UDK 621.24–2

Obnovitev turbine v hidroelektrarni Hubelj

Uprating of the Turbine in Hydro Power Station Hubelj

JOŽE TROHA

V članku je opisana posodobitev prek 60 let stare turbine. Prikazani so splošni napotki za poseg in stvarne rešitve posameznih hidravličnih in mehanskih problemov. Rezultati posega so bili preverjeni z meritvami pred zamenjavo gonilnika in po njej.

The paper describes the uprating of a turbine over 60 years old. The general approach and real solutions of individual hydraulic and mechanical problems are shown. The results of the approach were checked by measurements before and after changing the runner.

0. UVOD

Naraščajoča poraba energije in večja skrb za okolje sili uporabnike k popolnejši izrabi sedanjih virov energije. Obnova, posodobitev in povečanje zmogljivosti zgrajenih naprav so najučinkovitejša pot do povečanja pridobljene energije v starajočih se elektrarnah. Matematično simuliranje pretočnih razmer, laboratorijsko preverjanje predlaganih rešitev, napredna, računalniško podprta tehnologija izdelave pomembnih komponent, ki se najbolje prilagajajo dani geometrijski obliki turbine in dejanskim obratovalnim okoliščinam, omogočajo optimalno obnovo stare turbine in maksimalno izkoriščenost razpoložljivega vodnega potenciala.

1. PROJEKTIRANJE NADOMESTNEGA GONILNIKA

Pri projektiranju novega nadomestnega gonilnika moramo upoštevati omejitve, ki jih narekuje dana geometrijska oblika delov sedanje turbine. Sodoben gonilnik moderne hidravlične oblike prilagajamo dimenzijskim omejitvam stare hidravlične oblike. Zato je za rešitev zadane naloge nujno potreben kompromis med optimalno hidravlično obliko in geometrijskimi omejitvami. Rešitev ni v neposredni uporabi že razvitih modelov, ki so namenjeni za izdelavo novih turbin, ampak njihova prilagoditev ob upoštevanju vpliva modifikacij na hidravlične lastnosti. To je iterativen proces, ki končno pripelje do najboljšega kompromisa.

Uspešno reševanje problema obsega optimizacijo z uporabo računalniškega simuliranja toka skozi pomembne elemente in preverjanje končne rešitve v modelni velikosti na preizkuševališču v laboratoriju. Končna ocena rešitve problema pa izhaja iz primerjave turbinskih parametrov, npr.: pretok, moč in izkoristek, pred posegom v turbini in po njem.

Obenem ne smemo pozabiti na posledice, ki lahko spremljajo zamenjavo hidravlične oblike. Odprava vrtinca za gonilnikom, neželenih resonančnih pojavov ali nestabilnega obratovanja je prav tako pomembna kakor povečanje izkoristka in moči turbine.

0. INTRODUCTION

Increasing demands for energy and environmental concern push the user to more perfect exploitation of existing resources of energy. Refurbishment, modernisation and uprating of existing devices are the most effective ways of increasing energy production in aging hydropower stations. Mathematical modelling of through-flow conditions, checking the proposed solutions in a laboratory, up-to-date computer aided technology of production of vital components which are to fit the existing old fashioned turbine geometrical shape and existing operational conditions of the site, all together enable the optimum renovation of an old turbine and maximum exploitation of existing hydropotential.

1. PROJECTING A REPLACEMENT RUNNER

When projecting a new replacement runner we have to respect the constraints of the existing turbine parts geometry. A runner of modern hydraulic shape has to fit the dimensional restrictions of the old turbine water passages. The solutions of the given problem is therefore a compromise between the optimum hydraulic shape and geometric restrictions. The direct use of developed model runners, which serve manufacturer as a basis for new turbines is not a solution, an adjustment respecting the influence of hydraulic shape modifications on hydraulic properties is required. This is a kind of iterative process, which finally leads to the best compromise.

Succesful solving of the problem includes optimisation based on computer simulation of the flow conditions through the vital elements and checking the final solution in model size on a test rig in a laboratory. Final proof of the solution of the problem follows comparison of the turbine parameters, such as discharge, output and efficiency before and after the intervention in the turbine.

The effects of a change in the hydraulic shape must not be forgotten. Elimination of the vortex behind the runner, of the undesirable resonance or unstable running is as important as improving efficiency and output.

