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Continuation of Prof. Władysław Latek's research – revitalization of old power units

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Abstract. The research conducted by Prof. Władysław Latek (1916–1991) has contributed greatly to development in turbogenerator design. The economical transformation taking place in Poland after 1991 initiated the process of revitalization of old power units in electric power stations. For the past 25 years, a team of scientists continuing the work on perfecting the turbogenerator design and design methods has been working in the Faculty of Electrical Engineering of Silesian University of Technology. The work of this team has led to proposing and implementing many modernization projects for turbogenerators operating in Polish power plants, as well as in power plants in European Union and Asian states. Numerous novel and innovative solutions have made it possible to significantly increase turbogenerator power, improve effectiveness of electrical energy production and reliability and safety of operation.

Key words: turbogenerator design, modernization of power units, increase of installed power.

1. Introduction

Polskie Towarzystwo Elektrotechniki Teoretycznej i Stosowanej (Polish Association of Theoretical and Applied Electric Circuits Theory) and Stowarzyszenie Elektryków Polskich (Association of Polish Electricians) proclaimed Professor Władysław Latek the Person of the Year 2016. Prof. Latek had devoted a significant portion of his scientific activity to the design and construction of turbogenerators. He educated many outstanding specialists employed at universities and research centres in Warsaw. To this day, scientists and industry engineers working on design and operation of turbogenerators acquire their know-how from publications and books by Prof. Latek [1–3].

Prof. Władysław Latek died in 1991. In the same year, the market of electrical energy emerged in Poland, as a result of a transformation in the country's economy. The market activity had initiated the process of revitalization of old power units in power stations, aimed at increasing the installed power and improving the effectiveness of electrical energy generation. The most difficult technical problem faced here was the complex modernization of turbogenerators.

In order to fulfil the high demand set on turbogenerator modernization, it is necessary to work out new solutions of main constructional elements, and cooling systems in particular. The design work requires perfecting both simulation and physical models in order to increase their accuracy. This is caused by very high thermal utilization of turbogenerators, which results in the elements' temperature values being close to the allowable temperature limits.

Solving complex issues related to turbogenerator modernization requires support from scientific centres. In 1991, Prof. Władysław Paszek set up a team of scientists who investigated the matters related to perfecting turbogenerator design and developing design-aiding tools for 25 years.

Some selected turbogenerator modernization projects are presented in this paper. All of these projects were implemented by EthosEnergy Poland S.A., with cooperation provided by scientists from the Silesian University of Technology. The application of the new designs resulted in a significant increase of turbogenerator power, in some cases even in excess of 20%.

Additionally, effectiveness of electrical energy production was increased, reliability and safety of operation was improved and lifespan of turbogenerators was extended. Work was also undertaken aimed at adapting outdated turbogenerator designs to operation with variable loading.

Revitalization of old power units in power stations makes it possible to significantly increase installed power in the power engineering system, and in the situation of a growing demand for electrical energy, it should be taken into account in the development strategy of Polish power engineering. The need for such steps is recognized by big power engineering concerns [4].

2. Tools used in preparation of turbogenerator modernization design

Elaboration of new turbogenerator designs, aimed at increasing power and improving operational reliability, requires in particular a calculation of the temperature field, in order to assess the thermal conditions of elements and cooling media. The design work is aided by original computer programs created on the basis of the author's method regarding modified thermal networks [5–7]. The perfected thermal network method, basing on differential division, prevails over the standard method [1, 8, and 9], since it is enables to represent the temperature distribution in turbogenerator elements, caused by the heating of cooling media streams (air, hydrogen, or distillate). This orig-

