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Experimental results from the operation of aggregated wave energy converters

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ABSTRACT

Wave energy comes in pulses and is unsuitable for direct conversion and transmission to the grid. One method to smooth the power is to deploy arrays of wave energy converters (WECs), the geometrical layout and damping optimization of which many have studied analytically and numerically, but very few by experiments at sea. In this paper, the standard deviation of electrical power as function of various parameters is investigated. Two offshore experiments have been conducted. During the longer run, three WECs were operated in linear damping during 19.7 days. It is shown that the standard deviation reduces with the number of WECs in the array up to three WECs. The reduction compared to single WEC operation was found here to be 30% and 80% with two and three WECs respectively as a mean for an arbitrary array member. It is found that in sea states above approximately 2 kW/m, the standard deviation is independent of sea state parameters. This is contradictory to a previous study on the same device. The results are however in accordance with numerical results of the SEAREV device but show larger reduction in standard deviation with number of WECs. This could be due to suboptimal damping conditions.

1. INTRODUCTION

The energy in ocean waves comes in short pulses, at twice the frequency of the waves. In addition, random seas consist of a range of wave frequencies that can come from one or many different directions. Feeding this type of irregular power to the grid will result in unwanted voltage fluctuations. By aggregation of power from an array of wave energy converters (WECs), the power can be smoothed to some extent. A number of papers have investigated theoretically the smoothing effect from placing the WECs in an array in different geometrical patterns and how to maximize the power output from arrays by e.g. varying the damping among individual WECs in the array [1-13].

In the present paper, we study the aggregation of power from two and three WECs respectively and quantify the level of smoothing. The WEC array is part of the Lysekil wave energy research site on the Swedish west coast.

The so-called damping factor is taken to be the damping force per unit speed (Ns/m) experienced by the oscillating body. In non-linear damping, the preferred term is damping function. In a direct driven generator, the damping factor is determined primarily by the size of the generator and the external electrical circuit connected to the generator. Offshore measurements from a single point absorber, of the type presented below, has shown that the standard deviation of power is dependent on the sea state and on the level of damping [14]. With a constant damping factor, the normalized standard deviation of power decreased in more energetic sea states. The normalized standard deviation of power also decreased with a higher damping factor.

In a numerical study of an array of ten WECs of the direct driven permanent magnet (PM) linear generator (LG) point absorber topology, it was indicated that the park power from an array would vary less compared to an array with fewer WECs interconnected in the array [15].

In [16] the performance of two different array configurations in irregular waves is studied numerically. For arrays of equally spaced point absorbers results were found that indicate that device performance becomes practically independent of the device spacing, *d*, for $d>4R$ where *R* is the point absorber radius. These results were obtained with a linear power take-off.

With the assumption of large inter-WEC spacing, the so-called SEAREV wave energy converter was studied and it was concluded that the standard deviation of power decreases with increasing number of WECs in an array, at least up to 30 WECs where the standard deviation of power was reduced to 20% compared with single WEC operation [17]. Further reduction was believed to be unrealistic. The standard deviation of power decreased by around 27% with two WECs in the array and by around 38% in array operation with three WECs compared to single device operation. The study further concluded that the standard deviation of power is independent on wave direction, the distance between WECs and the sea state conditions. The independency of the standard deviation of power on sea state seems to be an effect of array deployment since, for a single WEC of the type studied here, the standard deviation has by offshore experiments been shown to decrease as the sea state gets more energetic [14]. Further research is hence needed to learn more about power aggregation from multiple WECs in random seas of varying intensity and damping levels.

Manifolding has been described clearly as "the principle of connecting a number of wave absorbing elements into a common pressure line through non-return valves…" [18]. This refers to the use of a power takeoff based on pumps for water or rams for hydraulic oil. The WEC system studied in this paper can be described as being based on electrical manifolding, the pumps or rams being linear generators, the non-return valves being diode rectifier bridges and the common pressure line being the marine substation DC-bus to which the WECs are interconnected in parallel.

To produce steady grid power from pulsating wave energy, the idea to use some intermediate energy storage is recurrent in the literature [19]. A high-pressure gas accumulator in oil hydraulic systems is frequently suggested as energy storage mechanism in several different WEC concepts, the most well-known probably being the Pelamis [20].

Over-topping devices store energy as potential energy in its reservoir from which the water spills back into the ocean via axial flow or cross flow hydropower turbines. In an oscillating water column, partial power smoothing is sometimes achieved via a mechanical flywheel on the turbine shaft. It has been proposed that "about 100 seconds of storage would produce a completely steady output from a single device in any typical wave spectrum" [18]. By aggregation of power in wave energy converter arrays, the power can be smoothed to some extent reducing the need for energy storage capability [7]. In this paper we attempt to quantify the level of power smoothing. This is made by analyzing experimental results from three aggregated WECs in mixed seas in an offshore location.

2. WAVE ENERGY SYSTEM

A first step towards a solution of how to practically implement offshore wave energy converter arrays based on direct-driven PAs has been taken at the Lysekil wave energy research site off the Swedish West coast. The Lysekil test site is relatively sheltered site with a wave climate of 2.6 ± 0.3 kW/m [22]. The water depth is 25 m and the sea bed is flat and consists of sandy silt and gravel. A marine (underwater) substation has been built and installed. It interconnects three WECs of the linear PM synchronous generator (SG) type. Its input is the pulsating power from each individual WEC. The power is converted and transmitted to shore where the electricity is converted to heat in a resistive load.

The first WEC prototype of the Lysekil research site was deployed in March 2006. A heaving buoy on the surface is via a line connected to the translator of a linear generator on the seabed. The generator is enclosed in a steel capsule and a piston in the top lid prevents water from entering the casing. The translator has surfacemounted Nd-Fe-B permanent magnets of pole width 50 mm. 100 mm of translator movement will thus result in a 360 degree rotation of the magnetic field in the stator and hence of the induced voltage. The rating of the linear generator is 10 kW and 200 V (line-to-line) at an electrical frequency of 6.7 Hz, which occur at a translator speed of 0.67 m/s. The induced voltage varies in amplitude, as does the electrical frequency, according to the translator speed. Several experiments on the offshore performance of this first prototype WEC in varying seas have been made [23-25]. A schematic figure of the WEC with its key components is shown in Fig. 1.

In the spring of 2009, two more WECs were installed together with the marine substation to form an array of WECs, see Fig. 2. The substation is located on the seabed some tenths of meters to the east of L2. The unique features of the marine substation are that it: (i) connects three offshore wave energy converters in an offshore location, (ii) directly interconnects generating units that operate at varying voltage amplitude and varying electrical frequency, and (iii) is located on the seabed well below the ocean surface as opposed to e.g. offshore substations for wind farms that are located on platforms above sea level, see e.g. [26].

The voltage from each WEC has, due to the use of a direct-driven linear PMSG, both varying frequency and amplitude. The voltage is therefore first rectified in the marine substation. For this purpose, a passive diode rectifier was chosen due to its benefits of being durable, cheap and having low losses. The three WECs are then interconnected in parallel on the DC-side of the rectifiers and the voltage is filtered with a capacitive filter. The DC-voltage is inverted to 50 Hz and transformed to a more suitable transmission voltage. The scheme allows for one single controller to set the level of damping for an entire array of WECs. This is implemented in the control of the three-phase inverter. To avoid running the WECs without any damping of the buoy and translator motion, they are connected to external dump loads when disconnected (electrically or physically) from the substation. A simplified one-line diagram of the electrical system is seen in Fig. 3.

