Summary of Performance After One Year of Operation with the Lifesaver Wave Energy Converter System

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***Abstract*—Fred. Olsen has operated the Wave Energy Converter *Lifesaver* at the *FaB Test* wave energy test site since April 2012. After one year of operation, significant experience has been gained, and a large amount of test data has been acquired. This paper presents the key performance data gathered through this test period, and compares the actual production with the expected figures obtained through theoretical simulation. The practical aspect of operating a WEC is also discussed, and figures for availability, uptime and accessibility for service is presented. In general, the actual results show good correlation with the simulation models. Through the test period, Lifesaver has performed very well without major incidents, and has demonstrated a moderate reliability acceptable for pre-commercial testing.**

I. Introduction

Lifesaver, pictured in Fig. 1, is a *Wave Energy Converter* (WEC) system developed by *Fred. Olsen* (FO). She is an electro-mechanical system for producing electricity from ocean waves for grid export. The system consists of a 16 m wide toroidal floater, three production machines and one electrical conversion package. She was installed at sea on 31. March 2012 for commissioning and sea trials, and has currently been in continuous service for one year. Lifesaver is currently not grid connected, and is equipped with a sophisticated stand-alone power system to emulate the grid connection functions to allow normal operation of the electrical machinery [1].

Lifesaver is operated at *FaB Test*, which is a UK test site for pre-commercial WEC concepts located in Falmouth bay outside Cornwall, England. The exact location of FaB Test is shown in Fig. 3. FaB Test is envisioned to be a preparation site for WECs planned for commercial operation at the Wavehub site [2], and has a moderate wave climate with good balance between production hours and availability for service. Lifesaver is designed with focus on modularity, serviceability and reliability. All mechanical and electrical parts are placed above surface for easy access, and the modular and autonomous *Power Take-Off* (PTO) configuration allows for maintaining system operation and power export with only one operational PTO. Fig. 2 shows an example of service work at Lifesaver, where one of the PTOs were lifted off for onshore maintenance.

Fig. 1. *Lifesaver* on site outside Falmouth, England.

Fig. 2. Lifesaver during PTO lifting operation

A. The FO Wave Energy Project

FO started with Wave Energy in 2000, and in 2004 the Wave Energy Converter *Buldra*, built as a platform with multiple point absorbers, was launched. Since then FO has tested out various concepts and built several different prototypes, all based on the point absorber principle. The series of experiences have led to the single body point absorber concept, as realized by our latest prototype *Lifesaver*. Point absorbers

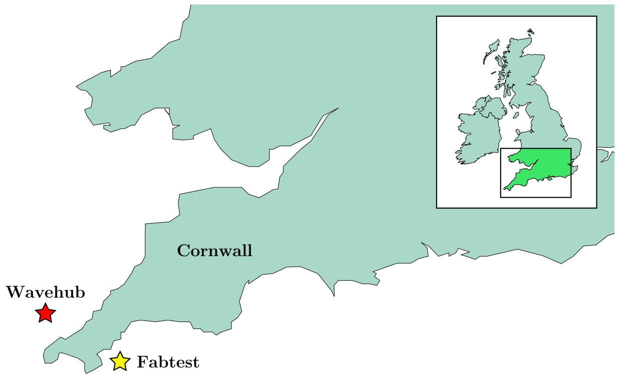

Fig. 3. Location of the UK test sites *Wavehub* and *FaB Test*

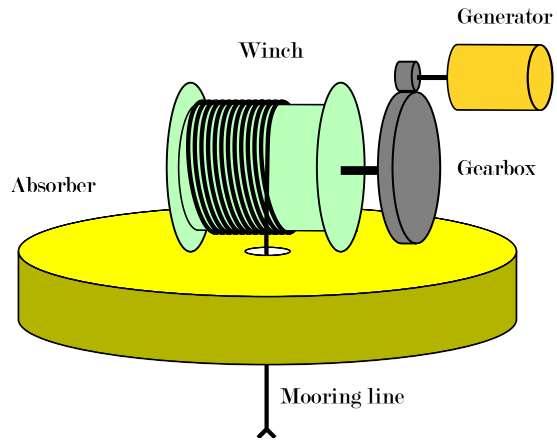

Fig. 4. Principal sketch of the WEC

are not the most efficient type of WEC measured in terms of captured energy, but have shown to be successful on total performance and cost of energy.

