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Adjustable (rotated) stator blade aerodynamics in adaptive control of extraction/condensing turbines

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Abstract

Cogeneration of electric energy and heat as well as seasonal changes of the condenser pressure in low-pressure extraction/condensing turbines require adaptive control to adapt the geometry of the blading system to the changing flow conditions. In this paper adaptive control is achieved by means of restaggering (rotating) adjustable stator blades. An increase of turbine efficiency and power coming from adaptive control is numerically estimated for a group of two exit stages of an extraction/condensing turbine of power 60 MW. The calculations are made with the help of a computer code FlowER – a 3D solver of turbomachinery flows based on Reynolds-averaged Navier-Stokes equations for perfect gas.

Keywords: LP turbine; Turbine stage group; Adaptive control

1 Introduction

Extraction of steam for district heating and other technological processes as well as seasonal changes of the condenser pressure in extraction/condensing turbines are examples of variable operating conditions of these turbines that can lead to their off-design performance. During steam extraction to the extraction point, the mass flow rate in the blading system is reduced, thus reducing the pressure drop and leading to expansions beyond the blading system. In the case of a decrease

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in the condenser pressure one can also expect further expansion to that pressure beyond the blading system. During an increase in the condenser pressure, the pressure behind the last stage is increased resulting in a decrease in specific volume of steam. Part of the blade-to-blade passage at the exit remains blocked by a separation zone, the mass flow rate through the blade-to-blade passages is decreased and off-design conditions propagate on stages located upstream.

The off-design performance of low-pressure (LP) turbine stages gives rise to uncertainty in operation of the exit diffuser and is a loss of turbine power, first due to largely increased flow losses (increased cascade losses and increased exit energy), and second due to the fact that not the entire available pressure drop is consumed by the blading system. The situation requires adaptive control to moderate the consequences of off-design turbine performance. The main element of adaptive control is the so-called adaptive stage of flexible geometry. For the case of cogeneration of electric energy and heat this stage is located directly downstream of the extraction point. Sample designs of adaptive stage nozzles are presented in Fig. 1. Most typical is a design with throttling nozzles that have movable leading edges (Fig. 1A) blocking part of the blade-to-blade passage if necessary, Budyka *et al.* [1], Dejcz *et al.* [2], Łuniewicz *et al.* [3]. The mechanical construction of this stage is relatively simple, however its flow efficiency is low, both at full and low openings of the flow channel. Similar properties can be attributed to the design B. Another idea of adaptive stage is based on flap nozzles with rotated trailing edges (Fig. 1C), Puzyrewski [4]. As compared with the design with movable leading edges, it keeps the continuity of shape of the blade profile even at very low levels of opening. The operation of an adaptive stage with flap nozzles since 1987 is reported at the Heat and Power Station of Łódź in Poland, Puzyrewski *et al.* [5]. This stage was installed alternatively to the adaptive stage with throttling nozzles for a 25 MW extraction/condensing turbine with the extraction pressure of 0.15 MPa. The comparison of measured cascade losses and stage efficiencies of these two types of adaptive nozzles shows that flap nozzles increase the flow efficiency of the system, however involve a more complex driving mechanism to enable rotating of the nozzles.

In this paper, the adaptive stage with rotated stator blades (Fig. 1D) is investigated numerically for the case of steam extraction and change of the condenser pressure. The concept of rotated stator blades is similar to the concept of flap nozzles, as it preserves the continuity of the blade profile and consists in varying stator throats according to changes of mass flow rate or available pressure drop in the blade-to-blade passage. General advantages of adaptive control in the form of increase of turbine efficiency and power coming from adaptive control are numerically estimated for a group of two exit stages of an extraction/condensing turbine of power 60 MW.

