3D FE Analysis of Transient Electromagnetic-Thermal Phenomena in a Turbogenerator Rotor

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Abstract—**A finite element technique and computer code for the numerical analysis of 3D transient electromagnetic fields and temperature distribution due to negative sequence currents in large synchronous turbogenerator rotors are developed. Electromagnetic-thermal phenomena in a 300 MVA class turbogenerator rotor during a line-to-line short circuit on two phases of the machine are numerically investigated. Effect of the various conditions of the rotor cooling on its thermal state is studied. Numerical results obtained can be used for the computer simulation of the thermo-mechanical behaviour of the rotor.**

Keywords—electromagnetic field; temperature distribution; rotor; synchronous turbogenerator.

I. INTRODUCTION

Modern large synchronous turbogenerators are complicated spatial structures with intrinsically 3D electromagnetic field [1], [2] and highly irregular spatial temperature distribution [1]. A problem of special interest is investigation of coupled 3D electromagnetic and thermal processes in turbogenerator rotors during a line-to-line short circuit on two phases of the machine. 2D field-computation approaches and software [3] are not able to simulate intrinsically 3D coupled phenomena in turbogenerator rotors. Even in the case of numerical solution of single-physics problems it is difficult to carry out accurate computation of 3D transient processes within whole structure of the turbogenerator rotor because of huge computational expenses. Consequently, such a difficulty concerns multiphysical electromagnetic-thermal numerical simulation. This paper is devoted to the finite element analysis of electromagnetic-thermal phenomena in a simplified model of the turbogenerator rotor. Effect of the various conditions of the rotor cooling (convective heat transfer to air and hydrogen with various values of the gas pressure) is studied.

II. COMPUTATIONAL MODEL AND PROBLEM SOLUTION

A simplified model of a 300 MVA class turbogenerator rotor (rotor’s end zone is not considered) is presented in Fig. 1 [2]. The rotor diameter equals 110 cm, its length equals 5 m. The rotor material is steel with electric conductivity of $\sigma = 0.5\cdot10^7$ S$\cdot$m^{-1} and is assumed to be linear with a magnetic permeability of $\mu = 100\mu_0$ [2]. Thermal conductivity of the rotor steel equals $\lambda = 48$ W$\cdot$m$^{-1}\cdot$K^{-1}, specific heat $\rho c = 3.54\cdot10^6$ J$\cdot$m$^{-3}\cdot$K^{-1}. Closed slots (excluding slots in the big tooth) are filled by copper windings with electric conductivity $\sigma = 6\cdot10^7$ S$\cdot$m^{-1}, thermal conductivity $\lambda = 384$ W$\cdot$m$^{-1}\cdot$K^{-1}, and specific heat $\rho c = 3.46\cdot10^6$ J$\cdot$m$^{-3}\cdot$K^{-1}. Non-magnetic slot wedges (excluding slots in the big tooth) are made of duralumin (electric conductivity $\sigma = 3.33\cdot10^7$ S$\cdot$m^{-1}, thermal conductivity $\lambda = 159$ W$\cdot$m$^{-1}\cdot$K^{-1}, specific heat $\rho c = 2.58\cdot10^6$ J$\cdot$m$^{-3}\cdot$K^{-1}). Slot wedges in the big tooth (there are no windings inside these slots) are made of the rotor steel ($\sigma = 0.5\cdot10^7$ S$\cdot$m^{-1}, $\mu = 100\mu_0$, $\lambda = 48$ W$\cdot$m$^{-1}\cdot$K^{-1}, $\rho c = 3.54\cdot10^6$ J$\cdot$m$^{-3}\cdot$K^{-1}). All mentioned electrical and thermal material constants are assumed to be independent on temperature. The reason is relatively low permissible working temperature of the rotor insulation (less 200 ^{0}C [4]).

In an additional copper sub-domain with $\sigma = 6\cdot10^7$ S$\cdot$m^{-1} representing a simplified model of the stator [2] (see cross-section of the proposed computational model of the machine under consideration depicted in Fig. 2), a travelling wave of negative sequence current density corresponding to a line-to-line short circuit on two phases of the machine is given as

$$J_S = (Ae^{-t/T_1} + Be^{-t/T_2} + C)\sin\theta,$$

[2] where A, B, C are the constants describing the fault current, T_1, T_2 are the time constants, $\theta=\omega t+\alpha$; $\omega=2\pi f$; f=100 Hz is twice the supply frequency of the negative sequence currents, and α is the angle counted out in the first quadrant of the coordinate system (see Fig. 2) from the Y-axis clockwise.

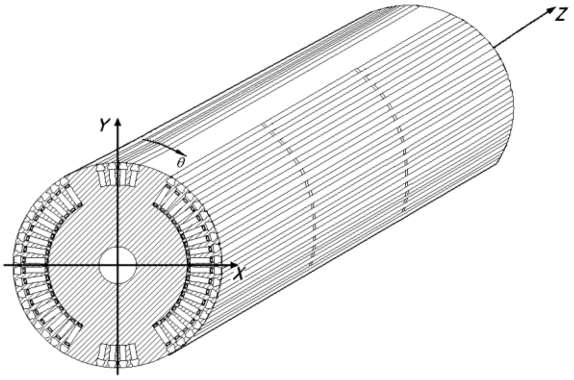

Fig. 1. A simplified model of a turbogenerator rotor.

