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The Söderfors Project: Construction of an Experimental Hydrokinetic Power Station

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***Abstract*—The Division of Electricity at Uppsala University is developing an experimental hydrokinetic power station for in-stream experiments at a site in a river. The purpose of this paper is to present some of the design choices made in the construction of the experimental station. For background purposes, an outline of the research project as a whole is also given.**

The experimental station will be deployed in the Dalälven River at Söderfors, whence the project derives its name. The site was selected based on several technical and non-technical reasons. The system comprises a vertically oriented cross-stream axis turbine and a directly driven permanent magnet generator to be situated on the riverbed. The necessary power electronics for control and power conversion will be housed in a small measuring station on shore.

The paper discusses several aspects of the project, that might be of interest to other researchers in the field. Various design choices, where different properties become the limiting or deciding factor in different cases, are discussed along with their respective advantages and disadvantages. A brief outlook as to the future of the project is also given.

***Index Terms*—hydrokinetic energy, vertical axis turbine, low-speed generator, experimental facility**

I. Introduction

At the Division of Electricity at Uppsala University, a hydrokinetic, or marine current energy conversion system is being investigated. The basic topology of the system is a cross-stream axis turbine with fixed blades directly connected to a low-speed, permanent magnet generator. An experimental version of the setup is being constructed and will be deployed in the Dalälven River at Söderfors. The research project, dubbed the *Söderfors Project* due to the location of the test site, has been underway for some years, and results have been presented at previous EWTECs and published in journal papers.

While the publication of scientific results is ultimately the aim of any research project, the organisation, execution and lessons learned along the way of such a project may also be of considerable interest to others involved in the field. A project description, outlining some of the engineering methods employed and design choices made, was published in 2009 [1]. The present paper is intended as a project update, with focus on the most recent work accomplished, as well as an account of a selection of design considerations and trade-offs that have been encountered or are anticipated in the course of the project.

Research on hydrokinetic energy conversion has been conducted at Uppsala University since 2000. A prototype low-speed permanent magnet generator was designed and built in a laboratory environment in 2007 [2]–[5]. The performance of the turbine and generator separately and combined has been studied [6], [7]. The test site at Söderfors has been analysed [8], [9]. Design and construction of the test equipment is currently ongoing with deployment planned for the summer 2011.

II. Purpose and Objectives

The overall purpose of the Söderfors Project is to contribute to the total sum of knowledge and insight regarding hydrokinetic energy conversion. Hopefully, such a contribution will serve to limit or even decrease to some extent the dependence of modern society on energy from fossil fuels. Having said that, a research project needs more concrete goals.

The experimental station at Söderfors is primarily intended for proof of concept, validation of simulation tools, and for experience. The project is distinguished from other hydrokinetic energy projects in that it is aimed at comparatively low water flow speeds (see Sec. III). If the threshold speed for technically and economically useful energy conversion is lowered, the number of exploitable sites will increase, as will the total extractable energy resource worldwide.

III. Site

The experimental station will be deployed in the Dalälven River at Söderfors, approximately 800 m downstream of a conventional hydro power plant belonging to Vattenfall AB (see Fig. 1 and 2). The selected site exhibits several properties favourable for making experiments:

- Water depth (6–7 m) and discharge (typically 300–1 100 m^3/s) are within reasonable ranges for the present purposes.
- Water speed at the site varies over a suitable interval (see Fig. 3).
- The location downstream of a hydro power station offers the possibility to control the flow to a certain extent through co-operation with the power plant owner.
- The test site is within the excavated outlet canal of the power station, which makes for a relatively "clean" conduit geometry.

Fig. 1. The location of Söderfors, approximately 1 hour's drive north of Uppsala.

