MODERNIZATION OF HPP ZAKUCAC / CROATIA COMBINED DEVELOPMENT BY CFD AND MODEL TESTING

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Abstract:
The presented paper deals with the modernization of HPP Zakucac. Because of its importance within the national system the expectations and requirements of the refurbishment have been quit high, leading to intensive investigations and hydraulic development - both in CFD Analyses and conventional model testing. The following pages are giving an overview of the activities and achieved results.

1. The Hydro Power Plant Zakucac

HPP Zakucac is part of a multipurpose system for utilization of the Cetina River watershed. Two big reservoirs are providing the water supply to the four Hydro Power Plants of the system, the largest one - HPP Zakucac - is also the most important one of Croatia. Zakucac has been built in two stages. The first stage was put into operation 1961, consisting of the Prancevici Dam, the headrace tunnel with the surge chamber, the penstocks and the power house with two generating units of 216 MW total capacity. About 19 years later the second stage was erected, comprising an additional headrace tunnel with surge chamber and penstocks, feeding the new units with 270 MW total capacity.

Short description of the system:

The intake structure of the head race is located at the Prancevici Reservoir, providing the daily discharge regulation of the Cetina River. The two pressure tunnels with a diameter of 6,1 and 6,5 m and about 9,85 km length are leading to surge chambers 1 and 2, 50 m upstream of the valve chamber. Each tunnel has a branch to two penstocks, equipped with butterfly valves of 3,5 m diameter at the first stage penstocks and 3,75 m for the second stage ones. The penstocks are steel pipes embedded in concrete and are leading vertically 289 m to the underground cavern. In front of the generating units (vertical Francis turbines and synchronous generators) spherical valves of 2,4 and 2,6 m are installed.

The tailrace system spills the water from the power house back to the Cetina River, just 1700 m upstream of its estuary to the sea. It consists of an open flow tunnel with horse shoe cross section (approx. 350 m length) and a 700 m long open channel.

The longitudinal profile of the system is shown in Figure 1:

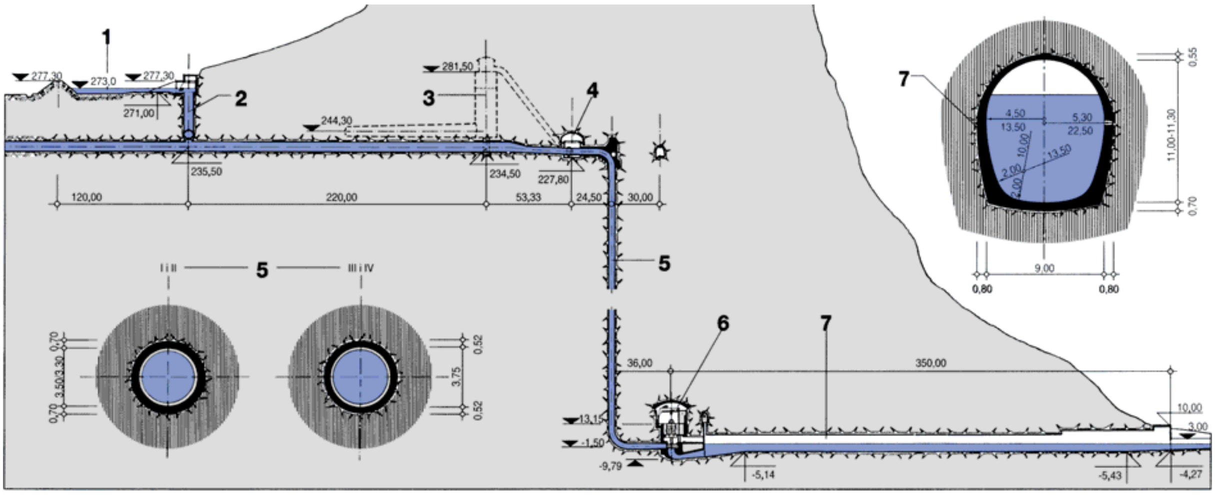

Figure 1: Longitudinal profile of the system (drawing by HEP)

Electromechanical Equipment:

The generating units are installed in an underground cavern. The arrangement of the machines is of vertical 3 - bearing design with one turbine guide bearing and a combined upper generator bearing and lower generator guide bearing. The general design of the units of both stages is the same but has different technical characteristics:

	1st stage, units A&B		2nd stage, units C&D	
Turbine:				
Rated speed	300	rpm	333,3	rpm
Rated output	110	MW	138,3	MW
at rated head of	250,4	m	252	m
Max. output	119	MW	152,6	MW
at max. head of	267	m	269	m
Max. discharge	50	m³/s	60	m³/s
Runner diameter	3440	mm	3226	mm
Guide vane height	480	mm	380	mm
Original supplier	Voith Siemens		Litostroj	
Generator:				
Rated power	120	MVA	150	MVA
Rated voltage	16	kV	16	kV
Original supplier	Koncar		Koncar	

Table 1: Characteristics of existing machinery

2. Requirements on the new turbines

The existing turbines are operated over a wide range of discharges, having in view the specific role of the power plant in the Croatian electric power system. Each of the units A&B is working on the average of 6000 hours per year. Because of its age it became necessary to exchange worn out equipment by new parts with state of the art hydraulic and design. Units C&D are showing some intensive cavitation problems at the leading edge of the runners, which require periodic repair.

Summarizing the results of the investigations the following topics for the modernization of the units have been specified by the Customer:

- Main goal for units A&B was the upgrade to larger output. Taking into account the given runner diameter, quite a large increasing of the turbine flow and output was reasonable when changing the rated speed.
- Therefore the new power output should be increased to about 2 x 150 MW at H_{max} = 270 m.
- Because of the importance of the plant, the improvement both in efficiency and annual production should be as high as possible, being reflected in the evaluation criteria.
- Replacement of the existing equipment with new developed hydraulics using state of the art design techniques.
- Keep the excellent cavitation performance of the existing Voith units, no cavitation at the leading edge was admissible.
- Keep the output of the Litostroj units but improve their cavitation characteristics.
- Very low output - and pressure fluctuations.
- For evaluation of the offers and to get the best performance available a competitive Model Test between the two most successful Bidders had to be performed for units A&B.
- The winner would get the Contract for units C&D also.

For Zakucac units A&B, the targets for future performance gains in power were determined by evaluating the potential cavitation limitations of a new design. Typical of modernization approaches, design investigations were undertaken to evaluate the effect of increasing blade area by increasing the number of runner buckets, and by extending the length of the band. Both methodologies showed promise of being able to achieve the desired goal of increasing the output of the existing machines to 150 MW under the given tail water condition at a head of 270 m while maintaining the excellent cavitation performance of the existing machines. The plant sigma (Thoma's) value of 0.05 which characterized the design objectives was challenging. The operating efficiency of the improved design is dependant on the final geometry of modified components within the machine and the discharge required to achieve the desired power. An analysis of the existing geometry to determine the extent of losses present in stay vanes, wicket gates, runner blading and runner seals was conducted and compared with state of the art designs.

The scope proposed to the customer, included new wicket gates, a new extended length band runner with larger discharge diameter, new stationary seals, new draft tube cone, a new bottom ring and a new head cover.

3. New Component Development by Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA)

The detailed design of the performance enhancements was conducted by applying three dimensional viscous Computational Fluid Dynamics (CFD) techniques for the evaluation of the turbine components for energy losses and cavitation performance. The numerical method used for the present results is based on a finite volume philosophy. It is a fully three-dimensional simulation method fulfilling the Reynolds averaged Navier-Stokes equations of motion for an incompressible fluid leading to the conservation of mass and momentum. The influence of turbulence is considered with the two-equation k-epsilon turbulence model. On each grid volume discredited equations for continuity, momentum, and turbulence are formed and solved simultaneously. An iterative solution is required due to the nonlinear nature of the equations. A quasi-steady approach uses the time dependent nature of the equations to evolve from an initial guess toward a steady state final condition.

The design of the modernization was started by selecting the point of peak efficiency (the design point). Taken into consideration for this selection was the expected operation of the machine within the expected head and tail water range as communicated by the customer.