3. EXPERIMENTS

To quantify the smoothing effect of aggregation of power, two of the WECs at the wave energy research site outside Lysekil were operated during 88 minutes in a sea state of 4.6 kW/m during May 25, 2009. A Waverider wave measuring buoy is located in the vicinity of the WECs. It samples the wave elevation at 2.56 Hz. The significant wave height, H_{m0}, was 1.3 m and the energy period, T_E, and peak period, T_{peak}, were 6.2 s and 5.7 s respectively. The possible influence of the wave direction during this experiment has not been investigated since the duration of the experiment is relatively short.

From voltage and current, sampled at 256 Hz, on each of the marine substation inputs, the instantaneous electrical power from the linear generator WECs was calculated as one-minute mean values. As a measure of variability, the standard deviation of power from a single WEC, along with the standard deviation of the sum of the input power of the two WECs (referred to as an array), were calculated for each minute of operation. The inverter, transformer and sea cable to shore were excluded from the study. In this experiment, calculation of electrical power was made from phase voltage and line current at the input circuit breakers, see Fig. 3. During the 88-minute run, the mean DC-bus voltage was 78.5 V. This was a first trial and should not be interpreted as an optimized value in the sea state in which the WECs were operated. The exact damping functions used during the experiment is unknown.

To investigate the statistical significance of the results, a longer experiment was conducted over 19.7 days (945 half-hours) in July 10-29, 2009, including the power from all three WECs of the array. This was achieved by running the WECs connected to their individual resistive dump loads, see Fig. 3. This results in linear damping of the WECs. The converted power was calculated from line-to-neutral voltages and resistance of the dump load immersion heaters, which is 12 ohms in delta-connection. Half-hour averages were calculated. The mean sea state during the 945 half-hour run was 2.24 kW/m. This can be compared with the wave climate at the Lysekil wave energy research site, which is 2.6 ± 0.3 kW/m. The mean energy period and the mean peak period during the testing period were 4.5 s and 4.9 s respectively. The mean significant wave height, H_{m0}, was 0.77 m. The maximum sea state was 20.6 kW/m which occurred after 10 days and 13 hours (503 half-hours) as can be seen in the largest peak in Fig. 4. The significant wave height during the same half-hour was 2.6 m.

The Waverider buoy at the test site does not measure wave direction. However, wave data from the SMHI's (Swedish Meteorological and Hydrological Institute's) measuring station Väderöarna, which is located about 50 km North to North-East of the test site, has been used to investigate the possible influence of the wave direction on the results of array operation. Due to the relatively small distance between the Lysekil wave energy research test site and Väderöarna measuring station, it is reasonable to assume that these wave directions are valid also for the Lysekil wave energy research site. The most common wave direction at the test site is from the West and South-West directions [22]. Waves from the West and South-West directions were also well represented during the 19.7 day experiment, see Fig 5. The wave direction data contains one-hour averages and was interpolated linearly to attain 945 half-hour averages as in the calculations of electrical power from measurements. The influence of different damping modes (linear vs. non-linear) on the standard deviation is out of the scope of the present paper.

The WECs of the array are referred to below as L1, L2 and L3. The spatial layout of the array is shown in Fig. 2 where the buoy shapes and sizes are in scale relative to one another and to the inter-WEC distances. Converter L1 has a torus-shaped buoy manufactured from six steel pipe sections with a diameter of 711 mm. The outer diameter (distance between the outsides of two parallel pipe sections) of the buoy is 5.2 m and the volume is approximately 6.1 m^3. Later in the paper, the capture width ratio (CWR), is plotted against energy period. The CWR is here defined by

$$CWR = \frac{P_{el}}{J \cdot 2R} \quad (1)$$

where P_{el} is the electrical power from a device measured either on the marine substation inputs (first experiment, non-linear damping) or in the WEC dump loads (second experiment, linear damping), see the connection scheme in Fig. 2. J is the wave energy transport and R is the buoy radius. Comparing the CWR between devices, the projected bottom surface of the torus can be converted into a circular surface of that of a cylindrical buoy. The projected bottom area is 11.0 m^2 and hence the radius of the corresponding circular surface from such a transformation is 1.87 m. (The torus volume of 6.1 m^3 thus results in a height of the cylindrical buoy of 0.56 m). Converter L2 has a cylindrical buoy of 3 m diameter and a height of 1.2 m. The buoy of L3 is also a cylinder, but the diameter is 4.0 m and the height is 0.69 m. The buoys of L2 and L3 thus have very similar volume, 8.5 m^3 and 8.7 m^3 respectively. At the test site, different sizes and geometries of buoys are tested to investigate different aspects of power absorption. The use of different buoy geometries is hence not intended for the particular experiments presented here. The damping factors applied to the WEC generators of L1, L2 and L3 during the second experiment of 19.7 days (linear damping), were 16.2 kNs/m, 7.4 kNs/m, and 7.3 kNs/m respectively, all with the accuracy ±5%. These were calculated from 12 one-minute raw data files sampled at 256 Hz where the time-stamps of the zero-crossings of the phase voltages were identified. This was done by interpreting values of phase voltage below 5 V (which corresponds to a translator speed of 0.03 m/s) as standstill. When a number of successive data points indicate standstill, the time stamp in the middle of this time interval was used as the time stamp of the zero-crossing of the phase voltage. The electrical frequency, and thereby the speed of the translator, can be deduced from these zero-crossing time-stamps. Neglecting iron losses and frictional losses, the damping factor, γ, can be calculated from the translator speed, *v*, the electrical power, P_{el}, in the dump load and the copper losses, $P_{Cu\text{-}loss}$, in the linear generator windings by

$$\gamma = \frac{P_{el} + P_{Cu-loss}}{v^2} . \quad (2)$$

The damping factors presented above are calculated as averages from 0.4 m/s and up to the maximum translator speeds detected during that minute.

To investigate if possible interaction effects within the array can be detected it is interesting to look at the CWR as a function of T_E. Significant differences in absorption that cannot be explained by other variables, such as buoy size or damping, could be due to strong interaction effects such as those originating from radiated waves from adjacent bodies. If there are strong array interaction effects, these will also vary with the wave direction. In [27], hydrodynamic simulation results of a cylindrical 6 m diameter buoy are presented for a sea state characterized by energy periods T_E, of 4-7 s and significant wave heights H_{m0}, of 1-3 m. The results showed that by including diffraction effects in the calculations the performance was lowered only to a very marginal extent. The largest buoy used in our study is significantly smaller, only 4.0 m in diameter, and so it is anticipated that diffraction effects are very limited at least for sea states characterized by $T_E \geq 4$ s.

