Lysekil Research Site, Sweden: A Status Update

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***Abstract*— At Uppsala University, a wave energy concept is developed on how to harvest wave energy and convert it into usable electric energy. The wave energy converter developed is based on a direct driven linear generator connected via a connection line to a point absorbing buoy. In connection to the wave energy converters, an electrical system is developed which enables a submerged interconnection and conversion of the power from the generators.**

The project has a test site on the Swedish west coast outside the town Lysekil. The test site has been running since 2002, and the first wave energy converter was installed at the site in March 2006. Since then, the site has been continuously updated.

The object of this paper is to present a status update of what has been done at the Lysekil research site from 2006 up until now. The authors will also present experimental results showing power absorption and power production from the generators connected to different buoys. To further improve the site, the possibility to connect the system to the grid is prepared and also a second underwater substation is being built for underwater connection of at least seven wave energy converters.

***Keywords*— Wave power test site, linear generators, offshore experiments, power production, point absorber.**

I. Introduction

According to the International Energy Agency (IEA) the Lysekil research site is one of four test sites in Europe that can be called a pre-commercial test site. In a pre-commercial test site it must be possible to investigate multiple device performance, device array interactions, power supply interaction, environmental impact issues and a full technical and economic due diligence [1].

The wave power research site in Lysekil has been ongoing since 2002. Research in this area is a multiphysics challenge that requires knowledge in different areas such as hydrodynamics, biology, mechanics, electricity, etc. which will be seen in this paper.

The first wave energy converter (WEC) based on the directly driven linear generator concept was installed in March 2006 and started to deliver power to a resistive load on shore [2]. Since then, seven more WECs have been built and installed at the test site. One marine substation has been installed for connecting and converting the electrical power from the WECs and transmit the power to shore. Moreover, another marine substation is being developed for connection to the grid. Other research groups working with linear generators for wave energy conversion have presented their work in [3, 4].

Environmental and buoy motion studies also take place at the Lysekil research site. The site has been equipped with approximately thirty biology buoys with the purpose of studying the environmental impact from buoys on the surface and concrete foundations on the seabed. For the motion studies, an observation tower has been installed.

In this paper, the authors present what has been done at the Lysekil research site and some of what the future holds. Moreover, the authors highlight important results and areas that need further studies.

The focus of this paper will be on the updates done after 2008. The work done prior to 2008 is presented in [5]. Experimental results will be presented from the second and the third WEC installed at the test site when connected to different buoys.

II. Lysekil Research Site

The research site is located outside the town Lysekil on the west cost of Sweden, about 2 km from the nearest island called Härmanö, see Fig. 1. Two navigational markers between a northern (58° 11´ 850 N; 11° 22´460 E) and southern (58° 11´ 630 N; 11° 22´460 E) are highlighting the site. The seabed at the site is relatively flat and consists mainly of sandy silts, it has a depth of around 25 m and covers an area of about 40,000 m^2. The idea is to have a test site where full scale wave energy converters can be tested under realistic circumstances, with possibilities to connect a number of generators together and transmit the power to the grid. To measure the wave climate, the test site is equipped with a measuring buoy positioned in the western corner of the site. The wave power project has permission to install ten WECs, thirty biological buoys, one substation, one observation tower placed on a skerry, called Klammerskär and one subsea power cable to shore until the end of 2013.

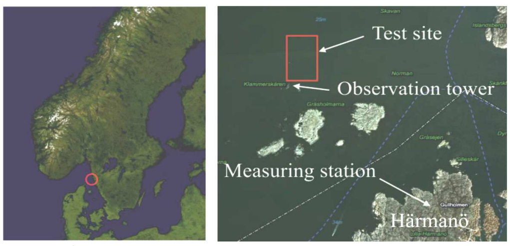

Fig. 1 Location of the Lysekil research site

In Fig. 2 an illustration of the test site subsea is presented with nine WECs, one substation, and a subsea power cable to shore. The WECs and the marine substation illustrated in the figure have all been or are installed at the test site, except for the WEC, L6.