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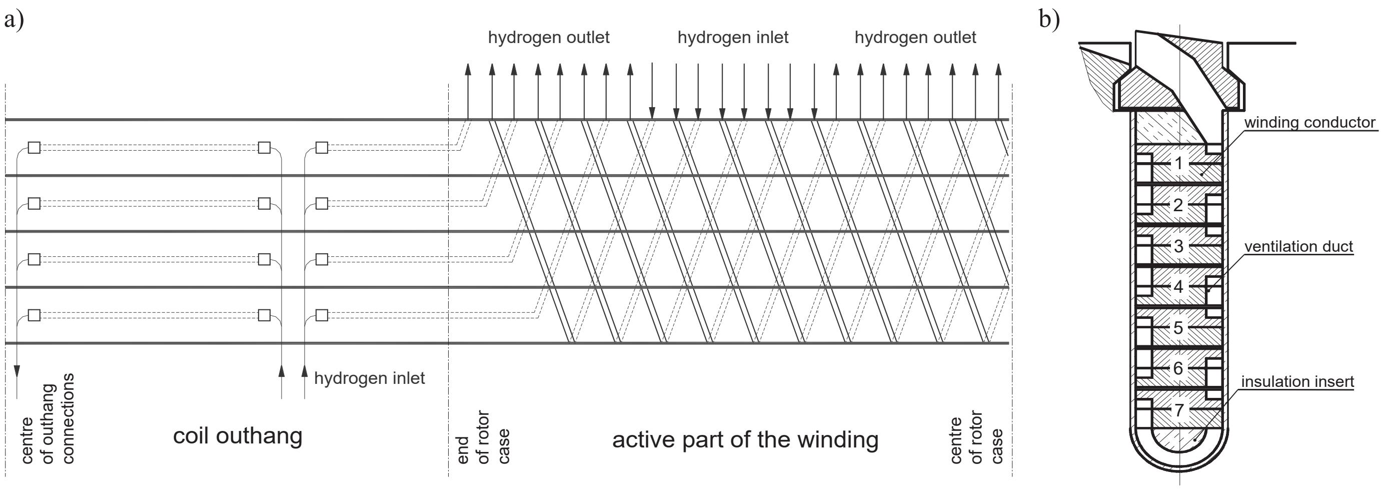


Fig. 1. Turbogenerator excitation winding with original radial-axial cooling system: a) network of ventilation ducts, b) cross-section of rotor slot

inal method of modelling the temperature field in turbogenerators is an alternative for the finite element method (FEM) [10]. It is possible to work out the thermal models and run the calculations much more quickly [5] for very different design variants in the early stages of the project, and afterwards, to carry out a comparative analysis on the basis of obtained results. The application of the modified thermal networks method in many turbogenerator modernization projects results from a high precision in representing the temperature distribution. This fact is confirmed by numerous measurements carried out on site, and with real objects [5].

Commercial software basing on FEM is used to calculate the electromagnetic field and mechanical stresses. Depending on particular requirements, 2D or 3D models are generated.

When working out new cooling systems, equivalent schemes of ventilation network are used. Some tests are carried out on physical models in a wind tunnel, e.g. the determination of optimum angle of incidence of rotor fan blades of the turbogenerator.

3. Rotor modernization enabling an increase of turbogenerator power while power factor is unchanged

Large power turbogenerators often use direct hydrogen cooling of the excitation winding, and direct distillate cooling of the stator winding. Thermal measurements of turbogenerators equipped with such cooling systems usually show full thermal utilization of the rotor winding, and partial utilization of the stator winding. In such case, there is a possibility of increasing the stator current and subsequently active power output to the power network, without introducing constructional changes. However, a projected modernization of a turbogenerator usually assumes that the power factor should be maintained at its rated value, and this requires an increase in the ampere-turns of the rotor. This cannot be achieved without changes in the construction of the rotor.

In 1991, work on the modernization of TWW-200-2(2A) turbogenerator type was started. This type of turbogenerator operated not only in Polish power stations, but also in other countries (e.g. Finland, Bulgaria).

The most difficult technical problem was to introduce changes which would enable an increase in the turbogenerator excitation ampere-turns. The design of the original excitation winding is shown in Fig. 1. The quintessence of this design lies in the use of profiled insulation inserts at the bottom of rotor slots in order to connect the ventilation ducts on the right- and left-hand sides of the winding conductors [11]. After the modernization, the insulation inserts were replaced with profiled wires of identical shape [5]. As a result, the number of turns in each coil of excitation winding was increased by one, making the ampere-turns go up without increasing the excitation current. This implemented innovation made it possible to raise the power of the turbogenerator up to 220 MW, while the power factor remained unchanged. Additionally, class F insulation was applied in the rotor winding (the manufacturer used class B insulation). This resulted in the temperature rise of the rotor winding lesser than the rise allowable for class B insulation.

