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Okrogla miza na konferenci ENRE v Termah Čatež 2011

Fakulteta za energetiko je v okviru konference **<En**Re> (*Energy and Resposibility*) prvi dan organizirala okroglo mizo na temo Trajnostna raba potenciala reke Save. Žal je bil skoraj sočasno organiziran posvet oz. razprava o pomenu graditve hidroelektrarn na srednji Savi tudi v Državnem svetu. Glede na to dejstvo je poleg obravnave osnutka Nacionalnega energetskega programa Republike Slovenije na okrogli mizi zato potekala razprava tudi v luči tega posveta. Diskusija je bila zelo živahna in pogosto tudi kritična, predvsem do državne oblasti, oz. resornih ministrstev. Navkljub temu smo lahko strnili sklepe okrogle mize v sledeče točke:

1. da se z ne-izgradnjo že začetih hidroenergetskih projektov na spodnji Savi povzroča velika gospodarska škoda,
2. da je država Slovenija že podelila koncesijo za koriščenje hidroenergetskega potenciala srednje Save in ga naj aktivnosti le formalno nadaljuje,
3. da je izgradnja verige hidroelektrarn na reki Savi lahko slovenski »New Deal« po ameriškem vzoru, ki bi lahko Slovenijo popeljal iz trajajoče gospodarske krize,
4. da je lahko izgradnja spodnjesavske verige hidroelektrarn dober zgled za izgradnjo srednjesavske verige hidroelektrarn,
5. da se bo »podnebni sklad« sedaj polnil na osnovi CO_2 kuponov, s čimer se bodo lahko sprostila sredstva iz »vodnega sklada«,
6. da bi bilo javno-zasebno partnerstvo pri tako kvalitetnih projektih škodljivo za državo Slovenijo,
7. da so subvencije na področju energetike v Sloveniji slabe in ne vplivajo spodbudno na slovensko gospodarstvo, npr. z izgradnjo sončnih elektrarn se spodbuja Kitajsko, z izgradnjo vetrnih elektrarn, pa nemško gospodarstvo, itd.
8. da je Nacionalni energetski program (NEP) Slovenije preobsežen, premalo konkreten in za Posavje nezadovoljiv.

Drugi dan konference so potekale predstavitve znanstvenih in strokovnih prispevkov s področij energetike. Predstavljenih je bilo 30 prispevkov domačih in tujih avtorjev.

Ob koncu konference je bil organiziran tudi ogled in predstavitev za posavski okoliš značilne turistične kmetije s tradicionalno gastronomsko ponudbo. Večina je potrdila ponovni obisk konference ENRE, ki bo čez dve leti v Velenju.

Round Table of ENRE Conference in Terme Čatež 2011

On the first day of the ENRE conference (ENergy and REsposibility), the Faculty of Energy Technology organized a round table on the energy potential of the Sava River. Unfortunately, almost a debate/consultation about the middle Sava River in the National Assembly of Republic Slovenia had been organized simultaneously. In view of this fact, a roundtable discussion in the light of this consultation and public hearing was sent to the National Energy Program of the Republic of Slovenia. The discussion was very lively and often critical of state authorities, or ministries. Despite this, we can distill the conclusions of the round table in the following points:

- To not complete the new-hydro projects that have been started on the lower Sava River will cause major economic damage,
- Slovenia is a country that has granted the concession for the exploitation of hydroelectric power potential of the middle Sava River, and proceeds with all activities not only formally, but in reality,
- The construction of hydropower plants on the Sava River could be a Slovenian "New Deal", which could help Slovenia out of the ongoing economic crisis,
- The project of building a chain of hydro-power plants on lower part of Sava River can be a good example for the construction of plants on the middle part of the river,
- The "climate fund" is now fully based on CO_2 allowances, which will free resources and the "water fund" that could be used for new of hydro-power projects
- Public-private partnership projects are of poor quality and detrimental to the country of Slovenia,
- Subsidies in the energy sector in Slovenia are poor and do not affect the Slovenian economy in an encouraging way; for example: to build solar power plants, to encourage China to build wind farms, the German economy, etc.
- The National Energy Program (NEP) Slovenia is too large, not concrete, and unsatisfactory for the Posavje region;

The second day was a presentation of scientific and professional contributions in the different fields of energy. Thirty contributions of domestic and foreign authors were presented.

At the end of the conference, a tour and presentation of typical farmhouses with traditional dishes of the Posavje district were also organized. Most of the conference attendees confirmed that they will revisit next ENRE conference, in 2013 in Velenje.

Krško, June, 2011

Andrej PREDIN

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INVESTIGATIONS OF PUMPED-STORAGE HYDRO PLANTS IN THE ALPINE AREA

RAZISKAVE NA ČRPALNIH HIDROELEKTRARNAH V ALPSKEM PROSTORU

Umboro Lasminto[ℜ], Roman Klasinc[1]

Keywords: pumped storage, investigation, scale model, numerical analysis

Abstract

One target of the European Union (EU) countries is that 20% of energy be supplied by renewable sources by 2020. To achieve this target, renewable energy production from wind power, solar power, hydro power, tidal power, geothermal and biomass should be increased. However, the production of energy from renewable energy is not at constant level, so it often does not meet demand, especially during periods of peak demand. Another factor in the rising demand for peak energy is the changing conditions of the European energy market. Therefore, energy storage is required to fulfil peak energy demand. A pumped storage plant is the most significant solution for storing and generating energy. There are some new pumped storage plants (PSP) in the Alpine area in Austria and Germany, such as Kops II, Limberg II, Reisseck II and Atdorf-Schluchseewerk. In this paper, the authors will present an overview of the new PSPs, the hydraulic problems that arise in the construction of PSPs, and some investigations and studies using scale models and numerical analysis in order to solve the problem.

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Povzetek

Eden od ciljev držav EU je, da bi do leta 2020 delež obnovljivih energetskih virov zvišale na 20%. Razumljivo je , da je za dosego tega cilja potrebno delež obnovljivih virov pa naj bo to energija vetra, sončna energija, geotermalna energija, energija biomase, itd, povečati. Problem pri tem je, da nekatere oblike energije niso konstantno na razpolago. Posebno kritična so obdobja, ko so zvišane potrebe po tako imenovani vršni energiji (peak energy). Z liberalizacijo energetskega trga pa dodatno rastejo zahteve po vršni energiji. Energijo je potrebno shraniti in za te namene so črpalne hidroelektrarne (ČE) najbolj primerne. V alpskem prostoru - Avstriji in Nemčiji - obratujejo oz. so projektirane ČE večjih moči. V prispevku so predstavljene ČE; KopsII, LimbergII in Reisseck. Poudarek v članku je na hidravličnih problemih, ki nastanejo pri konstrukciji ČE. Te probleme rešujemo z raziskavami, ki uporabljajo fizikalne in numerične modele.

1 INTRODUCTION

In the electricity markets in Europe, the increase in tariffs, liberalisation of energy sources, the increased consumption of electricity, network security systems and a decrease in energy supply are important issues. This encourages the development of various sources of electrical energy, such as nuclear, oil, renewable energy sources, etc. Nuclear energy tends to produce excess energy, especially at periods of low energy demand. Thermal power plants tend to produce an abundance of energy to optimise fuel usage. The growth in the construction of renewable energy sources has also been triggered by the agreement stipulated in the renewable energy technology road map, which targets the use of renewable energy in 2020 at 20% [1]. Renewable energy supply depends on the weather, so it does not match on demand and is not fully predictable [2]. For instance, wind power has unstable characteristics, i.e. the amount of energy produced fluctuates and power can be cut off due to high wind velocities. Furthermore, electric energy needs are not always stable either. This all leads to imbalances between energy production and demand. Therefore, a balancing media that can store energy when production is greater than demand and one that can be used when the demand arises is needed.

The pumped storage scheme is the most widely used solution for storing energy [3]. PSPs can generate power 100 times greater than batteries and 10 times greater than compressed air/thermal solutions. PSPs also have storage capacity about 100 times greater than batteries and 10 times greater than compressed air/thermal solutions; see Figure 1 (left). Therefore, at present the PSP is the most economical technology for large scale energy storage [4]. In the future, increasing energy demand will be followed by increasing the supply of renewable energy that varies in time, such as from wind and solar. Pumped storage can compensate for these variations by storing and releasing energy. Figure 1 (right) shows the predicted increase of the energy in 2020 that will be generated by PSP in some central European countries (Austria=AT, Germany=DE, Switzerland=CH, France=FR and Italy=IT). PSPs are also used for balancing the excess energy production from nuclear power plants or others plants in the network. PSPs pump water to the upper reservoir during periods of low electricity tariffs (low demand) and the pumped water is used in the turbines to produce electricity at high electricity prices (peak demand). The PSP can provide the fast and flexible balancing of production and demand that is needed by energy suppliers. Other power plants may take significantly more time to change their system mode than pumped storage hydro schemes can.

Recent expansions of PSPs in Austria and Germany are a response to the rising demand for readily available and flexible energy production. The projects currently under construction are

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Kops II, Limberg II, Reisseck II in Austria, and Atdorf-Schluchseewerk in Germany. Most PSPs are equipped with pump-turbines enabling operation in either pumping or generating modes. In the construction of PSPs, some hydraulic problems arise, requiring investigations and research to find solutions. The following investigation will discuss solutions to the hydraulic problems of PSP Kops II, Limberg II, Reisseck II and Atdorf-Schluchseewerk.

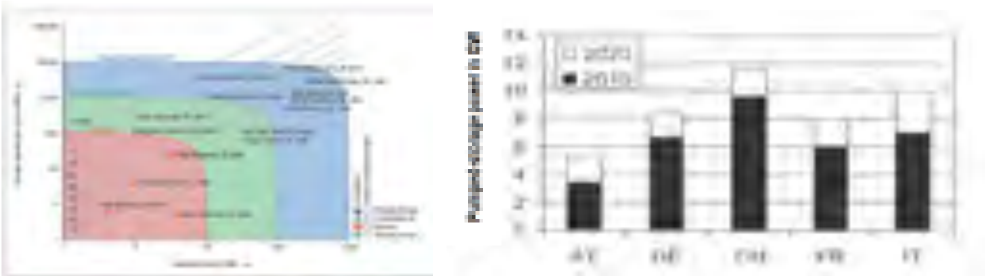

Figure 1: *Selected electrical site and project that represent of power and storage capacity (left) and Power generated by PSP in the middle Europe (right) [4].*

2 OVERVIEW OF NEW PUMPED STORAGE PLANT

2.1 PSP Kops II

The Hydropower Scheme Kops II is a PSP that can be used to regulate the grid in turbine mode as well as in pump mode. The Kops II power plant was built to generate electricity by using the head between upper Kops reservoir (1,800m) and the lower Rifa Reservoir (1,000m). The installed turbine capacity can produce 450 MW of electricity. The schematic of Kops the II power plant system in Figure 2 (left). It is different in comparison to others, in that it has separate pump and turbine equipment. The advantage of the PSP Kops II lies in permitting very rapid change-overs between the two operation modes, within approximately 20 seconds. Other PSPs have response times ranging around one minute. The special construction feature of Kops II is the “hydraulic short-circuit” enabling simultaneous pumping into the upper reservoir and power generation at the turbine, as seen in Figure 2 (right). For example, the pump station can receive 150 MW of energy from the surplus of the network (100 MW) and generated by the turbine (50 MW). This energy is used by the pump station to move water from the lower reservoir to the upper reservoir for producing 100 MW of energy for the network during peak demand and the rest of the energy for powering the turbines.

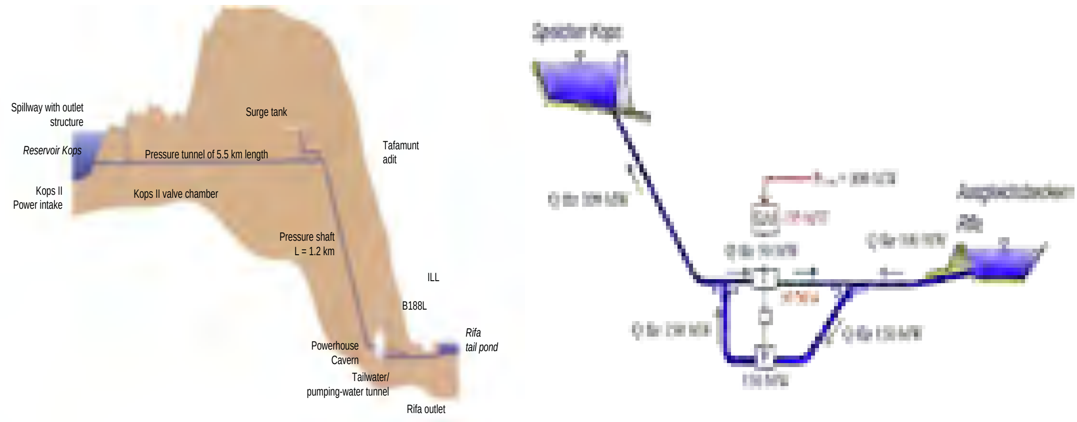

Figure 2: *Schematic of Kops II Pumped Storage system (left) and hydraulic short-circuit (right). Source: Vorarlberger Illwerke AG.*

2.2. PSP Limberg II

The new PSP Limberg II, which is being constructed by VERBUND-Austrian Hydro Power AG (AHP) to supplement the existing Kaprun power plant group, is located at the rear of the Kaprun Valley. PSP Limberg II utilises water from lower reservoir of Wasserfallboden (live storage of 81.2 million m³) to the upper reservoir of Mooserboden (live storage of 81.2 million m³) through a 5.4 km-long power conduit with a diameter of 4.8–6.8 m (see Figure 3). The capacity in generating and pumping modes is 2×240 MW. PSP Limberg II will increase the balance and backup power plant, by more than doubling the output of the Kaprun power plant group from 353 MW to 833 MW, by making optimal use of the difference in height between the upstream and downstream reservoirs.

Figure 3: *Hydraulic Scheme of PSP Limberg II [7].*

2.3 PSP Reisseck II

The PSP Reisseck II, located in Upper Carinthia, was constructed by Verbund Hydro Power AG (VHP), which is part of the Malta and Reisseck/Kreuzeck Power Station Group. With this project, the previous separate hydraulic system of Malta and Reisseck/Kreuzeck will be connected to increase the performance of the system. The objective of the PSP Reisseck II project is to supply the peak demand in electricity market by generating 430 MW of electricity. This output will be realised with the design of nominal output of machine set in a generation/pumping operation of 2×215 MW, the apparent power generator/motor is 2×240 MVA, the upgraded water quantity in generation operation of 2×40 m^3/s, the upgraded water quantity in pumping operation of 2×35 m^3/s and the average structural fall height of 595 m. The total power of the power station group will increase from 425 to 855 MW in pumping operation. Figure 4 (right) shows the hydraulic schematic of the Hydro Power Plant Malta and Reisseck II. The existing hydraulic system of Malta consists of two upper reservoirs (Galgenbichl and Gosskar) and one lower reservoir (Rottau). The PSP Reisseck II is planned to connect Großer Muhldorfer See as the upper reservoir and Galgenbichl and Gosskar as the lower reservoirs. A new surge tank in Burgstall will be built in addition to existing surge tank in Hattelberg [5].

Figure 4: *Hydraulic Scheme of Malta and Reisseck/Kreuzeck [5]*

2.4 PSP Atdorf-Schluchseewerk

PSP Atdorf-Schluchseewerk, the largest PSP in Germany, has been designed to produce 1400 MW of electricity. The PSP will utilise water from the lower reservoir of Hazelbeckel situated in the Haselbachtal Valley to the upper artificial reservoir of Hornbergbecken II. Both reservoirs each have a capacity of 9 million m^3, corresponding to a storage capacity of more than 13 GWh. The upper reservoir will be connected to pump turbines with two vertical pressure pipes, while the connection between pump turbines and lower reservoir uses an 8.4 km-long tail water gallery [4]. The fall head between both reservoirs is about 600 m.

Figure 5: *Overview PSP Atdorf (left), aerial photo of Hornbergbecken reservoir (right-top) and Haselbecken reservoir (right-bottom) (photos courtesy of Schluchseewerk AG)*

3 MODEL SCALE AND NUMERICAL ANALYSIS

Some hydraulic problems in the development of pumped storage that were investigated and solved in the Hermann Grengg Laboratory in Institute of Hydraulic Engineering and Water Resources Management of the Graz University of Technology will be presented here.

3.1 Model of PSP Kops II

A hydraulic study of PSP Kops II was made using scale modeling and numerical analysis. A scale model was used to investigate the upper surge tank and de-aeration of the tail water portion, while a numerical model was used to simulate the performance of the upper surge tank under unsteady hydraulic conditions. The objectives of the study were to investigate mass oscillation behaviour for the “boundary cycles” in the pumping and generating modes (a “boundary cycle” is understood as any desired switching sequence of turbines and pumps in the resonance frequency of the tail water surge tank system (turbine-pump interaction in time)); to design and test an orifice nozzle (the “Gufel” throttle) in the branch to the chamber surge tank; to assess the quality of air entrainment under the Pelton turbines, or de-aeration in the pressure surge tank; to test structures installed to reduce air entrainment or accelerate de-aeration, and to make a visual inspection of the general flow pattern and the performance of the air-release domes at the entrance to the tailrace tunnel.