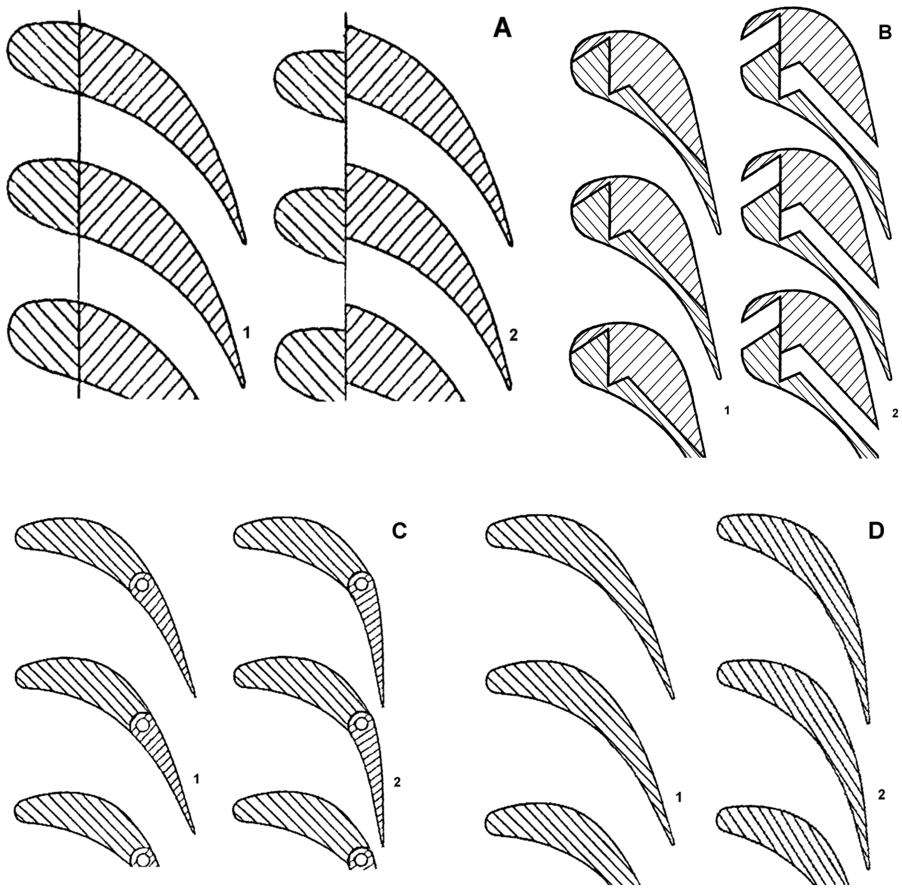

Figure 1: Adaptive stage nozzles: A – nozzles with movable leading edges (throttling nozzles), B – nozzles with a complex pattern of blade dividing line, C – nozzles with rotated trailing edges (flap nozzles), D – nozzles with adjustable stagger angle: I – nozzles fully open, II – nozzles partly open/closed.

2 The object of study and flow model

The flow path geometry for the LP part of the investigated extraction/condensing turbine of power 60 MW is presented in Fig. 2. The two exit stages have unshrouded twisted rotor blades of height 450 and 560 mm, respectively. The low-pressure extraction point (with the extraction pressure of 0.039 MPa, extraction temperature 89 °C) is located upstream of a group of two exit stages. The extraction steam user is the district heating company, where this steam is used for heating water up to 75 °C to fill the district heating network. The nominal operating conditions of the two-stage group are: inlet static pressure – $p_0 = 0.39$ bar, exit static pressure – $p_2 = 0.1$ bar, inlet static temperature – $T_0 = 89$ °C, inlet dryness fraction (quality) – $x_0 = 1.0$, exit dryness fraction (quality) – $x_2 = 0.96$, mass flow rate – $G = 35.6$ kg/s, rotational speed – 3000 rpm, giving the nominal power of 3.7 MW for stage L-1 and 2.8 MW for stage L.