To favor increased performance at higher gate openings the wicket gates have been redesigned. Figure 2 shows the gate shape selected based on fluid analyses considering the spiral case inflow, the influence of the stay vanes, and the requirements of the runner design point selected. Gate pressure loadings derived from CFD analyses were utilized to load the wicket gates for mechanical stress analysis. Several iterations were made to select the final gate thickness utilized. One of the key design challenges was in developing an acceptable stress level in the transition between the gate leaf and the gate stem. Fine grid meshes were applied to validate the gate structural design (Figure 3, 4).

Figure 2: Wicket gate

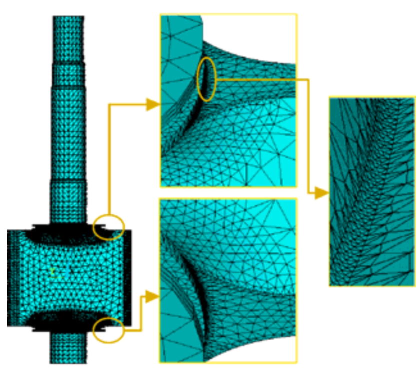

Figure 3: Gate meshing

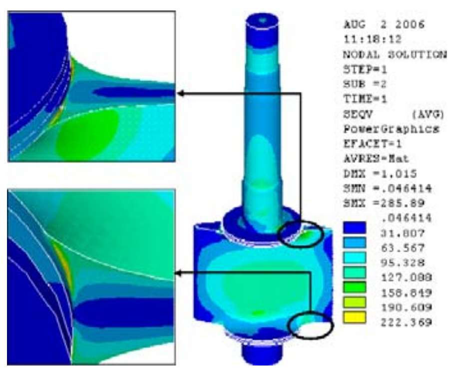

Figure 4: Gate stress distribution at gate squeeze condition

The design of the runner was made considering the inflow from the wicket gates within the expected operating range of head, tail water and discharges (Figure 5). Runner blade shape parameters were chosen to maximize performance across the operating range of discharge and head. The main challenge in the design was obtaining satisfactory cavitation performance at the challenging plant sigma values which characterized the desired new output. Designs utilizing 13, 15 and 17 runner blades were considered. At the low plant sigma characterizing the targeted performance, blade pressure distribution scheduling was critical to obtain the cavitation design objectives. Careful attention was paid to provide a design which was free of inlet cavitation which could arise from operation at extremes of the head range. Figure 6 shows blade pressures expressed as Thoma's sigma at the runner inlet with the machine operating at maximum head and maximum discharge. As can be seen in the figure, no pressures near plant sigma signifying the possibility of cavitation are shown.