4. RESULTS

Experiments have been carried out with two WECs and three WECs respectively. With two WECs, an 88 minute run was made having the two WECs L2 and L3 connected to the substation thus feeding power to the substation DC-bus. This results in a non-linear damping of the WECs. The three-phase inverter of the substation controlled the DC-link voltage so as to keep a certain reference value which is set by the user. In the loop control, the DC-voltage was measured and used as input signal. A simple integrating regulator was implemented. It works by increasing the modulation index one step if the DC-voltage exceeds the set voltage and decreasing the modulation index if the set voltage is higher. The loop time was 20 ms (one inverter voltage period). The modulation index can be changed from 0% to 100% in 16 steps. Hence a change from 0% to 100% is 0.32 s. In the second, 19.7 days long experiment, all three WECs (L1, L2 and L3) were operated and power was extracted in the individual WEC dump loads which results in linear damping.

The values of power are presented in per unit, *p.u.*, and have been calculated from produced electrical power divided by the nominal electrical power of the devices (10 kW) and where applicable the nominal array power (20 kW which equals 2 WECs and 30 kW which equals 3 WECs respectively). Values of standard deviation have been divided (normalized) by the mean power during that same time period to attain (the dimensionless) normalized standard deviation. This was made since relative fluctuations perhaps are more intuitive than absolute fluctuations. From this point onwards, for simplicity, “standard deviation” is used for the term “normalized standard deviation”.

4.1 - ARRAY OPERATION WITH TWO WAVE ENERGY CONVERTERS

Fig. 6 shows the 88 minute electrical power record taken in May 2009 (non-linear damping). The curves show the power of L2, the power of L3 and the aggregated power, the latter thus corresponding to the mathematical mean of the L2 and L3 curves. The electrical mean power during the testing period of 88 minutes delivered by L2 to the substation was 8.2% p.u. For L3, the electrical power delivered to the substation DC-bus was 8.4% p.u. The set (target) DC-bus voltage was 80 V which was almost reached. The mean DC-bus voltage during the 88 minutes was 78.5 V.

The standard deviation of power during the 88 minute testing period is presented in Fig. 7. This gives an indication of the smoothing effect from WEC aggregation in this array configuration and in non-linear damping. The mean standard deviation was found here to be 1.5 for L2, 1.6 for L3 (1.6 for an arbitrary WEC in the array, either L2 or L3) and 1.1 for the array power. The resulting reduction in standard deviation thus was 28% compared to single WEC operation with L2, and 33% compared to single WEC operation with L3. The reduction in standard deviation of an arbitrary device hence was 30% in array operation with two WECs compared to single WEC operation. This figure could be used for comparison with the results of array operation with three WECs later in this section.

4.2 ARRAY OPERATION WITH THREE WAVE ENERGY CONVERTERS

Fig. 8 shows the electrical power record during 19.7 days, July 10-29 in 2009. Note that here, the WEC linear generators are damped linearly as in [15] and [21] rather than in a non-linear fashion as in the above experiment with two converters and as in [22-23]. Each data point is the half-hour mean value of electrical power converted to heat in each of the WEC dump loads. The mean electrical power delivered by L1 was 4.8% p.u., for L2 and L3 it was 3.4% p.u. and 4.0% p.u. respectively.

In Fig. 9, the standard deviation of electrical power as function of sea state is shown. A standard deviation that is slightly increasing with sea state is seen for L2 and L3 while the data for L1 shows a very flat response except for sea states below 0.5 kW/m where the standard deviation increases exponentially for all WECs. The reduction in array operation compared to single WEC operation seems however to be maintained for these sea states.

The mean standard deviation during the power record was found here to be 1.7 for L1, 2.0 for L2, 1.8 for L3 and 0.37 for the array power. This corresponds to reductions in the standard deviation of power compared to single WEC operation of 78%, 82% and 80% respectively for L1, L2 and L3. The mean standard deviation of electrical power for an arbitrary individual in the array thus is 1.9. This results in that the reduction in standard deviation of an arbitrary individual of the 3 WEC array compared to when operated as a single device is 80%. Summarizing the experiments in non-linear and linear operation with two and three WEC respectively, the reduction in standard deviation is 30% with 2 WECs and 80% with three WECs compared to the standard deviation of electrical power from an arbitrary single array member.

To look further into the cause of the reduction in standard deviation resulting from farm operation, the dependence of the standard deviation on the energy period, T_E, is shown in Fig. 10. There is some spread in the data points basically across all values of T_E. A slight increase in standard deviation towards the lower and higher values of the energy period can be seen while minimum values are found for energy periods of around 4 s (3.5 s to 4.5 s). This effect is however significantly less pronounced for L1 than for L2 and L3. The standard deviation of electrical power of the array shows very little tendency of this slight parabolic dependence.

The standard deviation of electrical power to the significant wave height, H_{m0}, is shown in Fig. 11. As can be seen, the standard deviation depends strongly on the significant wave height. Comparing the results of the standard deviation of electrical power as function of sea state in Fig. 9, as function of energy period in Fig. 10 with the results of the standard deviation as function of the significant wave height in Fig. 11, it is apparent that the significant wave height is the dominating parameter over energy period studying the shape of the dependence of standard deviation on sea state. As for the results on standard deviation as function of sea state, the slightly increasing standard deviation of electrical power of L2 and L3 in higher sea states is seen also in Fig. 11 as the significant wave height increases. However, L1 does not show this behaviour. The standard deviation of the array power as function of H_{m0} shows no tendency of increasing in larger wave heights.

The three devices are not equally efficient in converting wave energy into electricity. This affects the results on reduction in standard deviation. The results of Fig. 12 and Fig. 13 give a deeper insight into how. Fig.

12 shows the half-hour average values of CWR as function of sea state. It should be stressed that in this paper, the CWR is based on the electrical power (see Eq. 1) and should not be interpreted as the capture width ratio based on the absorbed wave power as is usually the case when discussing CWR. The solid lines in Fig. 12 and in Fig. 13 are only intended as a guide for the eye and has no physical meaning.

The results show the highest CWR for L1, and slightly lower for L2 and L3. All three WECs show the highest CWR at sea states around 1 kW/m. In saying that the devices are not equally efficient absorbers, it should be noted that the resistive loads connected to the devices are equal, but an error in the connection of the generators of L2 and L3 resulted in a reduced electromagnetic damping of those generators compared to that of L1 at equal resistive loads and at equal translator speeds. It can hence be anticipated that the difference in CWR, or absorption efficiency, is primarily the result of the difference in damping and not of the slightly different frequency response of the devices originating from the different buoy sizes and shapes. Here one should recall the reference to the results in [15] where L1 was operated with a cylindrical buoy with 3 m diameter and a height of 0.6 m with three different damping factors. It was shown that the standard deviation of electrical power depends strongly on the damping applied. Heavier damping reduces the standard deviation.

Taking a closer look at the issue of the influence of the difference in damping, and of the difference in frequency response among devices on the standard deviation of electrical power in the present array configuration, the CWR as function of energy period, T_E, (the inverse of the wave frequency) was investigated. This diagram is illustrated in Fig. 13. The data points are, as in the previous figure, the half-hour average values of CWR. Which device that has the highest amplitude of the CWR could be seen already in Fig. 12. Fig. 13 shows basically the frequency response of the devices, but illustrates the absorption efficiency under the condition of damped oscillation in the time domain. As can be seen, the frequency response of L1 is slightly higher than those of L2 and L3.