Until now, FO has operated four WECs based on the single body point absorber in real sea conditions. The first, named *B33*, was a small proof-of-concept device that was operated outside Risør, Norway during the autumn of 2007 and the winter of 2008. B33 showed good results, leading to the second device, named *B22*, which was equipped with a full-scale control, communication and production system. B22 was operated outside Risør, Norway from the summer of 2008 until the spring of 2009. Based on these experiences, FO started the next development phase in collaboration with a selected few European companies and universities through the *SEEWEC* project. This work led to the full-scale system *Bolt*® that was installed outside Risør, Norway in June 2009. Bolt has, as on December 22, 2010, produced 3 360 kWh of energy (Bjerke et al.) [3].

Based on the success with Bolt®, FO decided to use the knowledge and experience gained so far to proceed to the next generation design. An agreement with several UK companies was made with funding from the UK *Technology Strategy Board* (TSB). The goal of the project was to improve the Bolt® concept towards a commercial level where it can be launched at Wavehub [2], and hence the project name *Bolt2Wavehub*. The project resulted in the Lifesaver system and is planned to stay in operation at FaB Test until October 2013.

Until now, FO has not had a single serious event with any of the WEC systems, which has allowed for continuous long term testing in real sea conditions. This has proved invaluable for building experience with wave energy. Based on our experience, the problems and issues that arise in real sea conditions are multifaceted and goes beyond the scope of the tests undertaken.

II. System description

Lifesaver is based on the point absorber principle, which has been extensively researched and is well described in literature (Falnes et al., 2003, 2012) [4], [5]. FO has designed the floater structure towards high surface area and low mass to obtain a cost efficient system with respect to absorbed power. This geometry results in a high resonance frequency and thus leads to a *Response Amplitude Operator* (RAO) (Falnes, 2002) [6] close to unity for most of the relevant wave states. The system is therefore quite stiff and well suited for power production by passive damping control. The absorber is tightly moored to the sea floor with a PTO system that produces power from heaving, pitching and rolling motion. The point absorber system is independent of wave direction, which simplifies the mooring system and makes the system robust against mixed directional waves. Table I lists the general system properties of Lifesaver.

Floater outer diameter	16	m
Floater inner diameter	10	m
Floater height	1.0	m
Mass	55	tons
Water depth	55	m
Number of PTO slots	5	
Currently installed number of PTOs	3	
Production force per PTO	100	kN
WEC rated export power	70	kW
Total installed generator capacity	400	kW

TABLE I
Lifesaver key parameters

The PTO system is realized as a winch and rope system, as illustrated in Fig. 4. The generator can only produce power during upwards motion, and has to operate in motoring mode during downwards motion to maintain rope tension. The detailed control principle utilized by FO is described in our previous publications [1], [7]. The generator used on Lifesaver is a high performance permanent magnet machine manufactured by Siemens® and is designed for industrial servo applications. It has high torque output and low inertia, and is suitable for direct-drive applications with low gear ratio or entirely without gearbox. The machine also has high efficiency, as demonstrated by the efficiency map plotted in Fig. 6. The generator is powered through a full bridge

