Automated Production Technologies and Measurement Systems for Ferrite Magnetized Linear Generators

TOBIAS KAMF
Abstract

The interest in breaking the historical dependence on fossil energy and begin moving towards more renewable energy sources is rising worldwide. This is largely due to uncertainties in the future supply of fossil fuels and the rising concerns about humanity’s role in the currently ongoing climate changes. One renewable energy source is ocean waves and Uppsala University has since the early 2000s been performing active research in this area. The Uppsala wave energy concept is centered on developing linear generators coupled to point absorbing buoys, with the generator situated on the seabed and connected to the buoy on the sea surface via a steel wire. The motion of the buoy then transfers energy to the generator, where it is converted into electricity and sent to shore for delivery into the electrical grid.

This thesis will mainly focus on the development and evaluation of technologies used to automate the manufacturing of the translator, a central part of the linear generator, using industrial robotics. The translator is a 3 m high and 0.8 m wide three sided structure with an aluminum pipe at its center. The structure consists of alternating layers of steel plates (pole-shoes) and ferrite magnets, with a total of 72 layers per side. To perform experiments on translator assembly and production, a robot cell (centered on an IRB6650S industrial robot) complimented with relevant tools, equipment and security measures, has been designed and constructed. The mounting of the pole-shoes on the central pipe, using the industrial robot, proved to be the most challenging task to solve. However, by implementing a precise work-piece orientation calibration system, combined with selective compliance robot tools, the task could be performed with mounting speeds of up to 50 mm/s. Although progress has been made, much work still remains before fully automated translator assembly is a reality.

A secondary topic of this thesis is the development of stand-alone measurement systems to be used in the linear generator, once it has been deployed on the seabed. The main requirements of such a measurement system is robustness, resistance to electrical noise, and power efficiency. If possible the system should also be portable and easy to use. This was solved by developing a custom measurement circuit, based on industry standard 4–20 mA current signals, combined with a portable submersible logging unit. The latest iteration of the system is small enough to be deployed and retrieved by one person, and can collect data for 10 weeks before running out of batteries. Future work in this area should focus on increasing the usability of the system.

The third and final topic of this thesis is a short discussion of an engineering approach to kinetic energy storage, in the form of high-speed composite flywheels, and the design of two different prototypes of such flywheels. Both designs gave important insights to the research group, but a few crucial design faults unfortunately made it impossible to evaluate the full potential of the two designs.

Keywords: industrial robotics, automation, self-sensing, calibration, ferrite, linear generator, wave energy, offshore, measurements, electronics, kinetic energy storage, reluctance motor

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In theory, theory and practice are the same.
In practice, they are not.
– Albert Einstein
List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


IV Erik Hultman, Boel Ekergård, Tobias Kamf, Dana Salar, Mats Leijon, "Preparing the Uppsala University Wave Energy Converter Generator for Large-Scale Production", *5th International Conference on Ocean Energy*, Halifax, Canada, 4–6 of November, 2014.


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# Nomenclature

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<th>Symbol</th>
<th>SI-unit</th>
<th>Description, where ( n = 0, 1, 2, 3, \ldots )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_n )</td>
<td>( \Omega )</td>
<td>Resistance of individual electromagnet ( n )</td>
</tr>
<tr>
<td>( R_c )</td>
<td>( \Omega )</td>
<td>Resistance of parallel electromagnets</td>
</tr>
<tr>
<td>( L_n )</td>
<td>( H )</td>
<td>Inductance of individual electromagnet ( n )</td>
</tr>
<tr>
<td>( L_c )</td>
<td>( H )</td>
<td>Inductance, parallel electromagnets</td>
</tr>
<tr>
<td>( L_d )</td>
<td>( H )</td>
<td>Inductance, direct axis</td>
</tr>
<tr>
<td>( L_q )</td>
<td>( H )</td>
<td>Inductance, quadrature axis</td>
</tr>
<tr>
<td>( P )</td>
<td>( W )</td>
<td>Power</td>
</tr>
<tr>
<td>( t_r )</td>
<td>( s )</td>
<td>Rise time of inductor current</td>
</tr>
<tr>
<td>( i_{\text{start}} )</td>
<td>( A )</td>
<td>Initial current in inductor</td>
</tr>
<tr>
<td>( i_{\text{end}} )</td>
<td>( A )</td>
<td>Final current in inductor</td>
</tr>
<tr>
<td>( u )</td>
<td>( V )</td>
<td>Instantaneous supply voltage</td>
</tr>
<tr>
<td>( \tau )</td>
<td>( \text{Nm} )</td>
<td>Torque</td>
</tr>
<tr>
<td>( \omega )</td>
<td>( \text{rad/s} )</td>
<td>Rotational speed</td>
</tr>
<tr>
<td>( \mathcal{R} )</td>
<td>( 1/\text{H} )</td>
<td>Reluctance</td>
</tr>
<tr>
<td>( N )</td>
<td>-</td>
<td>Number of turns in a coil</td>
</tr>
<tr>
<td>( p_n )</td>
<td>-</td>
<td>Pole-shoe point ( n )</td>
</tr>
<tr>
<td>( p_s )</td>
<td>-</td>
<td>Point of correct solution</td>
</tr>
<tr>
<td>( \hat{i} )</td>
<td>-</td>
<td>Randomized 3D unit vector</td>
</tr>
<tr>
<td>( \mathbf{Q} )</td>
<td>-</td>
<td>Quaternion</td>
</tr>
<tr>
<td>( \mathbf{Q}^* )</td>
<td>-</td>
<td>Quaternion conjugate</td>
</tr>
<tr>
<td>( q_n )</td>
<td>-</td>
<td>Quaternion component ( n )</td>
</tr>
<tr>
<td>( \mathbf{Q}_d )</td>
<td>-</td>
<td>Quaternion of imposed alignment error</td>
</tr>
<tr>
<td>( \mathbf{v}_{x,y,z} )</td>
<td>-</td>
<td>Orientation matrix components ( x,y,z )</td>
</tr>
<tr>
<td>( X )</td>
<td>-</td>
<td>Cartesian X-direction</td>
</tr>
<tr>
<td>( Y )</td>
<td>-</td>
<td>Cartesian Y-direction</td>
</tr>
<tr>
<td>( Z )</td>
<td>-</td>
<td>Cartesian Z-direction</td>
</tr>
<tr>
<td>( \mathbf{i}, \mathbf{j}, \mathbf{k} )</td>
<td>-</td>
<td>Imaginary unit vectors</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>-</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>( \circ )</td>
<td>Euler angle (alpha)</td>
</tr>
<tr>
<td>( \beta )</td>
<td>( \circ )</td>
<td>Euler angle (beta)</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>( \circ )</td>
<td>Euler angle (gamma)</td>
</tr>
<tr>
<td>( \Delta \varepsilon )</td>
<td>( \circ )</td>
<td>Angular tilt amplitude</td>
</tr>
<tr>
<td>( \Gamma )</td>
<td>( \circ )</td>
<td>Angular offset amplitude</td>
</tr>
</tbody>
</table>
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance, circuit symbol</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
</tr>
<tr>
<td>CCB</td>
<td>Current Control Board</td>
</tr>
<tr>
<td>D</td>
<td>Diode, circuit symbol</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital to Analogue Converter</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DOF</td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>Gen I</td>
<td>The first WEC measurement system</td>
</tr>
<tr>
<td>Gen II</td>
<td>The second WEC measurement system</td>
</tr>
<tr>
<td>I</td>
<td>Current, circuit symbol</td>
</tr>
<tr>
<td>I/O</td>
<td>Digital Input Output</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated-Gate Bipolar Transistor</td>
</tr>
<tr>
<td>IPS</td>
<td>Inductive Proximity Sensor</td>
</tr>
<tr>
<td>L</td>
<td>Inductance, circuit symbol</td>
</tr>
<tr>
<td>LSB</td>
<td>Least Significant Bit</td>
</tr>
<tr>
<td>MCU</td>
<td>Micro-Controller Unit</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro-Electro-Mechanical System</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>NdFeB</td>
<td>Neodymium Iron Boron</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>POM-H</td>
<td>Polyoxymethylene Homopolymer</td>
</tr>
<tr>
<td>P2</td>
<td>Flywheel Prototype II</td>
</tr>
<tr>
<td>P3</td>
<td>Flywheel Prototype III</td>
</tr>
<tr>
<td>R</td>
<td>Resistance, circuit symbol</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SMD</td>
<td>Surface Mounted Device</td>
</tr>
<tr>
<td>TCP</td>
<td>Tool Centre Point</td>
</tr>
<tr>
<td>TP</td>
<td>Touch-Probe</td>
</tr>
<tr>
<td>UU</td>
<td>Uppsala University</td>
</tr>
<tr>
<td>V</td>
<td>Voltage, circuit symbol</td>
</tr>
<tr>
<td>VHB</td>
<td>Very High Bond</td>
</tr>
<tr>
<td>WEC</td>
<td>Wave Energy Converter</td>
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</tbody>
</table>
1. Introduction

The interest of breaking the current dependence on fossil energy of today’s society and move towards more renewable energy sources is rising worldwide, as seen, in for example, the newly signed “Paris Agreement”\(^1\). Renewable energy has been rapidly growing over the latest decades [1], mostly focused around wind energy [2] and photovoltaic solar energy [3]. This is largely due to uncertainties in the future supply of fossil fuels [4], the rising concerns about humanity’s role in the currently ongoing rapid climate changes [5], and its effect on crucial ecological systems [6]. However, wind and solar energy are not the only sources of renewable energy available; tidal and wave energy are two other alternatives that are currently being explored by researchers around the world. Having a wider range of available renewable energy sources and combining them in smart ways also opens up for managing the inherent variability of many renewable sources [7]. Uppsala University (UU) has active research in all above-mentioned fields, peculiarly in wave energy.

Much research has gone into evaluating the wave energy resource itself, and trying to invent innovative ways of extracting it, as shown in for example the works of Cornett [8] and Falcão [9]. The concept developed at UU is focused on using linear generators, placed on the seabed, and point absorbing buoys, placed on the sea surface, which are connected via a steel wire. Figure 1.1 shows such a linear generator unit, from now on referred to as a WEC (Wave Energy Converter).

Up until now little research effort has been put into the question of how to actually build, and later mass produce, the proposed concepts at a competitive price. This is not only the case for UU but for most groups and concepts around the world. The work presented in this thesis will mainly be dedicated to introduce the first steps towards the invention and implementation of new manufacturing and production technologies needed to mass produce the linear WEC topology suggested by UU, all in order to reduce manufacturing costs. Lowering manufacturing costs is crucial if wave energy is to ever become an economically viable alternative [10]. However, the presented manufacturing technologies are not only of interest to the UU wave energy project, but for all automated production of large electrical machines such as motors, generators, and transformers. All these machines share common mechanical traits and any steps of the assembly processes of these machines, to this day, still require extensive manual labor.

\(^1\)http://unfccc.int/paris_agreement/items/9485.php (Accessed: 2017-09-04)
Figure 1.1. a) A photo of a buoy deployed at sea. b) A prototype wave power linear generator alongside a simplified section cut, showing the position of the stator and translator within the machine. The buoy has a diameter of 4 m, the translator is 3 m long, and the whole WEC structure stands just over 7 m tall.

Once a generator is built and deployed it is also of interest to be able to monitor its performance. Previous work done at UU in this area has relied on a central hub or substation to collect both energy and data from multiple generators, for example the substation presented by Ekström et al. [11]. More recent systems have focused on fitting each generator with a separate measurement system, to reduce deployment costs and remove the need for a substation to perform measurements. A chapter of this thesis will be dedicated to the topic of such stand-alone WEC measurement systems.

Lastly, due to the increasing integration of variable renewable energy sources into the electrical grid [12], and partly due to the rise of fully electric vehicles [13], the need for short-term energy buffers has become a popular research topic, with many competing technologies [14]. UU has had active research in this area as well. Therefore, a small part of the thesis will be dedicated to the topic of short-term kinetic energy buffers, in the form of composite flywheels.
1.1 Thesis outline and aim

As mentioned in the introduction, this thesis will present original scientific work in three main areas divided into three distinct topics, numbered I-III. The main topic, presented in Papers I to IV, will be on practical work and experiments performed in the area of automated WEC production, specifically how industrial robotics can be used to automate the production of the so-called translator inside the WEC. The second topic, presented in Papers V and VI, will discuss integrated WEC voltage and current measurement systems, and the work done towards the development of such systems. Lastly, Papers IX to XII, will be a brief touch on kinetic energy storage, with a focus on high-speed flywheel composite materials and mechanical design of electrical machines. The authors contribution in Paper VII and VIII was not deemed substantial enough to warrant a separate section, and as such, they will only be discussed in the summary of papers, found in chapter 10 in this thesis.

While the three areas presented above might seem uncorrelated at first glance they share common ground in that they all require the combination of material knowledge, mechanical engineering, electrical engineering, electronic engineering, communication, and control theory. A multidisciplinary mixture commonly summarized as “Mechatronics”. One of the goals of this research has been to approach each problem as openly as possible and use a combination of multiple disciplines to solve them.

The author chooses to make a practical distinction between natural science and engineering science, where the first is the art of trying to understand and categorize the fabric of the natural world, and the second the art of making this fabric work for us. Both are equally important, but they approach the subject of problem solving slightly differently. The presented work leans heavily towards the side of engineering science, therefore a choice has been made to focus this thesis on the presentation of practical work and problems instead of theoretical details and their underlying reasons.