The possible influence of varying wave directions on the standard deviation of electrical power was investigated, the results of which are seen in Fig. 14. The figure should be studied in conjunction with the wave directions in Fig. 5 since the more energetic sea states during the experiment appeared mainly in wave directions between the South and the West. The results should also be studied in view of the normalized standard deviation as function of sea state in Fig. 9 as the standard deviation has been shown to depend on this parameter for very mild sea states. High values of the standard deviation thus occur in easterly wave directions due to the occurrence of mild sea states in these directions.

5. DISCUSSION

In this paper, it is examined how the electrical power from a WEC can by smoothed by aggregating several converters in array operation. Fluctuations on the short time scale may thereby be decreased due to the stochastic nature of the waves combined with the geometrical spread of the WECs in the array. Possible effects of the wave direction on the standard deviation were investigated by including wave direction measurements from a nearby wave measuring station.

The standard deviation of electrical power of a single device has in previous research been shown to decrease with increased damping and as the sea state gets more energetic [14]. In sea states of about 20 kW/m, the standard deviation was shown to be reduced by about 25% by increasing the damping factor by a factor of

2.4. The standard deviation as function of sea state and significant wave height is shown in Fig. 9 and Fig. 11 respectively. The initial reduction transcending from calm water to mild sea states of around 2 kW/m, (corresponding to 0 to about 0.5 m significant wave height), is an effect primarily of that the absolute power fluctuation seems to persist while the absolute power increases which thus results in a reduction in the values of normalized standard deviation. Due to the geometrical spread of WECs in the array and the addition of electrical power contributions from the WECs of which the latter results from the parallel interconnection on the marine substation DC-busbar, the reduction in standard deviation can be further reduced. The reduction resulting from array operation was found here to be 80% while, for comparison, the reduction due to increased damping of a single device in [14] was about 25%. The 80% reduction might be lowered under optimal load conditions due to that reduced damping factors were used here for L2 and L3 (7.4 kNs/m and 7.3 kNs/m respectively) which would cause larger values of standard deviation than with higher damping.

By studying the results in Fig. 10, it is obvious that energy period does not have significant impact on the standard deviation of electrical power. As for the significant wave height in Fig. 11, some effect causes the standard deviation to slightly increase in energy periods above about 4 s. Possibly this could be related to the frequency response of the devices, but then the same effect should have been identified for L1. This is not the case and the indicative frequency responses shown in Fig. 13 are quite similar between the devices. Another explanation could be that it has to do with the reduced electromagnetic damping of the generators of L2 and L3 compared to L1. A non-linear effect related to this could possibly cause further reduced damping in the more energetic sea states and thus an increase in standard deviation. An increasing standard deviation in larger energy periods and higher significant wave heights as seen in Fig. 10 and Fig 11 is an unexpected result and based on previous research, it should indeed be caused by a shift in the damping factors.

The results of CWR as function of sea state in Fig. 12 are rather expected. L2 and L3 have lower amplitude CWR (see Fig. 13) which is probably a result of the fact that they had lower damping factors. The data points are very scattered so it is difficult to draw conclusions on possible differences between L2 and L3. As can be seen in Fig. 13, the CWR as function of energy period (basically the frequency response measured offshore) of L1 is higher in amplitude than that of L2 and L3. Converter L2 and L3 possibly have frequency responses that have their maximums at slightly lower energy periods than that of L1. The difference between L1 and the other two WECs could hence likely be explained by the lower damping factor of L2 and L3 compared to L1 since a lowered damping factor is known to lower the absorption in the damping range studied here (however as have been mentioned before, a significant increase in damping factor beyond a certain point would again decrease the absorption). The trendlines in Fig. 13 are very indicative as the data points are very scattered. The trendlines are only intended as a guide for the eye. It is therefore difficult to draw any conclusions on possible differences in performance between L2 and L3 based on this figure.

The direction of incoming waves might influence the performance among individuals in an array due to interaction effects. Fig. 14 shows the standard deviation of electrical power as function wave direction. The standard deviation data points are more scattered and higher for wave directions from the South-East to the North-East than in the other directions. Studying the sea state in Fig. 4 in conjunction with the wave direction plot in Fig. 5, it is clear that more or less all of the waves in the more energetic sea states appearing during July 10-29 2009 came from directions between the South and the West. Lower sea state means higher standard deviation of electrical power which thus explains the results in Fig. 14.

It has not been possible to detect any influence from wave direction on the main parameter under investigation in this paper; the standard deviation of electrical power. Attempts to find such a dependence was made by plotting subsets of the data in the significant wave height interval $0.8<H_{m0}<1.2$ m, but in the data set used in this study, these wave heights only appear in wave directions around -135 ± 20 degrees (South-West).

In [17], numerical results of array operation with the SEAREV device indicate that standard deviation of power is independent of both wave direction, distance between WECs and of sea state parameters. Regarding the wave direction and distance between WECs, it is however believed that the study in the present paper is based on too little data to be able to validate all of the above statements from [17] for the directly driven linear generator point absorber device. Beside the need for longer experiments, different array configurations would also have to be tested. Regarding the influence of sea state parameters on the standard deviation of power, the results in Fig. 9 could be studied further. Excluding the most calm sea states, no influence of sea state is seen on the standard deviation. This is most apparent for the standard deviation of the array power. The same is valid for the standard deviation as function of H_{m0} in Fig. 11 for significant wave heights less than about 1 m. Hence, the results on standard deviation as function of sea state parameters presented here seem to verify the result in [17] while they seem to contradict the results in [14]. More research is hence needed to clarify this issue.

6. CONCLUSIONS

The electrical power from an array of directly driven point absorber WECs calculated from 88 minutes of data in a 4.6 kW/m sea state was found here to be smoother than that from individual array members. The standard deviation of electrical power was reduced by 30% as a mean for converters L2 and L3. Results from a

19.7 day record, taken in mixed seas of mean intensity 2.24 kW/m (a maximum 20.6 kW/m), show that the reduction in standard deviation of electrical power was 80% as a mean for an arbitrary device in the three-WEC array. It has been shown that the standard deviation reduces with the number of WECs in the array up to three WECs and that standard deviation of array power seems to be independent of sea state parameters for sea states above approximately 2 kW/m. Below that, strong dependence of standard deviation on sea state was found. The reduction is due to the increase in significant wave height only. The above results are in qualitative accordance with numerical results of the SEAREV device where standard deviation reduced by approximately 27% and 38% respectively with two and three WECs in the array compared to single WEC operation. The results presented here however seem to contradict previous results on standard deviation as function of sea state for a single WEC of the direct driven linear generator point absorber device where strong dependence was identified throughout sea states up to slightly higher than 20 kW/m.

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Fig. 2. The array configuration. a.) Birds-eye view of the WEC array with distances between array members indicated. b). Photo taken on site approximately from the South. The small buoy in the foreground is intended e.g. for studies of marine fouling. c). Photo taken approximately from the North-West.

Fig. 3. The one-line diagram of the park and on-shore resistive load. The items within the dashed rectangle are located in the marine substation.

Fig. 4. Sea state and significant wave height during the 945 half-hour run in July 10-29 2009 with three WECs connected to individual resistive dump loads.