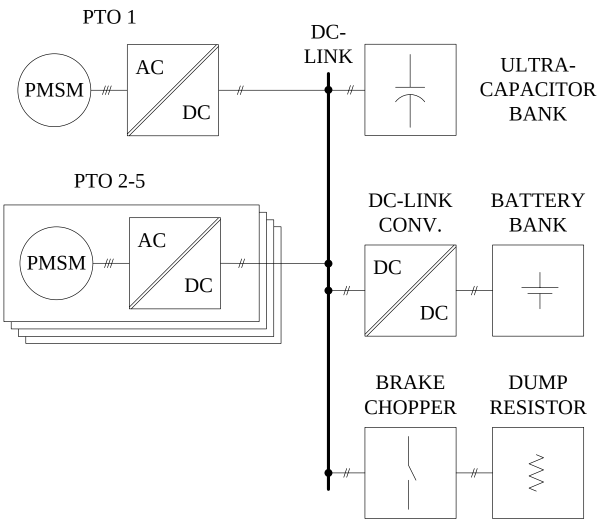

Fig. 5. Electrical system configuration on Lifesaver

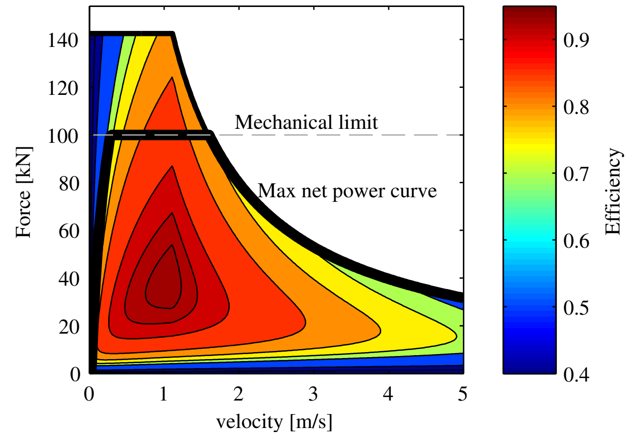

Fig. 6. Efficiency map for the generator used on Lifesaver

converter, which gives full control of the generator torque with high precision and quick response. In total, this gives a very powerful package with high performance that is well suited for the reciprocal wave motions. The electrical configuration of the WEC and the PTOs can be seen in Fig. 5.

WECs are different from most other power plants in that the prime mover operates with a sinusoidal-based velocity pattern. However, due to the irregularities caused by the random nature of ocean waves, and their varying frequency components, the peak to average power ratio will typically be around ten for a converter system like Lifesaver [8]. This is mainly due to the wave to wave variations that results in groups of waves referred to as *wave trains* [9]. This behavior results in a high peak to average power ratio and a poor power quality. FO has researched extensively on this issue and found that the power quality can be enhanced to an exportable level by clever system design without adding significant costs. This work has been published in a series of articles [7], [10]–[13].

III. Simulation Model

The simulation model used for Lifesaver is based on the work done at NTNU for the Buldra® platform (Molinas et al., 2007, Skjervheim et al., 2008) [14], [15]. The model solves Equation (1) for $\zeta(t)$ in the time domain, where the index i denotes the mode of motion, given by the six *degrees of freedom* (DOF), for the floater. The excitation force matrix $F_{e,i}$ contains the time dependent forces due to incident waves, and M denotes the mass of the system.

$$F_{e,i}(t) - F_{D,i}(t) = M\frac{d^2\zeta(t)}{dt^2} \qquad (1)$$

$$F_{D,i}(t) = F_{r,i}(t) + F_{d,i}(t) + C_i \cdot \zeta_i(t) + F_{PTO}(t) \qquad (2)$$

$F_{D,i}$ accounts for the sum of all the damping forces in Equation (2), where $F_{r,i}$ accounts for the time dependent forces on the floater due to radiation of waves. The term $F_{d,i}$ accounts for non-linear damping terms, mainly the drag forces. ζ_i is the time dependent motion of the floater, C_i is the restoring force matrix accounting for the hydrostatic pressure acting on the floater, and F_{PTO} is the time dependent force applied from the PTO. The PTO is modeled as a rope and winch system that is tightly moored to the sea floor. Detailed performance curves for Lifesaver is presented in our article [16].

Since the simulation is based on a detailed 6DOF model of Lifesaver, FO keeps the simulation model confidential. However, the high level of complexity is not essential to verify the basic principles presented in this work. It is possible for a third party to qualitatively verify the published results without detailed knowledge of the Lifesaver simulation model.

To simulate a wave state, a 20-minute time series of irregular waves is generated based on the JONSWAP wave spectrum [17]. The wave state is defined by the significant wave height h_s, the zero crossing period t_z and the wave direction θ. The subsequent excitation forces are then calculated and the simulation is performed for the full length of the time series. The simulation model also takes into account PTO and generator losses, and the model outputs a 20-minute time series of exported electrical power from the WEC. The simulation model has undergone many years of development and testing, and is verified against real production data from several prototypes, including Bolt and Lifesaver.