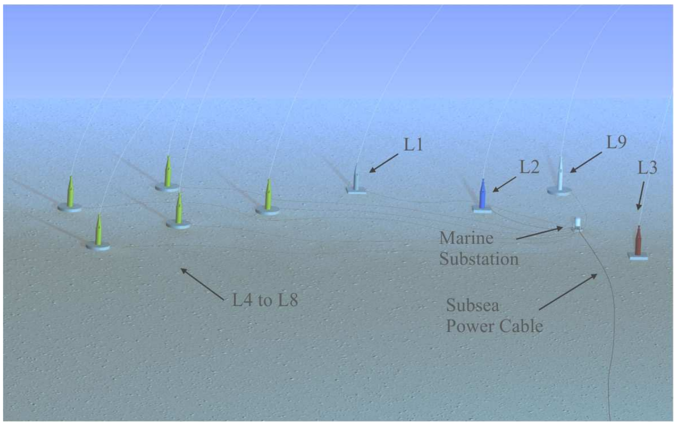

Fig. 2 Illustration of the Lysekil research site subsea

A. *Wave Energy Converter*

The WEC developed by the Division for Electricity at Uppsala University basically consists of a buoy connected via a connection line to a linear generator placed on the seabed. The linear generator is protected by a pressurized capsule and is kept down at the seabed by means of a concrete foundation. An illustration of the WEC with the most essential parts is shown in Fig. 3.

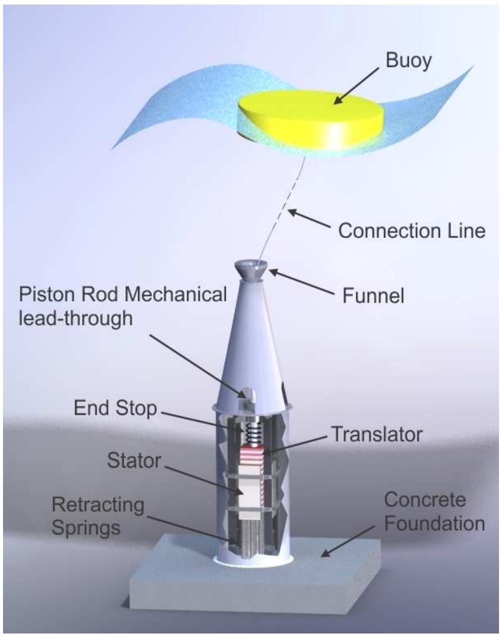

Fig. 3 Description of the WEC developed at Uppsala University

Table I presents the WECs installed at the test site and those planned to be installed in a near future. It also shows the number of phases, the number of translator stator sides and which type of retracting force is used, tensile springs or weight.

TABLE I
WEC: s at Lysekil Research Site

WEC	Generator	Retracting Force	Installed	Progress*
L1	3 Phase 4-Sided	Springs 6.2 kN/m Weight 1200 kg	Mar 2006	No buoy attached
L2	3 Phase 4-Sided	Springs 6.2 kN/m Weight 1200 kg	Feb 2009	Lifted-up Oct 2009
L3	3 Phase 4-Sided	Springs 6.2 kN/m Weight 1200 kg	Feb 2009	Lifted-up Oct 2009
L4	3 Phase 4-Sided	Weight 2900 kg	Nov 2010	No buoy attached
L5	3 Phase 4-Sided	Weight 2900 kg	Nov 2010	No buoy attached
L6	3 Phase 4-Sided	Weight 4200 kg	-	Planned 2011
L7	1 Phase 4-Sided	Weight 4200 kg	Nov 2010	Running
L8	1 Phase 4-Sided	Weight 4100 kg	Nov 2010	Running
L9	3 Phase 8-Sided	Weight 2700 kg	Oct 2009	Lifted-up Nov 2010
L10	3 Phase 8-Sided	Weight	-	Planned 2011
L11	4 Phase 8-Sided	Weight	-	Drawing Board

* 2011-04-29

The first WEC, L1, installed at the test site in March 2006 was a three phase linear generator. In this WEC, the generator was built on an inner framework structure with four sides. The stator sections are placed on each side and the translator with permanent magnets mounted on it, moves up and down inside the structure with the help of track rollers placed in each corner. For the retracting force, tensile springs were installed at the bottom of the structure. The inner framework structure was then sealed in a pressurized capsule. [6]