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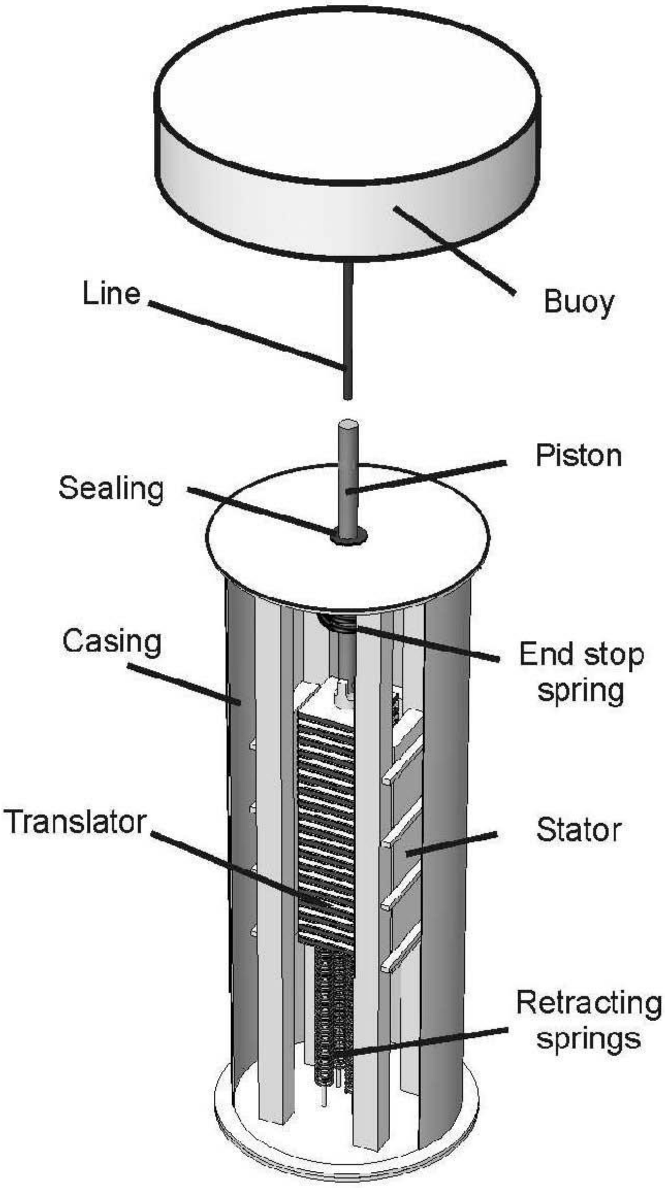
Fig. 14. Normalized standard deviation of electrical power as function of wave direction. Measurements were taken on July 10-29, 2009.

Fig. 1. The WEC with its components indicated. 54x98mm (300 x 300 DPI)



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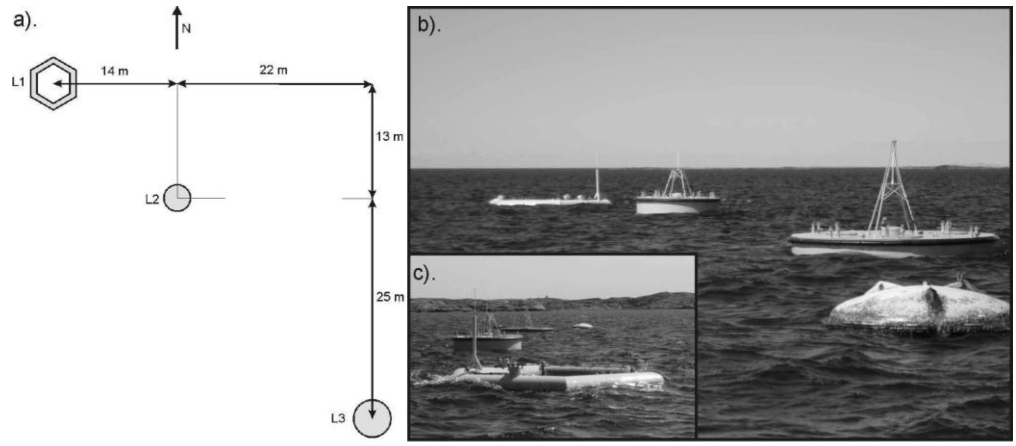

Fig. 3. The oneline diagram of the park and onshore resistive load. The items within the dashed rectangle are located in the marine substation. 109x44mm (300 x 300 DPI)

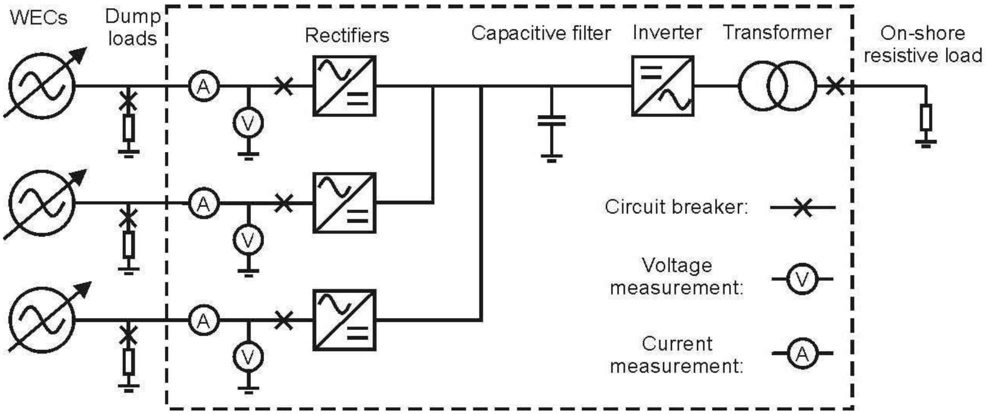

Fig. 4. Sea state and significant wave height during the 945 halfhour run in July 1029 2009 with three WECs connected to individual resistive dump loads. 472x247mm (96 x 96 DPI)