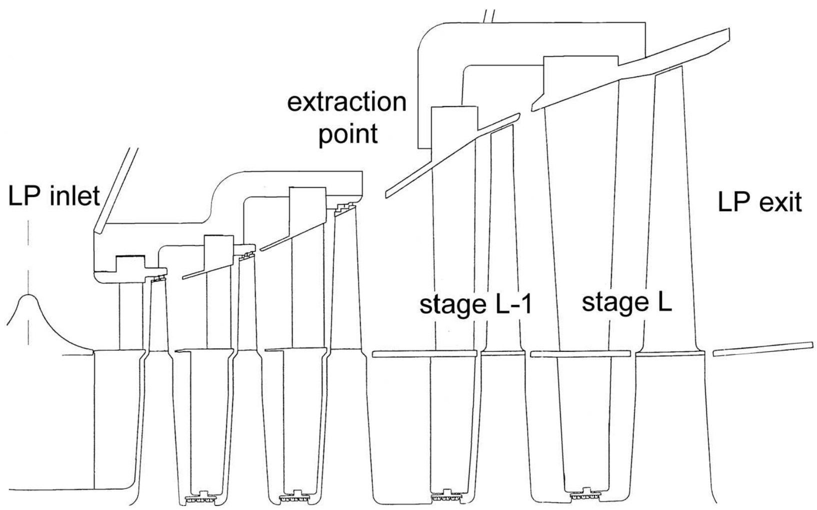

Figure 2: Meridional view of the flow path for the LP part of a 60 MW steam turbine.

A series of flow computations of the two-stage group located downstream of the extraction point were carried out with the help of a computer code FlowER, Yershov and Rusanov [6]. The turbulent flow of compressible viscous gas is described by three-dimensional Reynolds-averaged Navier-Stokes (3D RANS) equations with the perfect gas equation. Turbulence effects are modelled using the k-ω SST model of Menter. Discretisation of governing equations is made by the finite volume method. A numerical scheme of second-order accuracy in time and space is used. This is an upwind scheme of Godunov type with an essentially non-oscillatory (ENO) formula for the calculation of convective fluxes. To accelerate the process of convergence an implicit operator δ of Beam-Warming is used. The calculations are carried out in one blade-to-blade passage of the stator and rotor on an H-type grid refined near the endwalls, blade walls ($y^+ = $ 1-2, where y^+ is the dimensionless normal distance from the wall), leading and trailing edges.

Typically 12–16 points are used in the boundary layer. The total number of grid points per one blade-to-blade passage (of a single blade row) exceeds 400 000 (92 axially $\times$76 radially $\times$60 circumferentially). The calculations converge to a steady state. A mixing plane approach is used to treat the relative motion of the stator and rotor, based on circumferential averaging of flow parameters in the axial gaps between the blade rows. The calculation domain also extends on the radial gaps above the rotor blades. The assumed boundary conditions are typical for turbomachinery calculations, including no slip and zero heat flux at the walls, as well as spatial periodicity at the borders of the flow channel. The pressure drop across the stage (stage group) is imposed. Therefore, for a given flow geometry, the mass flow rate is resultant. The solver was extensively validated on real and model turbines, Lampart [7].

3 Turbine stage group characteristics

Investigations of the effects of adaptive control in the case of steam extraction were carried out in a group of two exit stages in the configuration as presented in Fig. 2, with the first stage of the group (stage L-1) assumed to have adaptive nozzles. In a series of numerical calculations of the group of two LP turbine exit stages, the back-pressure downstream of the stage L was varied in a range $p_2 = 0.010$—0.26 bar (note that the inlet pressure for the stage L-1 is kept unchanged $p_0 = 0.39$ bar) and the stator blade was restaggered as compared with the original geometry by rotating the blade by 1°, 2° and 3°. Characteristics of the stage group with restaggered (rotated) stage L-1 stator blades showing changes of the stage reactions, static pressure between the stages, enthalpy losses including the effect of exit energy and power (for each stage and for the stage group as a whole) as a function of stage L-1 stator blade geometry and mass flow rate are presented in Fig. 3. Bold solid lines in Fig. 3 link points calculated for the same nozzle geometry but for different pressure drops across the stage. Thin dashed lines link points calculated for the same pressure drops but for different stage L-1 nozzle blade stagger angles. The negative values of change of the stagger angle mean closing stator throats with respect to the original geometry.