As such, the aim of this thesis becomes to showcase the field of applied engineering science in the field of automated production technology, measurement electronics and machine design, using a multidisciplinary mechatronical approach. A secondary aim is to act as a source of documentation, giving a summary of the workflow for each project and highlight found problem areas.
1.2 Research questions and aim

The following main questions were asked with regard to the three topics of this thesis (in falling order of importance):

- Can the assembly of a ferrite based translator be automated by using mostly standard industrial robotics and equipment?
- Can accurate, yet cost-efficient, WEC measurement systems be built by using mostly existing components and technology?
- What are the mechanical considerations and problem areas when designing high-speed composite flywheels?

The overall aim and workflow in each topic was to investigate the above areas, identify the problem, and then develop real life working prototypes, proof of concept machines, and systems.
2. Background

2.1 The Uppsala University wave power project

This section will present a brief history and milestones of the UU wave power project, or as it is commonly known: The Lysekil Project. Some background will be presented as to when and why the topic of automated WEC production and stand-alone WEC measurement systems became interesting.

2.1.1 History

The project started in the early 2000s, among a range of different renewable energy projects at UU, initiated by professor Mats Leijon. The project has over the years mostly focused on the direct driven linear permanently magnetized generator topology. The first full-scale WEC was deployed in March 2006 in the sea outside Lysekil, a small town located on the west coast of Sweden. The experience from these first experiments are summarized in [15]. The test site, shown in Figure 2.1 has since been expanded, and as of the autumn of 2013 eleven different WECs [16], and two marine substations [17] [18], have been deployed at the site. The latest significant status update from the project was made by Parwal et al. [19] in 2015. In October 2014 the project managed to get a renewed environmental permit to continue research at the Lysekil test site for the coming 20 years.

Figure 2.1. Location of the Lysekil test site (N 58 11.700’, E 11 22.450’).
In addition to developing and building the WEC units themselves, the UU wave power group has engaged in categorizing the Lysekil site itself by performing geological [15] and environmental [20] studies, determining the local wave climate [21]. Research has also been done in developing custom power-electronics systems [22], studying tidal effects on WEC power production [23], studying the behavior of potential large WEC parks [24] and developing sonar based WEC monitoring systems [25].

The UU WEC itself, as seen in Figure 1.1b, contains three main components: the stator, translator, and buoy. During operation, the buoy is situated on the surface of the sea, while the translator and stator are sited on the seabed inside a watertight generator housing. The buoy transfers the buoyancy force of the waves from the surface of the sea down to the generator, via a steel wire, forcing the translator to move. The movement of the translator induces a voltage in the coils of the stator, and when the stator is connected to an appropriate load, electrical power can be extracted from the system.

Initial buoy designs were cylindrical, later to be replaced by torus-shaped buoys [26]. Stator designs having both 4 and 8 sides have been tested as well as stators containing either one or three electrical phases [19]. The translator, shown in Figure 2.2, was initially magnetized using rare-earth neodymium (Nd$_2$Fe$_{14}$B) magnets, leading to a comparably compact and light translator. Due to cost restrictions, these magnets were later replaced with ferrite (Fe$_2$O$_3$) magnets, resulting in a comparably heavier and bulkier translator but at a fraction of the cost [27].

![Figure 2.2. A comparison between the neodymium magnet translator (a), the ferrite magnet translator (b), and a simplified CAD model of the ferrite translator (c).](image-url)
The reason that reducing costs had become interesting was due to plans of commercializing the concept. To achieve this a previously created patent holding company, Seabased, separated from the university and began to set up a factory in the harbor of Lysekil, Sweden. Seabased and the UU wave power research group were initially close but separated more and more as the commercialization effort intensified. At the time of writing this thesis, in 2017, they operate as two separate entities.

2.1.2 Automated WEC production

During the commercialization efforts, it became clear that there existed no previous knowledge exactly of how to automatically assemble linear generators using available industrial tools and technologies, something that was deemed necessary if large-scale production of WECs is ever to be achieved at a competitive price. As a result of this, the research area of automated WEC production was born. The goal of this project mainly became to evaluate the suitability for automated mass production of WECs similar to the ferrite-based design presented by Ekergård [27].

Numerous prototype generators had been built during the span of the wave energy project, but each unit had always been built by hand. For small series prototypes this is doable, but for a full-scale wave power park containing hundreds of generators, this simply becomes too expensive. From the experience of manually assembling the initial WEC prototypes, two main components were targeted for automatization: the stator and translator. I was tasked with solving the problem of the translator in early 2013 while another Ph.D. student (E. Hultman) had previously been tasked with the stator in 2010. The results from the initial feasibility studies and early concepts were summarized in Paper IV in 2014. Figure 2.3 shows a rough estimation of the relative costs for manufacturing different parts of the G2 and G3 WEC design, as described in Paper IV. Judging from those results, the translator and the stator are indeed the parts with the biggest overall cost reduction potential.

The robotics and manufacturing group can be seen as a subgroup of the UU wave power group and has, since its conception in 2010, published work related to automated WEC manufacturing. As the first two Ph.D. students of the group, myself and E. Hultman has spent much time collecting and assembling the equipment needed to perform our research. Considerable amounts of time has also gone into building up the knowledge and practical expertise required to perform this type of research. One of the first projects published by the group presented a robot cell designed to stack the WEC stator laminates as shown in Figure 2.4. The cell consisted of an IRB1300 robot fitted with an electromagnetic tool, a number of sensors, and a laminate fixture. Initial calculations suggest that the yearly costs for stator stacking could be reduced by 75 % by using the presented setup [28].
Figure 2.3. Approximate costs for manual and automated production of different WEC parts of two different WEC iterations (G2 and G3), taken from Paper I. All cases are relative to the most expensive case.

Figure 2.4. The first prototype robot cell designed to accurately stack WEC stator laminates. Proper alignment of the laminates is crucial for the winding process.

Parallel to my own work, E. Hultman has continuously been developing his own robot cell, based on two IRB4400/60kg S4C+ M2000 robots, where he tries to automate the WEC stator cable winding process [29], and develop a cable positioning system using robot held proximity sensors [30]. A topic not too different from my own, and as such we have been able to exchange experiences between the two projects. Shown in Figure 2.5 is a photo of this setup during a test run of the winding routine. The group has also presented a robot cell designed to mount neodymium magnets on a translator body [31], a system that was developed before the invention of the ferrite based translator. The setup showed promising results and initial calculations suggest that the yearly cost for translator assembly could be reduced by 90% by switching from manual labor to an automated system.
Figure 2.5. Photo of a test run of the automated stator winding robot cell developed by E. Hultman. Note that only a small section of the stator is present, a full stator segment is typically 2 m long.

Worthy of note is that the developed tools and robotic setups have also been used for educational purposes, as shown in Figure 2.6. Thus, allowing students at the university to gain hands-on experience in the area of large-scale applied industrial robotics, an area previously mostly unexplored by UU. Judging from student feedback the robotic laboratory exercises and courses has been a popular and well-received addition to their education portfolio.

Figure 2.6. A group of students performing a laboratory exercise using a small section of a translator and the neodymium magnet mounting equipment presented in [31].
2.1.3 WEC measurement systems

Once a WEC is built and deployed it is also of interest to be able to measure and monitor its performance. Therefore, a number of measurement systems have been developed and tested over the years within the project. Historically, two main measurement alternatives have existed within the in the UU wave power project. Either the performance of the generator has been measured at its point of connection to a substation deployed on the seabed, as discussed in the thesis of R. Ekström [32], or it has been measured at its connection to a measurement cabin located on shore, as presented in for example [33].

The first deployed WECs, from 2006 to 2008, used an onshore measurement cabin. A setup that worked well for a single WEC, and allowed for easy reconnection of loads and measurement equipment, as these are located in the cabin itself. However, due to the high cost of deploying sea-cables, only a single sea-cable was deployed between the research site and the cabin, a distance of roughly 2 km. As such, this approach became problematic once more WECs started to be deployed and needed to share this connection. The solution to this problem was the development and implementation of the first and second substation as described in the thesis of M. Rahm [34] and R. Ekström [32], and shown in Figure 2.8. Both substations were designed to be connected to multiple WECs, measure the input from each unit, and then combine their power input before sending it to shore, using the single available sea-cable.

![Photo of the on shore measurement cabin, seen to the left, and the grid connection station, seen to the right.](image)

Since the deployment of the first substation, in spring 2009, both the substation and on-shore cabin approach have been utilized, depending on the current number of active WECs, working substations, and current research question. The decision to start developing stand-alone measurement systems was made to take the flexibility of the substation one step further. If each WEC could be fitted with its own separate measurement and load system, measurements could be performed in proximity to the WEC itself, reducing the amount of sea cables needed when simultaneously evaluating multiple WEC prototypes. Unfortunately, although numerous sea trials have been reported, few actors
reveal any details or schematics of their measurement systems [35], and few standards or recommendations exist of how to build offshore measurement systems.

\[Image\]

**Figure 2.8.** Two different substations developed within the project, presented in the theses of M. Rahm (a) and R. Ekström (b).

### 2.2 Industrial robotics

Due to the prominent usage of industrial robots within the automated WEC production project, the following section will be devoted to the topic of industrial robotics, its history and place in the modern world.

#### 2.2.1 A brief history

One of the earliest recordings of powered mechanical devices comes from ancient Greece, supposedly constructed by Hero of Alexandria, in the form of animated animals. More than a millennium later, the first simple anthropomorphic machines or “robots” began appearing in both Europe and Asia around the 16th century, often in the form of mechanical dolls performing tasks such as pouring tea or playing music [36].

Fast forwarding to 1961, the release of the Unimate, see Figure 2.9, by Unimation marks the start for the commercialization of the modern industrial robot. It is by many considered to be the first modern re-programmable industrial robot. The Unimate was based on a patent by George Devol, who in collaboration with Joseph Engelberger was the founders of Unimation [37]. The first generation of Unimates were hydraulically powered and used a specially designed drum-memory and a solid-state controller for logic, a somewhat controversial decision in a time when vacuum-tube logic was the standard. It could perform simple tasks such as pick and place objects or spot-welding [37].
Despite the success of the first Unimates, the manufacturing industry was initially slow at adapting this new technology. It was not until the Japanese industry started to show a serious interest in the technology, beginning in 1968 when Kawasaki Heavy Industries obtained a license from Unimation to access their technology, that things started to change. A few years later, in 1971, the first large industrial robot association was formed with the creation of the Japan Industrial Robot Association (JIRA), aimed to further the spread of industrial robotics in the region. Looking at the rapid progress made in Japan, it was not long until the rest of the industrialized world also started to catch on to the robotic revolution [38]. The first fully electric and microcomputer controlled industrial robot, similar to the ones we have today, was the IRB-6 and it was released by ASEA (now ABB) in 1973. The IRB-6 quickly became popular due to its ability to move along a continuous path, something that enabled the robot to perform arc-welding, and also its robust design, where lifetimes of over 20 years are not unheard-of [37].
From the 1980s up until now the interest for industrial robotics, and robots in general, has only been increasing. In the year 2000, around 100000 industrial robots were installed worldwide, a number that by 2015 had increased to 248000. It is estimated that by 2018 around 2.3 million industrial robots will be deployed around the world\(^1\). Today, the two main applications for industrial robots are component processing and welding/soldering, with 39\% and 30\% of the market, respectively. Two growing markets are clean-rooms and assembly/disassembly lines, currently occupying 12\% and 9\% of the market respectively. Historically the automotive industry has been the main user of industrial robotics, but both the food and semiconductor industry are growing markets [39]. Since the 1990s another application for accurate robotic arms has also emerged, that of active surgical robotics. These arms are usually not considered standard industrial robotics, but they build on the same principles. One of the first of these was the Robodoc, released in 1992, and it was mainly used for hip replacement surgery. In 2001 the first robotically assisted transatlantic surgery was performed by a doctor in New York, USA, operating on a patient in Strasbourg, France, using the Zeus robotic surgical system [40].

2.2.2 Robot limitations
The industrial robot has transformed many labor-intensive and dangerous workplaces for the better, and also enabled production lines working with unprecedented accuracy and speed. Despite this, the standard industrial robot remains in many ways a flawed creation, lacking many features that a human-worker brings. This list of flaws includes, but is not limited to, the following:

- A normal industrial robot does exactly what it is told to do. It is in essence a logical machine, following a list of logical commands.
- It can not innovate or solve problems. All eventualities and situations not precisely described in the program will normally be unsolvable.
- It lacks all normal senses, it is effectively blind, deaf, mute and lacks all forms of tactile senses. Therefore, it is oblivious to its surroundings unless this information is fed to it from external sources.
- Due to their physical strength and speed, many industrial robots are dangerous to both humans and their own surroundings during operation. If not programmed to do so, a robot will not stop if something goes wrong or gets in the way.

The above areas are being worked on by the scientific community, and progress is being made worldwide. The first two points are tackled by the fields of artificial intelligence and machine learning, where researchers try

\(^1\)World Record: 248000 industrial robots revolutionising the global economy, IRF
to use advanced mathematical algorithms often coupled to large databases to allow the robot to “learn” and to modify its own program to become better at a task, as discussed in [41]. Artificial intelligence and machine learning is, however, currently a long way from being able to compete with the ingenuity of the human mind, but the area is progressing rapidly as demonstrated by for example Duan et al. [42] and Tobin et al. [43], both within the OpenAI\(^2\) project. Regarding senses, much work has been put into the development of robot vision, and today robots can be programmed to use vision systems to find pre-defined objects and contours in an image. Sensors are also becoming available that can detect touch, as discussed in [44]. While robotic vision and sensors are getting better at imitating biological senses, they still lack the flexibility and robustness of their biological counterparts.

