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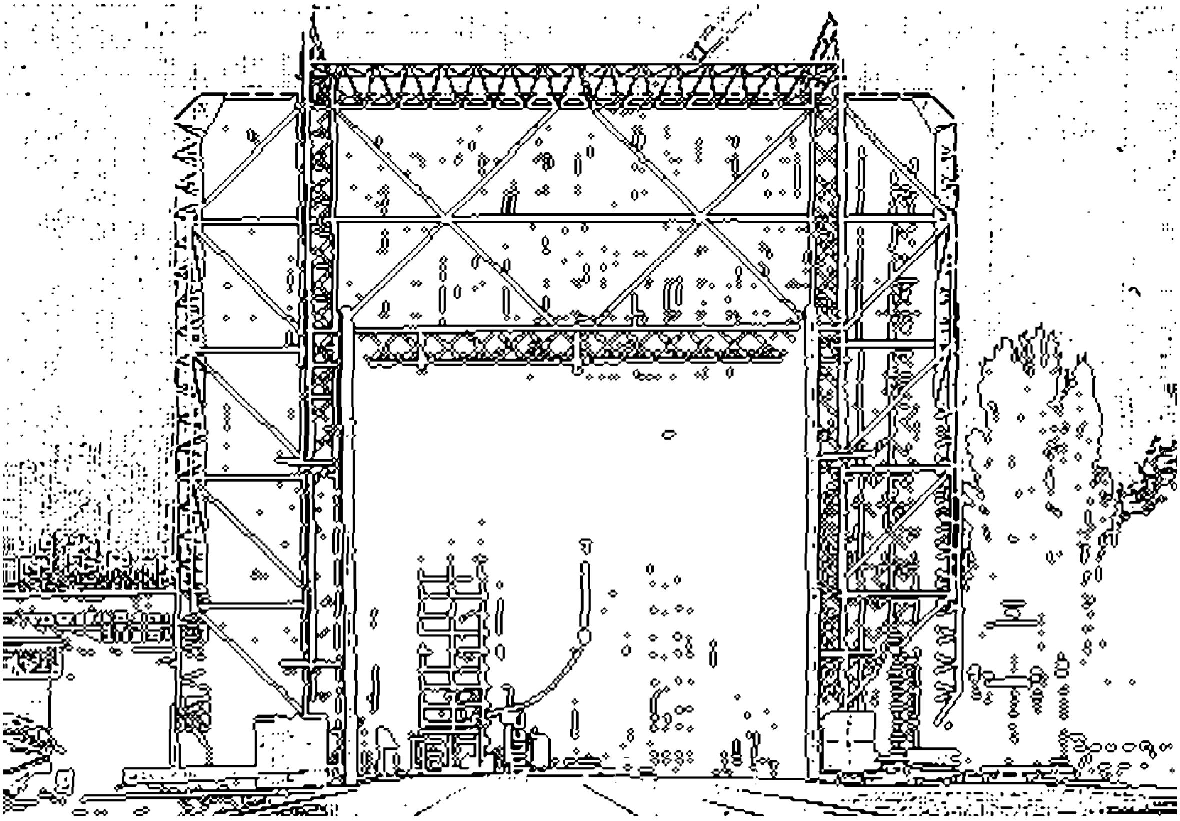

Institut für Hochspannungstechnik und Systemmanagement

Diplomarbeit

Machine Windings For Fully Flooded Generators

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Graz, im Oktober 2007

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Danksagung

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Thomas Judendorfer

Graz, im Oktober 2007 Thomas Judendorfer

Kurzfassung

Die Forschung im Bereich der Nutzbarmachung von Wellenenergie erlebt seit einigen Jahren ungeahnte Höhen. Aufgrund der verstärkten Forschung in diesem Bereich ist es zur Entwicklung von einigen komplett neuen und vielversprechenden Machinen gekommen. Eine dieser Neuentwicklungen ist eine Anlage mit dem Namen **Archimedes Wave Swing (AWS)**, die 1993 von Fred Gardner und Hans van Breugel entwickelt wurde.

Ein massiver Lineargenerator bildet das Herzstück von AWS. Dieser wandelt die Energie des Ozeans beziehungsweise der Wellen in elektrische Energie um. Aufgrund der verschärften Umweltbedingungen (Salzwasser ist sehr aggressiv zu sehr vielen Materialien, um nur ein gravierendes Problem zu nennen) gibt es hier besonders Probleme mit Dichtungen und Lagerungen der bewegten Teile.

Der Lösungsansatz zu diesem Problem klingt erfolgversprechend, aber er ist genauso problematisch: Wenn der **Luftspalt des Generators mit Meerwasser gefüllt ist**, können Dichtungen im Inneren der elektrischen Maschine angebracht werden. Dies hat den Vorteil, dass nur stillstehende Teile gegeneinander abgedichtet werden müssen.

Das mag zwar für die Lösung der Dichtungsprobleme hilfreich sein, für die elektrische Seite bringt diese Lösung aber eine Vielzahl von neuen und anspruchsvollen Problemen. Um diese beseitigen zu können beschäftigt sich diese Diplomarbeit mit verschiedenen Möglichkeiten der Isolierung und Materialien.

Ebenso gibt es eine Übersicht einiger aktueller Wellen- und Gezeitenkraftwerke. Obwohl der Archimedes Wave Swing, der ja Ausgangspunkt dieser Arbeit ist, zu den Wellenkraftwerken zählt, bleiben Gezeitenkraftwerke nicht unberücksichtigt. Unter Umständen können Ergebnisse dieser Arbeit auch für Gezeitenkraftwerke, man denke hier zum Beispiel an Konzepte wie SeaGen, relevant sein.

Schlüsselwörter: Archimedes Wave Swing, Wellenenergie, Gezeitenenergie, Meerwasser, gefluteter Luftspalt, elektrische Maschine, Isolationsmaterialien, Nachhaltigkeit

Abstract

Since several years there is a renewed interest in ocean power generation, especially in wave power. Extensive research produced some new concepts and novel solutions. One new prototype is the **Archimedes Wave Swing (AWS)** which was invented by Fred Gardner and Hans van Breugel in 1993.

Basically the AWS uses a large linear generator to transform the wave energy into electrical energy. Due to the difficult and aggressive operational conditions (corrosive seawater, just to name one), sealing and bearing are big issues for this machine type.

A possible solution for this problems could be a novel approach which is presented in this thesis: Running the machine **fully flooded** (the airgap is flooded with seawater) would ease the sealing issue - it is only necessary to seal non-moving parts against the seawater then.

Although this might be desirable for solving the sealing issue, filling the airgap of an electrical machine arises a group of new and interesting problems. Therefore several insulation and encapsulation methods and materials have been researched for this work.

A chapter within this work is dedicated to give an overview about current wave and tidal power projects. Although the Archimedes Wave Swing, which was some sort of starting point of this thesis, is clearly a wave power plant, tidal power is also covered in this thesis. This is because the outcome and the results of this thesis can be also of interest for tidal power plants, for example to concepts like SeaGen.

Keywords: Archimedes Wave Swing, wave energy, tidal energy, seawater, flooded air gap, electrical machine, insulation material, sustainable

Contents

Glossary

AWG	American Wire Gauge
AWS	Archimedes Wave Swing
CCP	Cathodic Corrosion Protection
DTI	UK Department of Trade and Industry
EMEC	European Marine Energy Center
HSE	Health and Saftey Executive
IEC	International Electrotechnical Commision
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
JAMSTEC	Japan Institure For Marine-Earth Science And Technology
LIMPET	Land Installed Marine Powered Energy Transformer
MEKP	Methyl Ethyl Ketone Peroxide
OSPREY	Ocean Swell Powered Renewable Energy
OWC	Osciallating Water Column
PD	Partial Discharge
PDIV	Partial Discharge Inception Voltage
PSS	Practical Salinity Scale
PTO	Power Take Off
TAPCHAN	Tapered Channel
TEAM	Thermal, Electrical, Ambient, Mechanical
TPES	Total Primary Energy Supply
VPI	Vacuum Pressure Impregnation
WEC	Wave Energy Converter

Chapter 1

Introduction

1.1 Background

It is now nearly five years ago since the interest in marine renewable energy increased notable, especially in Great Britain. This may be due to the fact that governments, companies and people are aware of effects like, for example, global warming and are therefore seeking for renewable and environmental friendly (sustainable) sources for electrical energy. An other fact is the return of governmental and European Union subsidy. Until the 1990's there has been nearly no subsidy money available for Ocean Power research. But with Kyoto targets and the need for clean energy sources the interest increased dramatically.
Recognition of wave and tidal energy as a contributor to a diversified energy mix is also reflected in the founding of the IEC Technical Committee 114 in 2007. The Committee is dealing with the standardisation for these technologies.
The Oceans seems to be a good solution for the demanded requirements as the energy resources are vast - it is estimated that there is a total potential of up to 22.000 TWh/a (some 79 EJ/a) for tidal energy and up to 18.000 TWh/a (about 65 EJ/a) for wave energy [33, 43]. Other sources estimate the global available wave power up to 80.000 TWh/a [39]

These figures seem to be tempting: the ocean as a way out of climate crisis, oil dependency and expensive energy. In fact, if the whole potential of the ocean could be harnessed (ocean thermal energy is not even included here), the 144 EJ (or approximately 40.000 TWh/a) [33, 43]are equal to some 30 percent of the worlds TPES [1] in 2004 (463 EJ) or about 229 percent of the worlds total produced electrical energy in 2004 (62,8 EJ) [38].

Unfortunately it is not that easy - Firstly it is hard to get good estimates of the *"real"* total existing energy and secondly this energy still needs to be harnessed. The *"usable"* tidal energy is estimated to some 7 % of the total potential or even lower - the economically resources are probably between 140 and 750 TWh/a [83]. Furthermore the development of the technology, markets, etc. is about 15 years behind wind and solar energy (photovoltaic). But nevertheless,

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[1] total primary energy supply

some promising technologies have entered the market and also a fistful of prototypes have been built. Marine renewables are definitely worth to be researched further [55].

1.2 Motivation

A very promising technology is the *Archimedes Wave Swing* which was developed in 1993 by the Dutch company Teamwork Technology B.V. (now AWS Ocean Energy [7]). Basically the working principle is quite simple. However the technology is novel and state of the art. The AWS is a fully submerged point absorber. This means, it can absorb wave energy regardless of their travelling direction. A more detailed description of this technology will be given in section 3.2.5.

To have a fully submerged device has several advantages: No visual impact, higher efficiency (see above), etc. But one big issue comes with immersion: Sealing. Sea water is very corrosive and has unfavourable electrical properties. The AWS has also some sort of design inherent problem with the bearings. High shear forces and a low speed of the alternator make heavy demands to the design of bearings because they have to cope with high forces, low speed and a corrosive environment. Fouling is also an issue.

A possible solution could be achieved with this approach: Flooding of the whole PTO[2]-mechanism and the air gap in the generator respectively. Therefore the sealing and bearing task could be divided - The sealing point could be moved inside the generator and therefore between non-moving parts and sea water could be even used as bearing [7, 55]. Clearly, a sealing material needs to be used which can cope with all the requirements mentioned above. It is quite likely that this also influences the design of the generator.

1.3 Scope

Satisfactory durability and minimised maintenance cost/time are one of the key issues for a successful market introduction of the new marine renewables.

This thesis contains an overview about (prototype) marine power plants currently in use and also about some, which are to be built within reasonable time. Furthermore, tidal power is taken into concern because there are also some machines that could profit from a successful outcome of this thesis, like the SeaGen (which uses a slow rotating turbine, that is placed in water depths at around 20 meters; see Section 3.4.1)

The main part deals with the problem how to "seal" the generator and the coils/windings respectively. Therefore miscellaneous insulating and sealing materials have been researched and

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[2] power take off

some basic endurance tests have been carried out.

Winding design for such machines could be the scope for further research - An additional demand on winding (and machine) design is the output voltage. Currently most marine renewable plants use generators with an output voltage of about 1 kV or even lower. Therefore a transformer is absolutely necessary for grid connection (6,6 kV or 11 kV for example). The transformer itself is not the issue here but it is the placement. Because the generators are located several kilometres offshore (typically in the region of about 5 km), a step-up-transformer is already needed in short distance to the device. For that reason the transformer needs to cope with a rough environment, which could be avoided by using a generator with higher output voltage. Designs like the *Powerformer*™ could be useful here, because the step-up-transformer would be integrated into the machine itself. But such research was not part of this thesis [50, 52].

Annotation: Please note that within this report the *dot* "**.**" is used as digit grouping symbol whereas the *comma* "**,**" is used as decimal symbol.

Chapter 2

Sustainable Energy Sources

2.1 Sustainability

The phrase *sustainability* can be traced back until 1713 where it was used by Hans Carl von Carlowitz. In his book *sylvicultura oeconomica* (Original title: ”Haußwirthliche Nachricht und Naturmäßige Anweisung zur wilden Baum-Zucht“) he described the process of forestry very detailed - knowledge which has been lost during the thirty-years-war.

Hans Carl von Carlowitz was the first to define the principle of sustainability. During his time there was a huge demand for wood for different reasons. Depletion and mismanagement was the order of business these days. So von Carlowitz summarised in his book:

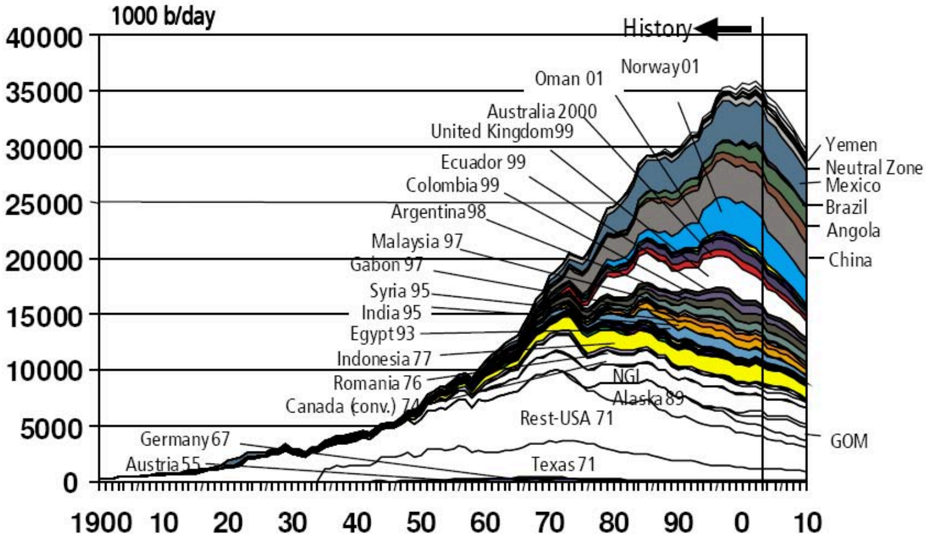
> **"To be the best utility for the heating, building, brewing, mining and smelting activities requires the careful management of sustainable forestry resources"**

The term of sustainability, as we know it today, was affected by the Brundtland Commission and the Brundtland Report in 1987. Sustainable development is defined as follows [21]:

> **"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."**

Sustainability could be described as process which is able to run indefinitely by definition. In terms of energy sustainability this would mean that mankind abandons fossil and nuclear fuels because they are finite.

As one can imagine, humanity can not switch to alternatives from one day to another. Therefore it is exquisitely important from now on that the limited resources are used wisely. Although it is predicted that the fossil fuel reserves will last for the short-to-medium term, they will be used up eventually. Experts discuss since the 1950's when the end will finally arise. The American geophysicist Marion King Hubbert developed a model that predicted the peak oil production



Source: Industry database, 2003 (IHS 2003)
OGJ, 9 Feb 2004 (Jan-Nov 2003)

Figure 2.1: Oil production from the 1900's up to now (from [86])

and the eventually depletion of the planet's oil fields.

Figure 2.1 indicates that the oil peak has already been reached in several countries. Hence the question should not be when the oil and gas are ultimately spent but what we could do instead [59, 60].

For a sustainable energy future, mankind will have to (from [9]):

- Develop and deploy renewable (and sustainable) energy sources on a much wider scale than nowadays
- Improve the efficiency at energy conversion, transmission, distribution and use by a considerable degree
- Implement greatly improved technologies for harnessing the fossil and nuclear fuels in order to ensure that their use, if continued, creates much lower environmental and social impacts

To achieve these aims the conflict of objectives between environmental, economic and social concerns needs to be solved (see Figure 2.2).

Renewable energy sources tend to be, in general, socially accepted. Wind energy seems to be an exception in several countries, when the turbines are placed on shore. People living nearby complain about the visual impact, the noise and some also about the impact on bird- and wildlife. Rightly, one has to say that wind turbines improved enormously to tackle these issues.

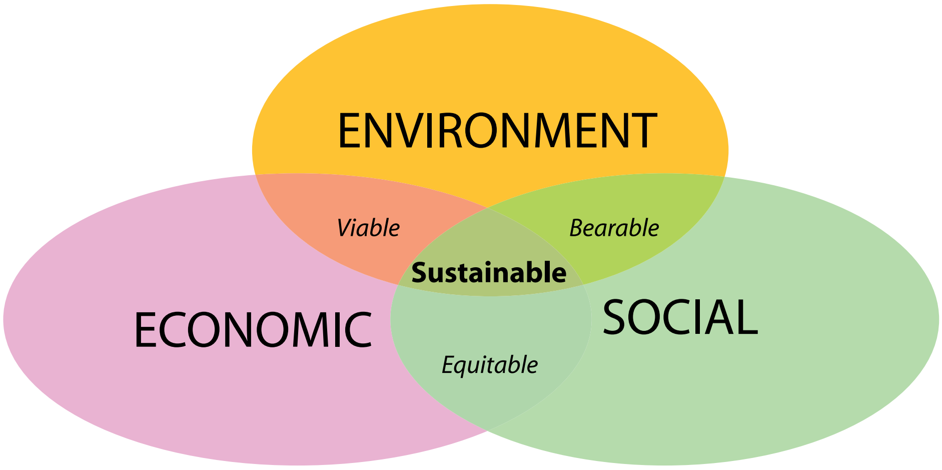


Figure 2.2: Relationship between environmental, social and economic perspectives for a sustainable development

The sustainability in concern with environmental issues is not so easy to determine. Critics are often mentioning the huge environmental impacts that arise with the erection of huge (also renewable power plants), for example, big hydro power plants like the *Three Gorges Dam* in the Hubei province in China.

Wave power and tidal (stream) power plants are expected to have low influence on nature and wildlife and are socially accepted as they are placed kilometres away from shore and therefore the so called *"visual pollution"* is expected to be low [82, 83].

2.2 Renewable Energy Sources

For a sustainable energy use,as described in section 2.1, it is necessary that renewable energy sources play an important role in the total energy mix. These are:

- Hydroelectric Energy
- Wind Energy
- Biomass Energy
- Solar Energy
- Tidal/Wave Energy
- Geothermal Energy

Figure 2.3 shows the change in electricity generation during the last 30 years. The most apparently difference is the change in total production: from 6.177 TWh in 1974 to 17.450 TWh in 2004. Sadly the total share of the renewable has not improved much (from 0,7 % to 2,1%). This is even worse, if hydropower is counted as renewable (as it is normally done) - the total percentage dropped from 21,7 % to 18,2%. This may also be due to the mentioned vast growth in electricity generation and consumption respectively.

Therefore it is absolutely necessary to emphasise the usage of sustainable energy production, to which wave and tidal power can make a notable contribution.

Already the famous technician and inventor Thomas Alva Edison made some thoughts about energy usage in 1916 (!):

> **"You see, we should utilise natural forces and thus get all of our power. Sunshine is a form of energy, and the winds and the tides are manifestations thereof. Do we use them? Oh no! We burn up wood and coal, as renters we burn up the front porch for fuel.**
> **We live like squatters, not as if we owned the property."** [30]

It is interesting to note that eventually the sun is the source for nearly all renewable energy, not only for photovoltaic, which is obvious. The sun is responsible for warming the earth's water resources which leads to evaporation, following precipitation and thus to a closed cycle. Solar power is also the cause for the growth of biomass and the origin of wind. Furthermore, wind is the cause of wave movement and wave energy respectively.

There are only two renewable energy sources which trace not directly back to the sun. Firstly this is tidal energy which is caused by the moon (and only to a small part by the sun). And secondly geothermal energy which hearken back to the processes in the earth's core [9].

Wave and tidal energy are the scope of this thesis and will be discussed more detailed in section 3.2 and 3.3 respectively. There will also be a listing of actual devices. This list is not complete, as some early concepts of the 1970's and 1980's already vanished from the scene. There is also continuous development so that it's quite impossible to cover all technologies within this work.

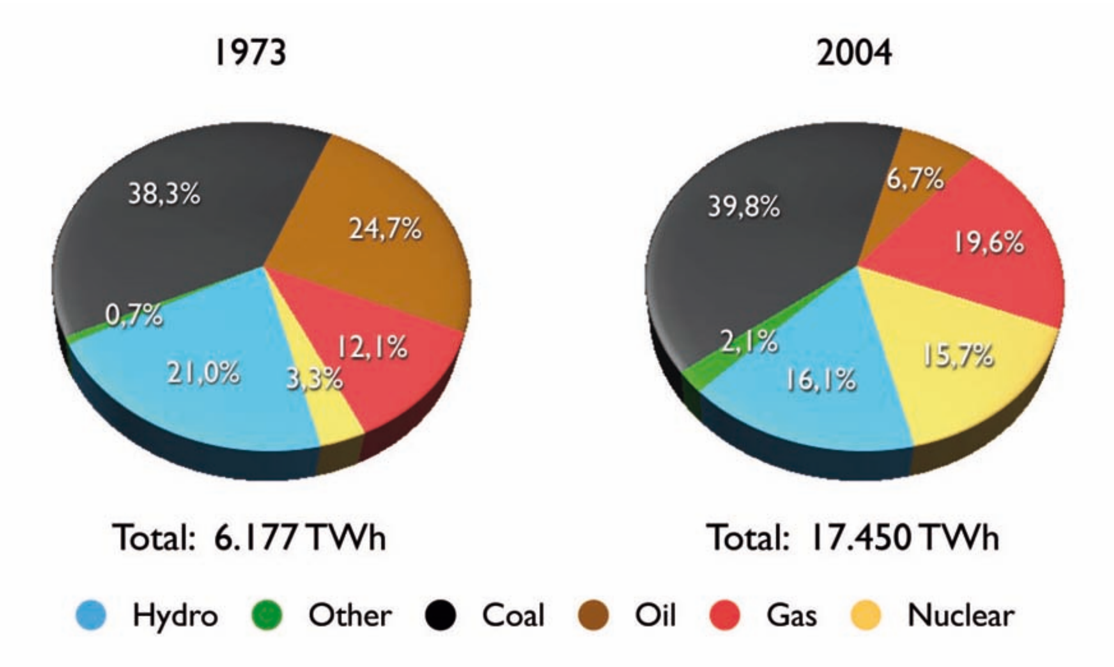


Figure 2.3: Comparison of world's electricity generation[3]in 1973 and 2004 (from [38])

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[3] pump storage is excluded from hydropower; Other means: Geothermal, Solar, Wind, Combustible Renewables and Waste

Chapter 3

Ocean Energy

3.1 Basics

As already noted in the introduction, the energy potential of the oceans are vast. The proposed tidal power plant at the Severn Estuary in Wales, Great Britain has an estimated potential of around 8.600 MW of installed, maximum capacity. Wave energy has also high potentials for electricity generation. But there is one pestering problem: Even if the ocean energy could be harnessed and finally converted - with an accordingly efficiency - into electrical energy: How could this energy be fed into local grids?

The ideal sites for wave energy (and also for most tidal power plants) are most likely kilometres away from shore. Electrical equipment, cables, etc. tend to be more susceptible to failures in this environment compared to "normal" usage onshore.

There is an additional issue: Because these regions are, in most cases, also far away from bigger settlements, the electrical network is not capable of transmitting such high energies to the places where it would be needed as this is indicated by Figures 3.1 and 3.2. Therefore the transmission network is most likely in need to be upgraded in this case as well [58].

But there are other solutions for energy usage: The energy could be used at the site of generation, for e.g. desalination of seawater (Figure 3.4), as it is currently done at a wave power research plant in Vizhinjam (Figure 3.3) in the Kerala province in India [42]. The plant uses the *Oscillating Wave Column* (OWC) principle (see Section 3.2.7). 10.000 litres of fresh water, which are used locally, can be produced with the equipment per day. Hydrogen production could be also an alternative.

An other proposal is the usage of hydraulics in the power take off mechanism. The novelty here is that the high pressurised fluid could be pumped onshore. This would solve some troubles because electrical equipment is much easier to place onshore than offshore [37].

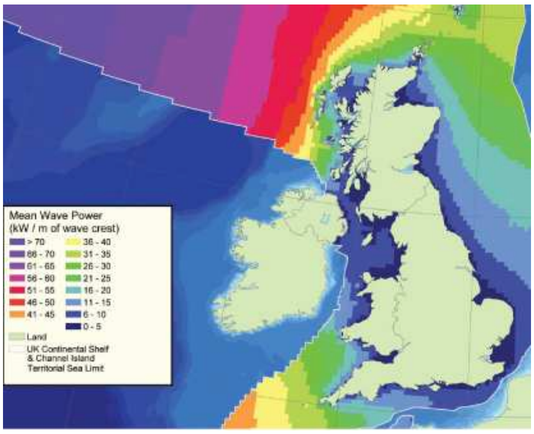

Figure 3.1: Wave energy distribution around the United Kingdom (Source [11])

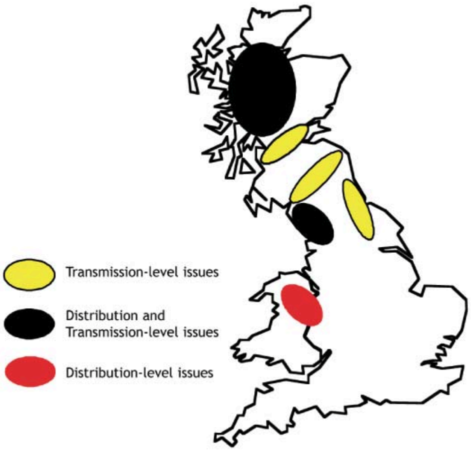

Figure 3.2: Transmission and distribution network constraints (from [11])

Ultimately the cheapest method is still the generation on the spot and the transmission of electrical energy - with all the included problems.

Figure 3.3: Wave power plant in Vizhinjam, India (from [42])

Figure 3.4: Desalination unit (from [42])

3.1.1 General Issues

These issues effect tidal energy as well as wave energy, because they are of general nature. The United Kingdom, itself probably the pioneer in wave power (and to some parts also for tidal power) technology, can act as an example for the following issue.

Researchers and companies willing to invest time, knowledge and money are facing problems, not only those, which were discussed in Section 2.1 - the balancing act between costs and benefits and also the impacts to the people and the environment - but also troubles with the authorities:

The industry is facing problems when it comes down to get permissions and licensees for test sites. These are hard to get and a lot of different authorities are responsible. Recently a research project of RV Power was moved from the coast to Scotland to a site in Iceland [4]. The reason was not that the company would not have got the necessary licenses - it was just about the time needed. It would have taken about 2 years to get them in Great Britain whereas they could start working from one day to another in Iceland. For a technology which needs to be tested to get fit for real-scale-operation and the market itself, such barriers can be fatal.

A delicate issue are also the costs of the technology. The erection of adequate power plants is expensive: Because of the relatively small power output of a single device, it is necessary to bundle a bunch of single units to a power plant for achieving a noticeable power output. This does not only affect wave power but - as noted above - tidal power as well.

Plants like La Rance, France (twenty-four 10 MW generators, see Section 3.3.6) wouldn't be built nowadays unless there is enough subsidiary money and a functional market for renewables [28]. Such plants are just too expensive to compete in the open market with "cheap" technologies like gas/coal, nuclear and even "standard" hydro power plants (although the energy costs at La Rance are competitive now).

France is anyway some sort of exclusion in respect of energy production, as it produced 448 TWh of electricity with nuclear power plants in 2004. This makes France second worldwide as only the United states produced more (813 TWh), but in France nuclear power was responsible for 78 % of total electricity generation in 2004 [38]. Hence it is self-evident that a "more-expensive" technology like tidal energy (or the renewable sector in general) play only a minor role in such countries.

3.1.2 Key Technology Issues

In Great Britain the DTI[4] carried out a study to identify the status of various wave power technologies. The main emphasis of the report[5] was to highlight key technology issues [6]. The following eleven points were identified:

- Regulatory Environment, HSE[6], Design Codes and Verification
- Construction Methods and Project Cost Estimation
- Marine Operations
- Mooring Systems
- Operations and Maintenance
- Materials
- Hydraulic Systems
- Pneumatic Systems
- Sub-sea Cables and Connectors
- Control Systems
- Power Quality and Grid Connection

It is interesting to note, that no technology based problems could be found [6]:

> **"No major technological barriers to the development of Wave Energy Prototypes have been identified. All the issues raised under design, construction, deployment and operation can be addressed by transfer of technology from other industries, especially the offshore industry. However, costs, risks and approvals will need to be addressed."**

But the report also pinpointed one of the biggest obstacle for boosted research and development [6]:

> **"The Wave Energy Industry is poorly co-ordinated. At present, all teams are working independently and commercial considerations force them to keep their ideas secret."**

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[4] UK Department of Trade and Industry

[5] known as the "Arup Report"

[6] Health and Safety Executive

This was also evident during the research for this thesis as company representatives were mostly reluctant to speak about technical details and especially about (technical) difficulties and problems.

Annotation: Because of the multitude of different existing and also emerging technologies the following listings of wave and tidal energy converters do not claim to be whole.

3.2 Wave Energy Converters

3.2.1 Basics

The majority of waves in the ocean are the ultimate outcome of the irradiation of the earth by the sun. Simplified, this radiation leads to the generation of winds which are responsible for the majority of waves in the ocean [68]. These waves are called *wind waves*. In simple terms, wind waves can gain the **more energy, the longer and stronger the wind blows and the larger the area of open water, where the wind can blow[7], is**.

It needs a summary of all these factors and time to generate waves in the end. These waves can be subdivided into 3 types:

- **Ripples**
- **Seas**
- **Swells**

Besides these *wind waves*, an other type is known - the so called *tidal waves* which will be addressed in chapter 3.3 [68].

Ripples are the most ephemeral waves. They depend strongly on the (light) wind, or in other words - if there is no wind then there are no ripples. These small waves are travelling downwind.

When the wind is able to blow for a certain time (and also at a certain strength) **seas** can emerge. This wave type can last even if the wind which generated them, already died.

Swells are the most persistent waves. They can travel over a noteable distance and they are therefore completely independent from local (wind) climate.
It is not surprising that the distribution of wave energy on a world wide scale (see Figure 3.6) correlates well to the distribution of wind energy.

The water depth and the topography of the sea-floor are also influencing waves. They became more important with a shorter distance to the shore. Additional phenomena are coming into action - they can be observed at every coastline. For example, it is much more likely that waves are breaking in shallow water and "loosing" their energy (or near/at the shore, like Figure

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[7] This area is the so-called *fetch*

Figure 3.5: Waves breaking near the shore (Source: University of Georgia)

3.5) than in deep waters.

The energy that can be extracted from waves is difficult to calculate and to estimate respectively. There are several different approaches in literature: (significant) wave height, energy spectra, etc. A method to estimate the power that is contained in a wave (in kW/m) is the one used in Formula 3.1 [30]:

$$P = \frac{\rho \cdot g^2 \cdot H^2 \cdot t}{8 \cdot \pi} \tag{3.1}$$

ρ ... density of the (sea)water in kg/m^3, g ... acceleration of gravity in m/s, H ... wave height in meters (measured from crest to trough) and t ... wave period (time between to wave crests) in seconds

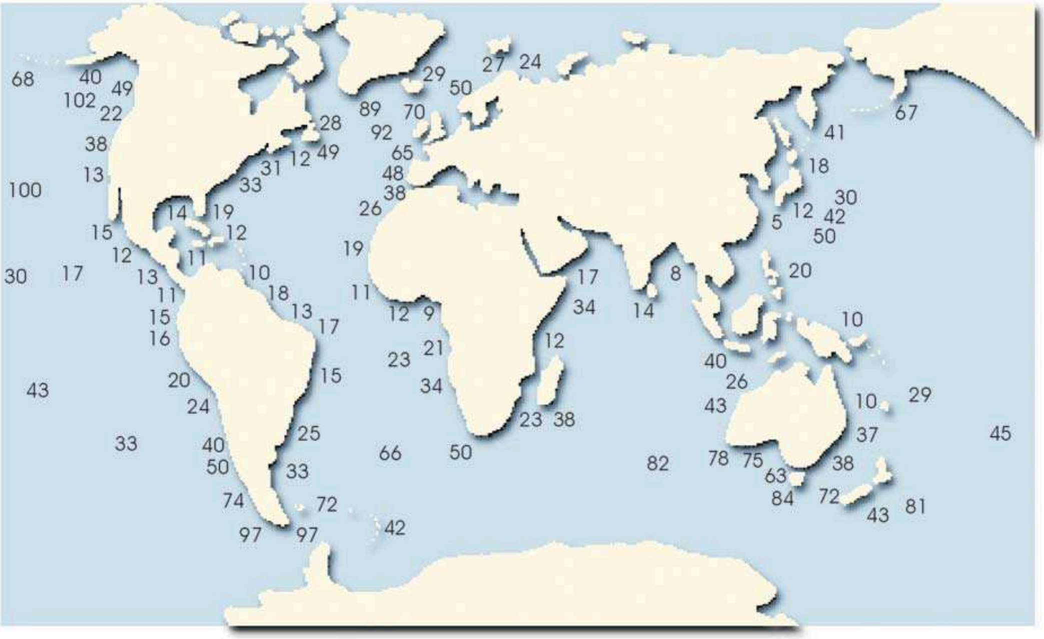

Figure 3.6: World wide wave power levels in kW/m wave front (Annual distribution; from [83])

And although there are charts of wave power distribution (like Figure 3.6) it is possible that these numbers can differ significantly at local sites. Recently there have been research activities in tidal energy resources for the UK and it is possible that the yearly potential was under-estimated by a factor between 10 and 20 [54]!

3.2.2 Types of Wave Energy Converters

A big issue for wave power extraction are the complicated and complex wave phenomena: wave travel and overlap, frequency, direction, wave length, superposition effects, etc. Different types of the so called Wave Energy Converters (WEC) have emerged on the scene, especially during the last 15 years. They can be classified into 5 groups [17, 30, 68, 74]:

- Floating Device
- Hinged Flap Device
- Oscillating Water Column
- Overtopping Device
- Underwater Buoyant Device

Floating Device

The **Pelamis** (see Section 3.2.6) is the most typical example for this group of WEC's. Floating devices consist in most cases of several, single structures, which move relatively against each other to drive a Power-Take-Off-Mechanism.

Hinged Flap Device

These are devices which react to change of water velocity. Such variations are bringing the device, which is mounted on the seabed into some sort of oscillating movement which is used to generate pressure in a hydraulic system. The hydraulic pressure is processed in turbines for electricity generation. The **Stingray** (see Section 3.4.3) is a typical example for a hinged flap device.

Oscillating Water Column

OWC's (see Section 3.2.7) are partially submerged devices which are, in most instances, placed onshore. Sea water flows into the structure and forces a certain volumina to leave the structure through an outlet at the top. This sets a turbine, which is placed there, in motion.

Overtopping Device

Sea water is captured inside such devices. The power is generated when the water leaves the device through a low head turbine. The **TAPCHAN** (see Section 3.2.8) was one of the first devices which used that principle.

Underwater Buoyant Device

A device on the seabed which reacts to changes in water pressure falls into this category. The **Archimedes Wave Swing** (see Section 3.2.5) is the perfect example for such a device.

The following classification by location is also common:

- **Onshore**
- **Near Shore**
- **Offshore**

Onshore

Refers to all wave energy power plants which are located on mainland. At first glance this might sound strange but there are several energy converters that fall into that category (OWC, Tapchan, ...)

Near Shore

The definition of near shore is not totally strict - Normally a distance between 0 and 12 miles from shore (with water depths of up to 50 m) will be considered as near shore. The range has been chosen arbitrarily, but 12 miles are considered as the approximate average limit of visibility of wave power plants from shore.

Offshore

Same as above, therefore: Distances bigger than 12 miles from shore and water depths of 50 meters and more are falling into this category.

3.2.3 History

The first patent on wave energy was granted in 1799 by Girard sen. and Girard jun. in Paris, France. Understandable that electricity generation was not the primary target of this patent because that was not an issue during these days. Its specification just speaks of

> **"...the idea of the most powerful machine which has ever existed."**[74]

Nothing is known about this "machine", if it worked or if it was even built. Over the years some hundred patents which dealt with wave energy, have been filed in Britain alone.
Thomas Alva Edison "nearly" invented a device for harnessing wave energy. He was thinking of

a method to power warning lights in buoys - his possible solution for this were generators which would have been moored in harbours and powered by wave energy. But a prototype or even a working device was never built [16].
Nearly 200 years and the oil crisis needed to come until further movement happened in the development of wave energy devices. It was Steven Salter at the University of Edinburgh (Scotland) in 1973 who started the development of a device

> **"... which would provide vast amounts of energy (...), would be clean and safe, would work in winter in Scotland and would last forever."**[74]

An article in Nature in 1974 [75] set everything in motion and sparked the interest in wave energy again. Here he first proposed a device which is later known as the Salter or Edinburgh Duck. Right then, several teams started working, most of them at Universities. Some interesting concepts could be developed but unfortunately a major share of them vanished already from the scene for several reasons (inefficiency, technical problems,...).

A prominent candidate of the not so successful prototypes is OSPREY[8] [56]. It used the OWC concept (although the OSPREY was designed as clear offshore device, which was more or less a novelty in that power region at that time) and was launched back in 1995. Interesting to note that OSPREY was rated at 2,2 MW and had a 1,5 MW wind turbine attached to its structure. Despite the fact that the concept in general was good, the reality looked different: OSPREY sunk off the coast of Scotland without being in service for a month [57, 74].

It took several years that the interest in wave energy took a turn and regained to unseen heights. This was mainly because small companies were able to solve the basic technical problems. A big contribution to this was done because renewable energy technicians and engineers helped themselves out with knowledge and experience of other industries - mostly the offshore industry. And this is somehow ironical: For further development of ocean energy it was necessary to rely on "old" industries like the (offshore) gas & oil drilling and exploration industry.
Because of the tireless effort of all of the small research groups to get (private) funding and venture capital it was possible to make quantum leaps in ocean energy technology. And only after the first prototypes were deployed into the sea for first tests, governmental interest was renewed and this made public subsidiary money available again.

Nowadays, nearly everyone is talking about wave and tidal power. This may be also amplified by governmental endeavours to mitigate climate change and to ban CO_2 from electricity production.

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[8] **O**cean **S**well **P**owered **R**enewable **E**nerg**Y**

Now a brief overview about some of the most important wave energy devices is given:

3.2.4 Edinburgh Duck

The so-called *Edinburgh Duck* was invented by Edinburgh University professor Steven Salter in the early seventies of the last century [75]. The working principle is shown in Figure 3.7. A cam-like structure converts wave energy into a form of nodding motion. Inside the cam a complex (hydraulic) mechanism converts this motion into electrical energy.

