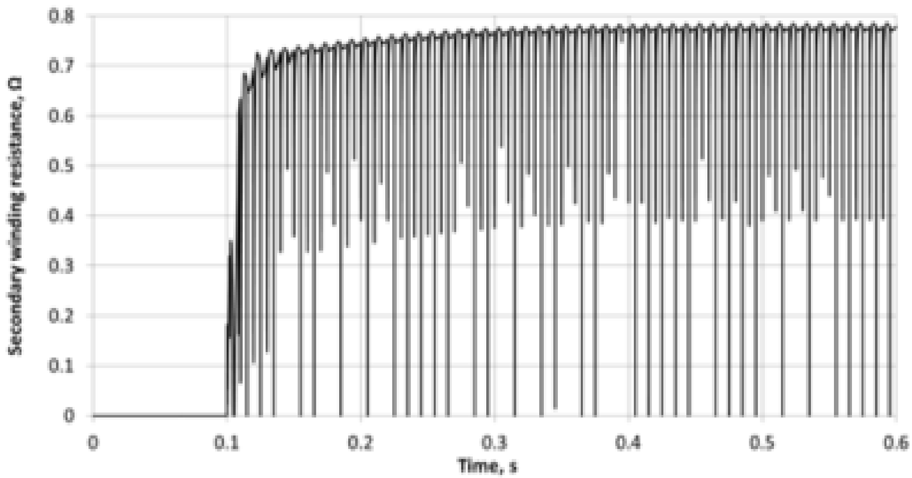


Fig. 15 Secondary winding resistance waveform

Figures 13 and 15 show the resistance of the superconducting windings of the 10 kVA transformer during the transition of the windings to the resistive state.
During a short circuit, the resistance of the HV (primary) winding reaches 0.9 Ω, while the resistance of the LV (secondary) winding tends to 0.78 Ω.

Temperature changes during short-circuit for primary and secondary winding using a computer model of a 10 kVA SC transformer

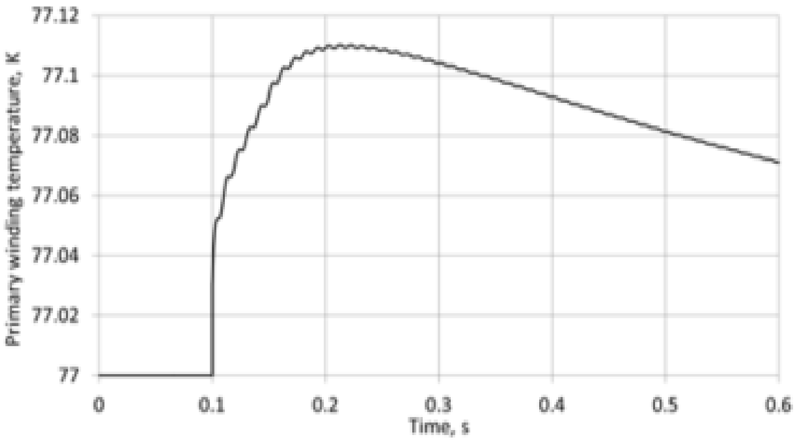


Fig. 14 Primary winding temperature during short-circuit

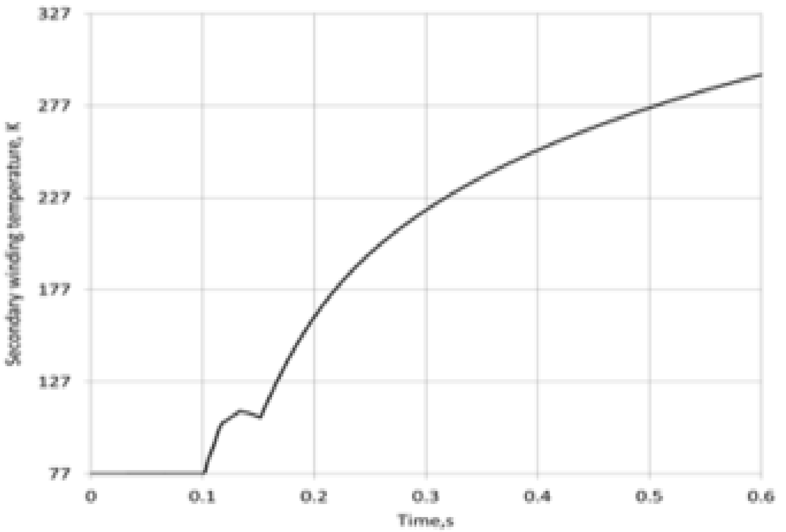


Fig. 16 Secondary winding temperature waveform during short-circuit

Figures 14 and 16 show the change of the temperature of the windings.

The temperature of the HV winding is almost constant (~ 77 K), because the winding remains in the superconducting state.
The low-voltage winding goes out quickly and its temperature reaches 294 K after 0.6 s.
This sharp rise in temperature will cause the tape to deteriorate.

Inrush current of 10 kVA SC transformer

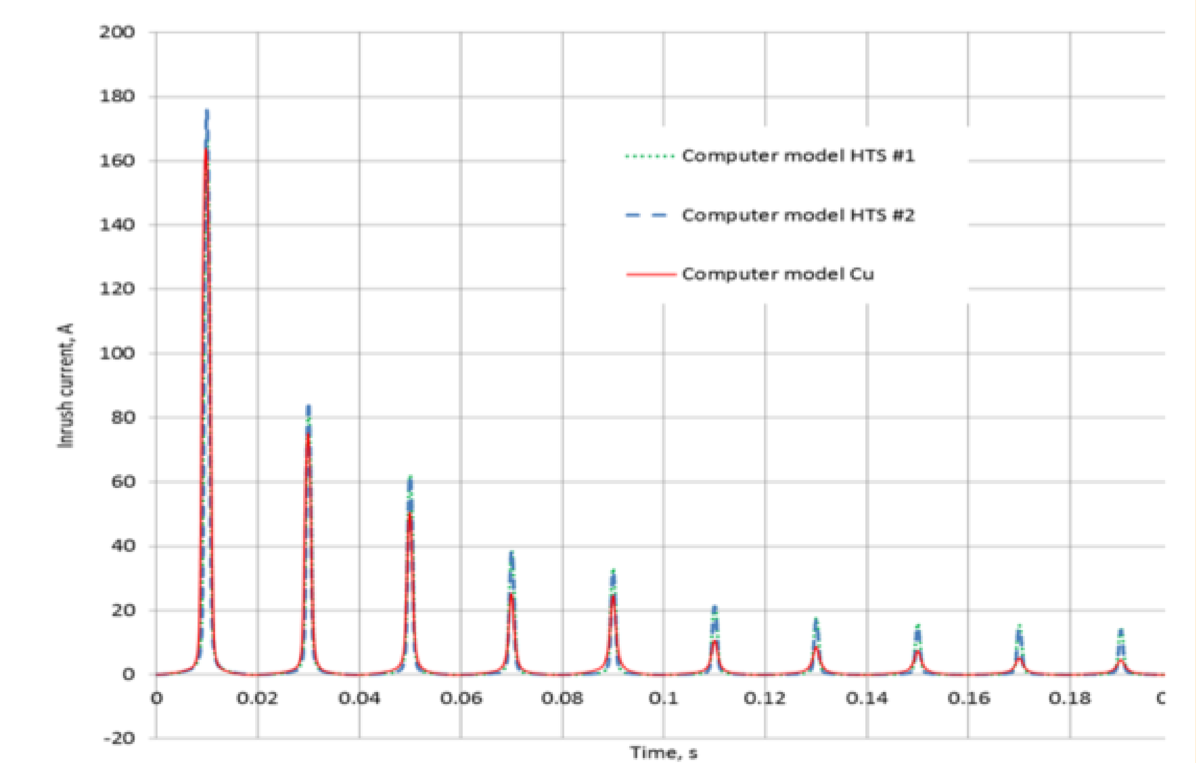
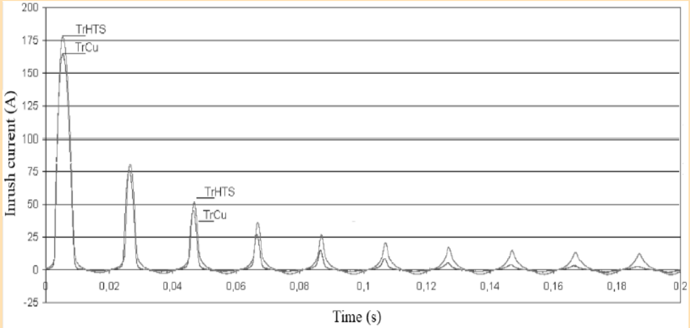


Fig. 17 Inrush current of the Cu and HTS 10 kVA transformer



Results of measurements

R_o=1 GΩ

The inrush current of the superconducting transformer for both values of an air gap (case #1 δ=0.1 mm) and case #2 δ=1 mm), as well as for the conventional Cu transformer.
Max inrush current of the SC transformer (case #1) amounts to 168 A, for (case #2) → 176 A, for conventional Cu transf. → 163 A.
Laboratory research: TrHTS1 (δ=1mm) -- 178 A, TrHTS2 (δ=10 mm) --167 A, TrCu -- 164 A

First pulse of the inrush current of SC transformer

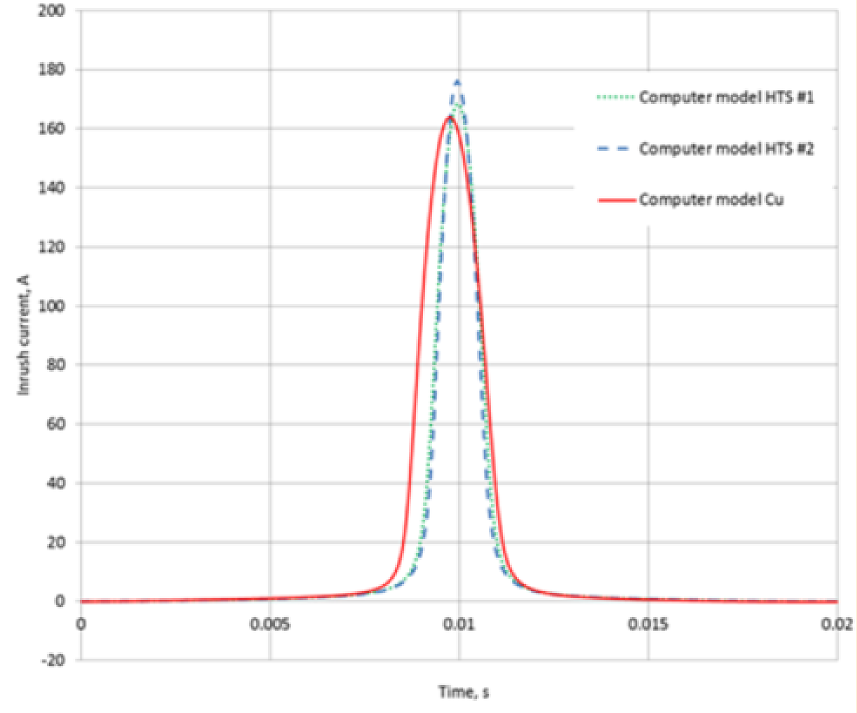
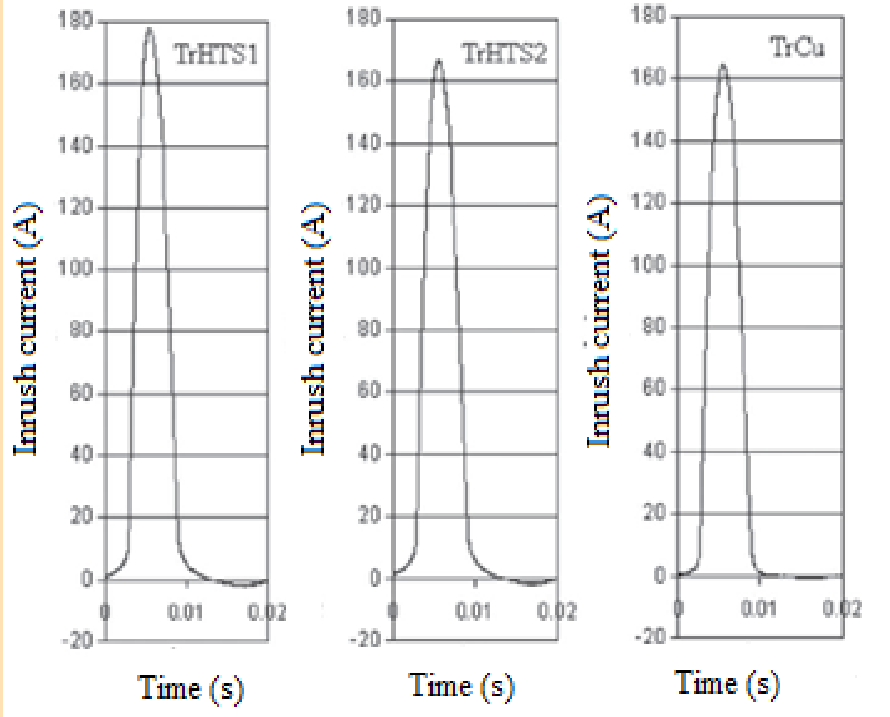


Fig. 18 First pulse inrush current of the10 kVA transformer



Computer model

Physical model

The first pulse of the inrush current of the transformer exceeds the tape's critical current value I_C = 125 A for 51 A in case #1 and for 43 A in case #2.