Stricter robot safety regulations, a focus on safer equipment, and better programming have made industrial robots safer to use, but rare cases of human injury and death still occur\(^3\). New robotic models such as the ABB YuMi from 2015, shown in Figure 2.11, and other similar robots, that are specifically designed to safely cooperate with humans, will hopefully reduce this number even further in the future.

\[\text{Figure 2.11. YuMi, a modern two armed robot from ABB.}\]

Despite good efforts from the scientific community, these limitations, for now, remain a reality and always has to be kept in mind when designing robotic systems or when designing products that are to be handled by industrial robots. In short, industrial robotics has both its strengths and weaknesses. Some tasks, which for a human can be trivial, can be nearly impossible for a robot and vice versa.

\(^2\)https://openai.com/ (Accessed: 2017-08-16)

\(^3\)Robot-related deaths are rare and becoming rarer, Financial Times  
https://www.ft.com/content/c9851cce-20b3-11e5-aa5a-398b2169cf79  (Accessed: 2017-08-08)
2.3 Flywheel kinetic energy storage

A kinetic energy storage (KES) is any mechanical device that stores energy in the form of a moving body. In practical applications, this body is often circularly symmetric and stores energy by rotating around a central axis, and is commonly referred to as a flywheel. Historically flywheels have often been made of steel and used to even-out mechanical power, see Figure 2.12. More modern iterations of the flywheel, aimed at higher energy storage capabilities, began incorporating composite materials into their designs in order to increase the amount of stored energy per unit volume or mass, a topic extensively discussed by Genta in [45]. The highest specific energy composite flywheel known to date was made by Takahashi et al. [46] and reached a specific energy of 195 Wh/kg before exploding. To remain safe and manage the problem of fatigue, practical composite flywheel designs have to settle for specific energies well below this level. Some of the best systems to date have been presented by NASA and can achieve a specific energy of 35.5 Wh/kg for the total system, including rotor, electrical machine, and containment [47].

Figure 2.12. An old metal flywheel fitted on a steam train.

The UU flywheel energy storage (FES) project began with a patent regarding a double wound stator conceived by Bolund, Bernhoff, and Leijon [48] in 2003. The idea and application were then further investigated and refined by de Santiago [49] and Lundin [50] and focused on electrical machines and flywheels designed for use in an all-electric driveline, in an electrical vehicle. An investigation into the required power-electronics was made by Goncalves de Oliveira [51], and a first flywheel prototype (P1) was constructed. P2, the first device to contain both a composite flywheel, a double wound electrical machine, and a magnetic-levitation bearing, was mainly designed by myself and Abrahamsson and presented in [52]. The P2 control system and its optimization have been investigated by Hedlund [53]. In his works, Hedlund also presented two new flywheel prototypes named P3 and P4, both of which I assisted in developing. The group has also presented innovative flywheel designs, such as a levitating cone-rotor [54] and a coreless axial-flux machine [55].
3. Topic I: Automated WEC translator production

This chapter will focus on my main research area: Automated assembly of WEC ferrite translators. The work presented here mainly comes from Paper I, II and III, work I mostly developed and performed on my own.

3.1 Experimental setup

A significant portion of my time has gone into designing, building and assembling the presented equipment, since none of it existed at the beginning of my Ph.D. studies. The equipment therefore had to be constructed and tested before the actual experiments could begin. The overall goal of the presented setup has been to act as a platform to evaluate different aspects of full-scale WEC translator assembly.

3.1.1 Robot cell

Crucial for both Paper I, II and III was the robot cell located in the assembly hall, “Hallen”, at the Electricity division (Ångström laboratory, Uppsala Sweden). The robot cell contains two main components, namely the ABB IRB6650S-200/3.0 robot and secondly a large rotary table. The IRB6650S, shown in Figure 3.1, has a specified lifting capacity of 200 kg and a reach of 3.0 m. Initially developed for use in heavy industrial applications such as car-manufacturing and spot-welding, this robot was chosen for this project for its ability to combine a high reach with a high absolute accuracy. When correctly calibrated the robot can, according to specification, repeatedly move between positions with 0.15 mm accuracy.

The rotary table, shown in Figure 3.2, is an old refurbished piece of West German engineering, fitted with a modern servo motor to allow for precise position control. Despite its age it still performs well and is able to position itself within 0.1° of requested position, if the software is allowed to compensate for the around 1° backlash in the table. On top of the rotary table a chuck is mounted, in which a central translator pipe can be mounted, and subsequently rotated, during experiments. The used servo motor is a MU-300 from ABB that can be directly integrated into the control system of the IRB6650S, allowing it to keep track of the position and speed of the rotary table at all times.
Figure 3.1. The IRB6650S-200/3.0 robot bolted to the floor in Hallen. A heavy-duty 6-DOF machine, kindly donated to the university by ABB Corporate Research, Västerås, in 2013.

Figure 3.2. The refurbished rotary table, retrofitted with a modern servo motor (lower left). Seen mounted on the table is the central translator pipe and a pole-shoe.

3.1.2 Translator parts

The translator design considered in this thesis consists of three main component types: one 3 m high central pipe, 216 pole-shoes, and 864 ferrite magnets. In addition to this there is also a number of support components, most notably the stainless connection wedges used to magnetically isolate the pole-shoes.
from the main pipe, the fastening threaded bars used to fixate the magnets in place by squeezing the magnets and pole-shoes together, and lastly the protective rubber film placed on each magnet to protect its brittle surface.

Figure 3.3 shows a close-up of the translator pipe and the “positive” protruding wedges milled into its sides, also seen is a lone isolation wedge with its corresponding “negative” indented wedge mounted on the pipe. Figure 3.4 shows a pole-shoe with the isolation wedge press-fitted in place and four trapezoidal ferrite magnets mounted on its surface. Normally the magnets are not stable in this configuration and repel each other, but to prevent this they have in this demonstration piece been fastened to the pole-shoe using double-sided VHB tape, something that is normally not be done during actual translator assembly.

Figure 3.5 shows two variants of a threaded bar that have been considered, either full-length bars that are to be used every 500 mm, or shorter linking stub nuts that are used on every layer individually. When all pole-shoes and magnets are in place, the translator typically measures 3 m high, 0.8 m wide, and weigh 5 tonnes.

Figure 3.3. Close-up on the aluminum translator pipe, showing a stainless isolation wedge mounted on the pipe. Notice that there is less than 0.1 mm air-gap between the pipe and the stainless wedge.

Figure 3.4. Pole-shoe with four magnets (A) mounted on a pole-shoe (B), and a stainless connection wedge (C) press-fitted in place. Notice the four stub nuts (D), used to fasten each layer to the previous one.
3.1.3 Plate lifter tool

The plate lifter tool is a multi-purpose robotic tool mainly developed to handle the pole-shoes during the translator assembly. The tool features current-controlled electromagnets, a self-sensing distance sensing system, a regular inductive position sensor, a planar sliding mechanism, and a set of pneumatic wrenches. The original idea behind the concept was that the inductive position sensor will be used to measure the location of the central pipe and the self-sensing distance sensing system used to measure the location of the pole-shoes. The electromagnets will then be used to attach the pole-shoes to the tool, after which the robot will move them to their final destination. Lastly, the wrenches can be used to fasten the pole-shoe in place.

A detailed description of the current control board (CCB) used to control the electromagnets, and the tool in general, can be found in Paper I. In short, the CCB consists of a micro-controller, an H bridge, a current measurement sub-system, three electromagnets, and a POM-H plastic support structure. On the CCB the micro-controller controls the state of the H bridge depending on the current measured by the measurement sub-system. Communication with the CCB was achieved using a serial interface, connected to an external PC.
One of the main features of the tool, and the focus of Paper I, is the self-sensing system, in which the electromagnets are turned into distance sensors. Robust self-sensing systems were long considered an inherently difficult problem, but as shown in the works of Malsen [56] this overestimation of the difficulty was partly due to oversimplification of the used models. When better models were used it was found that the system could indeed be made stable. The system presented in Paper I mostly takes inspiration from the works by Malsen [57] and Glück [58], where the basic idea is that if saturation and eddy-current effects are ignored the inductance of an electromagnet will mostly depend on the reluctance of the air-gap between electromagnet and target. The number of turns \( (N) \) in the coil, the reluctance \( (R) \), and inductance of the electromagnet \( (L_n) \) are related by Eq. 3.1, where \( R \) in this case is assumed to be a linear function depending on the length of the air-gap.

\[
L_n = \frac{N^2}{R} \tag{3.1}
\]

Estimation of the inductance was done by allowing the CCB to precisely control switch timing of the MOSFETs, regulating the current flowing through the electromagnet, and then measure the rise-time and amplitude of the resulting current waveform. Normally the implemented bang-bang current controller tried to keep the current ripple as low as possible, but to increase the accuracy of the rise time measurement the current controller was programmed to temporarily introduce a larger current ripple at the time of measurement. In Paper I this is referred to as a hybrid switching mode, as shown in Figure 3.8. This enabled the system to simultaneously have low average current ripple, and good accuracy of the measurements.
Figure 3.8. Simulated current waveforms during typical operation. Showing both normal operation and sample operation in three different modes.

The amplitude of the current step was controlled using a set of predetermined amplitude breaking points. Once the final level had been passed the current was returned to normal, and the time it had taken the current to reach this breakpoint was recorded. Using Eq. 3.2 the inductance of the electromagnet could be estimated using $t_r$, $i_{\text{start}}$, $i_{\text{end}}$ measured by the CCB during each measurement ripple.

$$L_c(t_r, i_{\text{start}}, i_{\text{end}}) = \frac{R_c t_r}{\ln \left( \frac{u}{R_c} - i_{\text{start}} \right) - \ln \left( \frac{u}{R_c} - i_{\text{end}} \right)} \quad (3.2a)$$

$$L_c \approx \frac{L_n}{3}, \quad R_c \approx \frac{R_n}{3} \quad (3.2b)$$

Another feature of the tool was its selective compliance fastening system. This system allowed the tool to move $\pm 2$ mm in the Cartesian XY-plane while remaining locked in the Z-direction. The system had a simple and robust design utilizing a set of square holes in the tools fastening plate, in which a bolt with a diameter less than that of the square hole was mounted. To ensure that the tool always returned to the same position pre-tensioned springs were mounted between the bolt and fastening plate, as schematically shown in Figure 3.9.
3.1.4 Touch probe

Mainly used in Paper II, the custom-made touch-probe (TP) was designed to measure the position of the pole-shoe once it had been lifted. The sensor consists of a central metal rod with a ball head, sticking out of a cylindrical plastic base. In the base a set of contacts are placed, that are designed to open when a sufficient force acts upon the central rod. A change in circuit resistance is then detected by a simple comparator circuit pulling a logical output signal either high or low. The design of the probe is based upon a set of old patents\(^1\), but by adapting the design, and using modern 3D-printing technology, the probe could be manufactured for a fraction of its original cost.

\(^1\)Patents: US4547971-A, US4769919-A, and US4153998-A
The TP was interfaced with the robot using the standard I/O card of the robot controller. To guarantee fast 0 to 1 signal transitions, the output of the TP was designed as an active pull-high signal, using a PNP transistor, with a passive 10 kΩ resistor as pull-down. Experiments using the tactile touch probe was made in the setup shown in Figure 3.11. One of the two industry standard inductive proximity sensors (IPS) was used as a reference, for comparing the performance of the TP, and the other one was used to measure the position of the central pipe.

![Figure 3.11. CAD drawing (a) and photo (b) showing the robot cell equipment. Showing the rotational table (lower right), the pole-shoe lifting tool (center) and the pole-shoe storage table (right). Marked A, B and C is the TP, the tool mounted IPS and the stationary IPS, respectively.](image)

3.1.5 Inclinometer PCB

The inclinometer PCB prototype, shown in Figure 3.12, was developed as an alternative to the previously described TP. The function of the prototype PCB setup was to measure the inclination of the inclinometer and transfer this information to the robot. This information could then be used to calculate the orientation of the inclinometer, and thus the object it was attached to. This prototype was the main sensor used to obtain the measurements presented in Paper III.

At its core, it consists of a high accuracy MEMS accelerometer, a microcontroller and a serial interface with a built-in level shifter. The used MEMS accelerometer, SCA100T, is a high accuracy digital dual-axis inclinometer, originally developed to measure the inclination of surfaces. The inclinometer produces two 11-bit integer values proportional to the angle between the earth gravity vector and the two orthogonal reference vectors of the inclinometer. To increase the resolution of the inclinometer, and to reduce the effects of measurement noise, a digital exponential decay filter was developed and used.
on the 11-bit measurements. The filter, schematically shown in Figure 3.13, scaled the original 11-bit value up to 15-bit while maintaining a noise level of just under 1 LSB at the cost of reduced response time, in this case, reduced from 50 Hz to 1 Hz. The inclinometer up-scaling was done using an assumption of uniform measurement noise centered around a true value, something that turned out to be mostly true. To save computational time, all parameters of the filter were implemented as powers of 2. In this way, all divisions and multiplications using these factors could be done using bit-shifts, speeding up the calculations on the used ATmega328p processor, an approach described in more detail in Paper III.

