Study of the operation characteristics of a point absorbing direct driven permanent magnet linear generator deployed in the Baltic Sea

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Abstract: To experimentally study how a wave energy converter (WEC) behaves when parameters such as weight on the translator and buoy volume are changing is of significant importance when trying to optimise the WEC system. This study presents results from a WEC deployed at the Baltic Sea near the island of Åland. Compared with earlier experiments, the weight on the translator has been significantly increased to suit the buoy volume. Experimental results show that the power output between the upward and the downward motions are comparable up to the maximum speed for the downward motion of the translator. To study the speed of the translator in downward direction a model has been derived. The model has also been used to study the impact of having a changing active area. Moreover, finite element (FE) simulations done on the generator have been compared with experimental data and show a good agreement, but at high speeds of the translator the FE simulations start to deviate from the experiments.

1 Introduction

There exists a large number of different wave power concepts, some are in an early development stage and a few wave power projects have reached the point where larger installations are carried out [1, 2]. The research within the area started in the 1970s and the largest challenge has been to develop a system that can withstand the harsh offshore climate and at the same time be manufactured for a reasonable price [3]. In 2012, the installed global ocean power capacity was 0.54 GW [4] and there is a potential to have 748 GW of capacity installed by 2050 [5]. However, to be able to reach this goal, more research and studies within the area are required, especially studies including offshore testing, since the nature of the waves are unpredictable and hard to model. One key issue for progressing is to perform more offshore experiments where the wave energy converter (WEC) or arrays of devices are tested. Thereby, analytical models can be verified and used as a tool for future development.

The aim with this paper is to study the behaviour of a point absorbing WEC which converts the energy in the waves with a direct driven linear generator, see Fig. 1. The WEC is based on the concept developed by Uppsala University [6, 7]. Examples of other technologies where a direct driven generator are used can be found in [1, 2, 8, 9].

Primarily, the power generated by the WEC and the speed of the direct driven generator will be analysed. This is carried out by a static model of the generator, FE simulations and studying experimental results from a WEC deployed offshore in the Baltic Sea near the island of Åland. To be able to develop the WEC further, it is of great importance to understand how the WEC will behave when main parameters in the system are changed. Four main parameters that will determine the output power for this type of WEC are; wave climate, electrical damping, buoy size and weight on the system. A study on the influence of buoy size and weight has been performed in [10] on a WEC, L9, deployed at the Swedish west coast. In this paper, the weight on the translator has been significantly increased, compared with L9. To predict the peak power and speed on the system, a model has been used and compared with experimental data. Studies on how the WEC system will perform during downward motion has been conducted to predict the maximum speed and to evaluate the impact of having a changing active area in the generator. Further reading on studies done on motion and power from linear WECs can be found in [11, 12].

2 Experiment

The experiment was carried out at the test site Hammarudda about 15 km west of the city Mariehamn located at Åland within the project Wave Energy for a Sustainable Archipelago (WESA). The WEC used in the WESA project was deployed at a depth of 25 m together with a subsea cable in January 2012. A complete description of the experimental site and the WESA project is presented in [13].

The subsea cable is 1.4 km long and is extending from the WEC to a measuring station located 100 m inland from shore. The station...
is equipped with a measuring, control and logging system as well as resistive loads. The current and voltage are measured with a sampling frequency of 100 Hz. The resistive load can be switched to different values to achieve different damping of the generator. During the experiment conducted in this paper, the resistive loads were Y-connected to a common ground and the value of each resistor in the Y-connection was either 1.67 Ω (a delta-equivalent of 5 Ω) or 6.67 Ω (a delta-equivalent of 20 Ω). The site is also equipped with a wave measuring buoy and a lattice tower for camera surveillance of the WEC buoy.

The WESA WEC consists of a four sided direct driven permanent magnet linear generator placed inside a pressurised capsule, see Fig. 1. The moving part, i.e. the translator, moves up and down with a point absorbing buoy at the surface which follows the motion of the ocean waves. The translator is fixated inside the generator with 64 wheels mounted at the corners of the translator to keep an air gap between the magnets and the stator of 3 mm and to force the translator to move only in heave. At the top and bottom of the WEC end-stop, dampers are attached to reduce the forces from the moving translator. The buoy used in the experiments is a hexagonal circular shaped torus, attached to the generator on the seabed through a steel wire. To keep the WEC seal, the translator is connected to a piston rod which moves through a sealing placed at the top of the pressure capsule. To keep the generator at the seabed a concrete foundation (mounting plate) is mounted at the bottom. Some of the main parameters for the WEC are presented in Table 1, where the nominal values are given at a translator speed of 0.7 m/s and a load resistance of 4 Ω/phase.