In February 2009, L2 and L3 were installed at the Lysekil test site. The generators were based on the L1 design with a four sided translator and stator. The aim of L1 was to verify the WEC concept on power generation and overall functionality basis. The aim of L2 and L3 was twofold. The first aim was to complete the first wave power park experimental set-up with three WECs and a marine substation and transfer the power to shore. The other aim of L2 and L3 was to enable the evaluation of individual mechanical subsystems, the operating conditions and the overall WEC performance by introducing measurement technology and a multitude of sensors. L3 was especially upgraded with a new and subsequently patented generation of the piston rod mechanical lead-through transmission. L2 and L3 contained many mechanical upgrades and improvements, but had the same electrical design as L1. L2 and L3 were to an extent customized to enable the fitting of some sensor set-ups, such as, L2 having a slightly higher generator capsule in order to make room for a laser sensor set-up and L3 having a slightly higher superstructure due to the new piston rod mechanical lead-through technology. To protect the WECs from going un-damped each WEC were equipped with a resistive load, dump load. This is used when the WECs are not connected to the marine substation or the measuring station e.g. during installation and maintenance.

In the end of 2009, L2 and L3 were lifted-up, and at the same time, L9 was installed at the site. L9 has a new design with an eight sided translator and stator. The stator sections are mounted directly on the generator capsule instead of using an inner framework structure as in L1-L3. This resulted in a generator capsule with a smaller diameter and with less material used. With the larger active stator area, L9 produces higher voltage at the same translator speed compared to L1-L3. L9 has the same length on the translator versus the stator and is using the translator weight instead of tensile springs for the retracting force of the translator. L9 was lifted for inspection in November 2010 and during the same month; four new WECs were installed at the test site; two three phase generators, L4 and L5 and two single phase generators, L7 and L8. They are all built on the old design with a four sided translator stator, but as L9, the translator weight is used as the retracting force and they use the L3 design on the piston rod mechanical lead-through. L7 and L8 also have built-in electrical circuits connected to them, L7 has a resonance circuit and L8 has a diode rectifier.

A number of different shapes and sizes of buoys have been tested on the generators. The aim is to find a buoy that is optimal both in absorption of the ocean waves and for the electric production at regular sea states, while reducing maximum strains in heavy sea states. Mainly three types of buoy shapes are tested; the cylindrically shaped, torus shaped and discus shaped buoys. In Table II, the buoys tested at the Lysekil research site and on which WEC they have been connected to are presented. In Table II, d=diameter, h=height. For Torus d_1=overall diameter and d_2=pipe diameter.

TABLE II
Buoys at Lysekil Research Site

WEC	Shape	Size	Weight	Measurements
L1	Cylindrical	d = 3.0 m h = 0.8 m	1.0 tonne	Force, Acceleration
	Torus	d_1 = 6.0 m d_2 = 0.7 m	2.7 tonne	Force, Acceleration
L2	Cylindrical	d = 3.0 m h = 1.2 m	2.0 tonne	Force Acceleration Pitch Velocity
L3	Cylindrical	d = 4.0 m h = 0.7 m	2.5 tonne	Force Acceleration Pitch Velocity
L4	-	-	-	-
L5	-	-	-	-
L7	Discus	d = 4.0 m h = 2.4 m	2.4 tonne	-
L8	Discus	d = 4.0 m h = 2.4 m	2.4 tonne	-
L9	Torus	d_1 = 6.6 m d_2 = 1.0 m	3.5 tonne	-
	Discus	d = 4.5 m h = 2.7 m	3.0 tonne	-

The buoys connected to L2 and L3 had the same type of shape and the same volume, but the buoy of L2 had a smaller horizontal area and was higher compared to the buoy connected to L3. Moreover, the buoys connected to L1, L2, L3 were equipped with two independent sensor measurements, i.e. axial force on the connection line and triaxial acceleration of the buoy. The buoys connected to L2 and L3 were also equipped with pitch velocity sensors. The data from the buoys is transmitted to Uppsala University by the GSM network. In Fig. 4a, three buoys connected to L1, L2, L3 and one biology buoy is shown, and in Fig. 4b, at the top L1-L3 and at the bottom L9 and L4-L6 is shown.