The simulation model also estimates the conversion efficiency so that accurate figures for exportable electrical power can be calculated. Most of the energy conversion loss occurs in the generator, and in the design wave state, the generator operates with an efficiency of around 80 %. This is the result of economical optimization of the system, and the relatively low system efficiency is the result of the large speed fluctuations enocuntered at the generator shaft. The details of this optimization are explained in our publications [1], [7],

[16]. A detailed efficiency map for the generator was produced by Siemens and is the basis for the efficiency plot presented in Fig. 6. This allows for calculating the generator power loss to a high level of precision. The mechanical efficiency of the winch and gearbox is estimated based on actual tests during PTO commissioning, where two PTOs were connected in a back-to-back configuration.

IV. RESULTS

Over the past year a large amount of operational data has been acquired. All measurements are logged continuously at 200 Hz while in operation, and gives a comprehensive database for analysis. Together with the advanced simulation model, this helps build a detailed understanding of the system, and complements the theoretical model of the system. The theoretical production from Lifesaver is listed in Table II and shows the simulated exportable power for all relevant wave states. This simulation is performed based on the current control parameter setting at Lifesaver, which is somewhat conservative. Thus, the presented figures are about 30 % lower than the expected production potential for Lifesaver.

Wavehub has been used as the design base for sizing the power system on Lifesaver. The wave state that produces most energy annually at Wavehub is hs = 2.75 m / Tz = 6.5 s, and this chosen as the design wave state for Lifesaver. The estimated production potential in this wave state is 70 kW on average, and this is selected as the name plate rating for Lifesaver. Defining rated power from a WEC is not straight forward as there usually is no clear and practical limit to how much power the WEC can produce. This is illustrated by the Lifesaver production scatter in Table II, which shows that the output is increasing with wave height, even though the power system is optimized for the design wave state. The method for defining rated power proposed by FO is site dependent and will vary with with the site case. However, it gives a good impression of the practical power that can be expected from the device, and that can be comparable to other renewable energy sources.

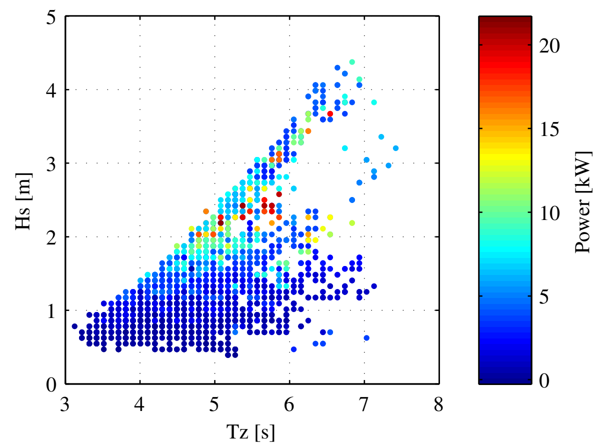

Fig. 7. Exportable electrical power for various sea states measured through one year on FaB Test

A. Actual power production

The actual measured power production from Lifesaver for the entire test period is plotted against the wave state in Fig. 7. The wave measurements are taken from a wave measurement buoy situated 1 km from the location of Lifesaver. There is a significant mismatch between this figure and the simulation results presented in Table II, and the figure also show a large spread in the produced output power. There are several reasons for this power discrepancy, some are related to the selected control parameters and some are related to the system:

- **Number of PTOs**
  The simulations are performed on a system consisting of five PTOs, while Lifesaver currently only has three PTOs installed.
- **Sub-optimal control parameters**
  After installation, much time was spent on verifying system operation through stepwise parameter changes. This has caused a large amount of production data with sub-optimal parameter settings, and is the cause of many of the poor production series close to the design wave state.