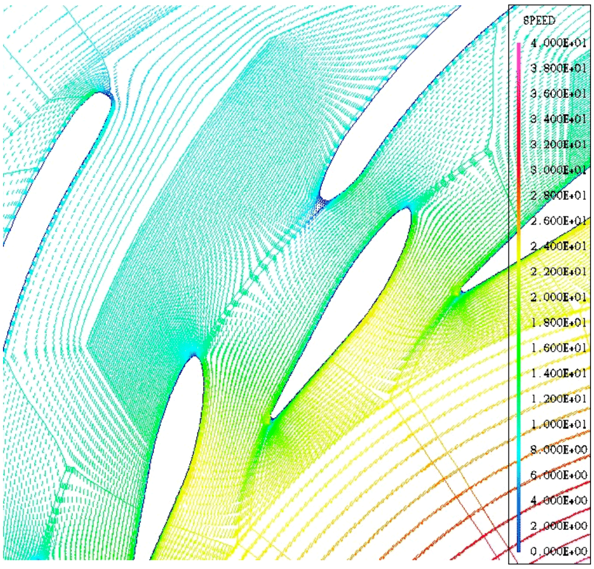

Figure 5: Velocity characteristics within the stay vanes and wicket gates

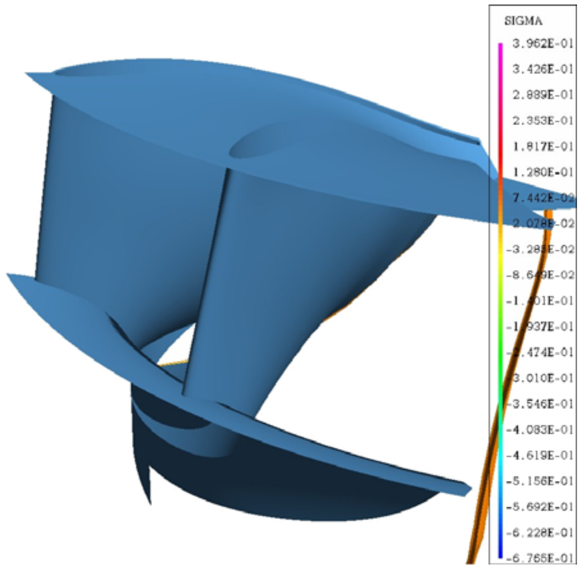

Figure 6: Pressure at maximum head and discharge at entrance edge on blade surface expressed as Thoma's sigma shows no cavitation at plant sigma

The discharge diameter of the turbine runner was made as large as possible based on the constraints of the draft tube inlet of 2500 mm so as to maximize the possibility for maintaining the excellent surface cavitation behavior of the existing machine at the increased discharge and power of the modernized design. The final design utilized a runner with an extended band compared to the original machine (Figure 7).

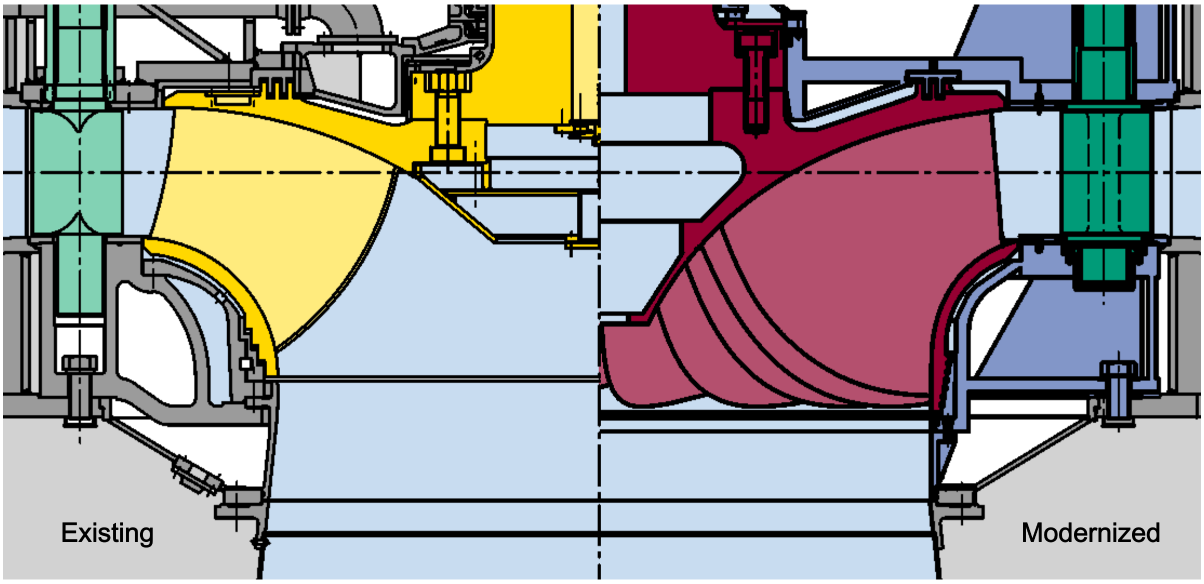

Figure 7: Comparison of existing and modernized turbines for Zakucac A&B.

When first runner design was evaluated in the model test laboratory of Voith Siemens Hydro in York Pennsylvania, USA it was determined that the draft tube performance of the machine was effecting the overall performance levels, a surprise because of the low specific speed of the machine. CFD analysis of the draft tube in conjunction with model testing was used to aid in diagnosing the source of the draft tube losses which sourced from the inner side of the draft tube elbow (Figure 8). Modifications to the draft tube geometry were made based on guidance from CFD analyses and were verified in the test laboratory to improve performance.