The second pulse occurs after 0.02 s and is well below the critical current of tape I_C; for the SC transformer (case #1) it amounts to 84 A, for (case #2) -- 85 A, whereas for the conventional Cu transformer -- 75 A.

Tenth pulse of the inrush current of SC transformer

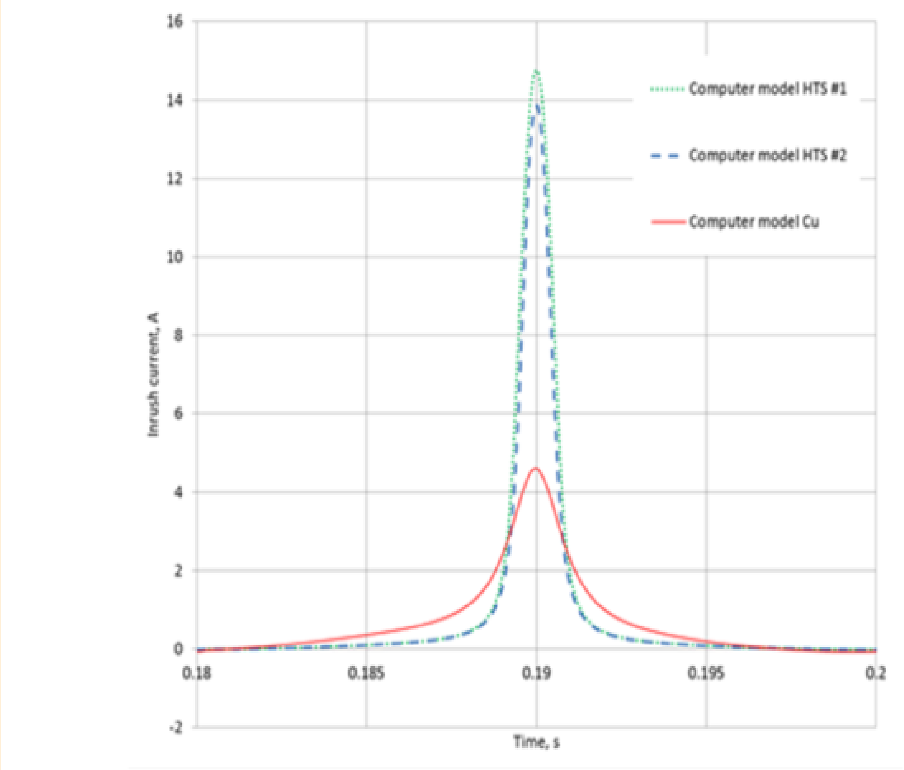
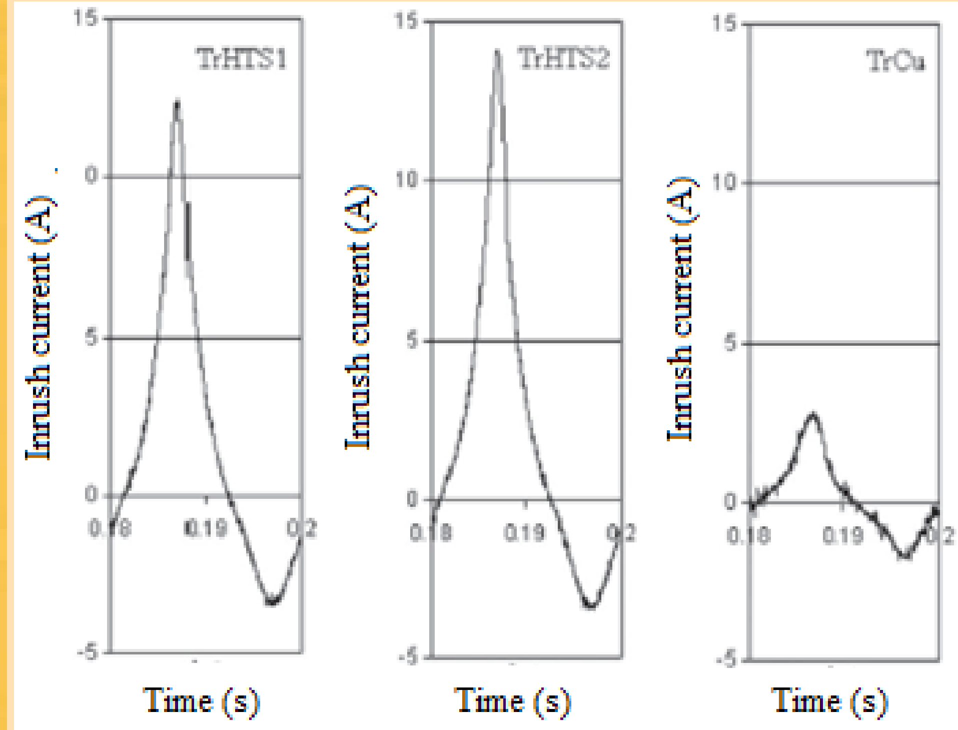


Fig. 19 Tenth pulse inrush current of the10 kVA transformer

Computer model



Physical model

After 0.18 s, the peak value of the inrush current of the superconducting transformer (case #1) amounts to 15 A and it is 11.2 times suppressed, for (case #2) --- 14 A , 12.6 times suppressed, whereas for the conventional Cu transformer -- 4.6 A , 35.6 times suppressed.

Analysis results of the inrush current of SC transformer

Parameter	Case #1	Tr_{THS1}	Case #2	Tr_{THS2}	Cu	Tr_{Cu}
Maximum starting current (first pulse)	168	167	176	178	163	164
Starting current value after 0.2s (10 pulse)	15	14	14	12	4.6	2.5
Relation between tenth pulse and the first pulse (i_{10}/i_1)	9%	7%	8%	8%	2.8%	1,5%

Case#1 – computer model transformer with HTS windings (δ=0.1 mm)
Tr_{THS1}– physical model transformer with HTS windings (δ=0.1 mm)
Case#2 – computer model transformer with HTS windings (δ=1 mm)
Tr_{THS2}– physical model transformer with HTS windings (δ=1 mm)
Cu – computer model transformer with copper windings
Tr_{Cu}– physical model transformer with copper windings

HTS 21 MVA transformer model

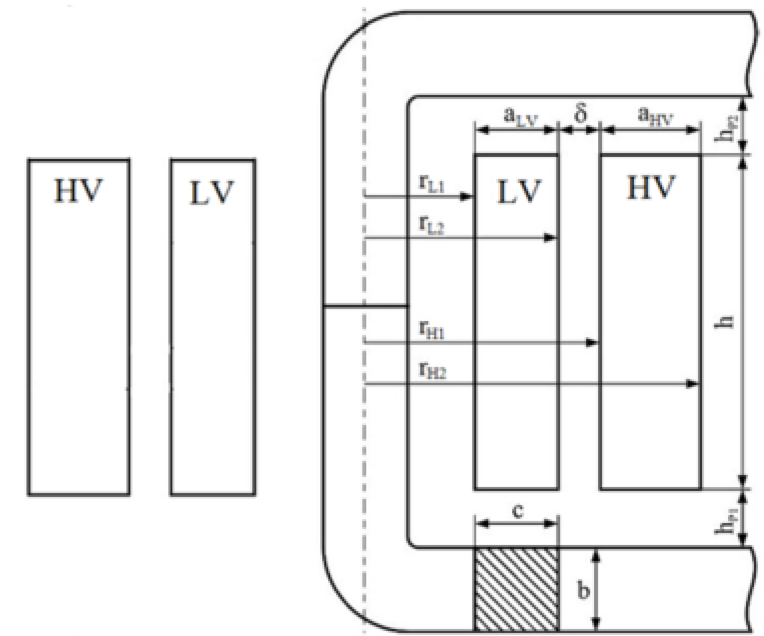


Fig. 8. Cross section of the transformer

TABLE VI. WYMIARY TRANSFORMATORA NADPRZEWODNIKOWEGO O MOCY 21 MVA

Symbol	Cu	HTS	Symbol	Cu	HTS
r_{L1}, mm	365		a_{HV}, mm	86	1.85
r_{L2}, mm	426	366.44	h, mm	1080	
r_{H1}, mm	482	422.44	h_{P1}, mm	120	
r_{H2}, mm	568	424.29	h_{P2}, mm	120	
δ, mm	56		b, mm	439	
a_{LV}, mm	61	1.44	c, mm	680	

One of the many advantages of replacing conventional transformers with superconducting transformers is to **increase efficiency by eliminating most of load losses in the windings**, due to the low effective resistance of the superconductor in the superconducting state and the reduction of core losses due to shorter yokes.
Due to the thickness of superconductor tapes, the **radial dimensions of superconductor windings are smaller than those of copper windings**, and thus the yoke lengths of magnetic cores of HTS transformers **are shorter**.
This results in a **reduction in the volume and weight of the core and the entire transformer**, as well as in a **reduction in the power losses in the core**.

HTS 21 MVA transformer model

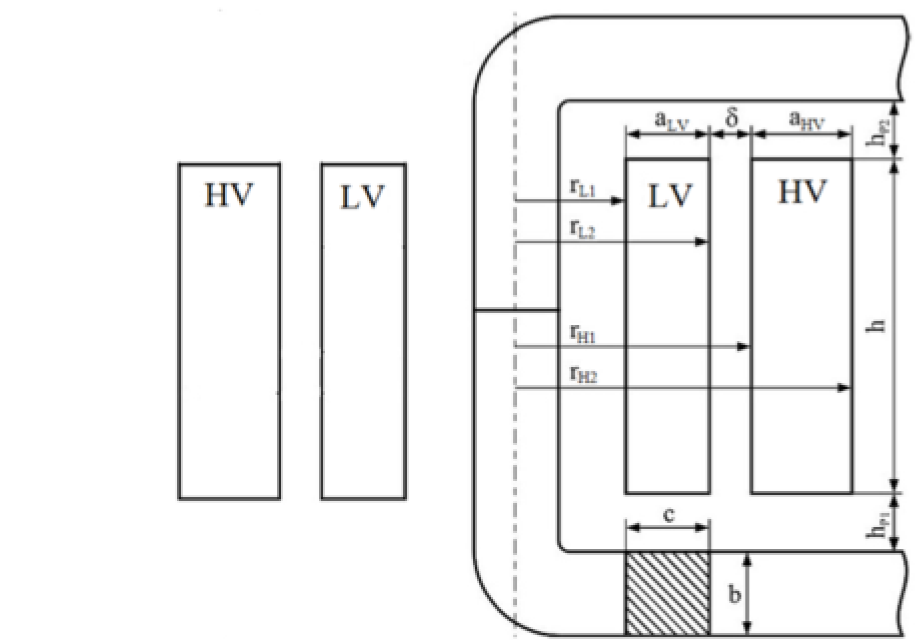


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TABLE VII. DANE ZNAMIONOWE TRANSFORMATORA KONWENCJONALNEGO I NADPRZEWODNIKOWEGO O MOCY 21 MVA

Parametr	Cu	HTS
Magnetic core cross-section, m^2	0.2844	
Core type sheet	ET 114-27	
HTS HV and LV windings made of tape	-	SF 12050 SCS 12050
Cu wire cross-section HV/LV, mm^2	86 / 571.4	-
The dimensions of the tape (width/thickness), mm	-	12 / 0.055 12/0.1
The critical current of the tape, A	-	280
HV side (primary) voltage, kV	69.86	
LV side (secondary) voltage, kV	10.5	
Rated HV winding current, A	301	
Rated LV winding current, A	2000	
Working flux density B, T	1.63	
No. of layers HV/LV	11 / 10	9 / 7
No. of turns/layer	240	88
Tape length HV/LV, m	-	3791 / 2360