A 1:22.5 scale model was built, mainly of Plexiglas, according to the dimensions of the tail water system, about 350m in length, and the local conditions at the laboratory (Figure 7). The Froude similarity was applied for the model, i.e. that the same relationship between inertial force and gravity applies both in the model and in the prototype. Several challenges in scale modelling under overpressure conditions arose due to the complexity and scope not being available or known, such as the scale effect and transferability of the result. Scale effects play an important role in the roughness and local head loss, and surface tension on suction vortice development. Other challenges are the simulation of pressure surge tanks discharges of both turbines and

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pumps within the times converted according to the model laws, the main criterion being the repeated mode change between generation and pumping as well as uncontrolled load drop for the pumps as a special condition.

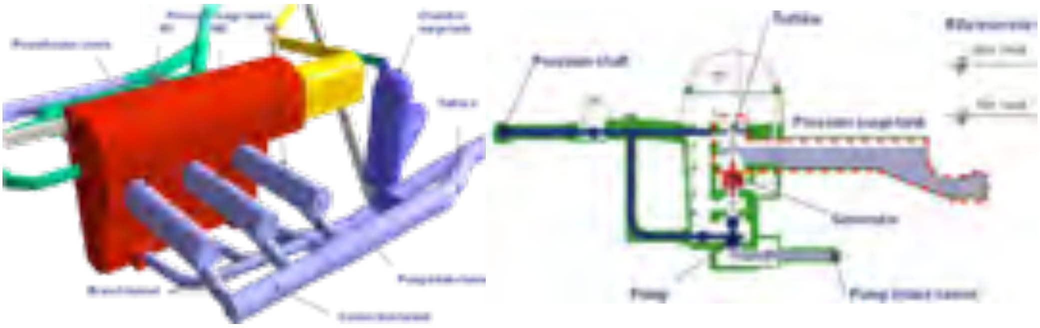

Figure 6: *3D view of power house cavern with the pressure surge tanks (left) and schematic drawing showing system under investigation (right) [6].*

Figure 7: *The Kops II scale model setup. Source: Institute of Hydraulic Engineering and Water Resources Management Graz University of Technology.*

The time curves of the discharge of tailrace, pump and turbine of the scale model are presented in Figure 8 (left) as an example result of a measured pump and turbine. The curves illustrate the change in magnitude and direction of discharge in the tailrace tunnel generated by the turbines and pumps operated alternately. The results of this model will be transformed to the prototype based on the scale used. Due to the requirements of the Kops II pump-storage scheme with the hydraulic short-circuit, air evacuation (degassing) needs to be completed before entering the branch tunnel and then the pumping devices. Figure 8 (right) shows the schematic drawing of air entrainment and evacuation. A supplementary study on a scale model is still needed for investigating the problem involved in the unsteady process and the air entrainment followed by the degassing process in the pressure surge tank [6].

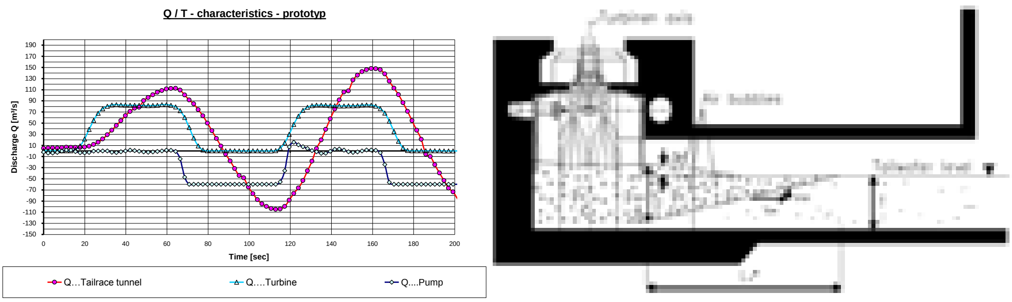

Figure 8: *Discharge curves of switching turbine and pump mode (left) and air entrainment and evacuation (right).*

3.2 Model of PSP Limberg II

Some hydraulic problems exist in the development of PSP Limberg II. The scale model was used to investigate the head loss at a damper component of the upper surge tank. The model was also used to study the hydraulic conditions for mode changes between generation and pumping. The pipe junction with nozzle was analysed in the scale model (Figure 9, left). Besides using a scale model, numerical analysis was used to perform calculations for the upper surge tank of Limberg II. The numerical analyses were made using ANSYS–CFX software. The conventional Reynolds Averaged Navier-Stokes equation system (RANS) in that form of continuity equation, momentum equations and the k-ε turbulence model was applied for flow simulation. Figure 9 (right) shows the comparison of pressure distribution resulting from the numerical model between model scale (top) and prototype (bottom) in the pipe junction with nozzle. The flow loss coefficient follows the experimental results at the area of lower Reynolds number values. The RANS model represents suitable tool for flow loss coefficient calculation, for the prediction of flow phenomena and as a fast method for geometry optimisation [7].

Figure 9: *Scale Model of pipe junction (left) and numerical model of nozzle (right) [7].*

3.3 PSP Reisseck II

Investigations and studies were conducted on the PSP Reisseck II project's Burgstall surge tank. For these purposes, a 1:25 scale model was built in the laboratory. Studies on the scale model aim to examine the hydraulic performance of Burgstall surge tank. The complex combination of Malta and Reisseck hydraulic systems is the special feature of this project. The partial stainless steel model is simulated under Reynolds similarity, while the full Plexiglas model is simulated under the Froude similarity. The design of the nozzle and the head loss is calculated using a numerical model. The flow velocity in the part of surge tank is investigated using Particle Image Velocimetry (PIV) to obtain picture of velocity profile and distribution (Figure 10, right). Overall, the numerical model result has good agreement with the scale model.

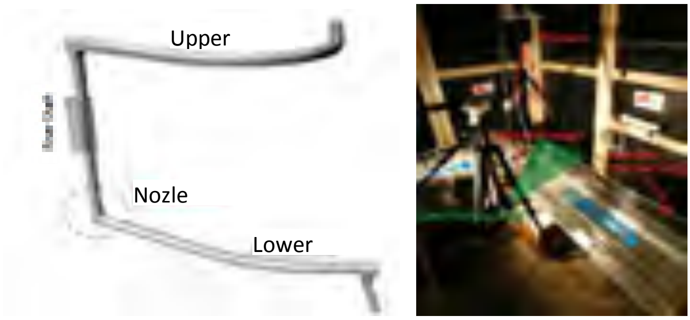

Figure 10: *3D view of Burgstall surge tank (left) and velocity investigation in the scale model using PIV (right). Source: Institute of Hydraulic Engineering and Water Resources Management, Graz University of Technology.*

3.4 PSP Atdorf - Schluchseewerk

The surge tank for the new PSP Atdoft was studied and investigated in the laboratory. A 1:40 scale model made from Plexiglas was built (Figure 11, left). The model was designed using the Froude similarity to investigate of performance of the designed surge tank. The scale model was used to investigate the maximum oscillation in the upper and lower chamber, and the maximum discharge flow through the surge tank. Figure 12 shows the example result of numerical model in drawing the velocity vector in the nozzle at the lower chamber. The pressure and velocity distributions in the upper chamber also investigated.

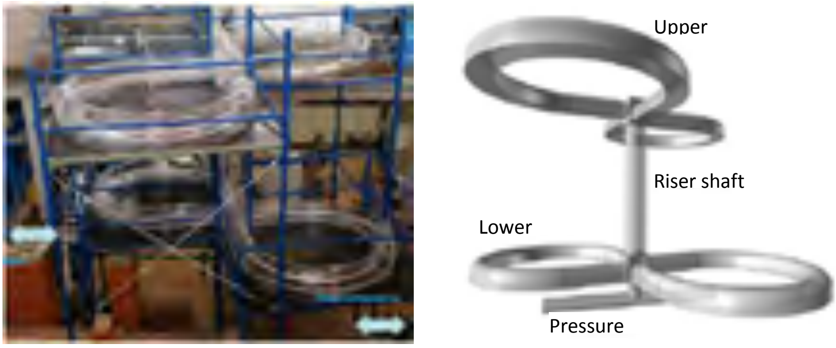

Figure 11: *Scale model setup (left) and 3D view of surge tank (right). Source: Institute of Hydraulic Engineering and Water Resources Management, Graz University of Technology.*

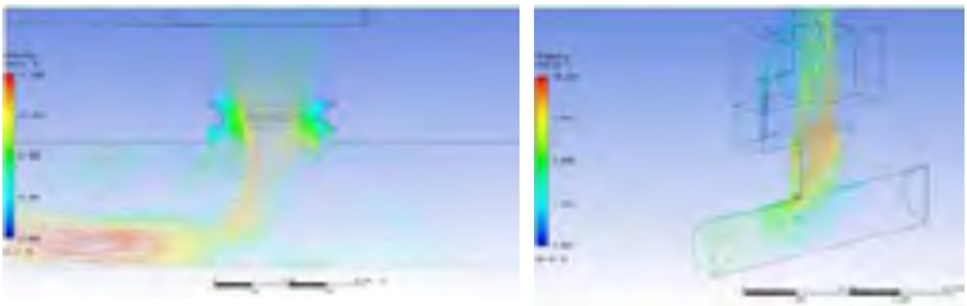

Figure 12: *Velocity vector in 2D and 3D in the nozzle at lower chamber. Source: Institute of Hydraulic Engineering and Water Resources Management, Graz University of Technology.*

4 CONCLUSION

Pumped-storage hydro power offers the advantages of storage energy and grid balancing. The hydraulic problems that arise in the construction of PSPs can be investigated and studied using a model. A one-dimensional mathematical model is not sufficient to illustrate the hydraulic phenomenon that occurs in pumped storage systems. A scale model is needed to solve the problems involved in the unsteady processes and the air entrainment followed by the degassing process in the pressure surge tank. Hydraulic scale models also offer the advantage of a 3D demonstration of flow processes. Numerical simulation produces results relatively close to the result of the scale model, so the use of combination of scale and numerical model provide benefits at the time and cost saving, as well as providing better pictures of flow processes.

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DOUBLE-REGULATED VERTICAL AXIAL WATER TURBINE

DVOJNO REGULIRANA VERTIKALNA AKSIALNA VODNA TURBINA

Janez Gale[ℜ], Edvard Höfler[1], Anton Bergant[2], Sandi Cizelj[3]

Keywords: Hydro power plant, Saxo - vertical axial turbine, Compact and low cost turbine

Abstract

A double-regulated vertical axial water turbine, known as a Saxo turbine, has become a very well-recognised product of the company Litostroj Power, with over 30 commissioned units in the North American market over the previous decade. While this turbine became popular in the North American market due to its compact design, simplified civil construction works, robustness and versatility, this has surprisingly not been the case for the European market, where the Saxo turbine has been overlooked. It seems that European investors prefer and trust more conventional turbines, i.e. classic Kaplan and tubular turbines, instead of the alternative Saxo turbines. This paper examines some of the most important design, hydraulic and economic advantages of Saxo turbines. Special attention is given to a description of the Saxo turbine and its main differences in comparison to tubular and Kaplan turbines. In addition, some of the main issues of hydraulic design and numerical investigations of the flow field in the entire water passage are described. The authors would like to draw the attention of professionals in the field of power generation to this turbine and to initiate discussions that may indicate the concerns of the European investors regarding the Saxo turbine.

Povzetek

Dvojno regulirana vertikalna aksialna vodna turbina, poznana kot turbina tipa Saxo, je v zadnjem desetletju postala zelo prepoznaven produkt podjetja Litostroj Power, s preko 30 uspešno

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zagnanimi turbinami na severno-ameriškem trgu. Medtem, ko so te turbine postale popularne na severno-ameriškem trgu zaradi kompaktne konstrukcije, poenostavljenih gradbenih del, robustnosti in vsestranskosti pri uporabi, pa to presenetljivo ne drži za evropski trg, kjer so turbine Saxo nekako prezrte oziroma sprejete z zadržkom. Izgleda, kot da evropski investitorji bolj zaupajo turbinam, ki so tradicionalno prisotne na tem trgu, kot pa turbini Saxo, ki bi jih lahko nadomestila. To so horizontalne cevne in Kaplan turbine. V pričujočem prispevku smo osvetlili nekatere najpomembnejše hidravlične, ekonomske in projektantske prednosti turbine Saxo. Posebno pozornost smo namenili splošnemu opisu Saxo turbine in primerjavi nekaterih ključnih razlik v primerjavi s cevnimi in kaplanovimi turbinami. Na koncu so predstavljeni tudi nekateri rezultati podrobne računalniške analize dinamike tekočine v celotnem pretočnem traktu. Avtorji želimo s tem prispevkom vzbuditi zanimanje za te turbine, prav tako pa želimo spodbuditi strokovno diskusijo, v kateri pa želimo prepoznati vzroke za nezaupanje do Saxo turbine s strani kupcev v Evropi.

1 TURBINE OVERVIEW

The Saxo turbine is a double-regulated, vertical axial water turbine with a construction that is similar to that of the tubular turbine (bulb/pit) in the section between the inlet elbow and the semi-axial distributor (conical guide vanes), while in the section between the runner and the turbine outflow, it is similar to the conventional Kaplan turbine (see Figs. 1 and 4). At first glance, the turbine is similar to the Kaplan turbine, but without a spiral casing and with a conical distributor instead of a cylindrical one. Due to its compact construction, the Saxo turbine is applicable for net heads ranging from several meters up to more than 30 m and discharges from 6 to up to 85 m³/s. The Saxo turbine output power ranges from 0.5 MW to up to 20 MW as shown in Fig. 2, which also shows the typical operational ranges of tubular, Kaplan and Saxo turbines. Furthermore, Fig. 2 shows application range of the Saxo turbine in greater detail according to the runner reference diameter D and the number of runner blades z_{rb}. The Saxo turbine is capable of covering the operating ranges of the Kaplan and tubular turbines. The company Litostroj Power has very good manufacturing and operational experience with Saxo turbines, as it is already successfully commissioned over 30 units in the North American market over the previous decade (see Table 1).

Table 1: *Litostroj Power's reference list of installed units in North America.*

HPP Project	H_n [m]	Q [m³/s]	P [MW]	n [min⁻¹]	No.of units	Year of supply	Owner
Sainte-Anne, Que.	24	25	5.38	300	1	1996	Axor Group, Inc.
Jean Guerin, Que.	24	27.85	5.78	300	1	1997	Axor Group, Inc.
Pouvoir Riverin, Que.	28	8	2.01	600	1	1999	Algonquin Power Fund, Inc.
Sainte-Anne II, Que.	24	25	5.38	300	1	2002	Société d'Énergie RSA
McDougall, Que.	16.5	28	4.18	257,14	1	2002	RSP Hydro Inc.
Magpie, Que.	20.5	70	12.95	225	3	2006	Hydromega GP, Inc.
Chute Allard, Que.	17.83	66	10.57	200	6	2007	Hydro Quebec
Rapides-des-Coeurs, Que.	22.69	66	13.62	225	6	2007	Hydro Quebec
Vernon, Vt.	10.97	50.97	5.08	144	4	2007	Transcanada Hydro NE, Inc.
Hound Chute, Que.	9.87	53.6	4.71	163,64	2	2010	Ontario Power Generation
Lower Sturgeon, Que.	12.45	63.2	7.02	180	2	2010	Ontario Power Generation
Sandy Falls, Que.	9.05	66.7	5.27	180	1	2010	Ontario Power Generation
Chute Garneau, Que.	10.26	57.2	5.32	180	1	2010	Ville de Saguenay
Pont Arnaud, Que.	15.68	56.2	8	200	1	2010	Ville de Saguenay

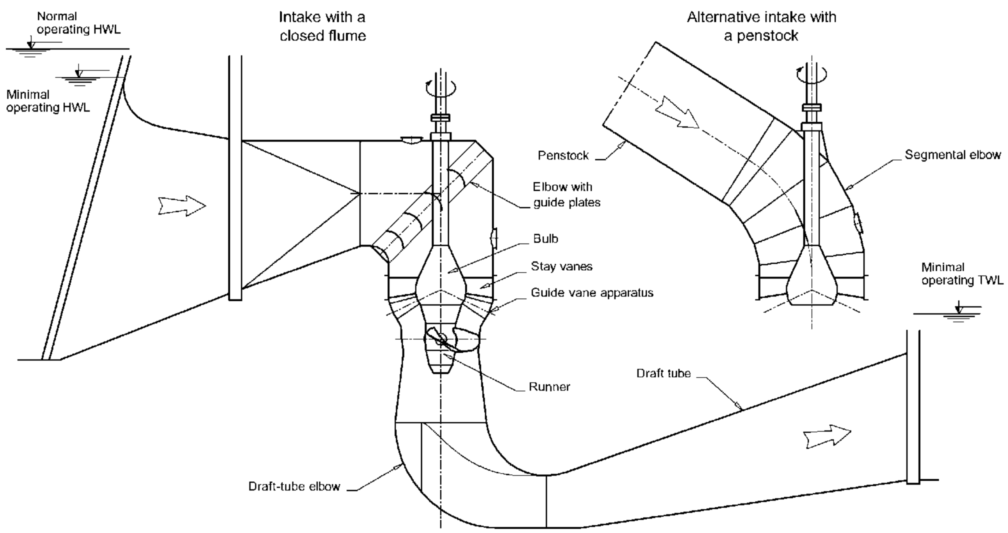

Figure 1: *Typical cross section through the Saxo turbine (water passage system).*