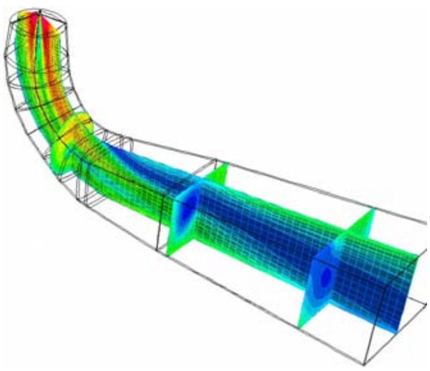

Figure 8: Draft tube velocity profiles showing Low velocity zone in blue

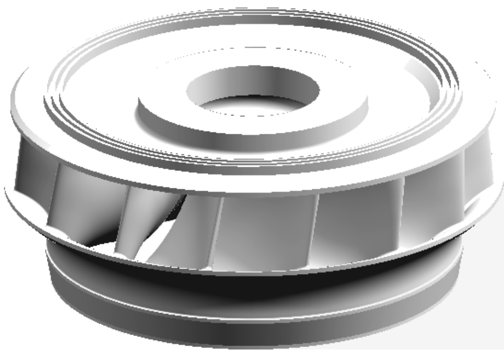

Figure 9: New runner

Hand in hand with the fluid design, structural evaluation of the new runner was made utilizing Finite Element analysis tool ANSYS to determine stresses and deflections in the components. Figure 9 shows the final design runner. Fluid loadings on the new structures were developed from the CFD analysis. Blade shape and thickness parameters were selected to achieve targeted stress levels at the critical blade sections near the intersection of the blade discharge edge and the runner crown (Figure 10). Of key interest was the deflection of the runner under load which was one of the parameters setting runner band seal clearance which was influential in controlling the overall performance for this project. FEA analysis at key operating conditions including maximum power at maximum head and runaway conditions verified that the targeted seal clearances could be obtained (Figure 11).

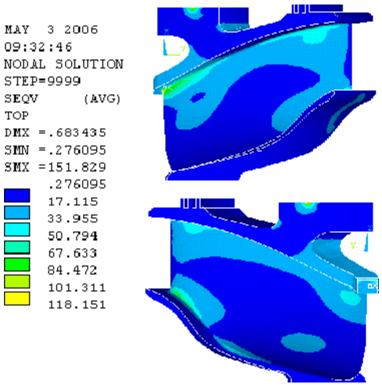

Figure 10: von Mises stress (MPa) distribution at maximum power at maximum head

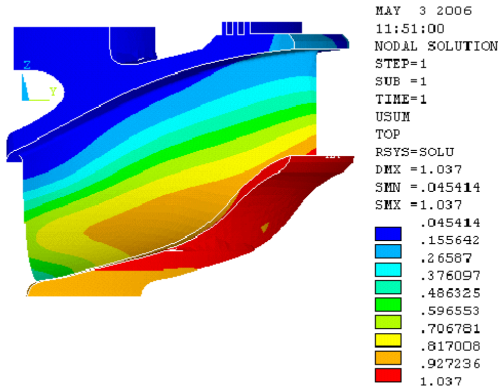

Figure 11: Total deflection (mm) distribution at runaway

The final design selected was determined based on model testing of several alternatives. Figure 12 shows the achieved performance of the machine at 260 meters head compared to the original.

At the peak efficiency point the achieved performance is as high as that of today's completely new machines, designed at the same specific speed.

The measured mean weighted efficiency is slightly higher than the predicted one, verifying the given guarantees.

