Summary

Dissertation title: Flow-dynamic modernization of a steam turbine rotor blade

This dissertation is considering the purpose and the process of development of steam turbine blade. The focus was on proposing a new solution for the outlets of the intermediate pressure part of the 13K215 turbines. The designed blade will also be used in other turbines from the 200MW family, such as the 13K200 or 13K210. In the last twenty / thirty years, most steam turbine manufacturers have focused on improving these types of turbines mainly by modernizing the low-pressure part and paying very little attention to solutions have used for the intermediate pressure part. The dissertation presents a description of subsequent modernizations carried out on the 13K215 turbines as well as a historical outline of its origin. As a result of preliminary analyzes, it was proved that improving the efficiency and increasing the height of the IM module last stage blade will bring measurable profits in the form of increased power generated by the turbine. Considering the current political and ecological situation, a highly efficient product reducing the heat rate in the electricity production process would be desirable and would have a positive impact on the natural environment.

Designing this type of elements is associated with several problems and requirements to be met. This dissertation presents the description of the topics based on the available literature, including: the mechanisms of the formation of forces acting on the blade profile or the basics of design methods. The last stage blade of the IP module works in parameters higher than the LP outlet blades (temperature, pressure), and thus the profiles are more loaded. The dissertation describes the experience of GE Power in the development of the last stage of the intermediate pressure section, which showed the sense of developing this product and the critical points of the design. The presented products in the company's assortment were a base to set a reference value for the newly designed blade. In the first place, the strength aspects were described, because they were associated with the greatest problems for this type of product (due to working in the specific conditions).

In order to achieve the aim of this dissertation, it was necessary to present the design requirements in terms of flow analyzes. It is known that every 3D FEM analysis method is based on a conventional computational approach. Necessary from the point of view of understanding the basics was to show the methods of designing blade systems and analyzing their efficiency described in the literature. Losses occurring in the turbine stage and the genesis of their formation

are listed and shortly described. Knowing the mechanisms of the formation of problematic effects in the canals built between blades, it is possible to better understand them and prevent or eliminate them.

The next step considered during solving the presented problems was to identify all the constraints determining the directions of the possible geometrical development of the blades. Attention was paid to improving one element of the turbine without degrading the others, e.g., by introducing an excessively long last stage blade into the steam path, causing mechanical, assembly or flow problems (e.g., by disturbing area grow of outflow). For this purpose, the geometry of the stationary elements, the rotor, interface locations were analyzed. Based on that the maximum possible height for the newly designed blade was determined. Referring to the company's previous experience with this product focus has been placed also on finding a solution to the rotating blades ring integrity problem. Subsequent analyzed proposals for the construction of the shroud were presented and their principles of production and assembly/disassembly were discussed. This element has a very important role in this type of blades due to rejection of the other solutions allowing to maintain the integrity of the rotor stage and damping the natural vibrations of single blade (e.g., damping wires). Dumping wires are not a solution anymore for blades located in this area of the turbine train, because they introduce losses that reduce the final efficiency of the stage.

Knowing the geometrical constraints, it was possible to prepare the model for flow calculations. It consisted of two blades, because in order to obtain the right angle of inflow to the newly designed rotating blade, it was necessary to prepare 3D representation of the stationary part of turbine stage. In addition to the inflow angle itself, such an approach allows to introduce more realistic flow conditions, such as e.g., pressure and velocity disturbances caused by the trailing edge effect. This dissertation shows what aspects should be paid attention to in order to properly evaluate the designed blade. This dissertation shows what the main importance should be attached to in order to properly evaluate the designed blade profile. The graphs of the profile load before and after the modernization were shown. With the iso-surface defined by the negative steam velocities in the axial direction, problematic places where easily and quickly localized. Problematic means the regions where the stream detachment from the blade surface or appearing of local vortices occurred. Number of blades in a single rotating row was selected to be as closed as possible to the parameters previously prepared for the 13K215 turbine retrofits steam path. Pressure between stationary and rotating row was a parameter to compare with ne designed blade inlet. Initially, 90 blades were installed in a row, but after the calculations and analysis of the results, 87 elements were used. Then, adjustments were made in the profile geometry, as a result of which the phenomena negatively affecting the efficiency were eliminated and the profile load diagrams were improved. Modernization concerned especially the upper part of the blade and was based on modifying the contours of the front part of the pressure side and the top part of the blade (suction side). For the final modernized model, an additional analysis was performed considering leaks above the shroud. This was done to calculate the actual end efficiency and the power generated by the new element. It was turned out that predicted profits from the development of this product are achievable. Efficiency was calculated as 94.28% and with the final parameters of the blade, the power generated by the rotating row should increase by 803.53kW in relation to the blade with a length of 400mm. Overall, the increase in power for the entire shaft line will be about 0.45 MW, which is a very good result.