The novel solution of excitation winding presented above was also applied in TWW-500-2 turbogenerator rotor (Fig. 2),

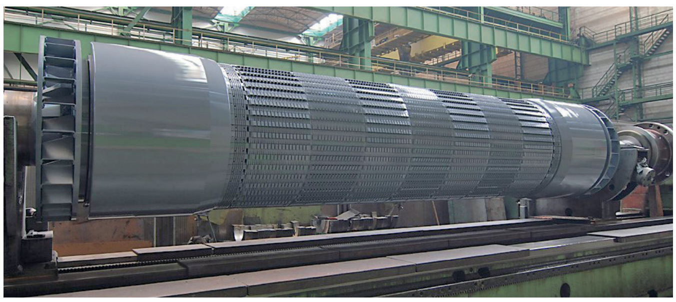


Fig. 2. New rotor enabling a rise in TWW-500-2 turbogenerator power up to 560 MW

in order to increase its power to 560 MW, while the power factor remained unchanged at its rated value.

In order to further increase the excitation ampere-turns of the TWW-200-2(2A) turbogenerator, new rotor fans with an increased capacity were designed. The shape and number of blades in the fan were selected by means of simulations. Then, tests in a wind tunnel were carried out, and the optimum angle of incidence of the adjustable fan blades was determined. The thermal measurements of the turbogenerator, fitted out with a new winding and new rotor fans, demonstrated the possibility of loading the turbogenerator with 230 MW of active power at a rated power factor. The measured increase of average temperature in excitation winding during this operation did not exceed the value allowable for insulation class B, and since the insulation is executed in class F, its lifespan is improved.

The excitation winding of the modified design and the new fans were used also during the modernization of the TWW-320-2Y3 turbogenerator rotor (Fig. 3), in order to increase the power of the machine by 10%. It must be noted that this modernized turbogenerator operates in Greece. Given the climatic conditions, the allowable temperature of cold hydrogen is 44°C, which means that it is 4°C higher than in Poland.

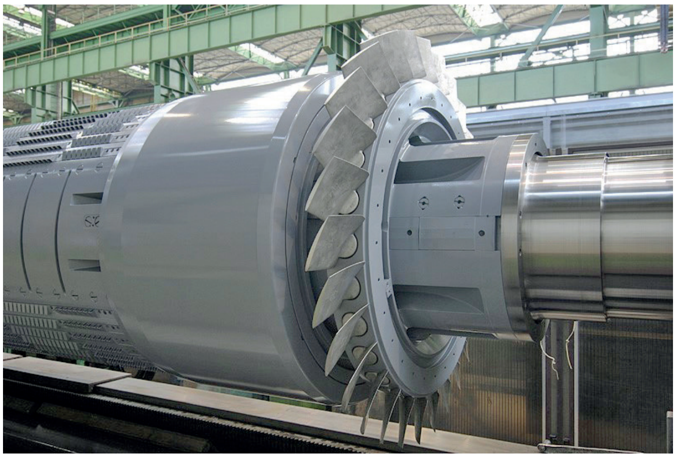


Fig. 3. Modernized rotor of TWW-320-2Y3 turbogenerator

In another modernization project of a TWW-200-2(2A) turbogenerator, we aimed at increasing the power up to 240 MW, while maintaining the rated power factor [12]. To attain this goal, lots of constructional changes in the turbogenerator were necessary. It was indispensable to apply a new axial excitation winding cooling system (Fig. 4), as well as new fans equipped with additional diffusers of increased capacity (Fig. 5). New stator winding was used, and the outermost elements of the stator core were modernized. The rated power of hydrogen radiators was increased.

The performed thermal measurements of the modernized turbogenerator showed that an increase of power up to 247 MW was possible, while the rated power factor remained unchanged. This increase is 7 MW greater than assumed in the project.