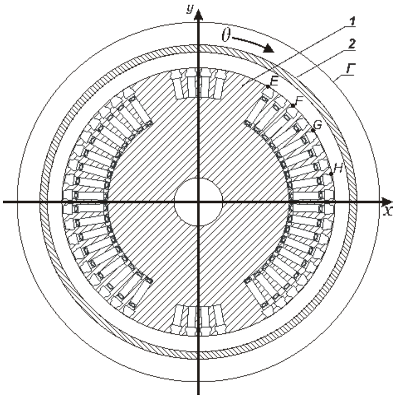

Fig. 2. Cross-section of the computation model:
1 – rotor steel, 2 – subdomain with the given stator current density,
Γ – distant bound with given zero boundary condition.

The length of the air-gap between the stator and rotor is 9 cm.

The governing equations for 3D transient electromagnetic fields with the Coulomb gauge using magnetic vector potential and scalar electric potential $\boldsymbol{A}$, $V - \boldsymbol{A}$ [5] are solved by the nodal finite element method in a Cartesian coordinate system that moves synchronously with the rotor. The transient heat transfer equation [6] is solved by the finite element method with internal heat sources (volumetric Joule losses) obtained from the transient electromagnetic field distribution. Boundary conditions describing the convective heat transfer from the rotor surface to the cooling gas (air or hydrogen with various values of the surplus pressure of the gas p) with different values of the heat transfer coefficient are taken into account.

III. OBTAINED NUMERICAL RESULTS

Results are obtained as spatial and temporal distributions of eddy current density components and temperatures in the rotor model. In Fig. 3 the calculated time evolution of the rotor surface temperature in the most heated point of the surface is shown. It is demonstrated that at a line-to-line short circuit on two phases of the machine the permissible duration of operation (when the maximal temperature of the rotor reaches the permissible working temperature of insulation of 155-160 °C [4]) equals about 1.02-1.22 s depending on the gas cooling conditions.

Fig. 4 represents the temporal distribution of the rotor surface temperature in the most heated point of the surface during the rotor cooling after termination of the short circuit. As obtained results show, after the termination of the short circuit, cooling of the rotor to the initial temperature of 20 ^{0}C requires about 20-30 s.

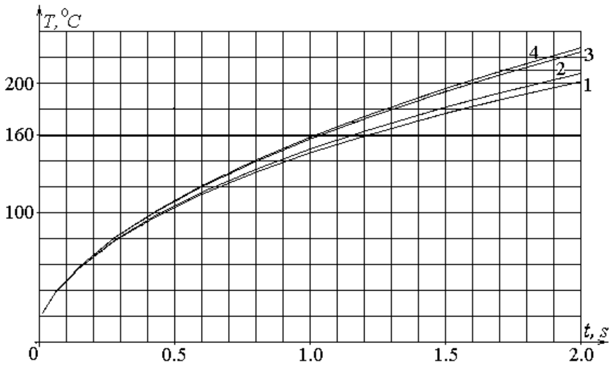

Fig. 3. Heating of the rotor surface: 1 – hydrogen cooling, p = 4; 2 – hydrogen cooling, p = 3; 3 – hydrogen cooling, p = 1; 4 – air cooling.

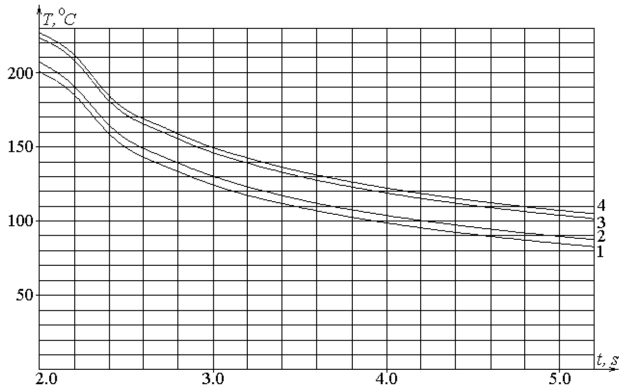

Fig. 4. Cooling of the rotor surface.

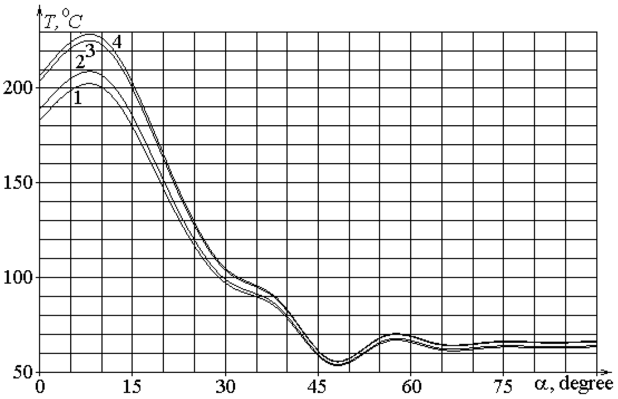

Fig. 5. Rotor surface temperature Vs angle α counted out in the first quadrant of the coordinate system from the Y-axis clockwise.

In Fig. 5 the dependence of the rotor surface temperature on the angle α counted out in the first quadrant of the coordinate system from the Y-axis clockwise (see section II) at the end of the short circuit can be seen. The maximal temperature of the rotor surface takes place at $\alpha \approx 8^0$, the minimal one – at $\alpha \approx 48^0$. The general course of the dependence presented in Fig. 5 corresponds to the results obtained in [3] for the 775 MVA class turbogenerator.

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