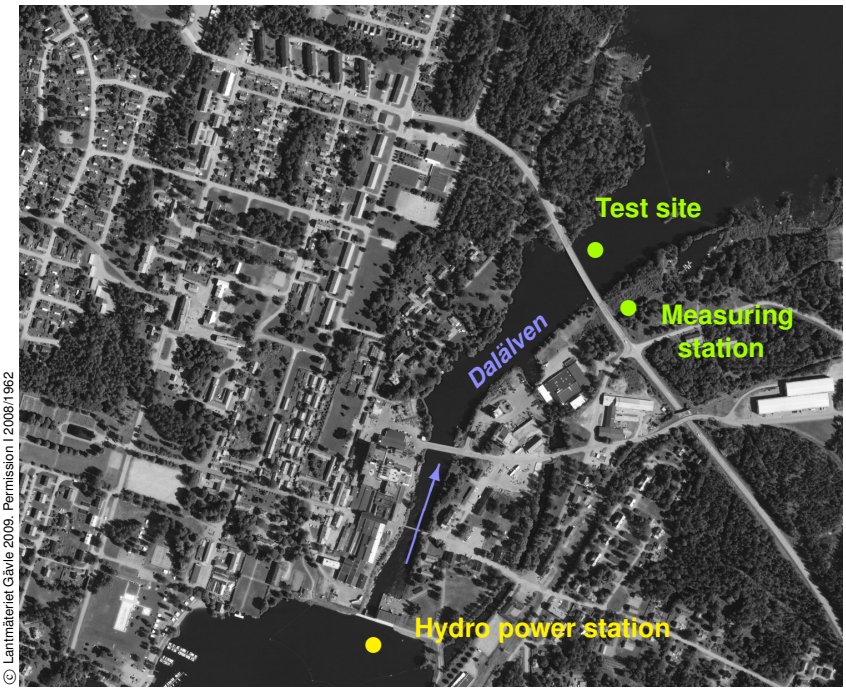

Fig. 2. A bird's eye view of central Söderfors. The experimental station will be placed some 800 m downstream of the conventional hydro power plant.

However, there are also several non-technical reasons for the selection of this site:

- There is little or no shipping or other boat traffic on the river at the site.
- A road bridge, from which the test station can be deployed, crosses the river at the same place.
- The power plant owner, local and regional authorities (the Municipality of Tierp and the Uppsala County Administrative Board) and private and corporate neighbours to the site in Söderfors have all taken a sympathetic attitude towards the project.
- Söderfors is about 75 km from Uppsala, making the site accessible from the University on a daily basis.

It is to be noted that the Söderfors site might not be the best choice for a hydrokinetic power station whose main purpose were electricity production rather than experimental research. While many requirements for these different purposes coincide, others do not, and a given site property that is very beneficial for one purpose may not be so for another.

IV. Technical Concept

The experimental setup comprises a straight-bladed Darrieus type turbine connected to a direct-driven permanent magnet generator situated on a tripod on the river bed. On shore, a small cabin will be placed housing the start and control system as well as measuring equipment. Details of some of the parts are outlined below.

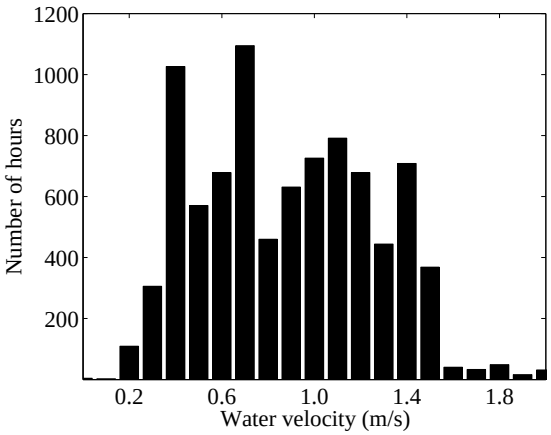

Fig. 3. Annual water speed distribution at the selected site, averaged over five years.

A. Foundation

The bottom of the river was investigated by divers. This work was difficult to perform due to very poor sight caused by humus particles in the water. The river bed has a fairly hard surface mainly of rough gravel, and there are occasional rocks of sizes up to a few decimetres.

A tripod design was chosen for the foundation. Initially, a solid concrete design was considered, but it was later discarded in view of the unevenness of the river bed and the relatively large amount of concrete required. A steel tripod solution makes for a smaller foundation volume for the same underwa-

ter weight, while at the same time being less sensitive to river bed smoothness. The gravity base concept was retained since it provides for deployment without underwater construction work, but it does offer difficulties of its own in terms of assessing the hardness of the river bed, the friction between the river bed and the tripod feet, etc.

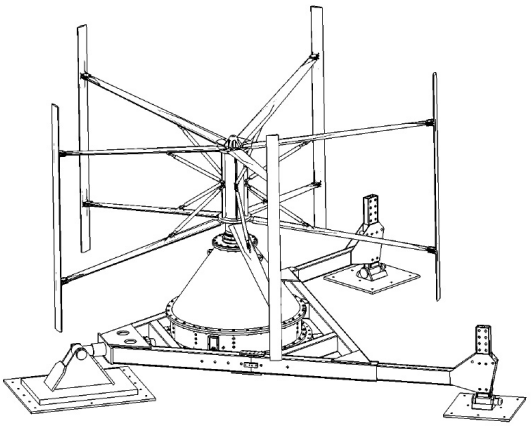

Fig. 4. Overview of the whole energy conversion unit with turbine and generator mounted on a tripod foundation. Design by Anders Nilsson.

B. Turbine

The vertical axis turbine will have 5 straight blades with a NACA 0021 profile and a chord length of 0.18 m, 3.5 m tall at a radius of 3 m. The height of the turbine is based on the depth at the site, leaving about 1 m free space to the water surface and enough room below for the generator and foundation.