HTS 21 MVA transformer model

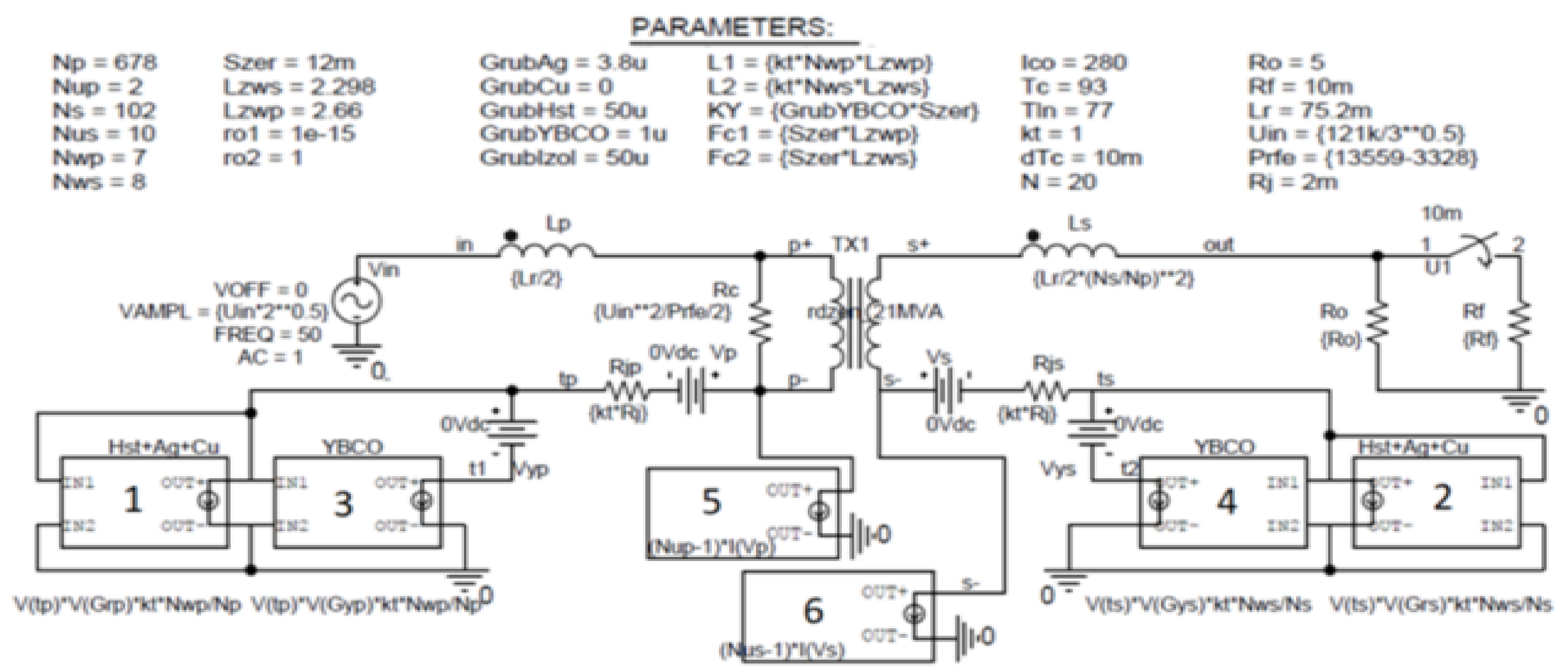

Fig. 20 Computer model of a single –phase HTS transformers with the power of 21 MVA made in PSpice

The layers of the tape substrate (Hastelloy) and lamination (silver and copper) are modelled with blocks ABM 1 and 2, and the YBCO superconducting layers – with blocks 3 and 4. Blocks ABM 5 and 6 model the electrical parameters of full windings.

PSpice modeling of the power losses of a 21 MVA Cu transformer

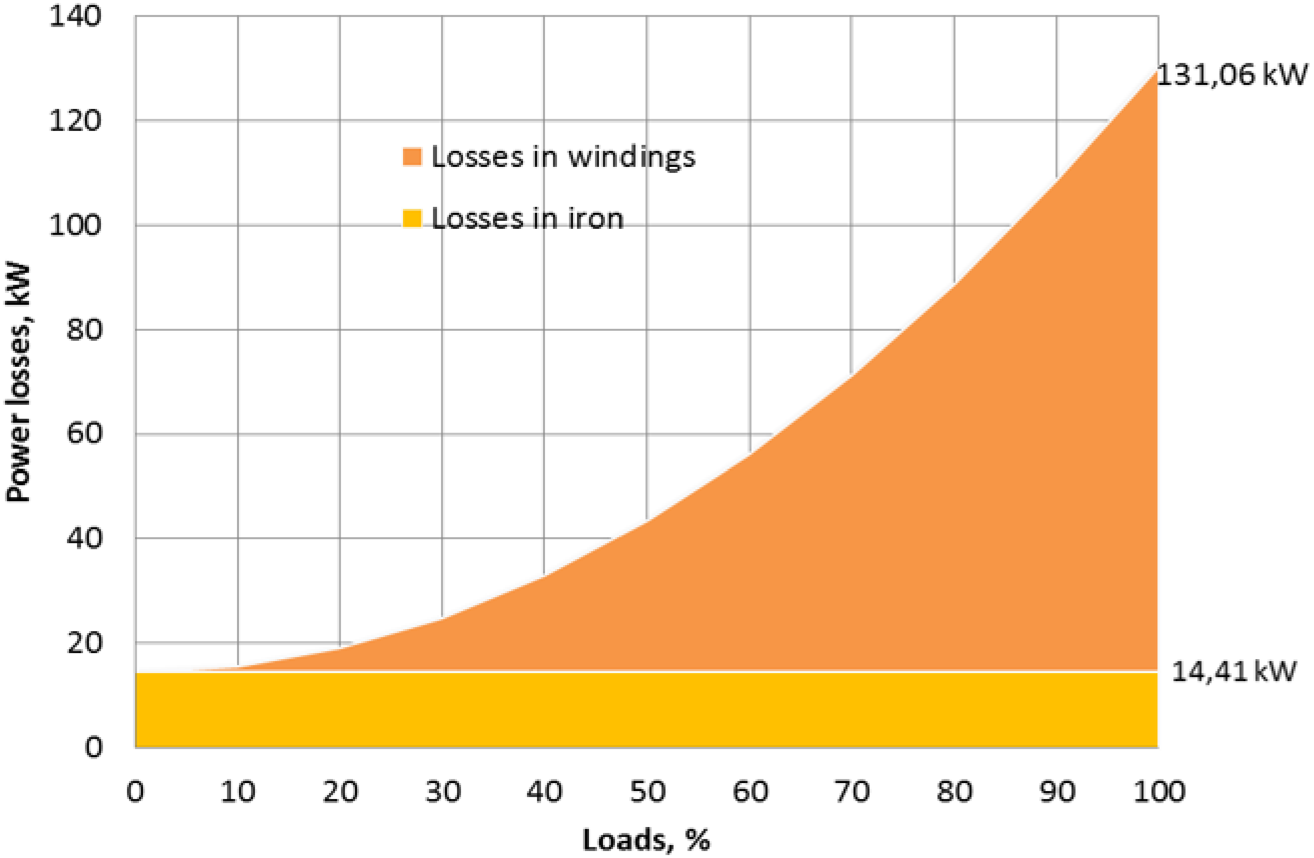

Fig. 21. Power losses of a single-phase 21MVA Cu transformer

PSpice modeling of the power losses of a 21 MVA SC transformer

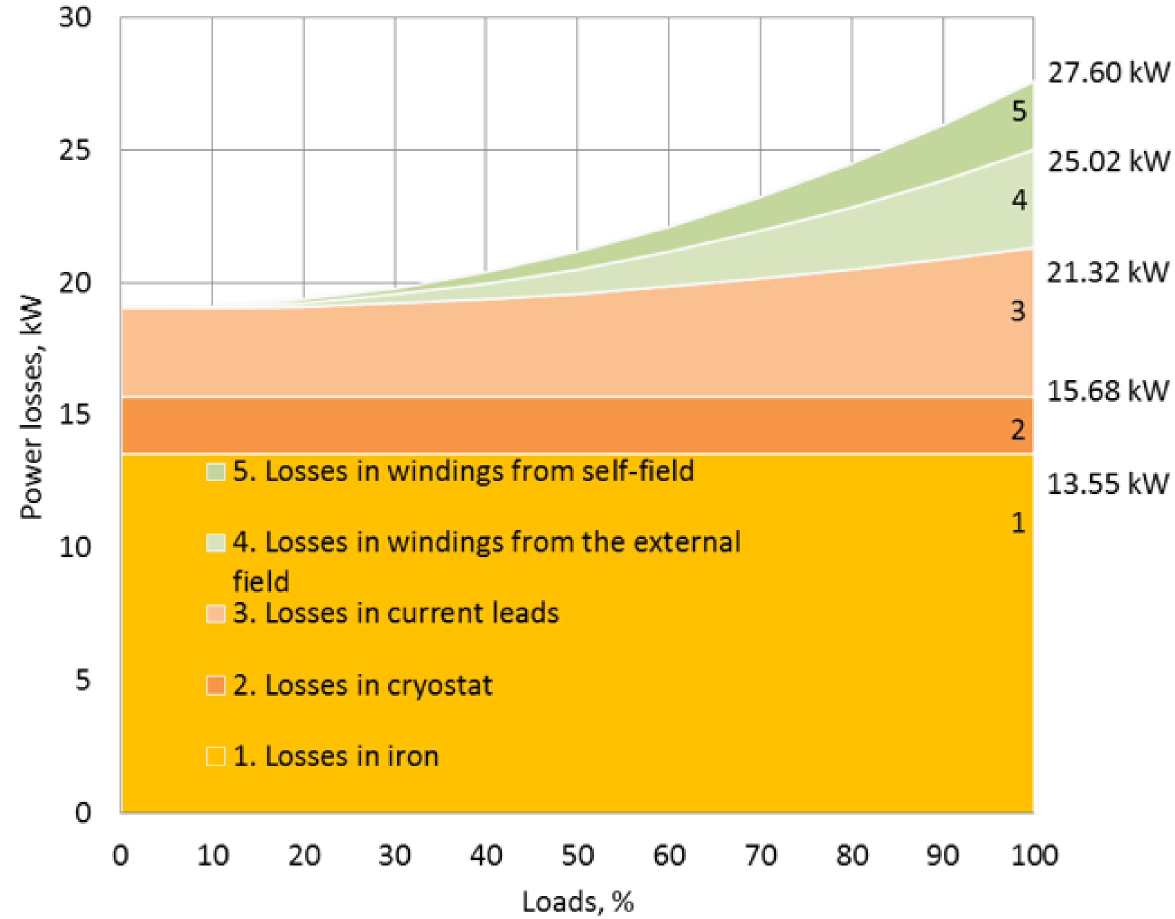

Fig. 22. Power losses of a single-phase HTS transformer with a capacity of 21 MVA