### Table 1 Parameters of the WESA WEC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>$P$</td>
<td>17.1 kW</td>
</tr>
<tr>
<td>Voltage L–L</td>
<td>$E$</td>
<td>257 V</td>
</tr>
<tr>
<td>Generator resistance</td>
<td>$R$</td>
<td>0.64 Ω</td>
</tr>
<tr>
<td>Generator inductance</td>
<td>$L$</td>
<td>20 mH</td>
</tr>
<tr>
<td>Iron losses</td>
<td>$W$</td>
<td>530 W</td>
</tr>
<tr>
<td>Translators mass</td>
<td>$m$</td>
<td>4300 kg</td>
</tr>
<tr>
<td>Buoy mass</td>
<td>$b_m$</td>
<td>3200 kg</td>
</tr>
<tr>
<td>Buoy volume</td>
<td>$b_v$</td>
<td>12.66 m$^3$</td>
</tr>
<tr>
<td>Stator length</td>
<td>$l_{st}$</td>
<td>1.199 m</td>
</tr>
<tr>
<td>Translators length</td>
<td>$l$</td>
<td>2.132 m</td>
</tr>
<tr>
<td>Free stroke length</td>
<td>$s$</td>
<td>1.998 m</td>
</tr>
<tr>
<td>Pole pair width</td>
<td>$w_p$</td>
<td>0.0795 m</td>
</tr>
<tr>
<td>Sea cable resistance</td>
<td>$x$</td>
<td>1.15 Ω/km</td>
</tr>
</tbody>
</table>

### 3 Theory

Two analytical models are used in this paper. A static model to roughly study the maximum upward and downward powers at different speed of the translator assuming no acceleration and to predict the power and speed output when the volume on the buoy and/or the weight on the translator is changed. The static model was derived in paper [10] which basically states that for a generator with a constant active area the peak power will occur when the lifting force from the buoy or the gravitational force from the translator is equal to the electromagnetic force in the generator.

The second model which is derived in this paper studies the behaviour and maximum speed of the translator when it moves downward. Moreover, the power distribution across one full stroke length in downward direction has been modelled. The length of one free stroke length excludes decompression length of the upper and lower end-stop dampers. FE-simulations on the generator have also been performed to verify the simulations with experimental results.

Fig. 2 illustrates the motion of the translator in downward direction which has been used as a boundary condition in the analytical model. During a stroke length of the translator, the active area, i.e. the stator–translator joint area, will change. The smallest active area will occur at the top and the bottom end points of the generator. The active area in percentage at these positions is 56% of the maximum active area during total overlap of stator by the translator. The end-stop dampers, i.e. springs are modelled as rigid in this model and no compression of the end-stop dampers will occur. In reality, this could decrease the active area further.

In Fig. 2a, the translator is positioned at the top of the generator and the active area has its smallest value, $x=x_0$. When the translator moves downwards in the $x$-direction, the active area will increase until the bottom part of the translator is aligned to the bottom part of the stator, Fig. 2b. During this period, the cogging force and damping will increase with the distance.

Fig. 2b represents the starting position for a constant active area, $x=x_1$. The amplitude of the cogging force and the damping will remain constant until the top of the translator is aligned to the top part of the stator, Fig. 2c.

The translator position in Fig. 2c represent the starting position for a decreasing active area, $x=x_2$. The amplitude of the cogging force and the damping will decrease during this period until the stator has moved a full stroke length and reaches the bottom end-stop at $x=l_b$, Fig. 2d.

The equation of motion of translator when it moves downward, neglecting friction, can be expressed with Newton's second law:

$$ma = mg - F_{em} - F_c$$

where $m$ is the mass of the translator, $a$ is the acceleration, $g$ is the acceleration of gravity, $F_{em}$ is the electromagnetic force and $F_c$ is the forces acting in the vertical direction. The electromagnetic force is equal to the absorbed active power divided by the speed of the translator:

$$F_{em} = 3 \cdot \frac{E^2 R}{(R^2 + X^2)} \cdot \frac{1}{v}$$

where $E$ is the no-load voltage of the generator, $v$ is the speed of the translator and $R$ is the total resistance of the system per phase. The no-load voltage $E$ and the reactance $X$ can be written as:

$$E = \frac{2\pi\lambda v}{w_p}$$

$$X = \frac{2\pi mL}{w_p}$$

where $\lambda$ is the magnetic flux linkage assuming no leakage flux, $L$, is the synchronous inductance and $w_p$ is the pole pair width.