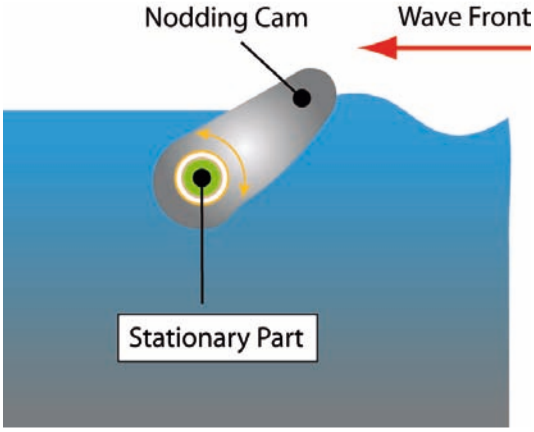

Figure 3.7: Basic Principle behind the Duck (Redraw according to [62])

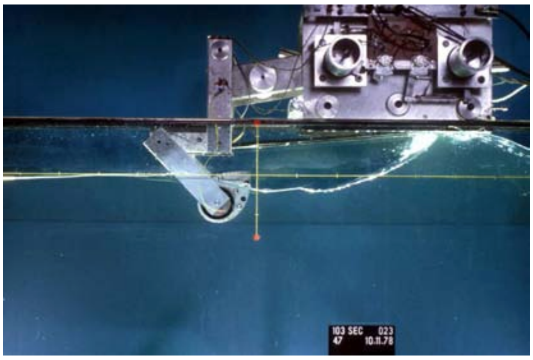

Figure 3.8: A scale model of the Duck in the wave tank (Source: Edinburgh University)

The "duck" still seems to be the benchmark for all other wave energy devices because of its high efficiency of about 90%[9]. Figure 3.8 shows that quite clearly: A scaled model of a duck is tested in the University of Edinburgh's wave tank. The waves are moving from right to left - There is a notable wave height in the right part of the picture whereas on the left side (after the energy extraction trough the duck) the water is quite calm.

Even though the concept is brilliant, the duck has not made it to the market due to several reasons. Firstly this can be traced back to the lack of governmental support (funding etc.). Secondly the hydraulic power mechanism is a totally new development and has therefore some teething problems.

Nevertheless the duck can still be considered as the most sophisticated wave energy converter. A lot of incipiently problems and issues have been solved but it is still a long way until the duck is ready for the open market [30, 75].

3.2.5 Archimedes Wave Swing

The Archimedes Wave Swing (AWS) is a fully submerged wave energy converter. This has some advantages compared to other wave energy converters. Firstly, this is a point energy converter,

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[9] It is quite likely that this can be only valid for a limited number of waves and wave frequencies respectively

which means it can convert wave energy virtually regardless of their travelling direction. Secondly there is next to nothing no visual impact or even "visual pollution" as this is caused, for example by offshore wind farms. The submersion also help the AWS to survive severe weather conditions, which is very important because survivability is one of the key factors for a successful ocean power device.

Development of the AWS started in 1993 by Fred Gardner and Hans van Breugel. Later, the Dutch company Teamwork Technology (now AWS Ocean Energy [7]) was formed. Already in 1995, after testing a 1:50 scale model, a 1:20 scale model could be built and tested successfully.

Basically the AWS consists of two main parts or two cylinders respectively: One cylinder is attached to a structure which is mounted at the seabed. This cylinder is fixed and is open at the top and beneath the second cylinder, the so called *"floater"*. With careful design of these two cylinders it is possible to design them in such a way, that a change in pressure (which means: waves are travelling over the AWS) is able to set the *floater* in motion and eventually leads creating an oscillating movement [72, 73].
The following figures demonstrate the working principle of the AWS (redraw according to [72]):

Figure 3.9: Undisturbed AWS system

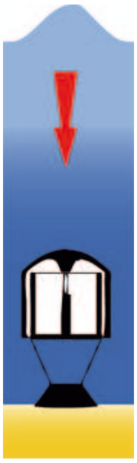

Figure 3.10: A wave is approaching

Figure 3.11: Expansion phase

Figure 3.9 shows an AWS device in standstill at calm sea. If a wave front is now travelling over the device, as indicated in Figure 3.10, the *floater* is moving downwards. When the wave has passed the AWS, the *floater* is, caused by the remaining air pressure "cushion", moving upwards.
The AWS therefore harnesses the potential energy of waves as it is reacting to the changes of static pressure, which is caused by surface waves.

If the amount of air between both cylinders is chosen properly, it is possible to set the device in an oscillating and more important, nearly sinusoidal movement. Furthermore it can be

possible that the movement of the cylinder is amplified by three or more times compared to the original wave elevation.
This is possible because the frequency of the AWS can be tuned by changing the volume of the chamber. The natural period of this prototype is between 7 and 13 seconds. Changing the volume is equatable with the change of the spring constant in a simple mechanical resonant circuit. Therefore it is possible to maximise the power output as the AWS can be adapted to the actual waves and their frequency respectively [19, 70]
For doing so, water is pumped into or out of the chamber [70, 72, 73]. And here we have **a big problem**:

Sea-water is constantly acting on the sealing of the linear generator. Furthermore high pressure - which is, to make matters worse, not constant - stresses the sealing (and also the bearings) additionally. This leads to a shortened lifetime of the sealing and to premature maintenance, which is undesirable.

This problem was the starting point of the thesis - To find a possible solution for the sealing issue.

There are some further disadvantages at the Archimedes Wave Swing which are also addressed in literature [71]:

- **Bearings:** Because of the high attraction forces between the stator and the translator, the bearings are stressed additionally. This is undesirable because that leads to additional wear and therefore shortened lifetime which eventually leads to maintenance. This should be absolutely avoided as such a repair is difficult to achieve and also expensive.
- **Generator:** The large linear generator (see Figure 3.13) is one of the core elements of the AWS. Because of its current design and size it is very expensive. Further research has to be carried out to lower the manufacturing costs.
  Recent results also showed that the flat construction style of the generator is also not ideal. A round set-up has much more preferable properties. The flat construction was only chosen for easier prototype manufacturing.
- **Losses:** Losses in the generator are needed to be reduced to achieve a good annual energy output and also solve some cooling issues (the stator needs to be water cooled already).

The sealing issues are not identified by literature so far and it is not expected that this will change within reasonable time. Although the bearings used now were not specially designed for doing their work in the AWS, it is not expected that the problem can be easily solved with a custom product soon [63].
To omit the current sealing and place them inside the linear generator, hence run the machine fully flooded would solve several delicate problems like seal lifetime, improvements in cooling and bearing lifetime, etc.

There are already ideas how to come around the troubles with the generator [71]: The usage of a transverse-flux permanent magnet machine (TFPM). The stator is carrying the magnets and the conductors whereas the translator only consists of iron. This concept was discarded at the beginning of AWS' development (too complicated, expensive,...) but it could be a possible solution and it is definitely worth to be further researched.

A pilot plant was built and submerged, after a delay of two and a half year, off the coast of Portugal in 2004. The submersion process can be seen in the following Figures (all from AWS):

Figure 3.12: The Archimedes Wave Swing during submersion off the Portuguese coast

This demonstrator is rated at 2 MW, whereas the rated stroke is 7 m and the velocity of the floater is 2,2 m/s. Although the device can handle/brake a force of 1 MN an additional braking system of water dampers is installed as a protective device in case of high(er) waves or component failure. This is done because it is nearly impossible to produce a linear generator that is capable of handling all forces that are caused by (strong) waves [70].

Figure 3.13: The AWS' linear generator during assembly (Source: AWS)

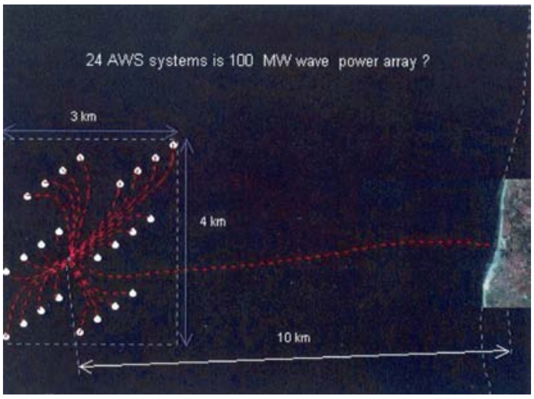

Figure 3.14: Proposed installation of a wave power farm to achieve increased energy output (Source: AWS)

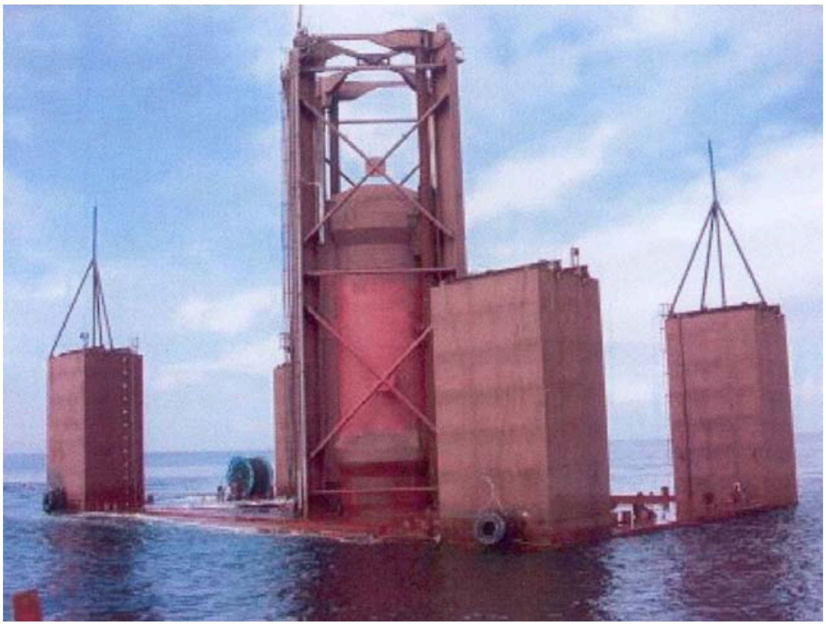

Figure 3.15: The demonstrator before submersion (from AWS)

3.2.6 Pelamis

Pelamis is the name of a tropical sea snake (*Pelamis platurus*) and this fits quite well on the description of this wave energy converter. The Pelamis WEC basically consists of 4 sections (see Figure 3.16) with the power take-off mechanism (PTO) in-between these sections.

First it is necessary to know that the PTO (and its control) and the WEC as whole have not been primarily designed for maximised power output but for survivability instead. This is all the more important because this technology is still to be proved and it is therefore necessary to demonstrate the functionality and the survivability during real operational conditions [35].

Figure 3.16: Pelamis wave energy converter: One of the units that have been sold to Portugal (left); a prototype (right) on it's way for open sea tests in Edinburgh (Source: Ocean Power Delivery Limited)

The PTO works as follows: Four tube-like sections (length between 30 and 38 meters and between 3,5 and 4,6 meters in diameter each) are "following" the movement of seawater which is caused by waves. The sections move relatively to each other because they are connected together via three joints (see Figure 3.17). Inside these joints there are 4 hydraulic cylinders: two for the sway (=vertical) movement and two for the heave (=horizontal) movement. Therefore the Pelamis WEC is able to harness wave energy practically regardless of the direction. This is also because the mooring system (and the Pelamis itself) is designed in such a manner, that it will align itself to the (main) direction where a wave is coming from.

The movement of the cylinders is responsible for a pressure rise in the hydraulic system. A complex control mechanism is then responsible that the over-pressure is processed in a system that consists of two hydraulic turbines and two asynchronous generators (rated at 125 kW each). The total rated power of one joint is therefore 250 kW and 750 kW for one Pelamis WEC respectively.

This WEC, although still in further development has reached some sort of readiness for the market. Portugal already bought 3 machines as a demonstrator and there is also a planned farm in Scotland and one in South England. One device is expected to produce 2,7 GWh of electricity per year. There is no clear estimate about the costs yet, but it is expected that it will be comparable and competitive with other long-established technologies [35, 66]

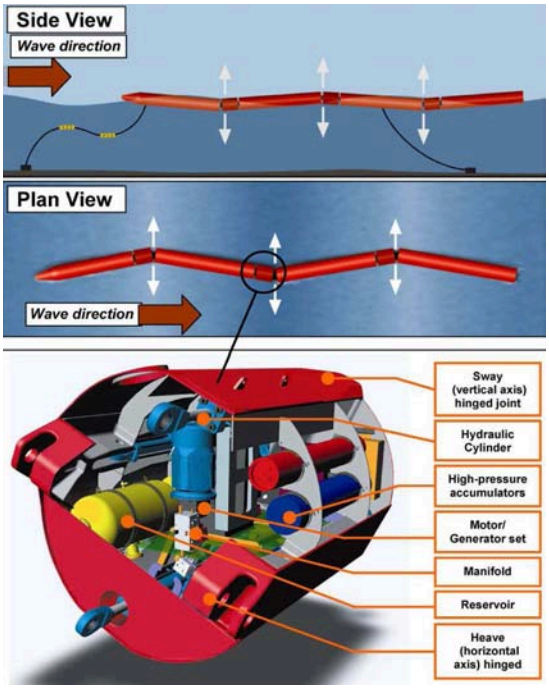

Figure 3.17: Side and top view of a Pelamis WEC (pictures above) and one of the three PTO mechanisms that are installed between the four tube sections (from [35])

3.2.7 Oscillating Water Column

An Oscillating Water Column (OWC) is a wave energy converter which works onshore and offshore as well. The technology was invented by the Japanase wave energy pioneer Yoshio Masuda as an energy source for navigation buoys in 1965. Such buoys got very popular as they could stay in service for 30 years or more [30]. A multiplicity of valves are used in such buoys to rectify the power output. Modern OWC's are using a Wells Turbine to get a continuous energy output. A Wells turbine always rotates in one direction regardless of the direction of airflow. Figure 3.18 shows the working principle that forms the basis of nearly every present-day OWC power plant:

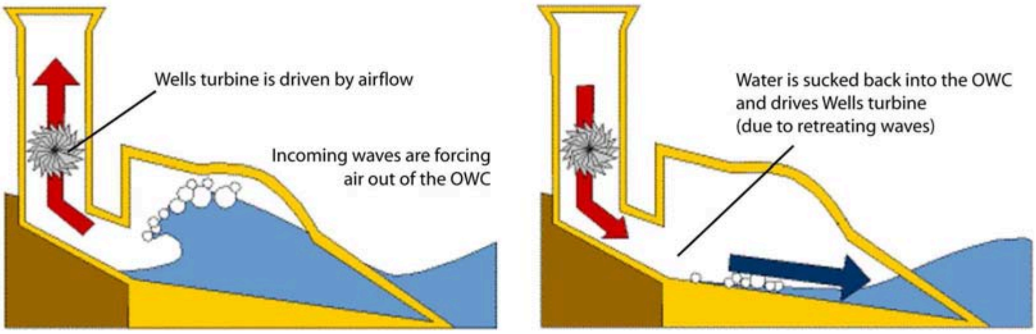

Figure 3.18: Simplified OWC working principle (from Fujita Research)

A partly submerged chamber is used to "capture" the waves which are travelling to the coastline. As waves and furthermore bodies of water are entering this cavern, the water level rises. With the increase of water level the air pressure also rises. This leads to an expulsion of air through a hole above the sea-water level where a Wells turbine is situated. With the retreat of water from the cavern, air is sucked into the structure again. Therefore the turbine is subject to a (more or less) continuous movement of air.

Some plants are using an impulse type turbine instead of a Wells type turbine. Until recently this turbine type had some efficiency problems. But still they have the potential to substitute the Wells turbines if further progress can be made [76].
Recently there has also been progress in increasing the efficiency of Wells turbines by introducing a variable pitch (Figure 3.20).
For an optimum of power output it is necessary, regardless of the used turbine type to adjust the natural frequency of an OWC plant to the frequency of the incoming waves.

Today there are many different OWCs in service, nearly all of them are equipped with Wells turbines. One of the most popular but also most unfortunate one was the OSPREY, which was already mentioned in the chapter's introduction [14, 56]. This offshore project itself was a failure because the supporting structure sank during installation. Nevertheless considerable technology progress could be achieved and a successor project was launched.
This time the OWC was mounted onshore, more precisely at the Scottish Isle of Islay. The 500 kW research power plant (see Figure 3.19), called **LIMPET**[10] is in operation since the year 2000.

Figure 3.19: The LIMPET power plant at Islay (Source: WaveGen)

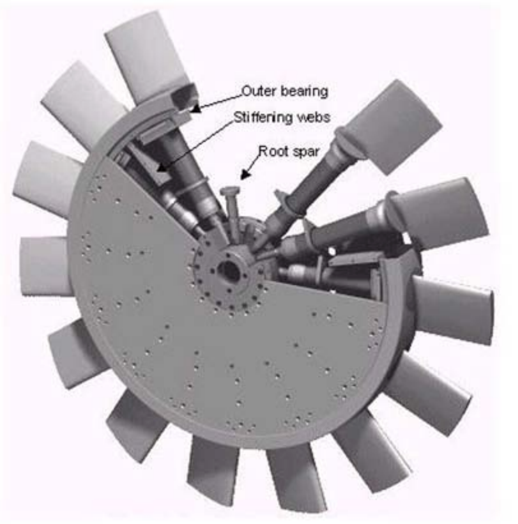

Figure 3.20: Rotor of a Wells turbine (with variable pitch, Source: University of Edinburgh)

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[10] **L**and **I**nstalled **M**arine **P**owered **E**nergy **T**ransformer

As already touched in the introduction, there are also Offshore OWC's besides the usage in navigation bouys. The Japanese development called **Mighty Whale** is one of them:

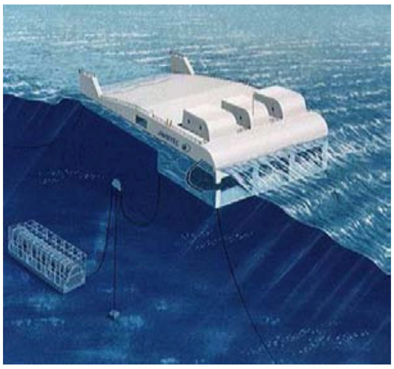

Figure 3.21: Artists impression of the Mighty whale (Source: JAMSTEC)

Figure 3.22: The Mighty Whale during installation (Source: JAMSTEC)

Average power output is between 6 and 7 kWh with a maximum total energy efficiency of about 15 %. Such OWC's are not only used for electricity production alone but as coastal protection as well. Because they extract energy from the waves they can prevent the shore from erosion or other severe and long-term damage [67, 81].

3.2.8 TAPCHAN

The first prototype of a TAPCHAN[11] power plant was built in 1986 in Norway. Figure 3.23 shows the basic layout of a TAPCHAN plant and Figure 3.24 the layout of the plant in Toftestallen near Bergen, Norway. The TAPCHAN is some sort of "natural" pump storage power plant:

Waves are pushing bodies of water through a tapered channel (that's where the name comes from) into a reservoir that lies above sea level. The level of the reservoir (here: with area of about 8500 m^2) in the plant in Norway is 3 meters above sea level. This prevents the water bodies from flowing back into the sea instead of moving into the basin.

2 GWh of electricity could be produced on average per year with this plant (350 kW maximum rated power) which is quite remarkable. And although this type of WEC has no serious technical issues (because it is placed onshore and uses nearly exclusive field-tested components) it also has its problems:

- Heavy rainfall often causes landslip which leads to a blockage of the inlet channel, or even worse, to a complete destruction.
- Construction of a TAPCHAN plant is also problematical because the inlet channel should be in an area with strong waves to get a decent power output later on. Such con-

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[11] **TAP**ered **CHAN**nel

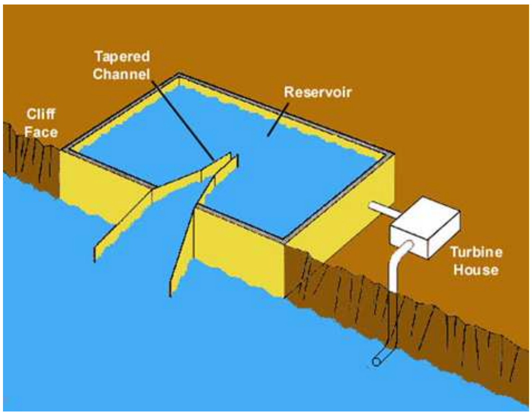

Figure 3.23: Simplified TAPCHAN design (from Fujita Research)

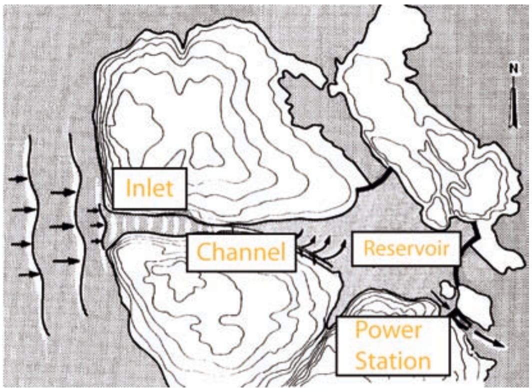

Figure 3.24: Layout of the Norwegian TAPCHAN (Source [30])

struction work tends to be expensive and time intensive. A potential solution is the pre-manufacturing of most parts offsite, as this was done for the LIMPET for example.

- Furthermore the number of suitable locations for a TAPCHAN are very marginal so that despite the fact, that the TAPCHAN is a stable technology, its future services will be limited [30]

3.2.9 Wave Dragon

Yet another WEC using the overtopping principle is the Wave Dragon. Unlike the TAPCHAN, the Wave Dragon is clearly an offshore device or in other words - it is an artificial TAPCHAN. Several prototypes have already been tested at the coast of Denmark. The Wave Dragon shares one major advantage over most other WEC's with the TAPCHAN: it has no moving parts (besides the power take off mechanism, which is a field-tested and reliable component). They also have quite a similar working principle as Figure 3.25 reveals. The prototype is shown in Figure 3.26 and 3.27

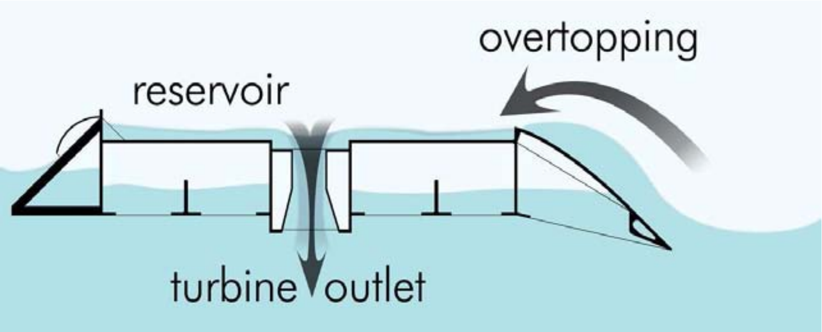

Figure 3.25: Working principle of the Wave Dragon (Source: Wave Dragon ApS)

Kaplan turbines are used as generation units. Therefore it is expected that there aren't any serious technical problems in operation. Nevertheless, one prototype has been damaged in 2005

in a very heavy storm.
Shortly a full size prototype is going to be deployed off the Welsh coast. It will have 16 turbines, each rated 250 kW which enables this WEC to produce a maximum of 4 MW [30, 70].

Figure 3.26: Wave Dragon prototype off the Danish coast (Source: Wave Dragon ApS)

Figure 3.27: Wave Dragon in action (Source: Wave Dragon ApS)

3.3 Tidal Energy Devices

3.3.1 Basics

The term *tide* references to changes of ocean water levels between their lowest point (low water or "ebb") and highest point (high water or "flood"). But this is quite an imprecise definition as the movement of water can be divided into 2 separate movements [15]:

- **vertical movement**
- **horizontal flow (often referenced as tidal stream)**

These movements are basically caused by the presence of the moon (and only to a very small part by the sun) and the gravity interaction respectively. Although the sun is much heavier than the moon, it is still the former which has a bigger influence due to the shorter distance to Earth. Besides the two heavenly bodies, gravity and centrifugal forces caused by the earth's movement also contribute to the tidal phenomena. Figure 3.28 show the correlations clearly.

The rise and fall of water level does not coincide with the earth's day cycle. The tidal cycle occurs - so called semidiurnal - which means twice a day. This is per definition imprecise as it takes 24 hours, 50 minutes and 28 seconds for two cycles, because it is the time that is needed by the moon to rotate once around the Earth. But that is just true for an observer, who is based on earth. Because the earth is also moving, it is the daily difference of 50 minutes and 28 seconds which adds up to a full rotation each 27 days, 7 hours and 43,7 minutes. The time difference is also responsible that it takes about 15 days for the tide (high water, for example) to happen at the same time.

Since the centre of the moon's way round the Earth is not equal with the Earth's centre point, its influence on the tides changes. This can be seen in Figure 3.30. Therefore it is of interest to discuss the different factors and tides.

Vertical Tidal Movements

The vertical movements of seawater (between high and low water) is the exact definition of the term *tide*. The difference between these two levels is relevant for a tidal power plant and it is advisable to choose the location of a tidal power plant wisely because of the direct relation between tidal range and (electrical) energy output.

Some locations have virtually no difference between low and high water (less than 1 meter) and are therefore unsuitable for common tidal power. On the other hand there are places which are perfectly adequate because of narrow bays or estuaries - for example: the Bay of Fundy (tidal range up to 21 meters, 11 meters on average) in Canada or the Severn estuary (tidal range up to 15 meters, 7 meters on average) in the United Kingdom which have the world's highest and second highest tidal range respectively [15, 33].

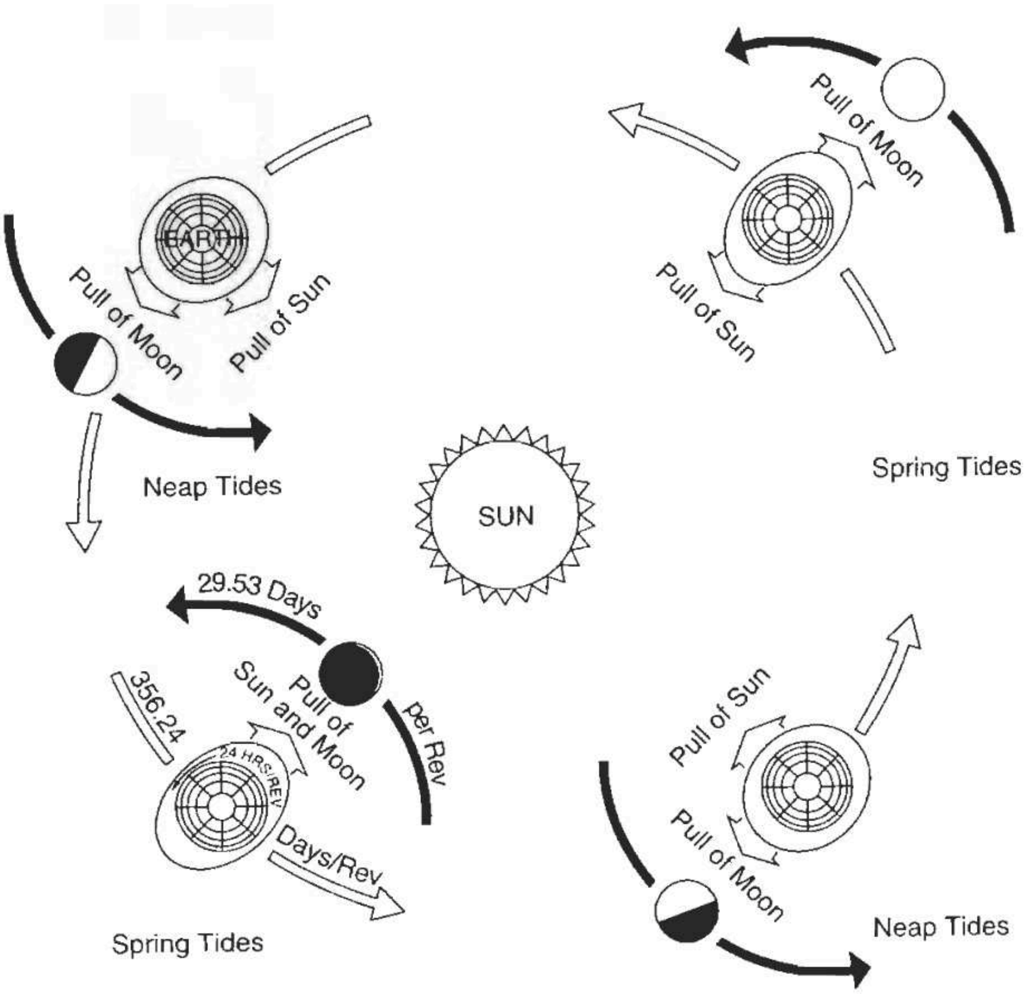

Figure 3.28: Origins of the tides (from [15])

Horziontal Tidal Movements

The horizontal movement of water, which is often referred as *ebb* and *flood* is described by the term *tidal stream*. The direction and the velocity of this stream is crucial for planning a tidal power plant [15].

There are also novel approaches to harness the tidal stream itself (see Sections 3.4.1). This is very favourable as water has a much higher density than air (more than 854 times), therefore water (tidal) streams with a typical velocity of about 5 knots (approximately 2,5 m/s) are able to generate much more electrical energy than this would be possible with wind of the same speed (see also Figure 3.35 which underlines this fact).

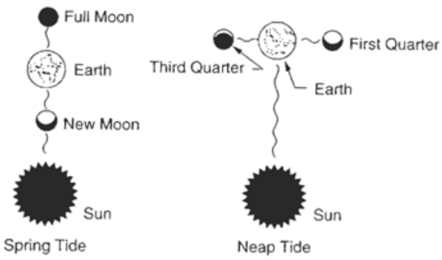

Figure 3.29: Origin of spring and neap tides (from [15])

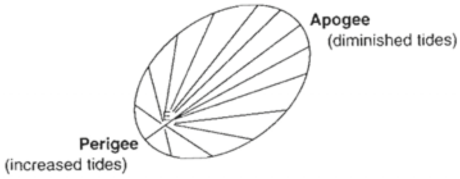

Figure 3.30: Tidal variations (from [15])

3.3.2 Classification of tides

Basically there are 3 different types of tides. It can be said that most of the tidal phenomena is some sort of a *mixed type* which means a combination of all of the three types. To cover all these phenomena in detail would go beyond the scope of this thesis, more detailed coverage can be found in [14, 15, 32, 33] for example.

- Synodic Tide
- Anomalistic Tide
- Declinational Tide

Synodic Tide

A Synodic tide occurs twice a month and is responsible for the generation of a spring tide (high tide). This is because the attraction of the sun and the moon are acting together, as Figure 3.29 shows. Because of the irregularities of the moon's movement the time between such two tides differs, but it is about 29,53 days on average.

Anomalistic Tide

As stated above, the path of the moon around the Earth is not circular, nor is the Earth the center of the movement. Therefore there are two points, that stick out (see Figure 3.30). This is the point, where the moon is nearest to Earth, which is called *Perigee*. The point with the largest distance from Earth is called *Apogee*.
It seems that there are no tides worldwide which are clearly of anomalistic type. Nevertheless there are places, like the Bay of Fundy, where there is a noteable influence of anomalistic tides: The range of the spring tides is about 2 to 3 meters lower at apogee than at perigree. For the neap tide the difference is smaller, but still perceivable with 1,6 to 2 meters difference [15].

Declinational Tide

Declinational Tides can be observed, when the moon is not in plane with the Earth's equator, as Figure 3.31 shows. If the moon is, for example, in the northern hemisphere, as this is pictured in the following figure, the crest of the diurnal tides is not equal - the tide at lunar noon is higher than the one at lunar midnight. These tides differ in their time of appearance from the semidiurnal tides. Therefore a diurnal inequality arises.

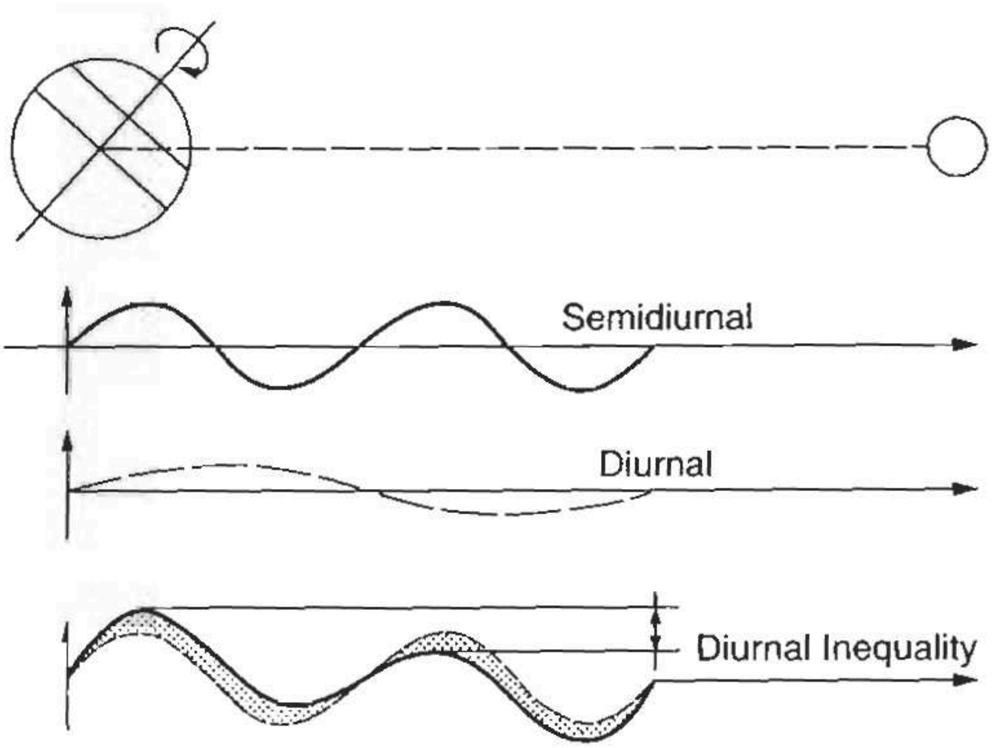

Figure 3.31: Declination influence from the moon (from [15])

3.3.3 Tidal energy

Basically the tidal phenomena and the power output (energy) is a sum of the kinetic and potential energy of the affected seawater. The potential energy can be estimated with [29]:

$$E_{pot} = g \cdot \rho \cdot A \int x.\mathrm{d}x = \frac{g \cdot \rho \cdot A \cdot h^2}{2} \tag{3.2}$$

g... acceleration due to gravity, ρ... fluid density (seawater), A... ocean surface area, x... vertical component of tidal range and h... tidal range.

For **one square meter of ocean surface** and a tidal range of one meter the theoretical energy, that could be extracted is (g is assumed to be $9,81\,\mathrm{m/s}$ and the density of the seawater $\rho = 1025\,\mathrm{kg/m^3}$):

$$E_{pot} = 0,5 \cdot 9,81 \cdot 1025 \cdot A \cdot h^2 = 5,03\,\mathrm{kJ/m^2} \equiv 1,40\,\mathrm{Wh/m^2} \tag{3.3}$$

The kinetic energy is calculated with the following basic formula [29, 30]:

$$E_{kin} = \frac{m \cdot v^2}{2} = \frac{\rho \cdot V \cdot v^2}{2} \tag{3.4}$$

whereas m is the mass of the seawater and v is its according velocity. V is the viewed volumina of seawater. The total energy that can be gained from one tide is therefore $E = E_{pot} + E_{kin}$. From the formulas above it is obvious that a high tidal range and a big ocean surface (estuary, reservoirs,...) are necessary for substantial electrical energy output.

An example for the potential energy of one tide is given in Equation 3.5. The figures originate from the south coast of the German island of Sylt, where 300 Million cubic meters of water are relocated during one tide. The mean stream velocity is assumed with $v = 1,5\,\mathrm{m/s}$. The viewed time-span is two hours (7.200 seconds) and the mean density of seawater is assumed with $\rho = 1.025\,\mathrm{kg/m^3}$. The potential energy is neglected because of the low tidal range.

$$P = \frac{\rho \cdot V \cdot v^2}{2 \cdot t} = \frac{1.025 \cdot 300 \cdot 10^6 \cdot 1,25^2}{2 \cdot 7.200} = 4,805 \cdot 10^7\,\mathrm{J} \approx 96\,\mathrm{MWh} \tag{3.5}$$

This energy could be harnessed in one tidal process or four times per day (in total nearly 400 MWh per day or 146 GWh per year). Even if it is not possible to use the whole energy (because, for example no efficiency rates have been taken into consideration), this is still a huge amount of electricity which could be produced - especially in comparison with other renewable energy sources. And there is an additional benefit of installing a tidal power plant in this area: Because of the energy extraction there is a reduction of stream velocity which has a positive (and slowing down) effect onto coast erosion [30].

3.3.4 Pro's and Con's

Advantages and disadvantages of tidal power are listed below (Sources: [14, 31, 65]) The technology is **favourable** because tidal

- current is predictable and regular
- power is independent of weather conditions and fuel prices (of any kind)
- power generation is not affected by lack of rain or snow-melt
- power plants have small environmental and physical impacts; "visual pollution" is expected to be small
- power is ideally placed to support hydrogen production and desalination

But there also some **problems**:

- Tidal power generation exists already for several decades but there has been nearly no further development from the 1960's up to the 1990's.
- There is no continuos power generation possible
- Erection costs of bigger tidal power plants are expected to be high(er) compared to other technology and the pay-off time is also long(er)

3.3.5 Evolution of Tidal Power

The provable history of harnessing tidal power dates back to 1170. Reference of installation of a tidal mill in the Deben Estuary (Suffolk, Great Britain) can be found in the records of the Parish of Woodbridge. Tidal energy was used along the Atlantic coast of Europe - in Great Britain, Spain and France.
The technology was also "exported" to America, where colonists built tidal-powered mills in the region of New England. London used some sort of tidal energy for it's water supply in 1824. A similar installation was used until the 1880's in Hamburg (Germany) for pumping sewage.
Despite of the fact that a lot of research work was done in the past - between 1856 and 1939 some 280 patents, which dealt with energy extraction of tidal power, were filed - there was no real initial success. In the 1960 Electricité de France (EDF) started a research program for usage of tidal power in L'Aber Vrach in Brittany and in the vicinity of the estuary of the Rance, near St. Malo. This program eventually led to the construction of the worlds first tidal power plant *La Rance*. The construction work was completed on November 26, 1966, when the plant was grid connected. Some more plants were built at other sites, as Table 3.1 shows. But the La Rance plant is still the only plant, which has produced a significant amount of electricity so far [15].

Quite a big number of sites for possible usage of tidal power have been identified over the years (see Table 3.3). The most popular sites are located in Canada (Bay of Fundy) and in

Location	Mean Tidal Range in m	Bassin surface area in km^2	Power in MW	Annual production in GWh	Inauguration date
La Rance (France)	7,85	17	240	600	1966
Kislaya Guba (Russia)	2,4	2	0,4	-	1968
Jiangxia (China)	5	2	3,2	11	1986
Annapolis (Canada)	6,4	6	20	50	1985

Table 3.1: Existing tidal power plants (Source: [28])

Great Britain (Severn). Besides these heavily researched sites there are some more places with an enormous potential, like the Penshinsk Bay in Russia, with an estimated energy output of 190 TWh. This would be by far the largest tidal power plant that could be built world wide. But the research in this site has been abandoned because there are no customers in the vicinity for this huge amount of produced electricity. Furthermore, additional (hydro) power plants would be needed in the area to cope with the irregularity of the diurnal tides [8].

