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THE MODERNIZATION OF TURBOGENERATORS AS A METHOD OF DECREASING ELECTRICAL ENERGY PRODUCTION COSTS

MODERNIZACJE TURBOGENERATORÓW SPOSOBEM NA ZMNIEJSZENIE KOSZTÓW PRODUKCJI ENERGII ELEKTRYCZNEJ

A b s t r a c t

This paper presents possibilities for reducing the costs of electricity generation as a result of modernizations aimed at increasing the rated power of turbogenerators. Programs for calculating temperature fields in large AC machines have aided work on turbogenerator modernization. Turbogenerators with increased rated power operate in many power plants in Poland and abroad, e.g. in Bulgaria, Finland, Greece, Slovenia, Korea and China. The example of TWW-200-2(2A) turbogenerator modernization is presented. The improved fans with increased capacity have enabled the increase in the turbogenerator rated power by 20%.

Keywords: *costs of electricity generation*, *modernizations of turbogenerators*, *CAD software*

S t r e s z c z e n i e

W artykule przedstawiono możliwości zmniejszenia kosztów produkcji energii elektrycznej w wyniku modernizacji zwiększających moce znamionowe turbogeneratorów. Programy do obliczeń pola temperatury w dużych maszynach prądu przemiennego wspomagają prace związane z modernizacją turbogeneratorów. Turbogeneratory o podwyższonych mocach znamionowych pracują w wielu elektrowniach w Polsce oraz między innymi w: Bułgarii, Finlandii, Grecji, Słowenii, Korei i Chinach. Zaprezentowano przykład modernizacji turbogeneratora TWW-200-2(2A). Udoskonalone wentylatory o zwiększonym wydatku umożliwiły podwyższenie mocy znamionowej turbogeneratora o 20%.

Słowa kluczowe: *koszty wytwarzania energii elektrycznej*, *modernizacje turbogeneratorów*, *programy wspomagające projektowanie*

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1. Introduction

Lots of scientific institutions all over the world conduct research aimed at decreasing the costs of electrical generation and ensuring the proper quality of electrical energy. To aid the national economy, it seems advisable to reinforce power units in power stations during modernization.

In Poland, as in many other countries, a significant role in the generation of electrical energy is played by turbogenerators. The results of implemented research show that an increase of power of steam turbines by even 20% does not usually require much structural modification. The most difficult technical issue is how to modernize turbogenerators in order to increase their power and, at the same time, to increase their durability and improve operational reliability.

The calculations and measurements conducted for a lot of turbogenerators show that the introduction of structural modifications makes it possible to increase power output. The rated power of the turbogenerator is mostly restricted by full thermal utilization of stator, excitation windings and stator core. Therefore, an increase of turbogenerators' power first of all requires the introduction of changes ensuring improvement in the cooling of active elements. The allowable load of turbogenerators in some cases is limited by the heating of terminal elements of the stator core and mechanical stresses occurring during short-circuiting.

The calculated temperature field is used to evaluate new designs of turbogenerators' principal elements. The conducted research has resulted in the elaboration of the modified thermal networks method [1]. This method makes it possible to model the temperature field in large AC machines. The developed software based on this method constitutes the most important element of computer-aided systems for the design of turbogenerators.

2. Modified thermal networks in turbogenerator design

The thermal network method is one of the oldest methods used in the calculation of temperature distribution in electrical machines [1]. The early thermal networks contained only a few nodes, and the resultant sets of equations were solved analytically.

Significant increases in the number of nodes in the thermal network became possible when analog computers were applied for computing and, later on, digital computers. The increase in the number of nodes in the thermal network [2–9] resulted in improved accuracy of calculations. A dedicated node representing average temperature was assigned to each element of the electrical machine engaged in the heat exchange. In the classic approach to the thermal networks method, medium flowing through the cooling duct corresponds to one node representing its average temperature. The drawback of this modelling method is that there is no possibility of calculating the temperature distribution in elements of the electrical machine and the streams of the cooling medium flowing through these elements.

