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Considerations of 2G HTS Transformer Temperature During Short Circuit

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***Abstract*—Superconducting transformer with the windings made of second generation HTS tape can limit short-circuit current effectively. Despite this, due to the small cross-section of normal metal layers and low thermal capacity of windings, fault current must be switched off by an additional device in relatively short time to prevent a catastrophic temperature rise. The paper presents the computer simulation of short-circuit fault suppressed by a single-phase 10 kVA superconducting transformer. Numerical results were compared with experimental data to validate the model. Authors attempted to extend the method to industrial-size HTS transformer and estimate the dimensions of copper co-windings.**

***Index Terms*—computational modeling, high-temperature superconductors, power transformers, SPICE.**

I. Introduction

TRANSFORMER with windings made of high temperature superconducting (HTS) coated tapes (second generation HTS, 2G HTS) have many potential advantages over conventional copper winding unit. Basing on theoretical calculations or small model tests, researchers frequently mention: higher efficiency, smaller footprint, lighter construction, improved insulation durability, safer operation and lower environmental burden [1], [2]. In the next place, technical benefits are enumerated: limitation of short-circuit fault current by superconducting winding transition to normal state (quench), low voltage regulation due to a small stray-field reactance, possibility to endure long overloads by controlling coolant temperature (liquid nitrogen) with cryocoolers [3]–[6].

Comparing to copper wire, superconducting winding made of 2G HTS tapes or their braided combination (Roebel cable) is very light and has a small thermal capacity. During a short-circuit fault, HTS layer of the tape quenches and thin normal metal layers have to conduct high density current. Winding temperature increases rapidly – an external device must break the fault in order to protect HTS windings.

In this work, authors try to evaluate the usefulness of additional copper wire wound in parallel to HTS tape for thermal stability improvement.

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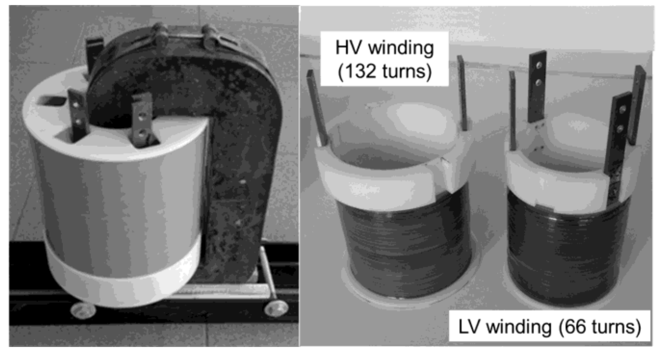

Fig. 1. Transformer model and HTS windings.

II. 10 kVA Superconducting Transformer Model

A. Physical Transformer Model

Warm-core single-phase transformer model was built using SCS4050 tape by SuperPower Inc. Superconducting windings were placed in the plastic cryostat filled afterwards with liquid nitrogen at atmospheric pressure (Fig. 1). Basic parameters of the superconducting transformer are described in Table I.

Transformer model underwent series of laboratory tests in no-load state, under nominal load and measuring short-circuit test at lowered supply voltage. However in the scope of this work, the most important experiment involved a fault test, i.e. LV winding short-circuit at the nominal supply voltage. Detailed information about setup and results of these tests may be found in [6]. The experiments confirmed electrical parameters of the transformer and provided short-circuit waveforms utilized later for the verification of a numerical model.

B. Numerical Transformer Model

Transformer numerical model was prepared using behavioral modeling blocks in Simulation Program with Integrated Circuit Emphasis (SPICE). Comparing to finite element method (FEM), this approach is extremely fast and it gives satisfactory results for quench simulation despite many simplifications [7].

Second generation high-T_c-superconductor coated tape has a layered structure (Fig. 2a). Electric behavior of the SCS4050 superconducting tape can be explained as the parallel connection of its conductive components (Fig. 2b).

HTS layer can be described by the Rhyner's *E-J* power law representing the flux creep behavior [8]. Neglecting magnetic field dependence and assuming uniform current density, it leads to the superconductor layer resistance

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$$R_{HTS}(i,T) = E_c l |i|^{n(T)-1} I_c(T)^{-n(T)}, \quad (1)$$

where: i – HTS layer current, T – temperature, E_c – constant (transition criterion), l – winding tape length, $n(T)$ – power-law exponent, $I_c(T)$ – HTS layer critical current.

Resistances of the silver layer R_{Ag} and copper stabilizers R_{Cu} may be considered as linear functions of temperature [9]. Hastelloy resistivity is assumed as constant [10].