Utilizing the tidal power in the Bay of Fundy was first discussed in 1910 but until now only a small plant was built near Annapolis. [8, 28, 32]

3.3.6 Actual Tidal Power Plants

Nowadays it is quite unlikely to happen that new tidal power plants are built, especially the projects discussed for the Bay of Fundy, the Severn Estate and the Penzhinsk. Mainly for two reasons: economical uncertainties and (probably) unknown or overlooked environmental issues. Here is a listing of operational tidal power plants at the moment:

La Rance (France)

The La-Rance tidal power plant is so far the only plant on an industrial-scale which makes a notable contribution to the electrical power generation. It was built by EDF[12] in 1966 and was used to supply high peak demands in electricity ever since. This is mainly justified with economical reasons. Therefore it was quite clear, also because of the low total energy output (compared to the rest of the French network), that this plant would operate to maximise the earnings and not to maximise the total electricity output. Because of the long lifetime the costs of the erection have already been regained and the plant is able to compete even with EDF's nuclear power plants (which also produce cheap electricity)[13].

Figure 3.32: The La Rance Tidal Power Plant in France (from [31])

During the building the Rance was entirely blocked by two dams. Recent studies show that this is not favourable in concern of the ecosystem and should not be done again at new tidal plants. The original ecosystem disappeared right after La-Rance went operational but an other ecosystem was formed which is now heavily dependent on the tidal power plant.

In La Rance there are twenty-four generators at 10 MW each, which are able to operate both ways (although this is used very rarely) and in some sort of pump storage mode as well. The pumping scheme is necessary to enable the production of peaking power. The pumping operations take up to 20 percent of turbine operation hours.

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[12] Electricité de France

[13] Electricity is generated at La Rance at about 3 €cents per kWh

La-Rance's yearly electricity production lies between 500 and 600 GWh. The plant availability is constant at about 97 % since 1982!

In connection with this thesis and especially corrosion protection it is interesting to note that no major failures have occurred after more than 150.000 operational hours! This is mainly due to the well chosen material pairings and a cathodic protection (1 Volt and 20 Amps).

Fortunately there are some sources in literature which describe the operational experiences and the problems that occurred during service [28, 31–34]. These were mainly caused by

- **Seawater salinity**
  Corrosion protection was achieved with clever material pairing and cathodic protection. The unprotected items faced heavy corrosion phenomena, which was caused by the seawater (and fouling as well). Therefore the unprotected steel parts where exchanged against plastic parts or eliminated (if possible).
- **Sealing**
  Sealing is a delicate issue: EDF had to learn that a sealing system which operates perfectly in a plant in one part of a country need not necessarily work well in an other plant. This gives already hints for the actual sealing problem: it has to be fitted to the according environmental and surrounding conditions. It was reported that polyamide, polyethylene, nylon and carbon seals performed well.
- **Electro-dynamic stress**
  Because of the tides the machines have to be started and shut down at least 4 times a day. The asynchronous coupling is causing high stress in the machines (thermal and mechanical stress).
- **Cavitation**
  Altough no serious problems aroused from cavitation, the bulb units in La Rance are more likely to get in trouble than other turbines used in hydro plants like the Kaplan-turbine.

Kislaya Bay (Russia)

The experimental Kislogubsk tidal power plant (rated power 400 kW) was erected in 1968 to gain basic knowledge in construction, erection and operation of tidal power plants. The site, located near the city of Murmansk, Russia at the gulf of Ura was already researched in 1938. There are some advantages that made this site a perfect place for basic research: the vicinity to the city of Murmansk, existing power lines, a moderate climate and most of all, a river that narrows from 150 m width down to 35 m for a length of 450 meters.
But it took up to 1959 until Dr. Bernshtein suggested a novel design, the usage of floating caissons. These structures could be assembled elsewhere, towed to the plant site and sunk there. These procedure lowers erection costs dramatically since no special dam needs to be constructed.

The turbine used at Kislogubsk is a standard 400 kW bulb turbine (72 rpm)[14] with 4 adjustable blades. Because of that, the plant is able to operate either in bi-directional, in pumping or in sluicing mode. The turbine is connected to the generator via a step-up gearbox (600 rpm). During the research operation, the maximum captured energy per year was 1,2 GWh.

The knowledge gathered with this experimental plant was used to develop design studies for much larger tidal power plants, like - for example - the Tugur (7 GW and 7,8 GW respectively), Mezen Bay (15 GW) and the largest one in Penzhinsk (87,4 GW). The WEC survey of energy resources in 2001 [82] identified the site of Tugur as the only feasible. Preliminary work was already carried out in 1972 but the project came to a halt soon and it is uncertain if it will be completed within a reasonable timescale [8, 14, 32].

Annapolis (Canada)

The Annapolis tidal power plant in the Bay of Fundy is also a research power plant to gather more information about the tidal phenomena. After being considered already back in 1910, a power plant was eventually erected in 1984. It uses a single STRAFLO-Turbine (rated at 20 MW) and is able to generate between 30 and 45 GWh of electricity per year. It is interesting to note that the plant only uses one turbine which operates only one-way [10, 31, 33, 77].

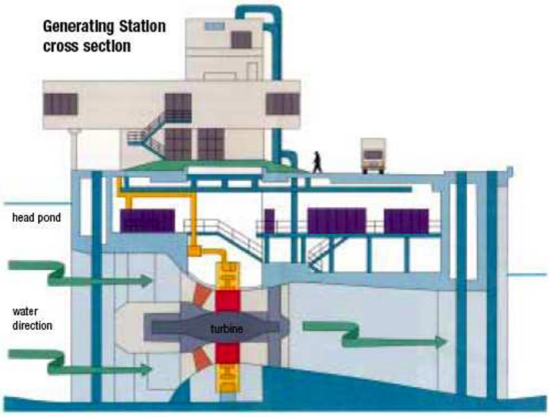

Figure 3.33: Cross-Section of the powerhouse (Source: [2])

Figure 3.34: The Annapolis tidal power plant (Photo is copyrighted by Hartmut Inerle)

Jiangxia (China)

There were also tidal research projects in China since 1959, when the first plant with 40kW rated power output was built. With the help of a further research plant, built in 1970 and rated at 165 kW China was able to build a tidal power plant near Jiangxia, which can be operated two-ways and has an electric power of 3,2 MW. This plant is well described in literature, because it was mainly designed as research plant. 5 different turbine types are used here. Newer papers

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[14] Although 2 turbines were planned originally, only one was installed

report of 8 further tidal power plants in China which are shown in table 3.2 [10].

Location	Mean Tidal Range in m	Power in MW	Inauguration date
Baishan-Rushan	1,2	0,96	1978
Ganzhtan Shune	1,3	5	1970
Gouzishan Longmengang	0,04	2	1977
Haishan Yuhuan	3,4	0,15	1975
Jiangxia Wenling	5	3,2	1980
Liuhe Taichang	1,25	0,15	1976
Shashan Wenling	2,5	0,04	1961
Xingfuyang Pinton	6	1,28	1989
Yuepu Yiangshan	3,5	0,15	1971

Table 3.2: China's 9 tidal power plants (from [31])

Country	**Site**	**Mean tidal range in m**	**Basin area in km^2**	**Installed capacity in MW**	**Approx. annual output in TWh/a**	**Annual plant load factor in %**
Argentina	San José	5,8	778	5 040	9,4	21
	Golfo Nuevo	3,7	2 376	6 570	16,8	29
	Rio Deseado	3,6	73	180	0,45	28
	Santa Cruz	7,5	222	2 420	6,1	29
	Rio Gallegos	7,5	177	1 900	4,8	29
Australia	Secure Bay	7	140	1 480	2,9	22
	Walcott Inlet	7	260	2 800	5,4	22
Canada	Cobequid	12,4	240	5 338	14	30
	Cumberland	10,9	90	1 400	3,4	28
	Shepody	10	115	1 800	4,8	30
India	Gulf of Kutch	5	170	900	1,6	22
	Gulf of Khambat	7	1 970	7 000	15	24
Korea (Rep.)	Garolim	4,7	100	400	0,836	24
	Cheonsu	4,5	-	-	1,2	-
Mexico	Rio Colorado	6 - 7	-	-	5,4	-
UK	Severn	7	520	8 640	17	23
	Mersey	6,5	61	700	1,4	23
	Duddon	5,6	20	100	0,212	22
	Wyre	6	5,8	64	0,131	24
	Conwy	5,2	5,5	33	0,06	21
USA	Pasamaquoddy	5,5	-	-	-	-
	Knik Arm	7,5	-	2 900	7,4	29
	Turnagain Arm	7,5	-	6 500	16,6	29
Russian Fed.	Mezen	6,7	2 640	15 000	45	34
	Tugur	6,8	1 080	7 800 [1]	16,2	24
	Penzhinsk	11,4	20 530	87 400	190	25
	Lumbovsk	4,2	70	670	2	?
	Mezen upstream	5,66	2.640	21.000	15	?
	Mezen downstream	7,53	6.451	?	?	?

Table 3.3: Prospective sites for tidal energy projects (from [14, 82])

[1] A 7000 MW variant was also studied

3.4 Tidal Stream

Tidal energy converters that are using the tidal stream itself are considered as much more feasible than "standard" constructions. This is mostly founded in the reason that the erection costs are much lower because no expensive barrages or dams have to be built. Also the environmental impact is assumed to be much smaller.

There are several different approaches how to harness the energy of tidal streams - some of them look more or less like wind turbine, which have been lowered to the seabed. But there are also some complete different types like the Stingray. The following listing of designs is intended to give a brief overview but it is not exhaustive.

The power, that can be harnessed by a turbine is described with [31]

$$P = \frac{C \cdot A \cdot \rho \cdot v^3}{2} \tag{3.6}$$

C is the turbine efficiency and lies between 0,3 and about 0,45 for existing designs. The formula is also used for the calculation of wind power where the theoretical maximum for C is about 0,593 (also known as the law of Betz). A is the area which is covered by the rotors of the turbine in m^2, ρ is the density of the fluid (the density of seawater is in the region of about 1020 to 1030 kg per m^3) and v is the (undisturbed) stream velocity in m/s.

Because the stream velocity is cubed in Equation 3.6, it is desirable to find sites with high stream rates. Increasing the size of the rotor is limited as the rotor needs to fit in between surface and seabed. Typical water depth in the near shore area is around 20 to 50 meters. Deeper waters are not desirable because installation costs would rapidly rise and the forces to the supporting construction would also increase [27, 49].

3.4.1 Seaflow and SeaGen

Seaflow

This concept was invented, designed and built by the British company *Marine Current Turbines Limited*[15]. In principle their approach was just to "put a wind turbine to the seabed". The fact that the stream velocity of the oceans is rather small compared to mean wind speeds is more than compensated by the fact that (sea-)water has a much higher density than air (about $\rho_{Sea} \approx 1025\,\mathrm{kg/m^3}$ compared to $\rho_{Air} \approx 1,2\,\mathrm{kg/m^3}$).

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[15] www.marineturbines.com and www.seageneration.co.uk

Seaflow is the name of the first generation: On a pile, which is mounted on the seabed sits a rotor which is driven by the tidal current, very similar as this would happen with a turbine onshore and wind. This "underwater windmill" has a rated power of 300 kW (maximum, average output was estimated to about 100 kW) at a tidal current stream velocity of $v = 2,7\,\text{m/s}$. It has been installed in 2003 near (about one kilometre away from shore) the south-west coast of England and has been operational ever since. This device is fully a research prototype which is, besides of the high costs, the reason why it is not grid connected.

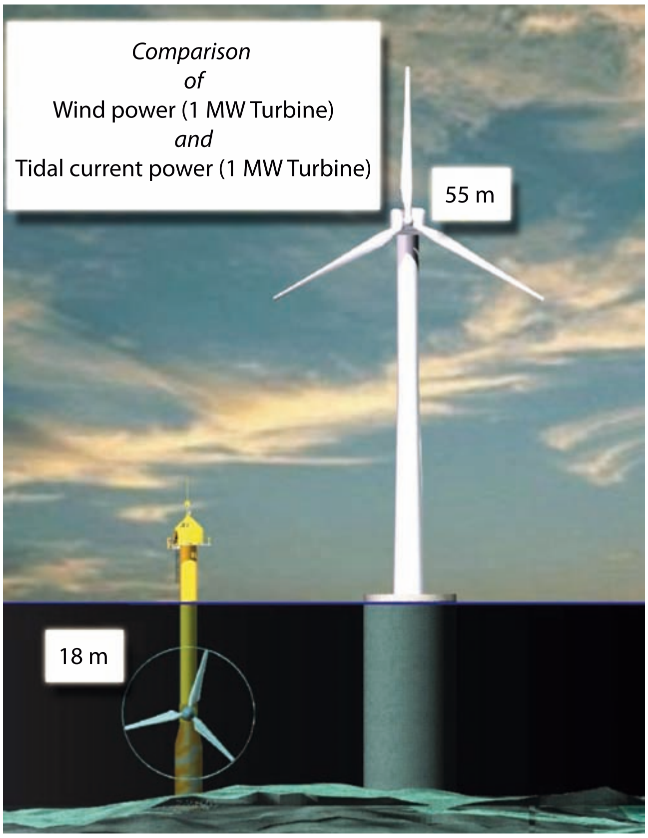

Figure 3.35: Comparison of sizes of a wind and a current stream turbine (from [31])

Figure 3.36: Seaflow prototype which was installed off the coast of Lynmouth (Devon, United Kingdom) in 2003 (Hybrid image, Source: MCT)

Figure 3.35 shows a fact, which was already mentioned in the introduction of this chapter: Because of the high water density the Seaflow turbine can be much smaller to gain the same power output as a wind turbine. What would be interesting in this connection: Mergence of wind and tidal energy - Only one pile would be necessary and also other infrastructure (like grid connection) could be shared. This could lead to lowered total costs (for both technologies).

The rotor of the Seaflow device is 11 meters in diameter and rotates with about 17 rpm. The blades of the rotor can be pitched so it is possible to generate electricity regardless of the direction of the tidal stream.

MCT also solved a problem, that can cause real trouble for ocean power devices, quite clever: maintenance. The whole mechanism (rotor, gearbox, generator, etc.) can be raised above sea level for servicing purpose. So there is no need for dismantling the whole device and towing it into a port for maintenance or repair work, like this is the case at other technologies. [49]

SeaGen

SeaGen is the second stage of development of this technology. Preliminary work has already been started back in 2004 and it is expected that a prototype is deployed in Strangford Lough, Northern Ireland by the end of 2007.

When SeaGen will be operational it will be by far the biggest tidal current power plant as it is rated at 1,2 MW. The power increase is founded in the lessons learned with Seaflow and due to the fact that SeaGen is a twin propeller system with 18 meters in diameter each. As it is a commercial demonstrator, SeaGen also will be grid connected.

Figure 3.37: A SeaGen rotor assembly before installation (from Wikipedia.org)

SeaGen still uses only two blades instead of three, as it is common for wind turbines. This is founded in the good experience from Seaflow (maintenance is easier) and it was found that for marine applications two blade - systems have a better cost efficiency.

The blades of the rotors can be still pitched, as this was possible already at Seaflow. It is also possible to bring the blades into some sort of *"neutral"* position, which stops the rotor from moving quite fast. This is an important feature for fault handling.

Corrosion of the structure is prevented by passive and active cathodic protection and by some sort of epoxy encapsulation [27, 61].

The SeaGen demonstrater is expected to be in operation for the next five years. The next step is the erection of SeaGen arrays (as shown in Figure 3.38). Such an array could consist of 10 Units, which would lead to a total farm rating of about 10 MW.

Figure 3.38: Impression of a SeaGen-Arrangement (Source: MCT)

3.4.2 Open-Center Turbine

Florida Hydro (now OpenHydro Group Ltd[16]) started to develop this turbine back in 1996. This turbine is quite unique in many respects, the most interesting feature is the fully flooded generator. But the whole assembly is still in its prototyping and testing phase - currently a device is being tested near the Orkney Islands (in Scotland, see Figure 3.39).

The design of the Open-Center turbine is simple but effective. Permanent magnets are used as a stator. The only moving part of the whole construction is the rotating disc in the centre of the construction. No gearbox or even sealing is needed. Unfortunately it was not possible to get any detailed technical information but what is understood so far is that the generator is encapsulated in epoxy. This is quite an interesting fact, because the conducted thermal tests (see Section 4.8.3) showed, that if no precautions are taken, the encaspulation will crack if the winding temperature rises during operation.

The Open-Center turbine is about 15 meters in diameter and is rated at about 1,52 MW. A two-pile structure is used for mounting the turbine. The structure also allows to raise the whole turbine above sea level so that maintenance work can be carried out.

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[16] www.openhydro.com

Figure 3.39: Open-Center Turbine before installation (left), mounted prototype Installation at Orkney, Scotland (right, both pictures from OpenHydro)

There is currently a grid-connected prototype under testing at the European Marine Energy Center (EMEC) in Orkney, Scotland (see Figure 3.39) which was installed in 2006. In January 2007 Nova Scotia Power signed an agreement with Open Hydro to install a demonstration device in the Bay of Fundy [66].

3.4.3 Stingray

Stingray is a hydrofoil tidal energy converter which was invented in 1997 by Engineering Business Ltd. The first prototype was installed in 2002 and the next demonstrator (rated at 150 kW) in the Yell Sound in Shetland, Scotland in 2003.

Stingray is a fully submerged device which is placed at the seabed. A hydrofoil is connected via a power arm to a hydraulic cylinder (Figure 3.40). This foil is intended to be set in some sort of oscillating movement caused by the tidal current.
A clever mechanism is responsible that the hydroplane is aligned with the tidal flow. Therefore it is possible to generate electricity regardless of the tide or the tidal direction respectively. Constant power output of the first prototype was between 45 and 90 kW in tidal currents between 1,5 to 1,9 m/s.
Electrical energy is expected to cost around 9 €cent, when about 100 MW of Stingray capacity is installed. Although a 5 MW version was planed for 2004, Engineering Business announced recently that the project was suspended (financial reasons) [12, 20].

Figure 3.40: Stingray prototype (Source: http://www.engb.com)

Chapter 4

Sea Water-Immersed Machine Windings

4.1 Introduction

The idea of flooding the air gap in an electrical machine is not so new as one may think. Already in the 1970's a machine was designed to operate fully flooded and at depths down to some 900 metres, where a pressure of about 13.200 PSI (about 910 bar) prevails. Although the motor was very small (rated power of only 7,5 HP/$\approx$ 5,6 kW), sea water was used for the lubrication of the bearings and as coolant medium [23].

The paper [23] also names the three main important issues that occur with flooding:

- Protection of the windings (electrical circuit) from sea water
- Protection of the magnetic circuit from sea water
- Lubrication of the bearings

Two layers of silicone rubber tape[17] were used for coil insulation. The tape has been heat cured (under pressure).

The work described in that paper sounded promising, nevertheless - as far as it could be found out - this motor has never been subject to a full pressure test. While the author made some contributions to material research for submerged applications [24] no additional results concerning the electrical machine have been published.

There has been further research in the field: Most of them are dealing with a fully flooded air gap - but the liquid was in most cases an insulating one. This was also proposed in [23, 24]: Filling the air gap with an insulating liquid can solve some construction and electrical issues [18].

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[17] 0,6 mm thick

There is even an IEEE - Standard[18] [40] which describes the testing of (more or less) fully flooded machines, but it doesn't make any specifications about the liquid.

It looks as though operating a generator fully flooded with sea water is an approach not covered by literature yet.

4.2 Sea water

4.2.1 Consistence

Sea water consists, besides of oxygen and hydrogen, for the most part of chlorine, sodium, magnesium, sulphur, calcium and potassium (see Figure 4.1). The proportions between the materials are quite constant whereas the total values differ from region to region. The totality of dissolved solids in sea water, often referred to as salinity, varies from 0 ‰ to 39 ‰ [53].

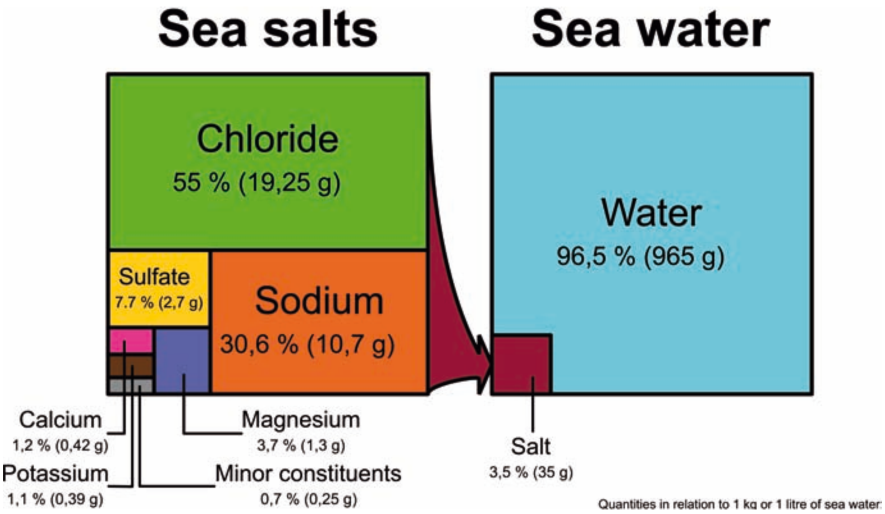

Figure 4.1: (Source: Hannes Grobe, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany)

This values are only valid for regions far from the coast. In the vicinity of the shore the salinity is fluctuating heavily. Nevertheless, the salinity is quite likely to be around 35 g/kg sea water, whereas the pH-Level is typically between 7,7 and 8,2 (thus slightly alkaline) [1, 46].

In lack of so-called synthetic sea water (as described in ASTM Standard Specification D1141-90 or DIN 50 905-4 for example) sea water from the coast near Edinburgh was used for all of the following tests. This is acceptable - also relevant technical literature (for example [46]) suggest to use "original" sea water for tests, although result comparison is difficult or impossible then.

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[18] IEEE Std 252-1995: IEEE Standard Test Procedure for Polyphase Induction Motors Having Liquid in the Magnetic Gap

Due to the lack of proper instruments it was not possible to do further analysis of the local sea water. Solely the conductivity could be measured.
The good news is, that the latest method of measuring the salinity (Practical Salinity Scale - PSS [25]) is based on the determination of the conductivity. The conductivity is then compared to a reference liquid (potassium chloride) to calculate a constant (R_T or K_{15}) which is necessary for calculating the salinity. If the proportion between the two liquids is equal to one, the salinity is 35 ‰ per definition.

The properties of sea water are mostly functions of temperature, salinity and pressure. Generally, the density of sea water for example, is inversely proportional to temperature and direct proportional to pressure.

4.2.2 Conductivity

The ability of a substance to conduct electrical current is termed as conductivity. Generally, there is a differentiation between three grades of conductivity - these are:

- **Conductors:** High conductivity, particularly all metals are within this category
- **Insulators:** They do not have the ability to conduct a distinctly electrical current
- **Semiconductor:** Their conductivity is between conductors and insulators. They are often named as Quasi-conductors as their conductivity varies with environmental conditions (temperature), frequency of the current and the composition (doping) of the material itself

Conductivity is, mathematically expressed via [45]

$$\vec{j} = \sigma \cdot \vec{E} \quad \text{or more applicatory} \quad \sigma = \frac{1}{\rho} \tag{4.1}$$

j ... Current density (in A/m^2), σ ... Conductivity (in 1/Ωm or S/m), E ... Electric field strength (in V/m), ρ ... Specific electrical resistance (or electrical resistivity, in Ωm)

According to the above classification, the conductivity of a conductor is $\sigma >\approx 10^6\,$S/m, of non-conductors lower than $10^{-8}\,$S/m and semiconductors are in-between these the two regions. Sea water is, by several orders of magnitude, a better conductor than "normal" tap water. The electrical conductivity of sea water is around $\sigma \approx 3$ to $5\,$S/m whereas for fresh water this can go down to $\sigma \approx 5 \cdot 10^{-6}\,$S/m. Conductivity is strongly dependent on salt (chloride) content and temperature [46].
Fresh water is often considered as a dielectric whereas sea water is seen as a conductor or at least as a quasi-conductor.

Conductivity is also frequency dependant as indicated in Figure 4.2 and also temperature and pressure dependent (conductivity rises with pressure).

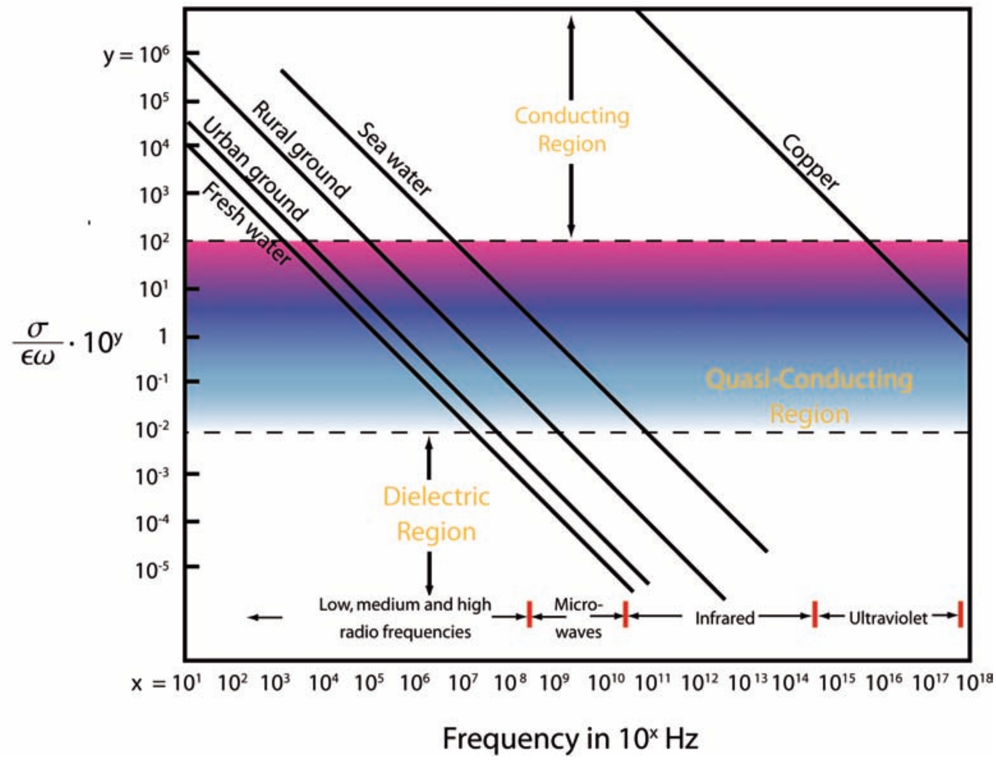

Figure 4.2: Ratio $\frac{\sigma}{\omega\epsilon}$ as a function of frequency (Redraw from [45])

σ . . . conductivity of the medium in $\frac{1}{\Omega m}$
ϵ . . . permittivity of medium in $\frac{1}{m}$
ω . . . radian frequency with $\omega = 2 \cdot \pi \cdot f$, where f is the frequency in Hz

Figure 4.2 shows the influence of frequency onto the relationship between the conductivity σ and the relative dielectric constant ϵ and ϵ_r respectively.
The summarisation of σ, ϵ and ω is advantageous, because now three conditions can be made [45]:

1. $\omega \cdot \epsilon \gg \sigma$
2. $\omega \cdot \epsilon \approx \sigma$
3. $\omega \cdot \epsilon \ll \sigma$

This classification is more or less a definition of a dielectric (condition 1), a semiconductor (imperfect dielectric, condition 2) and of a conductor (condition 3).

1: The electrical conductivity in a dielectric is ideally $\sigma = 0$. Therefore the displacement current is much greater than the conduction current → loss-less dielectric

2: A semiconductor is not so easy to classify as its conductivity is dependent on several factors. By definition, such a quasi-conductor is between a dielectric and conductor.

3: The conduction current is much greater by an order of magnitude than the displacement current (which is desired anyway) → conductor

The dielectric constant ϵ_r is the same for sea water and fresh water (ϵ_r of around 80) and much higher then the typical values of common materials in electrical engineering (for example Silicone Oil $\epsilon_r \approx 2,7$, Mica $\epsilon_r \approx 7$, Polyethylene $\epsilon_r \approx 2,4$, Porcelain $\epsilon_r \approx 2 \text{ to } 6$, etc.) [45, 47].

In consideration of the frequency dependance of the conductivity, the classification between conductors, insulators and semiconductors can be made as following [45]:

Dielectrics: $\frac{\sigma}{\omega\epsilon} < \frac{1}{100}$

Quasi-conductors: $\frac{1}{100} < \frac{\sigma}{\omega\epsilon} < \frac{1}{100}$

Conductors: $100 < \frac{\sigma}{\omega\epsilon}$

Table 4.1: Range of values for $\frac{\sigma}{\omega\epsilon}$

Medium	Relative permittivity ϵ_r dimensionless	Conductivity σ $\frac{S}{m}$
Copper	1	$5 \cdot 10^7$
Sea water	80	4
Rural Ground (in Ohio)	14	10^{-2}
Urban Ground	3	10^{-4}
Fresh water	80	10^{-3}

Table 4.2: Permittivity and conductivity of some selected materials (Source: [45])

The conductivity of the utilised sea water was measured straightly with an according, direct indicating, conductivity meter. It was found out that the conductivity was around 4 S/m on average at laboratory conditions (23° C).

4.3 Machine Windings

Basically one has to distinguish between stator windings and rotor windings. With the exception of some machines which have (permanent) magnets instead of stator windings, such a stator winding consists of three main parts [78]:

- **(Copper) Conductors**
- **Stator Core**
- **Insulation**

Rotor windings can be subdivided into [5, 78]:

- Insulated rotor windings
- Squirrel cage induction motor rotor windings

The latter are (commonly) used in AC induction motors whereas rotors with (dedicated) insulated windings can be used in nearly every type of electrical machine. It is also the type of winding that is being covered within this work. Such a dedicated winding system mostly consists of 5 parts [5]:

- Electrical conductor
- Coils
- Phases / Strands
- Turns
- Coil groups

By putting a conductive liquid in the air gap will make an additional layer between the stator and the air gap necessary.
(Stator) Winding constructions [78]:

- Random-wound
- Form-wound (Multi-Turn coils) and
- Form-wound (Roebel bars)

Random-Wound

This is a very common method of winding construction, because of the easy and cheap manufacturing process. Magnet wire is , either by hand or by a winding machine), just laid "randomly" into the slot. All prototype coils have been manufactured that way.
Disadvantage of this method is apparent: Practically a turn with low voltage/potential (e.g. the one directly connected to the neutral point) can easily adjoin a winding with high voltage/potential (e.g. the one connected to the phase terminal). Therefore each turn needs an insulation, that is able to withstand the full voltage. As this method is not applicable for higher voltages, such machines are limited to voltages in the region below 1.000 V and to power ratings below several hundred kW.

Form-Wound - Coil Type

Form-wound windings are typical for machines with an operating voltage of 1 kV and above (see Figure 4.3). The coils are pre-formed outside the stator. Despite the higher operational voltage, the insulation between the single turns is significantly thinner than this would be the case for random-wound windings. This is possible as the voltage difference between two turns is quite low (normally below 100 V). This method is the most common type for medium sized machines up to about 50 MW.

Form-Wound - Roebel bars

Roebel bars are the method of choice as they resolve two main problems that come with bigger power ratings: First it is difficult to insert large bars into the stator because they are quite stiff and the possibility of damaging the insulation is increasing. Here only the "halves" of the coils are inserted at one time and connected afterwards (winding overhang). Secondly, and most important, roebel bars effectively reduce effects like displacement currents (skin effects),...

4.4 Insulation Systems

4.4.1 Basics

A stator insulation system consists of 3 main components, which are [78]:

- Strand insulation
- Turn insulation
- Groundwall insulation

Strand insulation

Strand insulation is present both in form-wound stators and random-wound stators. For the latter, the strand insulation serves as turn insulation at the same time. As it was already stated above, in the worst case it is possible that the voltage difference between two turns is the full coil voltage. Therefore the strand insulation has to be dimensioned in such a way that it can easily withstand such stress. Therefore it is not possible to build large machines in random-wound style.

There are further reasons to insulate the strands in larger machines: The cross section of the conductors is distinctly large(r) (see Figure 4.3). Because of the skin effect, the current is not able to take advantage of large cross sections, as with a rise in frequency the depth of penetration is decreasing.

Skin effect can be estimated with ([48, 69]):

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \sigma}} \tag{4.2}$$

δ is the so called skin depth (in m), ω the frequency of the current (s^{-1}), the magnetic permeability is combined in μ ($\mu = \mu_0 \cdot \mu_r$, in N/A^2) and σ describes the resistivity of the conductor (in S/m). For copper ($\mu_r \approx 1$, $\sigma \approx 58 \cdot 10^6$ S/m) and a frequency of f=50 Hz, the skin depth is approximately

$$\delta = \sqrt{\frac{2}{2 \cdot \pi \cdot 50 \cdot 4 \cdot \pi \cdot 10^{-7} \cdot 1 \cdot 50 \cdot 10^6}} \approx 9,3\,\mathrm{mm}$$

The skin depth decreases with frequency: At a frequency of f=1 kHz, the skin depth is only about 2 mm, for f=5 kHz the skin depth has already fallen below 1 mm! For this reason, the conductors are divided into sections which are insulated against each other → strand insulation.

Turn insulation

The voltage between two turns is exactly defined for form-wound stators (because of the specified offset between the turns) and is in the region of some 10 V to 250 V. The turn insulation is heavily stressed during machine start and in case of (fast switching) power electronics. Failures in the turn insulation should be avoided in any case as such failures will lead to a significantly higher current through that turn and furthermore to (thermal) deterioration.

Groundwall insulation

The groundwall insulation has the important task to insulate the conductors (which are at high potential) from the stator (which has ground potential). This insulation is stressed heavily in service because it has to cope with high electrical, thermal and mechanical stress.

Flooding the air gap will mainly influence the groundwall insulation.
Figure 4.3 shows the insulation system of a typical stator. The picture on the right shows the proposed insulation technique with an additional insulation layer (coloured in green in the figure for illustration purposes):

Either the slot wedge is sealed (Figure 4.3 a.) or an additional layer of insulation material covers all parts (Figure 4.3 b.). The latter is more likely to be carried out, especially in regards to corrosion protection.

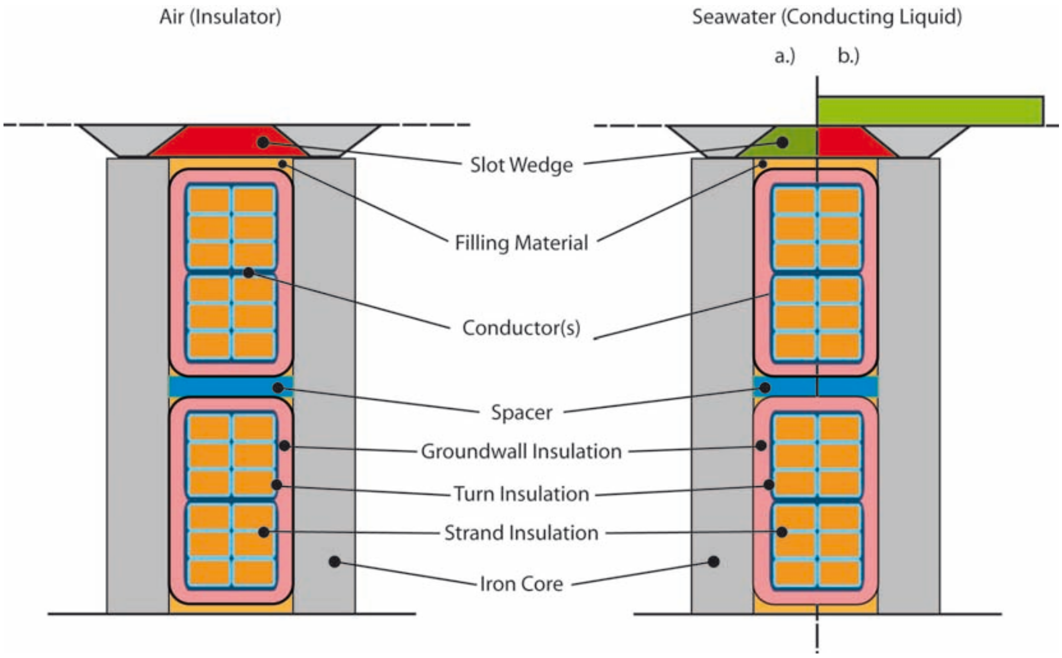

Figure 4.3: Standard machine insulation (left) and proposed insulation systems (a and b, on the right)

4.4.2 Stress and Aging

Insulation systems and whole electrical machines can be stressed in various ways. First it is important to differ between stresses which are present during each run → *constant stress* and stresses which occur only intermittent or once → - *transient stress*.
This is important because for a constant stress the aging and the time to failure respectively is in most cases proportional to the machine hours of operation. On the other hand, for a transient stress, the time to failure is commensurate with the number of transient incidents (and certainly their magnitude) [78].

Stress can be divided into 4 main groups:

- **T**hermal:
  poor heat dissipation, degradation of insulating materials,..
- **E**lectrical:
  partial discharges, inverter-fed-drives,..
- **A**mbient:
  moisture, oil, particles, radiation, aggressive environmental conditions ...
- **M**echanical:
  short-circuit forces, magnetic forces, centrifugal forces, transient forces,..

Allocated to an ocean power device, most of the stress will be caused by:

- Poor cooling conditions (Thermal)
- Current loading because of stray capacities and fast switches (Electrical)
- Sea water and a rough environment in general (Ambient)
- High forces (weight, water pressure, etc. - Mechanical)

4.5 Insulation Materials

4.5.1 Basics

Studies about ocean energy devices display high costs for the produced electricity. A distinct part of these costs is eventually caused by expensive or short-lived materials [37].

Main materials phenomena which may occur at ocean energy devices (from [37]):

- Corrosion
- Corrosion fatigue
- Wear and fretting fatigue
- Loading and fracture
- Fatigue
- Stray current corrosion
- Marine fouling

4.5.2 Corrosion Considerations

Basics

Corrosion is defined as the destruction or deterioration of a material (or its properties) because of reaction with its environment [26, 84]. It occurs to metals as well as to concrete, ceramic and synthetic materials.
The most commonly known corrosion process is the formation of rust on iron surfaces. This is an electrochemical process, as most of the corrosion processes are [84]. Generally, this happens because atoms of iron (or any other material which is affected by corrosion) are reacting with its surrounding (here: the oxidation of iron or steel with oxygen at the presence of water).
The maritime environment can be considered as very unfriendly for any kind of (technical) material. Therefore it is absolutely necessary that basic corrosion considerations are done here.

This section describes the phenomena of corrosion only briefly because its impossible to make qualified conclusions without further research. Covering the corrosion aspects of a WEC can be a separate research task [37]. So it would not make much sense to go too much into

the details here, as this would go far beyond the scope of this work. There are several complicated mechanisms which are effecting corrosion and corrosion rates: oxygen and carbon dioxide content, temperature, flow rates; just to name a few.
Furthermore it will be also necessary to conduct corrosion and erosion tests on scaled models or at least on similar machines. Testing just isolated samples would not yield to the scientific results envisaged [46].