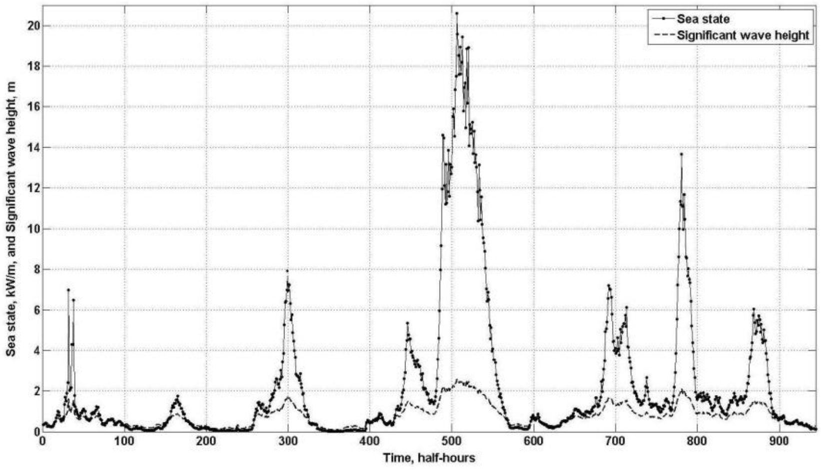

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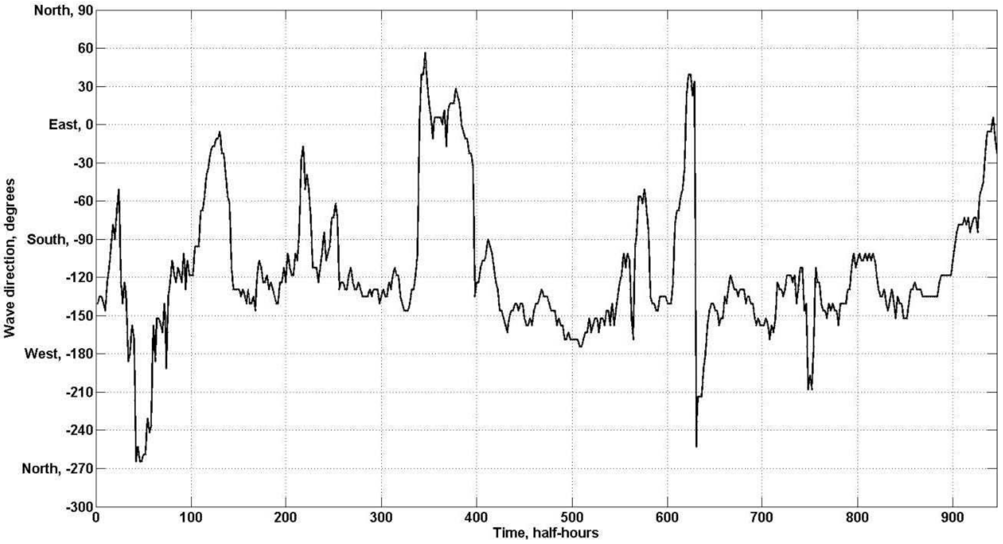
Fig. 6. Electrical power in nonlinear damping. Measurements were taken on May 25, 2009. 109x63mm (300 x 300 DPI)



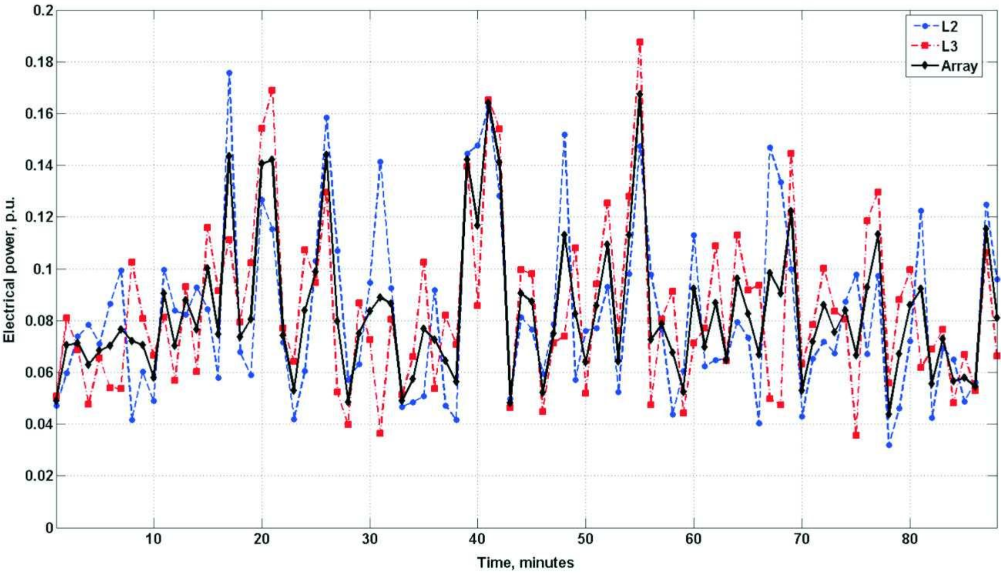

L2
L3
Array
Electrical power, p.u.
Time, minutes
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
10
20
30
40
50
60
70
80

Fig. 7. Normalized standard deviation of electrical power delivered to the marine substation (nonlinear damping). Measurements were taken on May 25, 2009. 109x63mm (300 x 300 DPI)

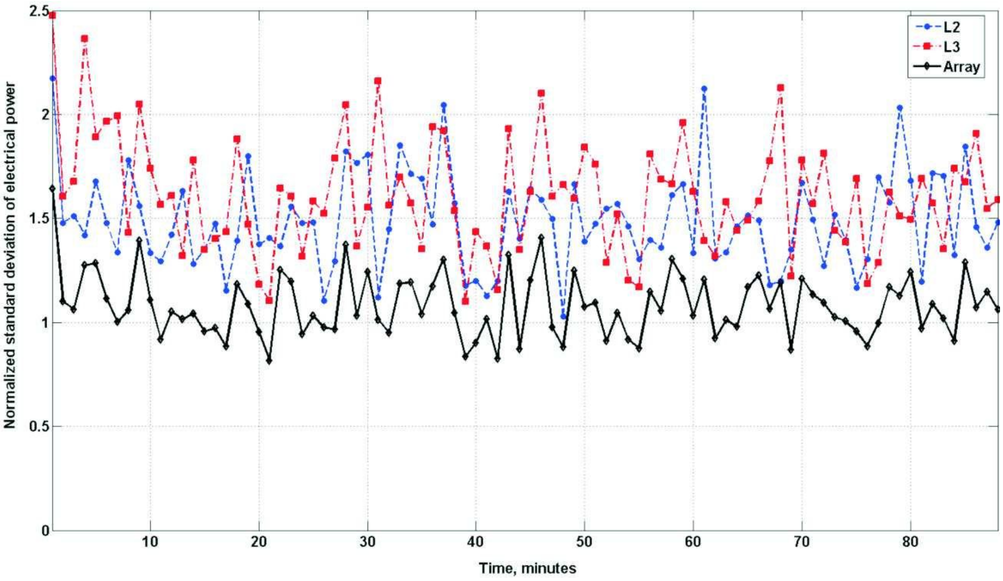


Fig. 8. The electrical dump load power (linear damping) from the WECs of the threeWEC array. Measurements were taken on July 1029, 2009. 169x92mm (300 x 300 DPI)