For the analysis of a fault short-circuit, the homogenous adiabatic hitting of transformer windings is assumed. This simplified approach leads to the formula of tape temperature

$$T = T_0 + \int_{t_0}^{t_1} i^2 R \, \mathrm{d}t \; / (D_{Cu}V_{Cu}c_{pCu} + D_{Ag}V_{Ag}c_{pAg} + D_{C276}V_{C276}c_{pC276} + D_I V_I c_{pI}) \quad (2)$$

where: T_0 – initial temperature (liquid nitrogen bath), i – winding current, R – winding resistance, D – material density (indices: Cu – copper, Ag – silver, C276 – Hastelloy, I – insulation), V – material volume, c_p – material specific heat.

Simulation circuit of the superconducting transformer is shown in Fig. 3. Equation (3) of the primary circuit contains: supply voltage u_1, voltage on the winding non-linear resistance R_1, voltage on the stray-field inductance L_{S1} and voltage induced by magnetic flux change $\mathrm{d}\phi/\mathrm{d}t$ in n_1 primary coil turns.

$$u_1 = R_1 i_1 + L_{S1}\, \mathrm{d}i_1/\mathrm{d}t + n_1\, \mathrm{d}\phi/\mathrm{d}t \quad (3)$$

Analogously, (4) can be formulated for the secondary circuit. In this case voltage u_2 represents output voltage.

$$u_2 = R_2 i_2 + L_{S2}\, \mathrm{d}i_2/\mathrm{d}t + n_2\, \mathrm{d}\phi/\mathrm{d}t \quad (4)$$

Magnetic circuit of the transformer can be described with Ampère's circuital law

$$n_1 i_1 + n_2 i_2 = (R_\mu + R_{\mu g})\, \phi, \quad (5)$$

where: n_1, n_2 – primary and secondary coils turn numbers, R_μ – non-linear reluctance of a ferromagnetic core, $R_{\mu g}$ – linear reluctance of a core air gap.

Non-linear reluctance of the ferromagnetic core can be derived from modified Jiles-Atherton model (6) available in SPICE.

$$B = \mu_0\{H + [\int (M_a - M) / (\delta K)\, \mathrm{d}H + CM_a] / (1 + C)\} \quad (6)$$

where: B – magnetic flux density, H – magnetic field strength, $M_a = M_s H / (|H| + A)$ – an hysteretic magnetization, M_s – saturation magnetization, A – parameter proportional to temperature and effective domain density, δ – directional parameter, K – domain pinning parameter, M – magnetization, C – measure of reversible change in magnetization.

To calculate reluctances, magnetic $PATH$ length and core cross-section $AREA$ must be taken into account as well as two additional parameters: $PACK$ – packing factor of core sheets,

TABLE I
PARAMETERS OF SUPERCONDUCTING TRANSFORMER MODEL

Parameter	Value
SCS4050 tape critical current @77 K	117 A
SCS4050 width and thickness	4 mm × 95 μm
tape layers (Hastelloy/HTS/Ag/Cu)	50/1/3.8/40 μm
polyimide insulation thickness	50 μm
rated power	10 kVA
winding voltages (HV/LV)	230 V/115 V
winding rated currents (HV/LV)	44 A/88 A
number of turns (HV/LV)	132/66
mean LV winding radius	67 mm
mean HV winding radius	77 mm
LV-HV air gap width	9.5 mm
windings height	132 mm
magnetic core cross section area	$4.9 \cdot 10^{-3}$ m^2
mean magnetic length of the core	0.763 m
magnetic flux density	1.6 T

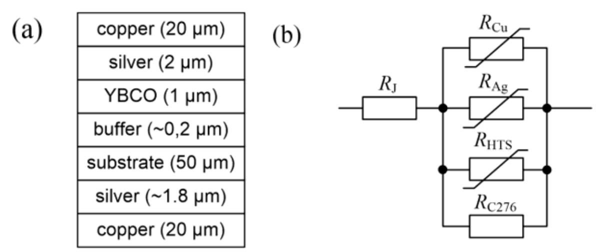

Fig. 2. (a) SCS4050 tape layers. (b) Equivalent circuit of SCS tape (Cu – copper, Ag – silver, HTS – high-T_c superconductor (YBCO), C276 – Hastelloy substrate, J – junctions and terminals).