Najzanesljivejša je rešitev, preverjena na modelnem preizkuševališču.

2. RAZVOJ HIDROELEKTRARNE HUBELJ

Na pobudo Družbe tržaških bombažnih predilnic je bila leta 1925 v Gorici ustanovljena električna družba SACEIO (Delniška družba za električne gradnje vzhodne Italije), ki je leta 1931 v Ajdovščini na potoku Hubelj zgradila lastno hidroelektrarno (HE), v tistem času najmočnejšo na Primorskem. Imela je dva agregata po 950 kVA in 1900 kVA, frekvence 42 Hz, napetosti 2 kV. Napajala je Ajdovščino, Idrijo, Postojno, Pivko in kasneje tudi Ilirsko Bistrico.

Družba SACEIO je že leta 1928 začela s pripravami za gradnjo HE in jo v letih 1929 do 1931 tudi dogradila. Dne 11. maja 1931 je HE Hubelj začela redno obratovati.

Zaradi hudourniškega značaja potoka Hubelj ni zmogla v vsakem času zagotoviti potrebne moči. Zato je bila povezana z daljnovodom 10 kV s preostalo mrežo.

2.1 **Prvotni tehnični podatki agregatov**

	Agregat A	*Agregat B*
Izdelovalec turbine:	R I V A Milano	
leto izdelave	1930	1930
štev.	3174	3173
padec	110 m	110 m
pretok	1,8 m^3/s	0,9 m^3/s
moč	1585 kW	777 kW
vrtilna hitrost	840 min^{-1}	840 min^{-1}

Izdelovalec generatorja:	BROWN BOVERI Milano	
moč	1900 kVA	950 kVa
napetost	2 kV	2 kV
tok	550 A	274 A
cos φ	0.8	0.8
frekvenca	42 Hz	42 Hz
vrtilna hitrost	840 min^{-1}	840 min^{-1}

V januarju leta 1950 so Primorske elektrarne v povezavi s preostalim slovenskim elektroomrežjem prešle na frekvenco 50 Hz. To je bilo izvedeno preprosto z nastavitvijo regulatorjev na večjo vrtilno frekvenco. Ukrep je povzročil poškodbe kavitacijskega značaja gonilnikov turbin, ker se je obratovalna točka pomaknila v področje večje kavitacijske ogroženosti. To je privedlo do zamenjave gonilnikov v turbinah HE Hubelj v letu 1952. Dela je uspešno izvedel LITOSTROJ, izdelovalec turbin v Sloveniji.

Po dolgoletnem uspešnem obratovanju so se v Soških elektrarnah odločili zamenjati gonilnik večje turbine, ki je medtem zaradi utrujenosti materiala in kavitacijskih poškodb odslužil svojo dobo trajanja. Delo je bilo zaupano Inštitutu za turbinske stroje iz Ljubljane.

The best solution is one checked on a model on a test rig in the laboratory.

2. HISTORY OF HYDRO POWER STATION HUBELJ

On the suggestion of the Society of Cotton Mills of Trieste, the Electric Society SACEIO (Societa Anonima Construzione Elettriche Italia Orientale) was established in 1925 in Gorizia. They built their own HPS on the stream of Hubelj in 1931, at Ajdovščina. It was the most powerfull HPS in the region at that time. It had two units, 950 kVA and 1900 kVA, frequency 42 Hz, 2 kV voltage, feeding Ajdovščina, Idrija, Postojna and later also Ilirska Bistrica.

Society SACEIO started preparations in 1928 and constructed the HPS from 1929 to 1931. HPS Hubelj started operations on May 11, 1931.

Because of the torrential character of the Hubelj, HPS could not ensure the necessary output at all times. It was therefore connected to the net by a 10 kV transmission line.

2.1 **The original technical data**

	Unit A	*Unit B*
Turbine manufacturer:	R I V A Milano	
Year of manufacture	1930	1930
No.	3174	3173
Head	110 m	110 m
Discharge	1.8 m^3/s	0,9 m^3/s
Output	1585 kW	777 kW
Speed	840 pm	840 pm

Generator manufacturer:	BROWN BOVERI Milano	
Output	1900 kVA	950 kVa
Voltage	2 kV	2 kV
Current	550 A	274 A
cos φ	0.8	0.8
Frequency	42 Hz	42 Hz
Speed	840 pm	840 pm

In January 1950, hydropower stations of the Primorska region changed the network frequency to 50 Hz, due to connection with the rest of the Slovenian electric system. This was done simply by readjusting the turbine regulators to a higher speed. The intervention caused cavitation damage to the turbine runners, because the operating range shifted to the field of higher cavitation susceptibility. This led to the exchange of HPS Hubelj turbine runners in 1952. The work was successfully done by Litostroj, turbine manufacturer of Slovenia.