Table 4.3 shows the basic factors that are influencing the corrosion in connection with sea water. Theses factors do influence each other, for example: the amount of solute gases (like oxygen, which has a strong influence on corrosion) are connected to temperature. Temperature itself has an influence on corrosion. Generally speaking, all chemical processes are accelerated with a rise in temperature. This is, for the majority of cases, also true in terms of corrosion.

Chemical factors	**Physical factors**	**Biological factors**
Solute salts	Temperature	Fouling
Solute gases • Oxygen • CO_2	Movement • wave movement • wave/tidal current	Animals • oxygen consumption • CO_2 production • sulfate reduction
pH-Level	Pressure	Plants • oxygen production • CO_2 consumption

Table 4.3: Main sea water corrosion parameters (from [46])

Fouling is the processes of the growth of mussels, bacteria, algae, etc. and the deposition of other bio-material on surfaces. Fouling is also linked to water temperature (fouling occurs above a certain water temperature where there is virtually none when the temperature is below this temperature). Effects on corrosion caused by fouling are poorly researched until now. This is also supported by the fact that fouling can either accelerate or hinder corrosion [37, 46].

Table 4.4 shows the effects that fouling can cause on marine equipment - corrosion is just one issue besides several other consequences.
Fouling is a well known and unloved process that also occurs at (the bottom of) ships. Various anti-fouling paints are available nowadays to combat fouling. These paints contain substances which are toxic for the bio-material normally involved in the process. The big disadvantage of such coatings is their short lifetime (maximum of two years). This is most likely not acceptable in concerns of maintenance of a WEC.

- Increased weight of structure
- Increased surface roughness
- Blockage of pipes, conduits, valves and gates
- Changes in corrosion fatigue life
- Reduction in heat transfer efficiency of condensers
- Masking of surfaces obviating routine inspection and maintenance
- Increased volume of structure
- Increased drag coefficient
- Changes in corrosion rate and mechanisms
- Changes in brittle fracture probability
- Tribology effects on moving parts in contact (e.g. reduction in wear life of bearings)

Table 4.4: Effects of fouling (from [37])

Corrosion Protection

According to [84], corrosion protection methods are divided - according to their field of application - into the following 4 groups:

- Substitution / Change of metals
- Modification of the corrosive medium
- Change of electrode potential / corrosive medium
- Separation of metal and corrosive medium through surface coating

Substitution of metals or of a material is mostly not possible as corrosion protection is just one demand of them as they have also to fulfil other requirements like mechanical strength, costs and so on. The modification of the corrosive medium is likewise not possible nor practicable in this case.
Therefore the only two feasible methods are the changing of the electrode potential and/or the attaching of surface coatings.

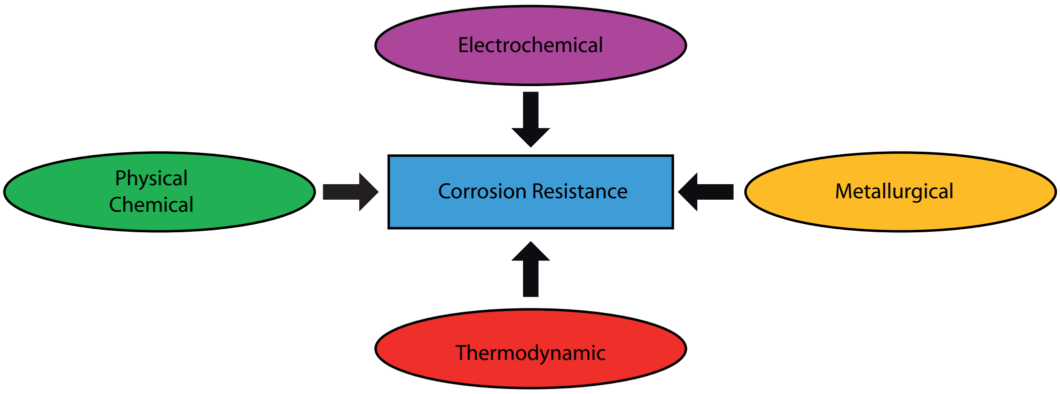

Figure 4.4: Corrosion resistance of materials (metals) (from [26])

Figure 4.4 shows the four main factors which are influencing the corrosion resistance of materials. The above mentioned points are either of physical/chemical nature (passive corrosion protection through coatings or encapsulations by using ceramics, synthetic materials, ..) or of electrochemical nature (active corrosion protection).

Passive Corrosion Protection

Although there are indices that coatings and encapsulations are not suitable for effective and long-term corrosion protection of immersed offshore structures [46], the testing of such methods is strongly recommended. This is especially important because these coatings fulfil the electrical (insulation) demands.

Active Corrosion Protection

Mainly two systems can be used for active corrosion protection: Either a cathodic corrosion protection (CCP) or current protection schemes. The latter is used for the protection of the turbines in the La Rance tidal power plant for example.

4.5.3 Tested Materials / Coils

All the coils used for testing are random-wound because they are easier to manufacture. Windings for Ocean Power Devices are most likely to be form-wound, as this brings some important advantages (see Section 4.3).

Standard magnet wire (enamel coated, AWG 16[19]) was used for the basic tests[20]. Such a wire is rated for a maximum current of 22 Amps (3,7 Amps for constant power transmission). The maximum freqency for 100% skin depth is 11 kHz.

For better comparability all the coils have been assembled by using the same, oval shaped template and they all have 20 turns.

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[19] Diameter: 1,29 mm

[20] Certainly this was not the case for the coils made of stranded wire

The following coil assemblies were used during the miscellaneous tests:

- Magnet Wire
- Stranded Wire
- Resin (Polyester)
- Other Materials
- Insulation Tape
- Paper-Varnish
- Silicone Compound

A variety of built coils is shown in Figure 4.5.3:

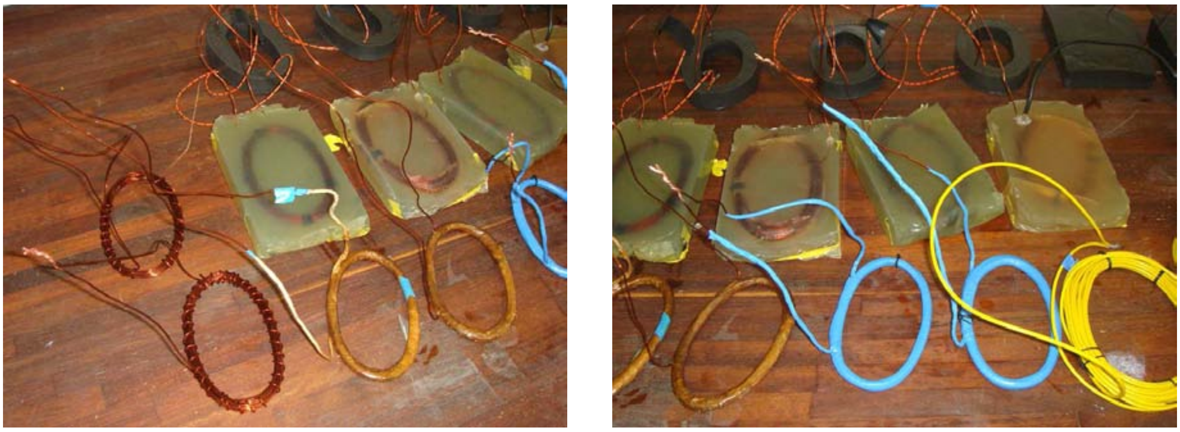

Figure 4.5: Selection of coils

4.5.4 Standard (Enamel Coated) Magnet Wire

The first approach for coil manufacturing was the usage of customary copper magnet wire. This is the most common material in the industry for this application, as it has sufficient electrical properties, competitive price and is easily available. No separate insulation was applied to the wire or to the completed coil, as the wire is coated with a protective enamel layer by default. This layer is sufficient for all - or at least most - standard applications.

Magnet wire was taken directly from the roll and partially submerged into a container filled with sea water. It was not even possible to conduct any (high-) voltage or other tests. This was because on one location or another (some) varnish was scraped off. The lack of varnish makes a conductible connection between the sea water (which can bee seen as ground potential) and the energised length of wire (high potential). Therefore it was not possible to conduct further tests as already the very basic tests failed.

Figure 4.6: Coils made of coated magnet wire

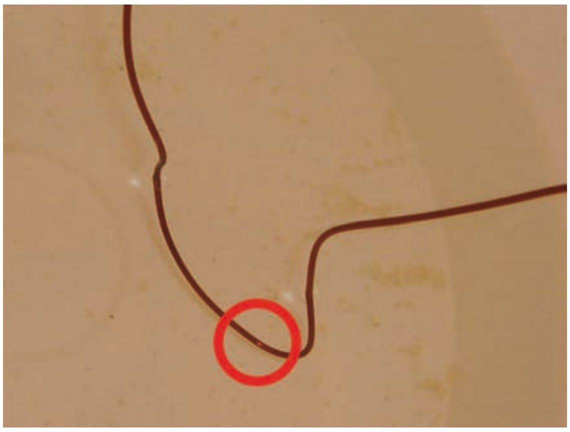

Figure 4.7: Magnet wire with insulation breakdown (marked with read circle)

Even if the same wires have a good behaviour when the same tests are run in air, they all fail miserably when running tests with the wires submerged in sea water. There are several test procedures to identify such material defects [5]. The problem here is that such tests and their results respectively can not be allocated to an ability for sea water submersion. Depending on the diameter of the magnet wire, a specific number of surface defects are allowed. This is possible because normally such defects do not cause a complete insulation failure at coils which are operated in a standard environment. But as mentioned before, a wire which would be appropriate for sea water immersion must not have a single (!) imperfection.
So it was quite early clear that some sort of encapsulation would be needed to address this problem.

4.5.5 Insulation Tape

Standard PVC tape was the second thought then. Although such tapes are definitely low-voltage insulation methods, they could overcome the issues with the varnish imperfections. As such tapes are quite common throughout the industry, wrapping the coils with tape seemed to be a solution.

According to [5], tapes that are used for insulation purposes have to fulfil the following requirements:

- No disposal of aggressive mediums or gases during operation (especially not at service temperature)
- No alteration of corrosion behaviour of the generator and its surrounding attachment parts
- The used tape must not lead to an additional absorption of water - for the intended use the tape must prevent the ingress of any moisture
- Temperature durability needs to be guaranteed

Figure 4.8: Two of the manufactured, tape wrapped coils

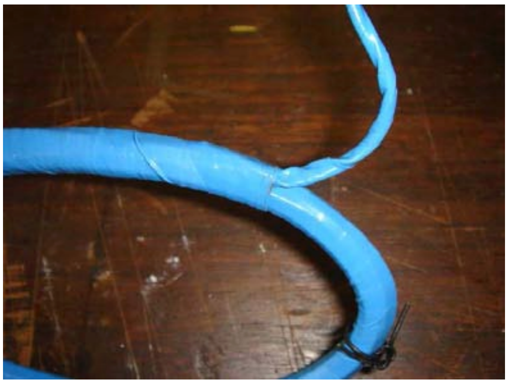

Figure 4.9: The connection-wire egression needs special caring

Figure 4.8 and 4.9 show some of the tape-wrapped coils. The black strip (made of synthetic material) was used during assembly to keep the coils in shape and the tape in place.

But it was not possible to encapsulate a whole coil sufficiently to ensure that no moisture/water comes into contact with the magnet wire. It was only a matter of time until the sea water made its way trough the tape or the adhesive area which leads to an eventual insulation system breakdown.

4.5.6 Stranded Wire

As it turned out that sealing-off any ingress of moisture or sea water must be prevented, stranded wire (AWG 16) seemed to be a way to go. This wire type is insulated with a layer of polyvinyl chloride (PVC). As PVC is much more robust and flexible than the varnish, this solved the troubles with the scraped-off insulation that occurred with magnet wire.
But because of the thick(er) insulation these coils got much bigger than the two other types tested before. This can be an issue later on for (prototype) machine design and manufacturing. Besides that, the PVC insulation is fine in reference to the electrical tasks. No moisture or water penetrated the protective plastic. The thermal behaviour of PVC is also satisfactory as it has a glass temperature of 87° C. The melting point is at 212° C.
Unfortunately the switching tests showed some shortcomings. On this account further materials have been tested.

4.5.7 Paper-wrap and Varnish

Because of the lessons learned from the stranded wire coils it was tried to improve the encapsulation of the wire. Wrapping the coils in insulation paper and dipping them afterwards in varnish (urethan base). Doing so solved the moisture problem indeed but then the varnish is some sort of limiting factor. This is because the used varnish has a withstand voltage of only 1 kV which is problematical for conducting any HiPot-Tests.

Figure 4.10: Coils made from stranded wire

Figure 4.11: Paper-wrapped coils

4.5.8 Resin Encapsulation

The next step that was taken was the encapsulation of whole coils into suitable materials. Polyester was the first thought, as it is widely used in the marine industry (to produce hulls for ships for example). This is reasonable as Polyester has a perfect resistance against water ingress. Furthermore, such polyester resins are cheap, they can be easily obtained and they can be cured at room temperature.

A polyester resin that contained the monomer styrene (one of the most common polyesters) was used for this first encapsulation tests. The styrene (whose volumetric content can go up to 50 %) is enabling the polyester resin to cure at low temperature. In addition, the styrene makes the whole liquid easier to handle.

Without adding a second component, the polyester doesn't have any of the required characteristics, it will not become solid nor is the polyester cross-linked with the styrene. The component

that enables the resin to do so, is called *catalyst* and it is responsible for starting the polymerisation. In this case, Methyl Ethyl Ketone Peroxide (MEKP) was used - mixed in a ratio of roughly 10 : 1 (resin to catalyst).
Four coils were put in moulds made of plastic and covered with this polyester resin. Afterwards they have been left for curing at room temperature (22° C) for about 48 hours. This turned the liquid resin into solid and half-transparent blocks with the desired properties, most of all the water resistance (or water repellence). The service temperature of this polyester is about 90° C (compare: IEC 60085[21] - Heat resistance class Y) [5, 79].

Polyester is quite common also for insulation tasks in the industry and moreover it has good corrosion resistance [46]. Besides the corrosion resistance, polyester scored well in all the other tests, except the thermal endurance test. Because of the high current and the big encapsulation blocks, the temperature has risen ways above the allowed 90° C. Therefore it was not a big surprise that this eventually led to the destruction of the encapsulation. That can be explained easily, as the coil and the copper respectively just had no space for expansion. When the coils were heated up during the current loading, they expanded and therefore cracked the resin encapsulation blocks (Figure 4.13).

Figure 4.12: Polyester encapsulated coil

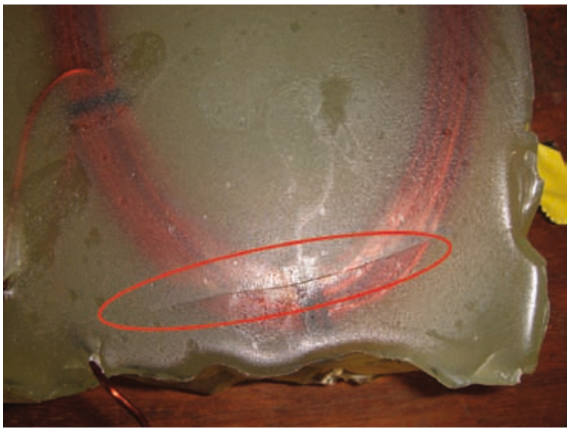

Figure 4.13: Crack caused by thermal stress

4.5.9 Silicone Compound Encapsulation

To overcome the temperature troubles that have been encountered with the polyester encapsulated coils, encapsulation in a (better) thermal conductive and (more) flexible material has been tried out. Silicones seemed a good try as they have several favourable attributes, for example nearly constant material properties over a wide temperature range. Furthermore these resins have good resistance against most acids, bases and other chemicals. They are also completely water-repellent [22].
The selected silicone was a 2 compound silicone elastomer from ACC Silicones (QSil553). This

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[21] IEC 60085, Third Edition: Electrical insulation - Thermal classification

was mainly for three reasons: Firstly it could be obtained easily (and it is - relatively - cheap), secondly this silicone is thermal conductive and thirdly, it stays flexible after curing.
The QSil553 is by far not the best silicone available on the market but it proved well during the first tests. One drawback is the high cost of the material: A kilogram costs about £40 (around €58)

Figure 4.14: Silicone encapsulated coils

At the beginning, the coils were encapsulated the same way as the polyester ones. This is not really desirable as it needs a lot of unnecessary (and expensive) material (Figure 4.14) and secondly this does not represent the real use case. The interior of the coil is not going to be filled with air or encapsulation material but with poles and iron respectively.
Therefore the next coils got an "improved" encapsulation, more precisely a shaped one (Figure 4.15). After the first results of the thermal tests, this opportunity was used to install temperature sensors right next to the coil to get a feeling about the difference between the calculated winding temperature and the "real" one.
The unclean surfaces in Figure 4.15 are easily explained: The coils just came out of the moulds and thus were not cleaned yet.

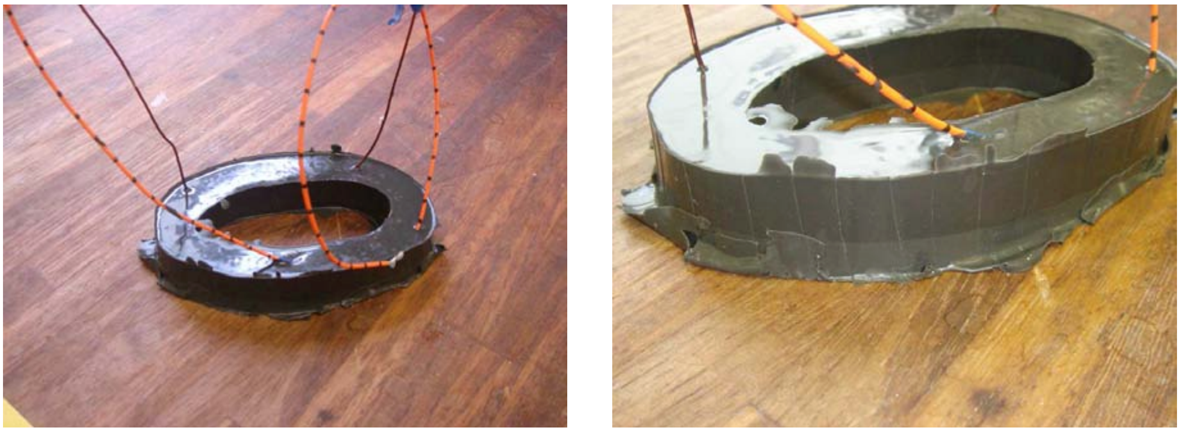

Figure 4.15: Silicone encapsulated coils with temperature sensor

4.6 Inductance Analysis

4.6.1 Basics

Having a look on the inductance and its potentially change is important, as the inductance is one of the most important parameters of electrical machines [80] - Basically, the torque in an electrical machine is proportional to the inductance, as a very elementary equation 4.3 shows [64]:

$$T = \frac{i_1^2}{2} \cdot \frac{dL_{11}}{d\alpha} + i_1 \cdot i_2 \frac{dL_{12}}{d\alpha} + \frac{i_2^2}{2} \cdot \frac{dL_{22}}{d\alpha} \tag{4.3}$$

T ... Torque (rotor)
L_{11} ... self inductance (stator)
L_{12} ... mutual inductance (between stator and rotor coil)
L_{22} ... self inductance (rotor)
i_1 and i_2 represent the current which flows through the stator and rotor coil respectively. α is used for the angle between the axis of the stator and the axis of the rotor.

4.6.2 Analysis

The magnetic permeability defines the inductance of a winding significantly. As sea water and air have similar permeability, the influence of immersion on the inductance is low. Nevertheless, all coils have been subject to inductance measurements, both in air and seawater.

Figure 4.16 shows the results of this test. For a better comparability the inductance values are normalised . The 50 Hz inductance was taken as 100 % or 1 p.u. It is interesting to see that all of the selected coils are staying between a tolerance band of about ± 8 %.

Detailed inductance results with diagrams for each coil can be found in Appendix A.

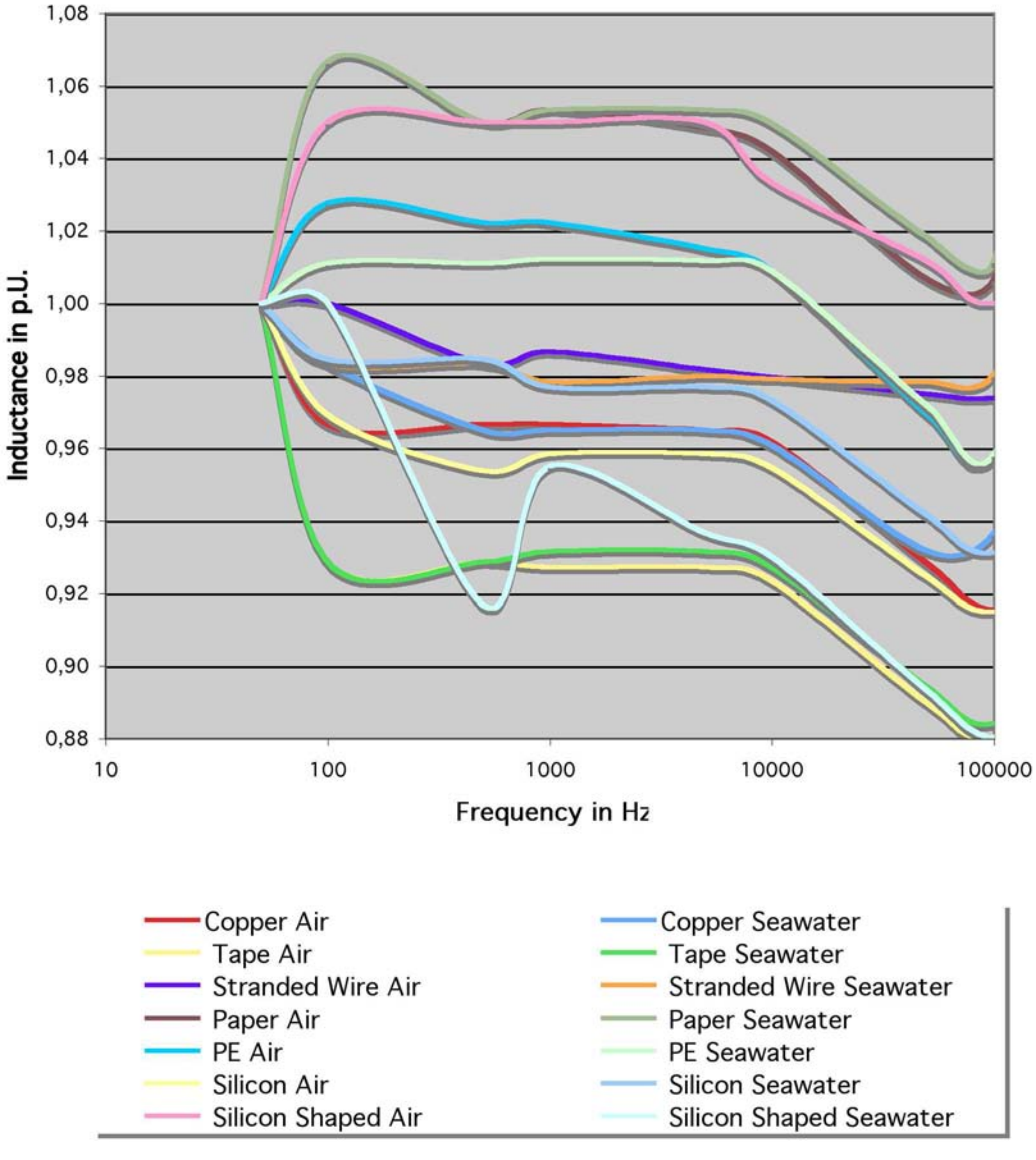

Figure 4.16: Comparison of the inductance of all coils

4.7 Capacitance Analysis

4.7.1 Basics

Under normal circumstances with a standard air gap, the majority of the electric field is in the air gap (because of $\epsilon_r \approx 1$). This results in a (relative) low electric field strength in the insulation. The capacitance of windings is in that case small, because of the low dielectric constant of air and the (relative) large distance between the conductor and earth (ground potential).

Equation 4.4 describes the capacitance of a simple, two plate arrangement [45]:

$$C = \frac{Q}{V} = \frac{\epsilon \cdot E \cdot A}{E \cdot d} = \frac{\epsilon \cdot A}{d} \tag{4.4}$$

C … Capacitance (in $\frac{As}{V} = F$)
V … Difference of potential (in V)
ϵ … Dielectric Constant (ϵ_0 in F/m)
d … Gap between electrodes (in m)
Q … Charge (in As)
E … Electric field strength (in V/m)
A … Cross section of one plate (in m^2)

These relations are going to change, when the air is exchanged against a (more) conducting material. Flooding the machine with sea water brings a (virtual) ground plane directly into the air gap and hence to borders of the insulation. Therefore the capacitance of between the winding and earth *ground capacitance* and between two windings *inter-winding capacitance* is expected to rise, which could be verified by measurements. Such a rise is likely to have negative effects for the operational behaviour of a generator and this is also a reason for doing the switching tests (see Section 4.8.2).

4.7.2 Ground Capacitance

The capacitance of the windings to ground has been measured in air and in sea water - the differences are enormous:

In air, the capacitance is between some 60 pF (Stranded Wire) and some 20 pF (Magnet Wire), whereas in sea water the highest capacitance measured was 10 nF (!) for the magnet wire coils. This is equivalent to an increase of nearly 10.000 %! Graphs with the distribution of capacitance can be found in Appendix B.1.

4.7.3 Inter-winding Capacitance

Basically, three test assemblies have been tested:

- Coils next to each other (0 % overlap)
- Coils are overlapping each other at 50 %
- Coils are overlapping each other at 100 %

The main outcome of these tests was that there is no big difference between the assemblies however there was a significant difference between an assembly in sea water to the same one in air.

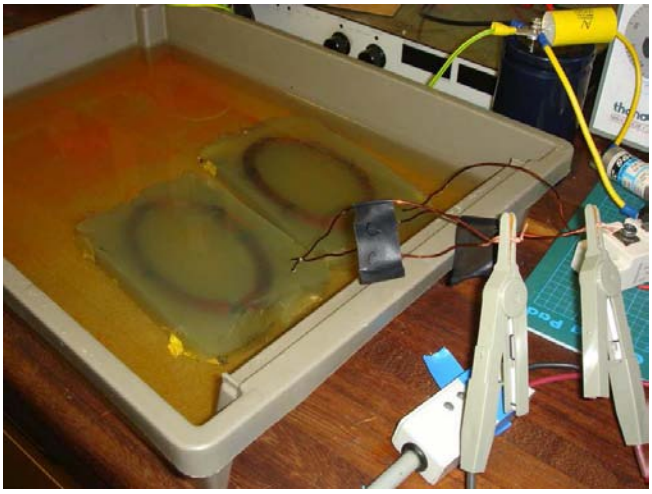

Figure 4.17: Measuring the Inter-winding capacitance between 2 resin-encapsulated coils

Detailed results of the capacitance analysis can be found in Appendix B.2.

4.7.4 Analysis

With a raised capacitance between the winding and earth or between the windings themselves, some negative effects arise. An increase of ground capacitance will inevitably lead to increased, capacitively-coupled currents (from the windings to earth/sea water). If the windings are controlled by fast switching, power semiconductors, these effects are getting worse, as because of the high rates of $\frac{du}{dt}$ and raised capacitances, the current through the (stray) capacitances will also rise significantly.

4.8 Conducted Tests

4.8.1 General

Several tests have been carried out to determine the behaviour of windings that are subject to an immersion in sea water.

These are:

- Switching Tests
- Thermal Tests
- HiPot Tests
- Efficiency Considerations

It has to be said that none of these tests was targeted to study durability or long term effects. This is especially true for corrosion protection. Either such tests are more of a chemical nature (material science) or they are run with WEC prototypes. Otherwise the significance is quite limited.

4.8.2 Switching Tests

The wave motion and hence the movement of the floating device of a wave energy converter is clearly disordered and chaotical. This is not desirable from the point of the electrical grid, as power quality is important and it needs to be maintained.Therefore it is necessary that several parameters (amplitude, RMS, frequency, etc.) are staying within a tight tolerance range. This could be also done with some fine-tuning of the mechanical system (changing damping and spring coefficients for example). But that would not substitute the "power conditioning" which is done with power semiconductors [51, 85]. Thus all coils have been subject to a basic switching test, which will be described now.

Test Description

IGBTs are commonly used for power conversion circuits for wave energy devices in different topologies [13]. Further insights into the topologies and the circuits are not necessary at the moment because firstly the basic switching behaviour and the comparison between air environment and sea water immersion of a coil needs to be researched.

Therefore a simple test system was built with a customary IGBT (SIEMENS BSM 50 GAL 120 DN2). The circuit diagram is shown in Figure 4.18. This IGBT is a prefabricated module with an included free-wheeling and a chopper diode. The IGBT's gate was controlled with a separate circuit which is equipped with a TTL-compatible control output. The switching itself was done with an external waveform generator in such a way that the pulse width of the

IGBT was about 2 μs in duration. A stabilised DC power supply unit was used - the charging voltage was varied between 50V, 100V and 250 V DC. For a sufficient fast and stable power supply during the switching process, two capacitors are connected in parallel to the power supply. One is a 3.300 μF, electrolytic capacitor and the second one a 1,5 μF, plastic film capacitor.

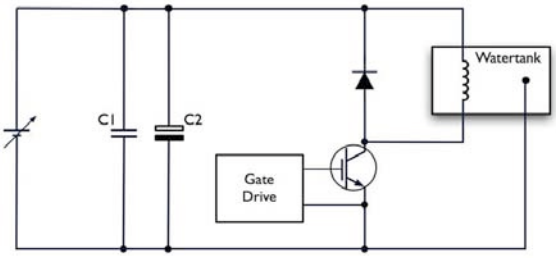

Figure 4.18: Test schematics

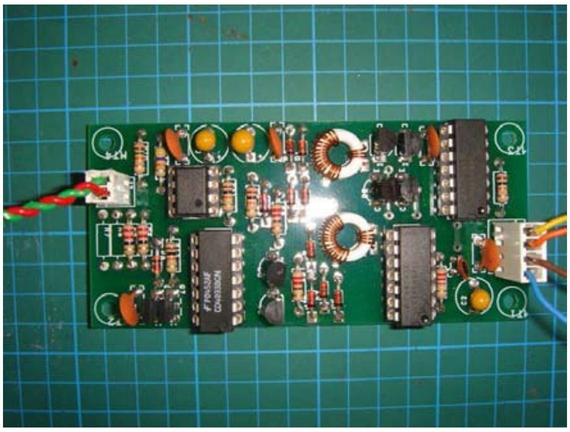

Figure 4.19: IGBT Gate Drive

Problems with sea water-immersed coils arise when they are switched with power semiconductors. The coil's capacitance, which was already determined in the previous tests, needs to be charged and discharged in every switching cycle. This leads to a displacement current through the sea water. The amplitude of this ground current differs for the different insulation materials (see Table 4.5, page 72).
Standard magent wire coils have been tested at reduced voltage (50 V and 100 V only) because they could not withstand the standard testing voltage of 250 V when immersed in sea water (even the smallest scratch in the enamel varnish leads to immediate dielectric breakdown).

The following devices where used for this test:

- **IGBT**: Siemens BSM 50 GAL 120 DN2
- **Gate Drive**: Customary control circuit
- **Waveform Generator**: Thandar TG503 function generator (Settings: Frequency 1,2 kHz, manually triggered, square-pulsed (pulse-width 2 μs), delay: 50ns x100, Output via 50 Ω TTL Out)
- **Oscilloscope**: Tektronix TDS 3032B 300 MHz, 2,5 GS/s
- **Current Probes**: Tektronix AM 503B Current Probe Amplifier

The main interest of this test was the estimation of the current trough the return path and the sea water respectively. Therefore, in Figure 4.22 and 4.23 the current (color: dark blue)

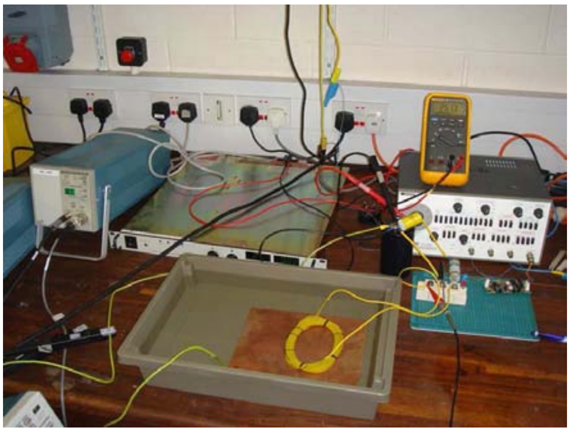

Figure 4.20: Tests setup

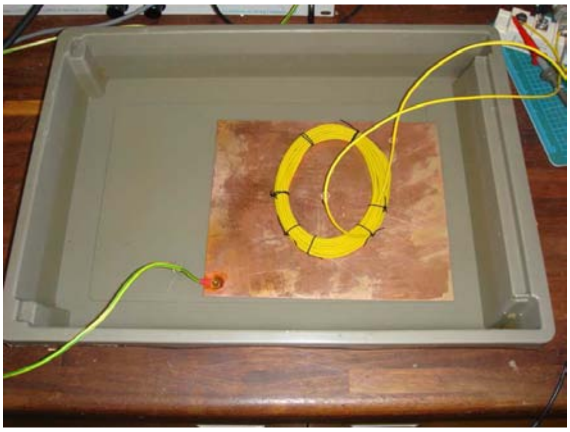

Figure 4.21: Testing a coil made of stranded wire

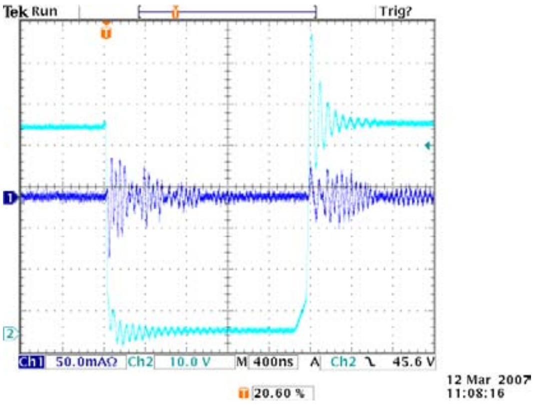

Figure 4.22: Coil at 50 V

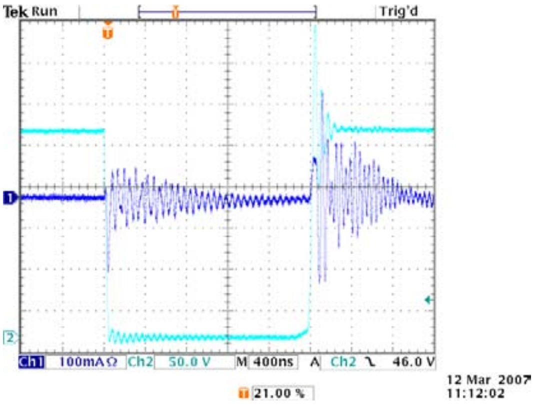

Figure 4.23: Coil at 250 V

has been measured synchronous with the Collector-Emitter-Voltage (color: cyan).

It could be shown, that the current, which flows during the switching process (gate turn-on and turn-off) rises with the charging voltages. 3 different charging voltages have been investigated: 50V, 100V and 250 V whereas the current is a maximum at 250 V obviously. The Figures 4.24 and 4.25 are showing this: The left picture shows the switching process at a silicon encapsulated coils (shaped) in air at 50 V and the right picture is the same coil at 250 V. Please note, that the current scale is different for both pictures (left: CH1: 50 mA/Div, CH2: 10 V/Div; right: CH1: 100 mA/Div, CH2: 50 V/Div).

Switching speed has also an influence on the current. To vary $\frac{di}{dt}$, 3 different gate resistances (R_G) have been researched: 22Ω (one resistor), 11Ω (two resistors in parallel) and 5, 5Ω (4 resistors in parallel). The slower the gate was switched (here: higher gate resistance), the lower was the current trough the earth conductor. Figures 4.24 and 4.25 are supporting this: The

		Air		Sea water immersed	
Type	Coil	on	off	on	off
Magnet Wire	#1	210 mA	100 mA	725 mA	425 mA
(tested at 100V!)	#2	320 mA	320 mA	450 mA	950 mA
Tape	#1	120 mA	140 mA	2.000 mA	3.400 mA
	#2	160 mA	200 mA	1.800 mA	3.200 mA
Stranded Wire	#1	200 mA	200 mA	6.000 mA	6.000 mA
	#2	250 mA	200 mA	6.000 mA	7.000 mA
Paper	#1	125 mA	125 mA	2.800 mA	5.400 mA
	#2	100 mA	100 mA	2.200 mA	4.400 mA
Polyester Resin	#A	80 mA	60 mA	1.200 mA	1.000 mA
	#C	160 mA	80 mA	1.000 mA	900 mA
Silicone	#1	240 mA	350 mA	500 mA	1400 mA
	#2	400 mA	480 mA	600 mA	2200 mA
Silicone (Shaped)	#1	400 mA	340 mA	700 mA	2.300 mA
	#2	650 mA	700 mA	1.000 mA	2.800 mA
	#3	240 mA	460 mA	1.000 mA	2.400 mA

Table 4.5: Maximum current measured during switching tests

switching characterisitcs with a gate resistance of 22 Ω is shown in the left picture, whereas with lowered resistance (5,7 Ω) the current rises (right picture).

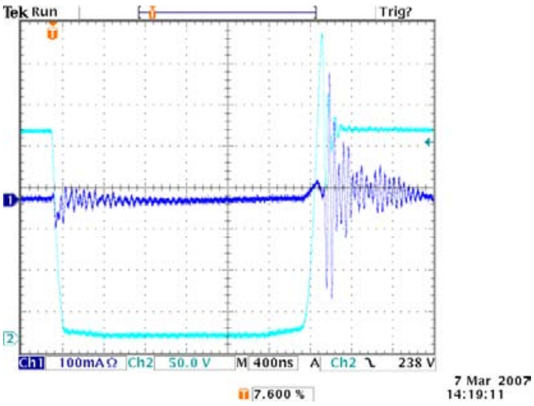

Figure 4.24: Gate Resistance 22 Ω

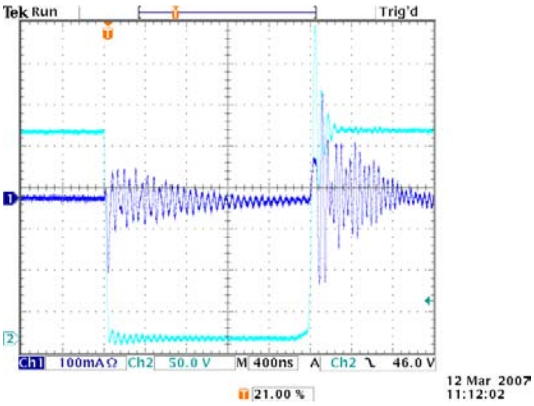

Figure 4.25: Gate Resistance 5,7 Ω

The maximum currents (peak-to-peak) for each insulation method is listed in Table 4.5. As expected, the coils with total encapsulation performed best (polyester resin, silicone compound). But there is a significant difference between the switching processes and the maximum currents respectively in air and sea water - A factor of 5 (and even more) is between the two setups.