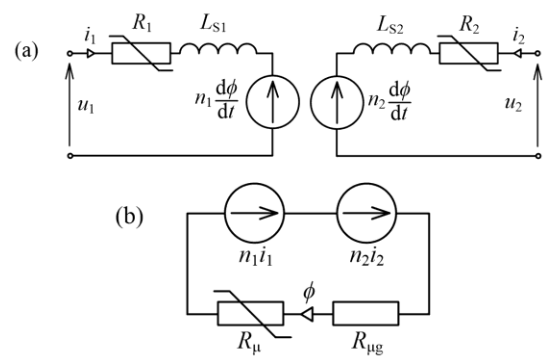

Fig. 3. (a) Electrical equivalent circuit of single-phase transformer. (b) Magnetic equivalent circuit.

TABLE II
SPICE SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
U_1 (rms)	230 V	A	110 A/m
R_{J1}	6.72 mΩ	K	10 A/m
R_{J2}	1.68 mΩ	C	0.2
L_{S1}	411 μH	M_S	1.52 MA/m
L_{S2}	102.7 μH	GAP	0.23 mm
D_{C276}	8890 kg/m^3	$PACK$	0.95
D_{Cu}	8920 kg/m^3	c_{pCu}	200 J/(kg·K)
D_{Ag}	10490 kg/m^3	c_{pAg}	155 J/(kg·K)
D_I	1420 kg/m^3	c_{pI}	350 J/(kg·K)
$\rho_{Cu}(T)$	$(6.89 \cdot 10^{-11} \cdot T - 0.33 \cdot 10^{-8})$ Ω·m	c_{pC276}	180 J/(kg·K)
$\rho_{Ag}(T)$	$(6.056 \cdot 10^{-11} \cdot T - 0.186 \cdot 10^{-8})$ Ω·m	ρ_{C276}	1.25 μΩ·m

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C. Fault Short-circuit Simulation

Transformer operating at nominal voltage was loaded with the resistance $R_L = 2\ \Omega$. At $t_1 = 130$ ms R_L was shorted. Fault lasted for 50 ms and then R_L was connected again.

Although temperature was not measured directly, its average value can be estimated from electrical measurements. The fault caused LV winding current decrease from 71 A (peak) to 43.5 A (peak). Neglecting relatively small short-circuit reactance, resistance increase $\Delta R = 0.723\ \Omega$ can be explained by complete quench of LV winding ($T_2 > T_c$). Using dimensions (Table I) and properties (Table II) of normal metal layers (Hastelloy, copper and silver) connected in parallel, $\Delta R = 0.723\ \Omega$ corresponds with the temperature change $\Delta T_2 = 37.1$ K.

Fig. 4 shows windings temperatures obtained from simulation and the comparison of LV winding current waveforms acquired from measurement and simulation. Computer simulation produced $\Delta T_{2S} = 39$ K and $\Delta T_{1S} = 0.58$ K during the fault ($\Delta t = 50$ ms). Comparing with measurement, numerical analysis gave LV winding temperature increase 5% higher due to the assumption of adiabatic conditions.

Good accordance of measurements and simulation entitles to state that simplistic SPICE electro-thermal model may be useful for superconducting transformer quench analysis.

III. 10 MVA Superconducting Transformer

A. Industrial-scale Transformer Design

Three-phase three-legged warm-core 10 MVA superconducting transformer was designed using procedure outlined in [5] and more clearly described in [12]. 2D FEM model was used to calculate magnetic field distribution in transformer windings. This was necessary to assess the field impact on critical current density and to estimate energy loss in HTS windings. Basic information on the transformer design are shown in Table III. Split low-voltage winding configuration (LV1 and LV2) was employed for minimization of energy loss generated by alternating magnetic field [5].

B. Numerical Transformer Model

Simulation circuit of three-phase superconducting transformer is shown in Fig. 5. Transformer phases are designated with index a, b and c. Circuit equations are analogous to these described earlier for the single-phase device. Controlled voltage sources e_{1a}, e_{1b}, e_{1c}, e_{2a}, e_{2b}, e_{2c} (Fig. 5a) represent electromotive forces induced in windings by respective magnetic flux changes. In the equivalent magnetic circuit (Fig. 5b) there is a fourth leg – linear reluctance of air flux path. Reluctances of core yokes have been added to outer legs reluctances $R_{\mu a}$ and $R_{\mu c}$ (magnetic asymmetry). Core air gaps have been neglected.

In this case, temperature dependence of specific heat coefficients was observed and programmed in TABLE components in SPICE using linearized data from [9] and [10].