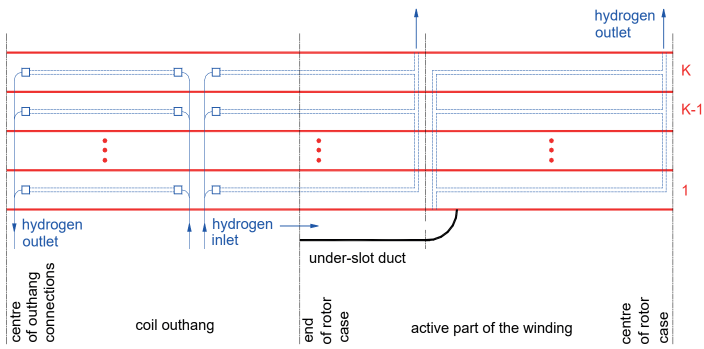


Fig. 4. Modernized rotor winding – the goal was to increase power of TWW-200-2(2A) turbogenerator up to 240 MW

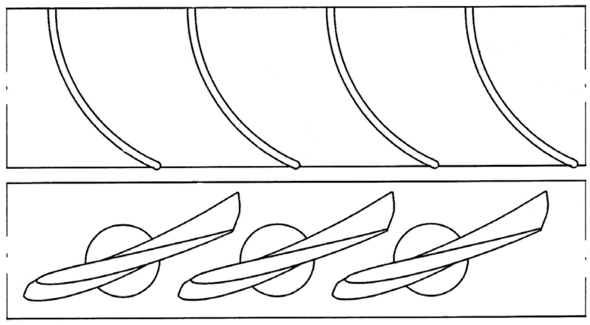


Fig. 5. Grid of blades of new fan and diffuser – developed view; new design makes it possible to increase TWW-200-2(2A) turbogenerator power up to 240 MW

The subsequent research brought about a granted patent for an invention related to a new and more effective cooling circuit for turbogenerator rotor [13]. Application of this method makes it possible to increase the excitation current density, and the result is that turbogenerator power may be increased by more than 20%.

4. Turbogenerator modernizations increasing operational reliability

Another field of research is focused on elaborating innovative solutions improving the operational reliability of turbogenerators.

We could illustrate this research using the modernization of a TGW-63 turbogenerator. A brand-new turbogenerator of this type has both the rotor winding and stator core cooled directly with hydrogen, and stator winding bars cooled directly with distillate. Leakages in distillate circuit are quite common, and cause high losses due to the necessity of emergency switch-offs of the turbogenerator and its subsequent repairs. It was necessary to modernize this turbogenerator in order to eliminate the system of cooling stator winding with distillate and to replace it with hydrogen cooling. In the project, it was assumed that the rated parameters of turbogenerator would be maintained.

The basic change in the turbogenerator was the replacement of stator winding consisting of bars directly cooled with distillate (Fig. 6a), with the winding bars cooled indirectly with hydrogen (Fig. 6b).

Replacing the very intense direct cooling of stator winding with distillate with the inferior indirect hydrogen cooling required decreasing the stator current density. It was therefore necessary to raise the active cross-section of stator winding bars by increasing their height and width. New stator core with larger slots was made, laminations of lower lossiness were used, and in addition, the thickness of bars' insulation from the ground was reduced. This was possible thanks to new electroinsulating materials being used.

The transfer of losses from the stator winding to the hydrogen (in previous, i.e. manufacturer's design, these losses were transferred to distillate) required increasing the power of hydrogen radiators. In modernized radiators, new tubes with an increased convective heat transfer coefficient were applied. Additionally, new fans were installed. These were equipped with rear-fixed blades. The fans' capacity was increased significantly in relation to the manufacturer's fans.