In very long cooling ducts of turbogenerators' active elements, the difference of medium temperatures between input and output may even reach several tens of kelvins. This leads to the emergence of very high non-uniformities of temperature distribution inside cooled elements. The approximate values of average temperatures of active elements, calculated by thermal network methods, are insufficient for a full assessment of the turbogenerator's thermal condition.

The novel method of modified thermal networks [10] makes it possible to model temperature distribution in medium streams in cooling ducts and inside the active elements of the turbogenerator. This is possible both for steady and transient thermal states.

In order to create a modified thermal network for steady-state conditions, active elements of the turbogenerator (excitation winding wires, stator bars etc.) are classified in accordance with the heat flow direction into differential zones (Fig. 1). Next, one thermal node is assigned to each active element. The nodes of the thermal network are connected by thermal conductances.

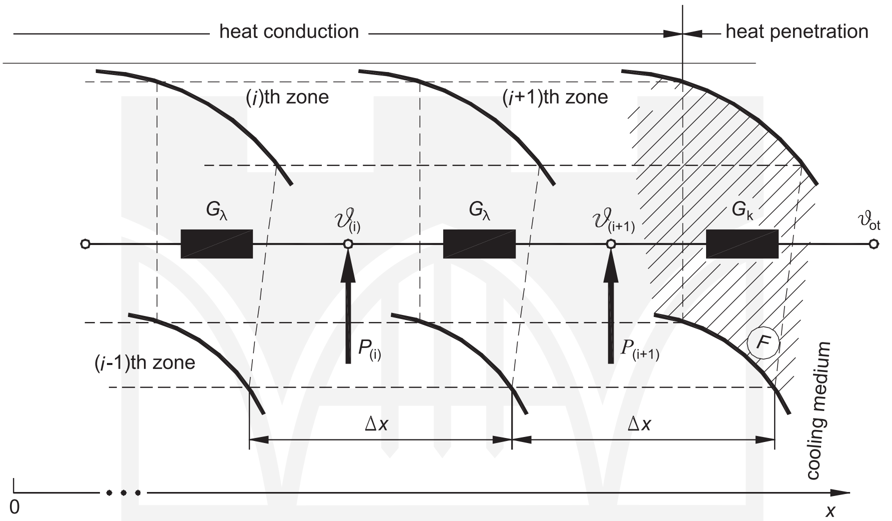

Fig. 1. Thermal network for element divided into differential zones in the thermal steady state

The conductance for thermal flux flowing between neighbouring differential zones due to conduction (Fig. 1) has been determined from the formula:

$$G_\lambda = \frac{\lambda_x \cdot F}{\Delta x} \tag{1}$$

where:
λ_x – specific thermal conductivity of the elemental material in the direction of the x axis,
F – area of face dividing neighbouring zones.

The conductance for thermal flux being removed from the face of the differential zone to the cooling medium coursing round it (Fig. 1) has been determined from the formula:

$$G_k = \alpha_k \cdot F \tag{2}$$

where:
α_k – heat removal factor,
F – area of face from which heat is removed to the cooling medium.

Additional power losses dependent on temperature are present in nodes representing differential zones singled out inside winding wires (Fig. 1):

$$P_{(i)} = P_o \cdot (1 + \alpha \cdot \vartheta_{(i)}) \qquad P_o = k_d \cdot j^2 \cdot \rho_o \cdot V \tag{3}$$

where:

P_o – power losses in the singled out zones at the reference temperature (in the models reference temperature was assumed to be 0°C),
α – temperature coefficient of the winding wire material,
$\vartheta_{(i)}$ – average temperature of i-th zone,
k_d – coefficient of additional losses,
j – average current density,
ρ_o – resistivity of the wire winding material at the reference temperature,
V – volume of singled out zones.