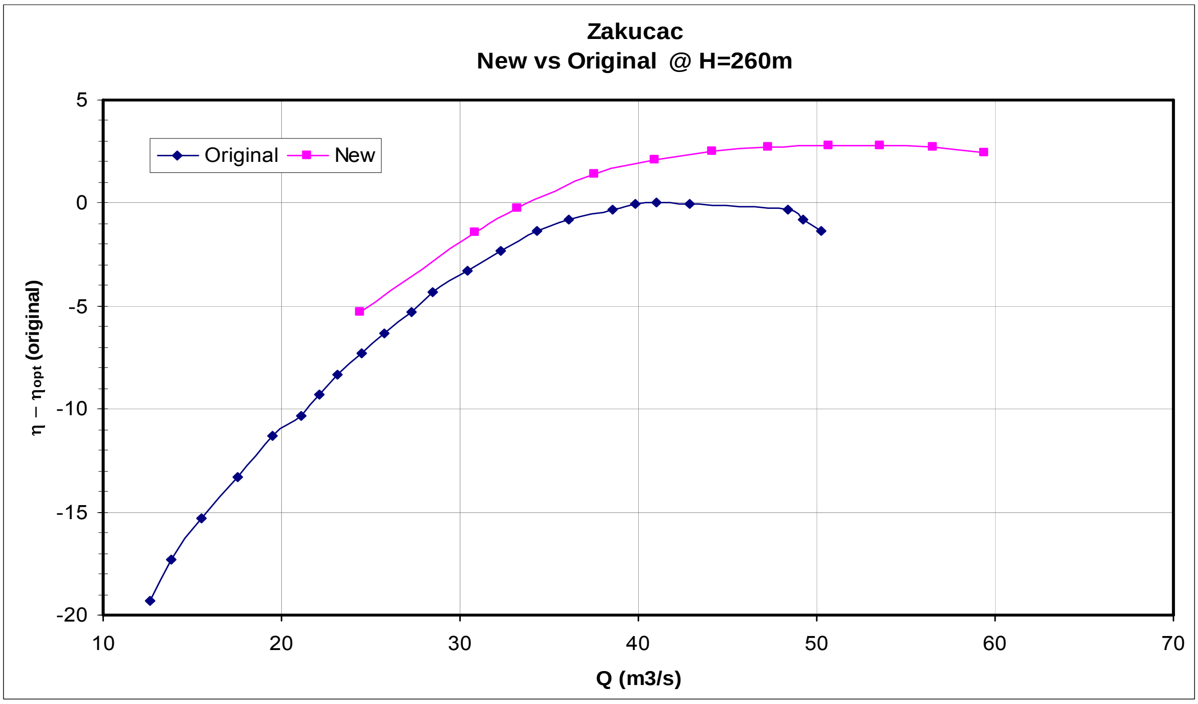

Figure 12: Performance comparison of achieved performance of the new design compared to performance of the existing machine.

Following the model tests at the VS laboratory, the model was shipped to the independent model test laboratories of Turbo Institute (TI) in Ljubljana/Slovenia for final evaluation by the customer in competition with a second supplier. Figure 13 shows the model in the test stand, figure 14 a view of the runner in operation at maximum output. Based on the performance of the model design of VS, the award for supply of the prototype machinery of Zakucac was placed with Voith Siemens Hydro Power Generation GmbH & Co KG in St. Poelten/Austria.