The measured temperature distribution on the surface of turbogenerator housing (manufacturer's version) (Fig. 7a) is

a) b)

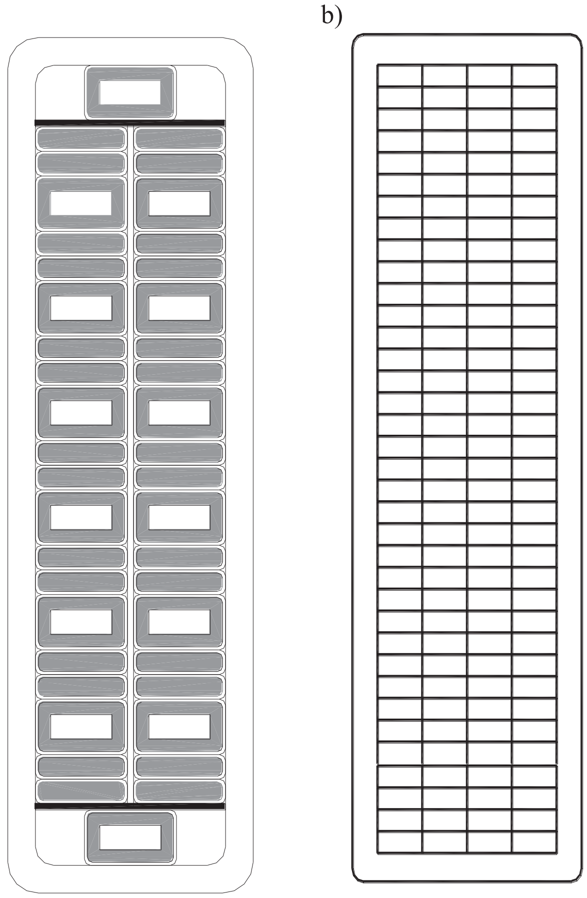
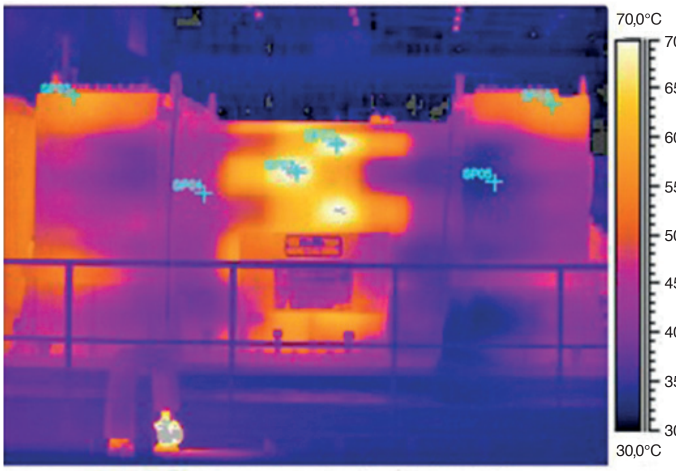


Fig. 6. Cross-section of stator bars of TGW-63 turbogenerator: a) manufacturer's design (direct cooling with distillate), b) after modernization (indirect hydrogen)

a)



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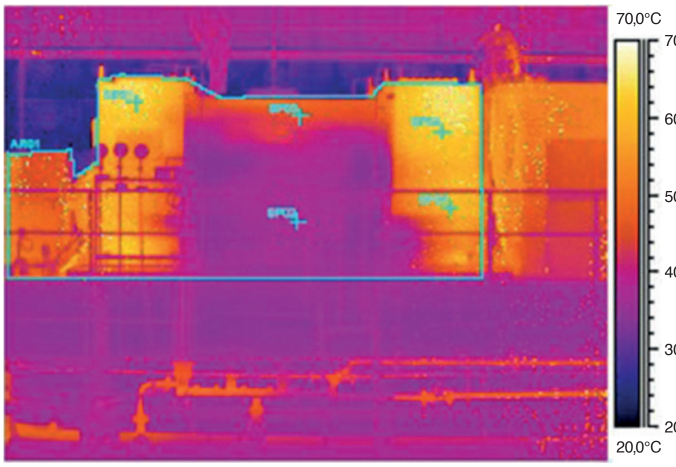

Fig. 7. Temperature distribution, surface of TGW-63 turbogenerator's housing (image from thermal imaging camera): a) before modernization, b) after modernization

characterized by high non-uniformity. The introduced change of the hydrogen flow in the turbogenerator caused an equalization of stator temperature (Fig. 7b).

The conducted thermal measurements of the modernized TGW-63 turbogenerator confirmed the required preservation of the rated parameters. At rated load, the temperature rises in active elements did not exceed values allowable for class B insulation, while the insulation systems of the rotor and stator belonged to insulation class F.