After a long period of successful running, Soča Power Company decided to change the runner of the bigger turbine, which had fulfilled its lifetime, and was suffering material fatigue and cavitation damage. Work was entrusted to Turboinstitute from Ljubljana.

3. PROBLEMI VGRADITVE

3.1 Sprememba značilne vrtilne frekvence

Pretočni trakt vgrajenih turbin in s tem vgraditvene gabarite je določila izrazito nizka značilna vrtilna frekvenca, ki je bila izbrana za takratno raven gradnje vodnih turbin. Sprememba frekvence z 42 Hz na 50 Hz je povečala značilno vrtilno frekvenco. Kasneje pa je bilo z meritvami ugotovljeno, da je neto padec v vzporednem režimu obeh turbin celo manjši od imenskega (102 m), kar še dodatno poveča značilno vrtilno frekvenco n_{sn} 1/min, m, kW) pri imenski moči turbine:

frekvenca mreže network frequency Hz	padec head m	agr. A n_{sn}	agr. B n_{sn}
42	110	93,9	65,7
50	110	111,8	78,2
50	102	122,8	86,0

Od povečanja specifične vrtilne frekvence pri francisovih turbinah so odvisni manjši vstopni premer, večja vstopna višina, daljši venec v aksialni smeri, večje imensko odprtje vodilnika, večji kritični kavitacijski koeficient in višji pobeg. Predlagana rešitev mora čimmanj odstopati od hidravlične oblike izbranega modela, če hočemo uporabiti njene rezultate. Po drugi strani pa se mora čimbolj približati sedanji obliki turbine zaradi trdnostnih zahtev in manjših stroškov posega. Z vsemi naštetimi problemi smo se morali soočiti tudi v obravnavanem primeru (sl. 1).

Da bi omogočili povečanje pretočne zmogljivosti, smo uporabili model z značilno vrtilno frekvenco $n_{sopt} = 576 \cdot \varphi^{1/2} / \psi^{3/4} = 156,5$. Manjši vstopni premer ne pomeni težav, saj ponuja večjo prostorsko zalogo za povečanje odprtja vodilnika.

Večja, z modelom zahtevana vstopna višina navadno pomeni znatno odstopanje od stare hidravlične oblike. V primeru, da ohranimo staro