4.8.3 Thermal Analysis

The thermal behaviour of the different insulation materials was also researched. Generally, when a material is heated up, three processes are effective: Firstly, there is the obvious temperature rise inside the material. In reference to insulating materials (especially synthetic materials) this can be dangerous if specific temperatures are excessed. Secondly an expansion of the material will take place which can be an issue when expansion coefficients are considerably different. And finally there is the phenomena of thermal conduction [22].

Although it could be possible that the thermal situation inside an electrical machine is better anyway with a flooded air gap (compared to a machine with a "standard" air gap), it is not so easy that this could be answered in general.
Because it is not granted that there is a sufficient recirculation of the water inside the machine, one has to assume that the general cooling issue is not better than in customary standard machines, probably it is even a bit worse.
Therefore all the manufactured prototype coils came under a basic thermal endurance test. For this, the coils were stressed with a current of approximately 9 Amps for more than 5 hours. The current and the voltage across the coils were measured continuously and the resistance of the coil was calculated with Ohm's Law. Because the resources for this test were quite limited and no sufficient cooling method for a sea water emerged test (to ensure that the water is in the same conditions for every test at any time) could be installed in the field laboratory. Therefore these tests have been conducted in air only. Nevertheless they can give a basic idea of the thermal behaviour of the different materials used.

Figure 4.26[22] shows the results: The horizontal axis shows the elapsed test time whereas the resistance is plotted on the vertical axis. For an easier comparison of the different insulation materials the base values (resistance at 22 degrees C) of each coil has been normalised (1 p.u.) and the change, according to this value is plotted.
Figure 4.27 shows the same results but here the temperature is plotted on the ordinate.

The figures are showing impressively that the used polyester resin is totally unsuitable if it heats up during operation, which is quite likely to happen. Because of the rigid encapsulation, the coil has no space to expand and therefore the resin block eventually cracks under the high forces. A possible solution would be some sort of flexible encapsulation: to have some space between the coil and the resin. This brings also a big disadvantage in electrical properties be-

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[22] Please note, that PE is used as an abbreviation for *Polyester* here (!)

cause this will introduce a further dielectric with additional properties (the dielectric constant of this space is quite likely to differ from the constant of the encapsulation and the coil material). Also having an additional space is quite unfavourable in terms of partial discharges *(*PD)[23].

Silicone #1 and #2 identifies the first production run whereas Silicone N#1 to N#3 labels the three improved and shaped coils. They have quite a favourable thermal behaviour and showed furthermore the best results of all the tested materials. The slower rise of the coils #1 and #2 can be explained with the bigger silicone compound block surrounding them: During the first "heat-up-phase" the rise of the temperature is defined by the thermal capacity of the whole system - in this case of the coil and its encapsulation. After some time a flow of heat will begin to leave the system. An equilibrium will then be reached which can be seen in the right part of the diagrams in figure 4.26 and 4.27. This happens, when the supplied heat (= lost heat) is equal to the heat, which leaves the system via its surface [64].

The tested materials are more or less suitable in terms of thermal behaviour (except the tested resin) but the change of resistivity is between 22 to 35 %!

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[23] especially when the majority of this space is filled with air

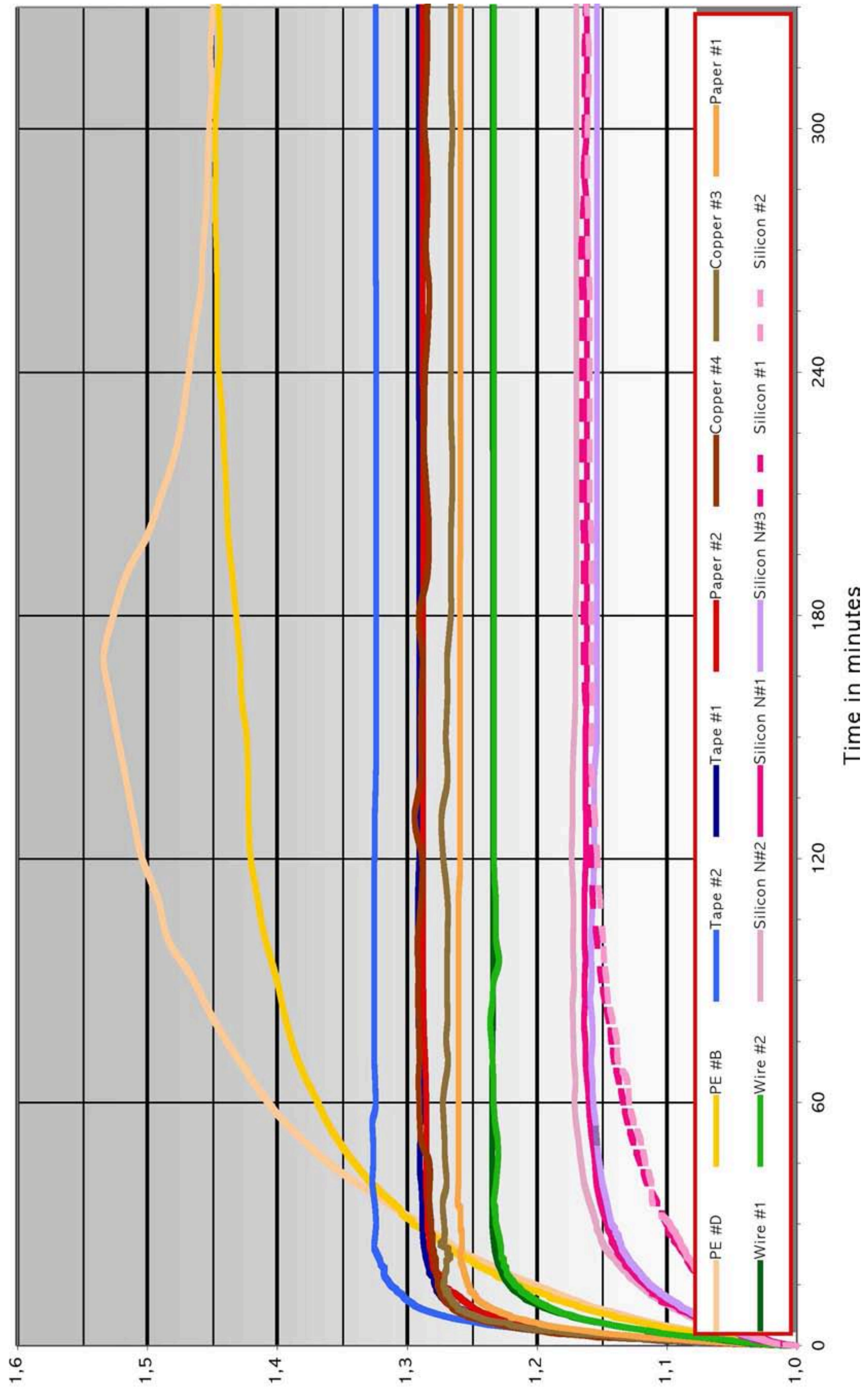

Figure 4.26: Change of resistivity during the thermal testing

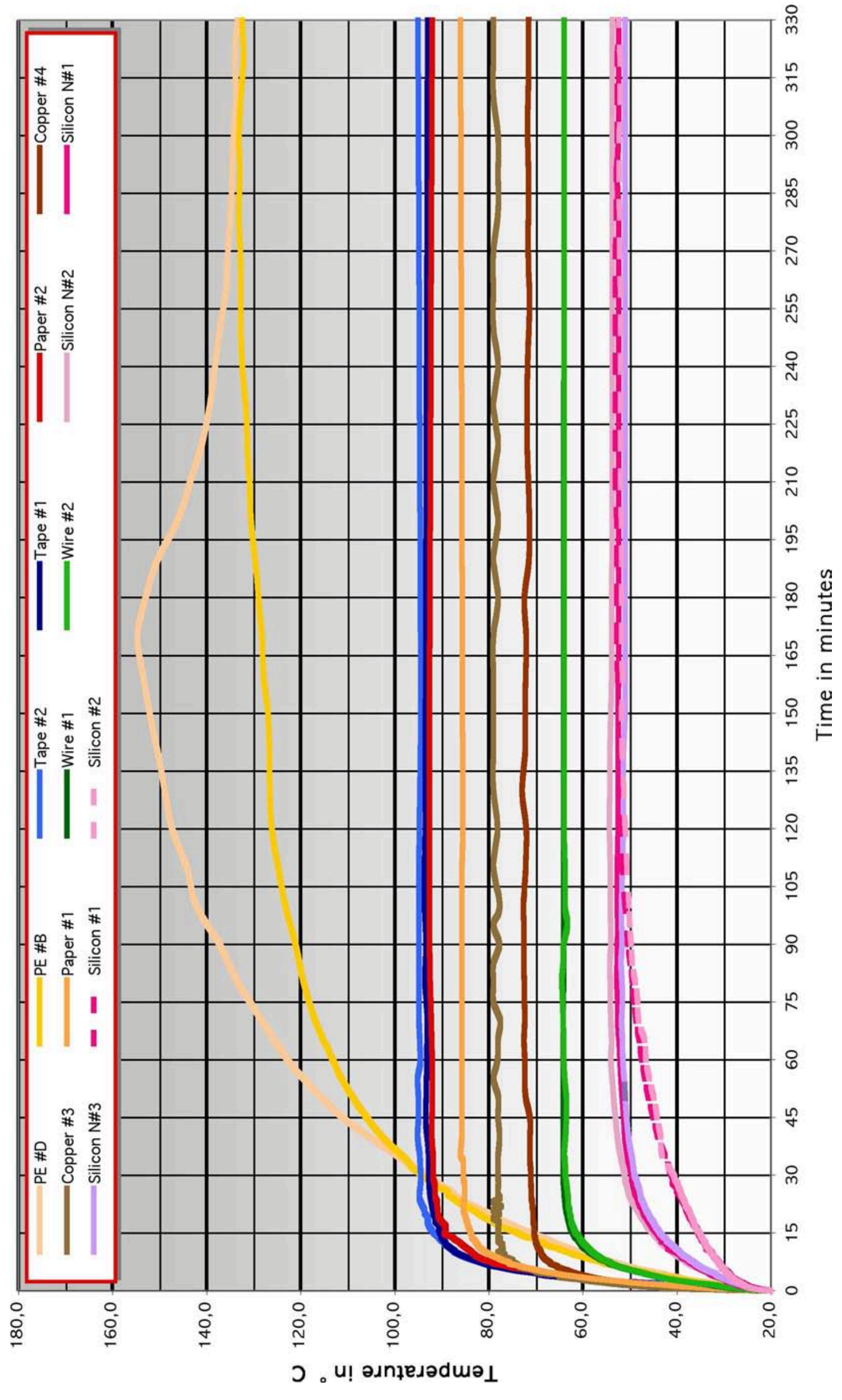

Figure 4.27: Change of temperature during the thermal testing

4.8.4 DC-HiPot Tests

Applying High-DC-Voltage to windings (except squirrel cages) is a common winding test method (for stator windings), as it can easily identify serious defects. This "rough resolution" can be a disadvantage as well. This test is of destructive nature in case of a defect. Test procedures are covered in several standards, like the IEEE Standard 95 or IEC 60034-1 [3, 41, 78].
Since this test is quite simple in terms of demands and it is also used as an acceptance test, all coils had to go through such a testing. Although the test, as described in literature and the technical standards, is targeted at complete machines, it is still worth a try.

Technical standards recommend to test the windings with the double rated voltage plus 1 kV. The test specifications state expressly to clean and dry a winding before the DC HiPot test and strongly advise against running a test with a wet winding. That is because testing a wet and/or contaminated winding is an unnecessary stress. For the use case of a flooded machine this advice is not very practical, although such an application was most likely not taken into consideration by the technical committees during the creation of the standards.
The DC test does, typically, not stress and age respectively an equipment additionally, as there are very few partial discharges at direct voltage [78]. Unfortunately a direct current amplifies the phenomena of water treeing and could therefore, for example, lead to a destruction of insulation made of synthetic material.

Test Procedure

As only individual coils have been available for the tests, consequently there was no *rated voltage* to which it could be referred to. The unit power can be an indication for the output voltage - and it is relatively low for single ocean power devices from experience. Additional factors are the limits caused by materials, fabrication techniques and the test equipment itself (5 kV DC Power Supply).
With the rule given in the standard, an assumed output voltage of 2 kV (which is reasonable) leads to a test voltage of about 5 kV.
The test was done quite conventionally: High-voltage was applied directly for 5 minutes. Due to the lack of either an (in small measurement ranges sufficient accurate) ammeter (with the according electrical strength) or an adequate voltage dividers it was renounced to measure the current. This is tolerable, because such a test is more or less a *"Go - NoGo"* - test and secondly the current should be compared with past measurements (condition monitoring).

Results

The outcomes of this test is not very surprising: If the encapsulation/insulation is good enough to prevent the contact of sea water and conductor, no difference could be observed between water and air. A possible change could be (possibly) seen in the current. Anyway, it showed that a total winding encapsulation performs well. The other methods are more or less inapplicable because a reliable ingress of moisture (sea water) can not be prevented. Therefore the breakdown of the whole insulation is just a matter of time.

Insulation Method	**Air**	**Sea water**
Magnet Wire	√	X
Tape	√	X
Stranded Wire	√	√
Paper/Varnish	(√)	(X)
Polyester	√	√
Silicone	√	√
Silicone (Shaped)	√	√

Table 4.6: DC HiPot-Test Result Matrix

4.8.5 AC-HiPot Tests

In principle, the AC HiPot test is similar to the DC test: Both are *"pass-fail"* tests and both methods are able to find major winding defects. Testing with alternating voltage has the advantage that the stress of a winding is (more) uniform along its dimension (compared to a DC test).

There are similar standards to describe the procedures [3, 41, 78]. IEC 60034 defines the test voltage as follows: $(2 \cdot E + 1)\,[\text{in kV}]$. E is the rated phase-to-phase voltage of the stator. Diagnostic information is difficult to obtain from an AC HiPot test (similar situation as with the DC test) - Measuring the in-rush and energising current respectively is only interesting in case of wet or uncured windings.

Test Procedure

Concerning a "proper" test voltage, the problems are similar to the test with direct voltage. Although the DC breakdown voltage is higher than the AC breakdown voltage (factor 1,7, see [41]), the coils have been tested for 5 minutes at 5 kV (50 Hz). Because of the relatively low voltage, no problems with charging current or reactive power occurred during testing.

Results

The results are more or less similar to the DC test. This is unsurprising because these coils haven't faced any operational stress so they should be able to withstand such a test without any major consequences. If the insulation is not able to prevent any ingress of moisture (sea water), the winding will fail the test naturally. This can be observed at the paper/varnish insulation: Normally the varnish of the magnet wire should be sufficient to insulate the conductor. As we have seen before, the imperfections make an additional insulation layer necessary. But the applied varnish on urethane basis didn't have the according electrical strength; therefore the flaws on the magnet wire led to various dielectric breakdowns.

Insulation Method	**Air**	**Sea water**
Magnet Wire	√	X
Tape	√	X
Stranded Wire	√	√
Paper/Varnish	(√)	(X)
Polyester	√	√
Silicone	√	√
Silicone (Shaped)	√	√

Table 4.7: AC HiPot-Test Result Matrix

4.8.6 Partial Discharge Measurements

Because of the early stage of testing and the out of date partial discharge measuring system in the field laboratory, no PD-Measurements (according to IEC TS 61934 or similar) have been carried out so far. Further research is recommended because resins are very susceptible to partial discharge [44]. This is so much worse because resins (as for example the tested polyester resin or epoxy) and the silicone encapsulation perform well in other tests.

It is assumed that the current encapsulated coil prototypes would not perform well in a PD-Test as neither the resin nor the silicone compound was degassed before the coil encapsulation process (see Figure 4.29).

Standard encapsulation processes are taking place in vacuum (VPI for example). Because already small hollow spaces in solid insulation materials can lead to an erosive material loss and furthermore to (material) degradation and insulation breakdown. Because of the small dielectric constant of the gas in these cavities (in the region of $\epsilon_r \approx 1, ..)$, the electrical field strength is considerably higher than in the surrounding insulation material.

Although the exact measurement of PD's is difficult and complex measurement devices are needed. This test procedure is getting more and more popular throughout the industry. Because PD analysis is very helpful in examining the condition of electrical equipment and material. Valuable information can be gathered [23]. Therefore such tests should be carried out with the test coils and furthermore with prototype machines as soon as possible.

Figure 4.28: Out-Dated Discharge Detector

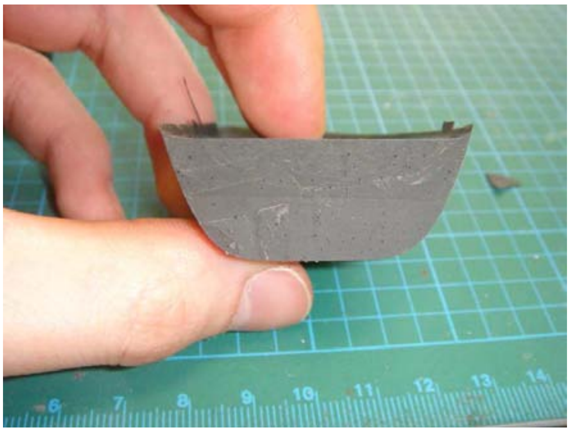

Figure 4.29: Hollow spaces in a test-block of silicone compound

Example

Gas inclusions like shown in the silicone block in Figure 4.29 should serve as an example. A silicone layer with a thickness $D = 5\,\text{mm}$ has one assumed flaw, which is - to simplify matters - cube-shaped (edge length $l = 0,7\,\text{mm}$).
The breakdown voltage U_{bd} of this hollow space can be estimated with [36, 47]:

$$U_{bd} = b \cdot p \cdot s + c\sqrt{p \cdot s} \tag{4.5}$$

U_d describes the breakdown voltage in kV, b and c are constants (material dependent), p is the pressure in the hollow in bar and s is the sparking distance in mm. It is assumed that the gas pressure is about 1 bar and the gas should be normal air. This leads to $b = 1,85$ and $c = 3,87$ and furthermore to:

$$U_d = 1,85 \cdot 1 \cdot 1 + 3,87\,\sqrt{1 \cdot 1} = 5,72\,\text{kV}$$

The inclusion is assumed to be cube-shped and air filled. Its capacity can be calculated very simply with:

$$C_i = \frac{\epsilon_0 \cdot A}{l} = \frac{\epsilon_0 \cdot 0,7^2}{0,7} = 6,198\,\text{pF} \tag{4.6}$$

The silicone has as relative permittivity of $\epsilon_r \approx 3$. The thickness of the remaining silicone is 4,3 mm (5 mm - 0,7 mm caused by the pin hole). Therefore its capacity is:

$$C_s = \frac{\epsilon_0 \cdot \epsilon_r \cdot 0,7^2}{4,3} = 3,027\,\text{pF} \tag{4.7}$$

With these two capacities it is now possible to estimate the partial discharge inception voltage (PDIV):

$$\widehat{u}_{IV} = \frac{(C_i + C_s) \cdot U_{bd}}{C_s} = \frac{(6,198 + 3,027) \cdot 5,72}{3,027} \approx 14\,\text{kV} \tag{4.8}$$

This value has to be seen in relation to the dielectric strength of a defect-free silicone block. As this silicone resin has a dielectric strength of more than 18 kV/mm this would add up to 90 kV for the whole block (!)

4.8.7 Flooded Air-Gap-Considerations and Tests

An electrical machine with a liquid-filled air gap will surely face heightened losses. As these additional losses (caused by water circulation, swirls, ...) are difficult to compute, measurements have been carried out with a simple setup: A small, 3-phase induction motor was filled with tap water. To avoid the insulation issues, the machine was not energised but it was driven externally by a DC machine. The whole setup with the torque dynamometer is shown in Figure 4.30.

Figure 4.30: Test Setup

Figure 4.31: Identification Plate (Induction Motor)

Nevertheless some constructive changes had to be carried out: The bearings and the shaft needed to be sealed as otherwise the water just runs through the machine. Furthermore the fan has been dismounted.

But before filling the induction motor with water, the modified machine was subject to a no-load test to estimate the friction losses (see Figure 4.32). The orange graph shows the torque over the engine speed, which was provided by the DC motor. The losses (caused by friction) are nearly constant over the engine speed (green graph).

Afterwards the same measurement has been carried out with the induction motor (and its air gap respectively) filled with water (see Figure 4.33). This time the losses (green graph) are direct proportional to the engine speed. The red graph is the difference of the total losses and the idle losses which have been measured before.

The circumferential speed was varied between approximately 2 and 5 m/s, which seems to be a reasonable speed for a WEC. To establish a connection between this test machine and an existing ocean power device is difficult. Nevertheless, for this motor the losses have gone up between 15 % (at 2 m/s) and 100 % (at 5 m/s) (!).

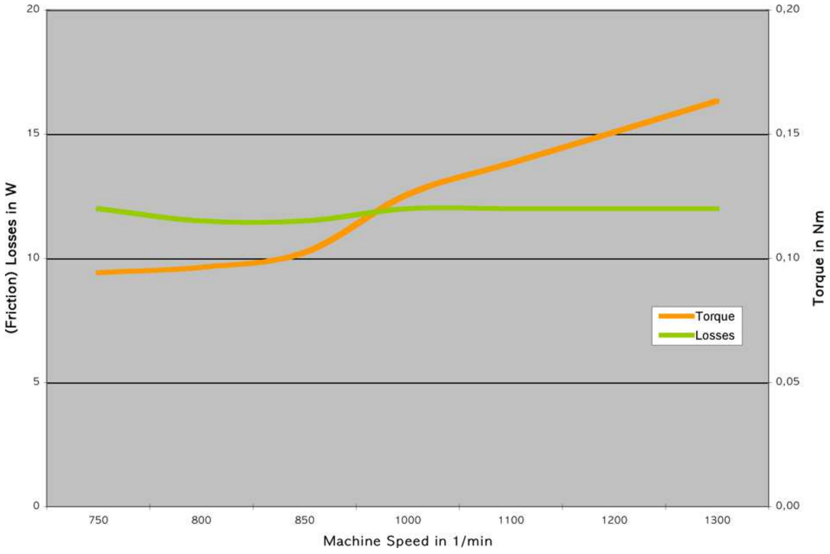

Figure 4.32: Friction losses of idle machine

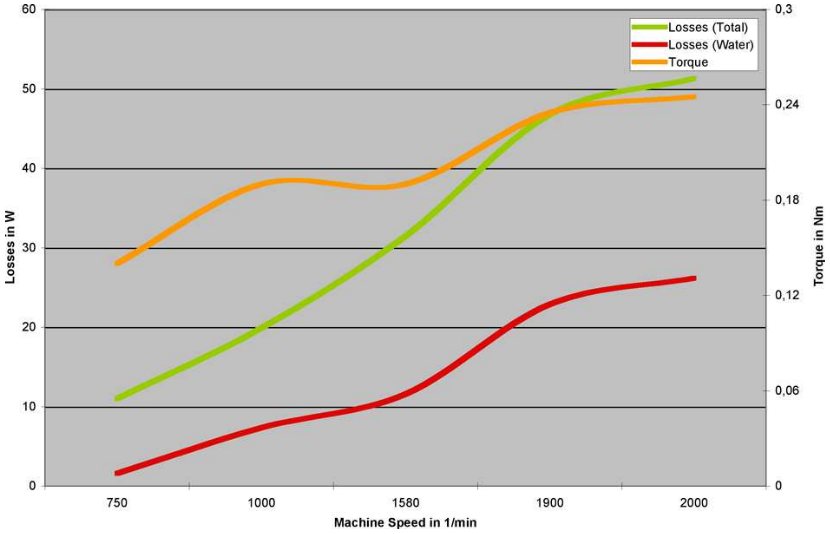

Figure 4.33: Losses of machine with flooded air gap

Chapter 5

Conclusions

5.1 Survey

Wave energy and ocean power in general is an interesting and fascinating field of activity. Huge energy potentials and renewed research activity combined with public and governmental subsidiary money led to big jumps in technology and furthermore to the construction of new devices to harness this clean energy source.

One such device is the Archimedes Wave Swing (AWS), a 2 MW wave energy point absorber, which was invented in 1999. The AWS is a fully submerged wave energy converter. The immersion has two big advantages: Firstly, energy can be extracted from the waves regardless of their travelling direction (point absorber) and secondly, the "visual pollution" near the coast is low (or non existent because of the submersion).

When waves are travelling over the AWS they create a change in water column and furthermore a change of force which acts onto the device. Although these changes are very randomly, a more or less equal movement of the AWS's floater can be achieved with a clever design of the mechanical components. The bidirectional movement of the floater is used to drive a linear generator on the inside of this WEC. With the help of power electronics it is possible to receive a output voltage with good power quality.

Because of the high weight and the nature of the movement, this device makes high demands on bearings and sealings. These two components are limiting the lifetime of the AWS as they are wear parts. A passable way to cope with those problems could be achieved by flooding the generator and its air gap with sea water.

Unfortunately, more problems are arising with flooding: Corrosion issues, (additional) stray capacities and currents, durability and so on. Several basic tests have been carried out to research the behaviour of such a machine and its components.

5.2 Conclusions

The applicability of different winding insulation systems for a fully flooded machine has been examined. Coils with 20 turns made of magnet wire have been insulated with the following materials:

- Standard Magnet Wire (no additional insulation)
- Insulation Tape
- Stranded Wire (PVC insulated)
- Paper/Varnish
- Resin encapsulation (Polyester)
- Silicone compound encapsulation

To evaluate the ability of the different insulation systems to cope with all the requirements and demands which arise with air gap flooding, several tests had been carried out

- Inductance and Capacitance Analysis
- Switching Tests
- Thermal Analysis
- HiPot Tests
- Efficiency Considerations

General considerations in matters of corrosion and durability have also been made. A result matrix of all the conducted tests is shown in Table 5.1. It turns out that the complete insulation/encapsulation systems score well in all the tests.
Using magnet wire without any additional measures will not work at all. A combination of different synthetic materials is perhaps (probably) the most promising solution.

Insulation System	**Switching Test**	**Thermal Test**	**DC HiPot Test**	**AC HiPot Test**	**Corrosion Character**
Copper Wire	×	○	×	×	○(-)
Tape Wrapped and varnished	○	-	○	○	++
Stranded Wire	- -	+	+	+	+(+)
Paper Wrapped and varnished	-	○	○	○	++
Polyester Encapsulation	++	×	+	+	+(+)
Silicone Encapsulation	++	++	+	+	++
Silicone Encapsulation (Shaped)	+	++	+	+	++

Legend: ++ very good + good ○ neutral - bad - - very bad × fail

Table 5.1: Result-Matrix of all conducted tests

At this point it is not possible to make a definitive statement, if an electrical machine with fully flooded air gap would perform (sufficiently) well during real usage conditions although it is likely that the technical issues can be solved . Further research is necessary to examine the different issues.

Although filling the air gap with sea water might solve several problems, it also generates a multiplicity of others. Such issues could affect lifetime and therefore total unit costs and the survivability of a technology eventually.

Inductance

The (possible) change of inductance and capacitance of sea water immersed windings was researched for the different insulation systems. No significant difference in inductance could be observed between air and sea water environment. In terms of torque and electrical power output, no problems are expected from this side. Although there could be changes in connection with fast switching processes, but this has not been researched so far.

Switching effects and stray capacities

Because of the heightened (stray) capacities of submersed windings, significant currents are expected at full scale machines. These currents are expected to rise additionally - caused by fast switching power semiconductors (because of the high $\frac{du}{dt}$).

These capacities cannot be influenced (= reduced) easily because of the given materials (and their ϵ_r) and the insulation thickness. It is important to note, that the current may differ significantly at full scale machines from the values that have been gained during this first tests. This is founded in the fact, that the insulation system may be different from the test setup used here. The shaped silicone coils represent an actual application much better than - for example - the encapsulation in whole polyester blocks. Also the before mentioned insulation thickness might be different.

Thermal qualification

The thermal influence of flooding an electrical machine with sea water is more or less unknown. At first sight it can not be said that the thermal situation inside the machine gets better with flooding. This is because (under the assumption that no further measures are taken) the circulation and the heat exchange respectively of the sea water can not be guaranteed.
Full encapsulation systems like the resin and silicone compound insulation might worsen the situation as they prevent the heat to be dissipated into the environment. The silicone encapsulation performed quite well whereas the epoxy is totally unsuited. Because of the rigid encapsulation, the epoxy is not able to deal with the stretching of windings under load and with the amounts of heat that are generated at full load.

HiPot tests

High voltage AC and DC tests have been conducted to evaluate the electrical qualification of the different insulation systems. The insulation and encapsulation systems do not limit or restrict the insulation co-ordination for the whole machine as they have a sufficient dielectric strength.

Efficiency

It is quite likely that a fully flooded machine will face heightened losses caused by turbulence of the liquid and additional friction. Tests showed that these losses are rising with rotational speed. This needs not to be a problem per se, but it is advisable to understand these losses already during the design stage.

Corrosion

Corrosion is a serious problem as it can shorten the lifetime of an ocean power device dramatically. It seems that synthetic materials are appropriate to withstand the ambient stresses. They are also able to fulfil electrical/insulation tasks. Of course, there are better materials available on the market than the ones tested. For an extended research, better (and more expensive) materials should be tested, especially in terms of mechanical strength and durability.

Durability

The durability and lifetime of a machine with fully flooded air gap is uncertain and needs to be researched, at least with small scale model in real operational modes. Several factors are influencing the total durability (lifetime) of an ocean power device and therefore conclusions should be only made after tests of a complete system.

5.3 Outlook

The conducted tests gave a basic idea what will happen with a sea water flooded machine. Further research will be necessary to get a better understanding of the involved processes. This will include the following topics:

Materials

The choice of materials is important as they have to fulfil several different tasks. Furthermore the demands are partly contradictory, as corrosion resistance, electrical (insulation) demands and costs need not to go hand in hand with each other.
Synthetic materials are promising and should be therefore researched further: epoxy resins, silicone compounds, etc.

Corrosion Tests

The above mentioned materials should be subject to corrosion tests. Such tests should be at least conducted with stator parts: Several poles with stacked up and insulated/encapsulated windings. Furthermore it will be necessary to run these tests with energised windings to research the influence of electrochemical corrosion.

Prototype machine

The production of a (scaled) prototype machine should be done soon, as some measurements can be conducted only at the complete system. Power output and quality, partial discharges, material behaviour and corrosion issues are such topics.

Chapter 6

Summary

This diploma thesis shows the difficulties and problems which are arising from flooding the air gap of an electrical machine with sea water.

Filling the air gap of an electrical machine (linear generator) with sea water and hence running the machine fully flooded simplifies sealing and suspension. But the tests which have been conducted in the scope of this project pointed out several other problems:

- Efficiency reduction
- Capacitance changes (ground capacitance and inter-winding-capacitance)
- Additional losses (due to the switching of windings)
- Corrosion issues
- Durability problems

Flooding the air gap will cause additional losses and therefore a reduced efficiency for sure. The conducted tests also support this: A small induction motor has been filled with water and the losses have been determined for several duty points (and rotational speeds respectively). These losses are not problematical but they should be taken into concern during the design process.

The change of inductance and capacitance of single windings has also been investigated. Windings with different insulation systems have been subject to several tests in air and sea water environment.
The (winding) inductance do not change with the immersion in sea water. However, the capacitance (winding to ground and inter-winding capacitance) are very different from the original ones which are apparent when the windings are operated in air.
This can be problematically for the output voltage and power quality because of the arising of stray capacitances. Furthermore, these additional capacitances are responsible for heightened losses when the machine is inverter-operated.

Conducting (long-term) corrosion behaviour tests would have gone far beyond the scope of this thesis. Nevertheless, basic considerations in matters of corrosion have been carried out.

Different insulation systems with various insulation materials have been tested. Especially the synthetic materials seem to fulfil all of the demanded requirements. Even so, the corrosion resistance and complete system durability will have to be further researched. An effective and cost optimised corrosion protection scheme needs to be applied to secure a safe service over years.
The durability of the corrosion protection and the sealing parts have to be evaluated in detail. Failure of one of these systems (or their subsidiary systems) will inevitably lead to a malfunction or failure of the whole generating unit and furthermore to (high) repairing costs and furthermore to a loss of energy and eventually of money.

It is too early to make further conclusions about the effects and the impact of replacing the air with sea water inside an electrical machine. Further research will be absolutely necessary to draw conclusions.

From the present point of view it is very likely that an operation of a fully flooded electrical generator is possible. But the operating expenses and the complexity of such a system should not be underestimated.

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Appendices

A Inductance Measurements

The results of the inductance measurements are presented in Appendix A. Different insulating materials (plain copper coils, tape, stranded wire, paper/varnish, polyester, silicone compound) have been tested. The inductance was measured with a *HP 4192 A LF Impedance Analyzer*. Although this device has a metering range between 5 Hz and 13 Mhz, the inductance was measured between 50 Hz and 100 kHz . This seems to be a suitable range and the measurement effort is still within reasonable limits.

Inductance was measured for each coil - First each coil was measured in "normal" environment (air) and afterwards all coils got emerged in a tank filled with seawater.