The cogging force and the forces occurring due to magnets slipping in and out from the stator are approximated as:

$$F_c(x) = a_n + b_\cos \left(2\pi \frac{1}{w_p} x + \theta_1 \right) + b_\cos \left(3\pi \frac{1}{w_p} x + \theta_2 \right)$$

where $a_n$ is the constant cogging force, $b_\cos$ is the amplitude of the cogging force, $\theta_1$ and $\theta_2$ are the phase angles.
where \(a_0\) and \(b_1\) have constant magnitudes and \(\theta_3\) have a changing magnitude depending on the position of the translator. \(\theta_1\) and \(\theta_2\) are the phases extracted from a fast Fourier transform (FFT) of the FE-simulations during no-load. The first harmonic amplitude, \(b_1\), arise from magnets slipping in and out of the stator. The third harmonic amplitude, \(b_3\), arise from the slot opening in the stator and is \(\theta_1\) is the vertical position of the translator, \(h_1\) is the vertical length of active area when the translator is positioned at the top of the generator, \(h_2\) is the sum of \(h_1\) and the free stroke length, \(l_{st}\), is the vertical length of the stator and, \(k\) is a constant expressed as

\[
k = \frac{12\pi^2 h R}{m}
\]

In the calculations, the friction force has been neglected, which would have an influence of the speed. The main parts adding friction are the piston rod sealing and the 64 wheels keeping the translator fixated inside the generator.

### Table 2 FFT values

<table>
<thead>
<tr>
<th>Condition</th>
<th>(\text{Mag}(a_0)/\text{phase})</th>
<th>(\text{Mag}(b_1)/\text{phase}(\theta_1))</th>
<th>(\text{Mag}(b_2)/\text{phase}(\theta_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x_0 \leq x \leq x_1)</td>
<td>1849 N/3.14 rad</td>
<td>1370 N/−2.25 rad</td>
<td>3203−5730 N/1.99 rad</td>
</tr>
<tr>
<td>(x_1 \leq x \leq x_2)</td>
<td>162 N/0 rad</td>
<td>2680 N/−2.47</td>
<td>5730 N/1.99 rad</td>
</tr>
<tr>
<td>(x_2 \leq x \leq l_{st})</td>
<td>1869 N/0 rad</td>
<td>1316 N/−2.57 rad</td>
<td>5730−3453 N/1.99 rad</td>
</tr>
</tbody>
</table>

### 4 Results

One of the main tasks in this paper is to study how a WEC with an increased weight on the translator would perform. Results from a static model studying the influence of buoy volume and the translator weight is presented in Fig. 3, comparing the WESA generator to L9. The translator weight and the buoy volume for the WESA generator are about 4.3 tonne and 12.66 m³, respectively, compared with the L9 translator weight of 2.7 tonne and buoy volume of 13.4 m³. Experimental data from the WESA project, presented in Fig. 4, are used to verify the static model in Fig. 3.

FE-simulations on the system are also compared with the results in Fig. 4. In the FE-simulations, the active area is modelled as constant. Moreover, the experimental data in Figs. 4 and 5 are not including iron losses in the absorbed power from the generator. Parts of the task have also been to study the downward motion of the translator. In Fig. 6, experimental results on the speed are compared with the model derived in the theory part. In Fig. 7, simulations on the absorbed power for a constant and a changing active area are presented.

Results from the static model in Fig. 3 present absorbed power versus translator speed for a fully submerged buoy and no acceleration. The red lines represent the WESA generator and the blue line represents L9. Dots represent upward motion and diamonds represent downward motion of the translator.

Owing to the increased weight of the translator for the WESA generator the power absorption when the buoy moves upward has been decreased and the power absorption when it moves downward is increased.

Fig. 4 presents 1 h of experimental data when the WESA WEC is connected to a 5 Ω respective 20 Ω delta connected load during similar sea states. Blue and purple dots are absorbed power for the upward and downward motions, respectively, of the translator and red and cyan dots are power in load for the upward and downward motions.
motions, respectively, of the translator. The black lines are FE-simulated results for the WESA generator.

In Fig. 4a, the absorbed power and the power in load have a large deviance; also visible is the deviation between the FE-simulations and the experiment, which increases with the speed of

**Fig. 4** Experimental data for the absorbed and load power compared with finite element method simulations

*a 5 Ω load  
*b 20 Ω load

**Fig. 5** Experimental data for absorbed power from L9 at 20 Ω load and a sea state around 2 m significant wave height. Result published in [10]
The deviance between the absorbed power and power in load in Fig. 4b, are significantly decreased compared with Fig. 4a, and the speed of the translator is reaching higher values. The deviation between the FE-simulations and experiments is about the same as in Fig. 4a. Comparison between power in load for the 5 and the 20 Ω load cases shows that there is a small difference between the powers in load for the two cases and when the translator speed is around 1.4 m/s, the two cases almost coincide.