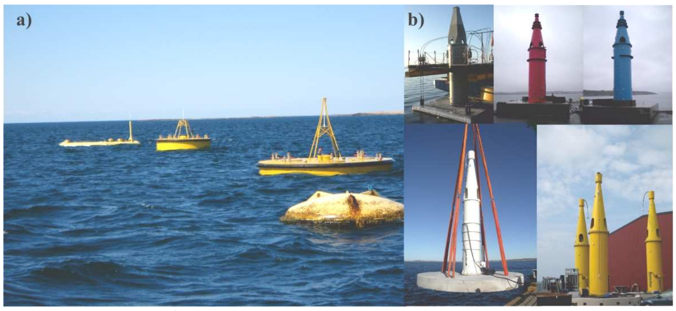

Fig. 4 a) Picture of the buoys and in b) the WECs installed at the Lysekil research site

B. Connection Line

Different types of connection lines between the buoy and the generator have been tested and evaluated. The aim is to develop a line that can be cycled during many years, and to be able to withstand the dynamic forces generated by the ocean waves that can be several times higher than that of the normal working load. Also forces generated between the guidance funnel and the connection line can have an influence on the service life of the connection line. Therefore, experiments at the test site are done on the connection lines and guidance funnels.

The first connection line between the buoy and the generator tested was made of a 36 mm in diameter MegaTwin Vectran with a minimum breaking load of 485 kN. It consists of a Vectran core and is covered with Dyneema Sling, made out of braided Vectran cores and over braided with white Dyneema, see Fig. 5a.

For the second experiment, a rotational resistant steel wire Powerplast with a diameter of 28 mm (tensile strength 1960 N/mm^2) made out of compacted strands with a minimum breaking load of 713 kN was chosen as the connection line see Fig 5b. The steel wire was fully lubricated and housed in a black high density (HD) jacketing compound.

The latest approach is to use another compound covering the HD compound. In this case, the steel wire is housed in 2 layers of jacketing compounds. Firstly, the steel wire was housed in a black HD jacketing compound. Secondly, the wire is covered with the new compound.

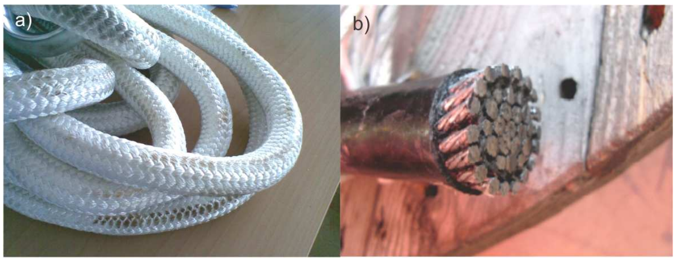

Fig. 5 Two connection lines, a) Dyneema line and b) a steel wire housed in HD jacketing compound

C. Marine Substation

The site is only equipped with one subsea power cable to shore and because of this there is a need for a subsea connection point for all the WECs. The connection point is called a marine substation.

To be able to transmit the power and connect the WECs to the substation there are underwater connectors at the end of the cables from the WECs and at the substation.
In the substation, the AC from each generator is first converted to DC in a diode rectifier and then connected together on a common DC bus to smooth out the power. The DC is inverted back to AC in an IGBT inverter, transformed and transmitted to shore through the subsea power cable to the resistive loads at the measuring station.

The first marine substation was installed in March 2009 and was able to connect three WECs together subsea. In May 2009, L1, L2 and L3 where connected together at the substation and power was delivered to the resistive load in the measuring station. More detailed information can be found in [7]. A one-line diagram showing the electrical connections between the WEC, substation and the measuring station is shown in Fig. 6.