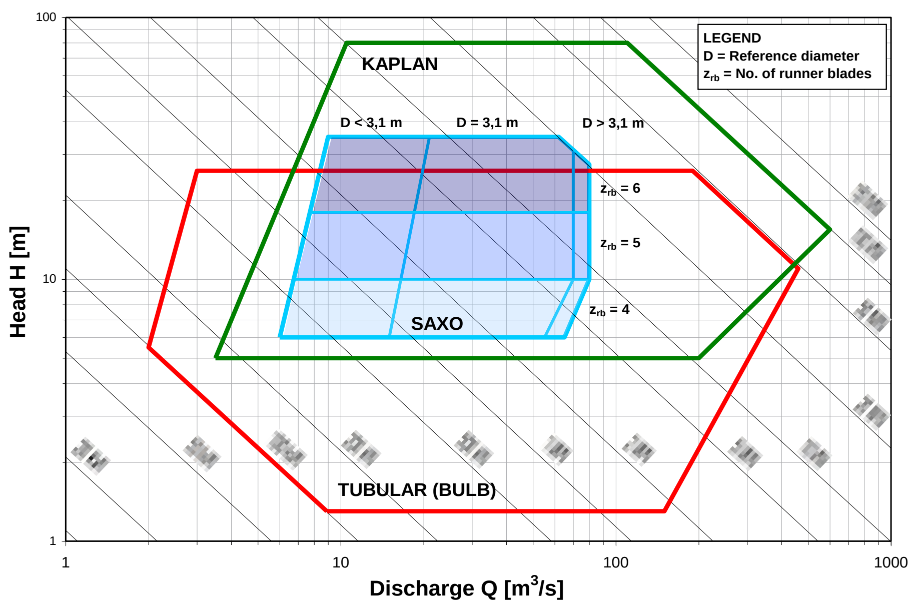

Figure 2: *Typical application range of Kaplan, tubular and Saxo turbines.*

Experience shows that investors of hydropower plants prefer Kaplan turbines with a vertical shaft, primarily because of their advantages during operation (reliability, maintenance, etc.), and the possibilities of easily installing generators with large rotating masses. In contrast, investors prefer tubular turbines with horizontal shafts because of their simplified civil construction works and relatively good hydraulics. The Saxo turbine, due to its compact design, has even better operational and maintenance characteristics than Kaplan turbines and has a better hydro-energetic design than tubular turbines. Saxo units have fewer problems with the

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handling and installation of the equipment due to smaller components, which allows the utilisation of a smaller powerhouse crane, a consequently less bulky powerhouse structure and quicker installation of factory pre-assembled components. For example, see Fig. 3, where the inlet elbow, stay and guide vanes with regulating mechanism were factory preassembled and are ready for concreting as a one single piece. From the perspective of civil construction works, the Saxo turbines have a significant advantage over conventional Kaplan turbines.

Figure 3: *HPP Pouvoir Riverin: The factory-preassembled part that includes inlet elbow, stay vanes and guide vanes with regulating mechanism is ready for concreting in one piece.*

2 TURBINE COMPONENTS

Figures 1 and 4 shows typical cross sections through the powerhouse and the Saxo turbine water passage with the inlet conduit, the elbow, the guide vane apparatus, the runner, the draft tube and the independently placed generator. Instead of a spiral casing as in Kaplan turbines, there is a compact elbow with deflector vanes, which predetermines the flow downstream to the stay vanes, the guide vanes and the runner. Water is led to the inlet elbow through a horizontal or an inclined penstock. Inlet elbows are rather uncommon in comparison to standard turbine configurations; however, compact elbows with guide vanes have been intensely numerically and experimentally investigated. With the correct configuration of the guide vanes, the elbow with deflector vanes produces a very small amount of local losses, Idelchik, [1], and yields a uniform flow field downstream the elbow. The shape of the penstock and the elbow depends solely on the available head water level comparing to the runner axis. Figure 4 shows alternative solutions of the intake elbow.

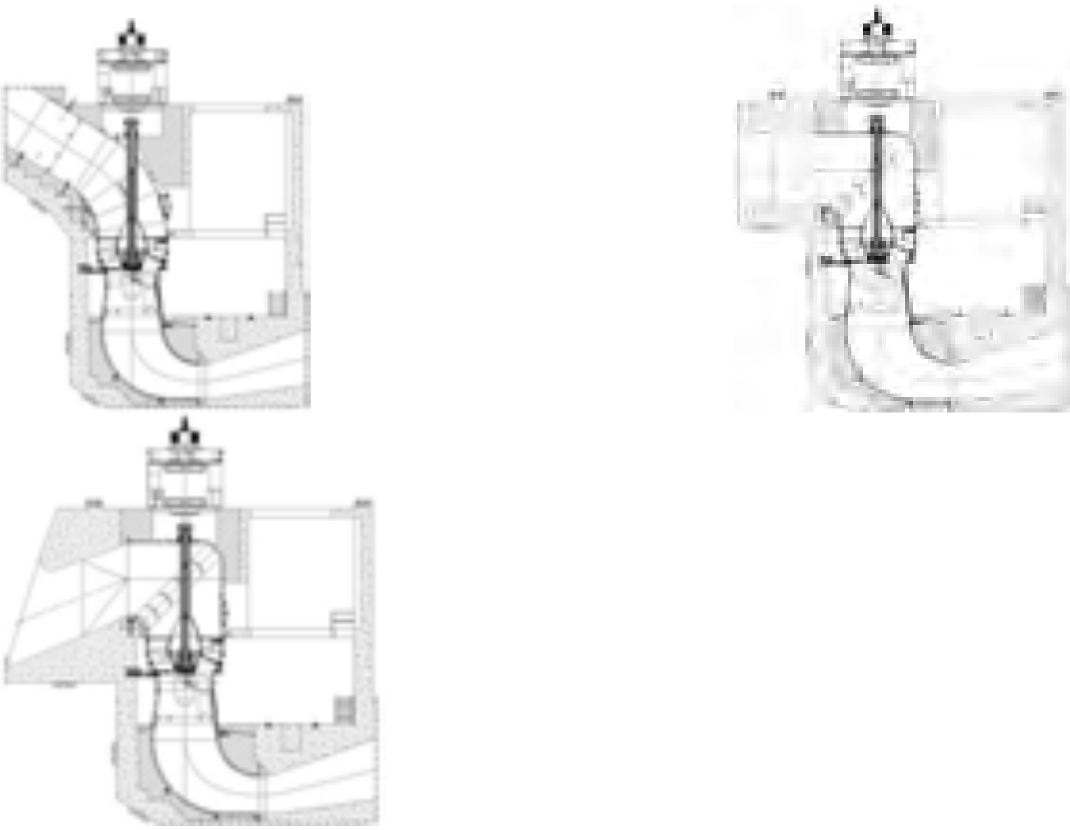


Figure 4: *Alternative solutions of the intake elbow; left: high head turbine, middle: medium head turbine, and right: low head turbine.*

The vertical shaft alignment for the torque transmission from the runner through the generator is fed throughout the elbow. The sealing of the shaft at the top of the turbine elbow is quite simple, while the sealing is not necessary at the waterside. The system of lubricating-sealing water was carefully considered (filtering, keeping pressure, i.e. discharge, etc.) because the inflow of the unclean water from the turbine passage must also be prevented when the turbine is not in operation. This problem has been successfully solved by using a closed system of lubricating-sealing water.

Stay vanes and conical guide vanes (distributor) are located downstream from the intake elbow. The guide vanes are used to adjust discharge and to enable best-efficiency operation (on-cam) by directing water to the runner blades. The guide vanes acts as a swirl generator whose advantage is that it generates slightly forced vortex flow, due to which the velocity field ahead of the runner blades becomes more uniform. However, the guide vanes also partially obstruct the flow, especially at partial openings. The runner can be assembled with four to six blades, which can be regulated. Below the runner, there is a relatively short conical diffuser (less civil construction work) with an elbow and the square-sectioned draft tube outlet.

The design of the Saxo type turbine is very rigid and the turbine shaft is vertical, which enables very good characteristics during operation. The generator, which also serves as a flywheel, can be attached directly to the inlet elbow for smaller units (see Fig. 3), while for larger units the generator is normally attached to the concrete block surrounding the inlet elbow (see Fig. 4). The generator can be driven directly by the turbine shaft or with the aid of a rotation speed gearbox. The bottom bearing of the generator is simultaneously the second guide bearing of the turbine, while the thrust (axial) bearing of the generator also takes the loading of runner.

One very important advantage of the Saxo turbine design, from the ecological point of view, is the application of the water-lubricated and -cooled turbine guide bearing near the turbine runner. The material of the bearing liner is moulded polymer PTFE (commercial name: Teflon) with additives or sintered metal based on bronze. The choice of such a bearing avoids the use of oil or grease, and it simplifies maintenance to a great extent. The use of a water-lubricated guide bearing in combination with the ecological water-filled runner significantly reduces the chances of contaminating the river water with oil or grease. The concept of the Saxo turbine is a fish friendly, which means that the water passage itself protects the fish population in front of the pressure shock and the relatively small diameter runner and low rotating speed further reduces the possibility of fish strike in comparison to Kaplan and tubular turbines.

In addition to the compact hydraulic power unit (HPU, see Fig. 5), the auxiliary systems of the Saxo turbine are limited to the system for the preparation of cooling, lubrication and sealing water and a relatively simple drainage system. The system for water preparation can serve for cooling the generator bearings if necessary. The generator also requires a lubricating system for oil bearing. The HPU is optimally minimised, which is achieved by increasing the hydraulic pressure up to 150 bars for the runner and distributor mechanisms, and the installation of a hydraulic piston pump. Auxiliary systems are located near the turbine itself.

Figure 5: *Typical Hydraulic power unit for Saxo turbine.*

The oil distributor is a hydraulic system device that is necessary for setting the angle of the runner blades. In the oil distributor, the oil flows under high pressure from the static tubes to the rotating tubes, which are installed inside the hollow generator and turbine shaft. In the Saxo turbine, it is possible to install the oil distributor at the top of the generator (Fig. 4) at the free end of the shaft. This is the best position for inspection, control and maintenance.

3 CIVIL WORKS AND PLANT ERECTION

Civil works with the Saxo turbine are considerably simplified in comparison to the Kaplan turbines (see Fig. 6). The overall width of the Saxo units powerhouse is about 5 to 30% smaller for the same head/discharge conditions. Because the Saxo units are typically smaller, more Saxo units have to be incorporated into the power station. The size of the Saxo units means an up-to-40% shallower dig-out than for classic Kaplan units and a significantly shorter length of the powerhouse. Significant savings regarding the civil works are also accomplished due to the absence of the spiral case at the Saxo turbine.

The erection of the Saxo turbine in comparison with the erection of the classic Kaplan turbine is also simplified. The draft tube elbow can be made of concrete or steel. In the latter case, the draft tube elbow is placed with a mobile crane. Afterwards, the powerhouse is finished and the powerhouse crane is put into operation. The single-part inlet elbow is placed by the powerhouse crane, centred, anchored, and concreted. Figure 3 shows an example of smaller unit, where the factory-preassembled stay ring and distributor assembly are assembled with the inlet elbow. For larger units, the preassembled stay ring and distributor assembly are lifted to the inlet elbow from bottom floor. The erection of the turbine shaft is similar to that of a Kaplan type turbine, but the runner is attached to the shaft with the aid of a shear ring rather than a classic flange. The runner is also lifted to the shaft from the floor bottom. The erection of the runner casing and the dismantling flange follows. At the same time, the generator and other equipment can be erected. The time needed for erection of two Saxo units is up to 50% shorter than the time needed to erect one Kaplan unit.

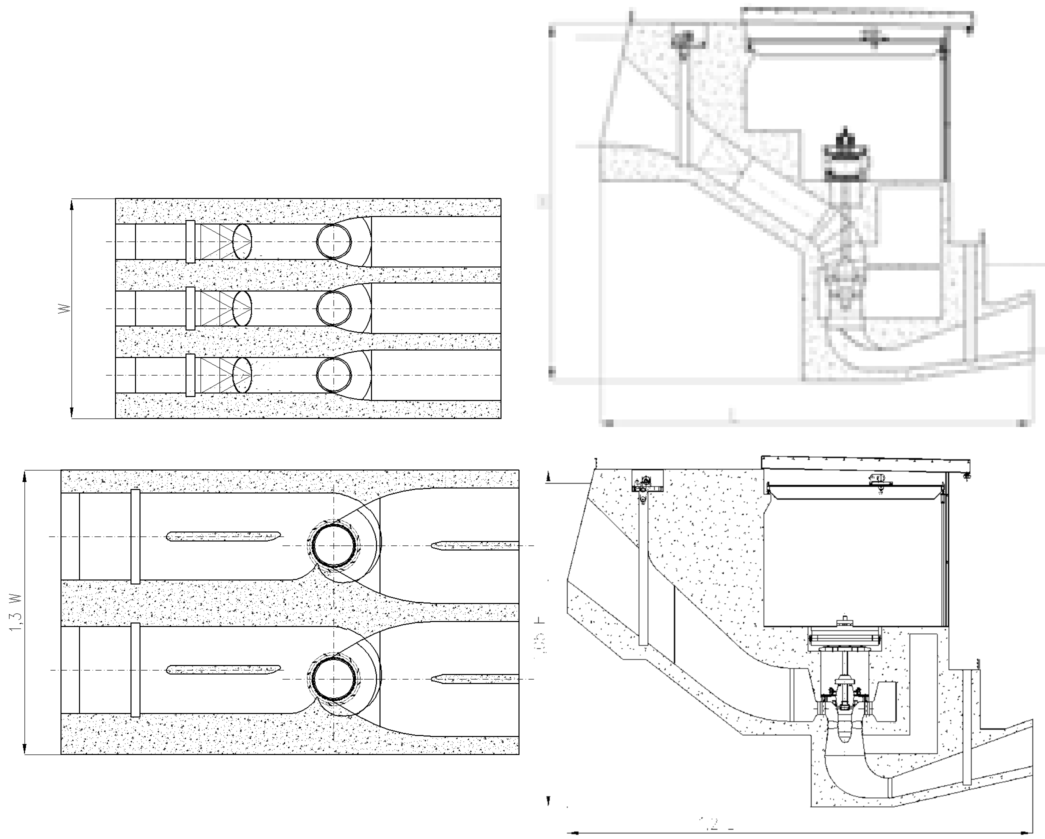


Figure 6: *Comparison of typical civil works dimensions for Saxo turbine (top) and for Kaplan turbine (bottom).*

4 HYDRAULIC DESIGN AND INVESTIGATIONS

Theoretical and numerical investigations of the Saxo turbine have mainly been focused on the design and validation of the hydraulic shape of the guide vanes and the runner blades, and the water passage region between them. First, the improved streamline curvature method (SCM) has been applied for designing a new runner blade row, Höfler et al., [2, 3], considering the actual apparatus and actual shape of guide vanes (Fig. 7). Second was an evaluation and analysis of the flow field by using CFD tools for viscous flow analysis, Gale, [4]. The considered water flow passage in CFD analyses started several meters before the inlet elbow (stable boundary condition) and ended with an extension after the draft tube exit; the whole turbine was considered at once. The analysis was performed for different guide vane openings and different runner blades positions; as a result, a 3D turbine efficiency charts were made. Cavitation occurrence was also thoroughly investigated (see Figs. 8 and 9). The hydraulic design and the CFD results have been successfully validated by model tests, Djelić et al., [5].

