Evaluation of Swedish Hydro Power Centre 2013-2016

Hydropower turbines and generators

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Summary

This report is a scientific evaluation of the competence area "Hydropower turbines and generators" (Vattenturbiner och generatorer) of the Swedish Hydropower Centre (SVC) for the years 2013-2016.

The competence area comprises Rotordynamics (LTU), Electromechanics (UU), fluid dynamics (CTH and LTU) and Machine element (LTU).

After reviewing the given documentation and conducting interviews with some of the senior scientists and in addition the steering committee chairman, we conclude that the competence area "Hydropower turbines and generators" within SVC is a highly successful initiative.

Our clear recommendation is to continue with SVC further along the same route as in the current program period, considering our suggestions. Our main conclusions are:

- The long-term commitment has created a high quality research environment which has produced results at international world class level.
- Within all the research groups there has been a large production of qualified personnel through master thesis, licentiate thesis and PhD thesis work.
- SVC has achieved to give a significant and tangible contribution to building competence and new knowledge within hydropower in Sweden and thereby secure future value creation from hydropower in Sweden.
- The framework with 4-year Program plan, yearly updated working plans and reference groups allocated to each senior scientist has resulted in good concordance between the program plan, the executed research and results.
- The reference groups gives valuable input and feedback to the research and increase implementation of the results in the industry. The project portfolios becomes relvant and balanced.
- The appointment of senior scientists is a key factor for the success. The continuity and duration is a very important factor in building scientifically strong and productive research groups.
- The long-term commitment also enables to increase the scientific quality through a step-by-step development where each PhD project can build on previous work.
- The three new system competency areas has contributed to increased collaboration between the disciplines and the alignment of some executed research projects.

Our main recommendations for a new program period of SVC are:

- Utilize the possibility for associate professorships, temporary guest research positions and professional training courses to bring the results into the industry and to promote innovation.
- With the high quality and volume of the research activity, we advise higher visibility at international conferences to present the work

performed and to establish international research collaboration. We further encourage participation in international for a and working groups such as IAHR, IEC and CIGRÉ. This applies not only to the senior researcher, but also to other members and to the industry partners.

- The electrical insulation is a criterial issue concerning failures and outages due to the aging of the machines and new operation schemes. Research on diagnostics, condition monitoring and new materials are highlighted topics in international research. Almost all refurbishment and upgrading of the generators involves replacing the windings. Sweden further has a large domestic industry fabricating windings. We therefore recommend SVC to appoint a senior scientist in this field.
- After evaluation of the groups Rotordynamics and Machine elements combined with interviews we conclude that these two groups (senior researcher) should continue to be two separate groups due to the distinction in competence needed to do research in these areas. At the same time it is important to encourage close collaboration between the groups.
- The ongoing work to strengthen the collaboration between the different research groups should be continued. This includes the three new system areas as well as specific multidisciplinary research projects. It should be considered if one senior researcher should have particular responsibility for the system areas.
- The recruitment of master students (*examensarbete*) is a challenge for some of the research groups. Consider to compensate the students with SVC funding or other active steps to increase the recruitment of candidates.
- The key importance of and investment in the senior researchers also make the groups vulnerable if the senior researcher leave his position. The robustness of the research groups must be evaluated by the steering committee and possible contingency plans considered.
- With the availability the Porjus Hydropower Centre the SVC has the ability to perform multidisciplinary research at industrial scale. This work should be continued and expanded whenever possible. This unique facility is also an excellent platform for international collaboration.

Approach

About this report

This report concerns the competence area "Hydropower turbines and generators" (Vattenturbiner och generatorer) of the Swedish Hydropower Centre (SVC) for the years 2013-2016. The evaluation is a two-step process, where this report is part of the first step – Scientific Evaluation.

The objective and instructions are given in the signed order 2016-04-22 and Work description (Uppdragsbeskrivning) from 2016-03-21.

According the above documents, the evaluation step one includes:

- Consistency between the research activities and targets as given in SVC Program Plan 2013-2016 (Programbeskrivning 2013-2016).
- Achievement of research goals compared to overall technical targets for SVC's competence areas.
- Achieved results compared to given project and activity descriptions
- Results and potential utilization
- Industrial relevance
- Scientific quality
- Cooperation within and with outside research organisations.