A.1 Copper Coils

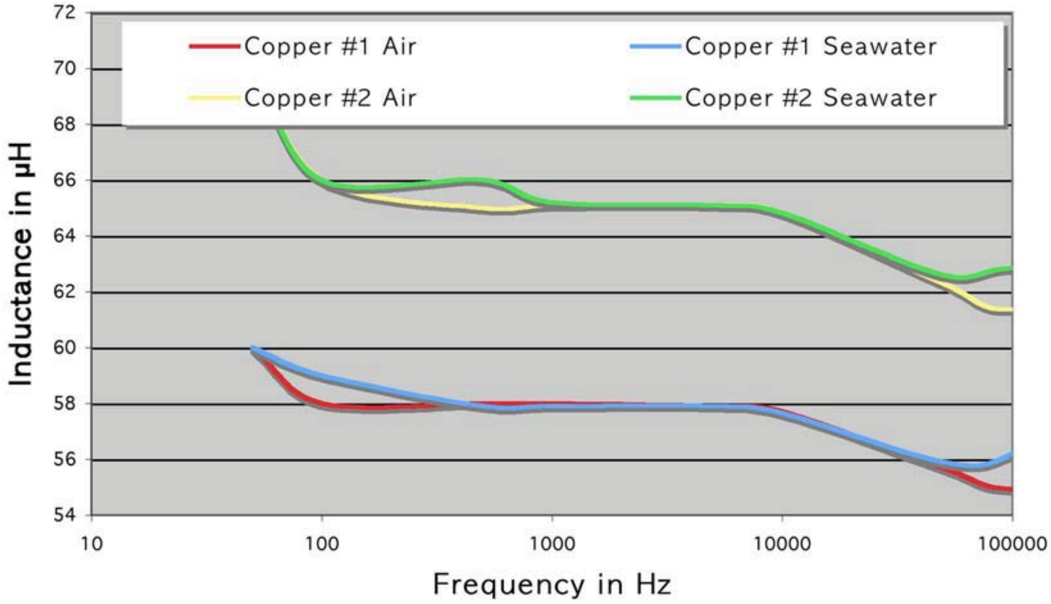


Figure A.1: Inductance of copper coils

A.2 Tape Coils

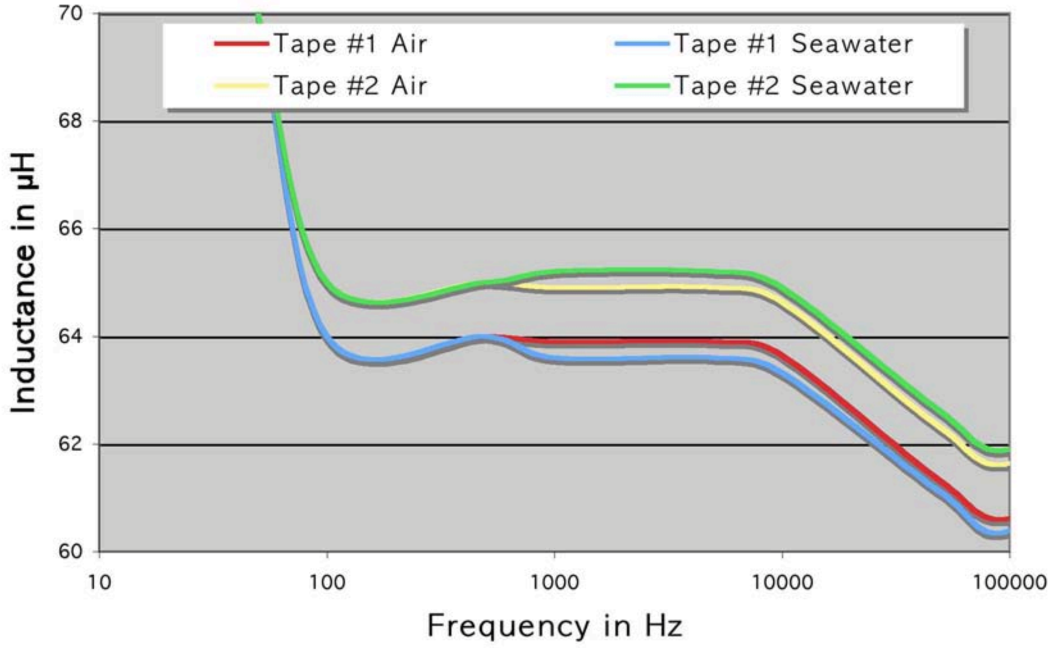


Figure A.2: Inductance of tape-wrapped coils

A.3 Stranded Wire Coils

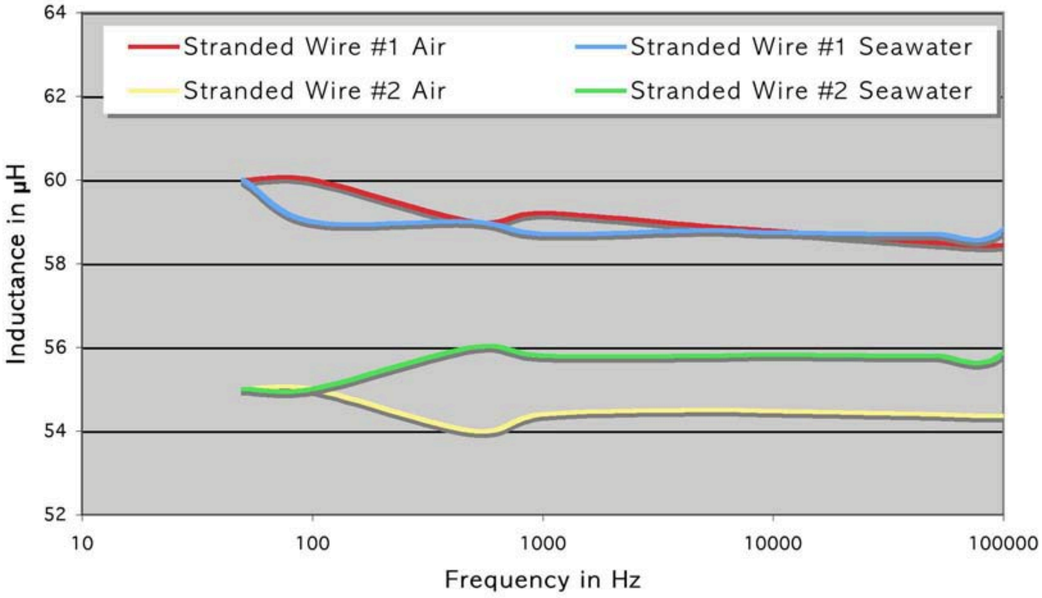


Figure A.3: Inductance of stranded wire coils

A.4 Paper-wrapped Coils

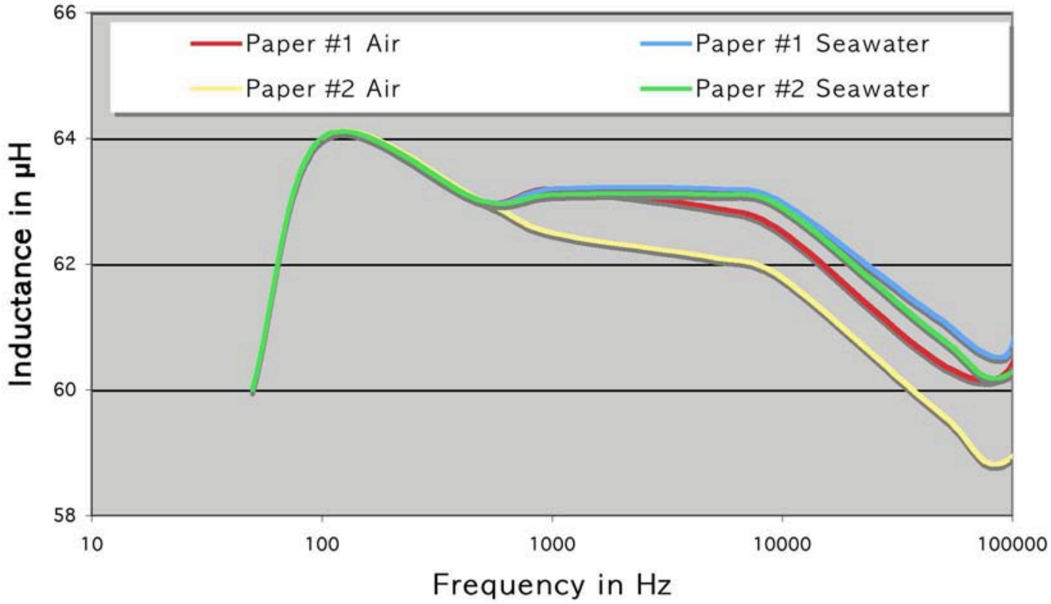


Figure A.4: Inductance of paper wrapped coils

A.5 Polyester-encapsulated Coils

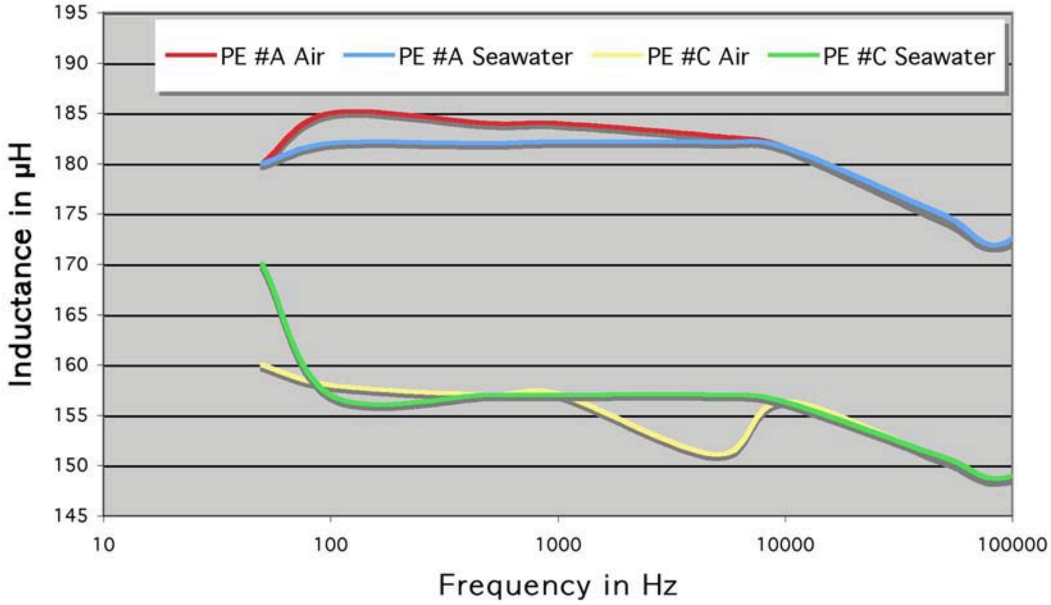


Figure A.5: Inductance of polyester-encapsulated coils

A.6 Silicone-encapsualted Coils

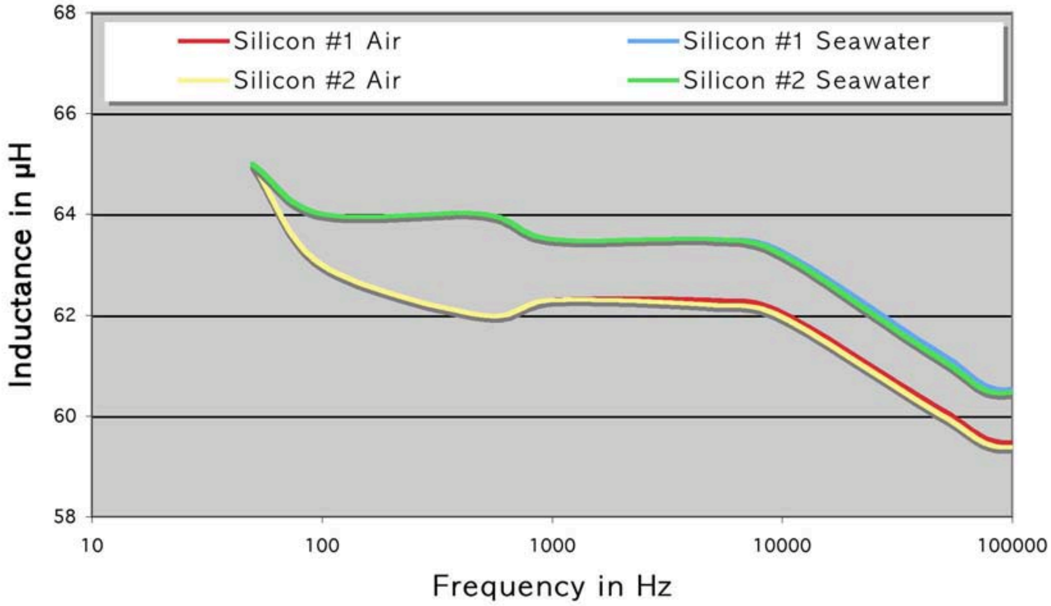


Figure A.6: Inductance of silicone coils

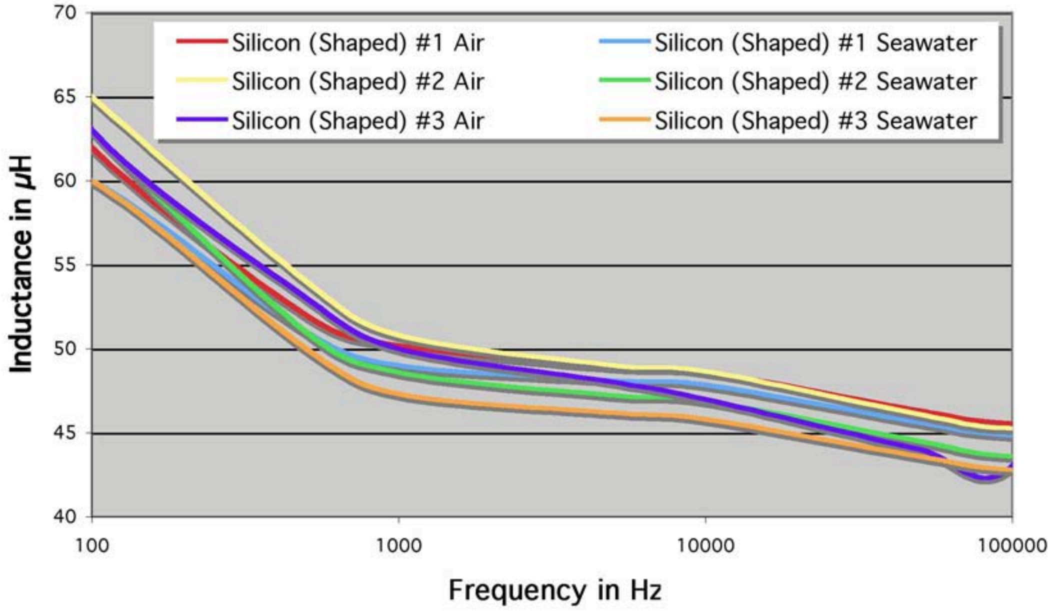


Figure A.7: Inductance of shaped silicone coils

B Capacitance Measurements

Appendix B shows the results of the capacitance measurements. Different insulating materials (plain copper coils, tape, stranded wire, paper/varnish, polyester, silicone compound) have been tested. The capacitance was measured with a *HP 4192 A LF Impedance Analyzer*.
Although this device has a metering range between 5 Hz and 13 Mhz, the capacitance was measured between 50 Hz and 1 MHz . This seems to be a suitable range and the measurement effort is still within reasonable limits.

B.1 Ground Capacitance

Ground capacitance was determined for air and sea water surrounding. The measurements have been conducted from 50 Hz to 1 MHz. But for the air-measurments the range from 50 Hz to 500 Hz didn't produce reasonable results (metering range).

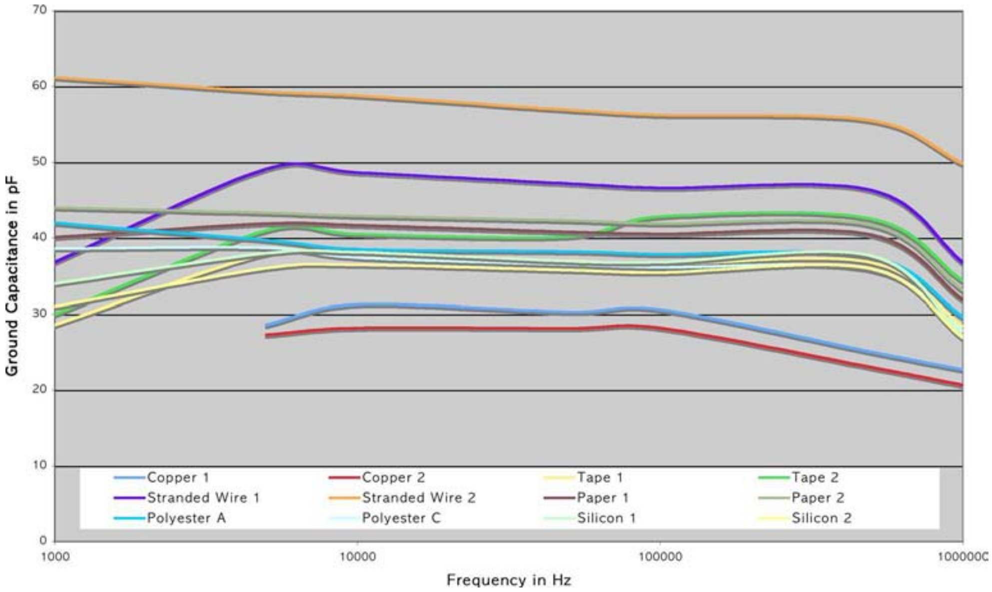


Figure B.1: Ground Capacitance in air

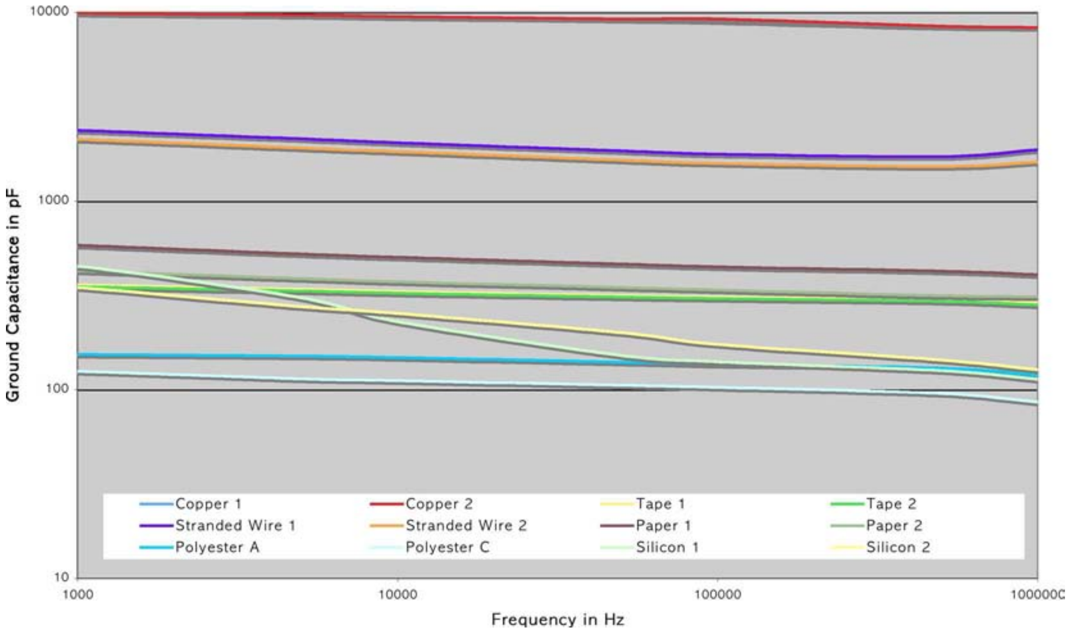


Figure B.2: Ground Capacitance in sea water

B.2 Inter-winding Capacitance

The capacitance was measured for each coil assembly at different setup. To determine the inter-winding capacitance, the measurement was divided into 3 parts:

First the coils were placed just next to each other (0 % overlap).
Then they have been arranged to the top of each other: one time with 50 % and
finally with 100 % overlap. These measurements were conducted in a "normal" environment (air) and afterwards they were repeated with the same setup emerged in a tank, filled with sea water.

Copper Coils

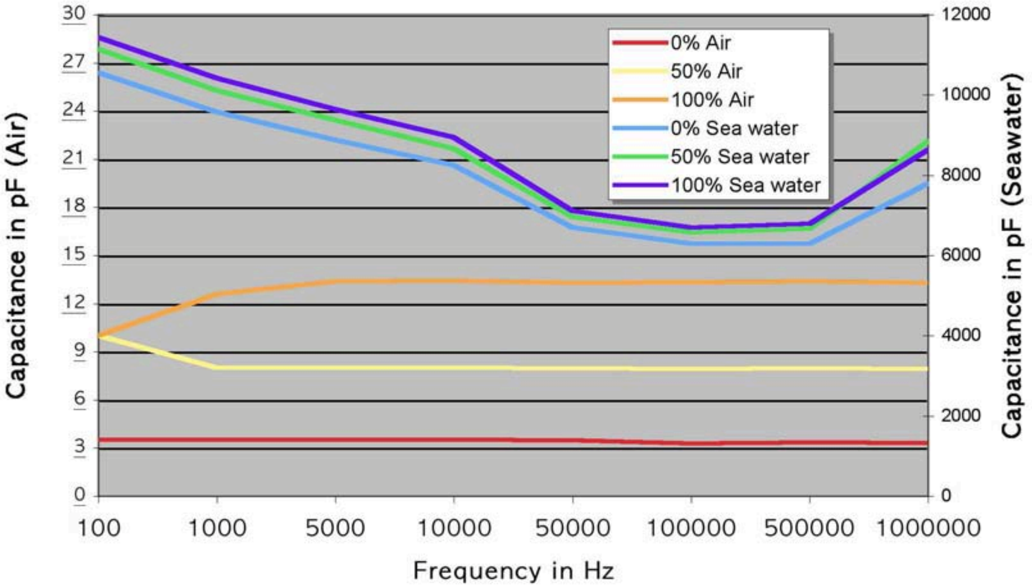


Figure B.3: Capacitance of copper coils

Tape Coils

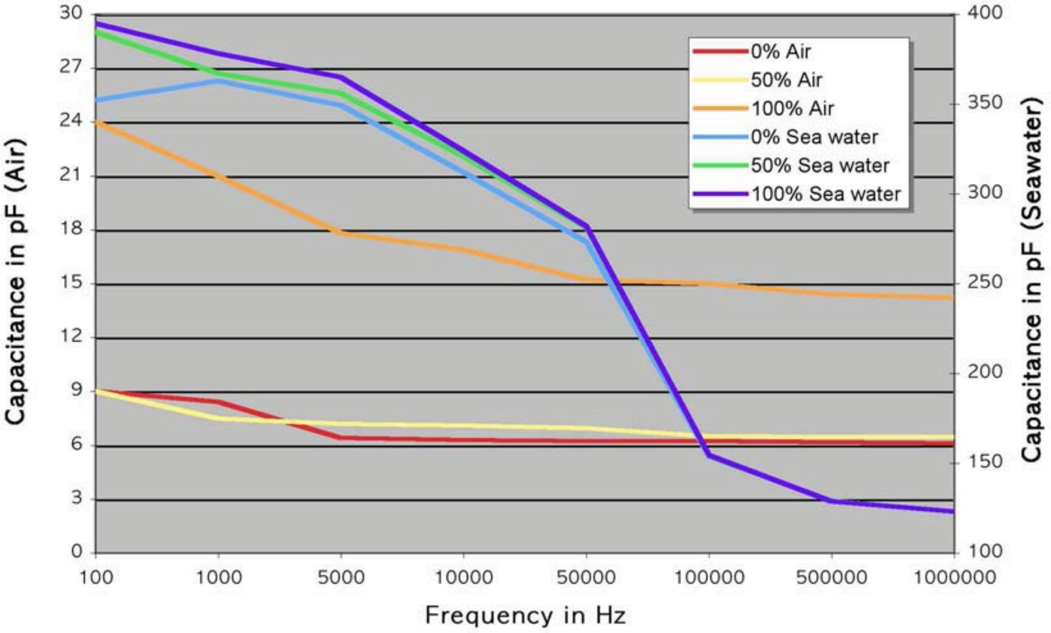


Figure B.4: Capacitance of tape wrapped coils

Stranded Wire Coils

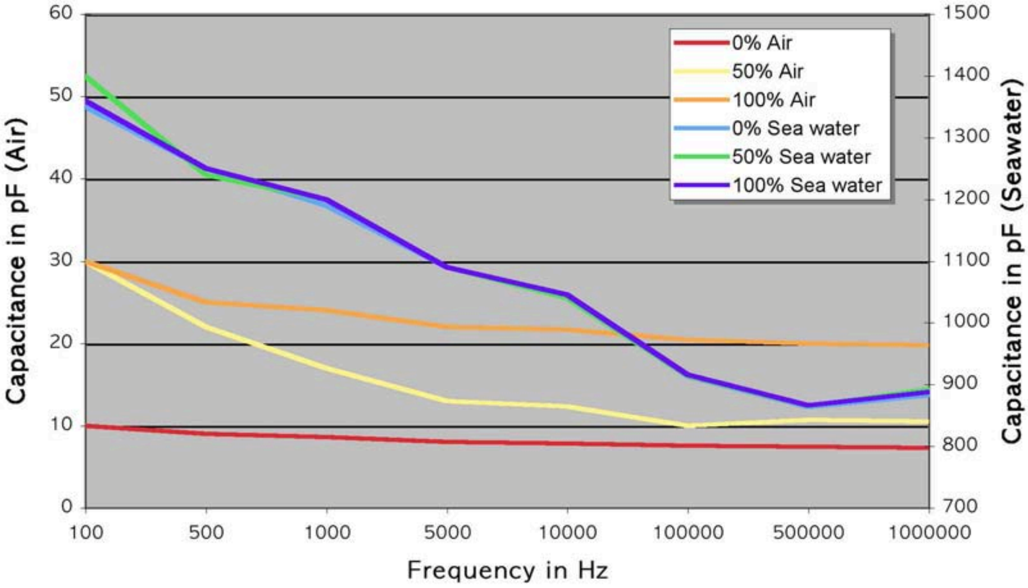


Figure B.5: Capacitance of stranded wire coils

Paper-wrapped Coils

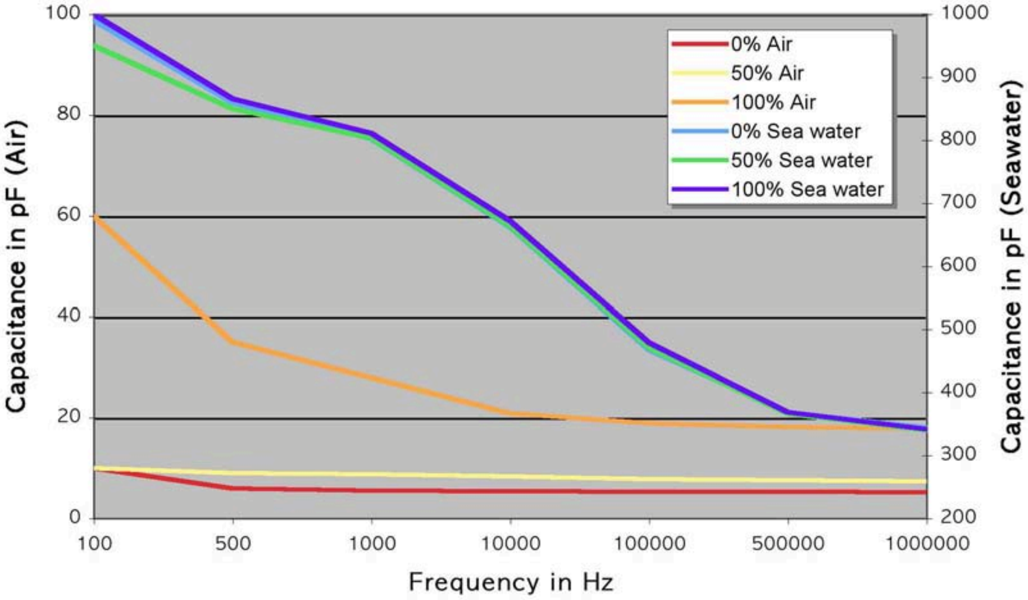


Figure B.6: Capacitance of paper wrapped coils

Polyester-encapsulated Coils

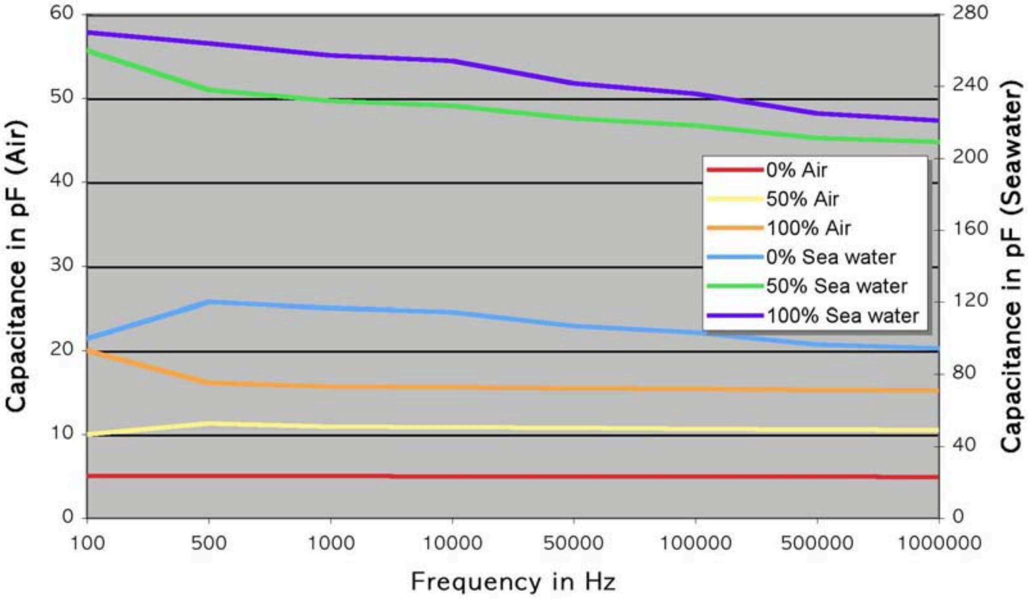


Figure B.7: Capacitance of polyester-encapsulated coils

Silicone-encapsulated Coils

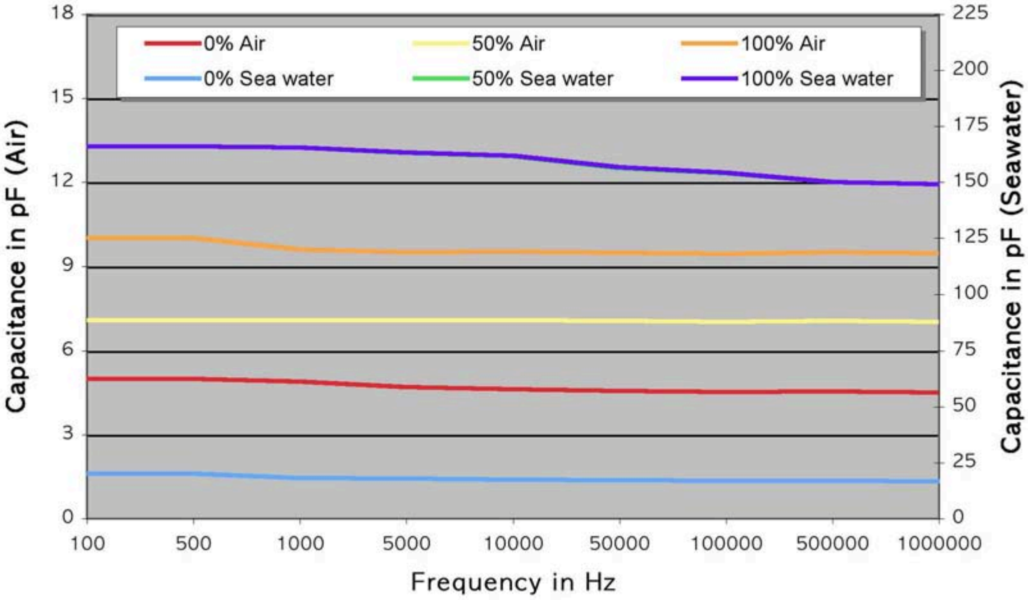


Figure B.8: Capacitance of silicone-encapsulated coils

B.3 Silicone-encapsulated Coils (Shaped)

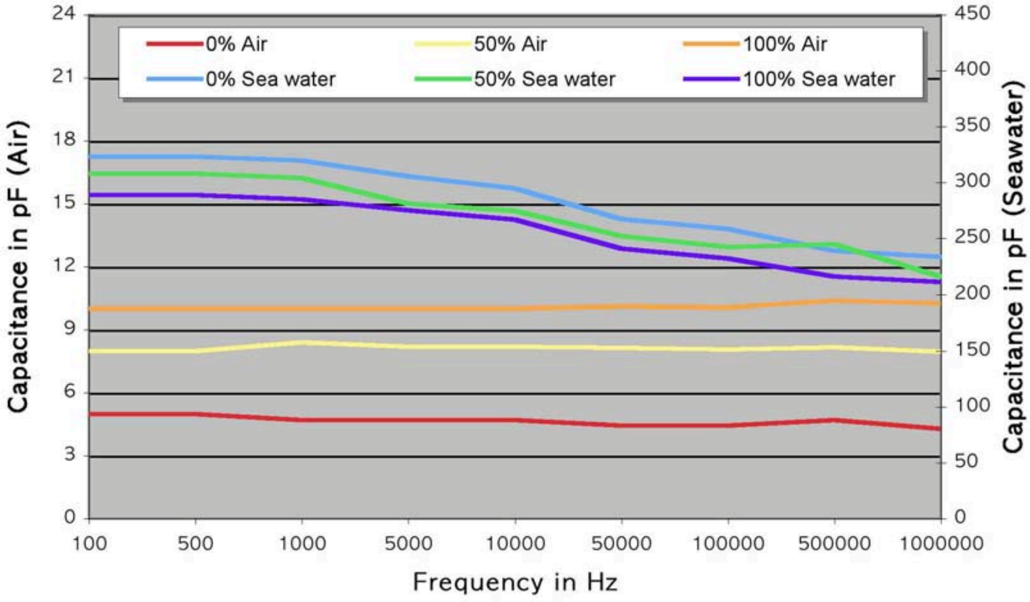


Figure B.9: Capacitance of silicone-encapsulated coils (shaped)

C Switching Results

Appendix C includes all captured scope images of the switching tests.

Annotation: The scale (especially the current scale) may differ between the images!

All the figures were taken with a *Tektronix TDS3032B* e*Scope™, a 2 channel, 300 MHz, 2,5 GS/s digital sampling oscilloscope. The currents were directly measured with *Tektronix AM 503B Current Probe Amplifiers*. These probes have a 50 Ω BNC-Output which can be directly connected to a scope (50 Ω input impedance, therefore a Ω symbol is in each image next to the unit "mA" to indicate that the scope's input impedance was lowered from its default 10 MΩ to 50 Ohms to cope with the current probe).

The scope was calibrated to the probes - therefore the scale at the bottom of each scope image is actual and there is no need for further conversion.

Colour Definition:

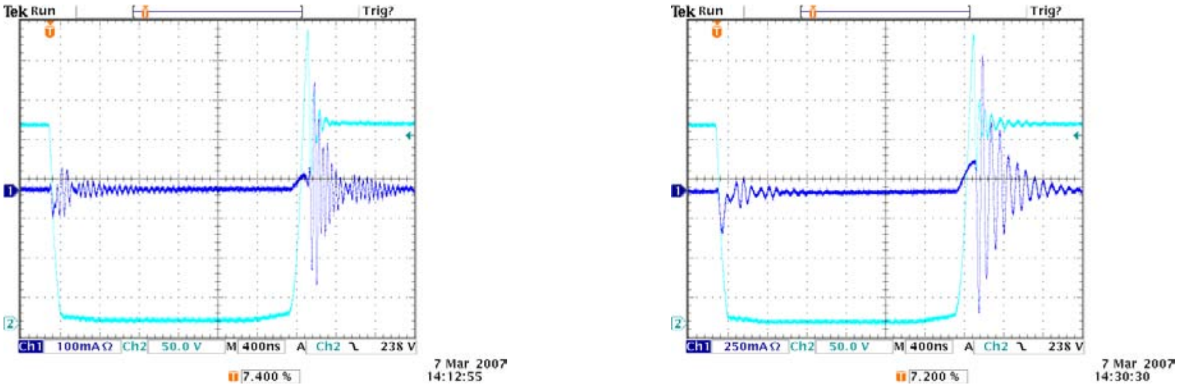
- Current: **Dark Blue**
- Voltage: **Turquoise (Cyan)**

This appendix is subdivided into 3 parts:

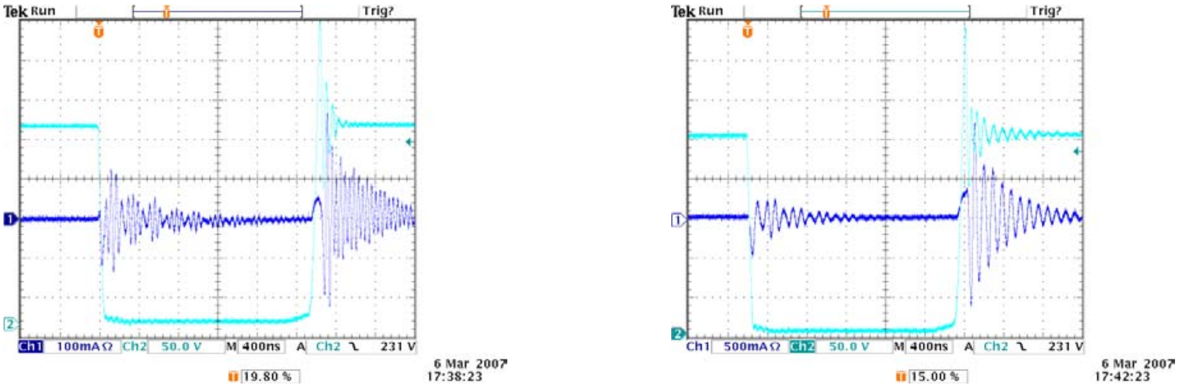
- Comparison of different Gate resistances (at 250V)
- Comparison of different switching voltages (50 V and 100 V, all at 5,7 Ω)
- Testing of all coils in air and immersed in seawater at 5,7 Ω and 250 V

C.1 Comparison Of Gate Resistances

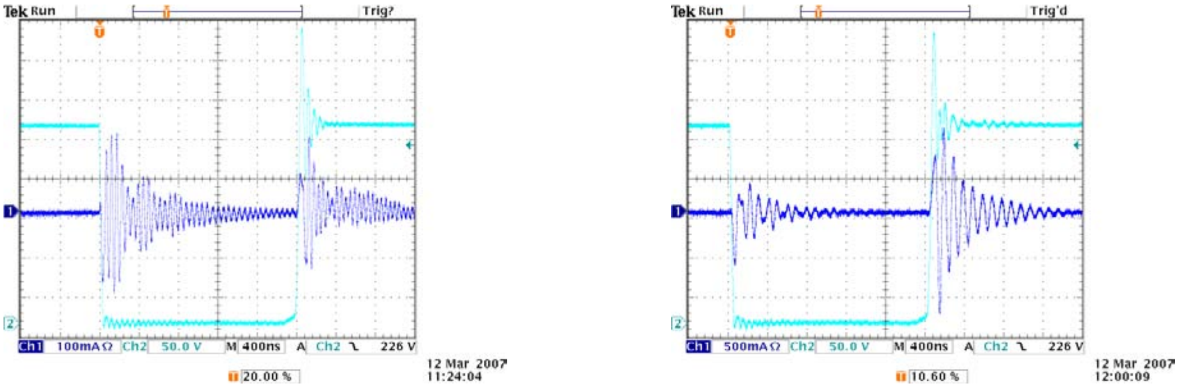
Silicone-encapsulated Coil #1 (Shaped)



(a) Air, 22 Ω (b) Seawater-immersed, 22 Ω



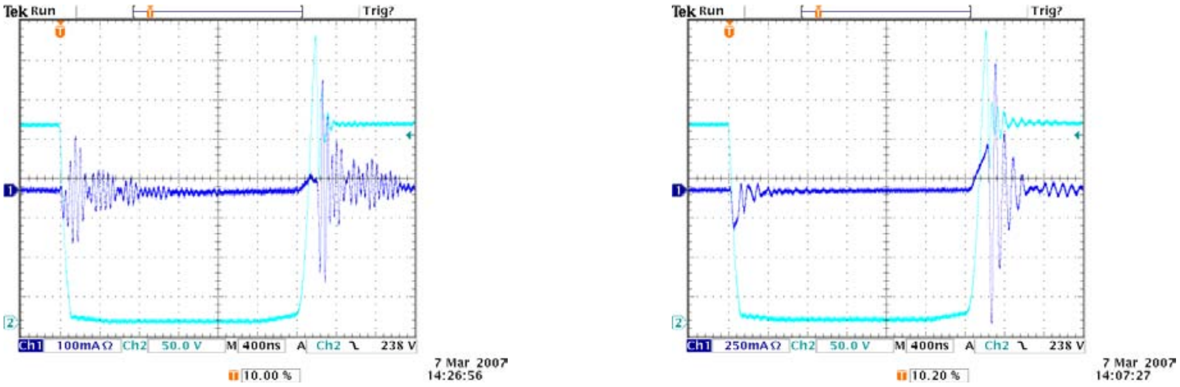
(c) Air, 11 Ω (d) Seawater-immersed,, 11 Ω



(e) Air, 5,7 Ω (f) Seawater-immersed,, 5,7 Ω

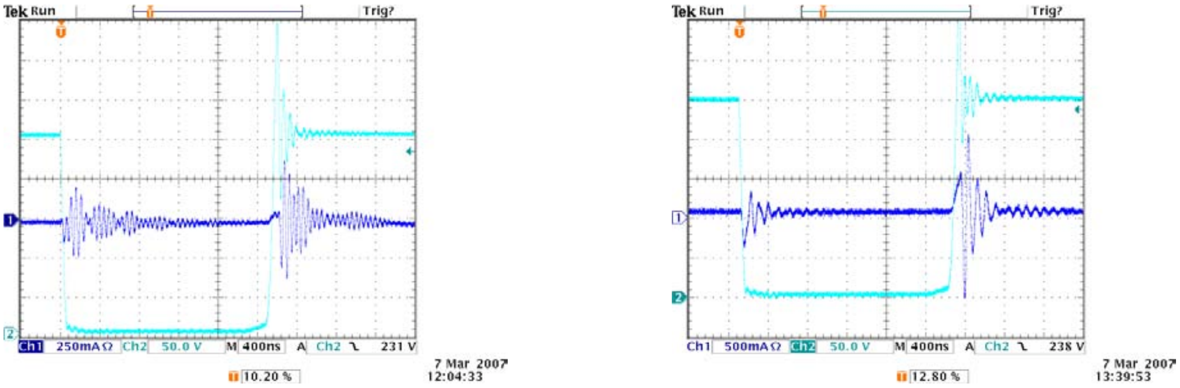
Figure C.1: Silicone-encapsulated Coil #1 (Shaped)

Silicone-encapsulated Coil #2 (Shaped)



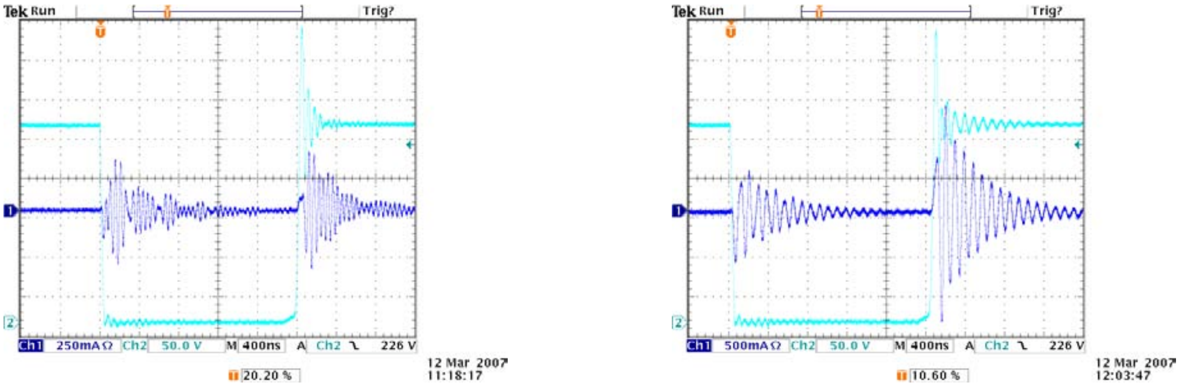
(a) Air, 22 Ω

(b) Seawater-immersed,, 22 Ω



(c) Air, 11 Ω

(d) Seawater-immersed, 11 Ω

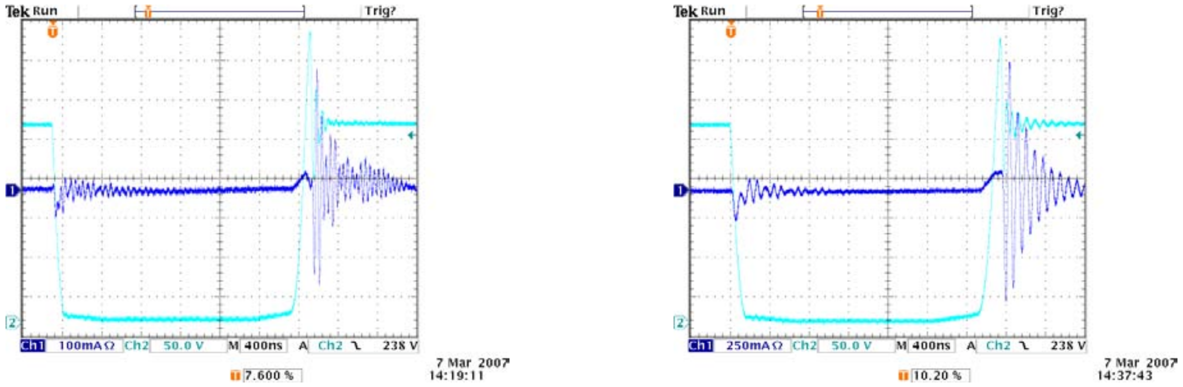


(e) Air, 5,7 Ω

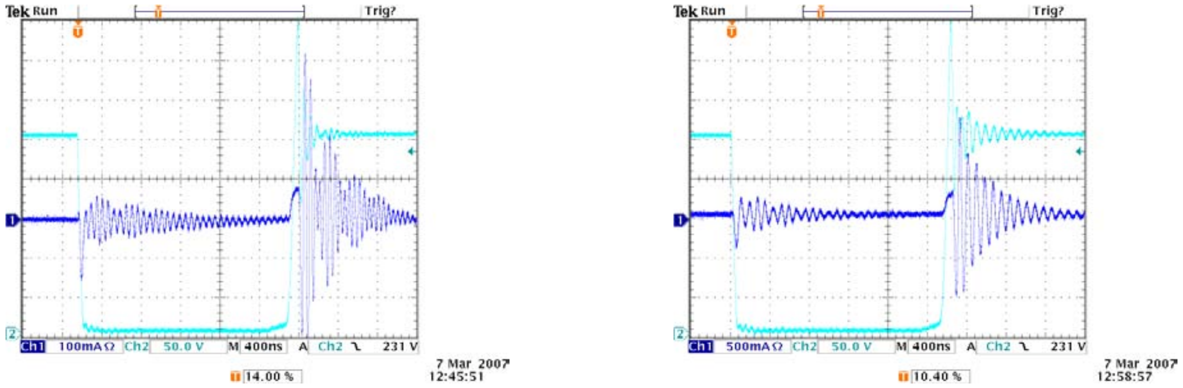
(f) Seawater-immersed, 5,7 Ω

Figure C.2: Silicone-encapsulated Coil #2 (Shaped)