A novel thermal network for fluid or gas stream flowing in the cooling duct of the electrical machine has been presented in [1]. This network contains equivalent current sources (Fig. 2), with capacities equal to thermal powers carried by the cooling medium flowing in the duct:

$$P_{m(i)} = \dot{m}\, c_p\, \vartheta_{m(i)} \tag{4}$$

where:

$\dot{m}$ – mass flow of cooling medium,
c_p – medium's specific heat at constant pressure,
$\vartheta_{m(i)}$ – medium's average temperature in i-th differential zone singled out within the duct.

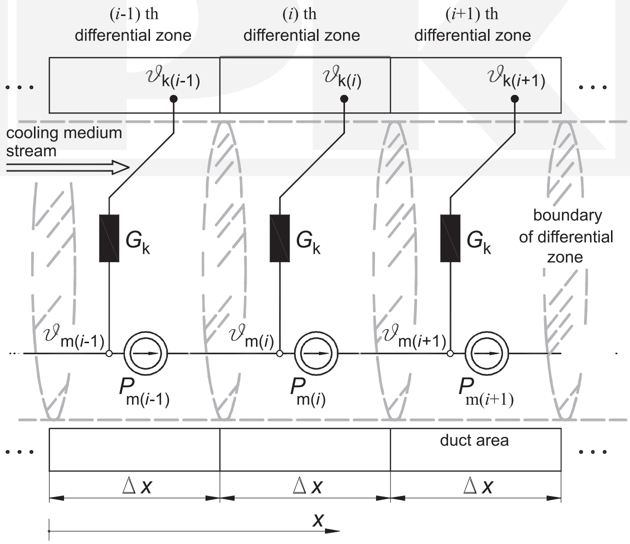

Fig. 2. Thermal network for medium stream flowing in the cooling duct of the electrical machine in thermal steady state

Increasing the mesh density (i.e. the partitioning of constructional elements of the electrical machine into differential zones) improves the accuracy of numerical calculations. At the same time, increase in the number of thermal network nodes must lengthen the calculation time. The optimum value of the Δx parameter, which determines the number of differential zone partitions of the constructional element and cooling duct, may be resolved by investigating the sensitivity of the solution (i.e. calculated temperature distributions in the element and medium stream) to its changes. For each generated modified thermal network we ran a series of calculations of temperature distribution, gradually decreasing the value of the Δx parameter.

When continued decreasing of this parameter at some point does not cause any further change in the calculated temperature greater than the assumed accuracy of numerical calculations (this accuracy has been assumed to be equal to 0.1 K), then the number of partitions obtained as a result of discretization is declared to be optimum. The optimum division of the element into differential zones ensures the achievement of the proposed accuracy of numerical calculations at the lowest possible number of singled out differential zones. The obtained results have not been compared with classic relative sensitivity according to Bode:

$$S_{\Delta x}^{R} = \frac{\partial R}{\partial \Delta x} \cdot \frac{\Delta x}{R} \tag{5}$$

where:
Δx – width of differential zone,
R – change in temperature distribution.

3. Example of TWW-200-2(2A) turbogenerator modernization

The developed computer software based on the modified thermal networks has been used in working out the plans of numerous modernizations of turbogenerators rating from 6 to 560 MW. These modernizations have been later implemented by TurboCare Poland S.A. in Lubliniec. The modernizations were aimed at increasing power with simultaneous rises in turbogenerator reliability.

In this section, we present the modernization of the TWW-200-2(2A) type turbogenerator. As a result of introducing constructional changes, we obtained an increase in the turbogenerator's power from 200 to 240 MW, i.e. by 20%, the rated power factor was unchanged. In addition, these modifications improved the operational reliability and lengthened the turbogenerator's durability.

The initial research related to modernization of this turbogenerator type, targeted at an increase of its power and aided by the modified thermal networks method was initiated in 1994. Then, modification in the excitation winding construction was introduced (but the cooling system constructed by the manufacturer [10] was not interfered with) and this caused a decrease in temperature rise of this turbogenerator element (it must be noted that excitation winding is the most utilized thermal element of the turbogenerator). As a result, we obtained an increase in the turbogenerator's power from 200 to 220 MW, while the rated power factor was unchanged. Thermal measurements of the modernized turbogenerator confirmed the effects anticipated in the modernization draft, i.e. the desired increase in power.

