Szczepan Opach

Modelling the Thermal Steady State of a Synchronous High-Speed Generator with Permanent Magnets Protected by a CFRP Sleeve

Abstract: The article presents the possibilities of using the Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) in the ANSYS Fluent software for modelling the thermal steady state of liquid-cooled electric machines. The FEM and CFD potential is illustrated with an example of a PMzK71-4 high-speed generator with permanent magnets having rated power P_N = 17 kW and rated rotational rate n_N = 15000 RPM, where the permanent magnets are protected against the adverse effects of centrifugal inertial force by a CFRP sleeve.

Key words: synchronous generator with permanent magnets, thermal calculations, Finite Element Method, Computational Fluid Dynamics, CFRP sleeve

DOI: 10.32730/mswt.2024.68.6.7

1. Introduction

The prototype of a PMzK71-4- type high-speed synchronous generator with permanent magnets, a rated power of P_N = 17 kW and a rated speed (rotational rate) of n_N = 15000 min^{-1} was created within the scope of a research project financed from a subsidy and performed at Łukasiewicz – GIT in 2023 [1].

The development of high-speed synchronous generators with permanent magnets characterised by high energy efficiency results from the constantly growing demand of the domestic economy for electricity, entailing the need to optimise production-related energy consumption in industrial plants. Recently, the projects of advanced organic Rankine cycle (ORC) power plants of small and medium power (using waste heat generated during the production of electricity) are becoming increasingly important. The type of generators discussed in the article below can find applications in the above-named ORC plants [1].

Fig. 1. High-speed generator PMzK71-4 having a power of 17 kW, fabricated by Łukasiewicz – GIT

Fig. 2. Rotor of the PMzK71-4 generator with CFRP composite sleeve and hybrid bearings

2. Generator mechanical design

The mechanical design of the PMzK71-4 generator included a wound stator placed in an aluminium housing, an SPM-type rotor with segmented permanent magnets (attached directly to the shaft), two aluminium bearing disks and two 6206-2RZ-type hybrid ball bearings. The generator was equipped with an integrated liquid cooling system (inside the housing) led outside by means of two nozzles. The starts of phases L1, L2 and L3 of the stator winding were led outside the housing by means of three separate power cables. On the drive side (DE), in the front connections of the stator winding there were Pt100 sensors, led outside the housing by means of an additional cable.

In the PMzK71-4 high-speed generator, a CFRP sleeve made of resin-impregnated carbon fibre layers was used to mechanically protect the permanent magnets (attached to the shaft surface) against the negative effects of centrifugal inertial forces of rotational motion [1].

Presented below are the values of the basic rated parameters and the total weight of the PMzK71-4 prototype generator [1]:

- rated power P_N – 17 kW,
- rated speed n_N – 15000 min^{-1},
- power factor $\cos\phi_N$ – 0,98,
- rated efficiency η_N – 96 %,
- rated voltage U_N – 190V_{LL},

mgr inż. Szczepan Opach – Łukasiewicz Research Network – Upper-Silesian Institute of Technology, Centre for Electric Drives and Machines, Poland / Sieć Badawcza Łukasiewicz – Górnośląski Instytut Technologiczny, Centrum Napędów i Maszyn Elektrycznych, Polska

Corresponding Author: szczepan.opach@git.lukasiewicz.gov.pl

- rated current I_{1N} – 54 A,
- rated frequency f_N – 500 Hz,
- rated torque on the shaft M_N – 10,8 Nm,
- total weight m – 22,5 kg.

3. Design and discretisation of the solid model of the generator

The solid model of the generator was prepared assuming appropriate geometric simplifications, in accordance with its intended use for thermal-flow calculations.

Afterwards, the solid model of the generator was discretised using the Finite Element Method (FEM) in the ANSYS software.