Figure 3.13. Schematic block diagram of the used IIR filter. The filter was implemented using a pre (P) and post (U) gain multiplier, a chain of four identical segments (F1-F4), and a gain error correction constant (E).
3.2 Background, experiments, and results

Using the experimental setup and tools described in the previous section a number of experiments were performed. The background, motivation, results and reflections on these experiments will be presented in the following text, centered around results presented in Paper I, II, and III.

3.2.1 Self-sensing electromagnets

**Background and motivation**

The main idea behind Paper I was to add a secondary function to the electromagnets commonly used within industrial robotics. Electromagnets are normally only used to lift and move ferromagnetic objects. But what if they could also be used as a sensor to detect said objects? Similar ideas of using an electromagnet as a combined sensor and actuator have been explored by for example Visher [59], Malsen [60] and Graca [61] for use in active magnetic levitation. Self-sensing systems have also been used to measure the rotor position and rotational speed of electrical machines, for example in the works of Wang [62] and Corley [63]. The experiments presented in Paper I were designed to evaluate the performance of such a self-sensing system implemented in the CCB of the plate lifter tool.

**Experiments and results**

Evaluation of the self-sensing setup was done at 75 different air-gaps. In order to precisely control the length of the air-gap, standard grade A4 plain paper were used as increments, as shown in Figure 3.14, corresponding to an evaluation range of 0–7.2 mm. Each air-gap measurement consisted of 2000 samples taken from the time of system start-up. Figure 3.15 shows the raw and filtered rise-times from 10 out of the 75 measurement series. It can be noted that the longest rise-time was measured at an air-gap of 0 mm and the shortest at open circuit, corresponding to an infinite air-gap.

Measurements of the current break points were much more stable than the rise-time measurements, to within 1 LSB of the used ADC, with regard to both air-gap and sample number. This corresponds to a measurement uncertainty of 2.4 mA for the current break point value. To evaluate the performance of the inductance estimation the calculated inductance was compared to that measured by a hand-held inductance meter, Agilent-U1732A, using an excitation frequency of 100 Hz, 1 kHz, or 10 kHz. As can be seen from Figure 3.16, the proposed inductance evaluation method gives inductance values corresponding to the reference values for an excitation frequency somewhere between 100 Hz and 1 kHz.
Figure 3.14. A pole-shoe laid on top of the plate lifter tool, distanced by two stacks of plain A4 paper.

Figure 3.15. Filtered and raw rise-times for the first 2000 samples from the CCB, after start-up.

In order to investigate the previously ignored non-linear effects, such as eddy currents, on the hybrid switching current controller and inductance estimator, a second measurement series was performed. During these measurements, the CCB was configured to keep a constant current ripple amplitude, but a varying DC offset. Seen in Figure 3.17 are the results of these measurements, measured using an external digital oscilloscope for six different air-gaps. Note that the slope of the current does not only vary in its amplitude, but also in its shape. The bent shape, most clearly seen in the closed circuit, is attributed to eddy-currents and other transient effects (presumably mainly in the large un-laminated target).
Figure 3.16. Inductance comparison between measured values, using a hand-held inductance meter, and calculated values, using Eq. 3.2.

Figure 3.17. Comparison of measured current waveforms for six different air-gaps: closed circuit, 1 to 4 layers of plain A4 paper, and open circuit.
3.2.2 Pole-shoe calibration and mounting

**Background and motivation**

With the tool presented in Paper I complete, the next step in the research was to try to use it to mount pole-shoes on the central pipe. The pole-shoe mounting is a crucial and time-consuming step in the production process of the WEC translator and in total, just over 200 pole-shoes are needed in each translator. They are mounted by accurately positioning and translating the negative wedge of the pole-shoe above the positive wedge of the translator and then forcing it down along the translator, a process sensitive to any misalignment between the positive and negative wedge. Therefore, the robot needs to be able to both lift the pole-shoe, and be able to precisely measure and calibrate the position of the pole-shoe and the central pipe. This calibration procedure is the focus of Paper II and also of the following text.

The need for work-piece calibration is nothing new and numerous solutions have been presented in the past, for example machine vision based ones such as the ones presented by Birk [64], Chen [65] and more recently Gans [66] or tactile touch-probes, such as in the works by Zhong [67]. There are many possible ways for a robot to obtain tactile information about its surroundings, as listed by for example Lee [68] and Girão [69], all with their own advantages and disadvantages.

For this application, a solution was needed that was robust and easy to use. Yet accurate down to less than 0.1° and 0.1 mm. As this specific application does not benefit from extensive surface contact information, supplied by tactile sensors such as capacitive films [70], the choice fell on using a simple digital touch probe.

**Calibration experiments and results**

Identifying the position and orientation of the used robot tool is a 6-DOF problem that needs to be solved in order for the lifted pole-shoe to be calibrated. Paper II shows that this can be solved by measuring three points on the pole-shoe, as shown in Figure 3.18, and combining this information with the approximately known geometry of the pole-shoe. Given that the three points \(p_{1-3}\), where \(p_n = [x_n, y_n, z_n]\), are successfully measured, the orientation of the pole-shoe can be found by solving the system of equations presented in Eq. 3.3, for the scalar value \(k\).

\[
\begin{align*}
    p_s &= p_1 + (p_2 - p_1)k, \quad k \in [0, 1] \\
    v_x &= \frac{p_3 - p_s}{||p_3 - p_s||} \\
    v_y &= \frac{p_s - p_2}{||p_s - p_2||} \\
    v_z &= v_x \times v_y \\
    0 &= v_x \cdot v_y
\end{align*}
\]
Using Eq. 3.4, the orientation can be converted from three orthogonal vectors \((v_x, v_y, v_z)\) into a more compact quaternion \((Q)\) representation, that can be understood by the robot control system. Here \(v_{a,b}\) denotes element \(b\) of vector \(a\), and \([v_{a,b} \geq v_{b,a}]\) is used as a logical operator, resulting in a value of either 1 or 0.

\[
Q = [q_1, i q_2, j q_3, k q_4],
\]
\[
Q^* = [q_1, -i q_2, -j q_3, -k q_4],
\]
\[
q_1 = \operatorname{Re} \left( \frac{1}{2} \sqrt{v_{x,x} + v_{y,y} + v_{z,z} + 1} \right),
\]
\[
q_2 = \operatorname{Re} \left( \frac{2[v_{y,z} \geq v_{z,y}] - 1}{2} \sqrt{v_{x,x} - v_{y,y} - v_{z,z} + 1} \right),
\]
\[
q_3 = \operatorname{Re} \left( \frac{2[v_{z,x} \geq v_{x,z}] - 1}{2} \sqrt{v_{x,x} - v_{y,y} - v_{z,z} + 1} \right),
\]
\[
q_4 = \operatorname{Re} \left( \frac{2[v_{x,y} \geq v_{y,x}] - 1}{2} \sqrt{v_{x,x} - v_{y,y} + 1} \right).
\]

The algebraic solution of Eq. 3.3 combined with Eq. 3.4 is over 2000 characters long, but was successfully implemented into a RAPID\(^2\) program, allowing the robot to solve the above equation system on the fly during operation.

\(^2\)RAPID: A programming language used to control modern ABB robots.

\[\text{Figure 3.18.}\] Positions of the three points used to calculate the orientation of the pole-shoe shown on a section of the pole-shoe. Corresponding coordinate systems are shown to the right.

A secondary aim for Paper II was to evaluate which sensor would be the best to use in this case, the IPS or the TP. Evaluation of the pole-shoe measuring algorithm was done using 200 individual measurements on the same pole-shoe. Before each measurement, the initial orientation of the pole-shoe was offset
by a random angular orientation error with a maximal amplitude of ±1.5°, in order to simulate the individual differences between actual pole-shoes. For each set of three measurement points, measured with both the IPS and the TP, both the position and orientation of the tool TCP was calculated. The results from the TCP position calculations are presented in Figure 3.19 and 3.20 for the TP and IPS, respectively. The results from the TCP orientation calculations can be seen in Figure 3.21 and 3.22 for the TP and IPS, respectively. The time required for the system to converge to its final value, using both the TP and IPS, is shown in Table 3.1. As can be seen, the TP is on average slightly faster to converge.

Based on these measurements the average time required to calibrate all pole-shoes in a single translator is around 10 h. When comparing the two sensors it stands clear that the TP is the better one, both with regard to absolute accuracy and repeatability. The standard deviation, \( \sigma \), of the error for the TCP position was 0.037 mm for the TP and 0.116 mm for the IPS, differing by a factor of 3.1. Looking at the TCP orientation, the \( \sigma \) of the error was 0.011° for the TP and 0.026° for the IPS, differing by a factor of 2.4.

Table 3.1. Average time needed to calibrate the pole-shoe, measured in seconds. Based on data from 200 consecutive measurement cycles.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductive sensor</td>
<td>139.9</td>
<td>168.3</td>
<td>178.7</td>
<td>15.6</td>
</tr>
<tr>
<td>Touch probe</td>
<td>124.4</td>
<td>164.1</td>
<td>167.8</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Mounting experiments and results

Before pole-shoe mounting could be attempted, the position of the central pipe also had to be calibrated. This was done by using a secondary IPS mounted on the plate lifter tool and using a similar point-based approach as the one used for the pole-shoe. Due to the comparably poor performance of the IPS used to calibrate the pole-shoes, mounting attempts were only performed using the TP calibration data. With the sliding mechanism of the tool disabled, mounting could only be performed after manually adjusting the calibration of the pole-shoe. With the mechanism enabled, mounting was successfully tested in the speed range 10–50 mm/s. Seen in Figure 3.23 is a snapshot from one of the successful mounting attempts. At speeds above 50 mm/s the tool began to wobble, and signs of self-locking could be observed. Due to the high risks of the equipment getting damaged, if a complete self-lock should occur, tests at higher speeds were abandoned.
Figure 3.19. Planar position point-clouds projected on the three main Cartesian planes (top) and deviation distribution (bottom) for 200 measurements of the pole-shoe TCP using the TP.

Figure 3.20. Planar position point-clouds projected on the three main Cartesian planes (top) and deviation distribution (bottom) for 200 measurements of the pole-shoe TCP using the IPS.
Figure 3.21. Calculated angular offset (measured between the ideal principal axes and measured principal axes) for 200 measurements of the pole-shoe orientation using the TP.

Figure 3.22. Calculated angular offset (measured between the ideal principal axes and measured principal axes) for 200 measurements of the pole-shoe orientation using the IPS.

Figure 3.23. Snapshot of a pole-shoe during mounting. Letters indicate the pipe wedge (A), the pole-shoe wedge (B), the pipe wedge gap (C), the lifting tool (D) and the main pipe wall (E). The mounting direction is here a downwards movement going in a direction from A to B.
3.2.3 Ferrite magnet mounting

**Background and motivation**

The mounting of the ferrite magnets has also been investigated, but has not yet been presented in any published paper. The magnet mounting process is still in its early stages and not yet as thoroughly investigated as the mounting of the pole-shoes. Tools and processes used are still a work in progress, but two main alternatives for mounting the magnets have been under consideration.

The first alternative is to lift each ferrite magnet individually, using a special magnet lifting tool, and then place it at the pole-shoe after it has been mounted on the pipe, as shown in Figure 3.24a. The second alternative is to use a separate magnet mounting table containing four pre-placed magnets, as shown in Figure 3.24b. In this case the plate lifter tool grabs a pole-shoe and places it over the magnet filled table, mounting all four magnets in one movement. With all magnets in place, the robot then proceeds to mount the pole-shoe on the central pipe.

![Figure 3.24. Ferrite magnet mounting alternatives. a) The magnet lifting tool prototype approaching a pole-shoe with a magnet lifted using a suction cup. b) Two out of four magnets placed on the magnet storage table. Each magnet is locked in the correct positions using guiding pieces and suction cups.](image)

**Experiments and results**

Initial tests using the magnet lifting tool prototype has shown that it is able to pick four magnets from a table and correctly place them on the pole-shoe, with a cycle time of just under 30 s. This was however done using preprogrammed positions of both magnets and pole-shoe. In a more realistic scenario, the robot would have to calibrate the components and positions prior to assembly, adding to cycle time. The magnet table has also been tested and shown to be able to hold all four magnets in position. But, in order to be able to lift both the magnets and the pole-shoe, the plate lifter tool needs to be further modified to cope with the repelling forces between the magnets, so that the pattern they placed in is not changed once they are lifted from the guiding pieces of the table.
3.2.4 Inclinometer based calibration

**Background and motivation**

While the pole-shoe calibration procedure presented in Paper II showed promising results, it was too slow to become a viable alternative in a real production line. A system was needed that could calibrate the pole-shoe faster than the 164 s used by the TP based system, from Paper II, preferably in less than 1/10th of that time. Paper III presents an alternative pole-shoe orientation calibration method based on a digital MEMS (Micro-Electrical-Mechanical System) accelerometer. Alignment, in this context defined as the process of finding the correct orientation or the robot tool, can be made using a number of different technologies as previously discussed in section 3.2.2, and one such technology is accelerometers. MEMS accelerometers are today used in various technological applications such as smartphones and medical equipment [71]. They have also been successfully implemented into robots as a means of pose estimation and control optimization, as demonstrated by for example Quigley [72] and Staufer [73]. To reduce measurement noise, it is also possible to combine the signal from multiple MEMS accelerometers, as shown by for example Madgwick [74].