In order to increase turbogenerator power even more, we decided to introduce an axial cooling system in the excitation winding. Figure 1 shows the cross-section of the rotor slot with visible axial ducts, and Fig. 2 shows the network of cooling ducts for a quarter of the excitation winding coil.

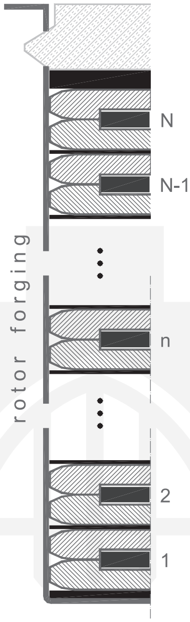

Fig. 3. Cross-section of rotor slot

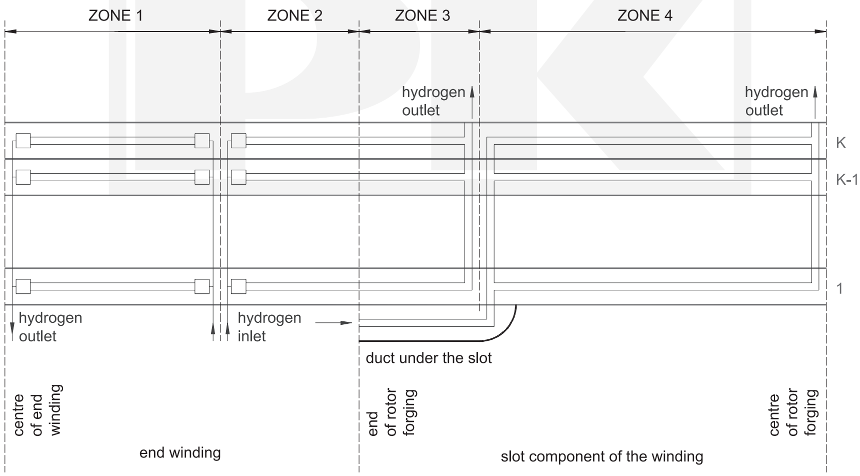

Fig. 4. Network of cooling ducts in one quarter of the excitation winding coil

Cold hydrogen flowing out of the cooler is forced under the covers by the fans. The wires of the excitation winding located near the end of the rotor forging contain holes, through which hydrogen runs into the axial ducts. One stream of hydrogen flows through the axial ducts in the direction of the end winding centre, and from there, it flows out by the outlet holes. The second hydrogen stream flows through axial ducts in the windings in the direction of the rotor forging. The slot wedges and winding wires contain radial outlet ducts (located at some length from the end of the rotor forging), and through these, the coolant stream flows out to the rotor gap. The third hydrogen stream flows through ducts under the slots and then runs into the axial ducts in the winding wires through radial holes. This stream then flows out through radial holes in the winding wires and slot wedges near the centre of the rotor forging and goes into the rotor gap.

New fans were designed and constructed for the modernized turbogenerator; they were additionally equipped with rear guide blades. The comparative measurements in the aerodynamic tunnel showed that efficiency of new fans with rear guide blades is 24% higher than that of original fans.

Construction of the new axial fan with rear guide blades is shown in Fig. 5; fan blades (3) are fixed to the fan rotor (1), and rear guide blades (5) are located in the fan housing (4).