Total power losses of a 21 MVA Cu and SC transformer

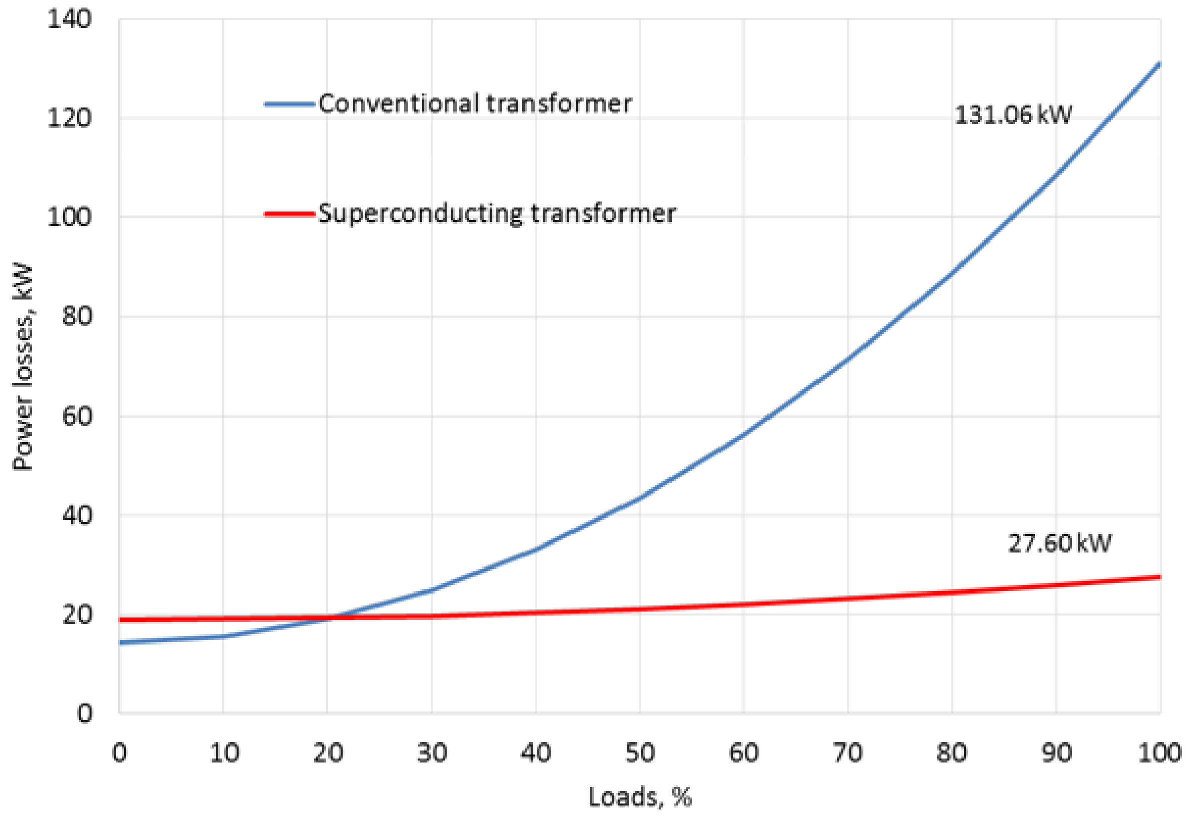

Fig. 23. Total power losses of a single-phase 21 MVA HTS and Cu transformers

For loads up to approximately 19%, a SC transformer has several kW higher losses due to its operation at 77 K — 2.13 kW must be used to remove heat through cryostat walls and 3.33 kW through current leads. This difference does not compensate for the smaller iron losses (14.41 kW for Cu and 13.23 kW for HTS). At full load, the total loss for a superconducting transformer is almost 100 kW less than for a conventional one of the same power of 21 MVA.

Efficiency of a 21 MVA Cu and SC transformer

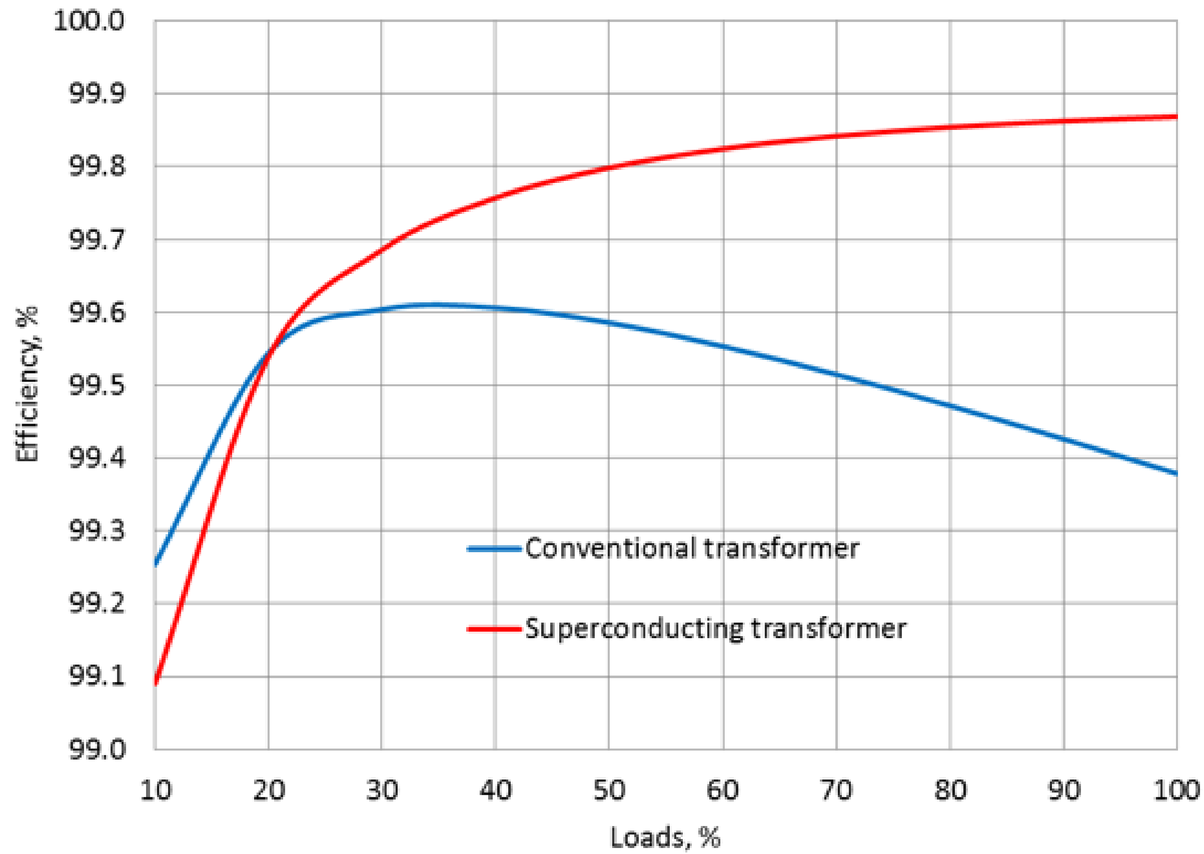

Fig. 24. Efficiency of a 21 MVA HTS and Cu transformers

A superconducting transformer has a lower efficiency for loads up to approx. 19%. At full load, the superconducting transformer efficiency of is 99.87% and the conventional transformer efficiency is 99.38%.

Power losses of a 21 MVA SC and Cu transformer

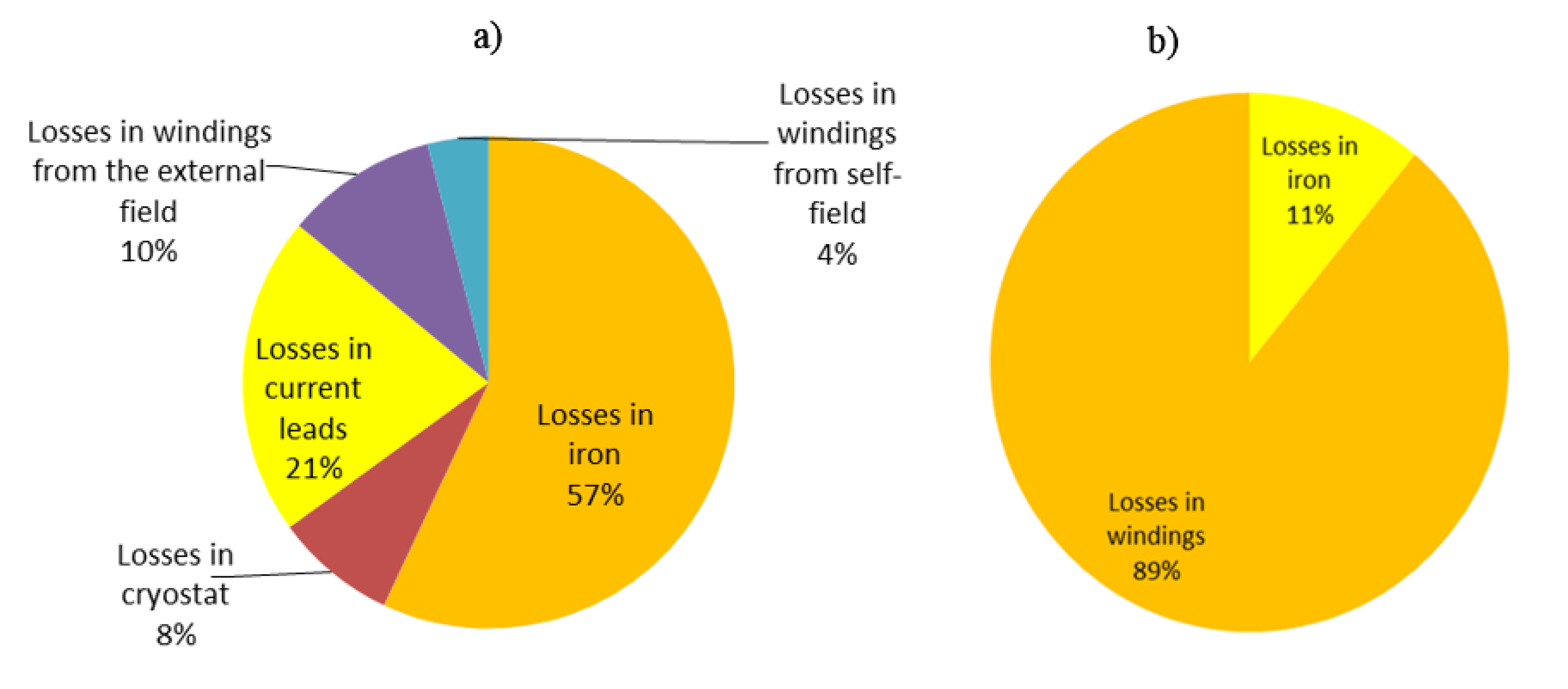

Fig. 25. Distribution of the power loss of the superconducting (a) and conventional (b) transformer

In a Cu transformer, 89% are losses in copper windings and 11% are losses in iron (core).

In a SC transformer, the load-independent constant losses amount to 65% of the total losses. The remaining 21% are current leads losses and external and self-field winding losses of 10% and 4% of total losses respectively.

Fields of pie charts for both types of transformers (Cu and HTS) are proportional to their total power (energy) losses.

Inrush current of a Cu and SC transformer 21 MVA

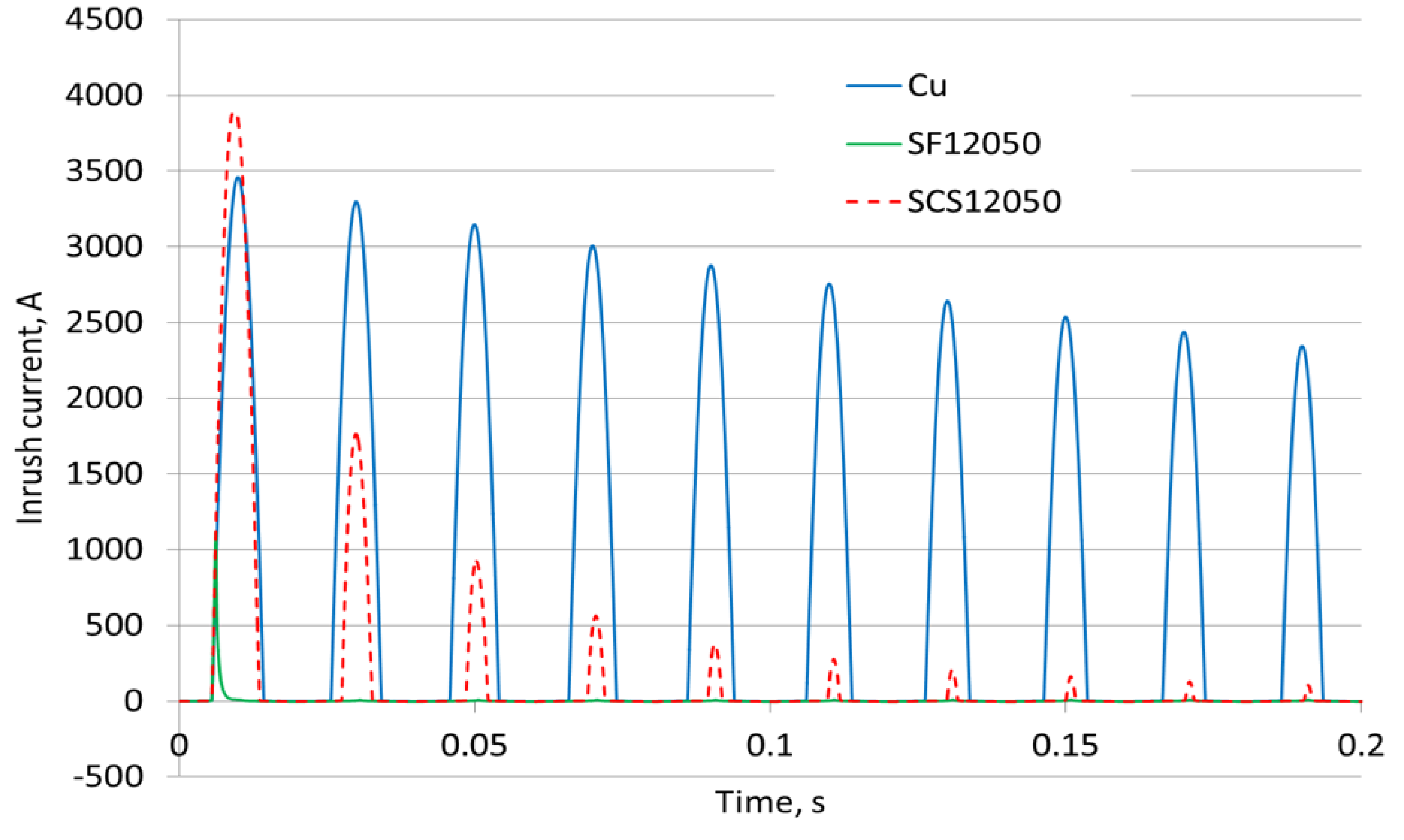

Fig. 26. The inrush current of the Cu transformer and HTS transformers

The computer model in PSpice allowed to obtain inrush current waveforms of superconducting transformers with SF12050, SCS12050 tapes and conventional copper windings.