**Experiments and results**

In Paper III a total of three experiments were performed, two of which will be presented here. The first experiment was a simulation of the performance of the derived equations using numerous random input values, in order to find the general characteristics and limits of the system. The second experiment consisted in fastening the accelerometer PCB prototype presented in section 3.1.5 to the end manipulator of the ABB6650S robot, and then moving accelerometer around in a predefined pattern, as schematically shown in Figure 3.25. At each endpoint of the movement, the accelerometer PCB took a measurement and sent this data to the robot. The mathematical details of how the derived equations and accelerometer data can be interpreted and used to calculate the orientation of the pole-shoe will not be covered here, interested readers are instead recommended reading the theory chapter of Paper III. But in summary, the system works by finding the gradient of the accelerometer measurements along the base axes of the robot and these gradients can then be converted into a quaternion representation of the orientation of the accelerometer relative to the coordinate system of the robot. Two works were of great help during the derivation of this theory, firstly the formula for a quaternion average presented by Markley et al. [75] and secondly the comprehensive list of conversion formulas for Euler-angles, quaternions and rotational matrices made by Henderson [76].
In the simulations of the system, Eq. 3.5 was used to introduce an alignment error quaternion ($Q_d$) into the system as a function of the angular error amplitude $\Gamma$, and a randomized 3D unit vector $\hat{t}$. One of the results from this simulation experiment was that the remaining error after calibration is related to both the amplitude of the initial error and used tilt amplitude as shown in Figure 3.26. It seems that regardless of the used tilt amplitude, the maximal error (relative to the initial error) is around 5.4 % for the tested range. The peak error interestingly occurs when the tilt amplitude ($\Delta \varepsilon$) used by the system to find the error is the same as the used $\Gamma$, suggesting that the system, if possible, should try to avoid using tilt amplitudes close to that of the absolute value of the initial error.

$$Q_d(\Gamma, \hat{t}) = [\cos\left(\frac{\Gamma}{2}\right), \hat{t}\sin\left(\frac{\Gamma}{2}\right)].$$ (3.5)

The hardware evaluation in the second experiment was performed using 2000 randomized orientation errors of varying amplitude and position. Each error position was misaligned by a random amount between 0–10° and 150 mm from the optimal origin. Analysis of the remaining orientation error, shown in Figure 3.27, revealed that if the remaining misalignment was represented as Euler-angles the system was most accurate for the $\alpha$ and $\beta$ angle, and about 1/4 as accurate for the $\gamma$ angle. Assuming a normal distribution of the error, the $3\sigma$-limit for $\alpha$, $\beta$ and $\gamma$ was calculated to be $0.022^\circ$, $0.024^\circ$ and $0.136^\circ$, respectively. Regarding the time consumption of the calibration, the system needed on average 20.9 s to align the accelerometer, a reduction of 87 % compared to the system presented in Paper II.
Figure 3.26. The effect of $\Delta \varepsilon$ on the maximum relative error for a given set of constant $\Gamma$. Tested in the range of $\Delta \varepsilon \in [0.01, 20.0]$.

Figure 3.27. Euler-angle($\alpha, \beta, \gamma$) distribution of the remaining orientation error around the X, Y and Z-axis, as reported by the control system of the robot. Errors are shown as the deviations from the mean of 2000 calibration runs. Note that the axis limits used for the $\gamma$-plot are different from that of the other two.
4. Topic II: WEC measurement systems

This chapter will focus on my secondary research area, stand-alone WEC measurement systems. The project was in large part a collaboration between myself and L. Ulvgård, another researcher at the division. The chapter will mainly present information from Papers V and VI. Overall, my role in the project was that of an electronic system designer and modeler, but I also assisted with data analysis and model identification.

4.1 Experimental setup

Here the two main iterations of the WEC measurement system will be presented. Both systems are based on current loop feedback, as current signals are generally considered more noise resistant than pure voltage signals [77]. The trade-off is that the signal bandwidth becomes limited by the inductance of the system and the used driving voltage. Bandwidth was not really an issue here, due to the comparably low frequency of the measured signals from the WEC, in the order of 10 Hz. A sample rate of 1 kHz was deemed high enough to be able to catch all relevant aspects of the performance of the generator. The main difference between the two measurement systems is their layout, where Gen I used a more modular design and Gen II sacrificed modularity for a more compact footprint and reduced power consumption. Both systems used the industry standard signal level of 4–20 mA.

4.1.1 Gen I: Multiple single phase PCBs

The function of this setup was to measure three AC voltages/currents and one DC voltage/current inside a WEC. The AC side was designed to measure in the range of ±1.2 kV and ±350 A, while the DC side was capable of measuring 0–2 kV and 0–400 A. Two different PCBs were designed, one for current measurements and one for voltage measurements. Both were based on the XTR115, an industry standard 4–20 mA current loop transmitter. This model was chosen for its low price, large input range (7–36 V) and on-chip voltage references. The voltage PCB used a resistor divider combined with an isolated amplifier, AMC1200, to generate an input signal to the XTR115, while the current PCBs used a galvanic isolated current hall-sensors, HAIS150P and HAIS200P. To power the sensors both PCBs were fitted with a DC/DC converter, TMR 1-2411, able to convert a varying battery voltage to a fixed supply voltage of 5 V. A schematic overview of the system is shown in Figure 4.1.
Figure 4.1. Schematic picture of the full system and its connection to the three phases of a WEC, and one additional position sensor.

Special care had to be taken to the layout of the voltage PCB components, as each PCB needed to provide galvanic isolation between the measurement signal and the WEC, up to a level of at least 2500 V. The choice to isolate the measurement system from the WEC was done in order to reduce the risk of ground loops and to protect the sensitive measurement logging electronics from unexpected voltage surges in the WEC. Shown in Figure 4.2 is one of each PCB, mounted in its protective box.

Figure 4.2. Single channel current (a) and voltage (b) measurement PCBs mounted in protective aluminum boxes, serving both as a physical barrier and electromagnetic noise insulator.

As each PCB only could measure one signal, eight PCBs had to be assembled to complete the voltage/current measurement system. One additional PCB was also added for measuring translator position, for a total of nine units. Each PCB was given its own protective box and power supply. The complete system was mounted on a POM-H plastic plate and bolted to the bottom of a WEC unit. Figure 4.3 shows the system just before its installation into a WEC.
Figure 4.3. Complete three-phase system measurement system. With one extra channel added for DC measurements. The power resistors (middle) are used as voltage dividers, converting the kV input to the mV signals required for the amplifiers.

4.1.2 Gen II: One three phase box

The second generation of the stand-alone WEC measurement system was designed to measure three AC voltages, in the range of \(\pm 1000\) V, and three AC currents, in the range of \(\pm 267\) A, omitting the DC measurement capability of the previous generation. The output for all channels remained 4–20 mA signals, in order to be compatible with previously designed hardware.

In order to reduce the power consumption of the Gen II system, compared to that of the Gen I system, the component layout was redesigned and all components put on the same PCB. Both the current and voltage measurement used the Si8920 series isolation amplifier and current sensing resistors. Shown in Figure 4.5a is a schematic layout of the system. Note that all six signals and additional power connections are combined into one single DSUB-9 connector.

The voltage and current measurements use slightly different isolation amplifiers, where the current circuit uses the Si8920A and the voltage circuit the Si8920B, the only real difference between them being their allowed input voltage range of 100 mV and 200 mV, respectively. Both circuits use the XTR115 IC to convert the output of the isolation amplifier into a 4–20 mA current signal.
Figure 4.4. Circuit layout for the measurement system, showcasing the current measurement circuit (top), voltage measurement circuit (middle), and the isolated power-supply (bottom).

Note that the Gen II setup connects one side of all sensing resistors to the same $V_{ref}$ voltage level, allowing all isolation amplifiers to be powered from the same DC supply, drastically simplifying the design of the power supply circuit. Figure 4.5b shows two Gen II measurement PCBs mounted in the lid of a protective aluminum box. By using two separate PCBs, two logging systems could be run in parallel and also allowed for redundancy in the system, should one PCB fail. Figure 4.5c shows the three current shunt resistors alongside the box containing the voltage divider resistors.
4.1.3 The stand-alone integrated logger

In order to record and store the data generated by the Gen II WEC measurement system, some kind of logging station was needed. To this end the stand-alone integrated logger, or “snigel” for short, was developed. Snigel consists of three main components: a PCB containing the actual logging circuitry and memory, a battery pack supplying both the logger PCB and Gen II PCB with power, and lastly a protective watertight pressure vessel acting as housing for both the battery pack and logger PCB.

The logger PCB was mainly designed and constructed by A. Risberg, a project worker at the division, and is based around the ATmega328P microcontroller and the ADS8345 ADC converter, as described in Paper VI. It is capable of recording 16 4–20 mA single-ended signals at a resolution of 16-bit at a sampling rate of 1 kHz per channel. Logged data is stored on a set of three 32GB microSD cards. A schematic overview and picture of the logger PCB is shown in Figure 4.6 and a full picture of Snigel is shown in Figure 4.7. The used battery pack consisted of 1.5 V alkaline cells, adding up to a nominal voltage of 15 V and 220 Ah of energy.
4.2 Background, experiments, and results

Using the designed measurement systems from the previous section a number of experiments were performed. Here the background, motivation, results and reflections of these experiments will be presented, mainly centered around Paper V and VI.

4.2.1 The first stand-alone WEC measurement system

Background and motivation

According to the IEA, worldwide wave-energy research is beginning to enter a phase of offshore testing and operation, and as such the interest in on-site monitoring and measuring systems is growing [78]. In offshore projects
entering a commercial phase, there is also an interest for real-time monitoring, for use in active control, forecasting and maintenance planning, as discussed by Martinez et al. [79]. But due to the challenging offshore environment and the high costs of installation and maintenance, constructing economically viable systems have proven to be a challenging task [80]. However, the field of monitoring systems for renewable energy is rapidly developing, especially for wind power [81], a trend that is likely to benefit wave power in the end as well.

Paper V presents a prototype for such a low-cost yet highly robust offshore measurement system aimed for use in wave power, and the successor to the previous system presented in [82]. The main goal of Paper V was to both evaluate and verify the performance of the first stand-alone WEC measurement system prototype (Gen I), both in a laboratory setting and in a real-life scenario. Evaluation and verification were done by measuring the system’s linearity, frequency response, gain and step response.

Experiments and results
Voltage linearity tests were performed by using a signal generator to generate sinusoidal voltages of varying frequency and amplitude. The performance of the system was evaluated at 10 Hz, 100 Hz and 1 kHz. Current linearity tests were only performed at 50 Hz, as this was the only frequency where equipment capable of delivering sinusoidal currents above 20 A was available. To further amplify this signal a cable was wound 20 times through the core of the HAIS current sensor, giving the evaluation setup apparent signal range of 0–400 A. The results of these tests are shown in Figure 4.8, where it can be seen that the system is highly linear. However, the 1 kHz signal shows a small deviation from the other two, mainly attributed to the 10 kHz low-pass filter beginning to take effect. Note that the figure shows the output current as the absolute deviation from the zero reference level, in both the voltage and current PCB set to 12.0 mA, meaning that an input signal of zero will produce an 12.0 mA output signal.

![Figure 4.8](image_url) Voltage and current linearity measurement of the voltage and current measurement PCBs, using sinusoidal input signals.
Evaluation of the frequency response and phase shift of the system was done in the range of 0–100 kHz, using a signal generator for the voltage PCB and a high current operational amplifier for the current PCB. The measured gain and phase shift performance are shown in Figures 4.9 and 4.10 respectively. Note that both the gain and phase shift remain close to zero up to the specified sampling frequency of 1 kHz.

**Figure 4.9.** Current and voltage gain for the Gen I PCBs. The top graph shows the difference between current and voltage gain.

**Figure 4.10.** Current and voltage phase-shift for the Gen I PCBs. The top graph shows the difference between current and voltage phase shift.
Shown in Figure 4.11 is a set of three-phase current and voltage measurements from an onshore test using a real WEC linear generator. Seen in the figure is the raw data from the logger PCB, a moving average of the same data, and reference measurement made using a PC oscilloscope. The reference measurement agree with the data from the logger PCB in all but one case, but that was later found out to be due to a faulty probe used during the reference measurement and not a fault of the logger itself. It should be noted that these tests were performed at around 2% of the full signal measurement range due to a lack of experimental equipment capable of driving the WEC at rated speed, and thereby rated voltage and current. At a supply voltage of 24 V each voltage and current measurement PCB was measured to draw 20.8 mA and 22.8 mA, respectively. Combining all six units, the AC measurement circuitry had an average power consumption of 3.14 W. The DC measurement circuitry consumed about 1/3 as much power.

Figure 4.11. Three-phase current and voltage measurements. Unfortunately one of the reference current measurements was faulty and is therefore showing abnormal values.
4.2.2 The second stand-alone WEC measurement system

**Background and motivation**

With the experience from the evaluation of the first stand-alone system, it stood clear that there was room for improvements within the system. The biggest concern was the 3.14 W power consumption of the first generation, something that directly influences the time the system can run while on battery power. An independent data logging and power source were also needed, in order to remove the need for a connection to a substation or the measurement cabin. The logging system had to be mounted outside the WEC and so that it could be retrieved when the experiment was over. The goal of the work presented in Paper VI was to construct and test an improved version of the measurement system (Gen II), and also to complete the system by incorporating the first prototype of a battery and logging unit.