Wave height (hs) - [m]	Wave period (Tz) - [s]																				
	2	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	9	10	11	12	14	16	18	20	22
0.25																					
0.5	0.3	0.8	1.2	1.4	1.5	1.6	1.6	1.4	1.3	1.1	1.0	0.9	0.7	0.6	0.4	0.4	0.1	0.0			
0.75		2.7	3.6	4.0	4.2	4.5	4.4	4.0	3.8	3.3	3.1	2.9	2.4	2.1	1.7	1.5	0.9	0.7	0.5	0.3	0.2
1		5.3	6.9	7.6	8.0	8.5	8.3	7.7	7.3	6.5	6.1	5.7	4.8	4.2	3.3	2.9	2.1	1.7	1.3	1.0	0.8
1.25		8.9	11.4	12.4	12.9	13.6	13.5	12.4	11.8	10.5	9.9	9.2	7.8	6.4	5.4	4.4	3.6	3.0	2.4	1.9	1.6
1.5			16.9	18.1	18.8	19.7	19.7	18.0	17.1	15.4	14.4	13.3	11.0	9.1	7.7	6.5	5.7	4.6	3.7	3.0	2.6
2			30.9	31.8	32.7	34.0	33.2	31.3	29.5	26.6	24.7	22.9	19.5	15.8	13.8	12.3	10.7	8.9	7.2	5.9	5.1
2.5				47.9	48.3	49.5	48.5	45.6	42.9	38.7	36.4	33.5	28.3	23.5	21.0	20.3	17.3	13.9	11.8	9.6	8.4
3					63.9	65.3	63.0	59.9	56.5	51.1	48.2	44.8	37.3	33.6	30.2	28.6	23.6	19.7	16.6	13.7	12.3
3.5						80.0	76.8	72.8	69.1	62.7	59.6	56.1	48.3	45.1	41.4	37.7	30.7	25.9	21.7	18.3	16.4
4						92.9	89.2	84.4	80.3	73.7	70.2	66.3	58.9	54.9	49.6	46.3	37.7	31.6	26.8	22.8	21.0
5							109	104	98.9	92.9	88.5	84.8	78.3	72.7	67.1	61.6	51.1	43.3	37.5	32.3	29.4
6									113	107	103	99.4	93.5	86.7	81.4	75.6	63.7	54.4	47.6	41.9	38.5
7									123	119	115	111	105	98.2	93.2	86.5	74.7	64.9	57.5	51.0	47.4
8										127	124	119	114	107	103	96.3	83.7	74.7	66.9	60.2	56.1
9											129	126	121	114	110	103	91.5	83.1	75.0	69.1	65.1
10												130	125	120	116	109	98.1	90.0	82.3	76.5	73.0

TABLE II
SIMULATED EXPORTABLE POWER [KW] FROM LIFESAVER WITH FIVE PTOS AND CURRENT CONTROL SETTINGS

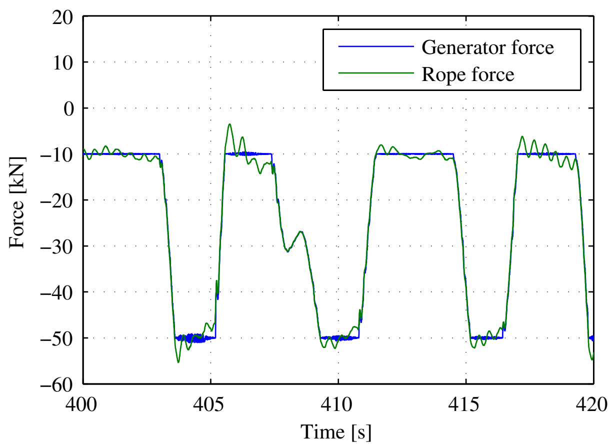

Fig. 8. Oscillations encountered in primary moorings due to system dynamics

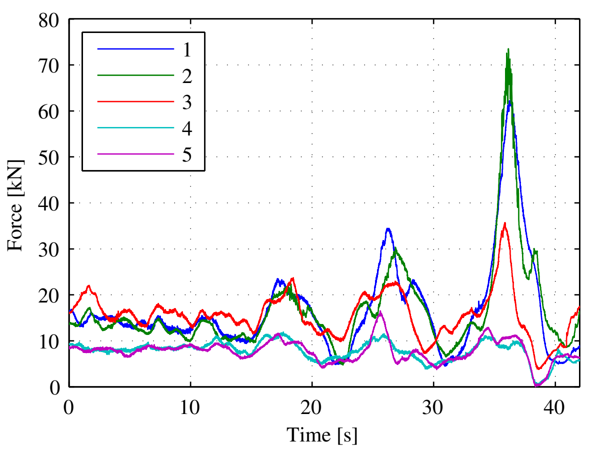

Fig. 9. Forces encountered in secondary moorings during normal production in a high sea state. The mooring lines are evenly distributed along the floater circumference in counter-clockwise order.