The four research groups evaluated in the report constitutes the competence area "Hydropower turbines and generators". They are:

- "Rotordynamics" (Rotordynamik) headed by professor Jon-Olov Aidanpää at Luleå Technical University (LTH)
- "Electromechanics" (Elektromekanik) headed by professor Urban Lundin at Uppsala University.
- "Fluid mechanics" (Strömningsmekanik) (computational and experimental) with senior researchers professor Håkan Nilsson (computational), professor Michel Cervantes and Dr. Berhanu Mulu (experimental)
- "Machine Elements" (Maskinelement) with senior researcher Dr. Kim Berglund

Arne Nysveen is responsible for the overall report and the evaluation of "Rotordynamics" and Bjarne Børresen for evaluation of "Electromechanics", "Fluid Mechanics" and "Machine Elements".

Evaluation approach

The report is based on the following documentation:

- SVC Program description for 2013-2016
- Working plans. These are made for the entire program period and updated on yearly basis.
- Senior scientist annual reports

- Publications

Interview with some of the senior scientists and chairman of the steering committee for "Hydropower turbines and generators"

Detailed assessment

Quantitative assessment

The quantitative assessment is made to show the overall volume of the research and the publications of its results.

Table 1 - Summary of quantiative results.

	Ongoing PhD projects	Number of MSc students	Number of Licenciate and PhD thesis	Number of publications
Rotordynamics	2	3	3+2	9+5
Electromechanics	4	26	2+1	10+2
Fluid mechanics	5	10	2+2	18+20
Machine elements	2	1	1+2	7+1

Notes: The quantitative numbers are based on the senior reports and the submitted overview. There may be some discrepancies in the number as results for 2016 is only partly included.

Project focus

The overall goal of SVC as described in the Program plan - "SVC Programbeskrivning" - in 2012 is to ensure Sweden's supply of competence and knowledge to ensure an efficient and reliable hydropower production and dam safety as part of a larger power system.

Within each of the competence areas robust research and teaching teams has been established. These teams have proven that they can deliver both in terms of quantity (number of master students, doctoral thesis and publications) as well as in terms of scientific quality. Within some areas innovations and new technology is under development, a result that clearly exceeds the expectations of what can be achieved with a modest program.

Rotordynamics

Hydropower aggregates deviates from other large rotating systems since they usually are vertically aligned. The rotating weight is considerable and the gyroscopic effect is present. The rotating shaft has two strong excitations from the turbine (water) and the magnetic forces form the stator.

For Rotordynamics, the focus areas for the program period are:

1. To improve analysis models and software for better understanding of instability phenomena – and how to avoid them.

2. Study of transient dynamic behaviour in order to better assess the load and thereby lifetime impacts.

The projects in the program period has been:

- Multi-physic models for rotordynamical analysis of hydropower stations
- Non-linear dynamics in hydropower rotors
- Simulation method for analysis of dynamics and life-time during start/stop of hydropower turbines
- Dynamic modelling of elastic generator components in Hydropower rotors
- The influence of fluid-structure interaction on stiffness, inertia and damping in turbines

The completed and on-going research project activities are well in the focus areas for Rotordynamics.

The judgement is that the projects are well focused such that new projects and new PhD students can capitalize on previous work in a consistent way. This is a clear strength of the research activity. Two of the projects have clear inter-disciplinary interactions with the two other research groups on Machine elements and Electromechanics.

The research group is quite small and the senior scientist share his working time with other application areas than hydropower.

Electromechanics

As a preface for the specific focus areas it is noted that typical for hydro generators is that these machines typically are large, low speed (salient pole) synchronous machines. Areas in which more knowledge is required includes service life and robustness of existing units. This includes knowledge about material properties and basic understanding of the types of loads and wear that the machines are subjected to.

The focus areas for the electromechanics area are

1. Increased understanding of how existing generators are affected by changing operating conditions.
2. Design and optimization of electrical machines with respect to rotor dynamics and how they function in the power system
3. To support the development and use of new innovations in the hydropower business.

Within the electromechanics realm, the research has been aimed at four different areas.

With respect to basic understanding of hydrogenerators one project has focused on electrical transients and how these are affected by the damping windings and axial leakage flux field. In relation with this, there has been a further development of computational tools based on the finite element method and experimental testing in the model generator.