**Experiments and Results**

The second generation of the measurement system was mostly based on the same hardware as the first, with just a new layout and minor tweaks. The system was evaluated in the same way as Gen I, namely: linearity, frequency response, gain and step response. Similar to Gen I, the new system was verified to be highly linear, with a coefficient of determination above 0.999, when curve-fitted against a linear model. Shown in Figures 4.12 and 4.13 are the results for the gain and phase-shift measurement for the Gen II system, measured in the range 1 Hz to 100 kHz. The cut-off frequencies of the voltage and the current signals were found to be 6 kHz and 6.5 kHz, respectively, with no significant phase-shift measured up to the sampling rate of the logger at 1 kHz. The main difference between these figures and the corresponding ones for the Gen I system is that the cut-off behavior is more similar between the voltage and current measurements in the newer setup, most likely due to the fact the new system uses sensing resistors for both voltage and current.

With a nominal battery voltage of 15 V the power consumption of the Gen II measurement system was measured to be on average 1.45 W, a reduction of 54 % compared to the Gen I system. The logger PCB itself was measured to consume 0.41 W when logging and 0.33 W when in standby. The sample resolution of the logger unit was measured to be around 1 µA (limited by the used ADC), and the noise level was measured to be approximately 30 µA, within a $3\sigma$ certainty. This corresponds to maximal resolution on the voltage and current measurements of 135 mV and 37 mA, and a measurement uncertainty of 12.9 V and 3.5 A, respectively. The noise levels can be reduced by at least 75 % by post-process filtering, using a moving average filter of length 16, without causing any significant phase-shifts to the signals of interest (~10 Hz), due to the 1 kHz sample rate.
By default, the logger was configured to keep the measurement PCB always on and continuously sample data at 1 kHz from all 16 available channels, regardless of them being in use or not, leading to the microSD cards running out of space in less than 5 weeks. To extend the operational time of the system the data collection rate was limited by forcing a duty-cycle on the active time of the logging algorithm. Making it measure in bursts of 5 min each, extending the operational time as shown by the “Data limit” line in Figure 4.14. Another limiting factor was the battery lifetime and, as shown in the same figure, the...
calculated operational time for the system is, with six active current signals, just above 10 weeks. Combining these two limitations lead to an optimal data collection duty cycle of around 46%.

Also shown in Figure 4.14 is a theoretical calculation (dotted lines) of the lifetime of the system if a duty-cycle limitation could also be implemented on the power supply of the current signals from the measurement PCB and not only the logger, and if the number of active channels in the logger could be set match the number of used current signals (in this case 6). In that case, the limiting factor for the system always becomes the lifetime of the battery.

Figure 4.14. Expected operational time for a 6 signal system with improved logger settings, showing battery and data storage lifetime as a function of duty cycle.
5. Topic III: Kinetic energy storage flywheels

This project was in large part a collaboration between mainly myself, M. Hedlund, and J. Abrahamsson, both researchers at the division of electricity. Information presented here mainly comes from Papers IX, X and XI. Overall my role in the project was that of a mechanical and electrical designer and, as such, that will also be the focus of this chapter. As the tertiary research subject, flywheel technology will not be covered in the same detail as in the previous two topics. Paper XII will also not be covered in this thesis as my contribution to it was deemed too small to motivate giving it its own section. Interested readers are instead recommended reading the paper itself or the corresponding section of the summary of papers, found in chapter 10.

5.1 Experimental setup

Here the hardware and design of the two flywheel prototypes used for Papers IX and X will be briefly described. Both machines were proof of concept machines, and each was the first of their kind ever to be built by the UU flywheel group. To distinguish between them, the prototypes were dubbed Prototype II (P2) and Prototype III (P3).

5.1.1 P2 – The first levitated composite rotor

The P2 was the first attempt of a complete flywheel system by the group. This includes composite-rotor, magnetic bearings, vacuum enclosing, electric machine, supporting power electronics, and measurement systems. A CAD drawing of the central parts of the machine can be seen in Figure 5.1, where the most important features have been marked. The flywheel rotor is designed to store 867 Wh at a design rotational speed of 30000 rpm. To reduce air friction losses the rotor was enclosed in a vacuum chamber during operation. To further reduce friction losses, the bearing system of the rotor relied on a combination of passive permanent magnet thrust bearings and actively controlled electromagnet radial bearings. While in operation, the magnetic bearing levitates the rotor inside the support structure, in such a way that it has no physical contact with its surroundings.

The rotor primarily consists of a carbon-fiber (Toray-T700) and fiber-glass (Advantex E-glass) composite cylinder, in a specially optimized quota that minimizes the radial stresses in the composite during standstill. This composite
cylinder was press-fitted onto an aluminum cylinder, carrying the permanent magnets of the electrical machine and central shaft of the rotor. As the machine utilized a coreless design, the permanent magnets of the rotor were arranged in a Halbach-array in order to strengthen the magnetic field in the air-gap. The stator consisted of Litz-wire coils glued to the surface of a plastic support structure for a total of six phases arranged in a double wound configuration, based on the previously mentioned patent [48].

The rotor was surrounded by a support structure consisting of two horizontal aluminum plates and six vertical steel square-pipes, joining the plates together. This design was chosen to allow for easy access to all parts of the machine. A more detailed description of the P2 prototype and its surrounding systems can be found in Paper X.

5.1.2 P3 – The first switched reluctance machine

This prototype was constructed to prove the functionality of the axial-flux reluctance machine presented in Paper X. To reduce the complexity of the system the prototype was not designed as a hollow cylinder as suggested by the theory part of that paper, and instead utilized a more bucket or bell-like design, containing a central shaft similar to P2. In general, many parts for this design was reused from the previous P2 project, both to save time and money. The machine also used normal ball-bearings, instead of magnetic levitation, further reducing complexity. A CAD drawing of the machine can be seen in Figure 5.2, where the most important features have been marked.

The most mechanically complex part of this machine was its stator. It consisted of a central pipe with three main pillars, where each pillar was made up of electrical-steel laminates supported by an aluminum pipe. Around each
pillar, the stator coil was then wound using Litz-wire, and to make the assembly of the machine easier, the top of the stator could be separated, allowing the rotor to slide over the stator during assembly. As the machine has only one magnetically active pole in the rotor, one-half of the rotor is filled with non-magnetic stainless steel, of the same density as the electrical-steel, to act as a counterweight. The rotor was connected to the support structure using a central shaft with ball bearings at each end, just as in a standard radial-flux electric machine. Figure 5.3 shows the P3 during construction. Note the detachable lid of the stator and the separation between the magnetic and non-magnetic sides of the rotor.

Figure 5.2. Rendered 3D CAD picture (left) and a 2D section cut (right) of the P3 prototype, excluding the composite shell. Picture courtesy of M. Hedlund.

Figure 5.3. Some pictures of the P3 during assembly. a) The stator support. b) The laminated rotor cylinder. c) The stator with windings. d) The stator lid. e) Support structure of the stator. f) The stator, rotor, and central axis.
The unusual topology of the hollow cylinder machine presented in Paper X offers some advantages and some disadvantages. On the positive side, it does not have a shaft, is able to withstand high centrifugal loads, and maintains a constant air-gap during radial expansion. All three suggest that the machine could perform well at high rotational speeds. Additionally, the option to operate the machine with homopolar excitation could also be used to decrease core losses. On the negative side, if compared to a radial-flux machine of similar size, the magnetically active area is limited by the thickness of the shell, and the stator also has a lower winding factor. Both of these factors have a negative impact on the maximal available torque. Therefore, the design rationale regarding the power output \( (P) \) of the machine is to trade torque \( (\tau) \) for an increase in rotational speed \( (\omega) \) in order to maintain a power output comparable to that of a similarly sized radial-flux machine, as \( P = \tau \omega \). A more detailed description of the P3 prototype and its theoretical background can be found in Paper IX.

5.1.3 Electronics
Both P2 and P3 required a great deal of external electronics and equipment to function, where some of the most notable components were: the current sensor, the position sensors, the power inverter, and the National Instruments compactRio with its FPGA (used for the control system). The inverter and compactRio could be shared between the P2 and the P3 prototype, but other than that all equipment had to be tailor-made for each prototype. Most of the electronic sub-systems were built in-house, except the position sensors for P2 that utilized the Micro-Epsilon eddyNCDT-3010S2. Figure 5.4 shows the electronic equipment used for the magnetic bearing system in P2 and Figure 5.5 shows the general purpose inverter used to drive the electric motor during experiments on both P2 and P3. The inverter was based around five Infineon F4-75R12MS4 IGBT-modules and an adjustable transformer, used to connect the inverter to the electrical grid.

5.2 Background, experiments, and results
Using the prototypes described in the previous section a number of experiments were performed. Here the background, motivation, results, and reflections of these experiments will be presented, mainly centered around Papers IX, X, and XI.
Figure 5.4. The control electronics and power supplies used to levitate the P2 rotor. To reduce electrical noise all components were mounted in separate aluminum boxes.

Figure 5.5. The general purpose inverter with its main components marked.

5.2.1 P2 – The first levitated composite rotor

**Background and motivation**

The P2 project was started after the success of the first flywheel drive-line described in [83]. The initial goals of the projects were to demonstrate the feasibility of the double-wound stator concept in a bigger machine and to minimize the internal losses of the electrical machine. To minimize losses a coreless stator topology was chosen, and the machine was to be operated in a vacuum. To increase the amount of stored energy the rotor of P2, compared to the previous prototype, while still keeping it small and light enough to fit inside a car, its rotational speed had to be increased. Therefore, a switch from a solid metal rotor to a carbon-composite rotor was made. While the choice to go for a carbon-fiber composite rotor that offers higher maximal rotational speed and specific energy was made, it was not without its problems. The main problem
was, and still is, that the fatigue and failure criteria of composites are very different from that of metals and other homogeneous materials and are hard to model and accurately predict as discussed by for example Talreja [84] and later Mao [85]. Additionally, the expertise of the group in the area of composite design and manufacturing was non-existent at the start of the P2 project. For these reasons the manufacturing and design of the composite shell were made in collaboration with an external partner, Swerea SICOMP\(^1\), and the result of this collaboration was the composite shell used for the P2 prototype, presented in detail in [86]. Paper IX focuses mainly on the design and initial tests of the magnetic bearings, while Paper X focuses on determining the losses and eigenfrequencies of the machine.

**Levitation experiments and results**

Using a stationary rotor, initial tests of the position and current control system of the electromagnets in the radial magnetic bearing showed promising results. The stabilized after about 20 ms after a step in the position reference. The maximal stiffness of the electromagnetic radial bearing was measured to be 120 N/A at a bias current of 1.5 A, at the nominal air-gap. Axial levitation was achieved using two opposing disks of NdFeB magnets arranged in a Halbach-array, with the same polarity, and achieved a stiffness off 544 N/mm at the nominal air-gap. This figure was later reduced to 360 N/mm by changing one of the opposing Halbach-arrays to a magnetic disk consisting of two concentric rings, shown in Figure 5.6.

![Figure 5.6](image)

*Figure 5.6. Two versions of the axial thrust bearing disks. The segmented Halbach-array (left) and two solid concentric rings with opposing magnetization (right). Both covered in a protective epoxy coating.*

Magnetic levitation with a spinning rotor proved more challenging, mostly due to eigenfrequencies in the mechanical system at approximately 400 Hz and 1050 Hz, but also due to rotor unbalance. During the design of P2, values close to these frequencies had been found during simulations, as seen in Figure 5.7, but their actual amplitude had been greatly underestimated.

\(^1\)https://www.swerea.se/sicomp (Accessed: 2017-08-24)
In the real rotor, the force from these vibrations were more than the radial bearings could handle, making levitation with a spinning rotor impossible, using the initial control-system. However, after successfully implementing a controller with a notch filter, that could filter out and suppress the excitation of these vibrations, the prototype could be levitated and rotated at the same time. This was, however, limited to rotational speeds below 1000 rpm. Above this eigenfrequencies and rotor unbalance again overloaded the radial magnetic bearings, something that is discussed in more detail in Paper XI.

![Figure 5.7. 2D section cuts of a 3D simulation, showing the first five eigenfrequencies of the P2 rotor. The shown deformations are highly exaggerated, and colours are only indicative of the magnitude of the translation.](image)

**Loss evaluation and results**

Even if the machine could not be operated at its design speed, measurement of the losses in the rotor could still be made. To do this, P2 was put inside a custom-made vacuum chamber that was then pumped down to a medium vacuum of 6 mbar. Lower pressures could not be reached due to leakage in the used couplings and possible out-gassing from the used materials. The spin-down time of the rotor, from 1000 rpm to 0 rpm, was measured to be 69 min at atmospheric pressure (1 bar) and 129 min in vacuum, as shown in Figure 5.8. The corresponding power loss for each rotational speed can be seen in Figure 5.9. Note that these figures only include the losses in the rotor and the bearings, not including the energy needed to keep the magnetic bearing active. If this energy is counted as a loss, another 40–50 W of losses need to be added. The power loss per stored watt-hour in vacuum converged to 1.7 W/Wh, at 1000 rpm. A figure lower than other similar flywheels for automotive applications, but larger than that of stationary energy backup flywheels, as concluded in Paper XI.
Figure 5.8. Spin-down time for the P2 prototype, from 1000 rpm, measured at two different air pressures.

Figure 5.9. Power losses for the P2 prototype, calculated from the deceleration of the rotor, at two different air pressures.