- **Unwanted system behavior**
  In higher production states, the winch and floater system occasionally showed rapid vibrations in the primary mooring force, as plotted in Fig. 8. This is due to unforeseen dynamic responses caused by the aggregate system configuration. This behavior is expected to be manageable through active generator compensation, but until such control is in place, conservative control parameters are set for the high wave states. This is the cause for the low production in the high wave states.
- **Secondary mooring system**
  Due to the strict regulations on FaB Test, Lifesaver is equipped with a strong five-point catenary mooring system, in addition to the regular production moorings. This is undesired from an energy point of view and is expected to cause some reduction in production. An example of the mooring forces experienced in the secondary mooring lines is plotted in Fig. 9.

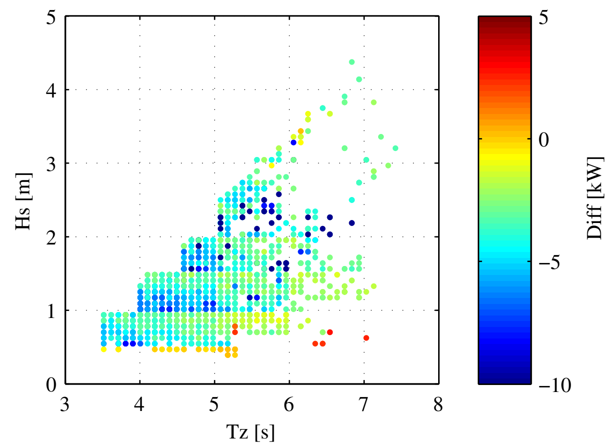

Fig. 10. Difference between actual produced power and simulated produced power for various sea states. Simulations are performed with actual parameters from test.

- **Floater freeboard**
  The floater was intentionally designed with very little freeboard to reduce the system cost and the horizontal forces, and to gain experience with required freeboard in an optimized system. Data from on-board draft sensors indicate that the waves are frequently over-topping the device already in the design wave state, and that some power production is lost to this.

To investigate further on these effects the simulation model was adjusted to match the number of PTOs and the control parameters used in the actual production series. Fig. 10 shows the difference between simulated produced power and actual produced power for all production series. The figure shows a good correlation between actual production and simulated production, but with a clear tendency of the actual production being lower than the simulated production. This is most likely caused by the combination of the secondary mooring damping and the unwanted over-topping of the device.

Upon close study of Fig. 10, several properties points out. The steps observed to the left in the plot are caused by wave states that where not simulated, and that has been taken out. The horizontal lines are caused by merging the observed wave states into the simulated windows of wave height and period, and there is an obvious trend of improved production towards the top of the wave height window. There is also a trend towards lower power deficit at higher periods, but the cause of this is currently not identified. Some groups of data points show large deviations from the general trend, mainly the lower row of orange to red dots and the band of dark blue dots between 2 and 3 m hs. The former is believed to caused by a measurement error in the wave rider buoy where long swells with high period and low amplitude is sometimes missed in mixed wave patterns. The latter group is probably caused by manual startup and shutdown, which will lead to a low average power for the measurement series. In an attempt to investigate further on the deviation between

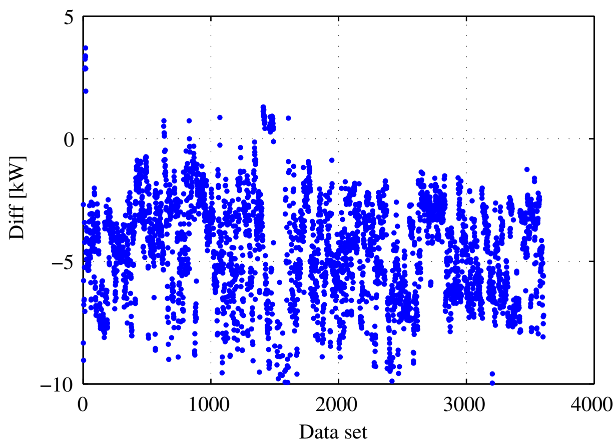

Fig. 11. Difference between actual produced power and simulated produced power for all logged data sets. Each data set lasts for 20 min. Simulations are performed with actual parameters from test.