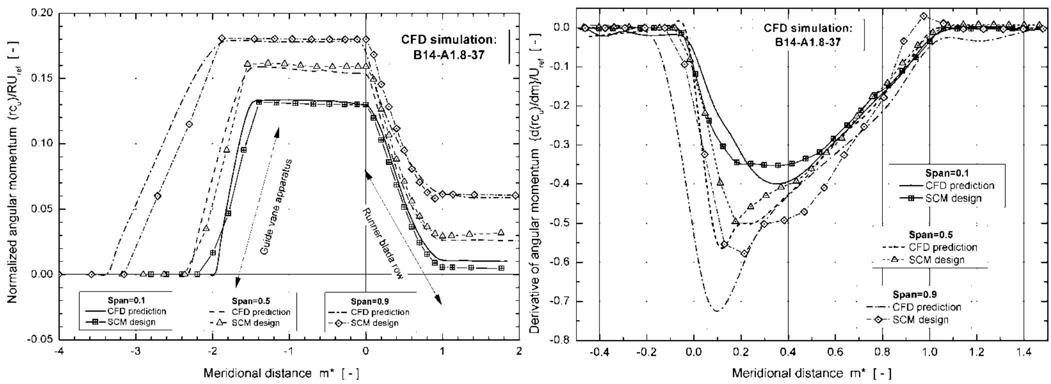


Figure 7*: Distribution of circumferentially averaged angular momentum alongside the turbine passage - comparison of CFD calculation and hydraulic design prediction based on improved streamlines curvature method, Höfler et al., [2]. Span = 0.1 - close to the hub, span = 0.5 - middle of the flow passage, span = 0.9 - close to the runner casing.*

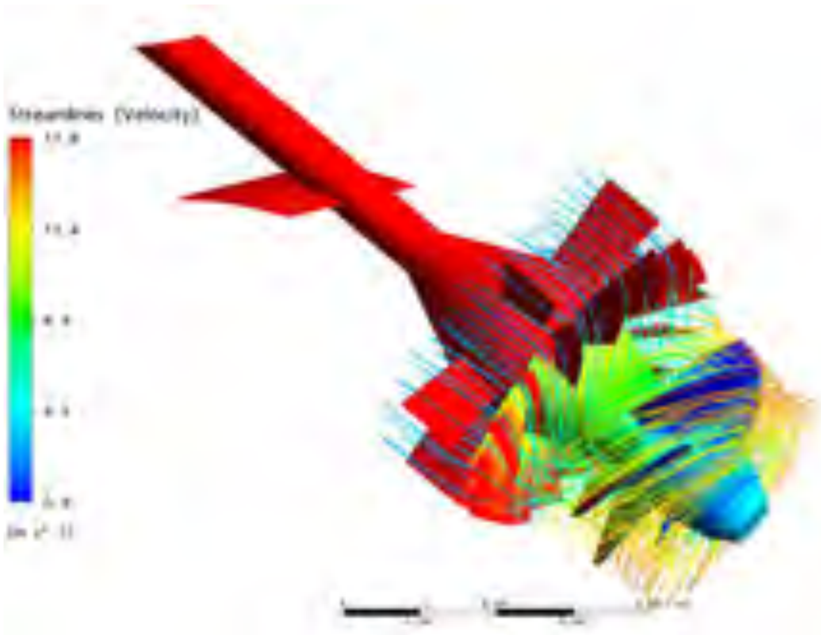
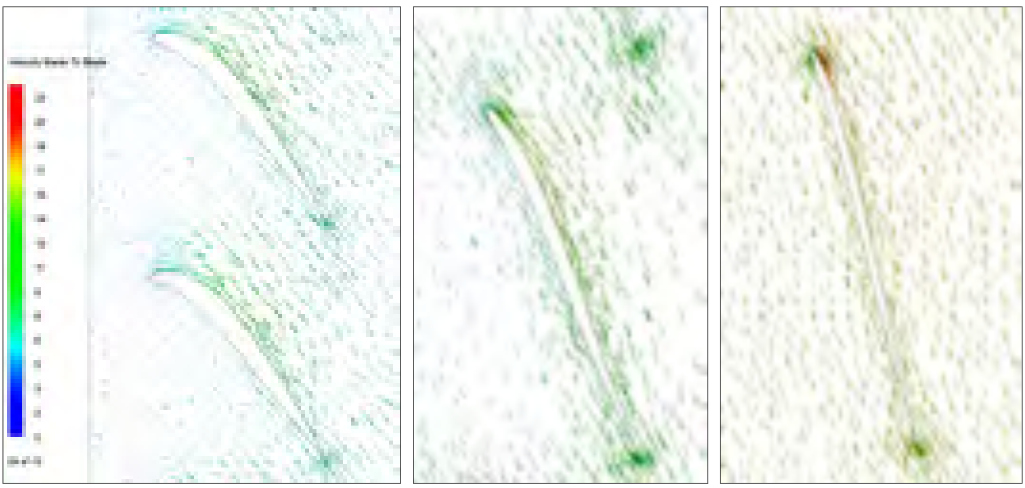


Figure 8: *A deep CFD analysis has been undertaken – an example of results shows static pressure and streamlines through stay vanes, guide vanes and five-bladed runner.*



Span = 0.1 *Span = 0.5* *Span = 0.9*

Figure 9: *Flow at the blade-to-blade stream surface with relative velocity vectors in operating point close to the BEP, Höfler et al., [2].*

5 CONCLUSIONS

The analysis of the design and hydraulic characteristics of the Saxo turbine and its comparison to Kaplan and tubular turbines clearly show the advantages of the Saxo for a quite wide range of operating conditions. The vertical axial tubular unit in S-configuration has been developed as a low-cost turbine. Its configuration ensures high performance and reliability, easy erection,

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minimised civil construction works, easy maintenance and long operation lifetime. The Saxo turbine has been optimised, standardised, and adopted for small and medium hydro power plants for net heads up to 30 meters, flows up to 85 m³/s, and rated output up to 20 MW. The Saxo turbine is suitable for new projects as well as for refurbishment of Kaplan unit power plants or low and even medium head Francis unit power plants. The core of the units is factory pre-assembled and tested. The cost-effective Saxo units are a good choice, offering the quickest return of investment.

Acknowledgment

The authors are thankful to ARRS (Slovenian Research Agency) for their generous support of research on the hydraulic characteristics of Saxo turbines.

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Nomenclature

(Symbols)	(Symbol meaning)
D	runner diameter
H_n	turbine net head
Q	discharge
P	turbine output
z_{rb}	number of runner blades
m	meridional distance
R	runner tip radius
r	radius
c_u	peripheral component of flow velocity

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FINE GEOMETRICAL MODELING OF THE NEUTRON TRANSPORT IN THE NPP KRŠKO'S FUEL, USING THE SERPENT MONTE CARLO TRANSPORT CODE

NEVTRONSKI TRANSPORTNI IZRAČUN GORIVA NUKLEARNE ELEKTRARNE KRŠKO Z MONTE CARLO PROGRAMOM SERPENT NA FINI GEOMETRIJSKI MREŽI

Marjan Kromar[ℜ], Bojan Kurinčič[2]

Keywords: nuclear reactor, PWR, nuclear core design, nuclear calculation, Monte Carlo

Abstract

The impact of some specific design features, such as grids, nozzles and in-core instrumentation thimbles on the neutron flux distribution was evaluated for the NPP Krško fuel. Fine geometrical models have been developed for the Serpent Monte Carlo code. The results obtained are compared to the CORD-2 calculations. The comparison has shown local variations of the neutron flux near the modelled material nonhomogeneities, which are however of minor importance for the global reactor results. There is no need for explicit geometrical treatment of the analysed fuel features in the CORD-2 system.

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Povzetek

Raziskan je bil vpliv nekaterih konstrukcijskih lastnosti goriva Nuklearne elektrarne Krško, kot so distančniki, zgornja in spodnja šoba, instrumentacijsko vodilo, na porazdelitev nevtronskega fluksa. Pripravljeni so bili podrobni geometrijski modeli za Monte Carlo program Serpent. Rezultati so primerjani z rezultati dobljenimi s CORD-2 paketom. Primerjava je pokazala lokalna odstopanja v bližini materialnih nehomogenosti, ki pa imajo majhen vpliv na globalno dogajanje v sredici. CORD-2 paketa ni potrebno nadgraditi z bolj detajlnimi geometrijskimi modeli.

1 INTRODUCTION

The determination of the 3-D reactor core power distribution and reactivity is essential to assure safe, reliable and economical reactor operation. Despite rapid computer development in recent years, core calculations based on the Monte Carlo approach are still not fast enough for the series of calculations needed for typical reload core design. Therefore, deterministic methods have to be applied in the solution of neutron transport and diffusion equation. Nevertheless, Monte Carlo codes enable very detailed geometrical modelling of the reactor fuel and core, and are suitable for verifying more general models usually used in the deterministic codes.

In this paper, several specific fuel assembly design features, such as grids, nozzles and in-core instrumentation thimbles, are investigated. Neutron distribution is determined with the Serpent Monte Carlo transport code [1], where a detailed geometrical model for each specific design feature has been developed. The results are compared to the neutron distributions obtained by the CORD-2 system [2, 3].

2 METHODS

The impact of some specific design features on the calculation of the neutron distribution was evaluated for the NPP Krško fuel. NPP Krško is a 2-loop Westinghouse plant with a gross electrical output of 730 MW. The core consists of 121 fuel assemblies. Each assembly has 235 fuel rods arranged in a 16×16 array. The remaining 21 positions are intended for control rods and the central instrumentation channel. In Figure 1, the NPP Krško fuel is presented.

Serpent is a three-dimensional continuous-energy Monte Carlo reactor physics burnup calculation code, developed at the VTT Technical Research Centre of Finland. The code is specialised for two-dimensional lattice physics calculations, but the universe-based geometry description allows the modelling of complicated three-dimensional geometries as well. Detailed geometrical modelling of the NPP Krško fuel assembly in the Serpent code enables accurate determination of the local neutron flux distribution in the vicinity of material nonhomogeneities.

The CORD-2 system, developed by the Reactor Physics Department of the Jožef Stefan Institute, is intended for the core design calculations of PWRs. The main goal in assembling the computational tools was to provide a non-commercial package that could be used for simple fast calculations (such as those frequently required for fuel management) as well as for accurate calculations (for example, core design after refuelling). The CORD-2 system enables the determination of the core reactivity and power distribution. The package has been validated for

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the nuclear design calculations of PWR cores and has been used for the verification of the NPP Krško reload cores since 1990.

In both codes, the ENDFB-VII neutron cross section library has been used.

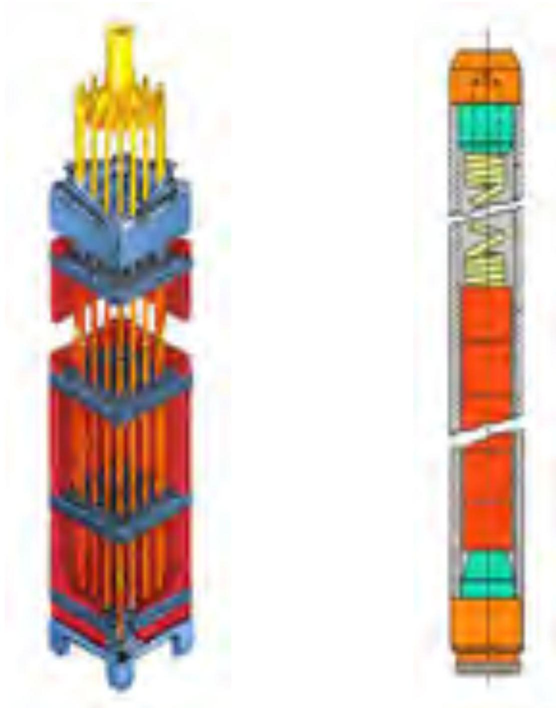

Figure 1: *NPP Krško fuel assembly and fuel rod*

3 RESULTS AND DISCUSSION

3.1 Simplified geometrical model of the fuel assembly

Grids are structural elements that assure the geometry of the fuel assembly. Those used in the NPP Krško fuel are made from the Inconel-718 alloy. This material exhibits significant neutron absorption and causes local flux depressions. In the Cord-2 system, grids are homogenised in the axial direction. Fuel rods and guide thimbles have an additional annular region with an appropriate amount of Inconel. A geometric representation of the model is presented in Figure 2. Water is represented in blue, fuel pellets with red, cladding with light green and additional annular layers, which represent grids, with dark green. Calculations were performed for the fresh fuel with enrichment 4.95% at zero (HZP – hot zero power) and full power (HFP – hot full power) conditions. The assumed state-point thermal-hydraulic variables at full power were: fuel temperature 900 K, cladding temperature 627.6 K, coolant pressure and temperature 15.5 Mpa and 580.46 K, and boron concentration 1000 ppm. The inter-assembly gap and fuel rod gap

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were explicitly treated. The dimensions take into account thermal expansion at full power operation.

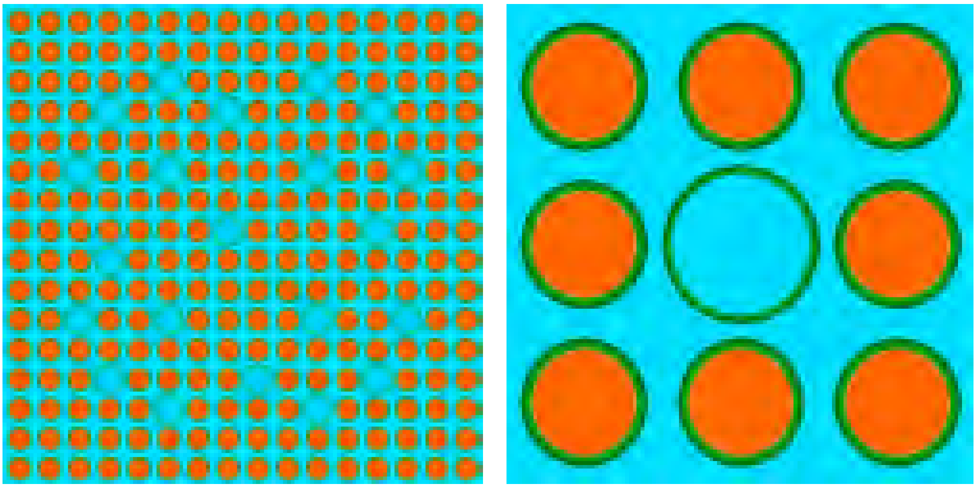

Figure 2: *Simplified geometrical model of the fuel assembly on the left, and magnified central 3×3 lattice cells on the right*

The infinite multiplication factor k_{inf} for both cases is given in Table 1; agreement of the CORD-2 reactivity is reasonably good. Pin power distribution for the HFP case is shown on Figure 3; the distributions are very similar. CORD-2 produces a little lower power on the assembly edge and little higher power in the centre. Power-peaking factors are practically the same (Serpent → 1.0822, CORD-2 → 1.0811). The difference of both pin powers is presented in Figure 4.

Table 1: *Serpent and CORD-2 comparison – simplified model*

	K_{inf} Serpent	K_{inf} CORD-2	Δ [pcm]
HZP	1.32459 ± 0.00014	1.32082	-377
HFP	1.30965 ± 0.00014	1.30423	-542

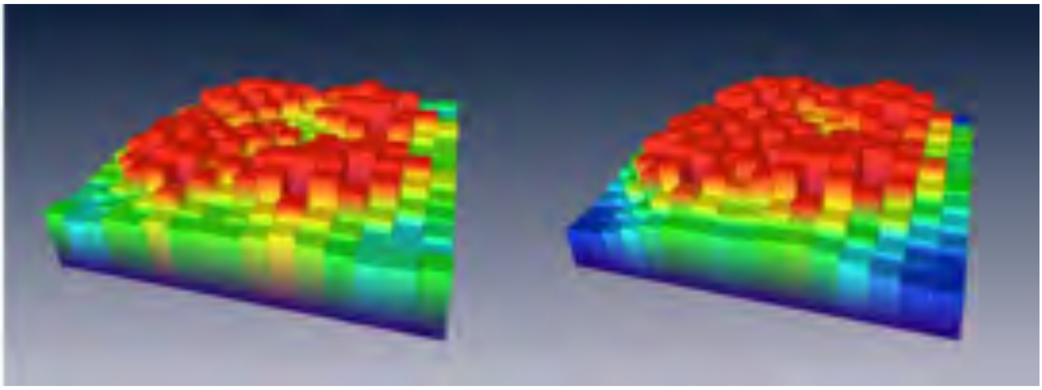

Figure 3: *Pin power distribution for the Serpent (left) and CORD-2 (right) calculation, HFP conditions*

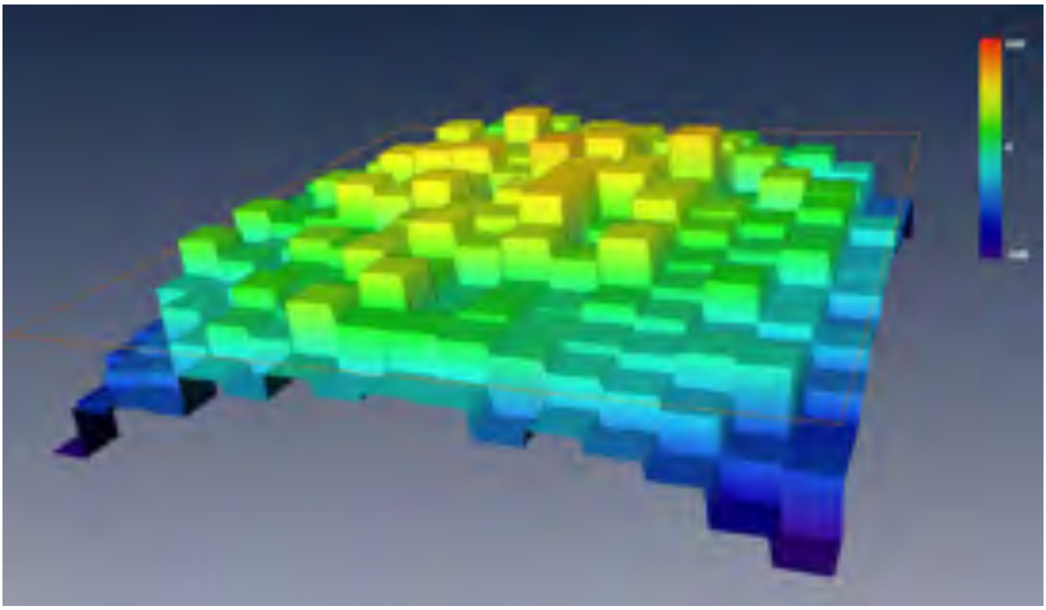

Figure 4: *Difference between the Serpent and CORD-2 pin power distribution, HFP conditions*

3.2 Explicit grid treatment

Explicit evaluation of the grid was performed with the Serpent code, since the CORD-2 system does not have this capability at present. The geometrical model is presented in Figure 5. Only one grid was considered with the mirror boundary condition on the top and bottom plane. Additional annular regions around the fuel rods and thimbles are present only in the central region. The height and mass of this region corresponds to the actual grid characteristics. Normalised axial thermal and fast-flux distributions are presented in Figure 6. It can be seen that local flux depression causes an increase of the thermal flux level (normalisation) in the non-

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grid regions of approximately 2%. Since the fast-flux variations are even lower, we can estimate that the core power peaking factors are up to 2% higher than ones calculated in the homogenised grid model. Calculated k_{inf} was 1.32676 ± 0.00006. This is 217 pcm higher than in the simplified geometrical model. CORD-2 therefore has a slightly overly strong grid effect on the overall result.