Fig. 5, presents published results from [10] on the absorbed power versus translator speed for L9. Blue dots represent power when the translator moves upwards and purple dots represent the power in downward motion. During the experiment, L9 was connected to a 20 Ω resistive load. Compared with Fig. 4, the upward and downward powers have larger deviation for L9 this is also visible in the analytical results in Fig. 3.

In Fig. 6, the analytical model for maximum speed of the translator versus the position of the translator in downward direction is compared with experimental data during one free stroke length. The vertical lines specify if the active area is changing or not. The shape between the analytical and experimental results is similar but there are deviations in speed which seems to increase with higher speed on the translator. Moreover, the translator position in the experimental data has a fixed initial point at zero during the turning point of the translator, i.e. when the translator starts to move downwards assuming no compression of the end-stop damper.

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Fig. 6 Analytical and experimental results on the speed versus the moving length of the translator (free stroke length) in downward direction
a 5 Ω load
b 20 Ω load

Fig. 7 Analytical results on absorbed power versus position of translator (free stroke length) in downward direction, matching a constant active area (dotted line) to a changing active area (line) for a 5 Ω case
faster than the translator weight allows, i.e. the translator speed filled active area see Fig. 6 of the free stroke length when the active area is not filled. Assuming a constant active area during the upward or downward motion on the translator. For upward motion, the full stroke length is reached at point 6. For downward motion, the full stroke length is reached at point 3. For upward motion, between points 2 and 3, the active area is constant. Between points 3 and 4, the active area is decreasing and the translator reaches the top end-stop at point 4. Assuming a constant active area during the whole stroke length for upward motion, between points 3 and 1, the full stroke length is reached at point 3. For downward motion, blue line, between points 1 and 5, the active area is increasing and between points 5 and 6, the active area is constant. Between points 6 and 7, the active area is decreasing and the translator reaches the bottom end-stop at point 7. Assuming a constant active area during the whole stroke length for downward motion, between points 6 and 1, the full stroke length is reached at point 6. For the static model, assuming constant active area and speed, the models coincide for upward and downward at points 3 and 6, respectively.

5 Discussion

The results in Fig. 4 show that the power out from the WESA WEC is produced more evenly between upward and downward motions compared with L9 as indicated by the static model presented in Fig. 3. The scattering in the data is partly due to the changing active area in the generator. For a translator speed higher than 1.5 m/s, the scattered data is also a result of low sampling frequency at high translator speed, this is mostly visible in Fig. 4b.

The FE-simulations are performed with a constant active area, this means that the FE-simulations should align with the peak power in the experimental data. As seen in Fig. 4, the FE-simulations agree well with the experimental data up to about 0.7 m/s. The deviation between the experimental and simulated results visible for speeds above 0.7 m/s could partly be explained by the changing active area in the experiments. In the FE-simulations, the active area is constant but in reality translator would not move faster than the translator weight allows, i.e. the translator speed would not reach values over 1 m/s for the 5 Ω load case with a filled active area see Fig. 6a. Moreover, the iron losses have not been taken into account for the absorbed power.

The results on L9 in Fig. 5 are used for verification and comparing. It correlates well with the static model and shows that if the weight on the translator is too low, the power and speed in the downward direction will be small compared with the power and speed in the upward direction. L9 has the same length on the stator and translator which means that the active area will be changing through the whole stroke length. This explains the wide scattering of experimental data in Fig. 5. The peak power out from L9 is higher compared with the WESA WEC this due to almost twice the size of active area.

Studying the power in the load in Fig. 4 shows the importance of having an electrical system close to the generator to keep the resistive losses in the sea cable low. The WESA WEC is designed for a 5 Ω load, but when used in this experiment, about 10 kW is (dissipated)/lost in the cable to shore at a translator speed of 0.7 m/s and increasing with the speed. Compared with the 20 Ω load case where about 2 kW (dissipated)/lost at the same translator speed in the cable to shore see Figs. 4a and 4b. The breakeven points for the 5 and 20 Ω load cases are reached around a translator speed of 1.4 m/s. Examples of electrical systems appropriate for these WECs can be found in [14, 15].