5. Changes in turbogenerator design enabling replacement of hydrogen cooling with air cooling

Many power stations are interested in modernization of the turbogenerators, which would allow to change the cooling medium – by replacing hydrogen with air. This would lead to elimination of the hydrogen supply system, which in turn would facilitate and increase the operational safety of turbogenerators.

In the cited example of a projected modernization of a TG-55 turbogenerator, some changes were proposed, enabling the replacement of the hydrogen cooling system with an air cooling system. The rated power and rated power factor were to be maintained.

The most difficult concern in this project was to keep the high efficiency of cooling the excitation winding, while the cooling medium was exchanged for one of a poorer quality. This goal was attained by exchanging the indirect cooling system of excitation winding for a direct radial-axial system.

The heating curves for TG-55 turbogenerator excitation windings are shown in Fig. 8. These are the results of measurements conducted before and after the modernization (air-cooled). Exchanging the indirect cooling system for a direct cooling caused a reduction in the average temperature rise of excitation winding from 88.5 K to 64.0 K, which is 11.0 K below the allowable limit. The tests were conducted under rated operating conditions.

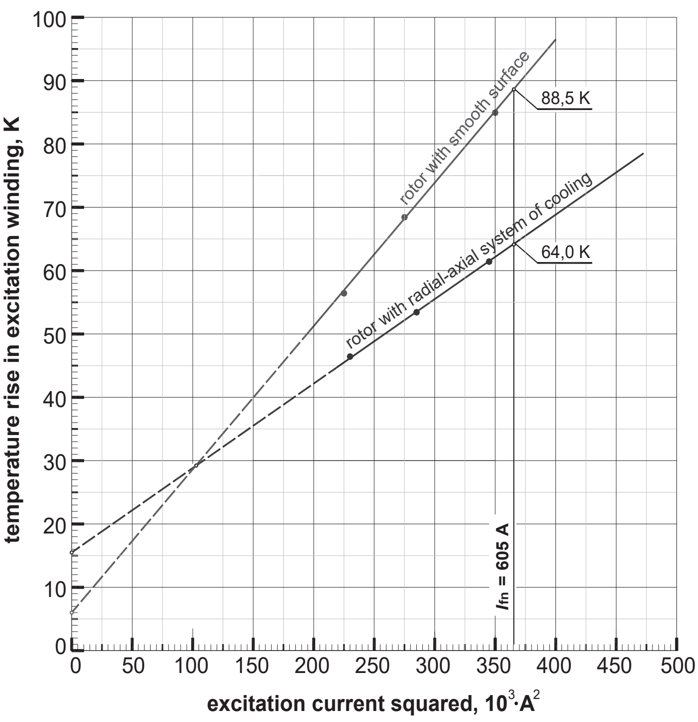

Fig. 8. Heating curves of excitation winding; TG-55 turbogenerator in manufacturer's variant (smooth rotor) and after modernization (air-cooled rotor with radial-axial cooling system)

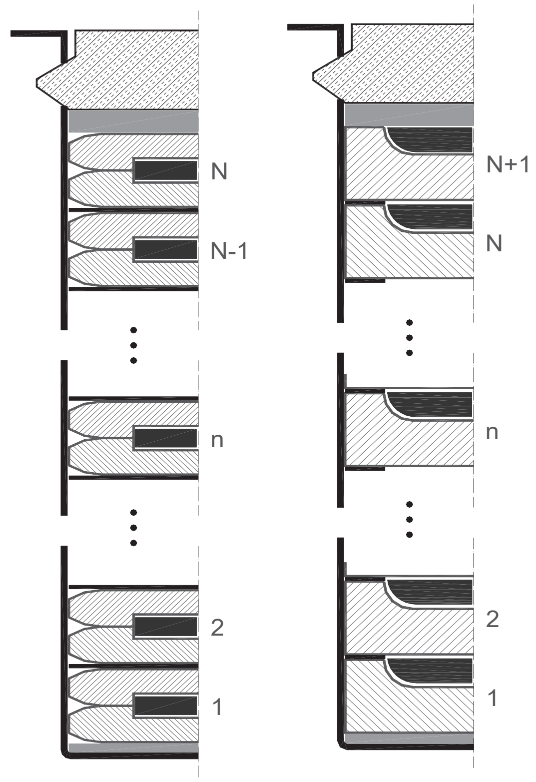

Fig. 9. Cross-section of TGH-120 turbogenerator rotor slot: a) manufacturer's design, b) after modernization