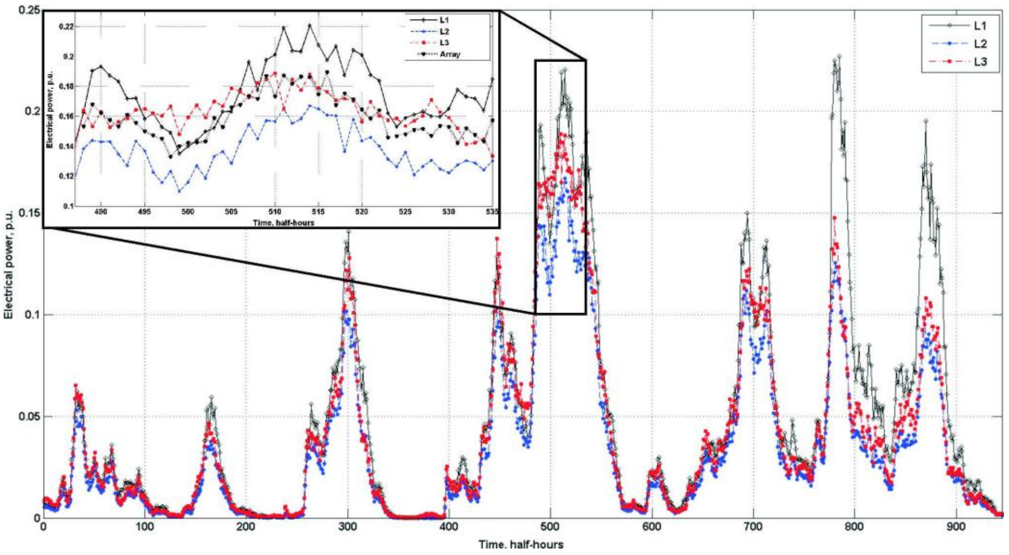
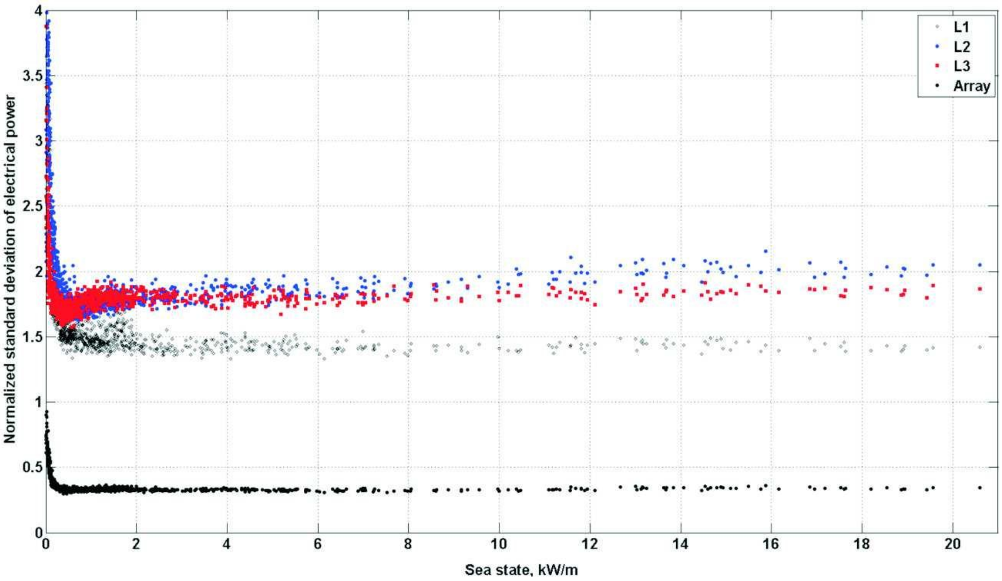


Fig. 9. The standard deviation of electrical power as function of sea state for the 3 WEC array (linear damping). Measurements were taken on July 1029, 2009. 109x63mm (300 x 300 DPI)

Fig. 10. The standard deviation of electrical power as function of energy period, TE, for the 3 WEC array (linear damping). Measurements were taken on July 1029, 2009. 472x247mm (96 x 96 DPI)



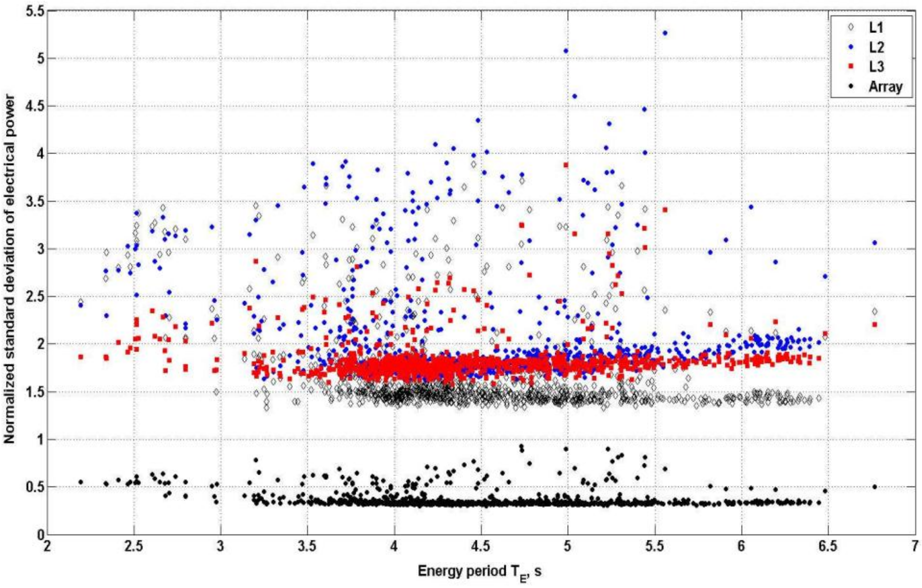
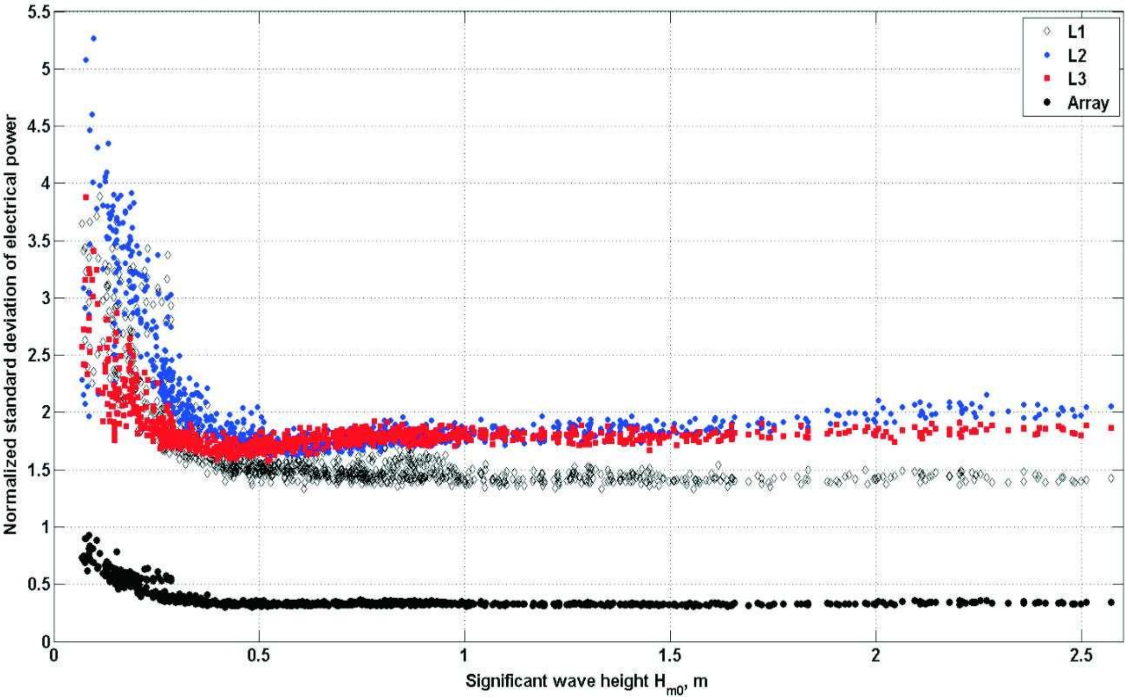