In Fig. 4, a limit in downward power is visible. The limit has a peak value depending on the weight, electrical damping, cogging force, friction force and the ocean waves. To model the peak speed in the downward direction the force from the ocean wave has been ignored, i.e. the buoy line is seen as slack. Results from the model are presented in Figs. 6a and 6b for a 5 Ω respective a 20 Ω load case and are compared with experimental data. The simulated shape on the speed over one free stroke length compared with the experimental data shows good agreement. In Fig. 6a, the peaks in speed occurring when there is an increasing or decreasing active area are clearly visible, studying Fig. 4a, there are peaks in the downward speed reaching over 1.3 m/s. These peaks could only occur when there is an increasing or decreasing active area.

The difference in speed between the experimental and analytical models in Figs. 6a and 6b is mainly caused by the ocean waves but can be partly explained by not having the friction force in the model. To find experimental data when the translator speed is not influenced by the ocean waves are difficult. Most of the time the downward motion is affected by the ocean wave especially when there is less damping of the generator and at higher speeds. The start point of the experimental data on the downward speed is fixed at a zero translator position, this is not necessarily true. The model treats the end stops as rigid, and thereby the zero starting point for the downward motion occur when the free stroke length starts. During the experiments in Figs. 6a and 6b the upper end-stop damper could be slightly compressed or the translator could turn before reaching the upper end-stop which would shift the curve slightly to the left or to the right. At a translator position between 1.9–2.0 m in Figs. 6a and 6b, the speed is decreasing fast in the
experimental data. This could be due to that the translator is hitting the lower end-stop or due to the lifting force from the buoy.

The cogging force and the magnetic force due to magnets slipping in and out of the translator does not seem to influence the speed of the translator in any significant way, though they are visible in Figs. 6–8 and they will induce harmonics in the induced voltage. Moreover, it will give rise to vibrations which could influence the life expectancy of the WEC. In Fig. 7, the analytical model has been used to compare two cases, one with and one without a changing active area for a damping of 5 Ω. When the WEC has a high damping the benefits of using a changing active area is quite clear. Though this is an ideal case, usually the speed will be higher where the active area is changing at some part through the downward stroke length when studying the experimental data. The value of the absorbed power in Fig. 7 is not the important part but rather the behaviour and shape of it. The drawback of a changing active area is visualised at the beginning of the translator motion between 0 and 0.1 m. The active area is too small and cannot be compensated by higher speed for the absorbed power when compared with a filled active area, see Fig. 7. On the positive side the acceleration will give a higher translator speed which will increase the power when the active area is the same for both cases between 0.5 and 0.8 m. When the translator has moved about 0.4 m, a peak in the absorbed power occurs with an active area of 0.88% of the total active area.

In Fig. 8, the analytical model shows a good fit to the experimental data, where a major part of the experimental data points are included within the analytical model. Moreover, it explains the wide scattering of experimental data. At points 5 and 6 for upward and downward motions, respectively, the speed limits are reached for a generator with a constant active area according to the analytical model. All the experimental data above these points are occurring when the active area is changing. Fig. 8 also point out the limitations assuming a constant active area during the full stroke length and constant speed of the translator assumed in the static model presented in Fig. 3. When studying the experimental results during this specific period, and connected to a 5 Ω load, the static model shows a quite good estimation of the maximum values for upward and downward motions. Only a few experimental data points are reaching over the limit and only in the downward motion when the active area is changing.

By studying the downward motion in Fig. 8, the two trends in downward motion for L9, Fig. 5 can be explained. The higher trend can be related to the line between 5 and 6 and the lower trend can be related to the line between 6 and 7. A linear load is used in the analysis in this paper, the use of a non-linear load has been studied in [16], e.g. a WEC connected to power electronics keeping a DC-voltage at a constant level. The results presented in that paper shows the benefits in having a WEC which easily can accelerate which suggests the use of a WEC with a changing active area. Further study of the system including friction force will be of high importance.

6 Conclusion

Experimental results presented in this paper show that by adjusting the translator weight to the buoy volume a good power absorption both in upward and downward motions can be achieved without using retracting springs. Moreover, comparing the experimental results from L9 and WESA WEC, Figs. 4 and 5, verify that the increase in translator weight for the WESA WEC level out the difference in power absorption between the upward and downward motions.

The static model can describe roughly how the generator will produce power between the upward and downward motions. Moreover, it can predict the peak limit in absorbed power for a constant active area.

The analytical model derived for the speed versus the position of the translator in the downward direction shows a good agreement with the shape of the speed which can be used to predict the behaviour of the WEC. Moreover, the absorbed power has been studied with the model, showing benefits using a changing active area.

7 Acknowledgments

The authors thank the SStandUP for ENERGY and the WESA project, financed to 75% by the European Regional Development Fund (ERDF) under the Central Baltic INTEREG IV A Programme 2007-2013.

8 References