Decreasing the pressure drop in the stage group decreases the mass flow rate in the blading system. For a constant stage group geometry, there is a decrease in the mean reaction of each stage with the decreasing mass flow rate. Especially significant is the decrease of reaction in stage L. The mean re-action of the exit stage (stage L) drops to zero when the mass flow rate is decreased by less than 2 kg/s. The calculations of the two stage group show that for the original geome-

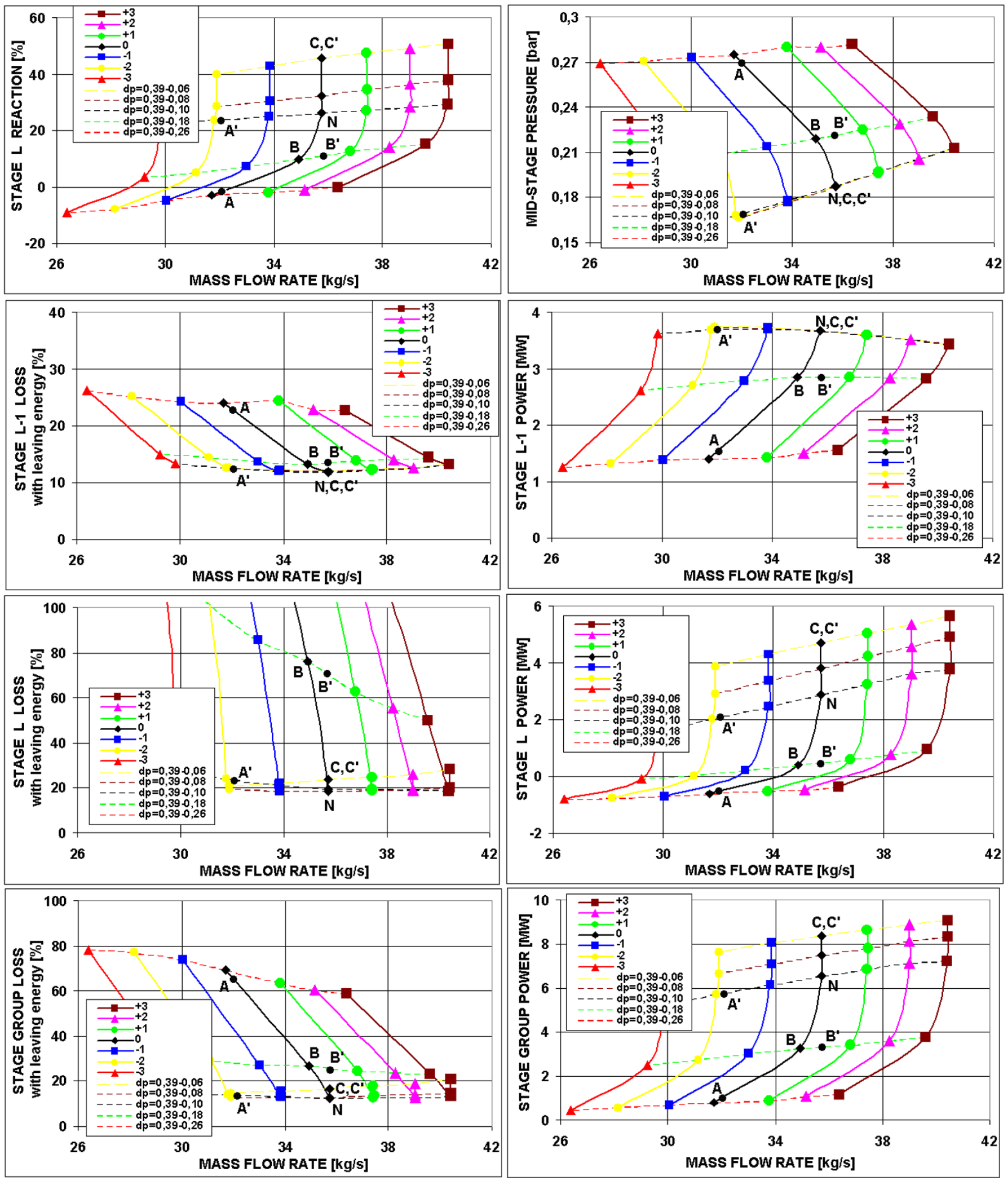

Figure 3: Change of mean reaction of stage L-1 and stage L, mid-stage static pressure (left column), enthalpy losses (including the exit energy) in stage L-1, stage L and stage group (right column) for given angles of stage L-1 stator blade restaggering as a function of mass flow rate.

try and for a fixed stage L-1 upstream pressure of 0.39 bar, the rise of downstream pressure above 0.20 bar yields negative power of the stage L. Enthalpy losses in stage L increase above 100% for the mass flow rates below 34.2 kg/s. This refers to the situation where energy must be supplied to rotate rotor blades of this stage. In other words, decreasing the mass flow rate by more than 1.5 kg/s means that the second stage does not produce power any longer and starts consuming power generated by upstream stages.

The flow is already choked for nominal operating conditions (point N in Fig. 3). Further increasing the pressure drop in the stage group does not increase the mass flow rate. The stage (stage group) power is increased, however at increased enthalpy losses.

4 Adaptive control in the case of steam extraction

Let us assume that upstream of the stage group operating at the nominal point (mass flow rate 35.6 kg/s, pressure drop *dp* from 0.39 to 0.10 bar), an additional portion of steam is extracted. Let the mass flow rate of the extracted steam be equal to 3.6 kg/s. As a result of this extraction, the mass flow rate in the blade-to-blade passage is reduced to 32 kg/s. Without adaptive control, the pressure drop across the stage group is increased with the mid-pressure increased to 0.27 bar and the back-pressure increased to 0.27 bar! Further expansion to the condenser