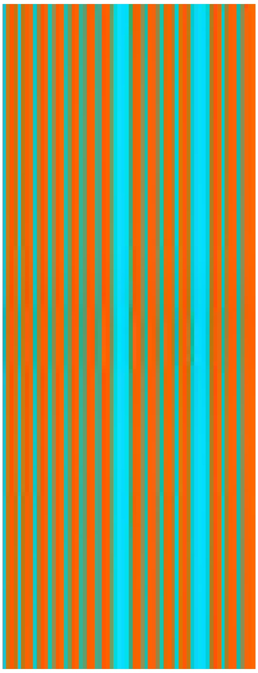

Figure 5: *Explicit grid treatment*

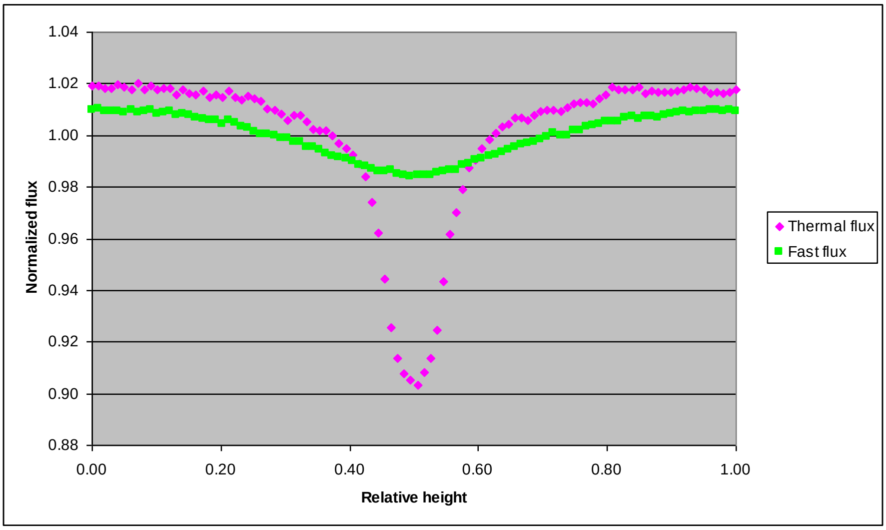

Figure 6: *Axial flux distribution in the explicit grid model*

3.3 In-core instrumentation thimbles

NPP Krško core has 36 locations where in-core fuel measurements are performed. Fuel assemblies on those locations have in-core guide thimbles inserted in the central instrumentation channel (Figure 7). In other fuel assemblies, the instrumentation channel is filled with a moderator (Figure 2). Since there is air and stainless steel instead of water in the guide tube, neutron moderation near the closest fuel rods is reduced, causing a slight power decrease. Pin power distribution is presented in Figure 8. The difference of both distributions is shown on Figure 9. It can be clearly seen that the significant difference is present only in the central region, while the other differences are inside the fluctuations caused by the Monte Carlo method. The largest power depression in the closest rod is -0.053. Power peaking factors are practically the same (without thimble → 1.0767, with → 1.0772). The calculated infinite multiplication factor k_{inf} is 1.32355 ± 0.00013. This is 104 pcm lower than in the simplified geometrical model. One should bear in mind that only 36 out of 121 locations are instrumented in the reactor. Therefore, the effect on the core k_{eff} should be only around 30 pcm.

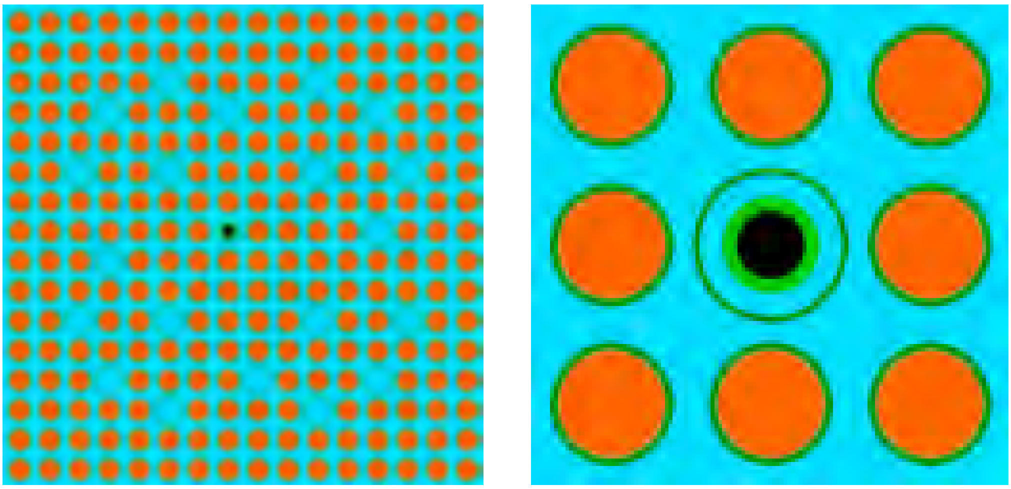

Figure 7: *Assembly with the in-core guide thimble on the left and magnified central 3×3 lattice cells on the right*

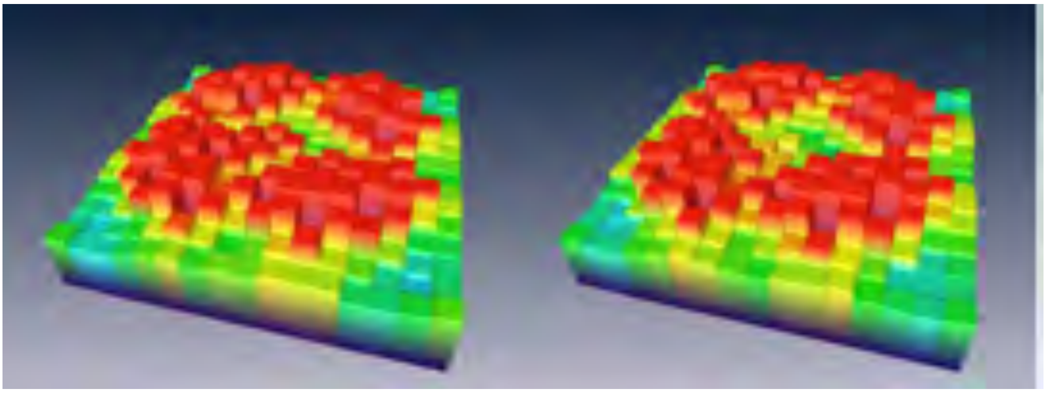

***Figure 8:** Pin power distribution for the assembly without (left) and with in-core guide thimble (right), HZP conditions*

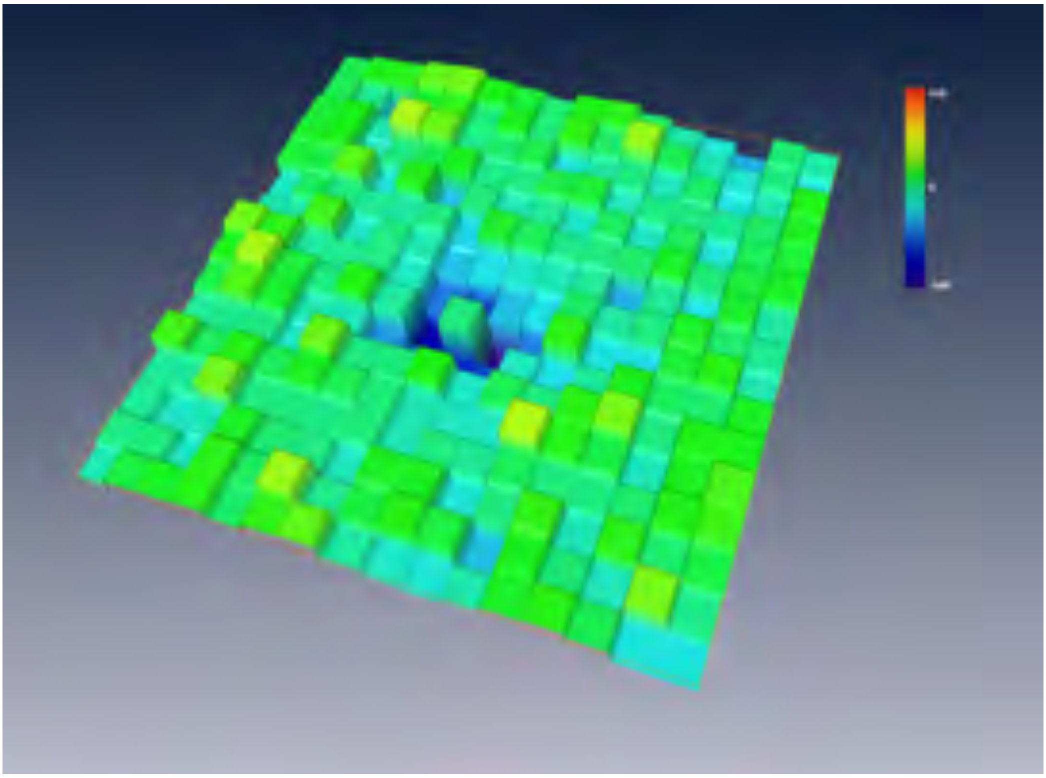

***Figure 9:** Difference between the pin power distribution with and without in-core guide thimble, HZP conditions*

3.4 Full axial model

In the final step, a full geometrical model of the NPP Krško fuel has been developed. The nominal fuel enrichment in the central part was 4.95%. The top and bottom axial blanket regions consist of annular pellets with an enrichment of 2.60%. The following fuel parts are modelled explicitly:

1. All 8 fuel grids
2. Annular pellets
3. Top and bottom fuel nozzle
4. Fuel rod end plugs
5. Rod plenum with spring
6. Top and bottom core plate

The geometrical model is presented in Figure 10. The calculated multiplication factor k_{eff} is 1.32141 ± 0.00006. The CORD-2 calculation with the simplified geometrical model gave k_{eff} 1.31524, which is 617 pcm lower. This corresponds well with the observed differences in the simplified model and in the grid evaluation. Fast and thermal flux distributions are presented in Figures 11 and 12. The global agreement between Serpent and CORD-2 is very good. Beside obvious grid depressions, the only noticeable difference is near the fuel nozzles. CORD-2 has a slightly too low thermal flux level in that vicinity. It is not clear whether the effect is caused by the reflector homogenisation or the diffusion approximation to the transport solution. However, neutron leakage is approximated correctly, since no major discrepancy in the k_{eff} has been observed.

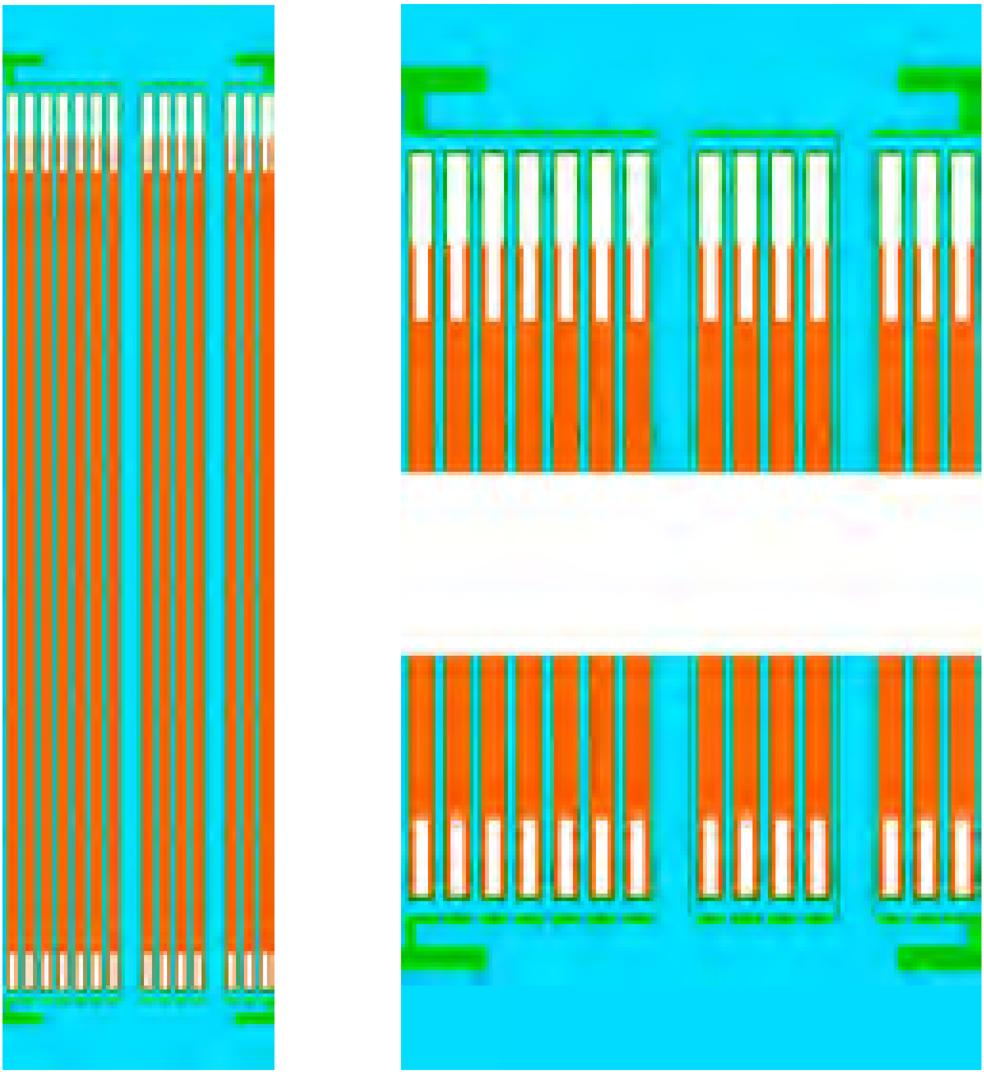

Figure 10: *Fine geometrical model of the NPP Krško fuel assembly with magnified upper and lower parts on the right*

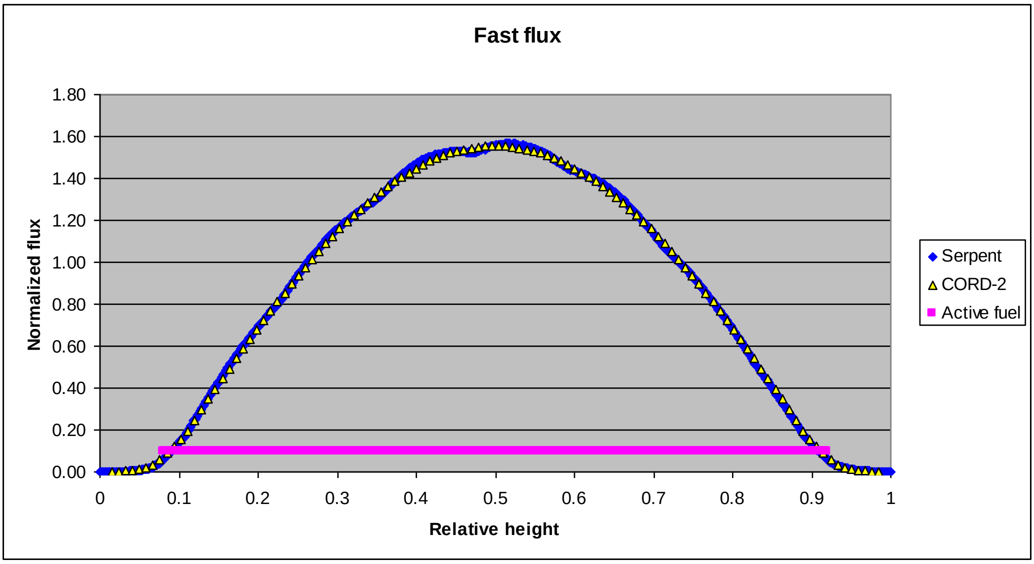

Figure 11: *Axial fast-flux distribution*

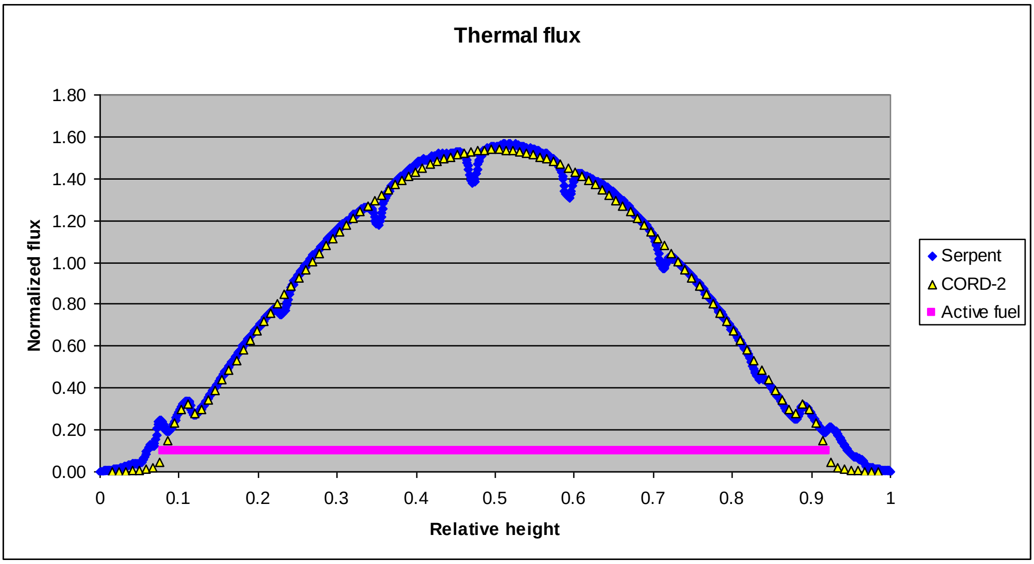

Figure 12: *Axial thermal flux distribution*

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4 CONCLUSION

The influence of several specific fuel assembly design features, such as grids, nozzles and in-core instrumentation thimbles, has been investigated. Fine geometrical models of the NPP Krško fuel have been developed for the Serpent Monte Carlo code. The Serpent and CORD-2 results are compared to determine influence level of the particular design feature. The study has shown that:

- CORD-2 multiplication factors are about 500 pcm lower than the multiplication factors from the Serpent code.
- The grid model in the CORD-2 yields overly strong neutron absorption.
- Explicit grid modelling causes up to 2% higher peaking factors.
- The inserted in-core guide thimble produces slightly lower power distribution in rods near the instrumentation tube. The global effect is small.
- A rather small effect near the fuel nozzles has been observed. CORD-2 produces a slightly too low thermal flux. It is not clear whether the effect is caused by the reflector homogenisation or the diffusion approximation to the transport solution.