Having a ready-made blade airfoil, the next stage describes steps for building a computational model for strength analyzes. Possible solutions for each of the designed elements of the blade were presented with noted what is associated with the use of each of them in terms of strength, processing and assembly. The selection was supported by the experience of GE Power, if possible. Specific two root types were chosen and the rationale for such a solution was presented: first for a new retrofit projects – fir tree root, and second for small modernization of OEM IP modules - pin root. The rotating blade of the steam turbine is a critical element of the reliability of the entire turbine set, so it was necessary to comply with the specific requirements. Referring to the currently available instructions and recommendations, there are no specified ones for the last stage blade of intermediate pressure module. Nevertheless, based on the guidelines for LP LSB was an excellent basis for drawing up a series of criteria for blades generally shorter but operated at higher temperatures and pressures. According to these parameters new limits have been established. At this stage, the process of building a computational model, discretization and assumptions for boundary conditions are presented. The profile load coming from steam was imported from the previously performed CFD analysis. The method of limiting the computational model to one blade was presented by cutting of a small piece of its upper part, shifting it by an angle in relation to the theoretical axis of the turbine and the adding of cyclic symmetry. This simplification allowed for more analyzes to be performed at the same time. A bit different approach must be used for pinned root variant calculation. In this case two blades have to be used for calculation but again the simplification for one of them was used.

Based on guidelines and evaluation criteria, several analyzes were performed for the subsequent considered design solutions. The point of reference was the calculation for a blade equipped with a simple bandage, without any additional element supporting the cooperation between adjacent elements. For all options, a list was drawn up showing the maximum principal stresses in specific locations and based on this it was easy to diagnose which of the proposals fulfill their roles. Three different options were considered for the root types: fir three root curved and straight and pin root (OEM design). The last one was used to check the possibility of improving the original 13K200 and 13K215 turbines, which have not had IP module modernized yet, by replacing only the last stage. Variant III as well as other two gave positive results. In case of fir three root solution, it was necessary to perform additional calculations considering creep. It was cause by the high stresses at the contact surface root-groove. Calculation had to prove whether the notch hooks would not be damaged. For the considered shroud solution, the best results were achieved by a design equipped with an integral elliptical pin. Apart from the difference in displacement between the tips of adjacent blades at the maximum level of 0.05 mm, it gave the lowest results for maximum principal stresses. This part describes the advantages and disadvantages as well as problematic locations of specific design, thanks to which the choice of the best solution was simplified.

Each blade stage must meet the frequency criteria to avoid resonance and the associated risk of damage to the elements of the turbine steam path. Interference graphs were prepared for the best solution of the shroud and for two types of roots, which show the characteristics of the first five modes of natural vibrations, lines of excitation from rotational speed and point of prohibited frequency defined by the stationary part of the stage. As a result of such a comparison, it turned out that the first mode of vibration crosses the excitation lines below the 8th nodal diameter, and therefore it was necessary to perform an additional stress check in the model for the 4th nodal diameter. The results showed that the effect of the described above situation is irrelevant to the final assessment, because the tested parameters were lower than those for operating at nominal speed.

The last analysis was the low-cycle fatigue calculation. They require more effort in defining the gradients of increase and decrease in temperature, pressure and velocity for successive elements of the 3D model in specific phases of the cycle. The basis for this activity were the previous experience on projects implemented by GE Power and knowing the number of projects implemented on the 13K215 turbines, it can be assumed that they reflect the actual parameters at a sufficient level. The final effect is assessed by the number of work cycles that the model components can work without failure. The usually used limit is a minimum of 5000 cycles for the newly designed blade, the more conservative approach was taken, and it was set to 10000 cycles. The results for the rotor and groove were 14242 and for the blade itself and the rest of the elements 189410.

Summarizing all analyzes and numerical calculations presented in this dissertation, one solution for the shroud was selected - the design with an integral elliptical pin and two types of the root. It was emphasized that the straight fir three root variant should be used in future modernizations of the entire SP modules due to the cost and labor-intensity of execution and the ease of servicing. The second variant could be used for small modernization, which increase the efficiency of the turbine by limited activity - replacement of one stage for the not yet modernized IP parts of the 13K200 and 13K210.

The product is fully validated only after its production and testing in the centrifuge balancing machine. It is one of the steps defined as the next in the conducted research. Another element is to refine the solution for the previously described small ranges of OEM turbine service. The blade of the last stage in this case is installed on the smaller diameter so it will be necessary to check and possibly correct the shape of the rotating blade profile. After proving, the possibility of installing the last stage blade with a length of 500 mm and a justified increase in power, in the subsequent stages of development of this solution, more attention should be paid to the stationary blade and the penultimate stage.