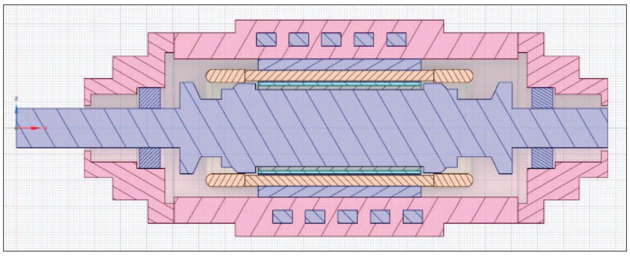

Fig. 3. Simplified 3D model of the PMzK71-4 generator prepared for FEM-based discretisation

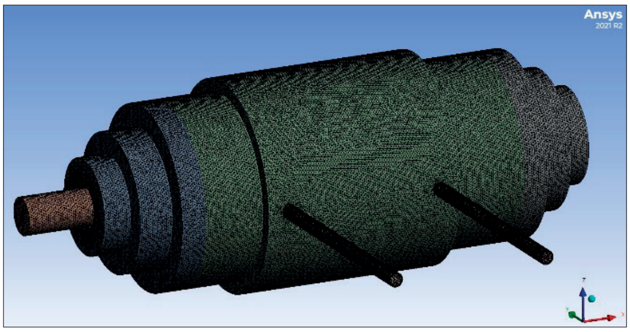

Fig. 4. Simplified 3D model of the PMzK71-4 generator subjected to FEM-based discretisation

4. Parametrisation of the generator thermal model

The individual elements of the generator solid model were assigned materials defined on the basis of the value of the thermal conductivity coefficient λ. The thermal conductivity coefficients λ of the winding and the stator sheet stack were orthotropic and significantly varying in the plane of the axial cross-section (z) and transverse cross-section (xy) of the generator [2–4]. The remaining structural materials used in the model were defined on the basis of the constant isotropic thermal conductivity coefficient λ.

The connections of the individual parts of the generator constituted thermal barriers to heat flow, defined by the value of thermal resistance R_t. The contact was established between the surface of the permanent magnets and the surface of the stator. The contact was defined by the value of equivalent thermal resistance R_{tz} (being the sum of the thermal resistance of the CFRP sleeve and the thermal resistance of the air gap), taking into account the rotational motion of the rotor [5].

In addition, the thermal model involved the phenomenon of convective heat exchange between the external surface of the housing and the generator environment (assuming ambient temperature T_a = 22 °C), defined by the value of natural heat absorption coefficient α_n = 15 W/(m^2·K) [3].

The load of the thermal model of the PMzK71-4 generator included power losses ΔP, converted to heat in the generator. The sources of the power losses along with their values are presented below:

- slot part of the stator winding ΔP_{Cus} – 150 W,
- front part (DE) of the stator winding ΔP_{Cude} – 60 W,
- front part (ND) of the stator winding ΔP_{Cund} – 60 W,
- stator core ΔP_{Fes} – 247,5 W
- permanent magnets + rotor core $\Delta P_{pm} + \Delta P_{Fer}$ – 6 W,
- air resistance in the rotor ΔP_w – 11 W,
- bearing (DE) ΔP_{bde} – 20 W,
- bearing (ND) ΔP_{bnd} – 20 W.

The boundary conditions of the simulation were the following:

- coolant (glycol/water) flow rate – 5 l/min
- coolant inlet temperature – 60 °C.

Table 1. Adopted values of the heat conduction coefficient λ of the generator structural materials

Generator part (element)	Material	Thermal conductivity coefficient
Housing, bearing disks	Aluminium	λ_{al} = 185 W/(m·K)
Shaft, bearing	Steel	λ_{st} = 58 W/(m·K)
Stator winding in slots	Composite	λ_{swxy} = 0.45 W/(m·K) λ_{swz} = 190 W/(m·K)
Stator winding front connections	Copper	λ_{cu} = 190 W/(m·K)
Stator sheet stack	Composite	λ_{coxy} = 30 W/(m·K) λ_{coz} = 3 W/(m·K)
Permanent magnets	NdFeB	λ_{pm} = 7.6 W/(m·K)
Sleeve (CFRP)	M46J	λ_{cfrp} = 83.6 W/(m·K)

Table 2. Adopted values of thermal resistance Rt in relation to the generator part joint

Generator part	Joint/ connection type	Thermal resistance R_t
Stator sheet stack – housing	pressed joint	0.00015 (m^2·K)/W
Bearing disks – housing	pressed joint	0.00015 (m^2·K)/W
Bearings – shaft	pressed joint	0.00015 (m^2·K)/W
Bearings – bearing disks	slip joint	0.00059 (m^2·K)/W
Stator winding – stator sheet stack	slot insulation	0.00178 (m^2·K)/W
Shaft – permanent magnets	adhesive-bonded joint	0,00033 (m^2·K)/W
Permanent magnets – stator sheet stack	air gap + CFRP sleeve	0,00841 (m^2·K)/W