In general, the comparison of results has shown local variation of the neutron flux near the modelled material nonhomogeneities, which are however of minor importance for the global reactor results. There is no need for explicit geometrical treatment of the analysed fuel features in the CORD-2 system.

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INVESTMENT EVALUATION FOR A SMALL HYDRO POWER PLANT

VREDNOTENJE INVESTICIJE V MALO HIDROELEKTRARNO

Klemen Dežekak[ℜ], Katarina Dežan, Jože Pihler, Gorazd Štumberger

Keywords: Small hydro power plant, net present value, internal rate of return

Abstract

In this paper, the investment evaluation in the process of constructing small hydro power plants is investigated. All calculations are performed for a small 27 kW hydro power plant. Both technical and financial aspects are presented, and all of the major indicators for investment approval are considered. The greatest attention is given to the impact of various financial parameters on the indicators for investment approval or rejection. Within the technical aspect, the main input and output technical parameters are observed. Input parameters include the head, flow, turbine type and generator efficiency, while the output parameters of the calculations include hydro power plant power, capacity factor and delivered energy. Within the financial aspect, the initial and annual costs as parameters of extended financial analysis (inflation, discount rate and credit) are considered in the calculations. In this work, the impact of the above parameters on investment approval, in the sense of indicators such as net present value, internal rate of return and the cumulative cash flow is studied.

Povzetek

V prispevku je obravnavana tematika vrednotenja investicij v izgradnjo male hidroelektrarne, pri čemer so vsi izračuni izvedeni za manjšo hidroelektrarno moči 27 kW. Pri tem sta predstavljena

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tako tehnični kakor finančni izračun vseh pomembnejših kazalcev vrednotenja investicij. Največja pozornost je posvečena vplivu različnih vhodnih parametrov finančne analize na kazalce sprejemljivosti, oziroma zavrnitve investiranja v malo hidroelektrarno. Znotraj tehničnega dela so obravnavani glavni vhodni in izhodni parametri izračuna. S terminom vhodni parametri mislimo na padec, pretok, tip izbrane turbine in izkoristek generatorja, medtem ko so izhodni parametri tehničnega izračuna moč, izkoriščenost in proizvedena energija. Po drugi strani je pri vrednotenju investicij v male hidroelektrarne, poleg tehničnega, izredno pomemben še finančni del izračuna. Pri tem je potrebno oceniti tako začetne, letne stroške ter remont, kakor parametre razširjene finančne analize, s čimer mislimo na inflacijo, diskontno stopnjo in tudi morebiten kredit. V tem delu je raziskan vpliv naštetih parametrov na kazalce sprejemljivosti investicije, kot so neto sedanja vrednost, interna stopnja donosnosti in kumulativni denarni tok.

1 INTRODUCTION

Small hydro power plants can be observed from two points of view: architectural and electro-mechanical [1, 2]. The main architectural emphasis is the actual construction of the dam, the water intake and the power house [3–5]. The dam and the water intake direct the water towards the channel, tunnel, penstock or the guide blade. The water flows through the runner blades at the turbine, which rotates with a sufficient speed to create electrical power in the generator. Finally, the water leaves the plant through the draft tube. Small hydro plants require little maintenance over the course of their lifetime, which can be more than 50 years [6, 7]. Most of the time, the supervision of operations and maintenance is the responsibility of only one person. Annual maintenance and refitting of the large components usually requires the cooperation of external co-workers. Technical and financial realisations of the potential project depend on the actual stage of the project [8–12]. The quantity of generated electric energy is primarily dependent on the head, the quantity of the available flow and the oscillation of flow throughout the year [1].

In this paper, detailed economic calculations are performed for a specific small hydro power plant, showing the extensive comparison between the important parameters of financial analysis and their impacts on the static and dynamic criteria of investment evaluation.

2 SMALL HYDRO POWER PLANTS

The process of planning small hydro power plants, from concept phase to completion, can take three years. In that period, numerous studies are made, and the plans are realised with the intention of obtaining the permits for the realisation of the project [2–4]. From an economic perspective, the evaluation of the potential project depends on the installed power and the amount of electric energy generated by the hydro power plant, as well as on the amount of electric energy sold and the validity of its evaluation [13]. Small hydro power plants, which are intended to cover local needs for electric energy in remote places, are generally more important than the small hydro power plants connected to the central electric network [1].

The turbines used in the small hydro power plants are usually smaller versions of the conventional turbines used in larger hydro power plants. The turbines used in cases of small or medium-high heads are of the reactionary type. A runner of the reaction turbine is submerged

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in the water. This type of turbine includes Francis turbines and Kaplan turbines with fixed and regulated runner blades. In case of high heads, action turbines are used [1–3]. They differ from reaction turbines in the ways that they rotate in the air (as opposed to being in water) and they are propelled by a jet of water. Pelton turbines, Turgo turbines and cross-flow turbines are all examples of the action turbines.

In small hydro power plants, two types of generators can be used: synchronous or asynchronous. The synchronous generator is suitable for local operations, while the asynchronous generator is appropriate for grid operations. A synchronous generator is used as the main source of energy for an independent, small or isolated network, which is supplemented by a diesel generating set. Asynchronous generators, with power of less than 500 kW, are demonstrably the most appropriate in cases when electric energy is generated in the small hydro plants and sent into existing grids [1].

3 EVALUATION OF INVESTMENTS

Evaluation or determining how appropriate the acceptance of an investment is from the viewpoint of a company or a specific investor is one of the most important business decisions [14–17]. There are alternatives for estimating the investments. For all economic investments, the valid principle of the return on investment should be considered. The criteria by which the success of the investment or the decision among possible investment projects are described can be divided into static and dynamic criteria [11, 18–21].

The static or conventional methods do not take into consideration the time value of money and suffice only for a rough decision on the investment business results. Therefore, they are used rarely or they are used in the conjunction with dynamic methods. The most well-known among the static criteria are the period of return on investment and the coefficient of profitability of investment [11, 18]. Dynamic methods, in comparison to static ones, take into consideration different investment terms and different time dynamics of the investments [18, 19]. In this sense, the financial parameters, such as inflation, discount rate and credit, can be considered [21]. In this paper, only the return of investment period is investigated from the static criteria, while for dynamic criteria the net present value and the internal rate of return are applied. Furthermore, the curve of cumulative cash flow is explained.

3.1 Return on investment period

With that method, the depreciation period of investment is defined [11, 21]. The Return on investment Period (*RP*) is defined as the expected number of years that are necessary to cover all costs of the investment with a net income (3.1). In (3.1), *IC* stands for the initial costs, *AI* is annual income, while *AO* is annual outcome.

$$RP = \frac{IC}{AI - AO} \tag{3.1}$$

3.2 Net present value

Net present value (*NPV*) is one of the most utilised measures for deciding whether to accept or reject an investment opportunity [11, 21]. It is calculated when all income, with the use of chosen interest rate or the discount rate, is reduced to the initial moment (2). In (3.2), R_t stands for the net cash flow, t is the time of the cash flow and r_i is the discount rate.

$$NPV = \sum_t \frac{R_t}{(1+r_i)^t} - IC \tag{3.2}$$

By taking into consideration the time dimension of current investing and income with a chosen discount rate, it can very quickly be determined whether the investment is reasonable or not [21]. The investment is accepted if its net present value is larger than zero, while the investment is rejected if its value is smaller than zero. In case of multiple investment possibilities, the one with the highest positive net present value is chosen [21].

3.3 Internal rate of return

The internal rate of return belongs to the concept of net present value, which presents the maximal discount factor, or in percentages revealed in annual income, during which it is still financially reasonable to accept a defined investment [11, 21]. The internal rate of return (*IRR*) can be understood as a parameter with which the highest acceptable interest rate is determined. The internal rate of return can be calculated with (3.3), where R_t stands for the net cash flow and t is the time of the cash flow.

$$0 = \sum_t \frac{R_t}{(1+IRR)^t} - IC \tag{3.3}$$

The investment is accepted if the internal rate of return is higher than the relative discount rate; if it is the same, we are indifferent. However, if it is smaller, the investment is rejected. In case there are more investment possibilities, the one with the highest internal rate of return is chosen.

3.4 Curve of cumulative cash flow

The curve of cumulative cash flow is obtained by calculating the yearly income and outcome difference, where parameters such as inflation, credit and varying cost of energy could have essential impact. Part of the cumulative cash flow curve, the year-to-positive cash flow parameter is very significant. It shows the number of years in which the value of cumulative cash flow is equal to zero.

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4 RESULTS OF CALCULATIONS

In this section, the results of technical and economic calculations of a small hydro power plant are shown. In the technical part (4.1), all important input parameters involved in the small hydro plant power and delivered energy calculations are described. The impacts of different financial parameters are shown in 4.2; these include inflation, discount rate and energy cost variation to the cumulative cash flow, net present value and the internal rate of return. All of the financial calculations are performed for the hydro power plant described in the 4.1, while the cumulative initial costs were estimated to be €4,000/kW and €5,000/kW.

4.1 Technical part

The power and produced energy of the hydro power plant are mainly dependent on the available flow of the river. In our case, the average values of available flow for each month of year Q are shown in Figure 1a. To calculate the delivered energy, instead of the curve in Figure 1a, the curve shown in Figure 1b should be considered in the calculations. There, the values of monthly flows, duration Q_{mod}, are defined. Apart from flow duration curve, the values of gross head, type of turbine used, design flow, and generator efficiency are very important. In our case, gross head is equal to 8 m, design flow is 0.46 m^3/s, generator efficiency is 93%, while the type of turbine used is Francis, with the short penstock and the spiral shaped inlet.

a) b)

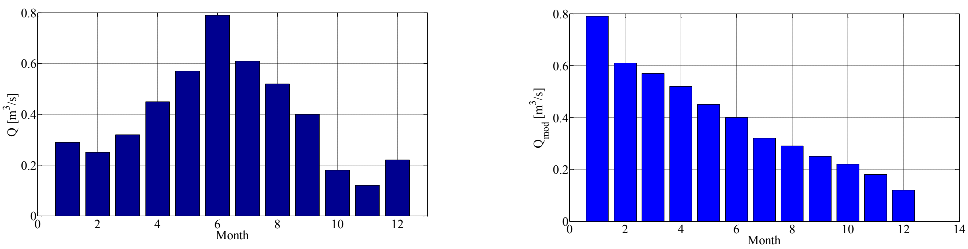

Figure 1: *a) average values of available flow for each month of year, b) monthly flows duration curve*

On the basis of above input parameters, the power of our hydro plant is equal to 27 kW, the energy produced in one year is equal to 154.42 MWh, while the capacity factor is 65%.

4.2 Financial part

In this section, detailed economic calculations are performed. The extensive comparison between the important input parameters of financial analysis and their impacts on the criteria of investment evaluation are shown. As has been already mentioned, the criteria are the net present value, internal rate of return and cumulative cash flow, while the input parameters are inflation, discount rate and variety of energy costs. All calculations are obtained for annual costs of €3,000/year (annual maintenance and accounting), a project life of 30 years, credit 60% of initial costs, a credit term of 10 years, a credit interest rate of 5.5%, while the initial costs were first estimated at €4,000/kW and second at €5,000/kW.

Figures 2 and 3 show the variation of cumulative cash flow and net present value (NPV) as years and the discount rate function.

a) b)

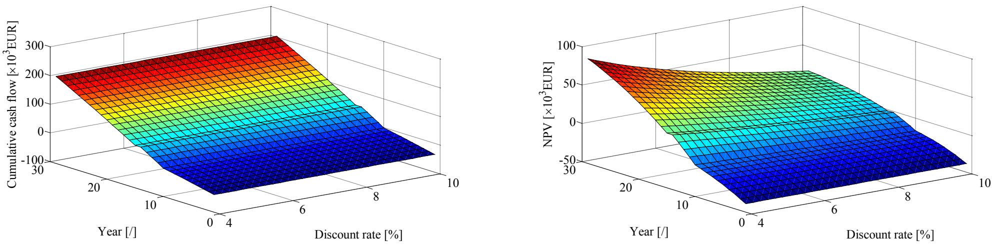

Figure 2: *Cumulative cash flow and net present value (NPV) dependent on the year and the discount rate (initial costs €4,000/kW)*

a) b)

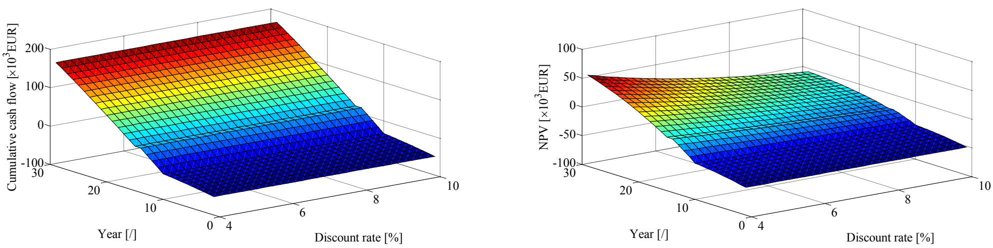

Figure 3: *Cumulative cash flow and net present value (NPV) dependent on the year and the discount rate (initial costs €5,000/kW)*

Figure 2 is valid for initial costs of €4,000/kW, while Figure 3 is valid for initial costs of €5,000/kW. In both cases, inflation is set at 2.5% and energy costs at €105.47/MWh. As can be seen, the cumulative cash flow does not depend on a discount rate, while the net present value is higher than zero in all cases. If the discount rate (Figure 2) increases from 5 to 7%, the net present value decreases by approximately 38%, while an increase from 5 to 10% leads to a decrease of 74% in net present value. In case of higher initial costs (€5,000/kW, Figure 3) both cumulative cash flow and net present value become lower, while net present value could be even lower than zero.

Figures 4 and 5 show that the variation of cumulative cash flow and net present value (NPV) are dependent on the season and inflation. Figure 4 is reflects initial costs at €4,000/kW, while Figure 5 is valid for initial costs at €5,000/kW. In both cases, the discount rate is set to 5% and energy costs to €105.47/MWh. As the figures show, the cumulative cash flow and the net present value are decreasing with increased inflation. If inflation (Figure 4) increases from 1 to 2.5%, the net present value decreases by approximately 15%, while an increase from 1 to 4% leads to a decrease in net present value of 33%. In that case, the cumulative cash flow is

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reduced from €233,000 to €203,000 and €163,500, respectively. In case of higher initial costs (€5,000/kW, Figure 5) the cumulative cash flow declines by approximately 10–20%, while the net present value declines by 30–50%.

a) b)

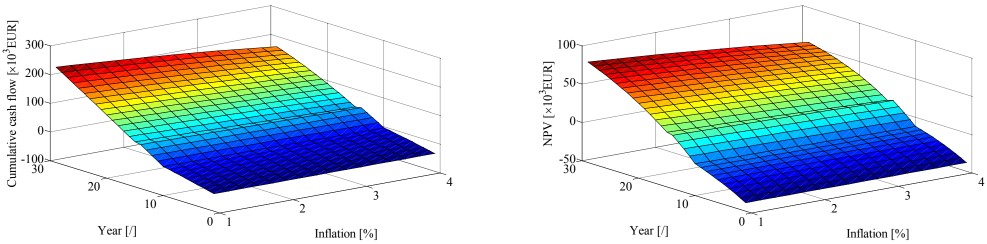

Figure 4: *Cumulative cash flow and net present value (NPV) dependent on the year time and the inflation (initial costs €4,000/kW)*

a) b)

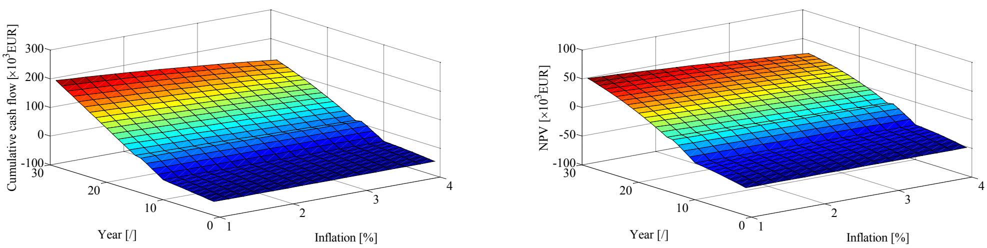

Figure 5: *Cumulative cash flow and net present value (NPV) dependent on the year time and the inflation (initial costs €5,000/kW)*

Figure 6 shows the variation of the internal rate of return (IRR) dependent on inflation. Figure 6a is obtained for initial costs €4,000/kW, while Figure 6b is valid for initial costs €5,000/kW. In both cases, the discount rate is set to 5% and energy costs to €105.47/MWh. As the figure shows, the internal rate of return is basically lower for higher values of inflation. In case of increased inflation (Figure 6a) from 1.0% to 2.5%, the internal rate of return decreases from 14.5% to 13.6%, while an inflation increase from 1.0% to 4% leads to an internal rate of return decrease of 12.5%. In case of higher initial costs (€5,000/kW, Figure 6b), the internal rate of return is reduced to approximately 8–10%.