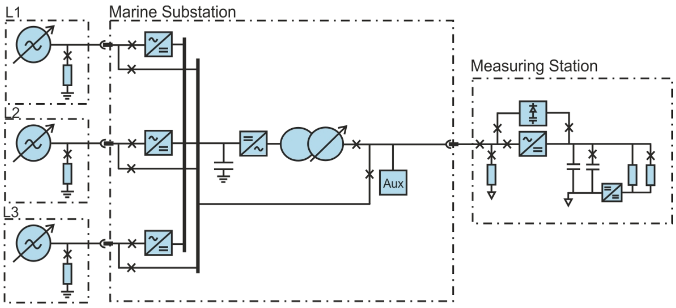

Fig. 6 Overview diagram showing the WECs connected to the marine substation and to the measuring station

D. Measuring Station

In the measuring station all the data from the WECs and the substation is collected. The station is also equipped with a number of different valued resistive loads. It is located on the island Härmanö about 2 km from the test site. A number of upgrades have been done with different electrical circuits since the first WEC was installed. Basically from 2006 to 2008, the measuring station has been equipped with resistive loads and a rectifier circuit with a capacitor bank [8].

In May 2010, a DC-chopper for active control of the DC voltage after the diode rectifier was installed in the measuring station. The idea is to control the damping of the generator, get it to accelerate at different points to produce a higher power.

A novel resonance circuit was installed in September 2010. The reason was to increase the damping of the generators and thereby increase the output power. The circuit is a combination of a rectifier bridge and a resonance circuit. The circuit enables some of the power to oscillate between the capacitors in the bridge and the generator windings and some of the power is delivered to the load. [9]

The measuring station has also been updated with a new electrical connection to be able to handle the two single-phase generators L7 and L8 which will be directly connected through the subsea power cable to the measuring station. This is done partly to further study the resonance circuit and partly to study the performance of a single phase linear generator.

In 2010, the station was upgraded with a grid connection point where the new marine substation will be able to connect to the grid. It consists of a transformer 1/11 kV and all necessary protection for the grid connection.

E. Observation Tower

A 12 meter high observation tower was built and installed at Klammerskär near the site during 2007-2008, see Fig. 7. The aim is to have a self supplying system with a network camera and a weather station to monitor the wave site and for complimentary weather data to the wave measuring buoy. The observation tower is supplied with solar cells connected to a battery bank. Data from the tower is transferred wirelessly to the measuring station through a 3G modem. Images from the camera are used to study buoy-water interaction such as draft and buoy movement and for surveillance of the buoy field. Due to storm and harsh weather the equipment has been exchanged a couple of times with upgrades. The equipment has also been placed higher up in the tower. More information about the observation tower can be found in [10].

Fig. 7 Observation tower at Klammerskär

F. Environment Studies

In 2003, the first location and bottom survey began at the Lysekil test site. Since then, studies of the seabed have been performed on a yearly basis. In conjunction to the environmental study, a number of biology buoys were installed at the site in 2007. They basically consist of a buoy and a rope which connects the buoy to a concrete foundation on the seabed. Due to some issues with the attachment of the rope at the foundations the mooring system has been improved continuously. Ten new biology buoys with a different design on the buoy and five with the old design were installed in 2010. All had a new design on the attachment to the foundation. Studies have been performed on biofouling on the buoys and colonization of species on and around the concrete foundations and on the sediments at the seabed.

Further studies will be performed in long time scale to see how the species will react to the structures placed on the seabed and at the ocean surface at the site. In Fig. 8, biofouling on the funnel and a fish hiding behind L3 is shown. For further readings on the environmental research done at the Lysekil test site, see for example [11].

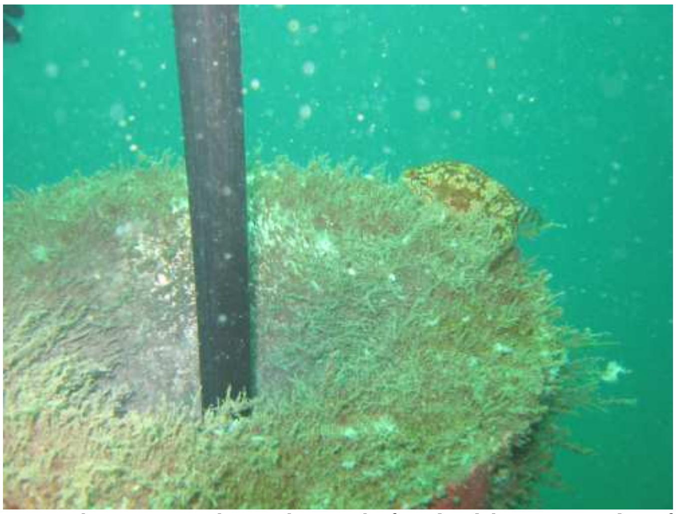

Fig. 8 Subsea picture at the site showing the funnel and the connection line of L3

III. Results

In this section some recent experimental results from the Lysekil test site will be presented. The results in Fig. 9 - Fig. 11, are published or submitted to journals. Results presented in Fig. 12 have not been published.