5.2.2 P3 – The first switched reluctance machine

Background and motivation

The reason for starting to investigate the hollow cylinder concept was that the shaft to rotor connection in P2 was found to be one of the most problematic parts of the whole setup. A comparably slim shaft together with a massive rotor formed a mechanical system that resonated like a bell, spreading vibrations thought the whole flywheel, a problem described in detail in Paper XI. The problem of connecting a shaft and a composite rim is a subject that is well addressed in the technical literature, resulting in innovate patents such as [87], but also solutions that forgo the shaft (and thereby the whole problem) completely, such as [88]. P3 was the first attempt by the UU flywheel group to design an electrical machine that could be used in a shaft-less rotor, even though the prototype itself had a shaft. In Paper IX, two main questions were under consideration when evaluating P3. Firstly, does it produce enough torque to be a viable design option? And secondly, how well do the analytical models compare to the real machine?
Experiments and results

The inductance of the prototype was estimated using four different methods, with the results being shown in Figure 5.10. From the figure, it can be seen that the different methods agree on the general characteristics but disagree on their exact numbers. Comparing the analytical solution and the identified system, the analytical solution overestimate the $L_d$ and $L_q$ quota, indicating that the actual torque of the machine is lower than the analytical solution would suggest, but the error is, in my opinion, not large enough to invalidate the model.

Unfortunately, one of the ball-bearings did get damaged during assembly, greatly increasing its friction. Therefore, the machine could not be run at its full speed and no accurate torque measurements could be performed. However, during testing the machine did spin-up to a few hundred rpm within a few seconds and could be stopped just as fast, even with a damaged bearing. This indicates that the produced torque would be enough to accelerate the machine to rated speed within a reasonable time. Thus, the prototype has proven both to be mechanically possible to build, and to be electromagnetically viable as an electric machine. Due to time and resource constraints, the machine was unfortunately never repaired and tested further.

Figure 5.10. $L_d$ and $L_q$ inductance estimations for P3, using four different methods: an analytical model, 3D-FEM simulation with non-linear steel, measured using a hand-held inductance meter, and inductance estimation from voltage and current measurements. The details of each method can be found in Paper IX.

In Paper X an extrapolation from the results from the prototype is done to that of a full-scale, true hollow cylinder machine, in order to estimate its performance. In that theoretical study, it was found that a full-scale electrical machine of this type using a carbon-fiber outer rotor shell, with a diameter and height of 1 m, could potentially reach rotational speeds of 20000 rpm and produce 50 kW of power.
6. Conclusions

This chapter will present the conclusions drawn from the previous chapters. Each topic will be given its own section and be reconnected to the research questions and aims.

6.1 Automated WEC translator production

In Paper I, it is shown that using tool mounted electromagnets as a way of detecting the distance to a ferromagnetic target is a viable solution, but that the system, for now, will require on-site calibration. Further research is therefore needed to find an accurate theoretical distance estimator. Keeping the implementation at a comparably low cost, without sacrificing too much accuracy, was done by using a hybrid switching mode. The system was found to work as intended. Using mounted electromagnets, distance sensing functionality could be demonstrated in the range of 0–5.2 mm. A simple magnetic connection and material saturation evaluation method was also presented and shown to work. However, the overall practical benefit of this self-sensing system, compared to using regular inductive sensors or similar, seems small.

In Paper II, a method for mounting high tolerance pole-shoe wedges on a translator pipe, using industrial robotics, is presented. Two types of sensors were evaluated for the system, where the tactile touch-probe was found to be the superior alternative. The combined accuracy of the pole-shoe and pipe calibration were not enough to allow for the use of a stiff robot tool during the mounting action. A tool with a selective compliance mechanism had to be used instead. While the system was able to accurately mount pole-shoes at a speed of up to 50 mm/s, the used calibration method was too slow to be a viable alternative in a live production environment, accounting for up to 87% or 164 s of the total cycle time. While slow, this result was a breakthrough for the project, as automating the pole-shoe mounting was one of the biggest obstacles to be overcome.

In Paper III, a theoretical model and a prototype for an inclinometer based orientation calibration system are presented. The prototype is mounted on an industrial robot, and the robot is tasked with aligning the prototype towards its own coordinate system. Over a set of 2000 test runs, the system was able to align itself with an average accuracy of 0.023° in the XY-plane, and 0.14° around the Z-axis. The inclinometer based system is much faster than the one presented in Paper II, with a 87% reduction in orientation calibration time, and
higher accuracy. However, a system to reliably and automatically couple the inclinometer to the pole-shoe remains to be developed. The system also needs to be extended with a simple vision system, or similar, in order to find the position of the pole-shoe, as the current iteration is only able to compensate for orientation errors.

In summary, the research question related to this topic was: Can the assembly of the ferrite translator be automated? The answer is yet to be confirmed, but it is highly plausible based on the results presented above. Although, this is but the first step towards a fully automated production line for ferrite based translators, one of the hardest challenges has been solved; that of calibrating and mounting the pole-shoes.

6.2 WEC measurement systems

In Paper V, a system designed to measure AC three-phase voltage and current signals, alongside one DC voltage and current, is presented. The output of the system consists of eight current signals, using the industry standard 4–20 mA signal range. The system was shown to be highly linear, and did not have any significant phase-shift over the relevant measurement range. It was constructed by using off-the-shelf electronic components at a low cost, if compared to commercial systems with similar specifications. The modular design of the measurement PCBs allows for easy scaling of the system to an arbitrary number of channels. Although not tested in an offshore environment, the system is theoretically an upgrade from previous systems used in the project in regard to noise levels, signal bandwidth, and power consumption.

Paper VI extends on the system presented in Paper V. By sacrificing modularity, and placing all components on the same PCB, the power consumption of the new system could be cut in half. The submersible logger unit is small enough to be deployed and retrieved by one person, and can collect data for 10 weeks before running out of batteries. This figure could be extended to over 40 weeks by simple software changes, at the expense of a reduced data collection rate. By having a portable logger unit, the project no longer needs to connect each WEC to the on-shore measurement cabin, or a substation, in order to perform measurements, something that should simplify future data collection.

In summary, the research question related to this topic was: Can accurate, yet cost-efficient WEC measurement systems be built? The results and devices presented in Paper V and VI arguably shows this to be true. However, much work still remains in increasing the usability and robustness of the systems. As it is now, the installation of the hardware and post-processing of measurement data requires a deep understanding of the function of the system. Ideally, this should be further developed into a more user-friendly setup, so that other groups and researchers could easily benefit from the system as well.
6.3 Kinetic energy storage flywheels

In Paper IX, the design for a novel axial flux reluctance machine is presented. The goal of the design is to function at high speeds, above 10000 rpm, and to be compatible with the hollow cylinder rotor concept. A non-hollow proof of concept prototype, dubbed P3, is constructed to evaluate the feasibility of the axial flux design. Experimental results proved the design to be functional and in reasonable agreement with the derived theoretical model of the machine. A damaged ball bearing and time constraints prevented full speed tests of the machine, but the prototype proved the concept viable. FEM simulations, extrapolated from the results of the prototype, suggest that a full hollow cylinder machine of this topology could potentially reach rotational speeds of 20000 rpm and produce 50 kW of power. However, much optimization of the geometry remains to be done, especially for reducing iron losses, since the current designed proved to have higher losses than expected.

In Paper X and XI, the design and evaluation of a high-speed (30000 rpm) composite reinforced flywheel and surrounding support structure is presented. The prototype, dubbed P2, utilizes a coreless permanent magnetized double wound electric machine, optimized for low losses and high speed. To further reduce the losses, the prototype was operated inside a vacuum chamber and fitted with a magnetic levitation bearing system. The magnetic levitation system utilizes passive axial thrust bearings and active electromagnetic radial bearings. The system is demonstrated to work at rotational speeds of up to 1000 rpm, both in a medium vacuum and atmospheric pressure. Unfortunately, higher speeds were not possible due to a combination of eigenfrequencies and rotor unbalance. As a machine P2 failed to reach its design specifications and must, therefore, be considered a partial failure.

In summary, the research question related to this topic was: What are the mechanical considerations and problem areas when designing high-speed composite flywheels? Based on experience of the P2 and P3 prototypes, the most challenging problems were rotor unbalance, eigenfrequencies and composite fatigue. The question if the performed fatigue and energy optimization estimations are correct remains open, as none of the composite shells constructed has yet been tested to their limit. The P2 and P3 prototype show two different types of machines that could be used in a kinetic energy storage system, but both systems require much work before they would be commercially viable.
7. Future work

This chapter presents a short overview of potential future works, both in the form of currently ongoing projects and new untested ideas.

7.1 Improved switching electronics

A new generation of the CCB presented in Paper I has been in development since the publication of that paper. A prototype of the new CCB can be seen in Figure 7.1 showing a completely new component layout.

![Figure 7.1. The next generation of the CCB with better switches, capable of handling up to 15 A, and a custom designed high-side current transducer.](image)

The new CCB has a custom designed 4–20 mA transducer circuit with a bandwidth of around 2 MHz according to simulations. Measurement to verify this remains to be done. The separation between the power side and logic side of the PCB has been improved, and the new gate-driver allows for MOSFET switching times in the order of 10 ns. By using separate pin-headers for power and logic, the CCB can be plugged into any system using the same pin-out, making it more modular. However, the MOSFET suffer from large overshoots (above 25 %) when switching inductive loads, and the current converter circuit shows an unexplained saturation behavior during 10–90 % signal step response tests. Additional work is therefore needed before this circuit is ready to replace the current CCB.
7.2 Improved ripple detection circuits

An improved current ripple detection circuit, shown in Figure 7.2, is under development. This circuit takes the 4–20 mA current signal from the new CCB, presented above, and converts the amplitude of the ripple into an integer value, that can then be read from the circuit using I2C communication.

![Image of the current ripple detector and amplifier circuit.](image)

The circuit works by separating the DC and AC part of the measured signal using a high-pass filter, amplifying the AC component, and then converts this AC signal into a DC signal using a high accuracy rectifying circuit. The DC signal is then filtered and sent to a 16-bit ADC that can be accessed from a pair of external I2C pins. Initial tests show a current resolution of 0.2 μA at a sample rate of 1 kHz. However, the circuit overloads when a current ripple above ten times the nominal value is fed into the circuit. After an overload, it takes up to 100 ms for the circuit to stabilize. This hardware bug needs to be remedied.

7.3 Stand-alone WEC measurement systems

While the last generation of the WEC measurement system showed promising results, there is always room for improvement. To further reduce power consumption, a move into digital optical signals should be evaluated. Given the limited amount of data, one single low-cost optical fiber connection going out from the WEC to the logger should be enough. If the system could then also be powered from the WEC itself it could have an almost unlimited deployment time, only limited by the available data storage. The data transfer to the logger could perhaps even be done wirelessly, meaning that the logger only has to be in proximity to the WEC in order to collect the data. As of August 2017, the second generation measurement system has been deployed at sea, and later retrieved. Extraction and analysis of this data is currently pending.
7.4 P4 – A true hollow cylinder reluctance machine

Inspired by the promising results of the axial-flux reluctance machine presented in Paper IX, and in combination with the knowledge gained from P2, a true hollow cylinder machine (P4) has been designed. The full machine has yet to be built, but some parts of it have been manufactured and are awaiting assembly. A CAD drawing of the machine can be seen in Figure 7.3, highlighting some interesting features. The suggested design solves many of the problems identified in the previous prototypes, at least in theory.

![CAD drawing of P4](image)

*Figure 7.3. A CAD drawing of the P4, a hollow cylinder axial flux reluctance machine. (Courtesy of M. Hedlund)*

7.5 Automated WEC translator production

As mentioned in the conclusions, the work presented is only the first step towards automating the translator production, but much work still remains to be done. The biggest challenge remaining, in my opinion, will be to keep the height tolerances while mounting all 72 layers, for each translator side. This will also require that the tools for fastening the threaded bars, or stub nuts are completed. Additionally, the tool used to mount the magnets is also in its early prototyping stages and need more work.

Regarding the magnets, the question remains of how to handle the repelling forces between the magnets in an automated environment and also how to detect potential damages on the ferrite magnets, as shown in Figure 7.4. If all above problems are solved, the next step is then to build a robot-cell that can do all the above simultaneously. This will require a whole new level of cell
complexity, error handling, and communication between different machines and tasks. Here the question of material flow also rises: how should the building material enter and exit the cell? All equipment used for this material flow then has to be constructed and tested.

As can be seen, there is no lack of remaining tasks within the scope of the project, and to solve them will require a broad range of expertise and engineering ingenuity. One tool that is currently under development is the bar handling tool, shown in Figure 7.5, designed to handle and mount the threaded bars used between the layers in the translator.

![Figure 7.4](image1.png)

Figure 7.4. A damaged ferrite magnet. Due to the brittle nature of ferrite, it does not require much force for these damages to occur. This particular damage occurred when the corner of the magnet touched a stub nut during its placement on the pole-shoe.

![Figure 7.5](image2.png)

Figure 7.5. An early CAD drawing for the bar handling tool prototype. The tool uses a retractable tip to guide the threaded bars into place and a pneumatic wrench to fasten them.

Det första området behandlar automatiserad produktionen av vågkraftverk, mer specifikt translatorn som sitter inuti varje generator. Automatiserad produktion ses som en förutsättning för att kunna att reducera priset per generator, något som krävs om konceptet ska bli ekonomisk lönsamt. Translatorn består av ett centralt placerat 3 m högt rör av aluminium, med tre långsägande kilspar infrästa. I varje kilspar sitter 72 så kallade polskor av stål monterade. Mellan dessa polskor ligger ferritmagneter, vilka står för magnetiseringen av generatorn.