A second topic has been the development of faster regulation of brushless exciters with rapid control by means of wireless control of various rectifier designs based on either thyristor bridges, IGBT's or MOSFET circuits.

The third topic is more directly related to developing new concepts and accompanying hardware. This includes a new device for rapid load shedding (load dumping) as well as work on magnetic bearings for large hydro units.

The forth topic is more related to the power market and how changes in the production mix and demand profiles may impact the integration of large hydro units into the system. The research includes work on modelling and evaluating frequency regulation and the interaction between the water conduits and the electromechanical installation.

The focus of the research in the program period is highly relevant for hydro generators and has produced good results throughout the period.

Fluid mechanics

Large geometries and large flow rates are typical characteristics of the fluid mechanics related to hydro turbines. Furthermore, many of the flow phenomena, such as the flow in the runner and the draft tube are related to transient flow. The flow during changes in the operating regime such as start-up, rapid ramping and load rejections is inherently transient. The flow of air inside and around hydro generators have large impact on cooling and thus also the ageing of the units.

Specific directions for the work in SVC are

1. Loss mechanisms, in particular after the turbine and in the draft tube where there is a potential for improvements and better performance.
2. Transient events such as start, stop, load rejection where improved understanding leads to improved safety.
3. Development of flow measurements in order to improve the accuracy of efficiency measurements for low head turbines and verification of upgrading of such units.
4. Understanding the air cooling flow in generators and thereby possibly improving residual life.

The work within the fluid mechanics team has been split into two parts related to

- Computational fluid mechanics
- Experimental fluid mechanics

The later topic is furthermore divided into work related to general experimental fluid mechanics work, activities in the model test rig of Vattenfall AB R&D and full-scale experiments in the Porjus research plant.

Within the computational fluid mechanics group there has been four research projects in the program period. These are:

- Coupling of 1D transients with 3D local flow details
- Implementation of cavitation models and application to hydro turbines

- Incompressible flow in rotating machines with emphasis on improved turbulence models in realistic hydro turbine geometries.
- Experimental and numerical investigation of cooling

Within the experimental fluid mechanics area the main research topics has been

- Development of the pressure-time method for flow measurement of low head machines
- Experimental and numerical investigation of a hydraulic channel during a gate closure at a high Reynolds number
- Rotor-stator interaction in Francis turbines
- Experimental investigation of a Kaplan model
- Determination of loads on Kaplan runners

The work on fluid mechanics is performed at two academic institution – Chalmers University of technology and Luleå Technological University. In addition, the experimental facilities of Vattenfall AB R&D and the Porjus experimental plant has been employed.

Machine elements

The machine elements particular to large-scale hydro units are typically assemblies with rotating parts, with large physical dimensions. There is often a large variation in age, condition and design details. For the large installed base, understanding of function at component level is important in order to determine the remaining technical life. There will be a need for tools and methods to predict the loads that the unit will submitted to in relation to repeated starts and stops. Specifically the direction of the research is stated to be:

Create a global mode for condition assessment that can be combined with measurement systems to give a good diagnosis

Create refined models for wear and fatigue in sensitive parts as input to a more comprehensive model for ageing.

Within the area of machine elements the main research project in the program period has been:

- Measurements of hydrodynamic properties in radial journal bearings with polymer coating
- Dynamic behaviour of low viscosity fluid film bearings with compliant linings.
- Prediction of remaining life of runner blade bearings in Kaplan hubs
- Development of measurement methods for condition monitoring of Kaplan runners

The research team within hydropower is still quite small with one senior researchers and two PhD students. In the beginning of the program period there was a change in senior researcher, which may have affected the initial progress. The focus within the theme of machine elements is relevant given that the age of

the installed based and foreseeable future challenges due to changes in operating pattern.

Overall goal achievements

The overall technical goals for the competence area "Hydropower turbines and generators" are:

- Develop tools and methods for design and construction of new equipment, upgrading and operation and maintenance with the purpose of securing the hydropower production and its flexibility in the power system.

This is a very bold goal and some aspects of it is discussed below.

The first part states that the tools and methods should cover all phases of the project development – new developments, refurbishment or upgrading and operation and maintenance. Further, the tools and methods are more applicable or relevant for either the manufacturer or the power producer. The project portfolio whiten each research group should include projects relevant for both parties.