6. Adaptation of turbogenerator construction to continuous high changes in load and frequent switch-offs

Nowadays, many turbogenerators in commercial power plants operate at continuous, high changes in load, and frequent switch-ons and offs to and from the network. This practice results in recurrent failures of some turbogenerator elements.

During detailed visual inspections of turbogenerators operating at variable loads, extensive damages to excitation winding are often encountered. These damages may even lead to turn-to-turn short-circuiting.

The modernization of TGH-120 turbogenerator demonstrates how to solve the problem of recurrent damages to the excitation winding coil outhangs. A change in conductor shape was introduced in the excitation winding outhangs (Fig. 9). The new wire used during modernization is almost twice as high in relation to the original wire used by the manufacturer (this is done to increase stiffness), the insulation separator with a decreased friction coefficient is glued at only one side (the decreased friction facilitates easy dilatation) and the wire is characterized by a significantly increased area of heat transfer to hydrogen. In addition, in each rotor slot,the number of wires was increased by one. This way, the excitation ampere-turns were increased without raising excitation current.

Photos of the TGH-120 turbogenerator excitation winding coil outhangs are shown in Fig. 10 (both the outhangs designed by the manufacturer and those modernized during a periodic inspection). It must be noted here that the modernized turbogenerator operated with power increased to 130 MW.

Similar modernization project was worked out for the GTHW-360 turbogenerator. The patent for novel shape of excia)

b)

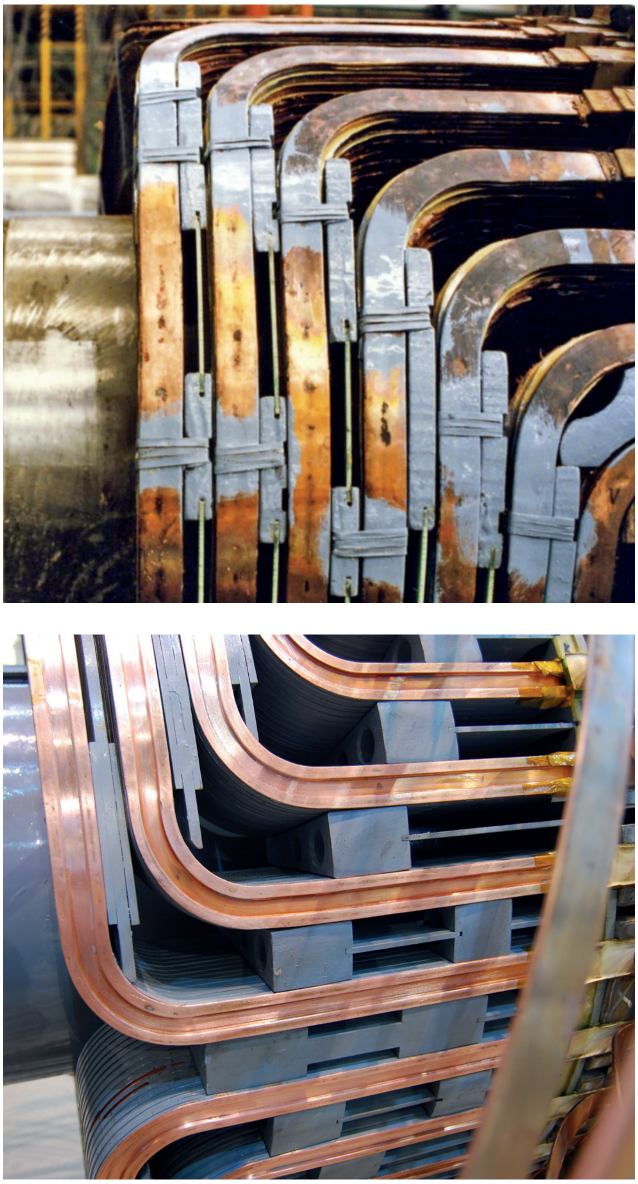

Fig. 10. Coil outhangs of excitation winding, TGH-120 turbogenerator during periodic inspection: a) manufacturer's design (turbogenerator's rated power 120 MW), b) after modernization (turbogenerator's rated power 130 MW)

tation winding conductor [14] was applied in this project. This innovative solution prevents damages caused by thermal dilatations of the excitation winding conductors in a turbogenerator.