The first ten pulses of unidirectional current (Fig. 26) were subjected to computer examination.

Inrush current of a Cu and SC transformer 21 MVA

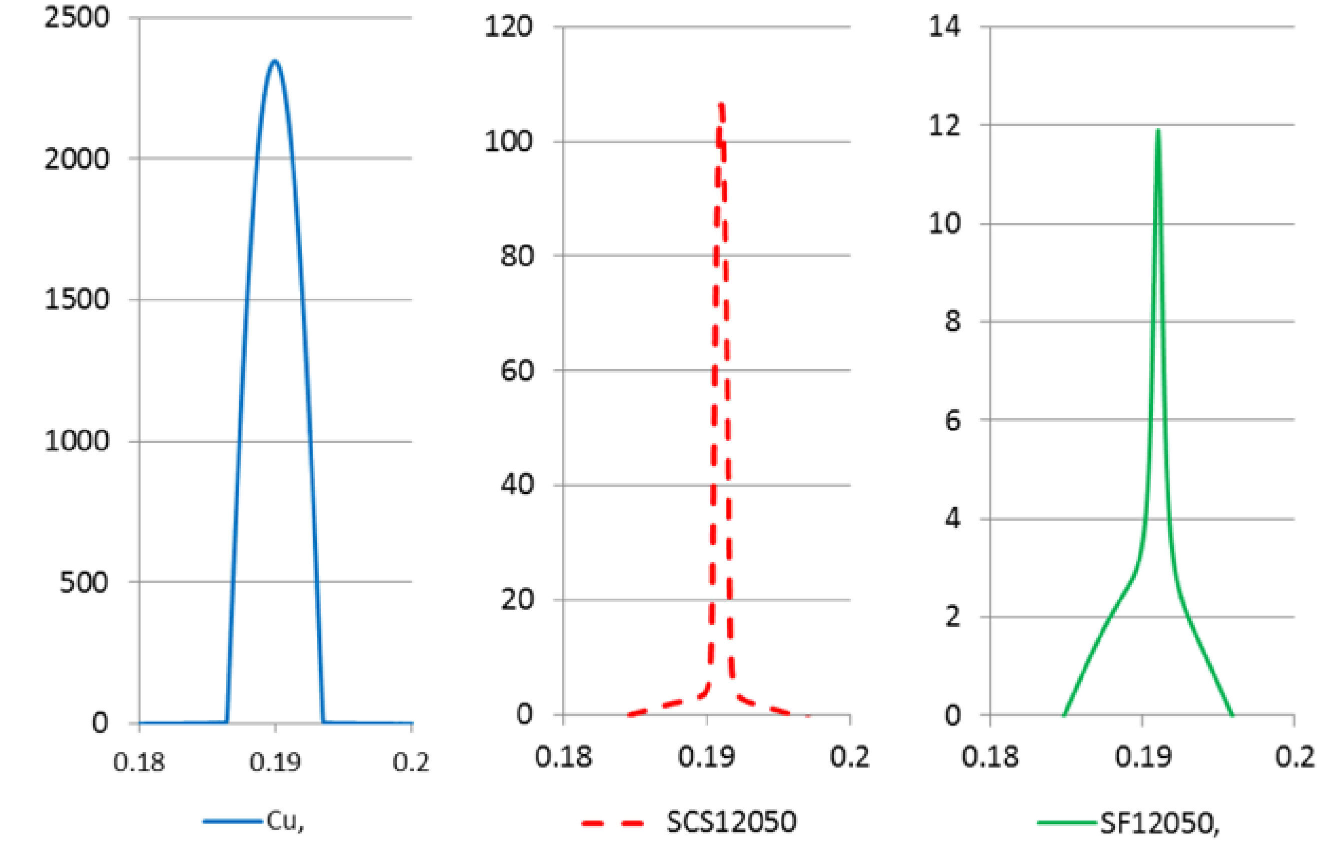

Fig. 27. The first pulse of the inrush current

The first pulse of the inrush current (Fig. 27) of the HTS transformer with SCS12050 tapes was 3888.8 A, and the subsequent pulses for this tapes were decreasing rapidly. For a transformer with SF12050, the first pulse is 1114.81A. The inrush current pulses for a transformer with copper windings decrease the most slowly.

Inrush current of a Cu and SC transformer 21 MVA

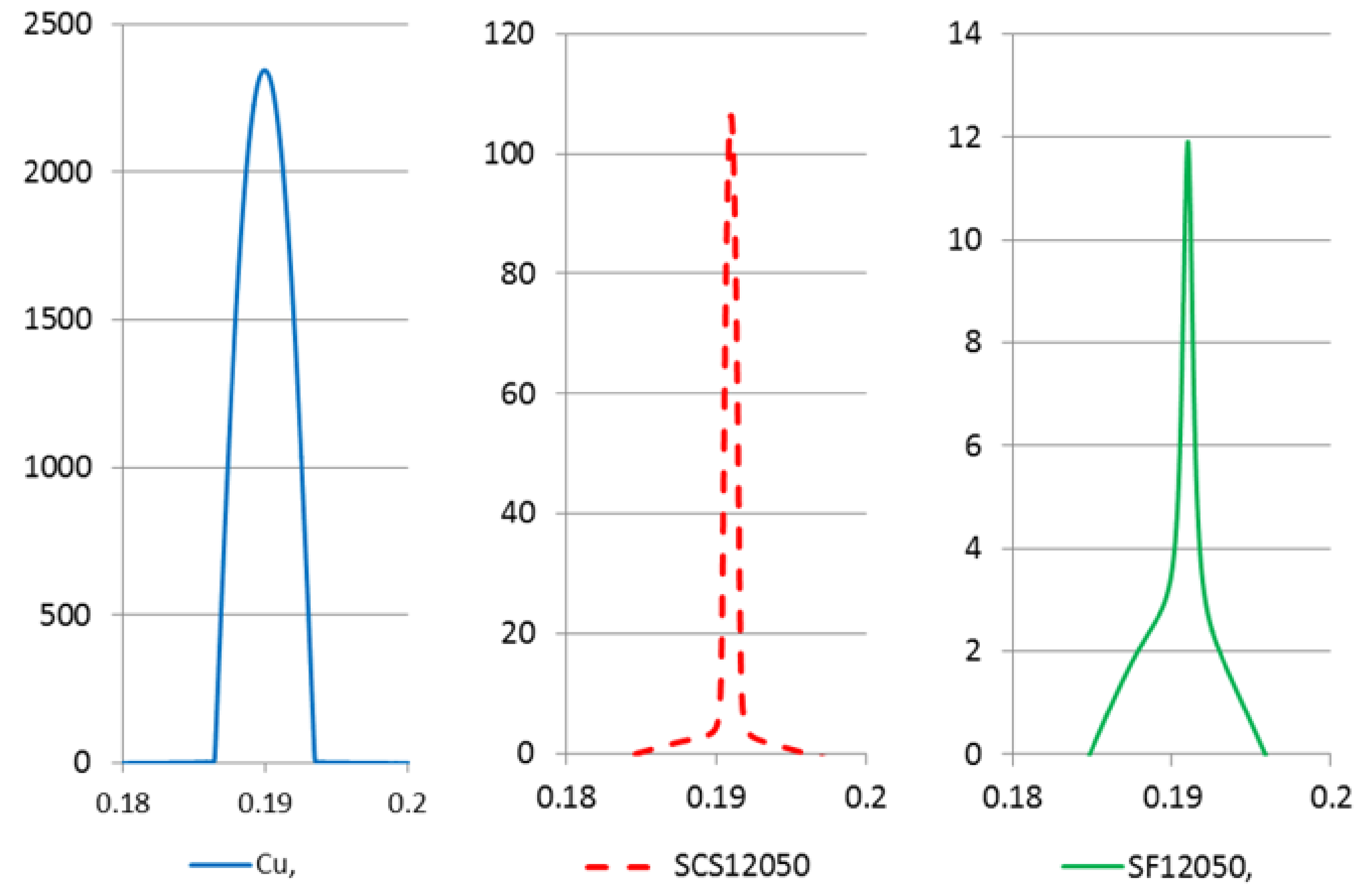

Fig. 28. The tenth pulse inrush current

For the tenth impulse of the inrush current (Fig. 28) of the HTS transformer with the SCS12050 tape, an amplitude of 106.3 A was obtained. In the case of the SF12050 tape it was 11.9 A, and for copper windings this value was 2345.2 A

Inrush current of a Cu and SC transformer 21 MVA

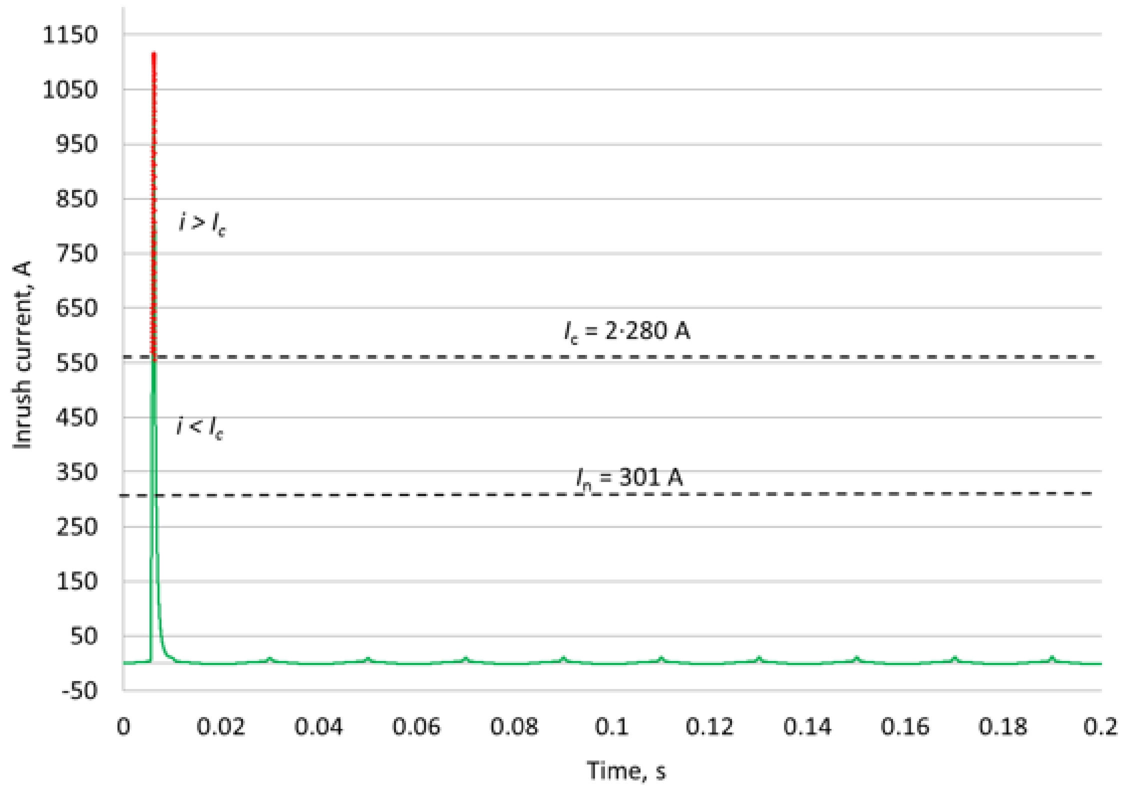

Fig. 29. The inrush current for the transformer with SCS 12050 windings with I_c and I_n levels marked

SCS12050 tape winding

Current waveforms with marked intervals in which $i > I_c$ were presented with windings SF12050 and SCS12050 in Fig. 29 and 30. The graphs show one exceeding of critical current I_c for tape SF12050 and four decreasing ones for tape SCS12050.