3. PROBLEMS OF INCORPORATION

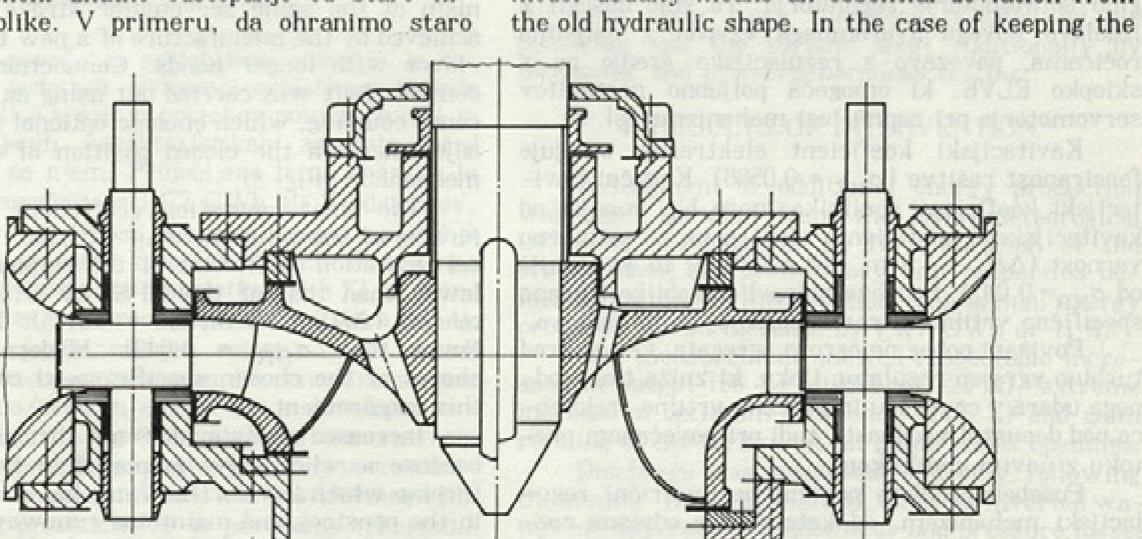
3.1 Change of specific speed

Turbine water passages and consecutive space limits were determined by a low specific speed selected on the basis of the level of water turbine manufacture knowledge of that time. The change of frequency from 42 Hz to 50 Hz increased the specific speed. It was found later by measurements that the net head when both turbines were running was even lower than declared (102 m), which additionally increased the specific speed n_{sn} (1/min, m, kW) at rated turbine output:

An increase of the specific speed of Francis turbines causes a smaller inlet diameter, higher inlet height, a longer rim in the axial direction, greater nominal guide vanes opening, higher critical cavitation coefficient and higher runaway. The proposed solution should deviate as little as possible from the hydraulic shape of the chosen model if the results are to be usable. On the other hand, it has to approach as closely as possible the existing shape of the turbine due to strength requirements and the lower costs of the intervention. We had to face all the problems above in the case concerned (Fig. 1).

To enable an increase of through flow capability, a model with a higher specific speed was used, $n_{sopt} = 576 \cdot \varphi^{1/2} / \psi^{3/4} = 156.5$. The smaller inlet diameter did not cause any problems. It offers a bigger space reserve for increasing the guide vanes opening.

The higher inlet height required by the basic model usually means an essential deviation from the old hydraulic shape. In the case of keeping the



Sl. 1. *Prerez turbine s starim (levo) in novim (desno) gonilnikom.*
Fig. 1. *Turbine crossection with old (left) and new (right) runner.*

vstopno višino, moramo ponoviti projektiranje hidravlične oblike in preizkus modelne turbine na preizkuševališču, s tem pa znatno povečamo stroške. V našem primeru z razvito hidravlično obliko zahtevana višina ni znatno presegala sedanje.

Daljši venec je povezan z daljšim lopatjem gonilnika, ki zmanjšuje kavitacijsko občutljivost. Vgradnjo smo omogočili s tem, da smo dodali vmesni obroč med pokrov in sesalno koleno ter tako podaljšali prostor, ki je na voljo gonilniku (sl. 1).

Večje odprtje vodilnika je omejeno s premerom predvodilnika, vstopnim delom gonilnika in manevrsko zmogljivostjo regulacijskega mehanizma. V takratnem času je RIVA uporabljala neobičajno obliko in veliko dolžino profila l z velikim prekritjem l/t = 1,44 [1] v primerjavi z današnjimi vrednostmi l/t = 1,07 do 1,13.

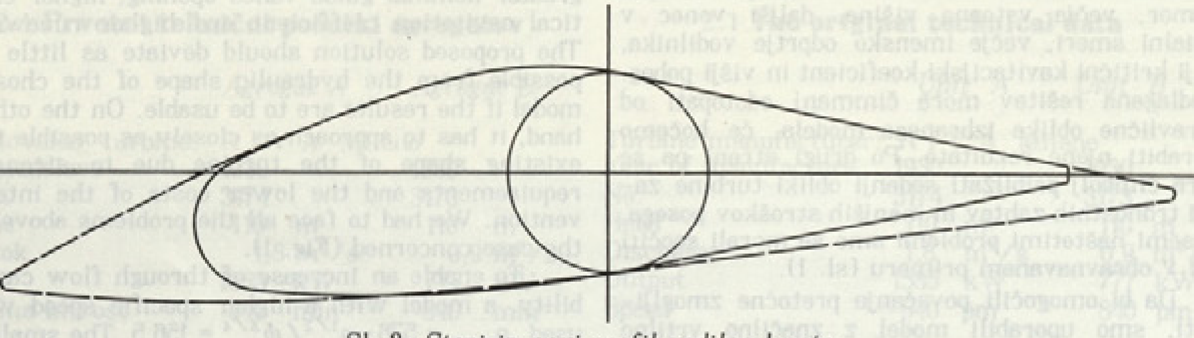
To je omogočilo ponovno profiliranje sedanjih vodilnih lopat brez dodatnega navarjanja. S tem smo posodobili obliko profila in zaradi manjše dolžine povečali možni zasuk lopat od 19,5° na 32° in odprtje vodilnika $A_0 = a_0\ z_0 / D_0$ od 0,89 na 1,29 (sl. 2).

existing inlet height, we have to repeat the designing of the runner hydraulic shape and testing the modified model turbine in the laboratory, which increases the costs. In this case, the height of the guide vanes fixed by the basic model did not essentially surpass the existing height.