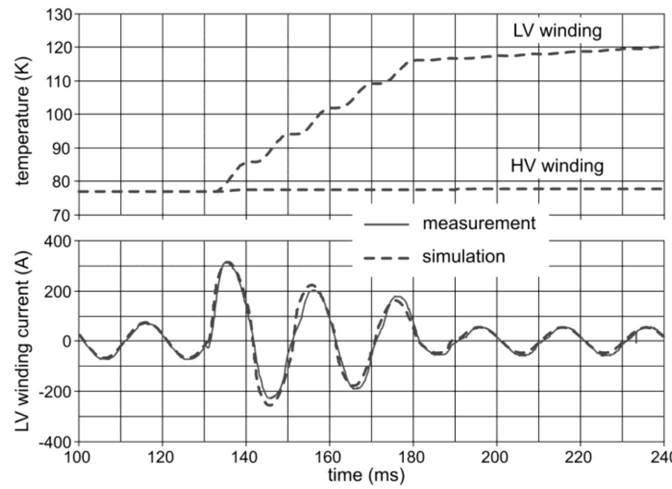

Fig. 4. Simulated temperatures of the windings (upper) and comparison of LV winding currents from measurement and simulation (lower).

TABLE III
Design Parameters of 10 MVA HTS Transformer

Parameter	Value
rated power	10 MVA
rated voltages (f = 50 Hz)	110/15 kV
vector group	Yd11
phase currents (HV/LV)	53/222 A
flux density	1.6 T
core limb diameter	0.49 m
core packing factor	0.783
core windows height and width	1.5 m × 0.332 m
core losses (warm core)	15 kW
number of windings turns	1211/286
winding wire (HTS tape)	SCS12050
number of parallel tapes (HV/LV)	1/2
mean LV1 winding radius	0.305 m
mean HV winding radius	0.331 m
mean LV2 winding radius	0.366 m
total SCS tape length	11.547 km
short-circuit reactance	26.9 Ω
short-circuit voltage (rel.)	2.3%
load losses (at T = 293 K)	10 kW

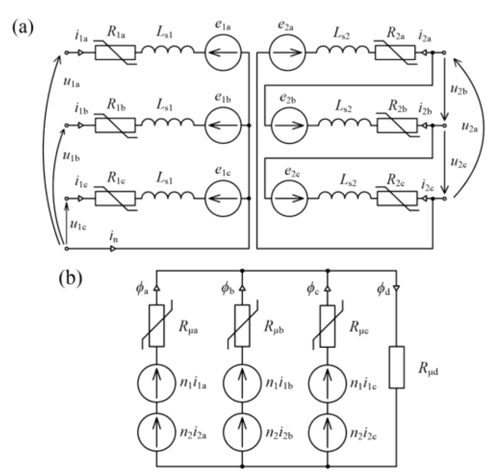

Fig. 5. (a) Electrical equivalent circuit of three-phase transformer – vector group Yd11. (b) Simplified magnetic equivalent circuit of three-legged three-phase transformer ($R_{\mu d}$ – represents air flux path).

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C. Fault Short-circuit Simulation

Selected results of the numerical analysis of the 10 MVA transformer short circuit are depicted in Fig. 6. Single phase fault at transformer phase A was initiated at t = 140 ms. It can be clearly seen that winding made of SCS tape only cannot survive the fault without a sophisticated protective device. Transformer operates as a poorly designed superconducting fault-current limiter. Initial current surge is limited mostly by the secondary winding resistance. Small thermal capacity of superconducting coil results in sharp temperature rise of the LV A winding. Average temperature slope dT/dt can be estimated as 5500 K/s. Thermal degradation of HTS tape is imminent in less than single period (20 ms). In fact, due to tape material inhomogeneity, localized hot-spots may destroy winding completely in this short time [11].

As it was mentioned in [5] and other papers, thermal endurance of superconducting transformer windings may be improved by additional co-windings made of copper braid. Still, this design problem was not discussed in details.

Taking information from conventional transformer theory, neglecting HTS tape and insulation heat capacity, the temperature rise during steady-state short-circuit can be described as:

$$\mathrm{d}T/\mathrm{d}t = \rho(T)U_\mathrm{p}^2 \,/\, [X_\mathrm{z}^2 c_\mathrm{p}(T) D A^2], \qquad (7)$$

where: $\rho(T)$ – co-winding wire resistivity, U_p – supply phase voltage (rms), X_z – short-circuit reactance of the transformer, $c_\mathrm{p}(T)$ – co-winding specific heat, D – wire material density, A – co-winding wire cross-section area.