The second part of the goal relates also to the application of the knowledge. This includes creating robust groups at the universities to conduct research, to give research education (PhD supervision) and to transfer the knowledge and competence to the end-users, that is to secure that the manufacturers, power producers and authorities have knowledge and competence on a high level.

Rotordynamics

The first part of the goal is clearly achieved. The portfolio is balanced with this respect. Some of the projects may change utilization potential based on the findings, such as the project on start/stop dynamics. Initially it seems most valuable for the operator of the machine, but it might also be a god tool to be used in the design phase.

When it comes to the second part of the goal, it is clear that robust research group able to do scientific research on a high international level is achieved. It also educate future researchers by supervision of PhD students. An overall (but not technical) goal is to promote inter-disciplinary research. Two of the projects are clearly inter-disciplinary. In the one of the projects (PhD study) input from Electromechanics have been given to the candidate for proper simulation of the influence of the magnetic field on the rotor dynamics. The submitted thesis demonstrate that the candidate has gained good inter-disciplinary insight into electromagnetic force calculation in magnetic devices.

The number of master thesis written by students (examensarbete) at the group is low. Some years none or one student. This should have been higher in order to bring the knowledge out to the industry.

Electromechanics

The research in the area of electromechanics has been very productive. In the current program period 4 PhDs has been completed within the domain and at least 20 MSc works in relation with this. In addition, a number of publications in well renowned and prestigious journals has come out of the work. The computational tool based on the finite element method has been updated and developed continuously.

One minor comment may be the lesser appearance of conference publications in the cited work compared to other teams. This may either be because conference publications are less merited and typically not counted in formal scientific performance indices and thus were omitted from the list. Conversely, if this reflects the actual participation in international conferences and work groups it should be noted that such participation is an important aspect of strengthening international collaboration and should be encouraged in the future.

The main lines of the research for the electrodynamics team is well founded with the industrial partners and contains a good combination of practical topics with direct industrial application combined with more basic research. The team has followed the plans as outlined in the program document.

The research within electromechanics has followed up the recommendations in the program plan to highlight three new system oriented areas and in particular the first and third topic "balancing power" and "active management" respectively.

Fluid mechanics

The computational fluid mechanics work is to a large extent centred around the development and use of the open source package OpenFOAM for hydropower and turbomachinery applications. Initially the work was focused on computation in hydro turbines and in particular Kaplan turbines. In this program period, the airflow in hydro generators has also been considered. Through the OpenFOAM work the senior researcher and the PhD students have participated in a vibrant and active community network.

The plans put forward in the program plan has largely been followed. The work on coupling 1D and 3D models establish a foundation for better inclusion of the effect of the water passage on the turbine flow and thus better ability to evaluate the effect of balancing power on the turbine flow. Likewise, the work on generator cooling can be considered to a first step towards better understanding of the thermal loads of the generator and this the ageing and degradation of insulation material.

The experimental fluid mechanics team has developed a broad international collaboration cantered around field measurements and laboratory experiments with the focus on various transient flow phenomena and losses. This is quite relevant with respect to better understanding of the dynamics in the power plants as a response to change in the power market. A better understanding of the time dependent forces will be crucial for predicting the loads on the components and thus subsequently the loading and possible fatigue and mechanical wear on turbines and thus is relevant for the system oriented area "active management".

Machine elements

Started in 2013, the work on Machine elements has a shorter history and accordinlgy less completed results to refer to compared to the other disiplinece within turbine and generator. One PhD in collaboration with KTH was completed in 2015. Two new thesis topics were established in 2014 and 2015. Both of these are in "licenciaetapp" at the moment. The chosen topics are highly relevant for hydro power, but no specific results is generally available. The research is conducted in a team and environment with strong synergies with domains outside hydropower and thus there is a large potential for achieving world class research despite the limited investment within the field.

Interdisciplinary system topics

Based on the evaluation of SVC 4 years ago, 3 new system topics were formulated:

1. Regulating power (ancillary services)
2. Environmental technology
3. Active asset management

Rotordynamics

System topic no 1 is addressed in some of the projects, not explicitly in the project description but the research topics as such addresses this. Here, we interpret "Regulating power" to also include fast ramping of power output and frequent starts and stops.

Topic no 2 is not so relevant for this competence area with the actual running projects.

Topic no 3 relates to condition monitoring and lifetime prediction. One of the doctoral studies clearly addresses this topic when it comes to the bearings.