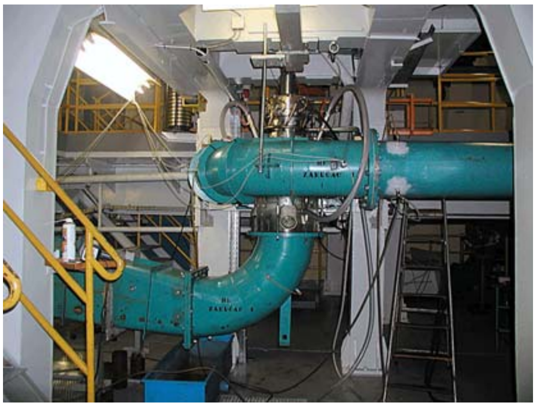

Figure 13: Model at TI laboratory

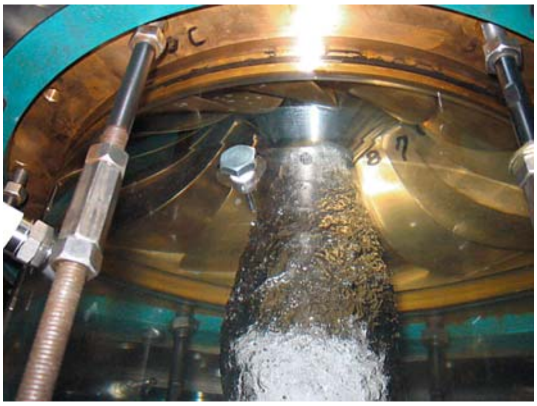

Figure 14: Model at full load operation

4. Main prototype design features to achieve tested performance

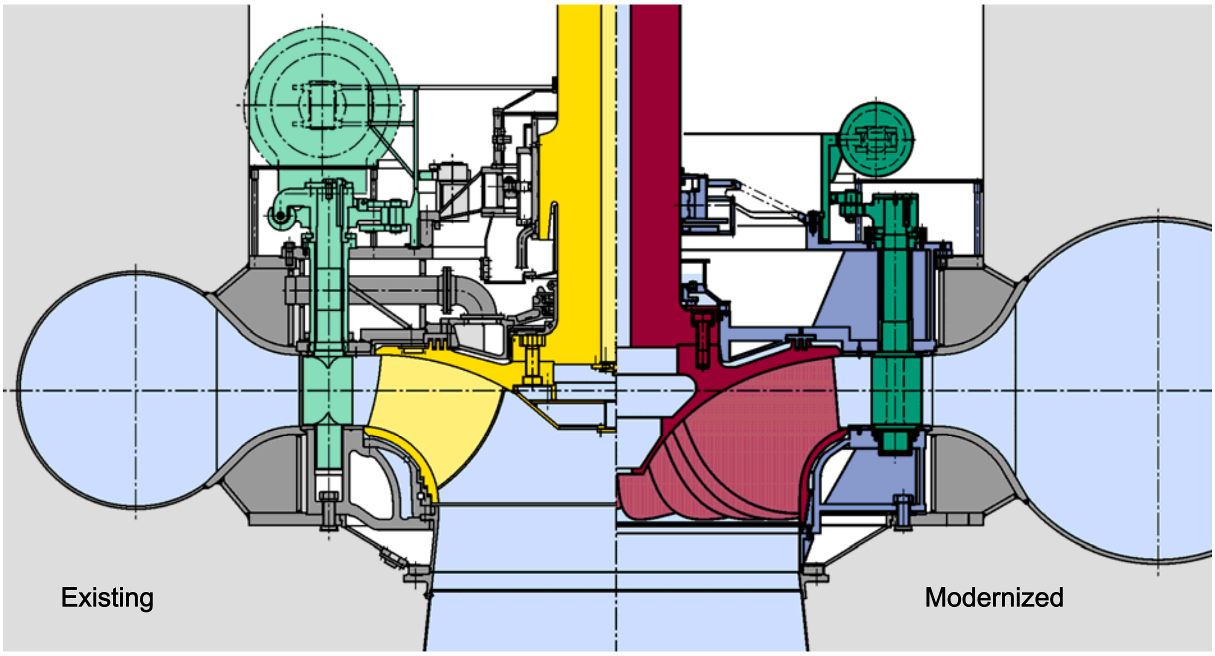

Figure 15: comparison of existing/modernized turbine cross section

To achieve the requested high performance the constraints due to reused components had to be as low as possible. Therefore the turbines have to be replaced by new designed components except embedded spiral case and draft tube.

This leads to the following main scope of modernisation:

- new runner with increased discharge diameter and extended length band
- new stationary seals
- new shaft
- new wicket gates and operating mechanism
- new upper draft tube cone
- draft tube modification
- new bottom ring
- new head cover
- new designed guide bearing, enabling shaft seal maintenance without dismantling the guide bearing
- new shaft seal

Beside the turbines the modernisation of HPP Zakucac includes refurbishment of the spherical valves, new turbine governor and valve control also. The Contract will be executed together with Litostroj on consortial basis under the leadership of Voith Siemens.

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