The size of the turbine and the water velocities at the site give indications of what power the generator and subsequent converters will have to work with. The design point for the generator relates to the cross section of the turbine (21 m^2), an estimated power coefficient C_P of approximately 0.35 and a water velocity of about 1.4 m/s.

The number of blades and the radius of the generator were chosen in an early design stage, and have not been optimized in any way. A larger number of blades will reduce the torque oscillations, but will also result in a shorter chord length and increased drag due to struts. The blade pitch angle is fixed at 3° outward in order to even out forces on the blades over a revolution.

The turbine runner will be constructed mainly from carbon fibre composite. Steel blades and struts were also considered, but not chosen mainly due to the difficulties involved in handling heavy components.

The turbine shaft is a sleeve that fits on the generator shaft. The assembled turbine will be lowered onto the generator shaft and secured.

No protection against ice or debris will be installed initially. The turbine is not entirely exposed since the turbine should be up to 1 m below the water surface, which ought to be sufficient to avoid most floating debris. The upstream power plant may filter some objects, though while investigating the site it was also noted that accumulated debris may be flushed through the floodgates. Without ice protection the unit should probably not be operated in the winter.

C. Generator

The generator design is essentially a cable-wound, permanent magnet generator. The basic design is similar to that of the prototype marine current generator constructed for in-lab use, presented previously at EWTEC 2007 [2], [4]. A relatively large number of poles (112 for the Söderfors station) and a diameter just under 2 m enable electricity generation at rotational speeds on the order of 10 r.p.m. Compared with the prototype generator, efforts have been made to reduce the volume of the stator in order to reduce the impact of iron losses at low speeds in accordance with the results described in [5]. Some figures relating to the generator design are tabulated in Tab. I.

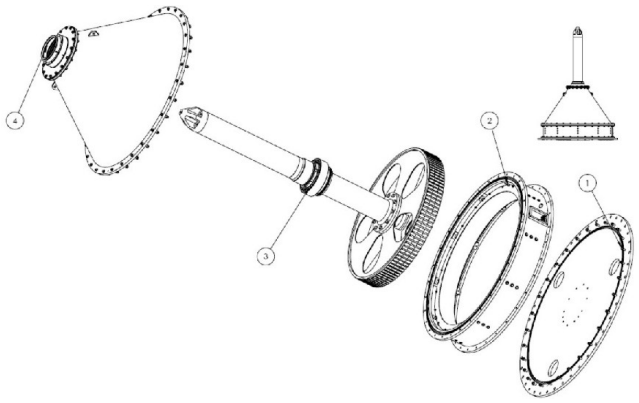

Fig. 5. Overview of the generator housing. 1: floor of housing, 2: stator support, 3: rotor and shaft 4: lid and turbine support. Design by Anders Nilsson.

Generator Housing: The generator housing performs two functions: to support the generator and turbine, and thus withstand the electromagnetic forces that arise, and to keep the generator dry. It must also be designed such that the generator can be built or inserted into it.

A piece of a steel tube, reinforced with beams and flanges was chosen as a basic structure. This spool-like structure (Fig. 5, item 2) has been sized such that it can be machined at a local engineering workshop (Sjölanders Mekaniska AB) to give the necessary tolerances. The height of the tube is taken to fit the length of the stator including coil ends. At the bottom, a bit of extra room is needed for the bearings that the rotor will rest on, and this extra space may be further utilized for measurement equipment. The stator is to be mounted on the beams in the support structure. As a result, the tube will be perforated by bolts holding the stator in place.

After the stator is finished (stacked and wound), the flat flanged end of the housing will be mounted on the bottom flange together with a seal. The unmagnetized rotor will be lowered into the stator and secured using the conically shaped lid. Once the lid is in place, the generator will be tipped

TABLE I
GENERATOR DATA

Parameter	Value
Dimensions	
Axial length	197 mm
Stator outer diameter	1 800 mm
Stator inner diameter	1 635 mm
Air gap	7 mm
Number of poles	112
Magnet thickness	10 mm
Magnet width	30 mm
Nominal performance	
Speed	15 r.p.m.
Armature voltage	138 V
Frequency	14 Hz
Apparent power	7.5 kW
Power factor	1
B in air gap (load)	0.73 T
B in tooth (load)	1.7 T
Iron losses	0.29 kW
Copper losses	0.96 kW
Nominal torque	5.6 kNm
Efficiency	86 %
Load angle	8.0°

on its side and fixed in a support for the remainder of the construction work and laboratory trials.

Permanent magnets (Nd Fe B) will be inserted into rectangular slots in the rotor through holes in the bottom of the housing. Hall effect sensors for the starter system and a webcam for surveillance purposes will also be mounted on the stator. The holes in the flat flanged end will later be permanently sealed.