Movement of the buoy has been studied with images taken from the observation tower camera and by accelerometers placed in the buoy connected to L2. Since the measurement systems at the tower and in the buoy are not synchronized, distributions of measured values over a period are presented instead of a time series. Experimental results from the observation tower on motion study are presented in Fig. 9. It shows that the buoy moves about 2 meters in heave and is drifting about 4 meters in sideway during the period studied.

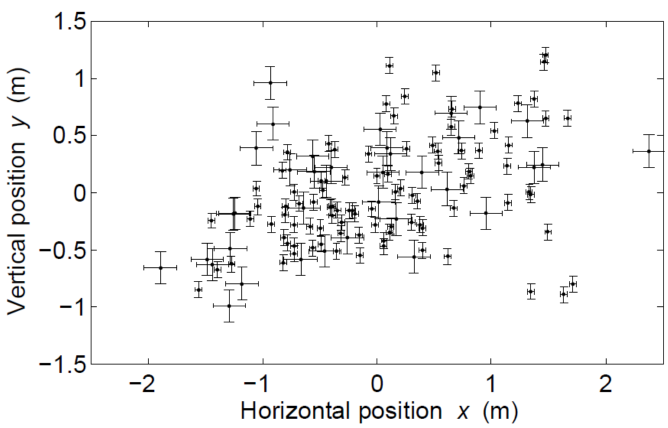

Fig. 9 Buoy position measurement from images, centered around the mean. The short error bars correspond to vibrations in the camera. The longer error bars correspond to uncertainties due to wave shielding. [12]

Results from the interconnection of two WECs, L2 and L3 to a common DC-bus in the marine substation are shown in Fig. 10. The normalized standard deviation of power is compared before the WECs are interconnected and when they are interconnected together on a common DC-bus during 15 minutes. The results show that the normalized standard deviation of power is decreased when the two WECs are connected to a common DC-bus compared to when they are connected individually.

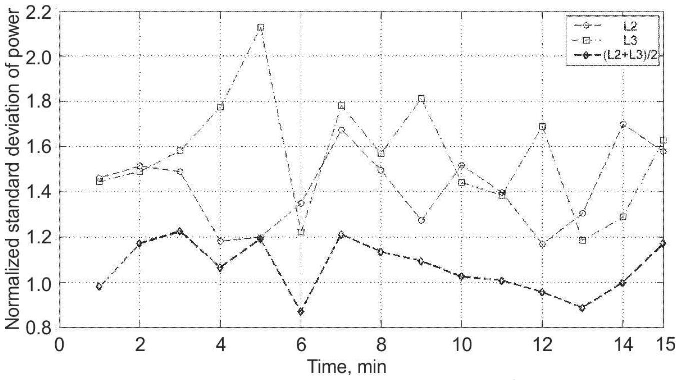

Fig. 10 Comparing the normalized standard deviation of power during 15 minutes between L2 and L3 connected to a common DC bus in the marine substation. [13]

In the experiment with the resonance circuit, L9 was used. In Fig. 11 experimental results on power vs. significant wave height are compared between L1 and L9. Two different load cases are compared. The first case when L1 is connected to 27.5 Ohm, L9 to 27.4 Ohm and the second case when L1 is connected to 9.2 Ohm, L9 to 14.1 Ohm. L9 shows a significantly higher power production compared to L1.