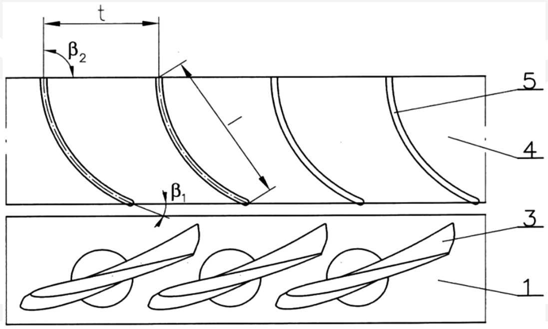

Fig. 5. Developed view of blade cascades of fan rotor and guide blades

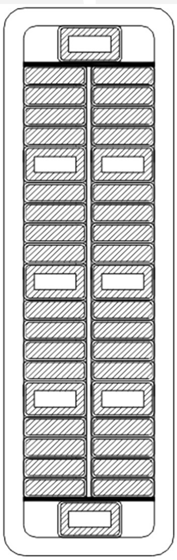

Fig. 6. Cross-section of stator winding bar

The stator winding of the modernized turbogenerator is cooled directly with distillate. The winding bars are made of both solid and hollow elementary conductors and distillate flows through them – see Fig. 6. The new bars differ from the original bars both in the number and the dimensions of the elementary conductors. The introduced constructional changes caused a decrease of losses in the turbogenerator stator winding as a result of the decreased additional power losses factor (these power losses are related to current displacement).

The construction of the turbogenerator stator core was unchanged. It is laminated and divided into axial segments; between these segments, radial cooling ducts are located.

Lots of additional changes were introduced into the turbogenerator, the most important were related to the modernization of the terminal elements of the stator core and hydrogen coolers.

Using thermal diagrams for the differential zone singled out in the wire (Fig. 1) and cooling duct (Fig. 2) in the steady state, a modified thermal network for the turbogenerator's excitation winding was created (Fig. 7). This network contained 206 thermal nodes.

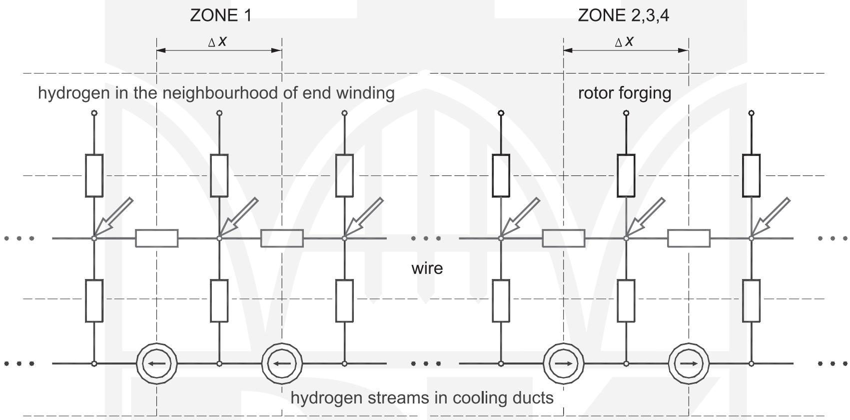

Fig. 7. Modified thermal network for excitation winding in thermal steady state

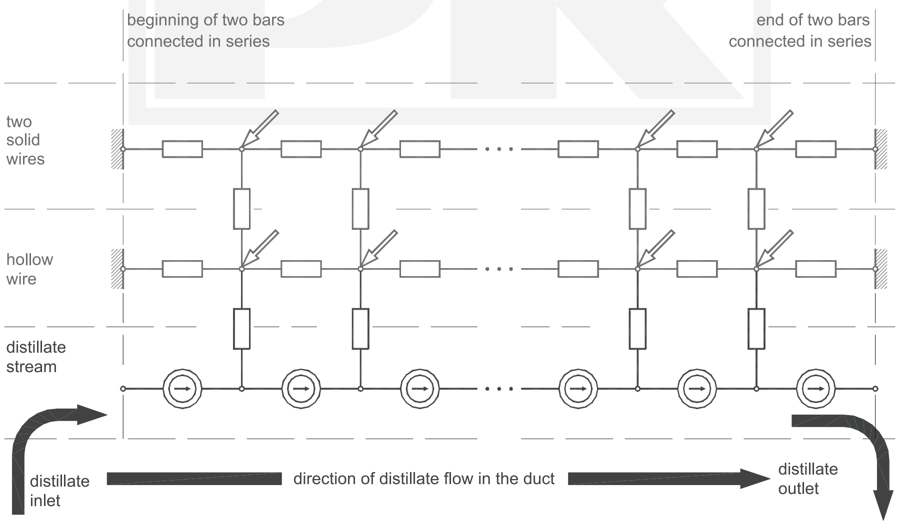

Fig. 8. Modified thermal network for stator winding in thermal steady state

Similar rules were applied in the creation of the modified thermal network for turbogenerator stator winding (Fig. 8). It contained 708 thermal nodes.