pressure takes place beyond the blading system without yielding work to the rotor. The following auxiliary points are indicated in Fig. 3 to help estimate advantages coming from adaptive control: N – nominal operation of the stage; A – sample point of operation under additional steam extraction, B′ – the same point after adaptive control.

The point of operation of the stage is moved in the characteristics from N to A. This is connected with a decrease of reaction in stage L-1 by approximately 7% (from 32% to 25%) and by 29% in stage L (from 27% to –2%). There is an increase of enthalpy losses in stage L-1 by 11% (from 12% to 23%); enthalpy losses in stage L increase from 20% up to above 100%, resulting in an increase of enthalpy losses in the stage group by over 50% (from 13% to 64%). The power of stage L-1 is de-creased from 3.7 to 1.6 MW, power of stage L is decreased from 2.9 down to –0.5 MW (negative value – stage L consumes power), resulting in the stage group power decreasing from 6.6 to 1.1 MW, see Fig. 3.

The aim of adaptive control in the case of steam extraction is to bring part of the expansion lost for the stage group back to the blading system. This can be done by closing stage L-1 stator throats and restaggering the stator blade by -1.8°. Point A is then moved to point A′ that lies on the line of constant pressure drop corresponding to the nominal pressure drop (from 0.39 to 0.10 bar) as before the extraction of steam. By restaggering the stage L-1 stator blades, the mid-stage pressure is decreased from 0.27 to 0.17 bar. The mean reaction of stage L is increased by 26% up to 24%. The enthalpy losses in stage L-1 are reduced by 10% to about 13% and from a value exceeding 100% down to 22% in stage L, resulting in a decrease of losses in the stage group by 50% (down to 14%). The power of stage L-1 is increased by 2.2 MW to 3.8 MW, power of stage L is increased by 2.6 MW to 2.1 MW, and the stage group power is increased by 4.8 MW to 5.8 MW, Figs. 3 and 4. The stage power after adaptive control is lower by about 11% than that before the steam extraction (6.5 MW) – it is decreased practically only by the reduced mass flow rate in the blade-to-blade passage.