Using formula (7), allowing 2 s fault duration and windings temperature change from 77 K to 277 K, assuming average copper resistivity in this temperature range as $8.9\cdot10^{-9}$ Ω·m and average specific heat 340 J/(kg·K), the primary co-winding wire dimensions may be calculated as 1 mm × 12 mm and secondary wire as 4.28 mm × 12 mm ($A_2 = A_1N_1 \,/\, N_2$). Simulation results obtained in this case are depicted in Fig. 7. Average temperature slope read from the waveforms is almost identical with one assumed for calculations dT/dt = 100 K/s.

During normal operation of the transformer, solid copper co-windings cause additional power loss due to eddy currents. Using the loss formula presented in [12], magnetic field distribution obtained using FEM and cryocooling penalty factor ε = 15, it is approximately 500 W at room temperature.

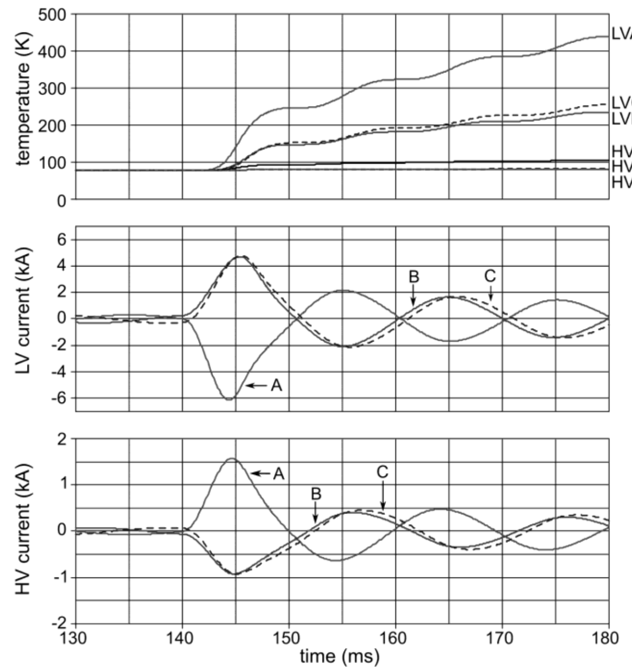

Fig. 6. Windings temperatures and currents during short-circuit in phase A of 10 MVA superconducting transformer (LV, HV – low voltage and high voltage windings; A, B, C – transformer phase designations).

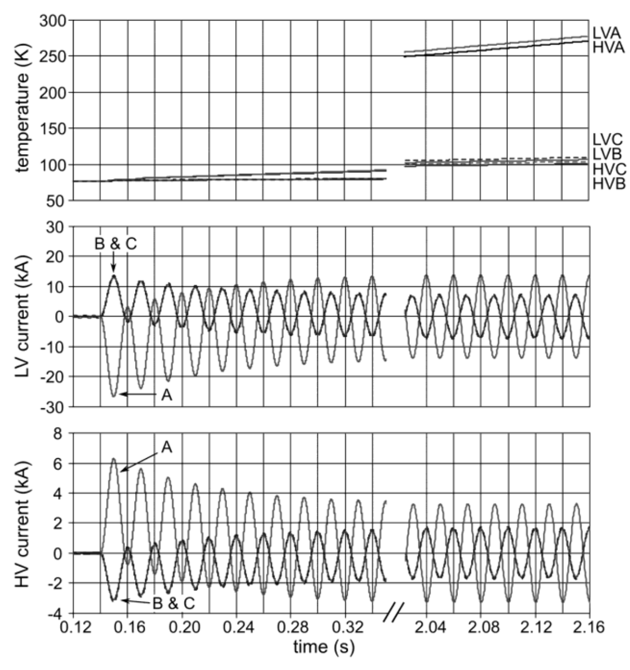

Fig. 7. Windings temperatures and currents during short-circuit in phase A of 10 MVA superconducting transformer with copper co-windings.

IV. Conclusion

The usage of transformer with windings made of second generation HTS tape as a fault current limiter is problematic. To survive thermal shock it has to be equipped with a protective device of a very fast response.

Copper co-windings vastly reduce current-limiting feature of HTS transformer – current is limited mostly by the transformer reactance. However, significantly increased thermal capacity permits endure relatively long fault with limited temperature rise.

In the simulations described earlier, the perfect contact between HTS tape and copper co-winding was assumed as well as infinite thermal diffusivity of all materials. Thermal subcircuit needs a number of improvements to deal with more realistic heat propagation model. This future work will also enable the numerical analysis of transformer cool-down condition after a short-circuit fault.

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