The calculations show that the time for which the unidirectional current pulse exceeds the critical current for the SF12050 transformer is t_{SF1205}=4.51 ms and for the SCS12050 it is t_{SF1205}=74 ms.

Inrush current of a Cu and SC transformer 21 MVA

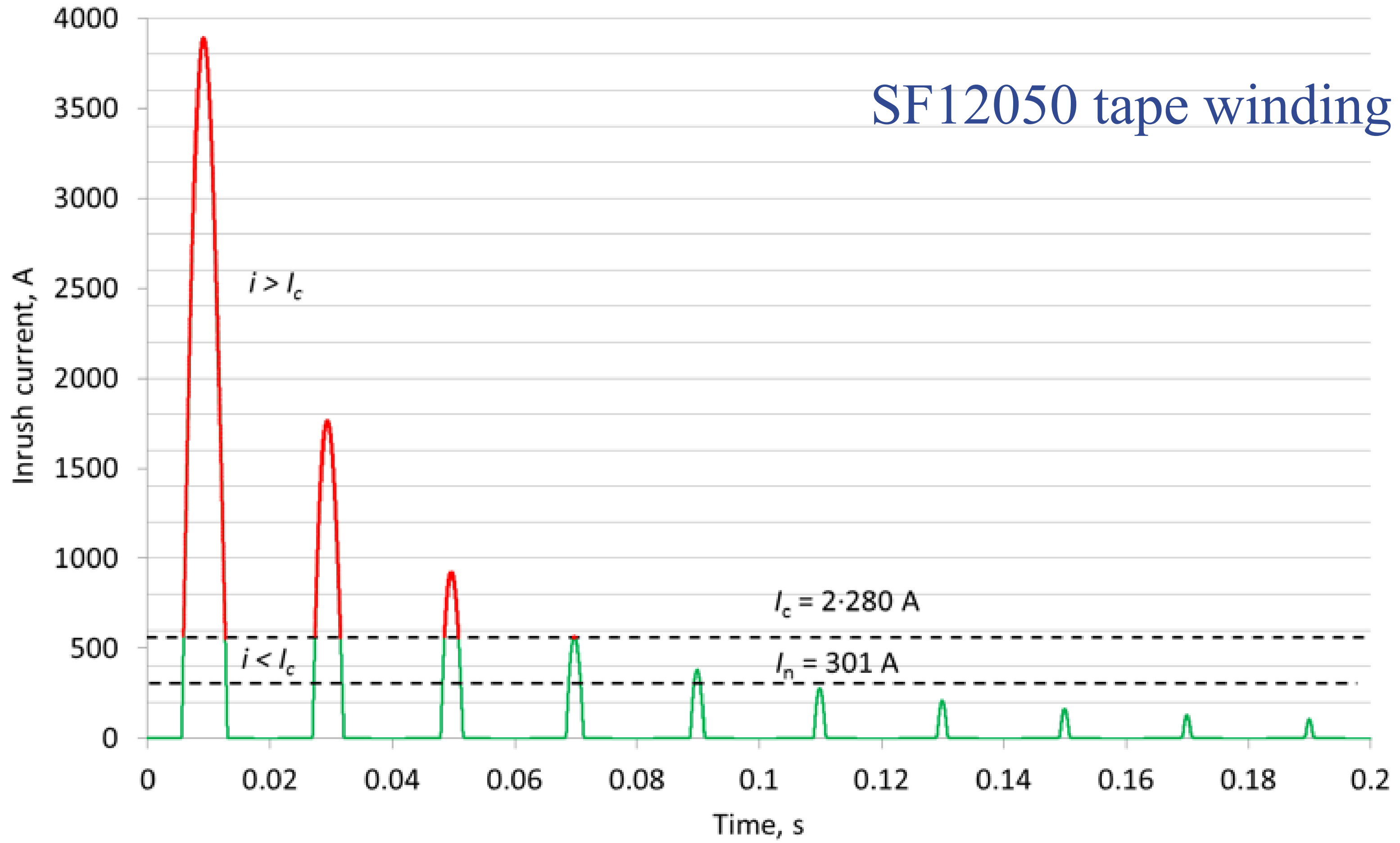

Fig. 30 The inrush current for the transformer with SF 12050 windings with I_c and I_n levels marked

Inrush current of a Cu and SC transformer 21 MVA

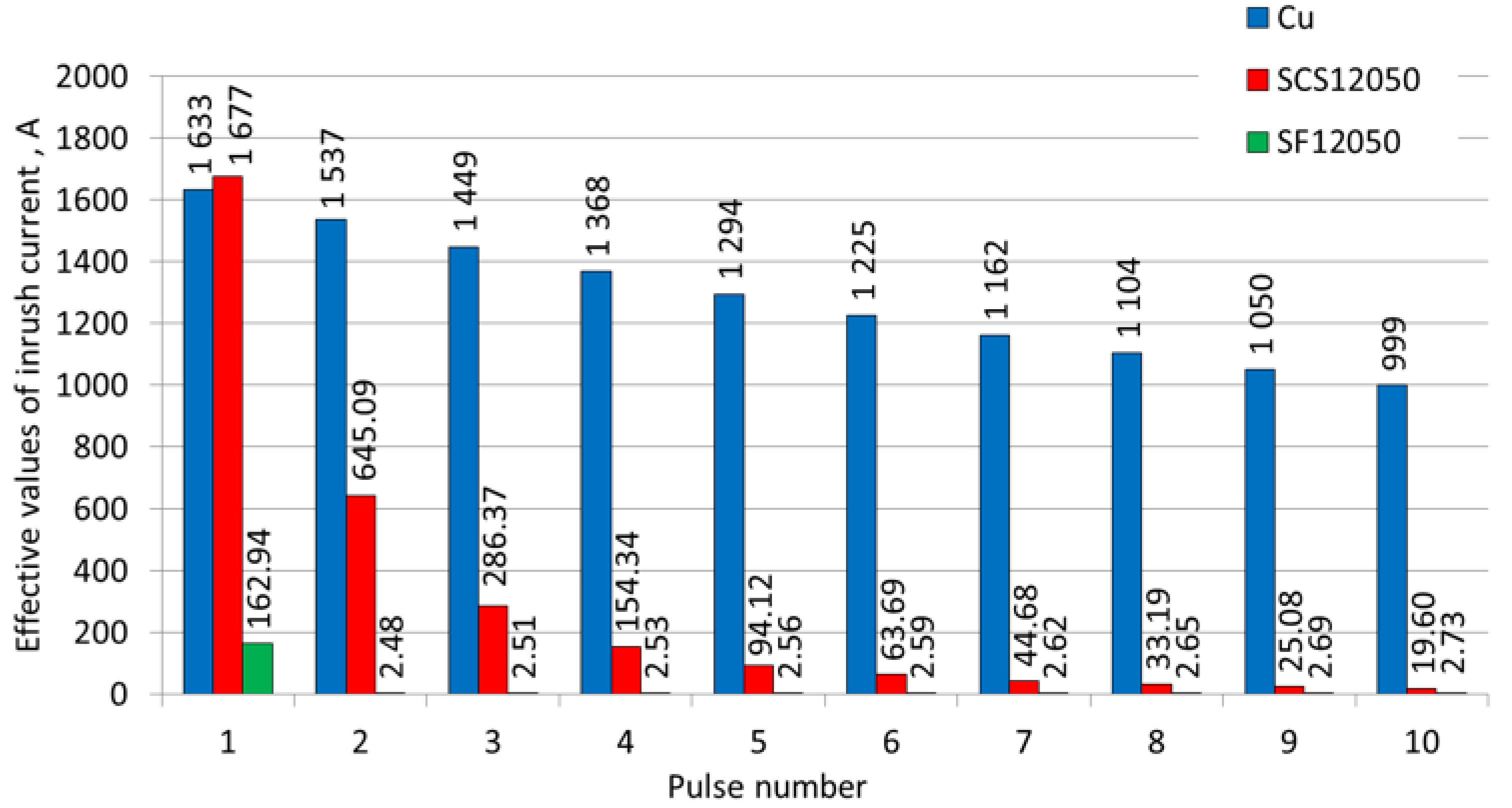

Fig. 31 Effective values of inrush current pulses

The effective value (Fig. 31) of the **first** unidirectional current pulse for the SCS12050 winding is 1677 A. The effective value of the **second pulse** is 2.6 times lower and is 645 A.

For a SF12050 tape windings the effective value of the first unidirectional current pulse is 162.94 A and the second pulse is 2.48 A.

Temperature increase – for inrush current

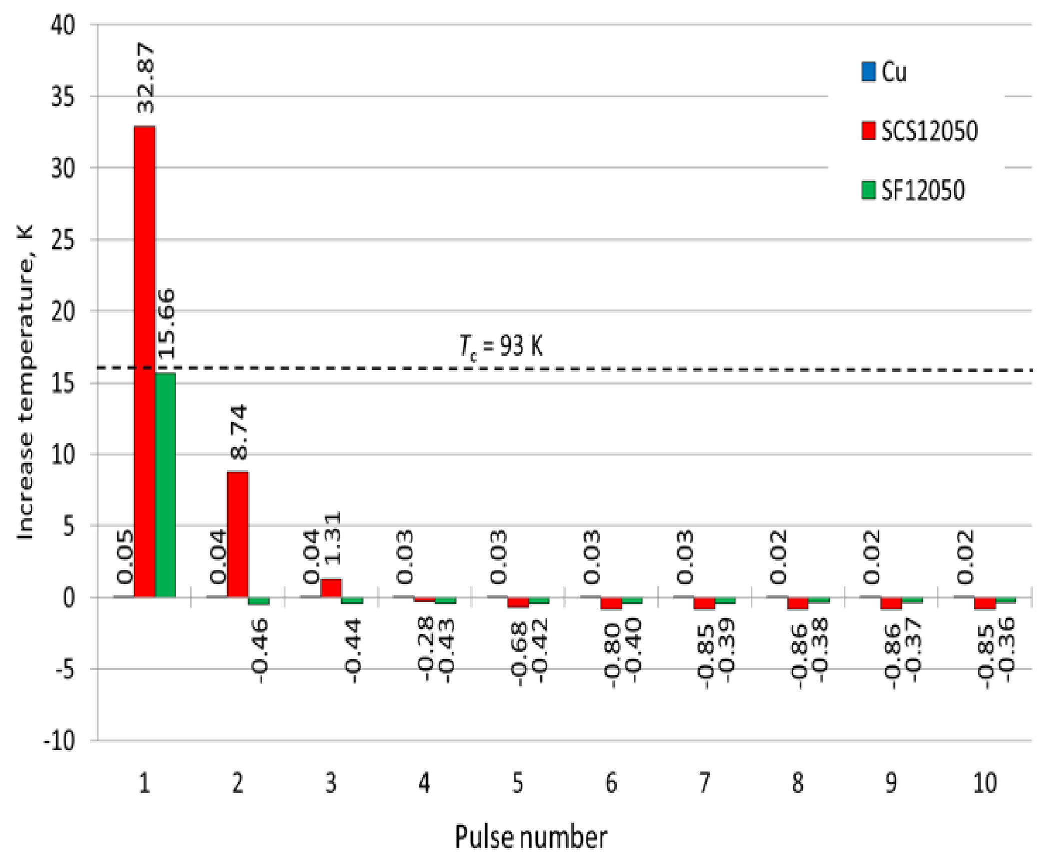

Fig. 32. Increase of primary winding temperature

The highest temperature increase is for SCS12050 tape transformer.
During the first pulse of the inrush current the temperature of the transformer winding increases by 32.8 K.
For a SF12050 tape transformer the temperature increase is 15.6 K.
In a Cu transformer, the temperature increase of the primary winding is the lowest and equals 0.05 K.
HTS transformer windings are cooled with liquid nitrogen and have a temperature of 77 K during start-up.
The critical temperature of the SCS12050 and SF12050 tapes is 93 K.
Calculations show that the temperature increments of the HTS primary winding made of SF12050 during the first pulse do not exceed the critical temperature.
The SCS12050 tape transformer during the first two pulses reaches a temperature of 118 K.