Electromechanics

Both topic 1 and 3 has clearly and specifically been addressed by the electromechanics team, both through master thesis work as well as several completed and commenced PhD dissertations.

Fluid mechanics

System topic 1 is directly addressed in the work of coupling 1D and 3D computations. Likewise the multidisciplinary work on "Damping, Stiffness and Added Mass in Hydraulic Turbines" is an example of how the fluid mechanics influence and gives premises for the forced response and loading which drives ageing and this is an important factor in the field of active asset management.

Machine elements

Within the research area machine elements there is focus both on using environmentally adapted lubrication as well investigating the possibility of using water lubricated bearings. This work is directly motivated by the goal to reduce polution through oils spills from the hydropower units. More dynamic operation of the plants because of the need to provide more regulating power as well as the desire to better understanding the degradation mechanisms and ageing of the units are also strong impetus to the research. Thus the interdisciplineary system topics are well accounted for in the research.

Project fulfilments of goals

The project descriptions are updated each year depending on the committed financial resources the projects. The formulated goals are of two kinds:

1. Descriptive goals such as objective and research goals for each project.
2. Quantification goals such as number of PhD exanimated and number of publications for the group related to hydropower

The descriptive goals remains consistent for each project through the project period as described in the yearly issued "Verksomhetsplan". Hence, the individual

projects seems to have a sound basis and is properly planned from the start. With a few exceptions, all projects are finished on schedule.

The other goals changes due to the resources allocated. This relates to the number of candidates exanimated and the number of publications. The positive is of course that the ambition raises with funding. However, putting the 4-year goals clearly forward in the Program description at the start of the program period would strengthen the long-term commitment and planning for the research group and industrial sponsors.

Rotordynamics

For the project period, the "Working Plan" for 2016 states that 6 degrees should be awarded, 11 conference publications and 8 journal papers submitted. According to the senior scientist reports until 2015, 9 journal papers and 5 conference papers are published. The number of conference papers are a little lower, but the numbers for 2016 is not now until the end of this year. The number of journal paper number as already above the target.

Number of PhD in the period will be 2, and number of lic. techn 3 if one count the planned lic. for the last candidate. Total of 5 degrees.

The quantitive goals must be said to be fulfilled in sum. I order to achieve more degrees, the students needed to start earlier.

Electromechanics

The quantitaive goal of the electromechanics team stated in the is to awards 7 degees (licenciates and PhD), publish 15 conference articles 10 journal publications. The latest senior research report is for 2015 and thus do not cover all publications and finished work for 2016. Thus at the current time it is not possible to determine exactly if the coals will be reached. Nevetheless it is clear that the annual production of candidates and publications is well within the expected level highly satisfactory. To find a good PhD candidate may take some time and thus such quantitaive goals should not be taken as an absolute measure, but rather as an indication of the expected order of magniuted of the results.

Fluid mechanics

The quantitative goals for the program period have been fulfilled or exceeded for some of the categories (see table 1). The planned research topics have been followed and the results presented according to plan.

Machine elements

The quantitative goals for the project is largely fulfilled despite the challenges observed during the program period. Lower number of conference publications is compensated by a larger number of journal publications. This is in itself an indication of the quality of the research.

Results and potential utilization with regards to industry, society and academy

The potential utilization of the project results varies between these 3 sectors. For the industry, the typical utilization is new procedures, services, products or operation schemes of the power plants. For the society, utilization is more to secure competence on a broad level such that rules, regulations, and management at large

becomes beneficial for the entire hydropower sector. In academy, the results are typically transferred into the teaching given and form a competence and skill basis for further research.

Rotordynamics

For this competence area, the academic utilization is obvious. The results are generally of good quality and forms a good basis for further research. The type of results are mostly simulation results or measurements. New products or services are not generated. With the types of results generated, the industrial results are more utilized in industry by adjunct professors and transfer of students. Here the low number of master students is worth mentioning.

Electromechanics

The results of the electromechanics research will have direct application both for equipment owners (power companies) as well as equipment suppliers. The ongoing testing of new inventions and technology will potentially ble developed to new products that can be sold both on the domestic and international market. The ongoing research have a large potential for further accademic work and development.