A longer rim is connected to longer runner blades, which decreases cavitation susceptibility. Adding an intermediate ring between the cover and the draft tube bend extended the space available to the runner (Fig. 1).

Enlarged guide vanes opening is limited by the stay vanes diameter, runner inlet diameter and manoeuvrability of the control mechanism. At that time, RIVA used an unusual shape of guide vanes, with long length of profile l, which caused high overlapping l/t = 1.44 [1] in comparision with contemporary values l/t = 1.07 to 1.13.

This enabled the reprofiling of existing guide-vanes without additional welding. In this way it updated the profile shape and, due to the shorter length, increased the possible twist of guide vanes from 19.5 to 32 degrees and the specific opening $A_0 = a_0\ z_0 / D_0$ from 0.89 to 1.29 (Fig. 2).



Sl. 2. *Stari in novi profil vodilne lopate.*
Fig. 2. *Old and new guide vanes profile.*

Hkrati je bilo treba povečati manevrsko zmogljivost regulacijskega mehanizma pri istem gibu servomotorja regulatorja. To smo dosegli z izdelavo novega dvoramnega vzvoda z daljšima ročicama, povezavo z regulacijsko gredjo pa s sklopko ELVE, ki omogoča poljubno nastavitev servomotorja pri zaprti legi mehanizma (sl. 3).

Kavitacijski koeficient elektrarne omejuje forsiranost rešitve (σ_{HE} = 0,0566). Kritični kavitacijski koeficient gonilnika mora biti manjši od kavitacijskega koeficienta elektrarne za primerno varnost (ΔH_s = 1,5 m, $\Delta\sigma$ = 0,0145) to je manjši od σ_{KR}= 0,0421. Sodobne hidravlične oblike izbrane specifične vrtilne hitrosti izpolnjujejo to zahtevo.

Povišani pobeg ne ogroža agregata, ker je pred turbino vgrajen regulator tlaka, ki zniža tlak vodnega udara v cevovodu in pobežno vrtilno frekvenco pod dopustni vrednosti, tudi pri povečanem pretoku z novim gonilnikom.

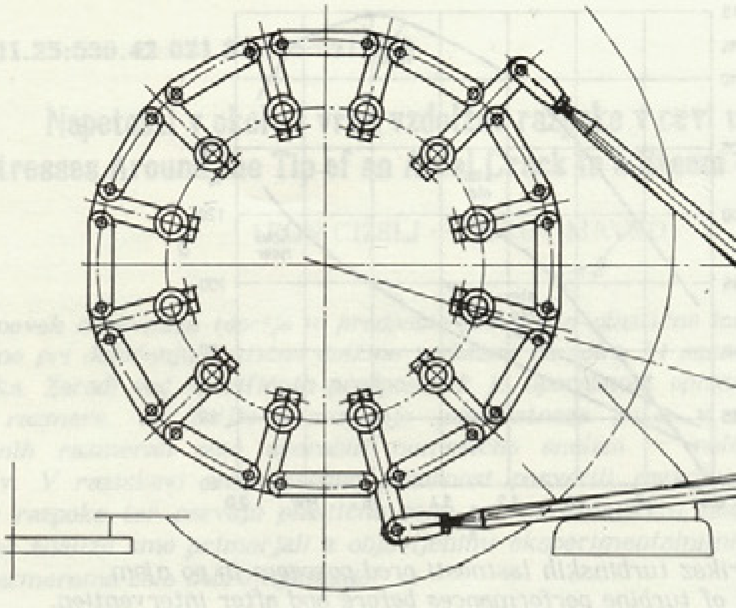
Poseben problem pomeni nesimetrični regulacijski mehanizem, od katerega je odvisna različna dolžina obeh regulacijskih drogov. Napaka, ki se pojavi pri premiku iz srednje lege, je bistveno odvisna od kota med obema ročicama dvoramnega vzvoda. Zato ta zahteva skrbno optimizacijo, da bi

At the same time, it was necessary to increase the manoeuvrability of the control mechanism at the same servomotor stroke. This was achieved by the manufacture of a new two-hands-lever with longer hands. Connection with the control shaft was carried out using an ELVE two cones coupling, which enables optional servomotor adjustment in the closed position of the control mechanism (Fig. 3).