7. Conclusion

Research aimed at perfecting the design of turbogenerators and their adaptation to new operating conditions had been conducted for the past 25 years in the Institute of Electrical Engineering and Computer Science of Silesian University of Technology. This research is a continuation of work carried out by Prof. Władysław Latek and his team before 1991. This previous research focused on increasing power and improving operational reliability of turbogenerators.

The scientists from Silesian University of Technology have been co-operating with EthosEnergy Poland S.A. A series of implemented modernization designs for turbogenerators resulted from this partnership. Turbogenerators with novel and innovative constructional solutions operate nowadays in many Polish electric power plants, as well as in Bosnia and Herzegovina, Bulgaria, China, Finland, Greece, South Korea, Slovenia, Ukraine and Uzbekistan. The obtained increase in power of modernized turbogenerators has been confirmed by thermal measurements and failure-free operating periods of many years, proving the correctness of new designs.

References

[1] W. Latek, "Turbogenerators", WNT, Warsaw, 1973, [in Polish].

[2] W. Latek, "On-site testing of electric machines", WNT, Warsaw, 1997, [in Polish].

[3] W. Latek, "Theory of electric machines", WNT, Warsaw, 1987, [in Polish].

[4] J. Tchórz, "Research programs conducted in TAURON Wytwarzanie S.A.", *VIII Scientific Conference on Environmental Protection in Power Engineering*, Katowice, (2013), [in Polish].

[5] R. Krok, "Thermal networks - application for modelling temperature field in ac electrical machines", D.Sc. Thesis., Silesian University of Technology, 2010, [in Polish].

[6] R. Krok and R. Miksiewicz, "Thermal models of turbogenerator rotors for different cooling systems used in CAD", *International Conference and Exhibition on Power Electronics and Motion Control EPE-PEMC 2000*, Kosice, 131–136 (2000).

[7] R. Krok, "Electric mine motor thermal models aiding design and setting thermal protections", *Bull. Pol. Ac.: Tech.* 60 (1), 103–110 (2012).

[8] M. Rioul, "Development of thermohydraulic modelling for the determination of hot spots in the bars and the slot thermal image for the stator 900 MW turbogenerators", *Proceedings of International Conference on Electrical Machines ICEM'95*, Paris, 437–441 (1995).

[9] G. Swift, T.S. Molinski, and W. Lehn, "A fundamental approach to transformer thermal modeling – Part I: Theory and equivalent circuit", *IEEE Transactions on Power Delivery* 16, 171–175 (2001).

[10] M.S. Rajagopal, K.N. Seetharamu, and P.A. Aswatha Narayana, "Finite element analysis of radial cooled rotating electrical machines", *International Journal of Numerical Method for Heat & Fluid Flow* 9 (1), 18–38 (1999).

[11] R. Krok and R. Miksiewicz, "Analysis of the thermal field in excitation winding of a synchronous generator with direct radial-axial cooling system made on the basis of a thermal resistance network", *ICEM'96*, Vigo, Spain, 405–410 (1996).

[12] R. Krok and M. Pasko, "The modernization of turbogenerators as a method of decreasing electrical energy production costs", *Technical Transactions* 1-E (8)*,* 191–201 (2015).

[13] J. Adamek, R. Krok, R. Maniara, and D. Baron, "Patent No. 224128: Cooling system of turbogenerator's rotor", Polish Patent Office (2016).

[14] S. Sieradzki, J. Adamek, D. Kardas, J. Kapinos, and R. Krok, "Patent No. 218474: Generator excitation winding wire", Polish Patent Office (2014).