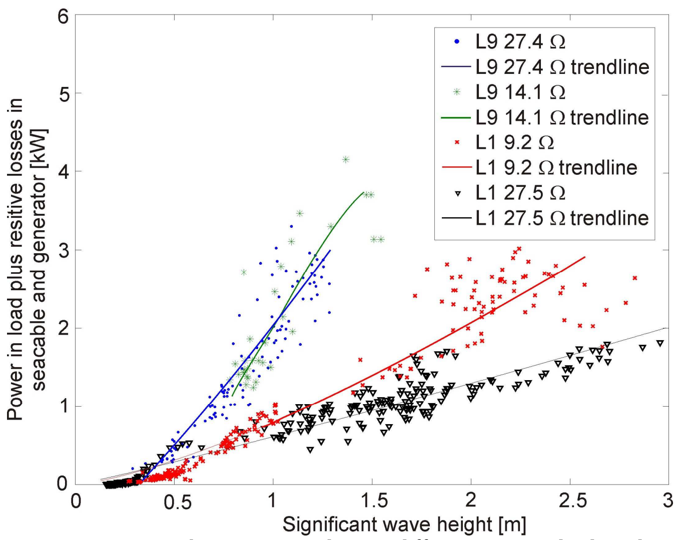

Fig. 11 Comparison between L1 and L9 at different resistive loads and L9 connected to a resonance circuit. [9]

In Fig. 12, experimental results from L2 and L3 are shown. Both of the WECs are connected to a 12 Ohm delta connected resistive load (dump load). The main difference between the two WECs are the buoy size, see Table II. Fig. 12a showing results during one day in July and Fig. 12b one day in August. Each power data point is a mean value over 60 seconds of data sampled with 256 Hz. The energy period data points and the significant wave height data points are calculated mean values over 30 minutes.

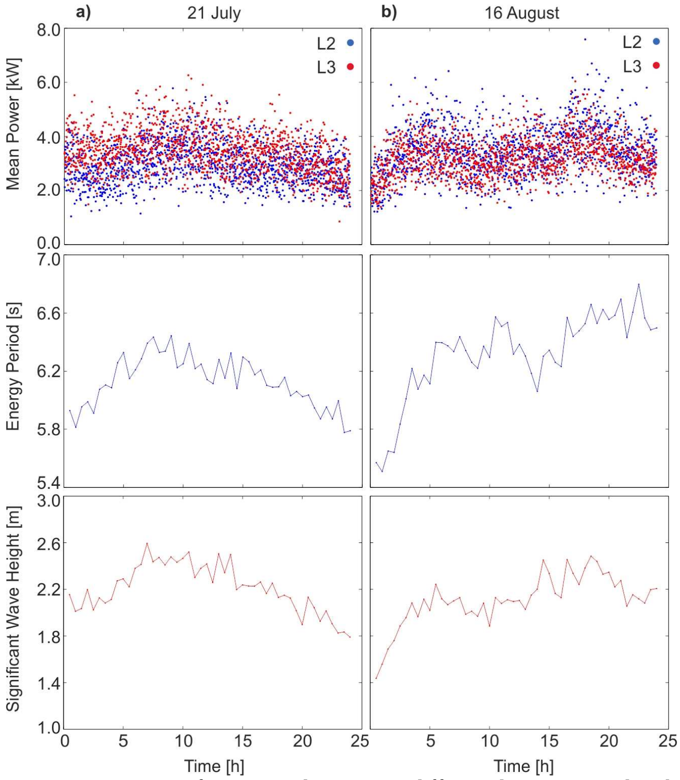

Fig. 12 Mean power from L2 and L3 at two different dates compared with energy period and significant wave height during 24 hours.

IV. Discussion and Conclusion

A lot has happened at the Lysekil research site since the start in 2002. A total number of eight WECs have been installed at the test site. Four have been tested, two has just recently been equipped with buoys and two are awaiting connection of buoys. All with new upgrades and improvements for further studies of the WECs.

The results from the comparison between L2 and L3 shows that the buoys have an influence on the power absorption even though there are small differences between them see Fig. 12. The buoys connected to L2 and L3 were both cylindrically shaped with the same volume but with different height and diameter. In Fig. 12, the significant wave heights in the two different cases are fairly equal but in July L3 is more frequent in the higher power regions. In August, L2 is more frequent in the higher power regions. Variance in the mean power seems to be higher for the buoy connected to L2 especially at higher energy periods compared to L3.