För att kunna utföra experiment på automatiserad translatorproduktion har en robotcell, med tillhörande utrustning, utvecklats och sen konstruerats. Den största utmaningen har varit att montera polskorna längs med kilspåren på centrumröret, då luftgapet mellan rör och polsko är under 0.05 mm, och minsta vinkelfel får systemet att låsa sig enligt ”byråladseffekten”. Detta löstes genom att utveckla ett precis kalibreringssystem för att mäta både polskorna och rörets lägen, kombinerat med användandet av ett robotverktyg med selektiv följsamhet. Med denna uppställning kunde polskor monteras med en hastighet på 50 mm/s. Mycket utvecklingsarbete kvarstår innan automatiserad translatorproduktion är något som kommer kunna kommersialiseras. De två största kvarvarande problemområdena är monteringen av magneter och hanteringen av mekaniska toleranser.

Att kunna mäta ström och spänning från en generator, även när den väl är färdigbyggd och placerad på havsbotten, har också varit av intresse för projektet som helhet. Därför har jag även ägnat tid åt utveckling av robusta mätsystem avsedda för användning i havsmiljö. Det system som har utvecklats är baserat på 4–20 mA strömsignaler, då dessa är vanligt förekommande inom

Kortsiktiga energilager, så kallade energibuffertar, är användbara för att absorbera och jämna ut effektvariationer i elektriska system. En typ av sådant energilager är elektromekaniska svänghjul. Detta är det tredje och sista området för mina doktorandstudier. Design och optimering av kompositmaterial har varit en central fråga i de projekt jag arbetat med. Två huvudsakliga svänghjulsprototyper har utvecklats under min tid; en prototyp för att undersöka magnetisk svävning som ett sätt att minska svänghjulet energiförluster, samt en prototyp för att evaluera en ny typ av axiellt magnetiserad reluktansmotor avsedd för höga rotationshastigheter. Båda prototyperna har visat lovande resultat, men har på grund av tekniska svårigheter inte uppnått de hastigheter som krävs för att testa kompositmaterialets hållfasthetsgränser. Mer arbete på området kommer att behövas innan det går att avgöra om kompositdesignen uppfyller designkraven eller inte.
9. Acknowledgements

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Finally, thanks to my trusty IRB6650S robot for putting up with me over these five years, and only breaking down once, but never giving up!
10. Summary of papers

This section presents a short summary and the author’s contribution to each of the papers presented in this thesis. Each paper is enumerated according to its Roman numerals defined at the beginning of this thesis.

Paper I

Self-Sensing Electromagnets for Robotic Tooling Systems: Combining Sensor and Actuator

This paper presents the implementation of distance sensing functionality into an existing electromagnet. The electromagnet is fitted onto a robotic tool and the distance sensing functionality is experimentally verified to work. Distance sensing is achieved by measuring the electromagnet current amplitude and rise time, as it is switched using a custom-built h-bridge controlled by a microcontroller. Using these measurements the inductance of the electromagnet is calculated using a simple RL-model of the electromagnet and from that, the distance to the target can be estimated. Distance sensing is demonstrated in the range of 0–5.2 mm. The author performed all experimental and theoretical work and wrote the paper.

The paper is published in MDPI Machines, vol. 4(3), no. 16, August 2016.

Paper II

Automated Mounting of Pole-Shoe Wedges in Linear Wave Power Generators – Using Industrial Robotics and Proximity Sensors

This paper presents the implementation of an automatic wedge mounting system for mounting pole-shoe wedges inside a linear generator. High tolerance wedges are challenging to mount due to their tendency to self-lock if they are misaligned, possibly damaging the wedges themselves or the surrounding equipment. A comparison between two types of probes, inductive proximity sensors, and tactile touch probes are performed in order to evaluate which is better for wedge calibration. It is found that the touch probe is the better option, but still not good enough. To get the finished system to work, a combination of the touch probe, a flexible tool, and a secondary inductive proximity sensor was needed. The system is shown to be able to calibrate the pole-shoes to an accuracy of 0.25 mm and 0.1°. The author performed all experimental and theoretical work and wrote the paper.

Paper III

A Method for Calibrating Work-Piece Orientation – Using a Dual-Axis MEMS Inclinometer

This paper presents the implementation of an automatic work-piece orientation calibration system aimed at industrial use. The paper contains both a theoretical description of the methods used and verification of those methods using data from practical experiments. The presented system uses a high accuracy accelerometer fastened to the object that is to be aligned, and by moving the object around and measuring the response from the accelerometer the orientation of the object, relative to the coordinate system of the robot, can be approximated. Signal quality was improved by implementing a digital exponential decay filter into the used MCU, processing the accelerometer data. For a set of 2000 random orientation errors the system achieved an alignment accuracy, within a $3\sigma$ limit, of $0.023^\circ$ around in the XY-plane and $0.14^\circ$ around the Z-axis. The system could perform its task in just under 21 sec, a reduction of 87% compared to the time needed by the system presented in Paper II. The author performed all experimental and theoretical work and wrote the paper.

*The paper is submitted to Elsevier Robotics and Computer-Integrated Manufacturing, October 2017.*

Paper IV

Preparing the Uppsala University Wave Energy Converter Generator for Large-Scale Production

This paper describes the current state of the third generation of the Uppsala University WEC, the latest result of a long-running project started in 2001. Applying automated production techniques, such as robots, is argued to be crucial in making the concept economically viable. A change form NdFeB-magnets to the cheaper ferrite-magnets also presents a set of new challenges in regard to automating the production. Overall, the new design has reduced the cost of each unit by around 50%, and successfully implementing robotized assembly has the possibility of reducing the cost even further, around an additional 20% per generator, according to estimations. The two assembly steps with the biggest potential cost savings are the translator stacking and the stator winding. Finally, the paper presents an outline for the work needed in order to realize the presented automization suggestions. The author supplied information and wrote parts of the section describing translator assembly.

*The paper was presented by E. Hultman at the 5th International Conference on Ocean Energy, Halifax, Canada, 4–6 of November 2014.*
Paper V

**Offshore Measurement System for Wave Power - Using Current Loop Feedback**

This paper presents the design and evaluation of a measurement system for WECs based on current loop feedback. Due to harsh operating conditions coupled with cost constraints, the system should be robust yet cheap, which is why a system based on the industry standard 4–20 mA current signal standard was chosen. The system is designed to measure both AC and DC currents/voltages in the range of ±1560 V and ±420 A from inside the WEC. The system was evaluated in a laboratory setting where its linearity, frequency response and step response and was tested. A voltage and current measurement bandwidth of 10 kHz and 7 kHz, respectively, was measured, which was in accordance with design targets. Once finished, the measurement system was mounted inside a WEC unit and tested on-shore at low generator speeds (around 1% of the voltage and current full range) and was verified to give the same result as a set of commercially available measurement tools. The power consumption of the measurement system was measured to be 3.14 W for the AC signals and 1.25 W for the DC signals, on average. The author designed the majority of the measurement electronics/PCBs, and also assisted with evaluating the performance of the finished system.

*The paper is published in MDPI Electronics, vol. 5(4), no. 86, December 2016.*

Paper VI

**Portable Data Acquisition System for Offshore Applications**

This paper presents a three-phase voltage and current measurement system using current loop feedback, and a stand-alone submersible logging station. The system is a continuation of the system presented in Paper V, with increased performance and reduced power consumption. By combining all measurement on the same PCB and exchanging the current transducers with shunt resistors, power consumption was reduced to 1.45 W for the measurement system, and the logger itself was measured to consume 0.41 W while active. Power was supplied to the system by a 220 Ah, 15 V battery-pack, giving an active lifetime of the system of just over 10 weeks. Reprogramming the logger, allowing for better control of the active time of the measurement system, could potentially increase this time to over 40 weeks at the expense of data collection rate. At a sample rate of 1 kHz, the $3\sigma$ noise levels on the raw voltage and current measurements were measured to be 12.9 V and 3.5 A, respectively. The author assisted in the design of the measurement electronics/PCBs and also assisted with evaluating the performance of the finished system.

*The paper is under review at IEEE Journal of Oceanic Engineering, May 2017.*
Paper VII

**Nearshore Tests of the Tidal Compensation System for Point-Absorbing Wave Energy Converters**
The energy production of the linear generator wave energy converter developed at Uppsala University is affected by changes in the mean sea-level where it operates. When the sea-level changes, the distance between the point absorbing buoy located at the surface and the generator located on the seabed will change as well. This will shift the average position of the translator, relative to the center of the stator, reducing overall performance of the generator. This paper presents a system that can adjust the line-length to a buoy, in order to compensate for these changes in water level. Once deployed at sea, the system can be remotely controlled via SMS. An on-board 3G-modem allows the system to wirelessly send measurement and diagnostic data directly to a Dropbox server, accessible from the internet. The author assisted with the development and laboratory tests of the presented system, and also gave suggestions for future work to further improve the system.


Paper VIII

**Control System for Compensator of Mean Sea Level Variation at The Lysekil Research Site**
As previously mentioned, the wave energy concept developed at Uppsala University consists of a linear generator located on the sea-floor that is directly driven by the motion of a buoy at the ocean surface. This paper presents laboratory tests for a mean sea level compensator system intended to be used with the linear generator, in order to adjust the line length between buoy and generator. The system uses an algorithm to estimate the position of the translator using the zero-crossings in the generator voltage. The system is designed to send measurements of the position, acceleration, deformation, and motion of the compensator mechanism back to land, using SMS based communication. The author assisted with the development and laboratory tests of the presented system. This conference paper was later expanded to the full article presented in Paper VII.

*The paper was presented by V. Castellucci at the Proceedings of the 2nd Asian Wave and Tidal Energy Conference, Tokyo, Japan, 28–31 of July 2014.*
Paper IX

**Reluctance Machine for a Hollow Cylinder Flywheel**

This paper presents a novel concept for a high-speed reluctance machine, mainly designed to be used in hollow cylinder flywheels. The proposed flywheel rotor is without a central hub or spokes, and can store up to 181 Wh/kg. Due to its axial flux path, and therefore insensitivity to radial displacement, the machine can theoretically reach high speeds without changing its air-gap.

If reinforced with carbon-fiber composite, the rim-speed of the machine, with a radius of 500 mm, is estimated to be able to reach 1050 m/s at UTS. To evaluate the concept, a prototype containing an axial flux reluctance machine was constructed. In order to simplify its construction a more standard hub and shaft design was used instead of a hollow cylinder. The electrical characteristics of the machine were measured and compared against theoretical models, both analytical and FEM-based, and the measurements were found to be in agreement with theory. The author performed a majority of the mechanical design and physical assembly of the presented prototype. The used stress/strain calculation software is based on previous work of the author.


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Paper X

**High-Speed Kinetic Energy Buffer: Optimization of Composite Shell and Magnetic Bearings**

This paper presents the design and optimization of a high-speed mixed composite flywheel prototype. The composite rotor consists of unidirectionally wound glass and carbon-fiber, embedded in an epoxy matrix, that is press-fitted onto an aluminum cylinder. The inside of this cylinder is covered with permanent magnets configured in a Halbach array. De-lamination in the composite at high speeds is avoided by using the weight of these magnets to control the radial stresses in the outer composite layers. To reduce friction losses the whole rotor is suspended in a magnetic field. This magnetic levitation is achieved by a combination of active radial electromagnets and passive permanent magnet axial thrust bearings. Rotor torque is provided by a double wound coreless three-phase electrical machine that uses the magnets on the inside of the aluminum cylinder for magnetization. The author was responsible for most of the mechanical design and supplier contact during the construction of the prototype. The author also derived the stress/strain relations for the composite and wrote the bulk of the Matlab-code used to optimize it.

*The paper is published in IEEE Transactions on Industrial Electronics, vol. 61(6), pp. 3012–3021. © 2013 IEEE. Reprinted, with permission from the authors and IEEE Transactions on Industrial Electronics, April 2013.*
Paper XI

**Spin-down Losses and Vibration Analysis of a Flywheel Energy Storage System**

This paper presents the results of the vibration tests performed on the magnetically levitated flywheel presented in Paper X. Simulations are compared to measurements, and a method to partly compensate for the vibrations is presented. Both measurements and simulations found eigenfrequencies in the rotor at around 400 Hz and 1050 Hz. By implementing a notch filter into the control loop, the excitation of these vibrations could be suppressed. However, even with the notch filter in place, the flywheel could not rotate faster than approximately 1000 rpm due to a combination of rotor imbalance and under dimensioned radial magnetic bearings. Spin-down losses are measured in both medium vacuum and at atmospheric pressure, and the losses per stored watt-hour while in a vacuum is found to be 1.7 W/Wh, a figure which is comparable to that of other similar systems. The author had an advisory role and assisted with performing the presented vibration simulations. The author also had a part in the design and assembly of the used experimental setup.

*Unpublished manuscript, October 2017.*

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Paper XII

**High-Speed Flywheels for Vehicular Applications**

This paper analyses two business cases using flywheels in vehicles. Firstly, a diesel based car ferry and secondly, a diesel based city bus. Both cases used a theoretical high-speed flywheel, designed to store up to 870 Wh at a rotational speed of 30000 rpm. A theoretical analysis of the technical and economical benefits of electrifying these vehicles using flywheels is performed. The flywheel is optimized for low energy losses as well as low cost. It is found that introducing a flywheel into the drive-train is profitable in both cases, especially for the ferry. This introduction will come with additional infrastructure costs, not considered in this paper, as both the ferry and city bus will need charging stations. The author had an advisory role and participated in discussions about the two cases, from the standpoint of mechanical viability.

*The paper was presented by J. Abrahamsson at the 14th International Symposium on Magnetic Bearings, Linz, Austria, 11–14 of August 2014.*
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