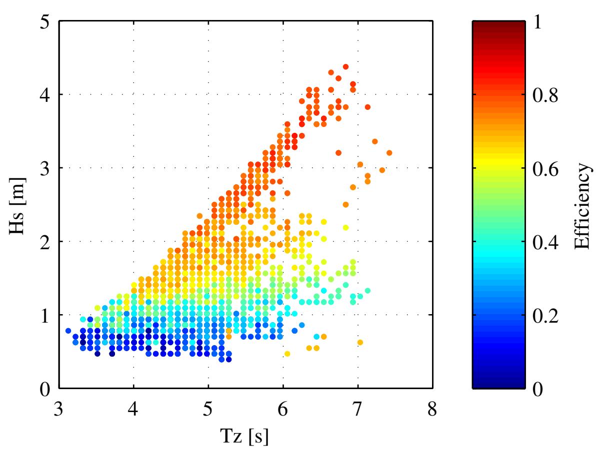

Fig. 12. Conversion efficiency: Ratio between actual exported electrical power and actual absorbed mechanical energy for various sea states

simulated and actual production, Fig. 11 was produced, and shows all production series up to date in chronological order. The figure could reveal time dependent effects on the actual production, but the figure does not give any clear trend towards this.

The generator system at Lifesaver estimates the actual torque on the generator shaft with high precision, and also measures the exported electrical power. This allows for accurate measurement of the generator efficiency and can be used to verify the figures obtained through simulations. The actual conversion efficiency is calculated and presented in Fig. 12, and includes the measured generator and inverter loss, in addition to the estimated mechanical loss. The figure shows that there is a strong dependency between system efficiency and wave height, which is supported by the theoretical work, and is mainly linked to the generator speed. As the production force follows the thick black line drawn in Fig. 6, it can be seen that the speed has to go beyond the 0.3 m/s threshold to enter force saturation before the efficiency starts to move towards a reasonable level.

As Lifesaver is currently not grid connected, the system has to produce net positive power to remain in operation. When the net production drops below zero, the system automatically shuts down and enters a power save mode with minimum power consumption. Shutdown typically occurs between 0.5 m and 0.6 m hs, but has been measured as low as 0.4 m hs for higher periods. This ability to maintain net power production at such low levels is unique for Lifesaver when compared to our earlier devices, and is made possible by the all-electric configuration. This allows for a high uptime, and can lead to almost continuous production on high energy sites.

B. System operation and availability

Lifesaver has been in operation for more than one year as this paper is being written, and has given significant experience on how to operate and service a WEC system over time. The key performance indicators up to date are listed in Table III and shows that the system has been available for production for the majority of the deployment time. A graphical presentation of the KPI is plotted in Fig. 13 and gives an impression of the time line of accessibility of the device, and the WEC production state. As experience with the system was gained, it was discovered that Lifesaver could maintain net positive power production down to hs = 0.5 m, and subsequently the wave height threshold for production startup was lowered in September 2012. This contributed to a significant share of the increased production uptime seen in Fig. 13 after this date, together with rougher weather as the autumn season set in. The accumulated energy production for the test period is plotted in Fig. 14.

Production hours	1 468	h
Electrical energy produced	4 644	kWh
Mechanical energy absorbed	7 192	kWh
Overall efficiency	64.6	%
Average power during production	3.2	kW
Time on site	376	days
Time ready for production	234	days
Time ready for full production	23	days
Longest continuous production period	24	days
Time available for service	211	days
Uptime hull	100	%
Uptime communication	98	%
Uptime scientific instrumentation	79	%
Uptime control dependent instrumentation	100	%
Uptime storm moorings	100	%
Uptime cooling system	99	%

TABLE III
KEY PERFORMANCE INDICATORS

It is important to note that the goal of the Bolt2Wavehub project is not to maximize power output, but to gain experience with all the operational aspects of operating a wave energy power plant. The FaB Test site was selected for its high availability for service and moderate wave climate. This allows for close monitoring of the device, which is crucial for providing practical feedback into the design process, and to