The plant cavitation coefficient limits the forcing of the solution (σ_{PL} = 0.0566). The critical cavitation coefficient of the runner has to be lower than that of the HPS, by an appropriate margin (ΔH_S = 1.5 m, $\Delta\sigma$ = 0.0145). This means lower than σ_{SR} = 0.0421. Modern hydraulic shapes of the chosen specific speed comply with this requirement.

Increased runaway does not threaten the unit because a relief valve is placed in front of the turbine which lowers the water hammer pressure in the penstock and maintains runaway under the permitted values, also at the higher discharge enabled by the new runner.

The unsymmetrical control mechanism with different lengths of the two control rods



Sl. 3. *Regulacijski mehanizem.*
Fig. 3. *Control mechanism.*

se napaka zunaj srednje lege zmanjšala pod vrednost ohlapa v zgibih regulacijskega mehanizma. Pri montaži je treba nastaviti točno dolžino obeh drogov, ker bi sicer prišlo do deformacije posameznih elementov (sl. 3).

Ponovna vzpostavitev prvotne razbremenitve prostora med gonilnikom in tlačnim pokrovom, ki je bila pred leti opuščena, bo dodatno zmanjšala aksialno silo in s tem zmanjšala obrabo tesnilnega obroča.

Vgraditev starih delov brez preverjanja materiala z neporušnimi metodami ob načeloma večji obremenitvi bi lahko imela za posledico lom stroja. Zato so bili vsi pomembni deli pregledani s penetranti, turbinska gred pa dodatno ultrazvočno in na trdoto materiala.

4. REZULTATI POSEGA

Ocena povečanja pridobljene energije je temeljila na podatkih Hidrometeorološkega zavoda Slovenije [2] o trajanju pretokov potoka Hubelj in predpostavljenih karakteristikah agregata pred posegom in po njem. Pridobljena letna energija bi se morala povečati za 1,177 GWh ali 11 odstotkov.

Meritve na HE so pokazale znatno povečanje moči (36 %), pretočne zmogljivosti (28 %), izjemno povečanje optimalnega izkoristka (14,8 %) in mirnost obratovanja pri vseh odprtjih vodilnika (sl. 4).

Pretok je bil merjen relativno, po metodi Winter-Kennedy z obrnjenim diferencialnim manometrom voda/zrak in z izgubami v dovodnem cevovodu, padec z natančnim utežnim manometrom in moč na sponkah generatorja z dvema merilnikoma moči na vgrajenih mernih transformatorjih.

Najbolj presenetljivo je povečanje izkoristka turbine na celotnem področju obratovanja. Navadno se s povečanjem pretočne zmogljivosti prestavi optimalna točka obratovanja na večje moči, poveča izkoristek v območju optimuma in največje moči

is a special problem. Error arising from the move out of the central position essentially depends on the angle between the two hands of the two-hands-lever. Careful optimisation must therefore be carried out to minimise the error to a lower value than the gap in the joints of the control mechanism. The exact lengths of the two rods must be adjusted on errection, otherwise deformation of the mechanism elements could appear (Fig. 3).

Restoration of the original depression of the space between the pressure cover and runner, which was abandoned previously, will additionally lower the axial thrust and also reduce wear of the axial seal rings.