The increase in power obtained from adaptive control of the stage group is significant, as it forms 8% of the turbine power (60 MW). Note also that due to the decreased mid-stage static pressure resulting from rotating the stage L-1 stator blades, the obtained value of power of stage L-1 exceeds the nominal value for the original geometry, even though the mass flow rate is reduced. Extracting more steam increases absolute gains in stage group power due to adaptive control as the rate of power loss along the line N-A is larger than along the line N-A′. More detailed results of investigations of adaptive control in the case of steam extraction can be found in the paper of Lampart and Puzyrewski [8].

5 Adaptive control in the case of change of condenser pressure

Another situation where the adaptive control can be effective corresponds to seasonal variations of pressure in the condenser. There are very many reasons of pressure variations, only to mention a few such as changes in the ambient temperature or air inleakage to the condenser. To investigate the advantages of adaptive control in the case of change of the condenser pressure, the following auxiliary points are indicated in Fig. 3 to help estimate advantages coming from adaptive control: N – nominal operation of the stage; B – sample point of operation under increase of the condenser pressure, B′ – the same point after adaptive control; C – sample point of operation under decrease of the condenser pressure, C′ – the same point after adaptive control.

The aim of adaptive control under conditions of pressure rise in the condenser is to assure the nominal rate of mass flow through the blading system of the last stage and to exempt LP turbine stages located upstream of the considered stage group from off-design conditions, thus re-instating the nominal operating conditions for those stages. Advantages of adaptive control in this case, for a sample rise of back pressure from its nominal value of 0.10 bar to 0.18 bar, can be read from Fig. 3 by tracing points N-B-B′. With some degree of uncertainty over upstream effects of pressure rise in the condenser, we assume that during the above pressure rise, the mass flow rate through the blade-to-blade passage is reduced to 34.9 kg/s (point B). This represents the hypothetical situation, where the all loss due to the rise of back pressure is quantitatively assigned to the considered stage group, although more likely it may also be distributed over a group of upstream turbine stages. This is due to the fact that only part of the mass flow rate surplus can be accommodated by leakage flows or extracted to the extraction point. Most likely the pressure at the inlet to the last but one stage should rise, resulting in propagation of off-design conditions on stages located upstream. Then, the mass flow rate surplus will be lower and easier to be consumed by leakage flows or extraction points. Anyway, the uncertainty of determination of the operating point in the characteristics concerns only point B, but not point B′.

The point of operation of the stage is moved in the characteristics from N to B. This is connected with a decrease of reaction in stage L by approximately 16% (from 27% to 10%). There is an increase of enthalpy losses in stage L-1 by 1% (from 12% to 13%); enthalpy losses in stage L increase from 20% up to above 76%, resulting in an increase of enthalpy losses in the stage group by 14% (from 13% to 27%). The power of stage L-1 is decreased from 3.7 to 2.9 MW, power of stage L is decreased from 2.9 down to 0.4 MW, resulting in the stage group power decreasing from 6.6 to 3.3 MW, see Fig. 3.

The aim of adaptive control in the case of pressure rise in the condenser is to increase the mass flow rate in the blade-to-blade passage to its nominal value. This can be done by opening stage L-1 stator throats and turning the stator blade by 0.5°. Point B is then moved to point B′ that corresponds to the nominal mass flow rate. By restaggering the stage L-1 stator blades, the mean reaction of stage L is increased by 2%. The enthalpy losses in stage L-1 remain unchanged, in stage L are reduced by 6%, resulting in a decrease of losses in the stage group by 2% (down to 25%). The power of stage L-1 does not change, power of stage L is increased by 0.1 MW to 0.5 MW, so the stage group power is increased from 3.3 to 3.4 MW, Fig. 3. Gains in stage group power are not very impressive due to a low pressure drop available for this case. They are due to an increased mass flow rate in the turbine stage group.