The design of L9 was a big step forward with an increase in power production and a decrease in weight and size compared with L1. The increase in power shown in Fig. 11 has partly to do with the increase in the active stator area. Still, there are improvements to be made and some of them are applied to L10. A new design on the piston rod mechanical lead-through is developed which reduces the height of the WEC considerably. Also, the translator length is increased to increase the activated stator area. L9 and L10 are using the weight of the translator for the retracting motion instead of tensile springs, initial studies has pointed out that the weight of the translator might be too small on L9, further studies on this is needed to improve the WEC further.

In Fig. 11, L9 is connected to a novel resonance circuit. The idea behind the circuit is to increase the damping of the generator and thereby increase the power produced, to avoid high currents at optimal damping of the generator as with the passive rectification with a controlled DC voltage, see [14]. The results show a higher damping of L9 compared to L1 but as mentioned earlier, L9 has been improved and a reference case is needed when L9 is not connected to the resonance circuit to evaluate the impact of the resonance circuit. Further reading on the resonance circuit and the results in Fig. 11 is found in [9].

There has been a lot of work on the connection line between the buoy and the generator. So far, three main types have been tested with some improvements each time. The challenge is to find a connection line that can be cycled a great number of times and also to withstand excessive loads, several times higher than the normal load. A forth type of connection line is being developed which hopefully can handle the extreme forces. Also the material used between the connection line and guidance funnel is studied to reduce friction between them.

Results from the interconnection of two WECs to the substation show as expected a reduction in the deviation of power compared to one single WEC as shown in Fig. 10. More experiments in this area are needed to understand how the interconnection of several WECs will work in different wave directions and wave climates, and to optimize the number of WECs connected together in the marine substation. More information about the results in Fig. 10 can be found in [13]. The ability to connect wave energy devices subsea is of great importance to reduce the cable lengths and also as an alternative to the offshore platforms used in offshore wind power. These results have shown that a subsea substation for wave power can be built and operate subsea. The next step is to connect a marine substation to the grid.

The network camera placed on the tower at Härmanö has worked well to observe the site and to transfer images from the test site. It is also used to study the motion of the buoys at the site. The tower is equipped with one camera which limits the capture of the motion into two dimensions. Experimental results from the motion studies can be seen in Fig. 9 and are compared with results from the accelerometers placed in the buoy of L3 and with simulations in [12]. The results show that the images from the camera can be used for studies on heave motions and draft of the buoys to further understand how they behave in different wave climates.

V. Future Work

Since the permission for the Lysekil research site will expire at the end of 2013, new applications will be initiated to prolong the permission starting with 5 years at a time.

Permission for another subsea power cable to shore and a new substation will also be applied for.

On the WEC side, analyses on the four new WECs will be carried out, starting with the two single phase generators. Also, two more generators are under construction, L10 and L11. L10 has a new design on the piston rod mechanical lead-through transmission. It will reduce the height of the generator capsule and make the WEC considerable shorter. L11 will be fitted with the next generation of mechanical lead-through transmission. It will reduce the number of components and material used even further. The translator on L10 and L11 will be made longer compared to the translator in L9, to increase the active stator area.

On the buoy side, three new torus shaped buoys will be built with an outer diameter of about 6.6 m and a pipe diameter of approximately 1.5 m. They will be connected to L9, L10 and L11.

A new substation is being built at the division. The substation will be able to connect together seven WECs on two different DC buses. It is equipped with two DC/DC converters and two inverters and two transformers with different taps to be able to connect to the grid at Härmanö. It is also possible to connect the first marine substation to the new one to be able to connect a total number of ten WECs together into the grid at Härmanö. The first marine substation will be upgraded with a new multilevel inverter developed at the division and later connected to the new substation at the test site. Multilevel inverters can handle higher power and voltage compared to normal two level inverters used so far in the marine substation. It reduces the dV/dt stress across the devices. Thereby, the output filter size can be considerably reduced.

A hydrophone has just been installed at the test site to study ambient noise and subsea sounds from the WECs and the marine substation. The purpose is to study how different species are affected by the eventual noise and vibration from the WEC and the substation. A set of cameras placed subsea at the test site is planned to be installed to study how fish respond to the WEC in different wave climates. Also test fishing will be started to get an idea of the fish fauna at the site, this will be done at two different locations, the test site and a reference location to compare the fauna. The work on the biofouling on the biology buoys and the sediment test will be ongoing for long-term studies.

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