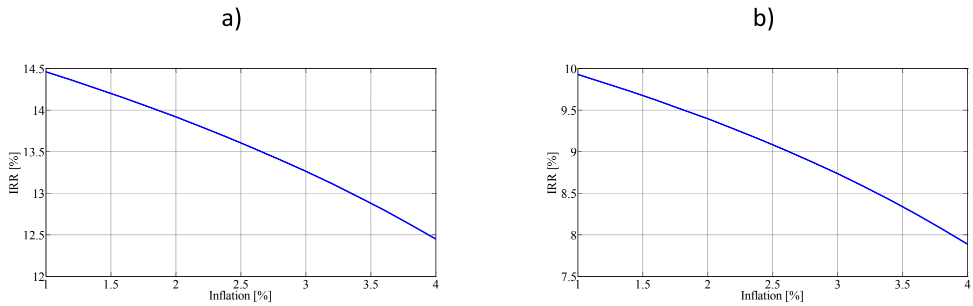

Figure 6: *Internal rate of return (IRR) dependent on the inflation: a) initial costs €4,000/kW, b) initial costs €5,000/kW*

5 CONCLUSION

In this paper, a detailed economic analysis of a small hydro power plant is performed. Financial parameters, such as inflation, discount rate and credit, are considered regarding their impact on the dynamic criteria for the investment evaluation. Those criteria, explained in this work, are the net present value and the internal rate of return. Additionally, the curve of cumulative cash flow is observed. In the technical part, all important input parameters involved in the power and delivered energy calculations of the small hydro power plant are described. In contrast, the impacts of different financial parameters like inflation and discount rate on the cumulative cash flow, net present value and internal rate of return are observed. All of the financial calculations are performed for a specific hydro power plant, where the cumulative initial costs are firstly €4,000/kW and secondly €5,000/kW. During calculations, the annual costs were set at €3,000/year, while 60% of initial costs are invested by a credit.

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FEASIBILITY STUDY OF USING A SINGLE-PHASE Z-SOURCE INVERTER IN PHOTOVOLTAIC SYSTEMS

ŠTUDIJA IZVEDLJIVOSTI ENOFAZNEGA Z-PRETVORNIKA ZA UPORABO V FOTONAPETOSTNIH SISTEMIH

Tine Konjedic[ℜ], Mitja Truntič[1], Miro Milanovič[2]

Keywords: DC-AC converter, single-stage, single-phase, Z-source inverter, pulse-width modulation;

Abstract

This paper presents a single-phase Z-source inverter intended to be used in grid-connected photovoltaic systems. The Z-source inverter is a single-stage converter that has buck-boost features. The operation principle of this converter was analyzed by using equivalent circuits during shoot-through and non-shoot-through states. For these states, voltage conditions were described with mathematical equations. Two types of pulse-width modulation (PWM) were proposed as well as verified and tested with simulation in Matlab/Simulink software. A control scheme was presented with the purpose of placing a Z-source inverter in a grid-connected photovoltaic system.

Povzetek

V članku je predstavljen enofazni Z-pretvornik, ki je namenjen uporabi v omrežno priključenih fotonapetostnih sistemih. Gre za enostopenjski pretvornik z impedančnim prilagodilnim vezjem,

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ki lahko na svojem izhodu generira izmenično napetost z višjo ali nižjo efektivno vrednostjo, glede na enosmerno vhodno napetost. Osnovni princip delovanja Z-pretvornika je predstavljen z uporabo nadomestnih vezij v kratkostičnem in nekratkostičnem stanju. Na osnovi nadomestnih vezij so posamezna stanja opisana z matematičnimi enačbami. V nadaljevanju sta predstavljeni dve vrsti pulzno-širinske modulacije za krmiljenje stikal pretvornika, ki na različne načine vključujeta kratkostična stanja med ostala stikalna stanja. Oba načina modulacije sta preizkušena s simulacijo v programskem okolju Matlab/Simulink. Z namenom vključitve Z-pretvornika v omrežno priključen fotonapetostni sistem je v članku predstavljena tudi regulacijska shema.

1 INTRODUCTION

Global warming, the increasing scarcity of fossil fuels and the recent nuclear disaster in Japan have raised many environmental concerns, as well as many questions about the use of conventional energy sources in the future. As a result, renewable energy technologies are being developed faster than ever before. The photovoltaic industry, for one, has experienced rapid growth in the previous decade and, since photovoltaic systems use the world's most abundant energy source, such growth is expected to continue in the future.

A key component of a grid-connected photovoltaic (PV) power generation system is an inverter, which is an interface between the PV array and the electrical grid. Its major task is the conversion of DC power, produced by PV cells, to AC power that is fed to the grid. In addition, a PV inverter must assure efficient operation in a wide range of DC input voltages; for this reason, voltage amplification is needed. Conventional transformerless PV inverters execute these tasks in two conversion stages, as shown in Figure 1. The first conversion stage is represented by a DC-DC boost converter, which amplifies the DC voltage to the desired level. In the second conversion stage, this voltage is converted into AC voltage, using a conventional H-bridge inverter. As every conversion stage generates a certain amount of loss, the idea of single-stage converters has become prevalent among researchers.

In order to improve inverter efficiency, which is theoretically possible with single-stage conversion, a few single-stage converter topologies have been proposed. The most promising is the Z-source Inverter (ZSI) [1-5]. Its simple structure, with a low number of passive and active components, offers high-efficiency power conversion. ZSI employs an impedance network that couples the converter main circuit to the power source.

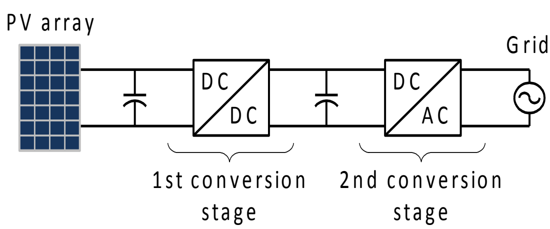

Figure 1: *Conventional two-stage conversion system*

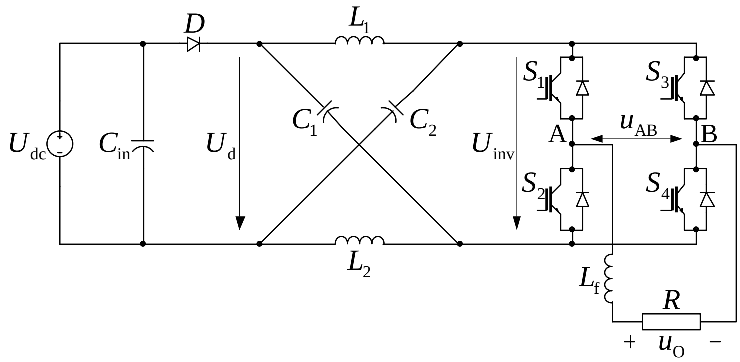

Figure 2: *Basic circuit of a single-phase Z-source inverter*

This network allows both switches of a phase-leg to be turned on simultaneously (shoot-through state) without damaging the inverter. Correct implementation of shoot-through states gives buck-boost features to the ZSI, as well as the potential to achieve higher efficiency than conventional PV inverters, on the basis of single-stage conversion.

This paper presents a detailed analysis of a single-phase ZSI, which is shown in Figure 2. It starts with a description of the operation principle and modulation requirements [6]. With the intention of determining the best means of shoot-through state inclusion, two different types of pulse-width modulation (PWM) are presented and evaluated. In order to place ZSI in a grid-connected PV system, a control scheme that would assure proper operation of the system is proposed.

2 OPERATION PRINCIPLE

From the operation of conventional inverters, active and zero switching states are known. When switching exclusively between those two states, only the buck feature of ZSI can be achieved. The boost operating regime is reached with the inclusion of shoot-through states, during which at least one phase-leg of the inverter is short-circuited. These kinds of switching states are allowed, due to the use of impedance network for connecting the power source with the main circuit of the ZSI. The impedance network consists of two capacitors and two inductors connected in an "X" shape. The capacitances and inductances of all passive components must have the same value in order to achieve complete symmetry of the network, which is required for proper operation of the converter.

The operation of the ZSI in the boost regime is easily explained with the use of equivalent circuits shown in Figure 3. When in a non-shoot-through active state, the current flows from the source through the impedance network and inverter circuit to the load, while no current flows from the inverter circuit to the load in cases of non-shoot-through zero state. For this reason, the inverter side of the ZSI can be represented as an equivalent current source with finite current during the non-shoot-through active state and zero current during the non-shoot-through zero state. For the duration of non-shoot-through states T_{NS}, which include active and zero states, the following equations can be written:

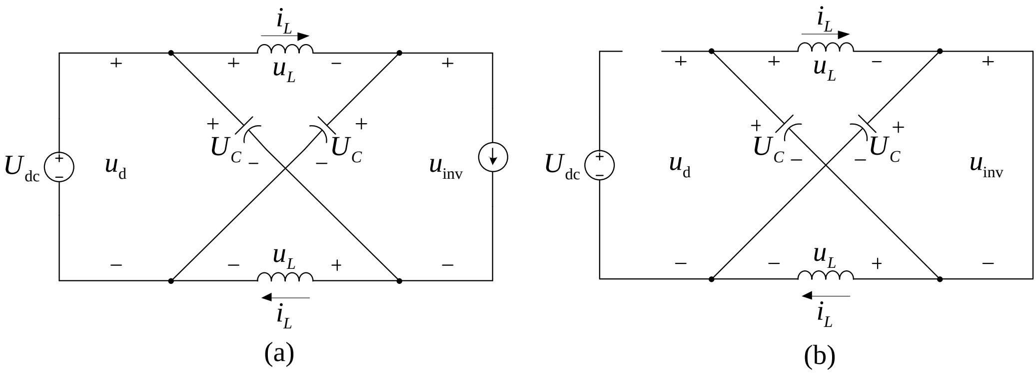

Figure 3: *Equivalent circuits of Z-source inverter in (a) non-shoot-through state and (b) in shoot-through state*

$$\begin{aligned} u_{\mathrm{d}} &= U_{\mathrm{dc}} \\ u_L &= U_{\mathrm{dc}} - U_C \\ u_{\mathrm{inv}} &= U_C - u_L = 2U_C - U_{\mathrm{dc}} \end{aligned} \tag{2.1}$$

In the shoot-through state, the inverter side is represented by a short circuit. Input diode D blocks the current flow from impedance network to the source, as the resulting voltage across both capacitors is higher than the voltage of power source. For the duration of shoot-through states T_{ST}, the following equations can be written:

$$\begin{aligned} u_{\mathrm{inv}} &= 0 \\ U_C &= u_L \\ u_{\mathrm{d}} &= U_C + u_L = 2U_C \end{aligned} \tag{2.2}$$

Hence, the average voltage across the impedance network inductor over one switching period ($T = T_{\mathrm{NS}} + T_{\mathrm{ST}}$) should be zero in steady state. The voltage across impedance network capacitor can be obtained as:

$$U_C = \left(\frac{1-(T_{\mathrm{ST}}/T)}{1-2(T_{\mathrm{ST}}/T)} \right) U_{\mathrm{dc}} \tag{2.3}$$

Using (2.1) and (2.3), the peak DC link voltage across the inverter bridge can be written as:

$$\hat{U}_{\mathrm{inv}} = 2U_C - U_{\mathrm{dc}} = \left(\frac{1}{1-2(T_{\mathrm{ST}}/T)} \right) U_{\mathrm{dc}} = BU_{\mathrm{dc}} \tag{2.4}$$

where

$$B = \left(\frac{1}{1-2(T_{\mathrm{ST}}/T)} \right) = \left(\frac{1}{1-2d} \right) \tag{2.5}$$

is the DC voltage boost factor, which is set by the shoot-through duty cycle $d = (T_{\mathrm{ST}}/T)$.

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3 PULSE-WIDTH MODULATION

The use of shoot-through states for voltage amplification in combination with the employment of a suitable pulse-width modulation (PWM) gives the ZSI its unique buck-boost feature. PWM must assure the proper inclusion of shoot-through states between active and zero states. In addition to that, inverter output signal quality and switching losses must be taken in consideration when developing PWM schemes. For achieving low harmonic distortion of output voltage and current, active switching states must be centrally placed within the switching half-period [6], while in order to generate minimum switching losses during operation, the number of switching events over one switching period must be reduced to minimum. In the following sections, two different types of PWM for the ZSI are presented.

3.1 Pulse-width modulation with sinusoidal envelope

PWM with a sinusoidal envelope is based on the method proposed in [4]. It follows the idea to achieve minimum switching losses. Although there are twice as many state transitions over one switching period as with conventional PWM, the total count of switching events is the same. Shoot-through states are placed at the transitions between active and zero states, as shown in Figure 4 (a), while active states are kept in the centre of each switching half-period.

Figure 4 (b) shows PWM signals and their effect on inverter output voltage. Equations for generating PWM reference signals can be written as:

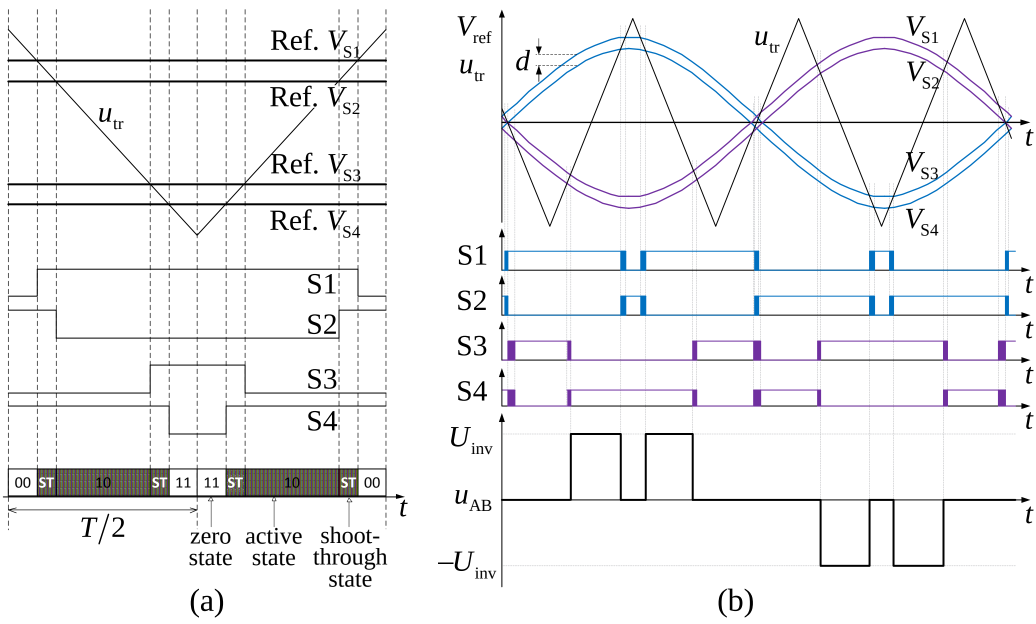

Figure 4: *PWM with sinusoidal envelope; (a) PWM signals over one switching period and (b) sketch map of output voltage generation principle*

$$\begin{aligned} V_{S1} &= m_I \sin(\omega t) + 0{,}5d \\ V_{S2} &= m_I \sin(\omega t) - 0{,}5d \\ V_{S3} &= -m_I \sin(\omega t) + 0{,}5d \\ V_{S4} &= -m_I \sin(\omega t) - 0{,}5d \end{aligned} \tag{3.1}$$

where V_{S1}, V_{S2} are used for modulating phase-leg {S1, S2} and V_{S3}, V_{S4} for modulating phase-leg {S3, S4}. The shift between both pairs of reference signals represents duty cycle d, which sets the duration of shoot-through states and consequently the voltage amplification level. The output voltage of ZSI that is generated using PWM with sinusoidal envelope is defined as:

$$u_{AB} = \left(m_I \sin(\omega t) - \frac{d}{2} \right) U_{inv} \tag{3.2}$$

3.2 Pulse-width modulation with central pulse

PWM with a central pulse is derived from [5], where a similar method was used for the modulation of a three-phase inverter. Its main idea lies in the inclusion of shoot-through states inside zero switching states. In this way, the position and duration of active states within the switching period is maintained. Although this way of employing shoot-through states is theoretically considered to be advantageous in comparison with other PWM methods, it leads to a higher number of switching events over a switching period.