The rotor is supported by one bearing on the flat flanged end of the housing and one at the top end of the conically shaped lid. The conical lid proved to be a good option compared to e.g. a flat lid and an exterior framework to support the shaft closer to the turbine. The conical lid gives adequate support without influencing the flow to any great extent, is easily manufactured and only requires one seal on the shaft.

D. Control

On shore, some 150 m from the generator and turbine, a small cabin will be placed, housing the starter, load control system and monitoring equipment.

Start-up: While the turbine may be self-starting under certain circumstances, this cannot be presumed to always be the case, and thus a start-up system will be required. To start the turbine, the generator will be run as a motor using the three-phase winding in the stator. As the turbine increases in rotational speed, it will begin to give a torque contribution. Turbine simulations at low tip speed ratios are more uncertain than at higher ratios, and frictional losses in several components are not yet known; thus the precise course of the start is not yet well defined. Although a sensorless start is ultimately desired, the uncertainty in the start-up motivates the installation of Hall effect sensors triggered by the generator rotor magnets to enable a sensor controlled start.

The start-up system is separate from the load control system, i.e. a dedicated voltage source and inverter will be used for start-up. Parts of the start could be combined with the load control system, but the two are kept apart for the time being for reasons of simplicity.

Load Control: Initially, the electricity from the generator will be rectified using a passive diode bridge and then spent in a resistive load, i.e. the step of inverting to grid standards will be omitted as a means of simplifying the system. The load control system will essentially regulate the power extracted on the DC-side, thus regulating the rotational speed of the generator rotor and the turbine. The rotational speed of the turbine, or rather the tip speed ratio, will determine the amount of power absorbed from the stream.

Such a control system was constructed and tested in the laboratory using the prototype generator for marine current energy conversion [10]. A microprocessor was used to determine the duty cycle of an IGBT connected in series with the load. Using this system, fixed speed (or voltage) and fixed tip speed ratio operation were demonstrated. At Söderfors, a similar system will be employed.

E. Safety

The safety of the experimental station itself, its operators and not least third parties must be acceptable. This is not only in everyone's best interest, but is also a prerequisite in order to obtain all necessary permits and fulfil other applicable legal requirements (see Sec. V).

Electrical: The electrical system will be designed and built in accordance with relevant national and EU standards. In this manner, sufficient electrical safety will be ensured for operators as well as the general public.

Rotational safety: The control system is completely electrical. If, during operation, the turbine shows a tendency to increase its rotational speed beyond the current setting of the control system, an emergency stop will be effectuated by the connexion of an "emergency stop load" with a low resistance. This will dramatically increase the power take-off, effectively slowing down the generator and turbine.

In case divers need to work on the station, it must be secured from unintentional start-up. For divers to be able to work, the water speed must be low, which is accomplished by regulation of the flow by the upstream hydro power station. Furthermore, the generator will be short-circuited in order to lock the rotor in place, and the start-up system will be physically disconnected. The last two measures will also be in effect when the station is not in use between experiments.

Navigation: The area around the turbine will be marked as off-limits to boat traffic. The restricted area will be on the order of 1/5 of the total river width, still allowing any boats able to pass under the bridge (clearance below approx. 2 m) free access up river.

The Dalälven is not a busy waterway. The river is fully regulated, with hydro power dams without locks effectively

barring all shipping. Private recreational boating does occur locally. At Söderfors, and in the river section extending downstream to the next hydro power dam (approx. 8 km), the typical boat is an open rowing or motor boat with an overall length of 5–6 m and a draught counted in decimetres, making the chance of even a stray boat wandering past the markings actually hitting the turbine blades minute.

V. Non-technical considerations

Although the majority of the work involved with constructing an experimental station as described here relates to interdiciplinary engineering work, there is a quite significant workload that is not principally engineering. Securing necessary permits for contructions in the water and on land, negotiating with interested parties, etc. also take significant time.

The installation of generator and turbine in the river require permission from the land-owner (the local municipality) and the owner of the hydro power plant upstream (Vattenfall AB). For a construction in the water, a special permit is required, and a five-year permit from the County Administrative Board has been obtained.

The on-land station for measurements and control requires a special building permit from the municipality as it is in close proximity of the water. Cables mounted on the bridge and buried on land also require permits.

The on-land station needs to be erected and provided with electricity. Initially a small cabin was thought to be most unobtrusive to the locals. Upon discussing the matter with the local building authorities however, it was revealed that a less homely-looking building was preferable. Apparently, the general public is more concerned not to disturb someone's summer cottage than to walk nearby a utility installation, and not disturbing the general public walking in the area was essential.

VI. Future Work

Construction and deployment is taking place in spring and summer 2011. First experimental results should appear later in the year.

Once the experimental station has been established, there are innumerable opportunities for research at the site. The research potential of a properly established experimental station is essentially limitless. The future of the Söderfors Project will be a function of, among other things, initial results obtained and the possibilities of securing continued funding.

Acknowledgments

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