Cooling of the primary winding for inrush current of SC transformer 21 MVA

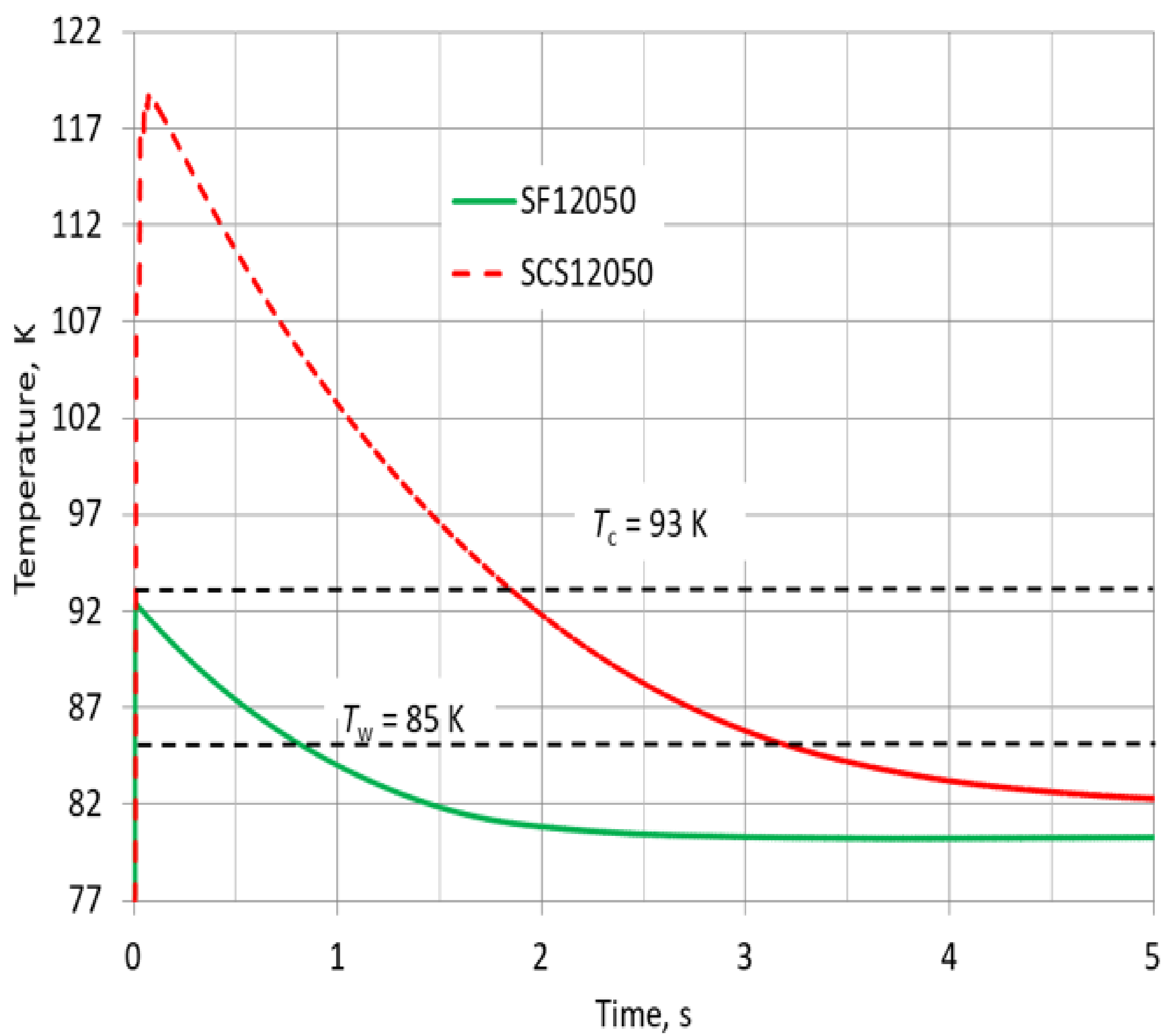

Fig. 33. Cooling time of the primary winding

The primary winding made of SF12050 will be cooled to working temperature T_w = 85 K after 0.83 seconds.

For windings made of SCS12050, the cooling time to critical temperature is 1.86 s, and to T_w = 85 K it is 3.22 s.

Short-circuit current of a Cu and SC transformer 21 MVA

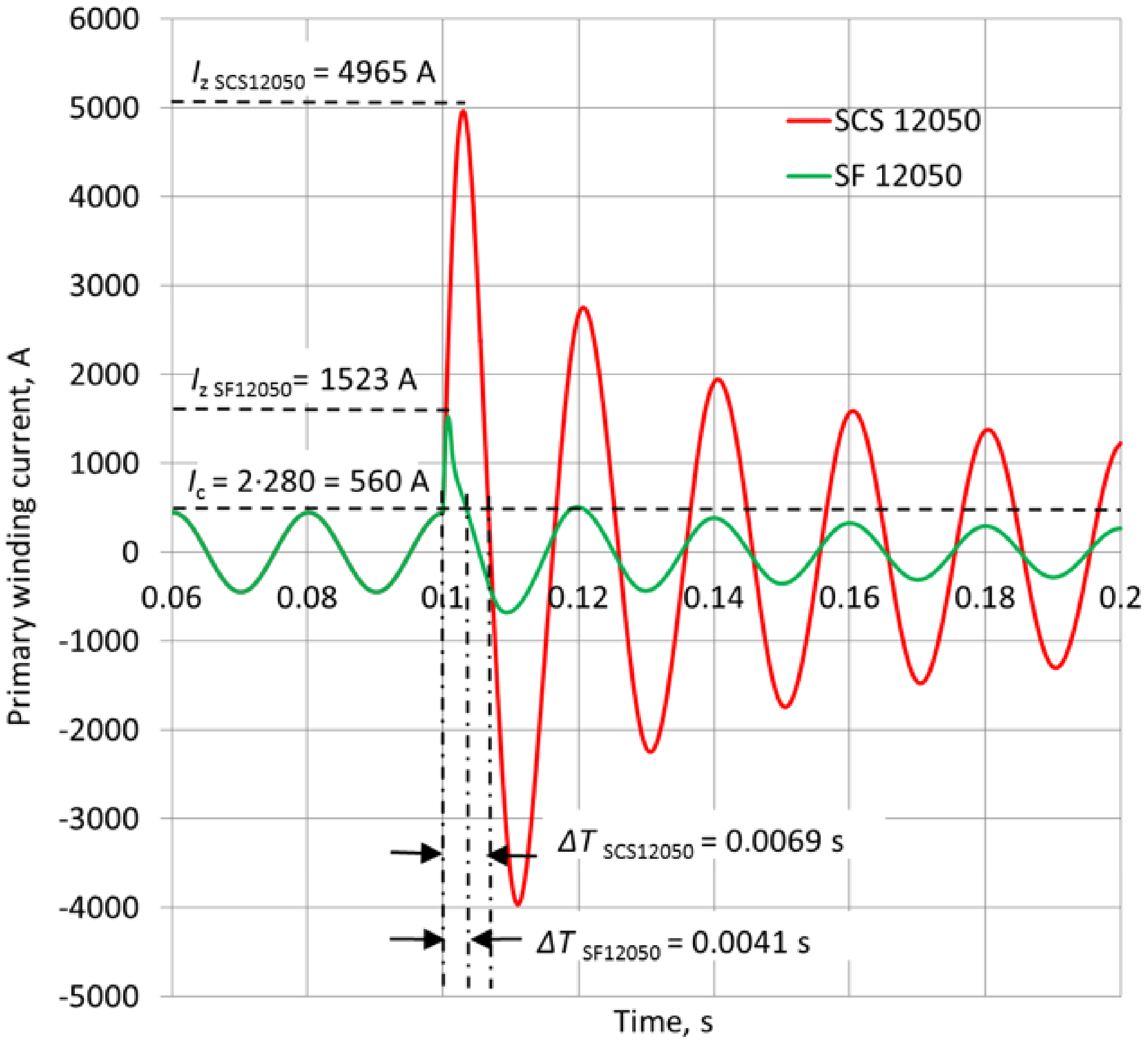

Fig. 34. Primary winding current during short-circuit of 21 MVA HTS transformer

For primary and secondary transformer windings, the peak current for windings made of SCS12050 tape (Fig. 34 and 35) is 5 kA and 33 kA respectively,

and for windings without copper lamination SF 12050, the peak current is 1.5 kA and 10,1 kA respectively.

Subsequent pulses for SF12050 are limited below the critical current for both primary and secondary windings, while for SCS12050 the subsequent pulses are still above the critical current of the tape.

Primary winding

Short-circuit current of a Cu and SC transformer 21 MVA

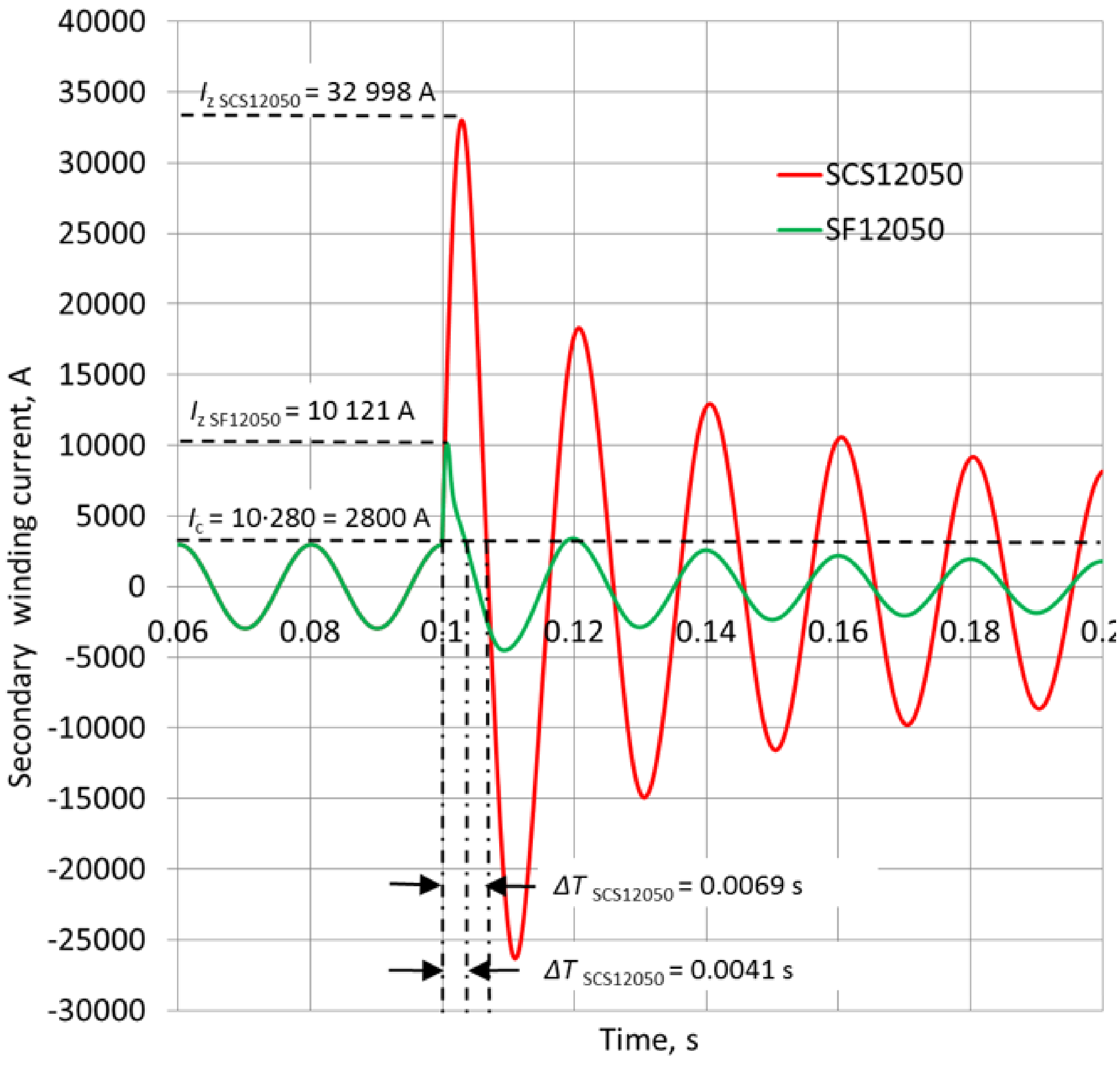

Fig. 35. Secondary winding current during short-circuit of 21 MVA HTS

For primary and secondary transformer windings, the peak current for windings made of SCS12050 tape (Fig. 34 and 35) is 5 kA and 33 kA respectively,

and for windings without copper lamination SF 12050, the peak current is 1.5 kA and 10,1 kA respectively.