5. Generator thermal model solution

The subsequent stage involved the performance of a coupled steady-state thermal-flow simulation using a two-equation turbulence model k-ω SST. The temperature values obtained in relation to the individual parts and units of the generator are presented in Fig. 5–9:

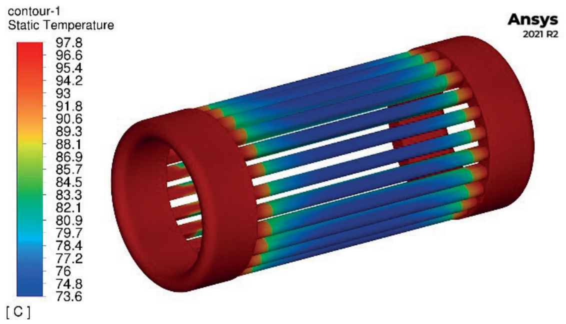

Fig. 5. Stator winding steady-state temperatures

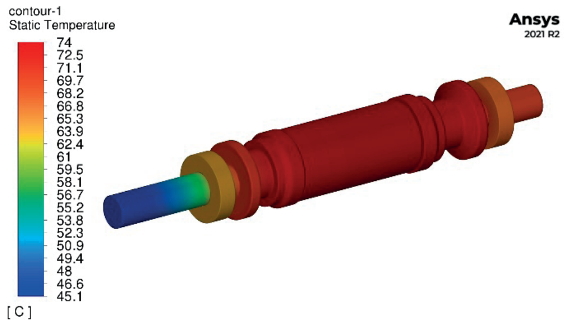

Fig. 8. Steady-state temperatures of the shaft and permanent magnets

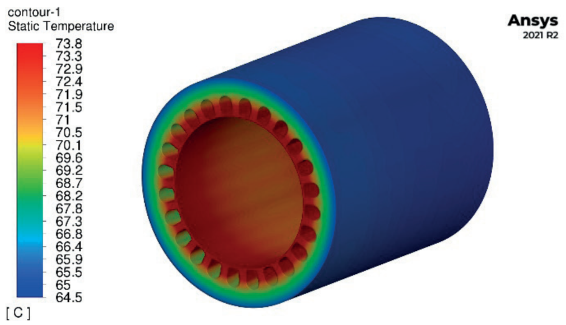

Fig. 6. Steady-state temperatures of the stator sheet stack

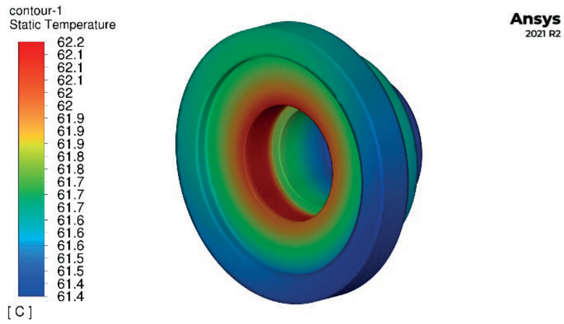

Fig. 9. Steady-state temperatures of the ND bearing disk

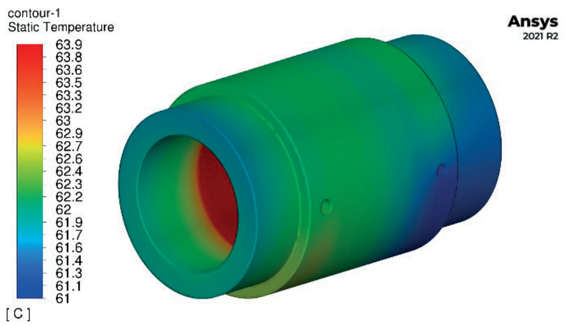

Fig. 7. Steady-state temperatures of the housing

6. Conclusions

The performance of the thermal-flow simulations enabled (at a very early stage of generator design) the determination of the efficiency of the internal liquid cooling system as regards the possibility of heat discharge, resulting from power losses ΔP.

The modelling of the steady thermal state of the generator led to the optimum selection of structural materials, dimensions of the generator itself, the shape of the cooling channel and the parameters of the coolant flow, thus improving the ratio of generated power to the machine weight.

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The article was presented at the 32nd Scientific and Technical Conference "Problems of Exploitation of Electric Machines and Drives" – PEMINE (Słok near Bełchatów, 2–4.10.2024).