Fig. 11. The standard deviation of electrical power as function of significant wave height, Hm0, for the 3 WEC array (linear damping). Measurements were taken on July 1029, 2009. 109x63mm (300 x 300 DPI)


Normalized standard deviation of electrical power
Significant wave height H_{m0}, m
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
L1
L2
L3
Array

109x62mm (300 x 300 DPI) 109x61mm (300 x 300 DPI)

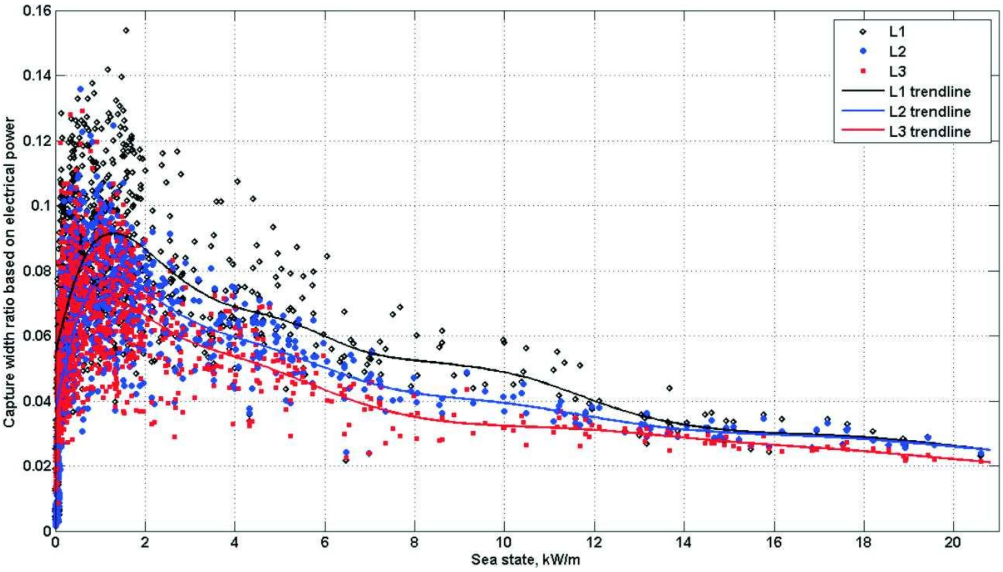
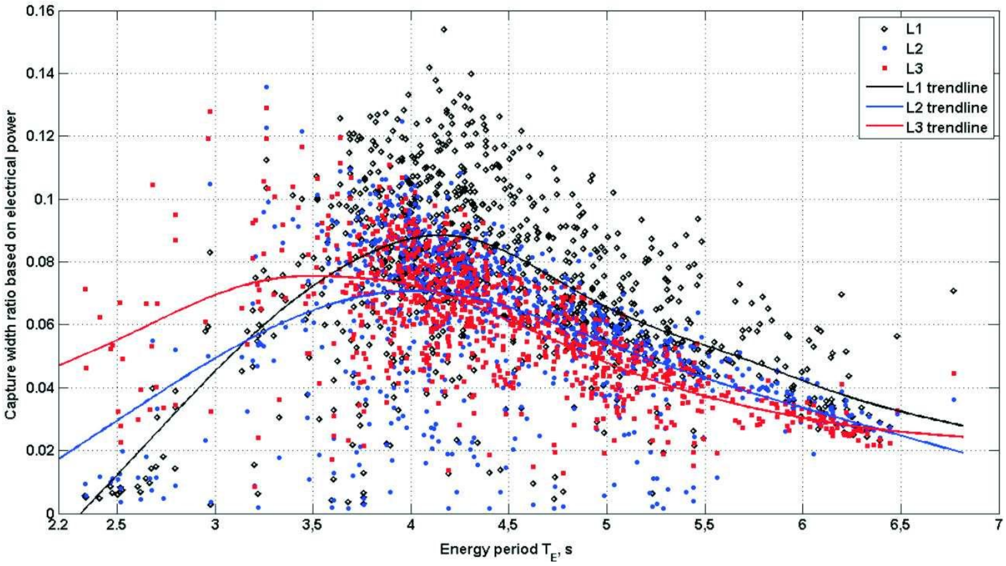


Fig. 14. Normalized standard deviation of electrical power as function of wave direction. Measurements were taken on July 1029, 2009.
109x64mm (300 x 300 DPI)



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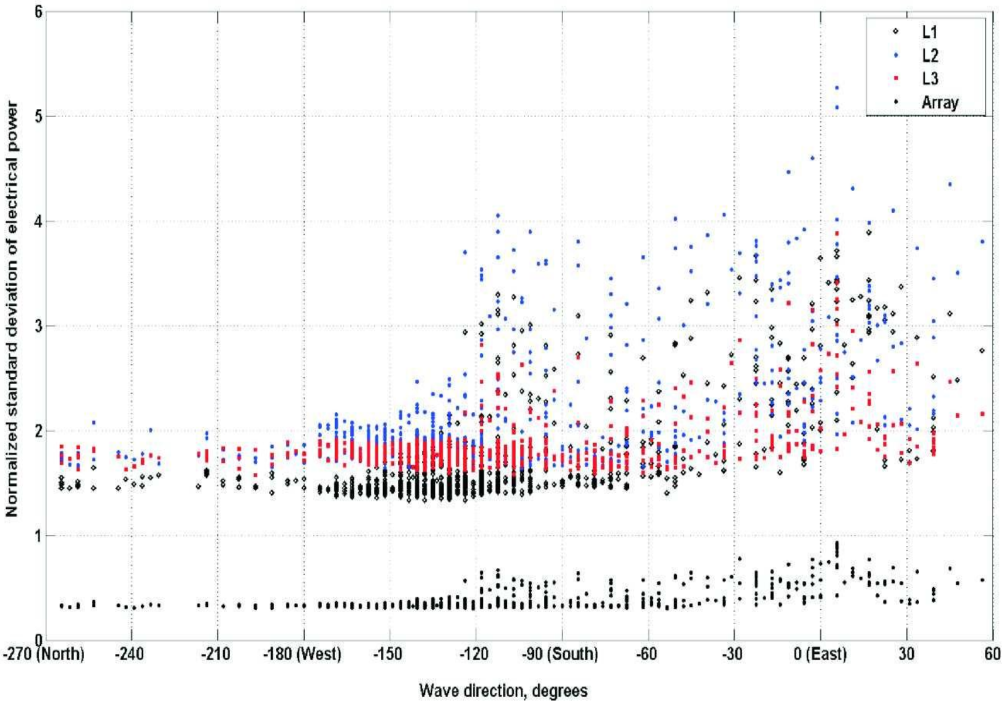
Normalized standard deviation of electrical power
Wave direction, degrees
L1
L2
L3
Array
0
1
2
3
4
5
6
-270 (North)
-240
-210
-180 (West)
-150
-120
-90 (South)
-60
-30
0 (East)
30
60

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