Subsequent pulses for SF12050 are limited below the critical current for both primary and secondary windings, while for SCS12050 the subsequent pulses are still above the critical current of the tape.

Secondary winding

Short-circuit – winding resistance

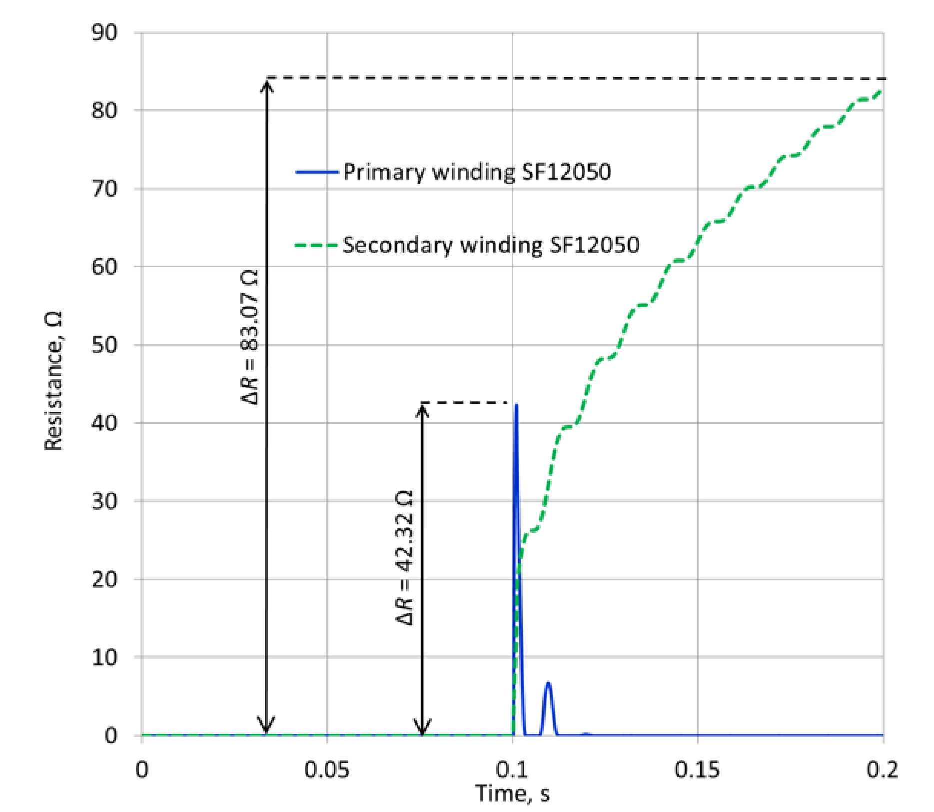

Fig. 36. Primary and secondary winding resistance (SF12050)

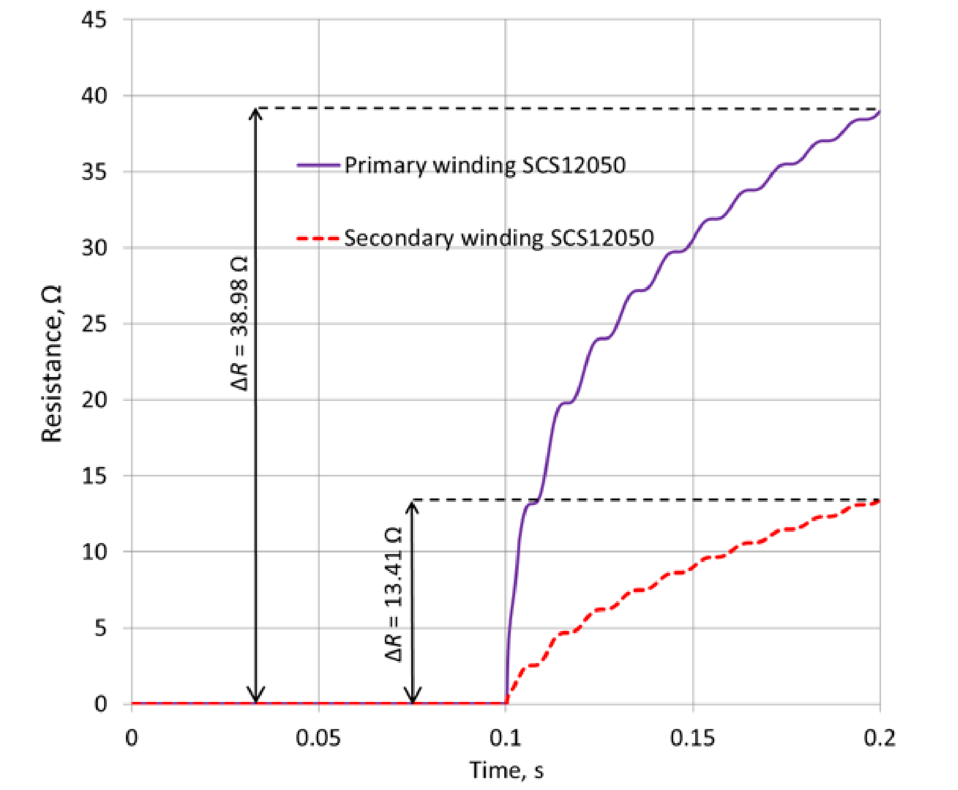

Fig. 38. Primary and secondary winding resistance (SCS12050)

During a short circuit, the resistance of the primary winding current reaches 42 Ω, while the resistance of the secondary winding is 83 Ω.

In case of a HTS transformer with SCS12050 windings (Fig. 38) during a short circuit, the resistance of the primary winding is 39 Ω, while the resistance of the secondary winding is 13.4 Ω.

Short-circuit – winding temperature increase

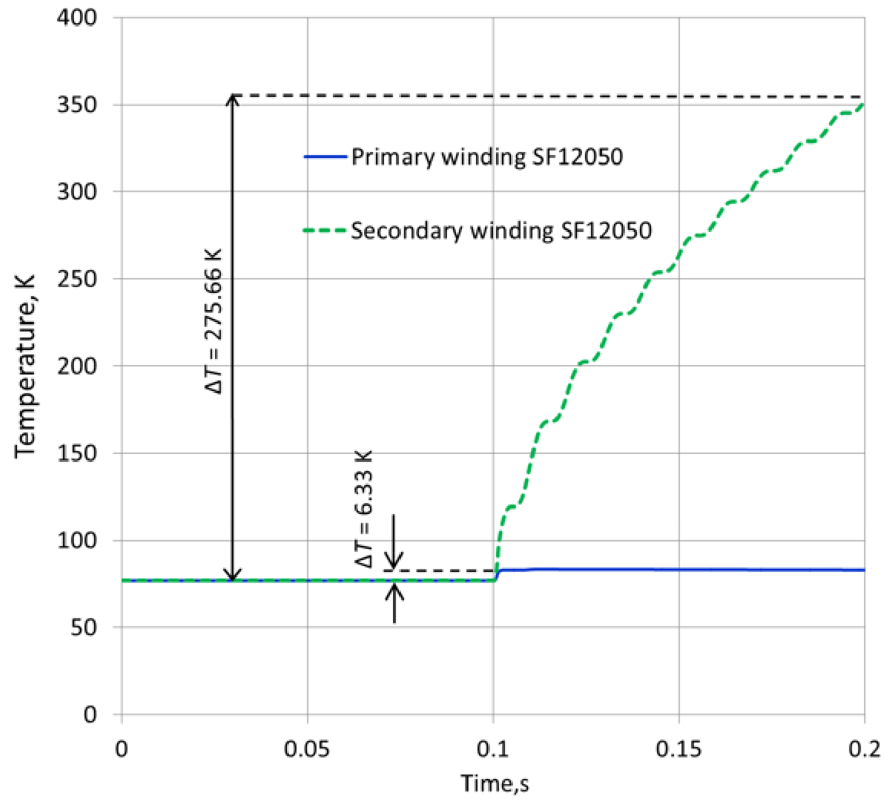

Fig. 37. Primary and secondary winding temperature (SF12050)

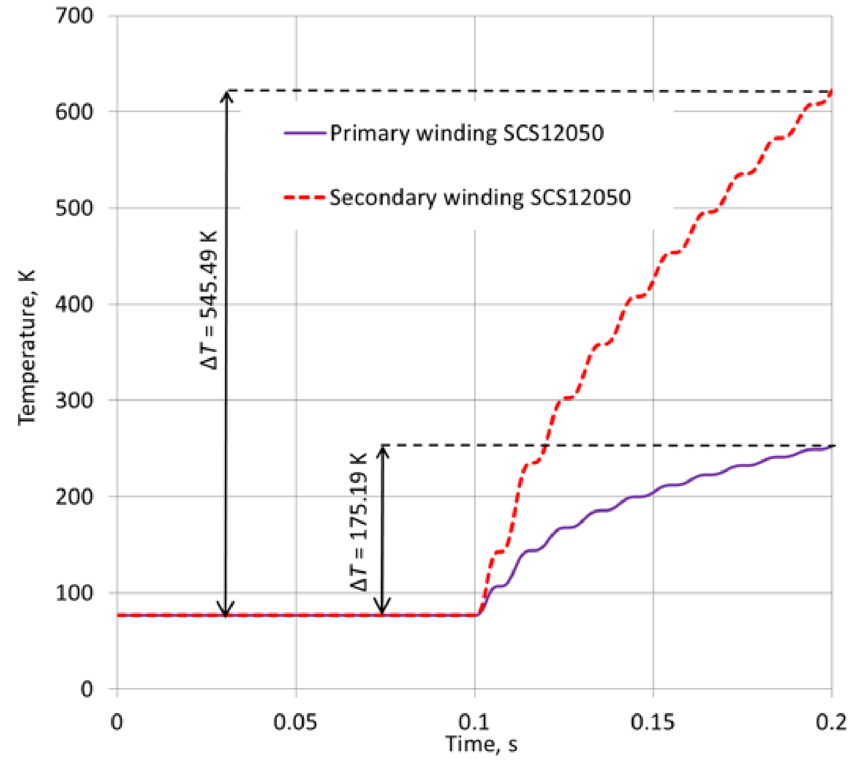

Fig. 39. Primary and secondary winding temperature

SF tape windings **SCS tape windings**

The temperature increase for the primary winding made of SF tape is 6.33 K for the primary winding and 276 K for the secondary winding. For the copper laminated SCS tape (Fig. 39) the temperature increase is 175 K for the primary winding and 545 K for the secondary winding.

Conclusions

- The PSpice program allowed for the creation of computer model of highly non-linear electrical component like SC tape.
- The results obtained from the computer modelling are in a good agreement with the laboratory measurements of the physical model of the 10 kVA SC transformer.
- Electrical circuit simulation seems to be a reliable and fast tool for the simplified analysis of SC devices.
- The computer analysis conducted in the PSpice program can be an important verification element of the superconducting transformers' structure.
- The computer model presented in the paper well describes the phenomenon of the inrush current and short-circuit current of SC transformers.
  Using the given relations at the transformer design stage, it is possible to predict the maximum values of the inrush current and short-circuit current impulses and the time of decay of this current wave.
  It can be determined whether the superconducting windings will go to a resistive state, as well as calculate how long this state will last and how much heat will be released in the windings.
  This allows to calculate the temperature of the windings, and thereby to eliminate the risk of their thermal damage.