Fluid mechanics

The fluid mechanics research (both experimental and computational) have large relevance for equipment users as well as suppliers. The work on efficiency measurement will probably be most relevant for the turbine owners (power companies) while the use of new CFD tools and methods probably is more important for the equipment suppliers. The ageing and degradation of the insulation in rotor and stator windings is highly temperature dependent. Better understanding of the flow of cooling air in the generator will give better understanding of this mechanism and potentially the ability to reduce the wear by minor modifications to optimize the flow pattern. Overall the research and knowledge gained will permit maintaining and enhancing the value of the installed hydro power base and permit further refinement of the installation towards more regulating capacity.

Machine elements

The results from the machine elements team is highly relevant for all the represented stakeholders. Rebuilding bearings on existing units to reduce pollution or increase reliability are possible outcome of the research that will profit local communities as well as the society in large. LTU has a very strong research team within tribology that mainly caters to other industrial areas such as transportation and heavy machines. Through the arrangement with a senior researcher this knowledge and be adapted to the hydropower industry as well.

Industrial relevance

The industrial partners in SVC roughly comprises three groups, which are the equipment suppliers, engineering consultants, and power companies (operators of equipment). These groups are represented in the board for SVC and in various reference groups. The overall work program as well as the detailed annual plans indicate that there has been a fruitful dialog between the industrial partners and academia and the projects undertaken are a mixture of more short term, industrial relevant project that readily can be implemented and more long term development

which may be considered more alike basic research. With the unique Porjus Hydropower Centre there exist a facility to perform large scale testing which is rarely available elsewhere in the world. This gives the SVC groups the possibility to perform industrial scale research rarely seen elsewhere in the world.

Rotordynamics

This research area has its industrial relevance as a precaution to prevent serious operational problems and even failures. Operational wear of the bearings, oscillations and vibrations may lead to long outage times for repair and sometime redesign.

It is important to have good mechanisms to transfer the research results and competence to the designers and engineers responsible for procurement and operation of the aggregates.

Electromechanics

The industrical releavance of the research within electromechanics clearly focuse both towards the manufacturer of hydro generators as well as the power companies who own and operate such equipment. Both the research looking into relation between operating pattern and loads on the units as well as possiblities of improving operational characteristics e.g. improved dynamcis of brush-less exciters are examples of research that are valuable for both groups. Even the system operator such i.e. Svenska Kraftnät may profit from this knowledge and undertanding of dynmic performance of hydro power units.

Fluid mechanics

Fluid mechanics is a key knowledge for several parts of the hydropower business. The hydrodynamic forces is an important design criteria for all elements in the hydro power plant, from intake, trash rack and gates, through the water conduits, tunnels, pipes and concrete structure to the valves and turbines with all its components. Most obviously, the turbine designer is using these tools in the day-to- day work. In developing the existing plants for coming decades through refurbishment, upgrading and modernization an understating of cavitation, losses in the water passages and hydrodynamic forces is crucial in order to assess the potential and limitations.

Machine elements

The current work of the machine element group is mainly related to better understanding of ageing and wear of bearings and other critical components in hydropower units. Another direction of the research is on more environmentally friendly solutions. This is clearly very important knowledge for the power companies that own a number of units and need to plan and optimize their condition assessment and maintenance of the units in order maximize the reliability and availability. It is expected that the increased knowledge gained by the research quite readily and rapidly can be employed by the operators. Clearly, the knowledge will also profit equipment suppliers and service companies that assist with the refurbishment, upgrading and modernization of the units. Understanding and documenting the limits and possibilities of new and more environmentally friendly lubrications and other technical solutions will also assist the suppliers of these products to more easily penetrate into new domestic and international markets.

Quality of the scientific work

For university research, the scientific quality of the work is normally documented by peer-reviewed publications. Generally, for all research areas covered in this report, the publication rate is high and above the targets given in the plans (see table 1). Further, for both "Rotordynamics", "Generators" and "Machine elements" the majority of publications are journal papers. Within the different topics of fluid mechanics (computational and experimental fluid mechanics) there is a broader mixture of journal publications and conference publications. However all groups have references to well-known and highly cited journals.

As agreed with Energiforsk the evaluation do not include reading the individual papers. However part of thesis and some papers have been checked. Our judgment is that the research as documented in the papers and thesis are on a high international level.