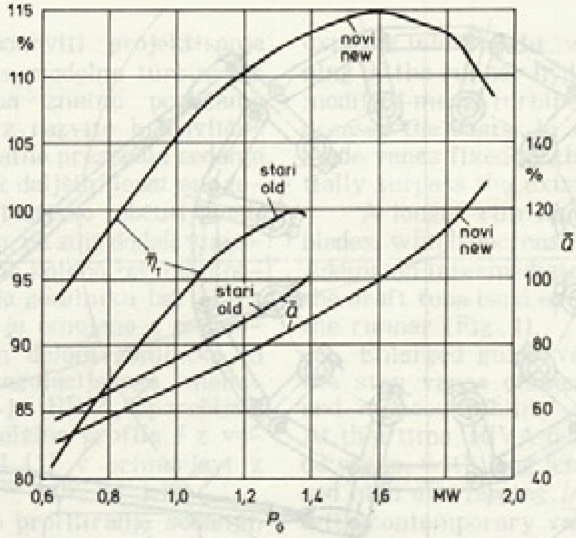
The use of old parts without non-destructive methods of material inspection at regularly higher thrust, could cause the fracture of machine parts. All vital parts were therefore checked by die penetrant and the turbine shaft additionally by ultrasonic and material hardness testing.

4. RESULTS OF INTERVENTION

Assessment of additional energy production was based on data from the Hydrometeorological Office of Slovenia [2] on flow duration of the brook Hubelj and preliminary unit properties before and after the intervention. The annual energy produced should increase by 1.177 GWh or 11 %.

Site measurement showed respectable increases in output (36 %), discharge (28 %), extreme increase of optimum efficiency (14.8 %) and calm running of the turbine at all guide vanes openings.

Discharge was measured relatively, following the Winter-Kennedy method, using an inverted water/air differential manometer and pressure losses in the penstock. The inlet pressure was measured by precise dead weight manometer and the output at the generator terminals using two Watt meters on the installed measuring transformers.



Sl. 4. *Prikaz turbinskih lastnosti pred posegom in po njem.*
Sl. 4. *Layout of turbine performances before and after intervention.*

ter zmanjša izkoristek pri delnih obremenitvah. V našem primeru se je dvignila celotna krivulja izkoristka na celotnem področju obratovanja (sl. 4), kar je zelo redek primer. To nastane namreč zaradi zelo majhnega izkoristka starega gonilnika.

Pretočna zmogljivost se je povečala zaradi manjšega preobremenjevanja starega gonilnika in majhnega odprtja vodilnika. Odprtje vodilnika je bilo prilagojeno nizki značilni vrtilni frekvenci, izbrani v prvotni rešitvi. Preobremenjevanje novega gonilnika ne presega v novejšem času uporabljanih vrednosti, saj je izstopna hitrost iz gonilnika okoli 10 m/s.

Moč se izdatno poveča za 36 % zaradi večjega pretoka in povečanega izkoristka.

5. SKLEP

Predstavitev primera obnove in posodobitve prek 60 let stare turbine ima namen prikazati koristnost takega posega in osvetliti probleme in težave, ki se pojavljajo ob takem posegu. Vsak agregat je prvenec in ima posebne zahteve. Zato ni moč postaviti enotnega pravila za uspešen poseg, pač pa je treba vsak primer obravnavati posebej, celostno in z vsemi njegovimi posebnostmi, pri tem pa vključiti strokovnjake s posameznih področij. Posodobitev pomeni tudi svojevrsten izziv za izvajalca zaradi posebnosti obravnavanih primerov, ki terjajo široko poznavanje problematike in izdatno mero domiselnosti pri premagovanju težav na poti modernizacije.

Most surprising is the increase in turbine efficiency over the whole operation range. An increase of discharge usually shifts the optimum efficiency point to higher loads, the increase in efficiency in the optimum range, but the decrease in the efficiency at part loads. In this case, the efficiency curve was raised over the whole operating range, which is very rare, and an indication of the very low efficiency of the old runner.

The increase in discharge is a result of less forced old runner and smaller guide vanes opening. The guide vanes opening was originally adjusted to the low specific speed chosen in the initial design. Forcing the new runner does not surpass the up-to-date values because the outlet velocity is 10 m/s.

The major increase in output of 36% is a result of the increased discharge and higher efficiency.

5. CONCLUSION

Presentation of the case of the renovation of a turbine over 60 years old is intended to show the benefit of such intervention and to clarify problems which arise in such work. Every unit is unique and raises its own special problems. It is therefore impossible to provide a general rule for a successful approach. Every case must be treated in particular in its entirety, and in all its particularities, involving specialists from various fields. Uprating also provides a special challenge to the executant. Because of the paticularity of the cases concerned, a sound knowledge of the problems and high degree of inventiveness are required in overcoming the difficulties on the way to modernisation.

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