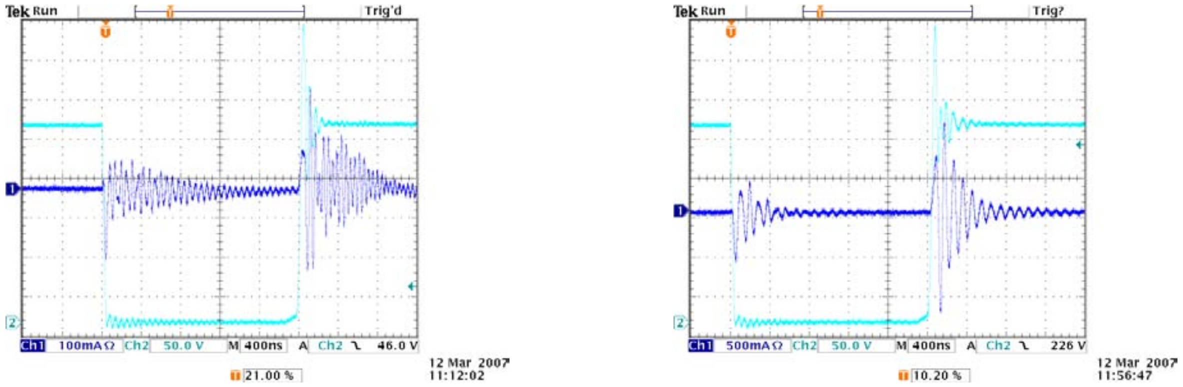
Silicone-encapsulated Coil #3 (Shaped)



(a) Air, 22 Ω (b) Seawater-immersed, 22 Ω



(c) Air, 11 Ω (d) Seawater-immersed, 11 Ω

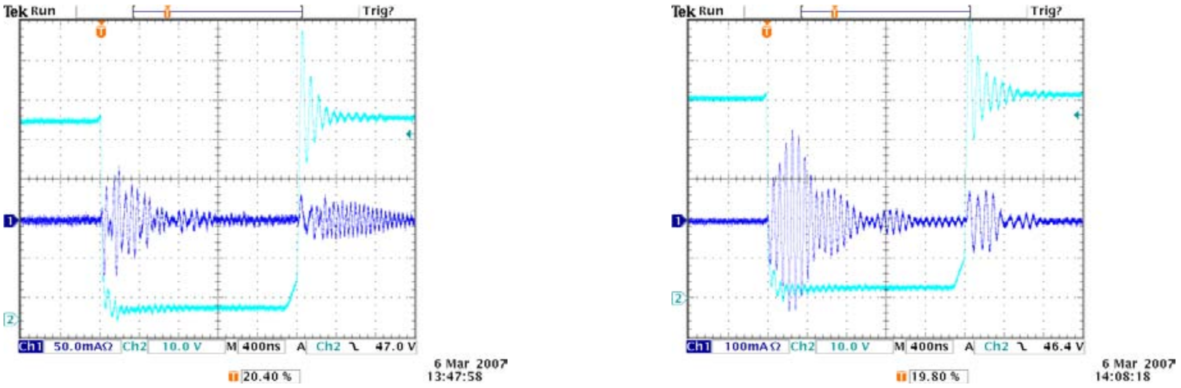


(e) Air, 5,7 Ω (f) Seawater-immersed, 5,7 Ω

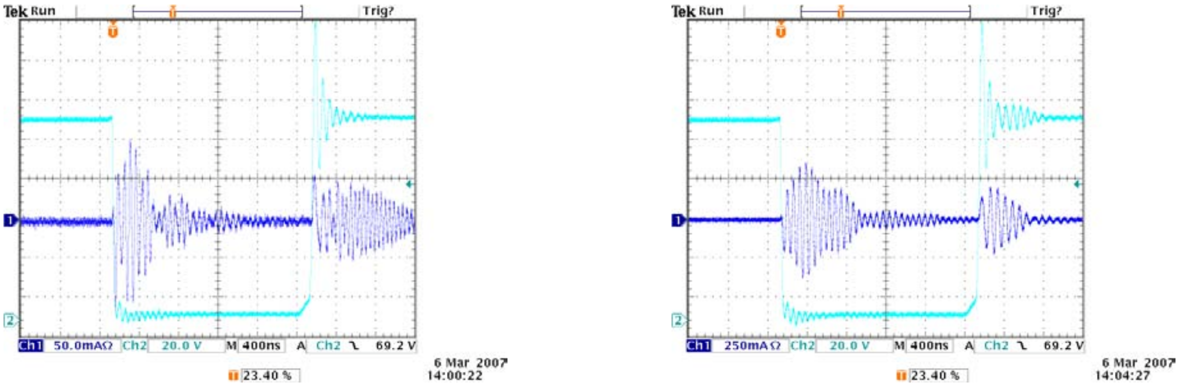
Figure C.3: Silicone-encapsulated Coil #3 (Shaped)

C.2 Comparison Of Different Switching Voltages

Copper Coils

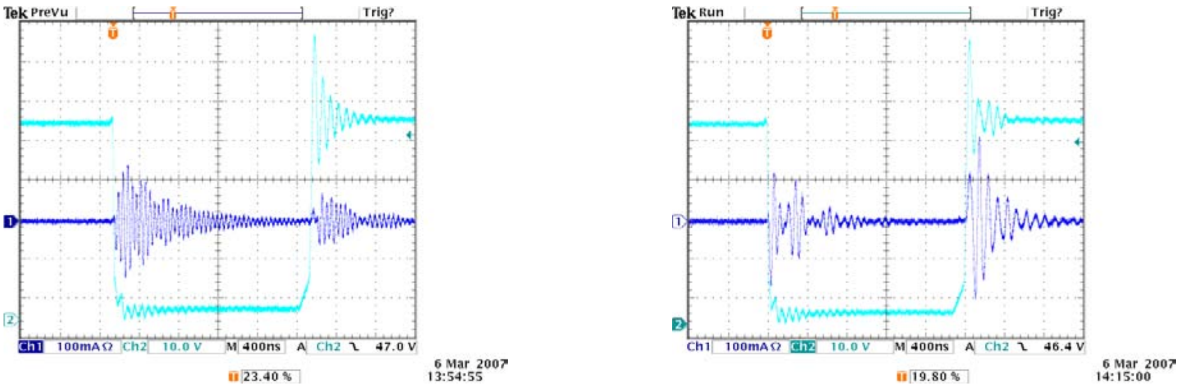


(a) Air, 50 V (b) Seawater-immersed, 50 V



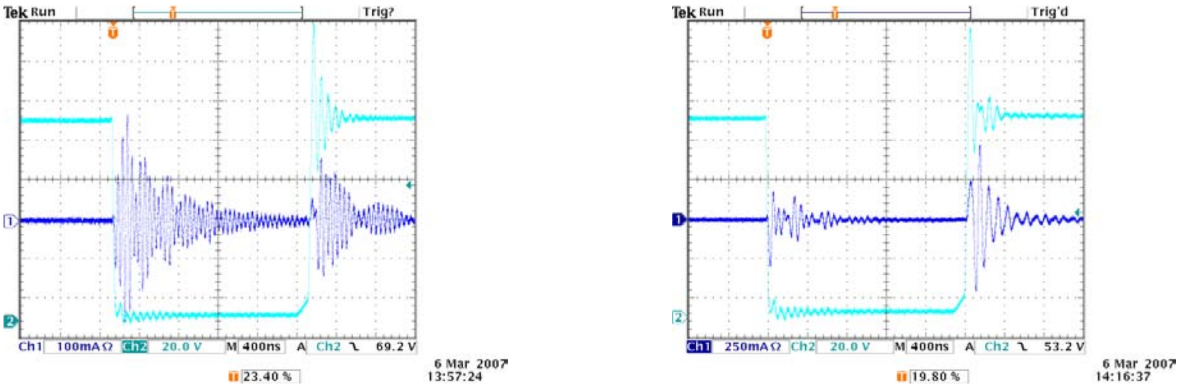
(c) Air, 100 V (d) Seawater-immersed, 100 V

Figure C.4: Copper Coil #1



(a) Air, 50 V

(b) Seawater-immersed, 50 V



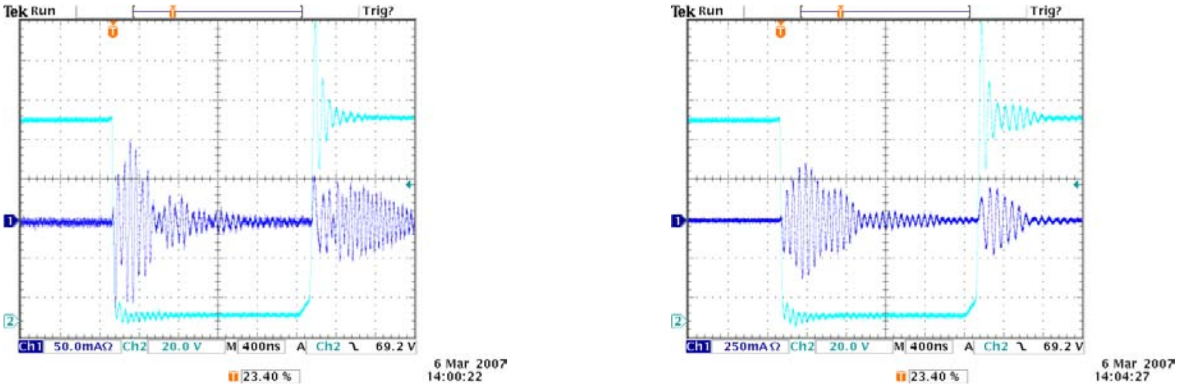
(c) Air, 100 V

(d) Seawater-immersed, 100 V

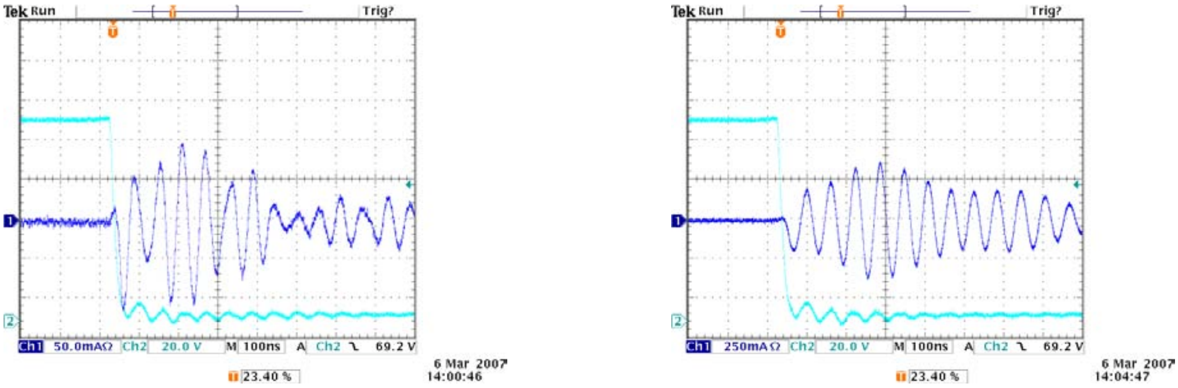
Figure C.5: Copper Coil #2

C.3 Coils

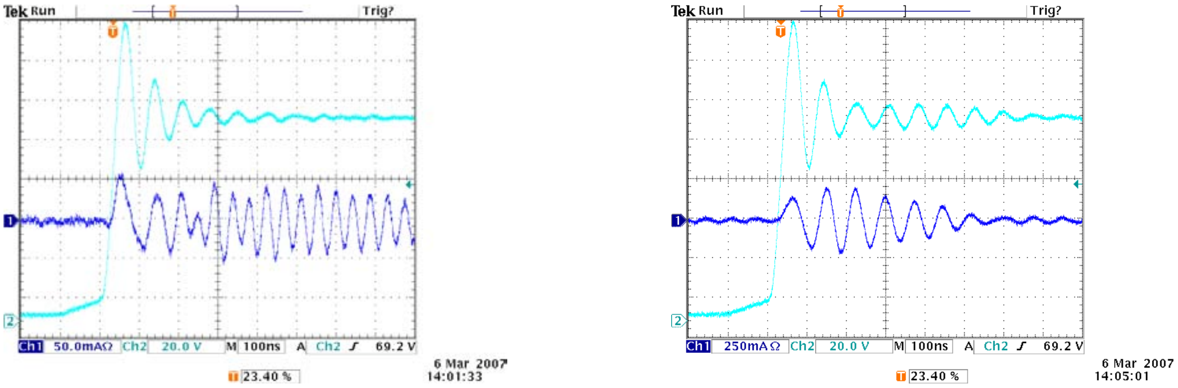
Copper Coils (only at 100 V!)



(a) Air (b) Seawater-immeresed

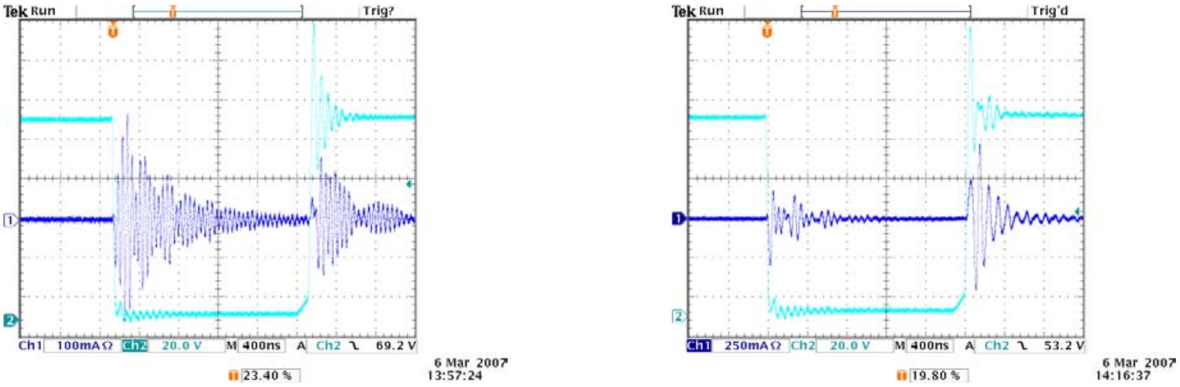


(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)

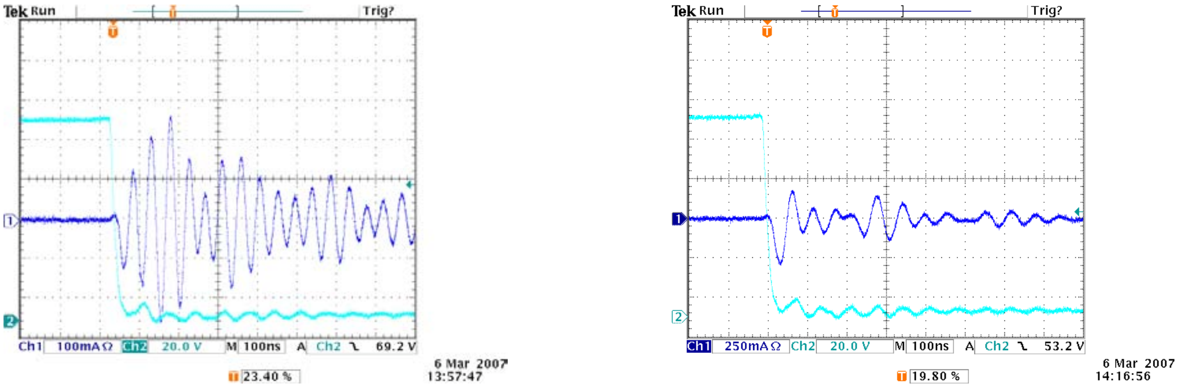


(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

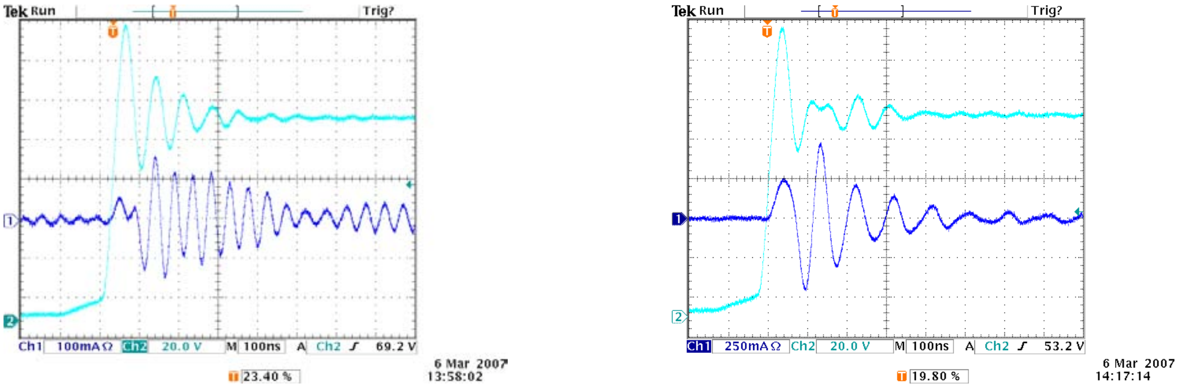
Figure C.6: Copper Coil #1



(a) Air (b) Seawater-immeresed



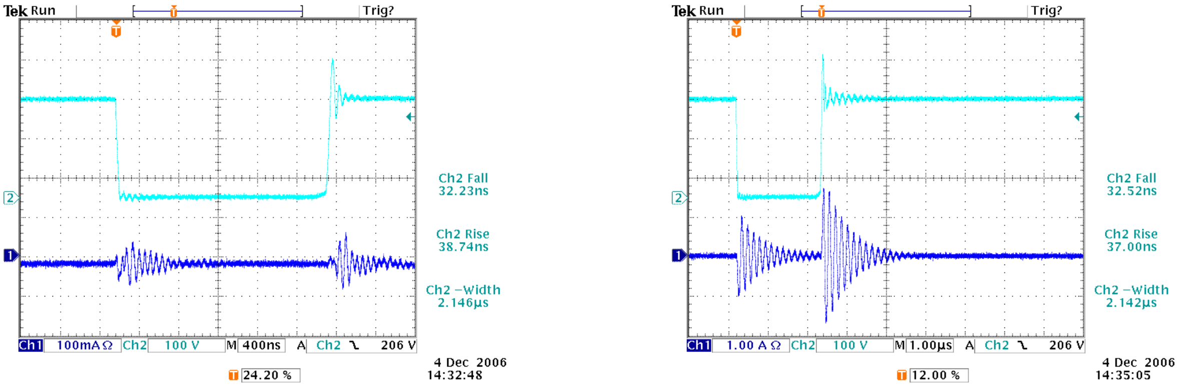
(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)



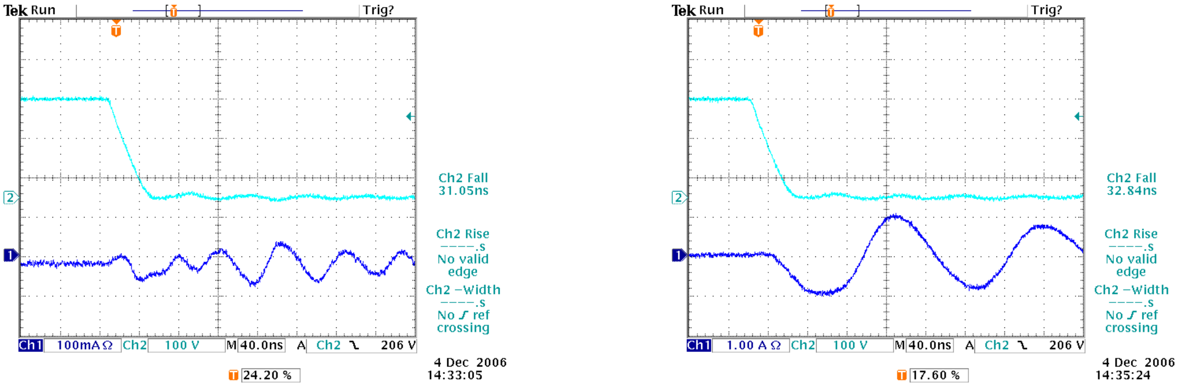
(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

Figure C.7: Copper Coil #2

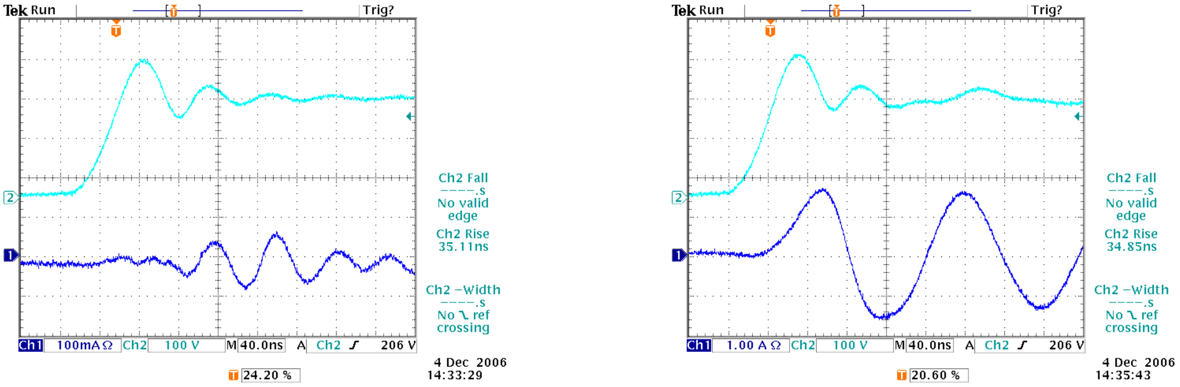
Tape-wrapped Coils



(a) Air (b) Seawater-immeresed

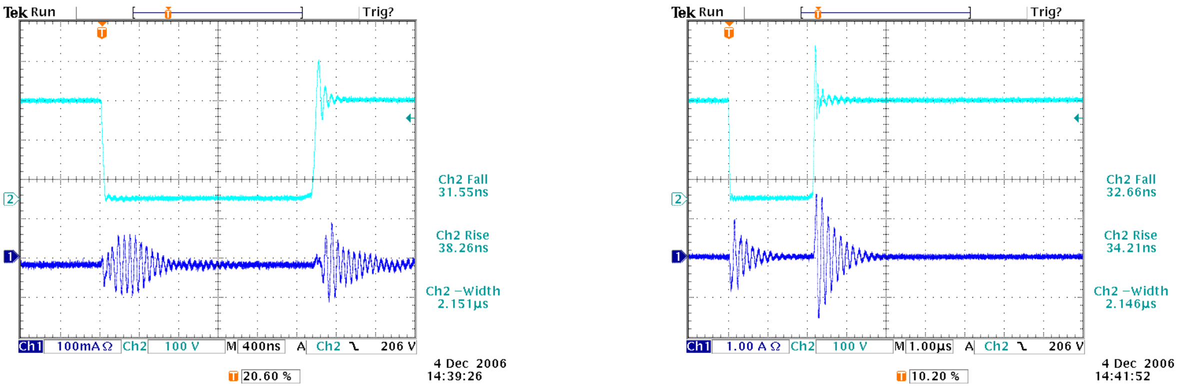


(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)

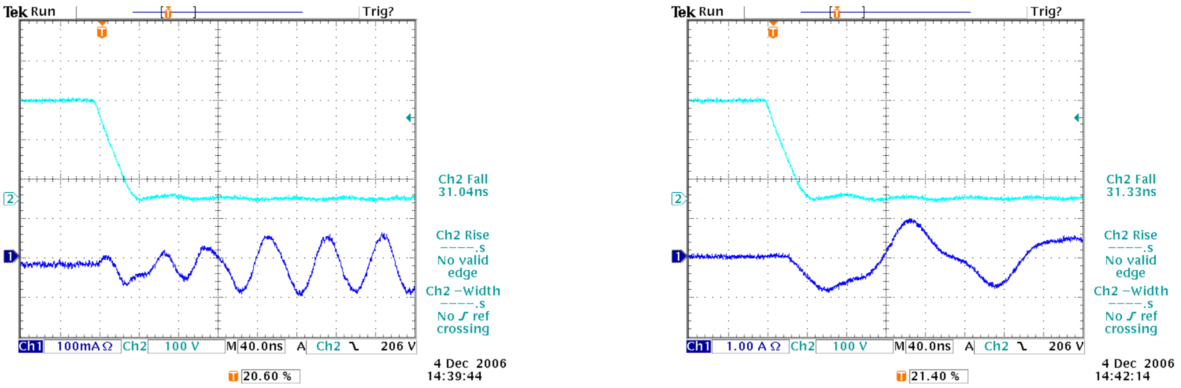


(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

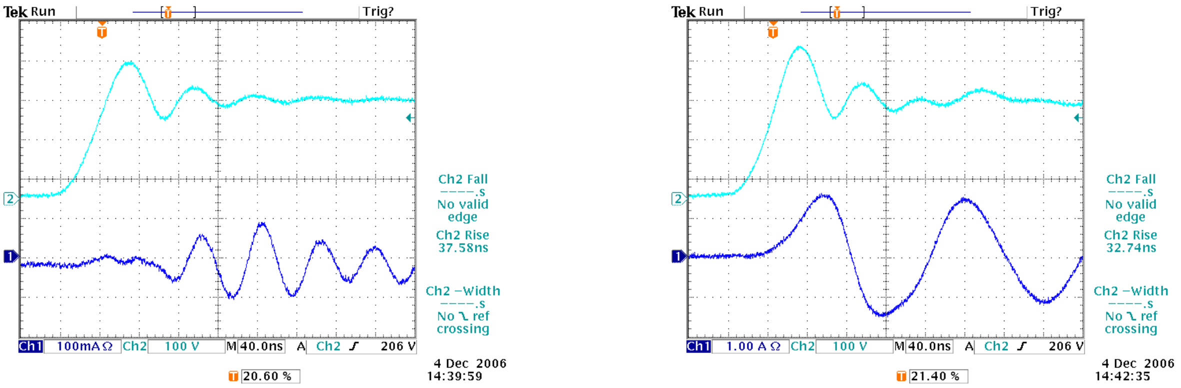
Figure C.8: Tape-wrapped Coil #1



(a) Air (b) Seawater-immeresed



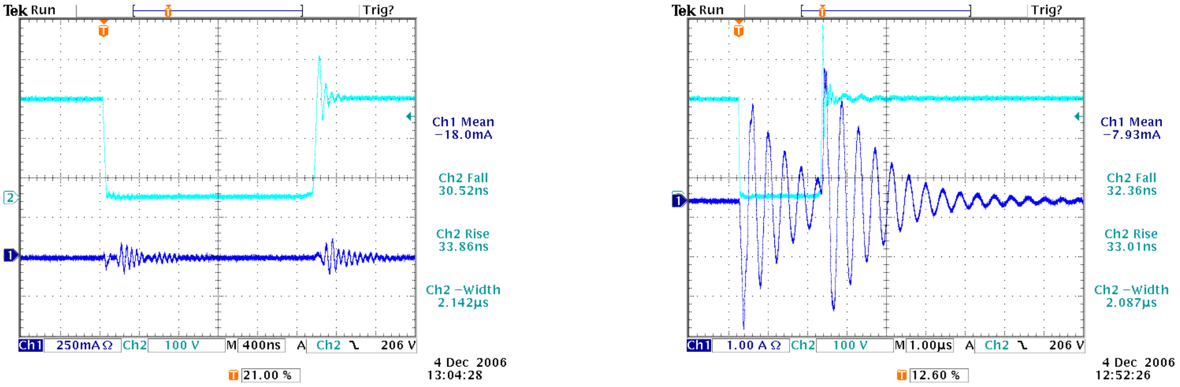
(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)



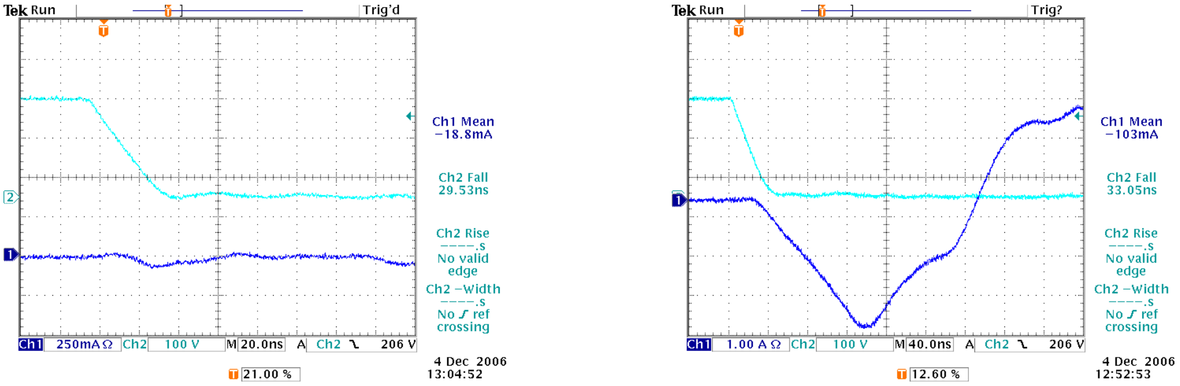
(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

Figure C.9: Tape-wrapped Coil #2

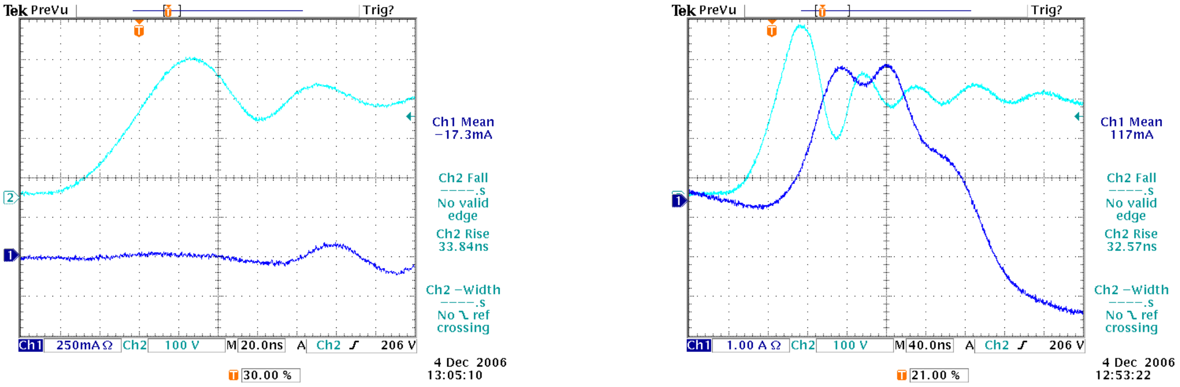
Stranded Wire Coils



(a) Air (b) Seawater-immeresed

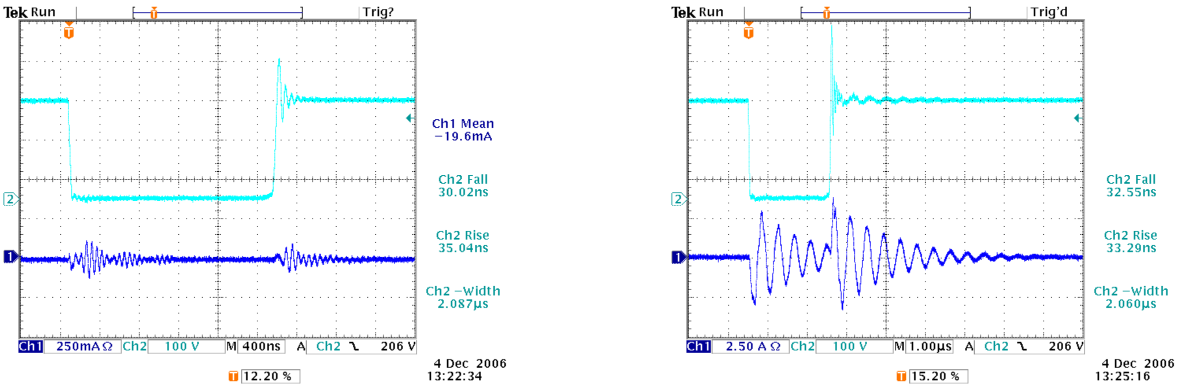


(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)

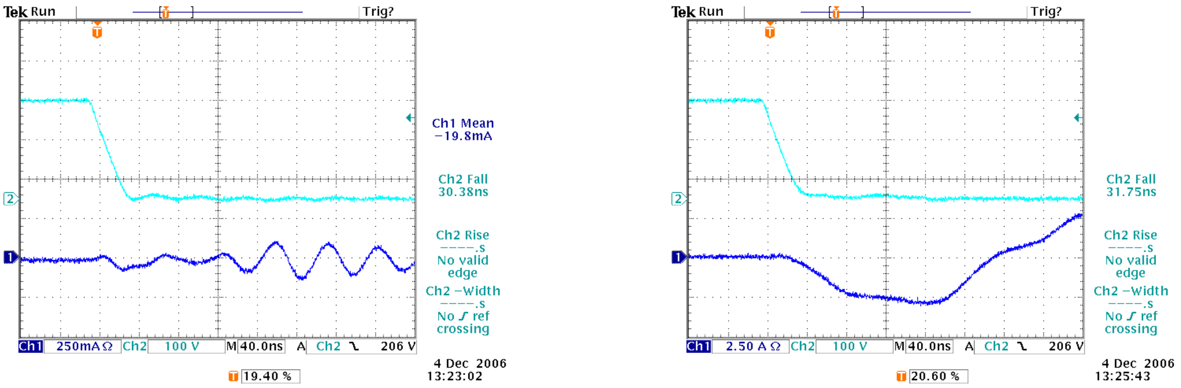


(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

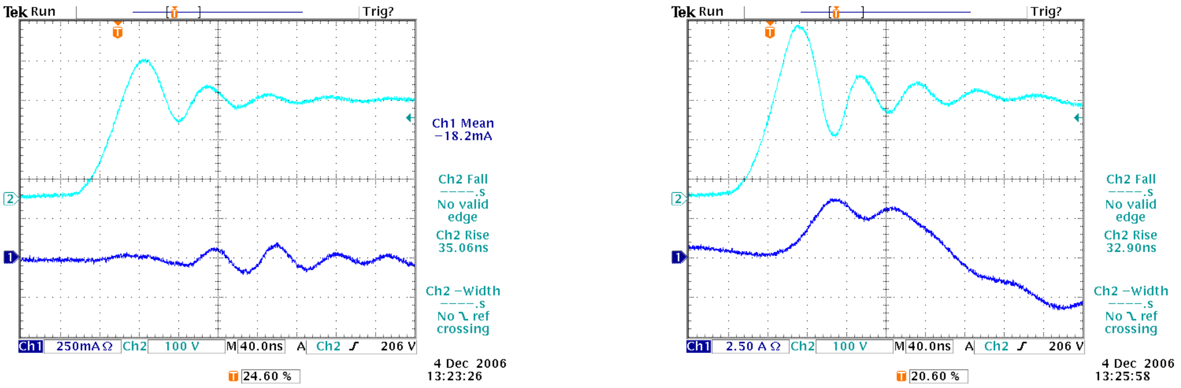
Figure C.10: Stranded-Wire Coil #1



(a) Air (b) Seawater-immeresed



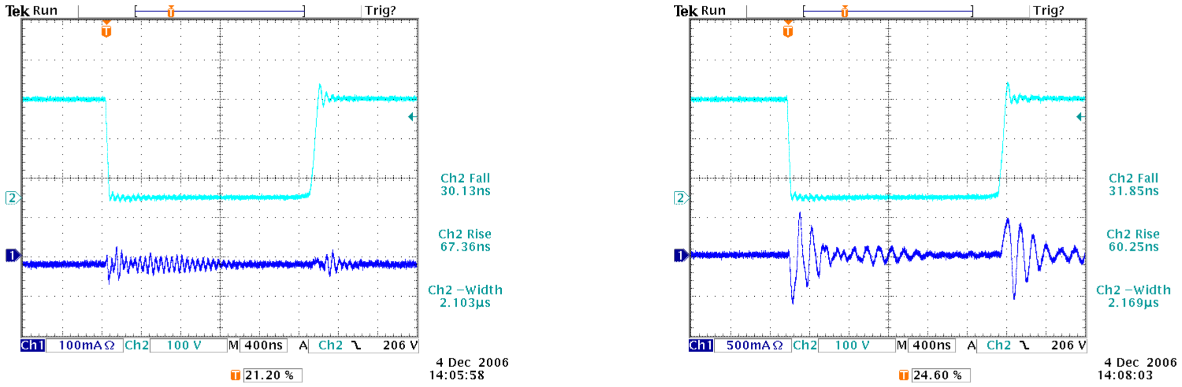
(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)