Figure 5 shows PWM signals, state transitions and their effect on output voltage of the inverter. PWM reference signals can be written as:

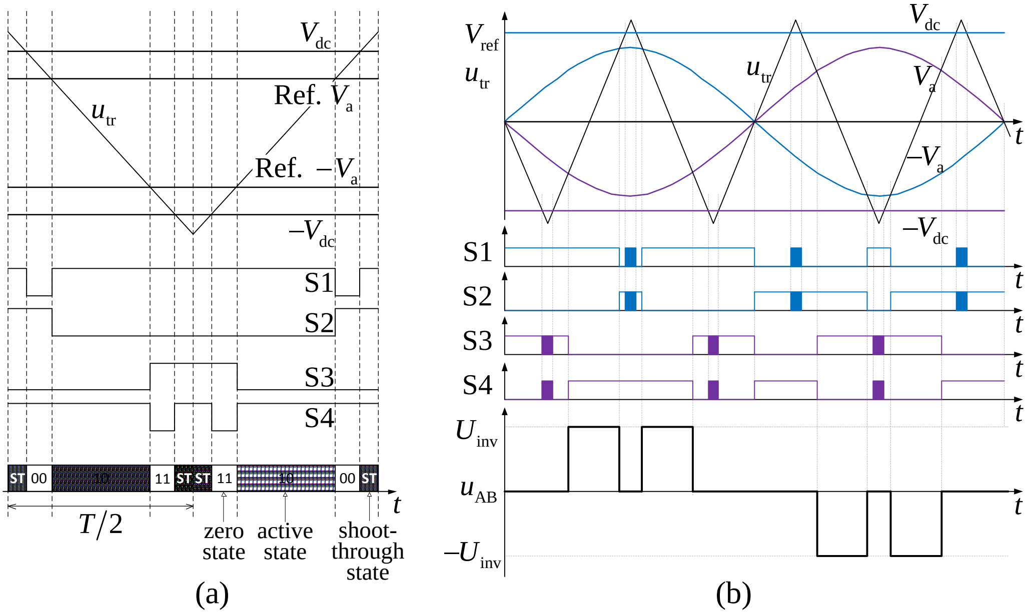

Figure 5: *PWM with central pulse; (a) PWM signals over one switching period and (b) sketch map of output voltage generation principle*

$$\begin{aligned} V_{\mathrm{dc}} &= 1-d \\ V_{\mathrm{a}} &= m_{\mathrm{I}}\sin(\omega t) \\ -V_{\mathrm{a}} &= -m_{\mathrm{I}}\sin(\omega t) \\ -V_{\mathrm{dc}} &= -1+d \end{aligned} \tag{3.3}$$

where V_{dc}, V_{a} are used for modulating phase-leg (S1, S2) and $-V_{\mathrm{a}}$, $-V_{\mathrm{dc}}$ for modulating phase-leg (S3, S4). Shoot-through states are employed exclusively with the manipulation of switches S1 and S4, while their duration (and consequently voltage amplification) is set by duty cycle d that is applied through DC reference signals V_{dc} and $-V_{\mathrm{dc}}$. The output voltage of ZSI that is generated using PWM with central pulse can be defined as:

$$u_{\mathrm{AB}} = m_{\mathrm{I}}\sin\left(\omega t\right)U_{\mathrm{inv}} \tag{3.4}$$

4 CONTROL SCHEME

In addition to voltage amplification and DC-AC conversion, each PV inverter must assure operation at the maximum power point of the PV array, while transferring sinusoidal current to the grid. For achieving this, control systems are employed. As presented in the previous section, the main control variables of ZSI are the shoot-through duty cycle d and modulation index m_{I}. In Figure 6, a control scheme for ZSI is proposed. In order to minimise the value of input capacitance C_{in}, DC current control is used. The DC current control loop ensures that constant current is drawn from the PV array. This is done by altering the shoot-through duty cycle, which is one of the parameters for PWM reference signal generation. The other PWM parameter, modulation index m_{I}, is generated by the AC side-control loop, which must assure that clear sinusoidal output current is synchronised and fed to the grid.

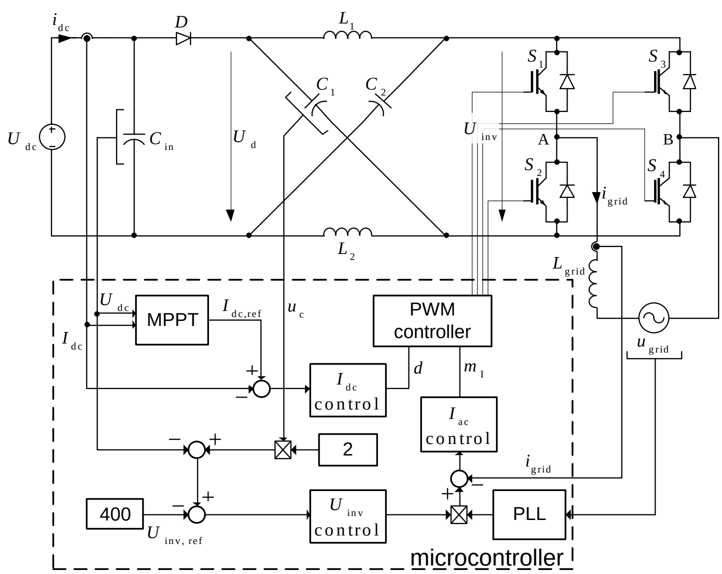

Figure 6: *Z-source inverter circuit with proposed control scheme*

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5 SIMULATION RESULTS

In order to verify the described operation principle and to evaluate the proposed PWM methods, a simulation model of ZSI was built using Matlab/Simulink software. The simulation of operation in the boost regime was carried out with the same initial conditions, the same simulation model and the same input as well as the desired output voltage and current for both PWM methods.

Input DC voltage was set to $U_{\mathrm{dc}} = 300\ \mathrm{V}$, capacitance of input capacitor $C_{\mathrm{in}} = 3000\ \mu\mathrm{F}$, impedance network parameters $L_1 = L_2 = L = 300\ \mu\mathrm{H}$ and $C_1 = C_2 = C = 500\ \mu\mathrm{F}$, while the purpose of the system was to generate a single-phase 230 V RMS, 50 Hz voltage at about 2.3 kW of power transferred. The switching frequency was set to 16 kHz. From the above-listed parameters, modulation index m_{I} and d were calculated for both PWM methods.

The simulation results have shown some advantages as well as disadvantages of both PWM methods. The advantage of PWM with the sinusoidal envelope is the lower number of switching events per switching cycle that result in lower switching losses. Its disadvantages are discontinuous output current and voltage, which are seen in Figure 7 (a). Discontinuity appears at the crossing of zero as a consequence of repeating transitions between shoot-through and zero switching states, without any active state among them. Alternatively, PWM with central pulses offers a clear sine wave output current and voltage, shown in Figure 7 (b), while its disadvantage is represented by a higher number of switching events per switching cycle. Figure 8 shows voltage conditions on the DC side of ZSI for both tested PWM methods and proves the described operation principle as well as equations (2.3) and (2.4).

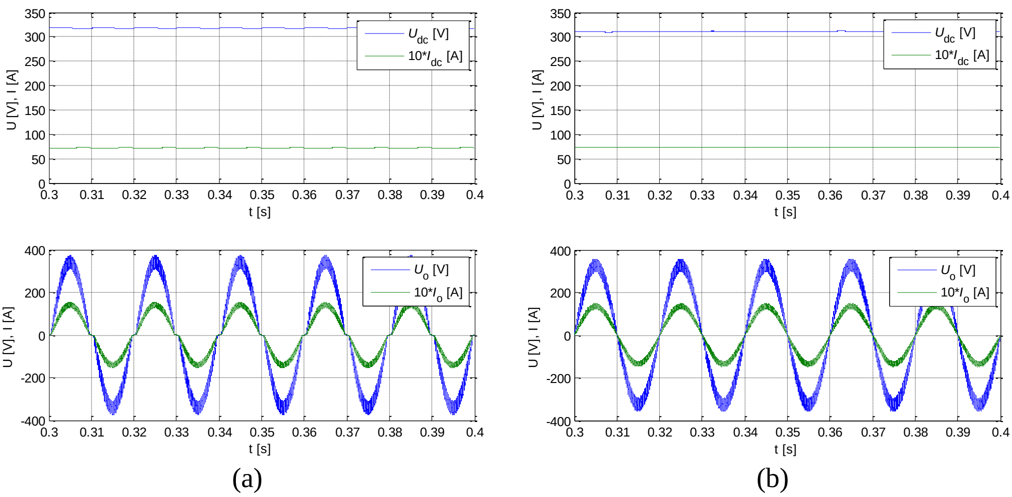
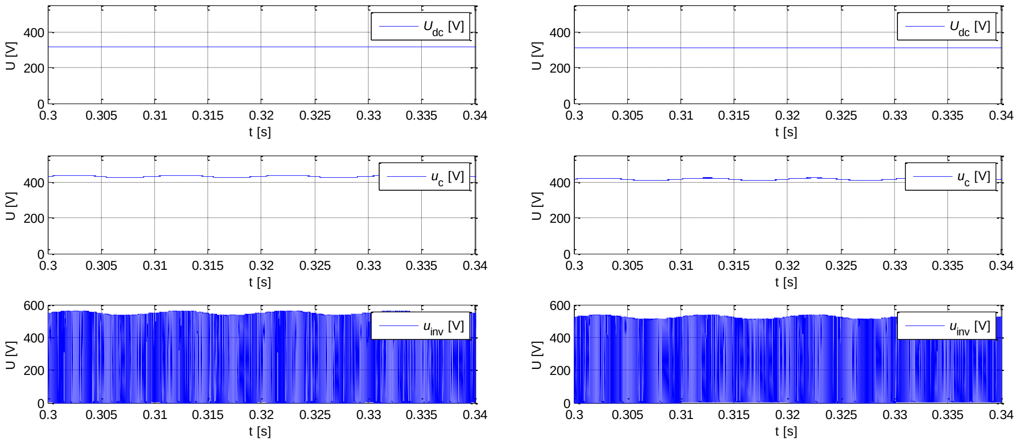


Figure 7: *Converter input voltage U_{dc} and current I_{dc} (upper) and output voltage u_{O} and current i_{O} (lower); (a) PWM with sinusoidal envelope and (b) PWM with central pulse*



(a) (b)

Figure 8: *Converter input voltage* U_{dc} *, voltage across Z-source capacitor* U_C *and DC voltage across inverter bridge* u_{inv} *; (a) PWM with sinusoidal envelope and (b) PW with central pulse*

6 CONCLUSION

In this paper, a feasibility study of a single-phase ZSI was discussed. As part of the study, the operation principle was analysed, two types of PWM were introduced and tested with simulation, and a control scheme was proposed. The ZSI employs a unique impedance network that couples the inverter bridge to the power source and provides unique features that overcome the conceptual and theoretical barriers of conventional inverters.

The comparison of both PWM methods has shown that PWM with central pulses has four additional switching events per switching cycle, i.e. 12 in total. Because switching manipulations directly result in switching losses, it was estimated that PWM with central pulses generates 50% more switching losses than PWM with a sinusoidal envelope at the same switching frequency. Switching losses represent a major share of total losses of switching power converters operating at switching frequencies of 16 kHz and above. For this reason, it is unacceptable to use PWM with central pulses for a ZSI used in residential PV systems, although it offers better output voltage and current shape. Inverter efficiency is a crucial parameter, especially regarding selling the product on the market; for this reason, PWM with a sinusoidal envelope was chosen for the upcoming phases of single-stage ZSI development. Future research will be focused on eliminating the discontinuity in output current and voltage as well as on implementation of the proposed control scheme to make ZSI suitable for use in photovoltaic applications.

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Nomenclature

(Symbols)	(Symbol meaning)
B	boost factor
C_{in}	converter input capacitor
C_1, C_2	impedance network capacitors
d	shoot through duty cycle
D	converter input diode
I_{dc}	converter input DC current
i_{grid}	grid current
i_L	impedance network inductor current
i_{O}	converter output AC current
L_1, L_2	impedance network inductor
L_{f}	output filter inductor
L_{grid}	grid inductance
m_{I}	modulation index

R	resistor
S1, S2, S3, S4	switches/IGBT transistors with anti-parallel diode
t	time
T	switching period
T_{NS}	non-shoot through state interval
T_{ST}	shoot through state interval
u_{AB}	converter output voltage
U_C	impedance network capacitor voltage
u_{d}	impedance network input voltage
U_{dc}	converter input voltage
u_{grid}	grid voltage
u_{inv}	voltage across the input of inverter bridge
U_{inv}	mean value of voltage across the input of inverter bridge
$\hat{U}_{\mathrm{inv}}$	peak voltage across the input of inverter bridge
u_L	impedance network inductor voltage
u_{O}	filtered converter output voltage
u_{tr}	PWM carrier signal
V_{a}, V_{dc}	reference signals for PWM with central pulse
V_{S1}, V_{S2}, V_{S3}, V_{S4}	reference signals for PWM with sinusoidal envelope

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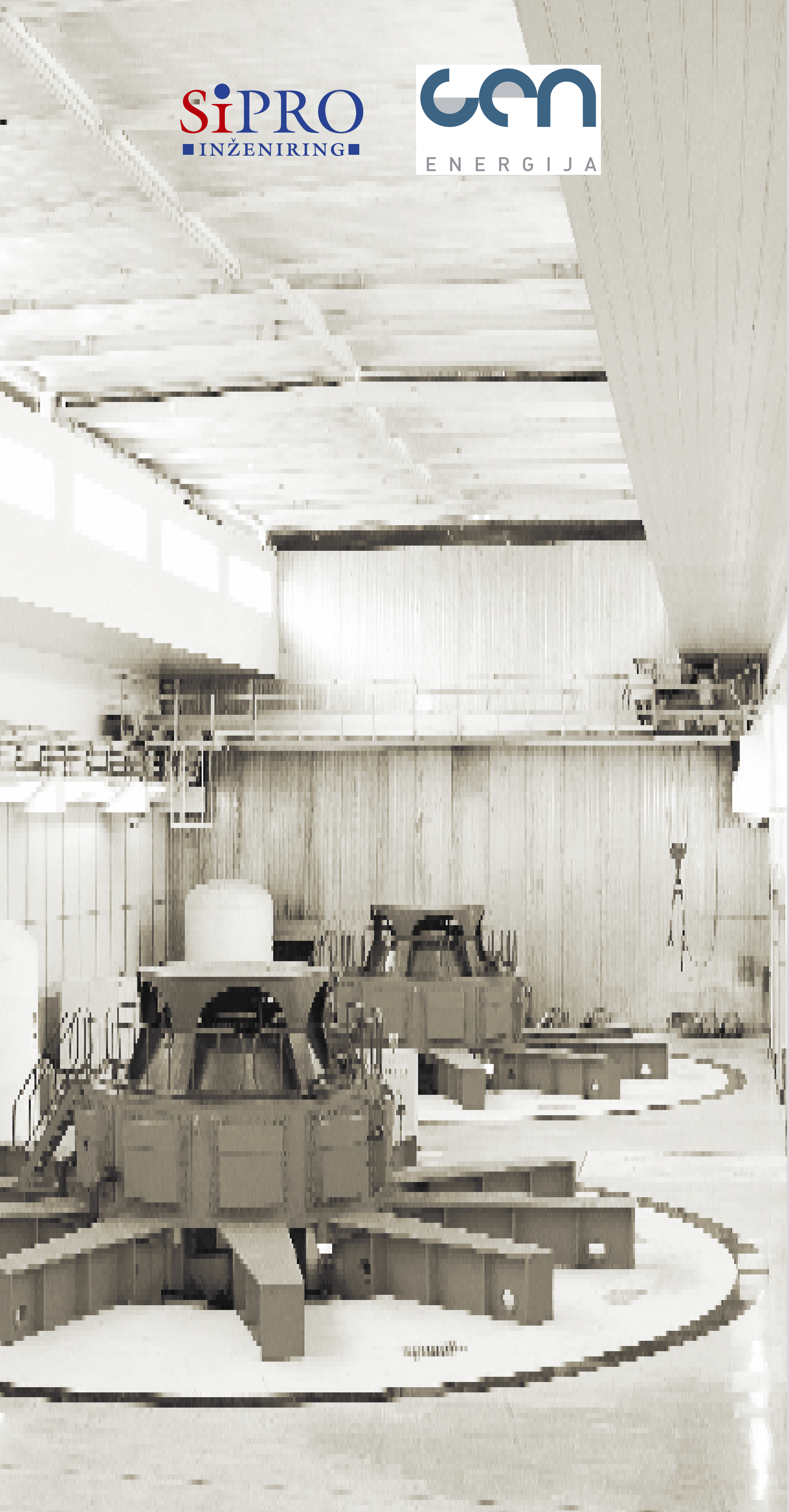

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