However, we think that with the volume of the research conducted more publications and presence at conferences and international workshops is advised. In particular, this applies for the two research groups on "Rotordynamics" and "Generators". Thus, the achievements and activity level will be communicated better to the research community. Also for international co-operations, conferences ae a good starting point for collaboration talks.

Co-operation within and outside of SVC (between universities and international)

Rotordynamics

The research group has internal research cooperation with Michal Cervantes (fluid mechanics) and Urban Lundin (Generators). There are two interdisciplinary projects, project no 1 and 5 listed in table 1. The research group has some joint meetings discussing projects with Uppsala. The two groups now also have the same reference group. This initiative can promote more cooperation between the two groups.

Internationally they have some cooperation with NTNU and Polytehnica University in Bucharest on fluid-structure interactions and their influence on the dynamics of the turbine.

Electromechanics

The electromechanics team have some international collaboration, amongst others with Norway and with China through two of the PhD projects. There has also been some international (e.g. Norwegian participation) in the reference group. Given the width and quality of the research within the area of electromechanics, more participation with international groups such as Cigre and IEC is recommended. This could also be a useful way of implementing and transferring the scientific results into standards and international best practice.

Fluid mechanics

Both the experimental and computational research groups have extensive international collaboration. Within the field of experimental fluid dynamics, there has been extensive Nordic collaboration as the senior researcher also fills an adjoint professorship at NTNU in Norway. In addition this work includes collaboration

with Canada, India, Iran and Romania. Through the work with OpenFOAM and in particular with the Turbomachinery Special Interest Group the computational fluid mechanics team has been a central hub and part of global network of research and development.

Machine elements

The machine element team has strong collaboration with the broader tribology team at LTU as well as with the Department of Machine Design at KTH. In light of the relative recent establishment of the team and the challenges to recruit new doctoral candidates it is not so surprising that the international collaboration has not yet been fully developed.

Conclusions and recommendations

The competence area "Hydropower turbines and generators" within SVC is a highly successful initiative. With modest resources committed, a high quality research environment has been created. The long-term commitment has created a high quality research environment which has produced results at international world class level.

Within all the research groups there has been a large production of qualified personnel through master thesis, licentiate thesis and PhD thesis work. The principal and most effective way of diffusing this knowledge into the industry is by employing these candidates into the industry – e.g. equipment manufacturer, engineering consultants and power companies. We have not obtained any firm statistics regarding this, but based on verbal feedback from the senior researcher it has been confirmed that to a large extent this has happened.

Our clear recommendation is to continue with SVC along the same route as in the current program period, considering our suggestions.

- SVC has achieved to give a significant and tangible contribution to building competence and new knowledge within hydropower in Sweden and thereby secure future value creation from hydropower in Sweden.
- The framework with 4-year Program plan, yearly updated working plans and reference groups allocated to each senior scientist has resulted in good concordance between the program plan, the executed research and results. The reference groups gives valuable input and feedback to the research and increase implementation of the results in the industry. The project portfolios becomes relvant and balanced.
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Out main recommendations for a new program period of SVC are:

- Utilize the possibility for associate professorships, temporary guest research positions and professional training courses to bring the results into the industry and to promote innovation.
- With the high quality and volume of the research activity, we advise higher visibility at international conferences to present the work performed and to establish international research collaboration. We further encourage participation in international fora and work groups such as IAHR, IEC and CIGRÉ. This applies not only to the senior researcher, but also to other members of the team and to the industry partners.
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- After evaluation of the groups Rotordynamics and machine element combined with interviews we conclude that these two groups (senior researcher) should continue to be two separate groups due to the distinction in competence needed to do research in these areas. At the same time it is important to encourage close collaboration between the groups.
- The ongoing work to strengthen the collaboration between the different research groups should be continued. This includes the three new system areas as well as specific multidisciplinary research projects. It should be considered if one senior researcher should have particular responsibility for the system areas.
- With the availability the Porjus Hydropower Centre the SVC has the ability to perform multidisciplinary research at industrial scale. This work should be continued and expanded whenever possible. This unique facility is also an excellent platform for international collaboration.
- The recruitment of master students (*examensarbete*) is a challenge for some of the research groups. Consider to compensate the students with SVC funding.
- The key importance of and investment in the senior researchers also make the groups vulnerable if the senior researcher leave his position. The robustness of the research groups to be evaluated by the steering committee.