For another sample rise of back pressure from its nominal value of 0.10 bar up to 0.26 bar, gains in stage group power from the adaptive control can be relatively larger as the mass flow rate increases there from 31.7 kg/s to the nominal value of 35.6 kg/s. As it can also be estimated from Fig. 3, in this case the adaptive control done by opening stage L-1 stator throats and turning the stator blade by 2.5° can yield decreased efficiency losses in the stage group by about 12% and increased stage group power by about 0.25 MW.

The aim of adaptive control in the case of pressure drop in the condenser is to take advantage of the available increased pressure drop and prevent steam expansion beyond the blading system. Advantages of adaptive control in this case will depend very much on whether or not the flow is choked for nominal operating conditions. A situation described in [9] corresponded to no-choke conditions where an available pressure drop in the blade-to-blade passage could not be increased without a mass flow rate increase. Then, by some closing of stator L-1 throats, it was possible to obtain the increased pressure drop within the blading system at the same available mass flow rate. The increased pressure drop across the stage group yielded a largely increased enthalpy drop and in-creased stage power.

In the conditions described in the present paper the flow is already choked for nominal operating conditions. Further increasing the pressure drop in the stage group does not increase the mass flow rate. For a pressure decrease in the condenser down to 0.06 bar, the operational point N is moved in the characteristics to point C. In this case the reaction of stage L-1 does not change, so does the mid-stage pressure for choke flow. There is an increase in reaction of stage L by 20% (from 27% to 47%). Enthalpy losses in stage L-1 do not change, however enthalpy losses in stage L increase from 20% to 24%, resulting in an increase of enthalpy losses in the stage group by almost 4% (from 13% to 17%). The power of stage L-1 remains constant, however the power of stage L is largely in-creased from 2.9 to 4.7 MW, resulting in the stage group power increase from 6.6 to 8.4 MW, see Fig. 3. As already mentioned, this increase in the stage group power was achieved at slightly increased flow losses (especially increased leaving energy losses). On the other hand, it was achieved without any adaptive changes in geometry as the conditions of choke flow do not require adaptive control in the case pressure decrease in the condenser.

6 Conclusions

Extraction of steam in extraction/condensing turbines can lead to severe off-design performance of turbine stages located downstream of the extraction point and cause expansions beyond the blading system. It was found that the extraction of additional 5% of the mass flow rate to the extraction point located prior to the stage group of two exit stages of an extraction/condensing turbine of 60 MW makes the exit stage (stage L) stop producing power any longer. The adaptive control (e.g., based on the rotated nozzle blades) allows the reduction of stator blade throats, by means of which measure the stage group returns to near-nominal conditions and the expansion is brought back to the blading system. The enthalpy losses in the adaptive stage and especially in downstream stages are significantly reduced. There is a significant increase in stage (stage group) power. For the extraction of a 10% mass flow rate upstream of the investigated group of two exit stages, the power increase was found to be even as high as over 2 MW per stage, which is not only significant in terms of these stages but also in terms of a turbine as a whole.

Adaptive control can also be effective at seasonal variations of pressure in the condenser. In the case of rise in the condenser pressure (that is when the available pressure drop for the blading system is decreased), one can think of opening nozzle throats of the adaptive stage (e.g., the last stage). In this case gains in stage power are moderate, mainly due to maintaining the nominal mass flow rate in the blade-to-blade passages, which prevents the propagation of off-design flow conditions on upstream turbine stages. In the case of decrease in the condenser pressure (that is when the available pressure drop for the blading system is increased), one can think of reducing nozzle throats of the adaptive stage. This helps to avoid expansion beyond the blading system and to take advantage of the full available increased pressure drop. Gains in stage power are significant, although in this case they take place at a slightly increased level of flow losses.

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