Using modified thermal networks, the temperature field in the active elements of the modernized turbogenerator was calculated. The generator was loaded with active power equal to $P = 255$ MW, at rated power factor $\cos\varphi_n = 0.85$ (lagging). An example of the temperature rise distribution in the wires of the excitation winding outer coil and its cooling hydrogen stream is shown in Fig. 9.

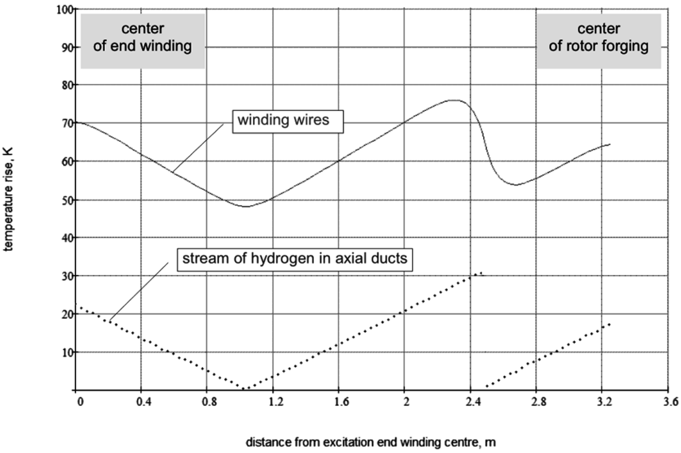

Fig. 9. Distribution of temperature rise in excitation winding outer coil – turbogenerator running at $P = 255$ MW, $\cos\varphi_n = 0.85$ (lag)

The calculated and allowable temperature rises of the active elements of modernized turbogenerator are compared in Table 1. All values relate to turbogenerator loaded with power $P = 255$ MW at rated power factor $\cos\varphi_n = 0.85$ (lagging).

Table 1

Comparison of calculated and allowable temperature rises

Temperature rise [K]	Calculated	Allowable
Average, excitation winding	60.5	70
Maximum, stator winding	36.5	49
Maximum, stator core	13.5	55

On account of the thermal utilization of the active elements, there exists a possibility of increasing the power of the modernized turbogenerator up to even 255 MW (with rated power factor unchanged). The presented modernization scheme was implemented in practice. The manufacturer took into account additional factors limiting the power (in the particular heating of the terminal elements of the stator core and mechanical stresses during short-circuiting) and stated the rated power as equal to 240 MW after modernization. It must be noted that after modernization, the temperature rises in the active elements at rated operational conditions are significantly lower than the allowable rises – this fact must result in increased durability. It must also be emphasized that the modified thermal networks used in calculations were verified experimentally. They ensure a high accuracy of representing the temperature distribution in the turbogenerator. The maximum difference between the calculated and measured temperatures was equal to 6.5 K. In view of the complexity of the design of the modelled object, this must be acknowledged as a very satisfactory result.

4. Conclusion

Power stations all over the world try to lower the costs of electricity production. The operators wish to combine necessary repair work on the turbogenerators with modernization in order to increase the rated power and improve operational reliability. Research presented in this paper has resulted in numerous implemented modernizations of turbogenerators for power stations in EU and Asian countries (e.g. China and Korea). In addition, perfecting the design of turbogenerators has helped to eliminate many different types of failures. The modernization of the TWW-200-2(A) turbogenerator described in this paper may be considered a rather interesting case, since a very large increase in rated power was obtained (20%) with a simultaneous decrease of temperature rises in all active elements.

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