(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

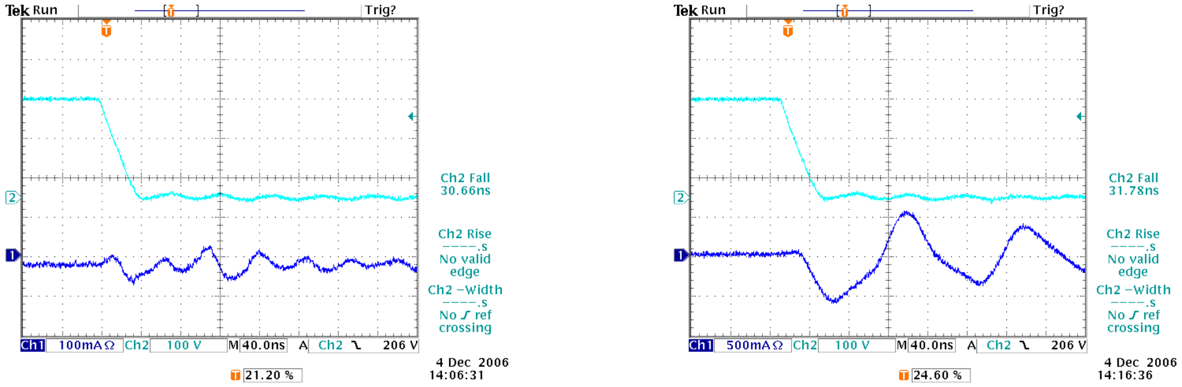
Figure C.11: Stranded-Wire Coil #2

Polyester-encapsulated Coils



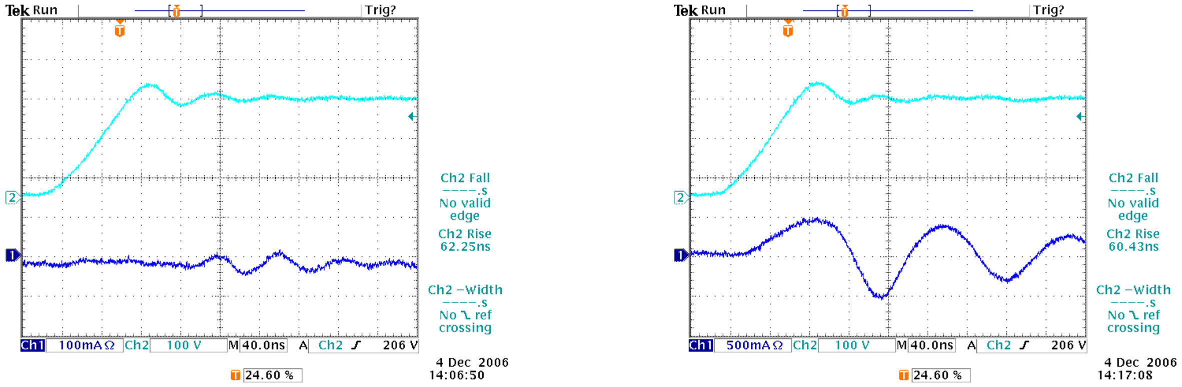
(a) Air

(b) Seawater-immeresed



(c) Air, Switch-off (Detail)

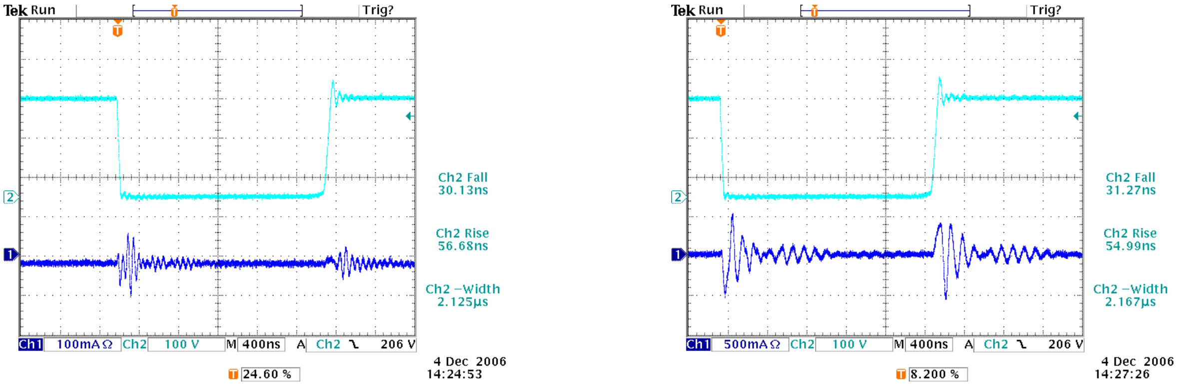
(d) Seawater-immersed, Switch-off (Detail)



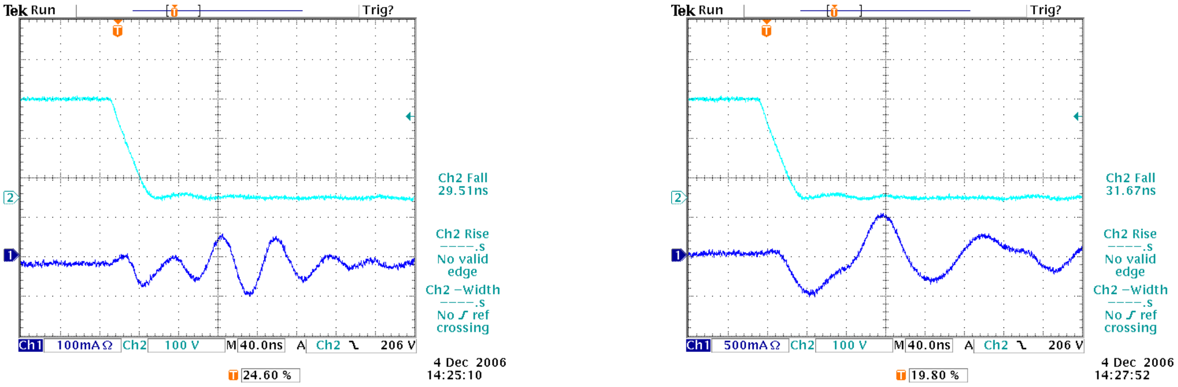
(e) Air, Switch-on (Detail)

(f) Seawater-immersed, Switch-on (Detail)

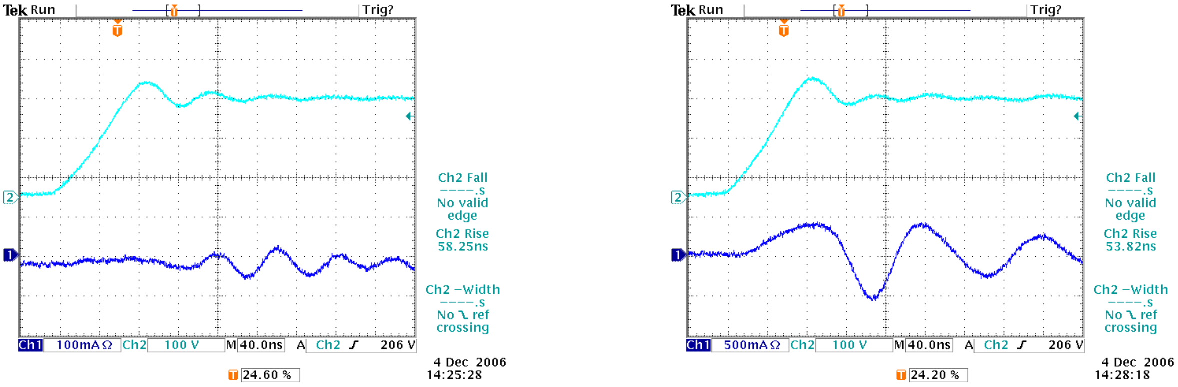
Figure C.12: Polyester-encapsulated Coil #A



(a) Air (b) Seawater-immeresed



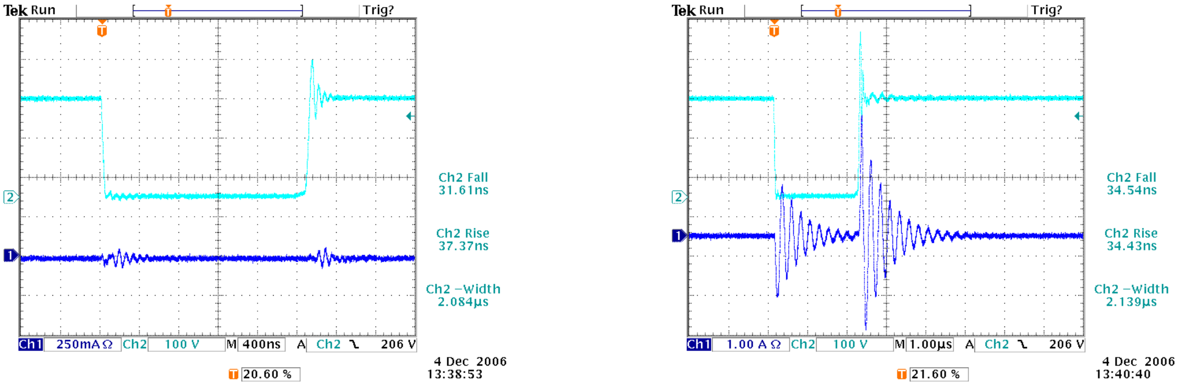
(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)



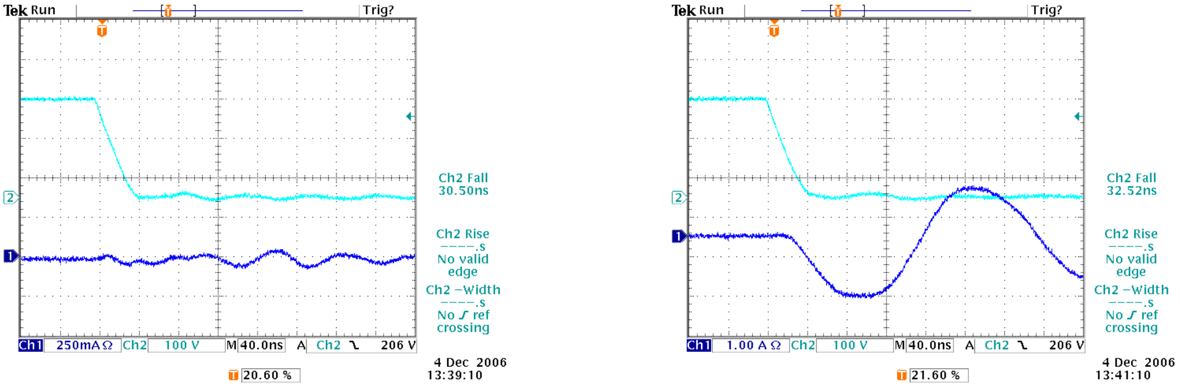
(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

Figure C.13: Polyester-encapsulated Coil #C

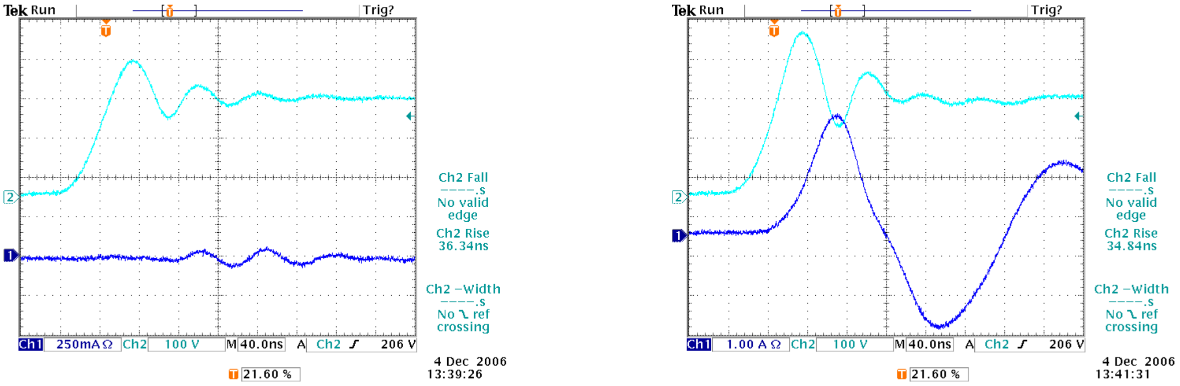
Paper-wrapped/Varnished Coils



(a) Air (b) Seawater-immeresed

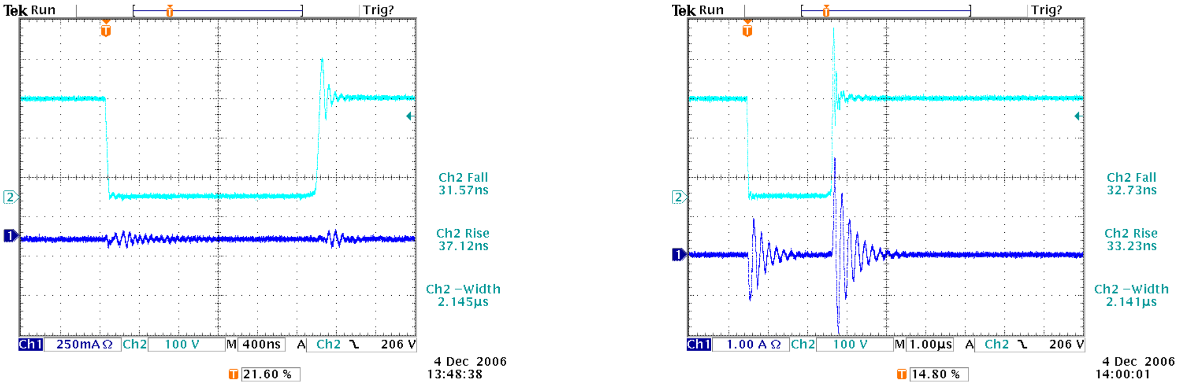


(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)

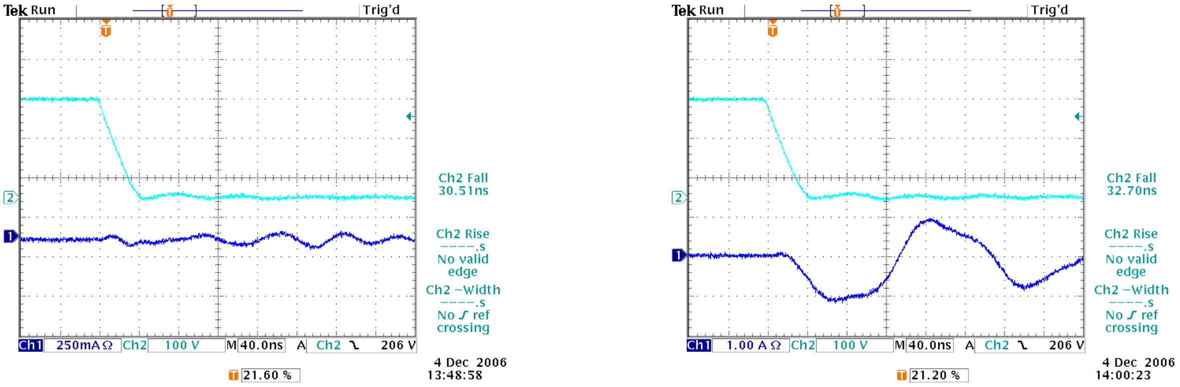


(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

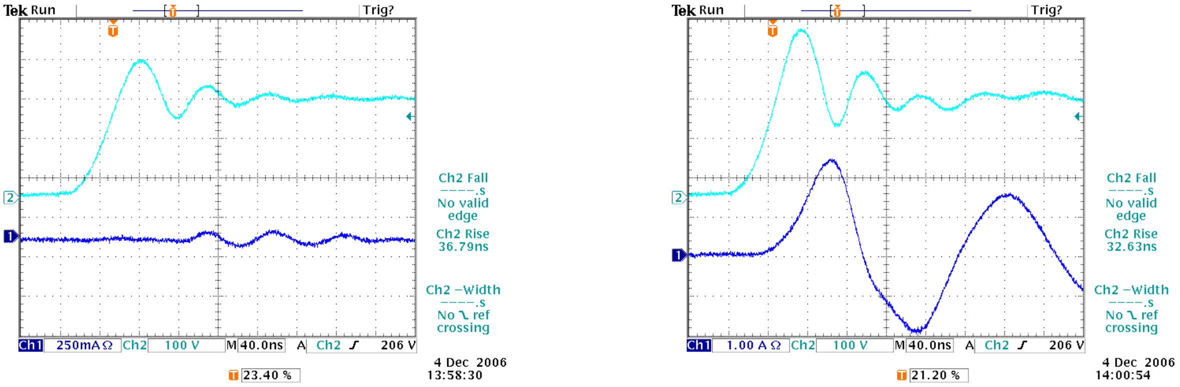
Figure C.14: Paper-wrapped/Varnished Coil #1



(a) Air (b) Seawater-immeresed



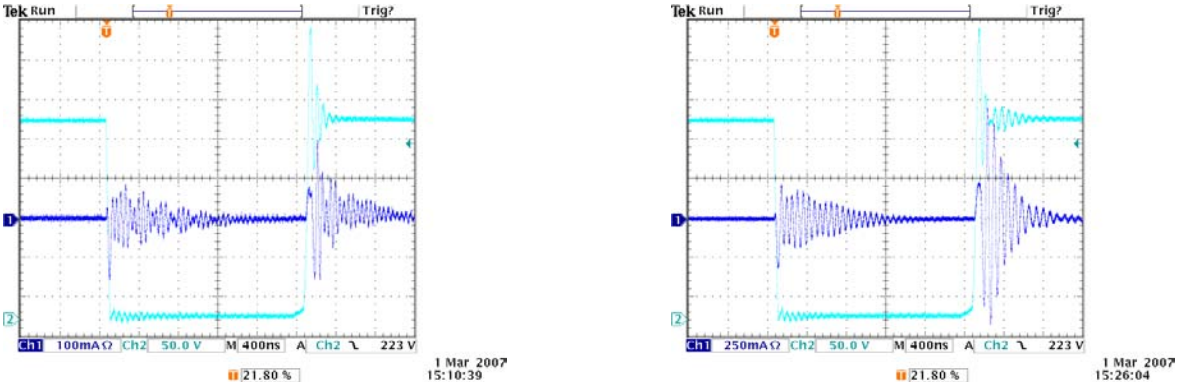
(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)



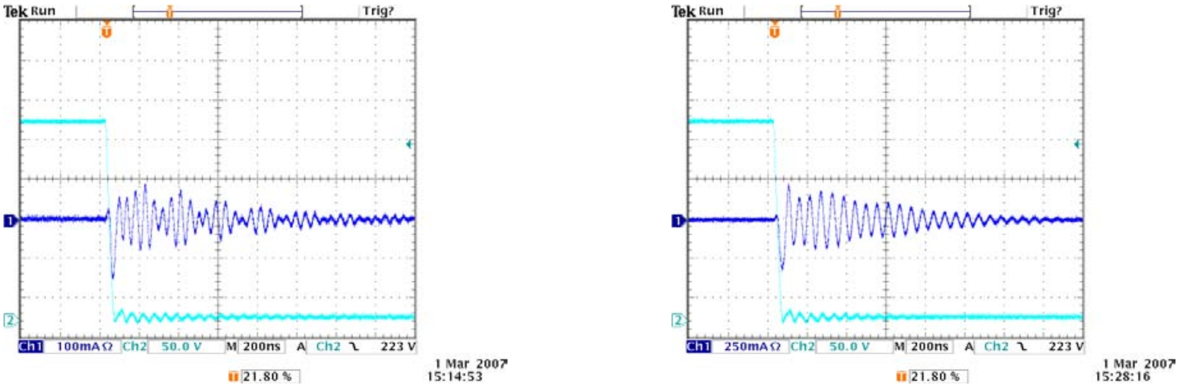
(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

Figure C.15: Paper-wrapped/Varnished Coil #2

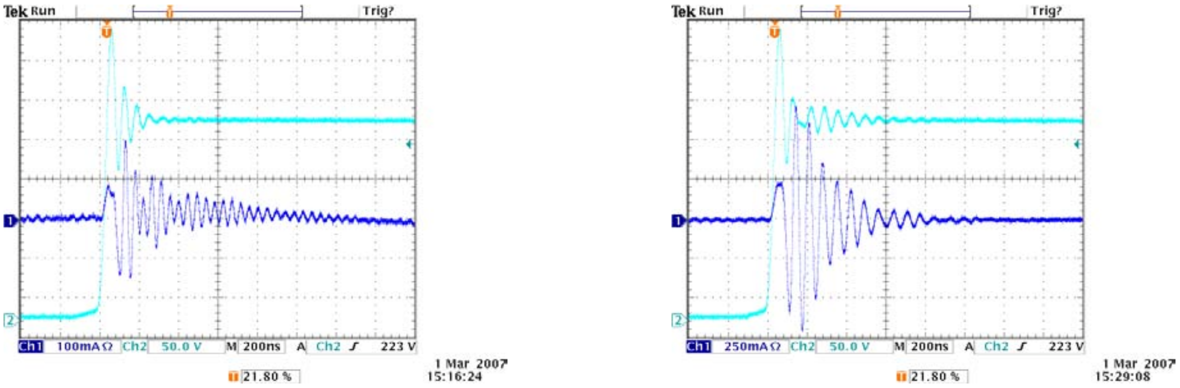
Silicone-encapsulated Coils



(a) Air (b) Seawater-immeresed

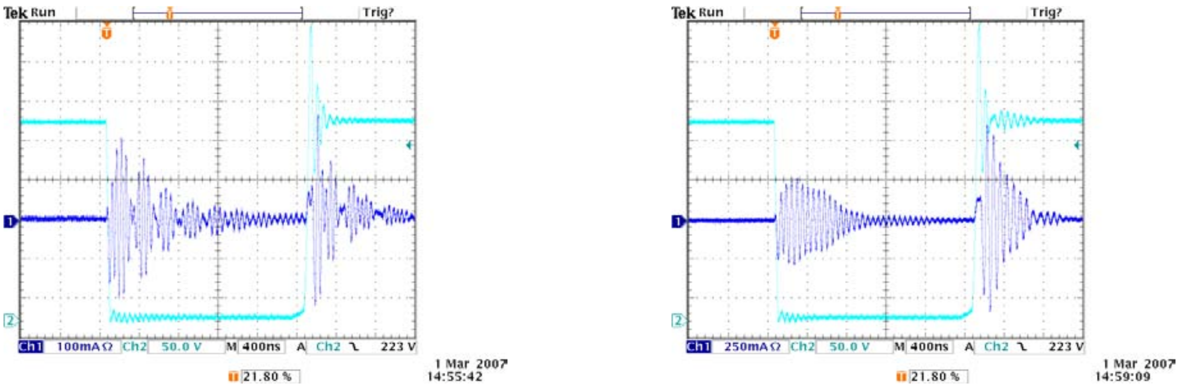


(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)

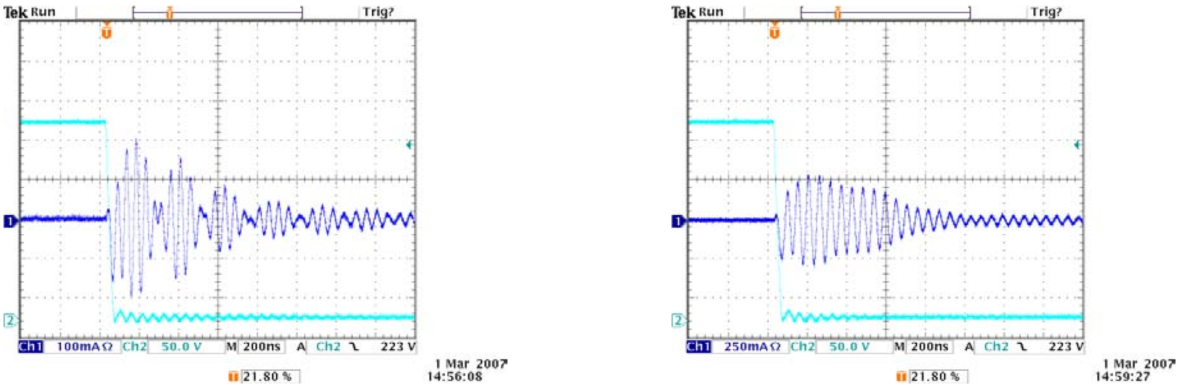


(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

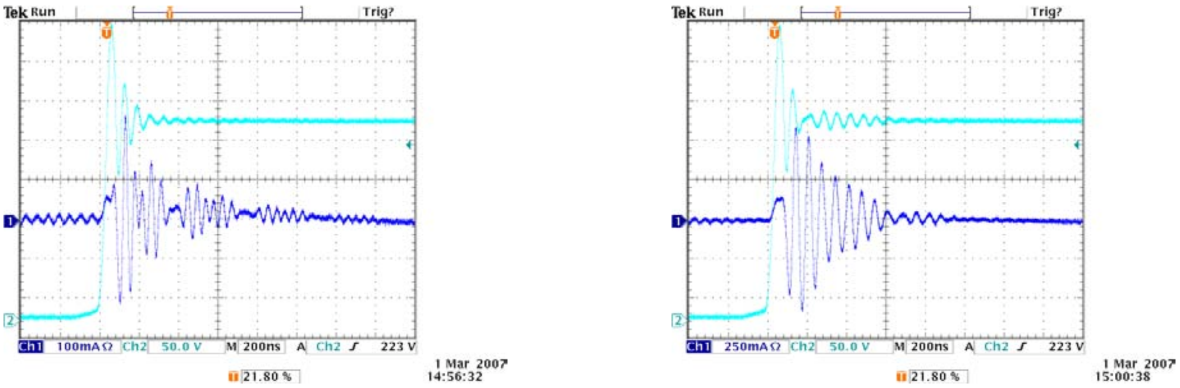
Figure C.16: Silicone-encapsulated Coil #1



(a) Air (b) Seawater-immeresed



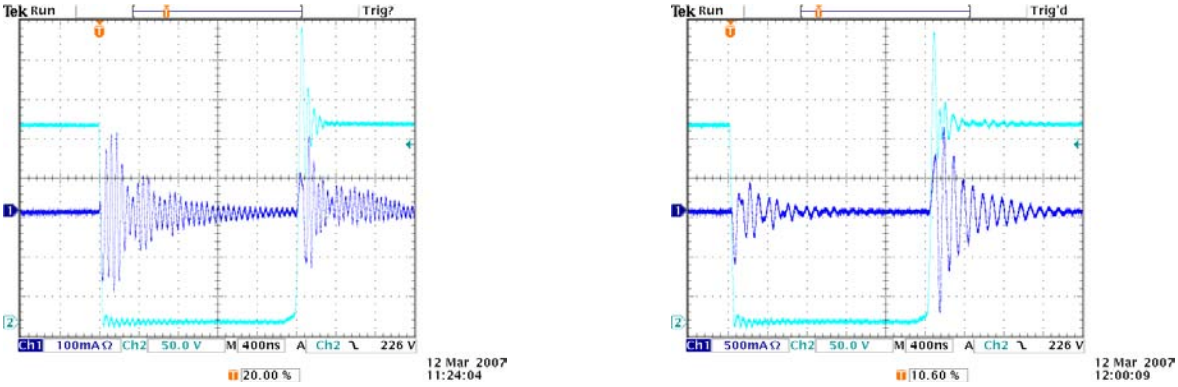
(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)



(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

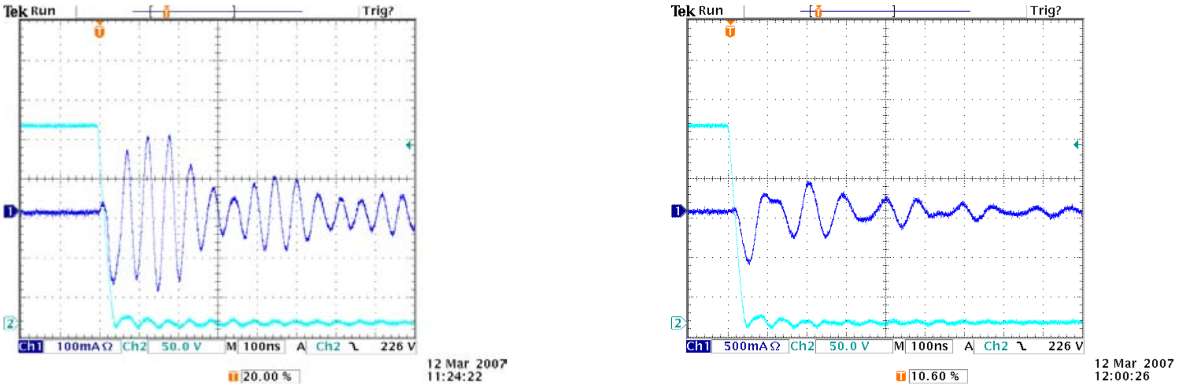
Figure C.17: Silicone-encapsulated Coil #2

Silicone-encapsulated Coils (Shaped)



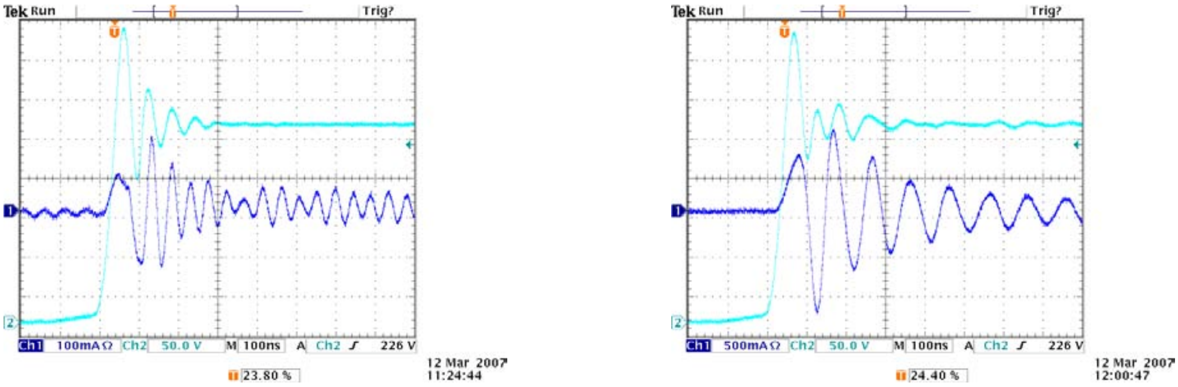
(a) Air

(b) Seawater-immeresed



(c) Air, Switch-off (Detail)

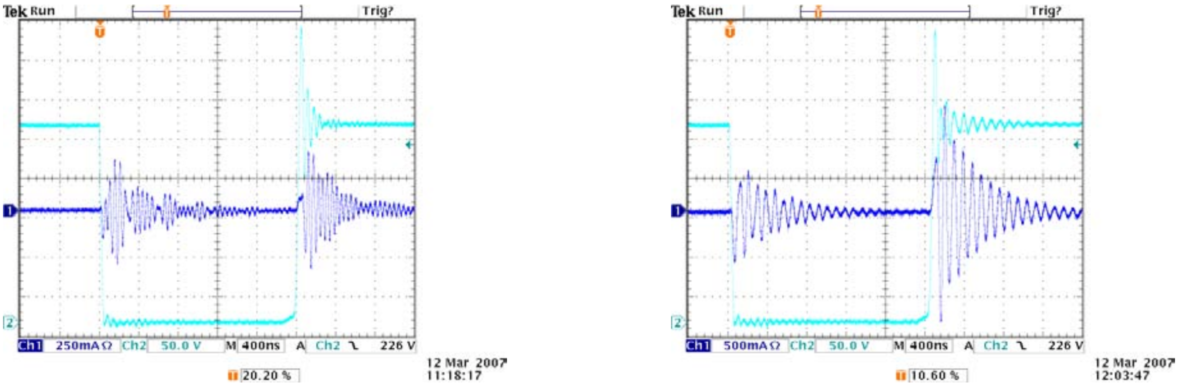
(d) Seawater-immersed, Switch-off (Detail)



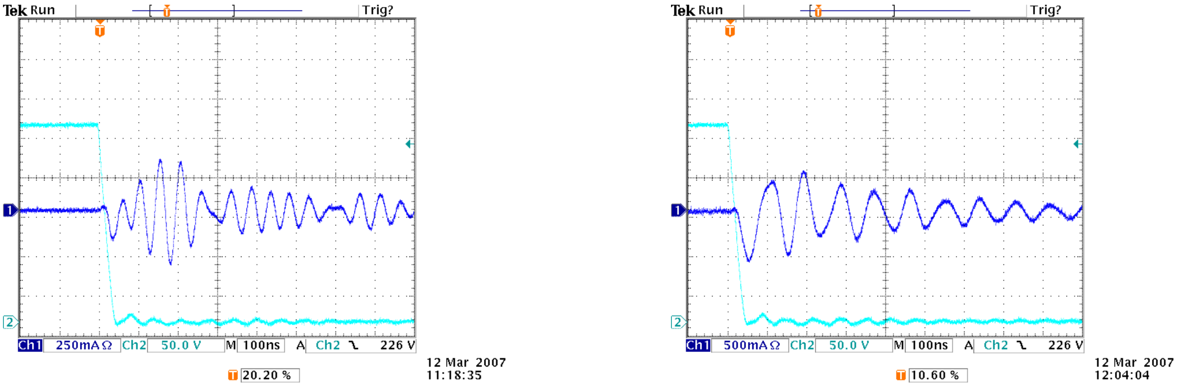
(e) Air, Switch-on (Detail)

(f) Seawater-immersed, Switch-on (Detail)

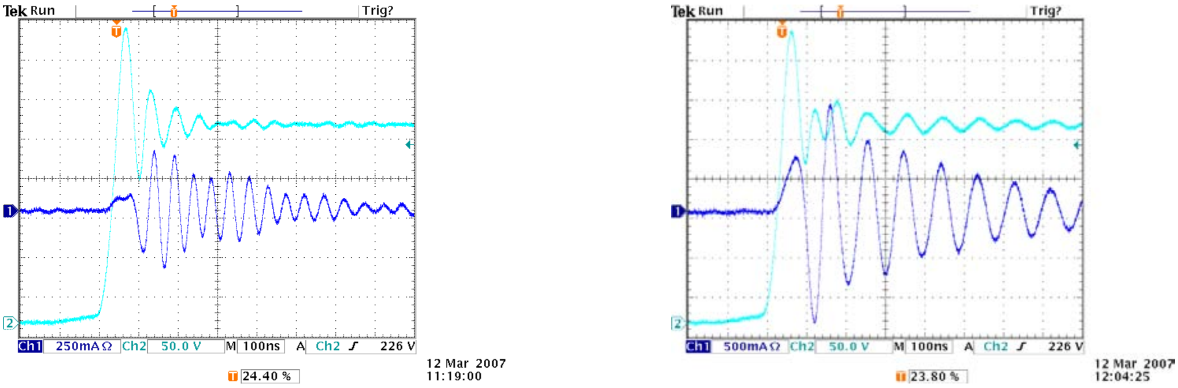
Figure C.18: Silicone-encapsulated Coil #1 (Shaped)



(a) Air (b) Seawater-immeresed

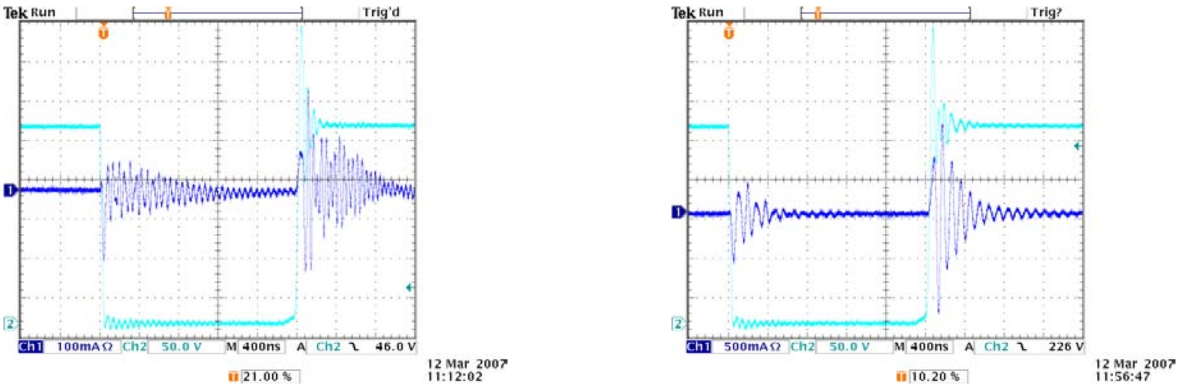


(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)

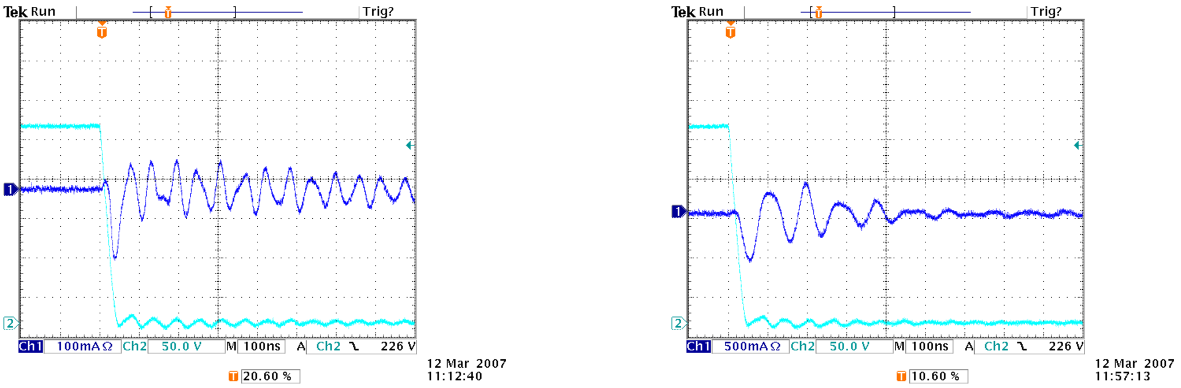


(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

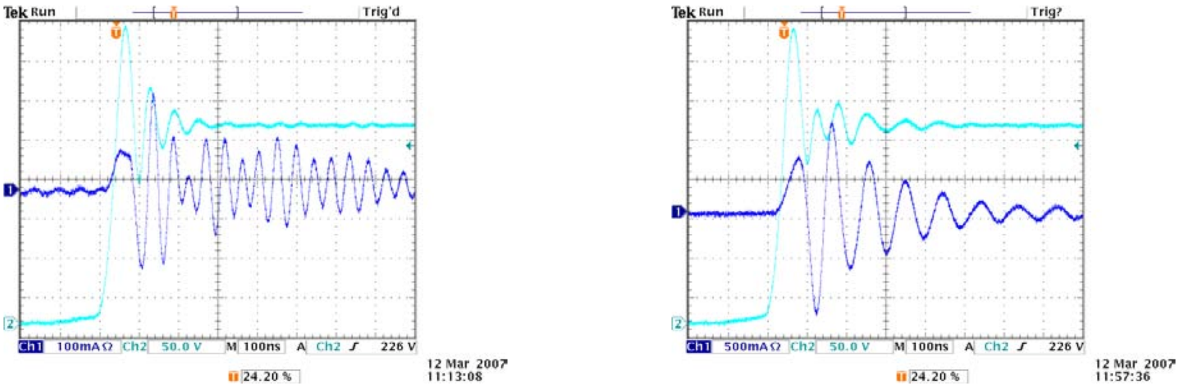
Figure C.19: Silicone-encapsulated Coil #2 (Shaped)



(a) Air (b) Seawater-immeresed



(c) Air, Switch-off (Detail) (d) Seawater-immersed, Switch-off (Detail)



(e) Air, Switch-on (Detail) (f) Seawater-immersed, Switch-on (Detail)

Figure C.20: Silicone-encapsulated Coil #3 (Shaped)