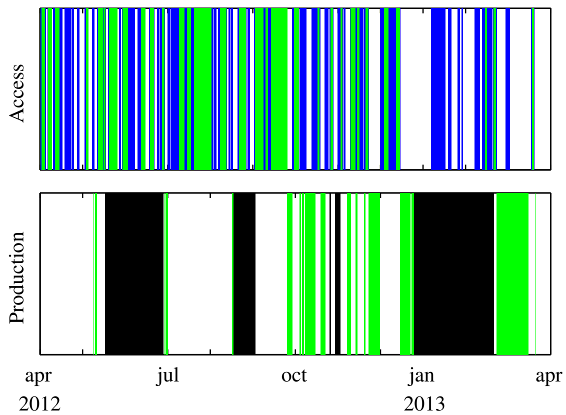

Fig. 13. **Upper plot:** Lifesaver accessibility for service (Green = accessible for heavy lift, Blue = accessible for service). **Lower plot:** Lifesaver production state (Green = production, White = ready for production, Black = Planned or unexpected downtime).

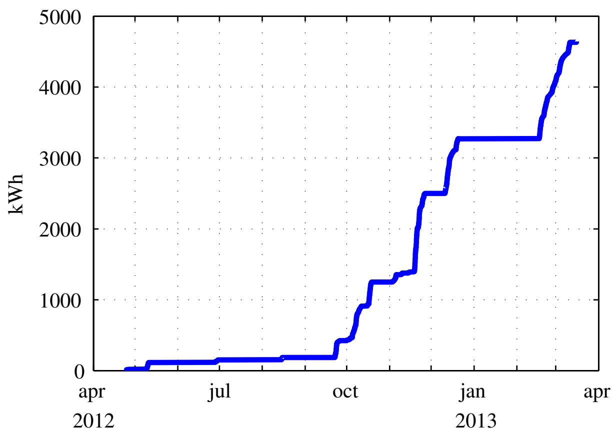

Fig. 14. Accumulated electrical energy produced at Lifesaver

understand the operational expenditures (OpEx) of operating the device. Moreover, the device has been used as a test bench for testing out different service methods. For instance, when some mechanical components had to be replaced in all the PTOs early in the test period, two different service approaches were tested out. The first PTO was lifted off and brought ashore for service, as shown in Fig. 2, while the second PTO was serviced on site. It became clear that heavy-lift operations between two moving objects demanded much calmer weather than on-board service, and the latter method has been adopted as the preferred approach. Except for the heavy-lift trial, all maintenance during the test period has been performed on site.

The most critical component on Lifesaver for reliable power production is the production mooring, usually referred to as *primary mooring*, due to the high wear on the winch. FO has put serious effort on investigating alternative line types and winch mechanisms. Most of the downtime on Lifesaver is related to the primary moorings, either due to planned maintenance for switching winch components, or due to unexpected failures in the primary mooring. In case of a failure, the other PTOs will still be operating as before, due to the independency of the individual PTOs. The winch concept currently pursued is a high performance system with high potential lifetime, but is more fragile to abnormal loads and wear mechanisms, which has caused problems in the early stages of testing. The issues with the primary moorings are not yet solved, but significant steps have been taken towards a reliable system in close collaboration with with the manufacturer, and we have reason to believe that the reliability will be improved to a level suitable for commercial operation within the remainder of the Bolt2Wavehub project. However, an increased level of maintenance and monitoring must be expected for a prolonged period, also in commercial operation, and makes high energy sites like Wavehub less attractive in the near future due to the difficult service regime.

V. Conclusion

Lifesaver has showed good performance at FaB Test with no major incidents or problems, and has demonstrated acceptable power production and reliability. The FaB Test test site has a moderate wave climate with good availability for service, and has proved to be a valuable test site for gaining operational experience and testing out various service methods. The practical work has shown a clear advantage towards on-board service, as opposed to bringing heavy equipment ashore. The main failure mode causing downtime on Lifesaver is failing primary moorings. This is a well known challenge with this kind of device, and FO is pursuing several paths towards solving this issue. Although the primary moorings are not yet performing flawlessly, significant steps have been taken in the right direction, and there is reason to believe that the problem will be solved within the remainder for the test period. Thus, Lifesaver should soon be ready to operate on a commercial level, although elevated monitoring and maintenance must be expected for still some time. Operation on high energy sites is therefore less likely in the near future.

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References

[1] J. Sjolte, I. Bjerke, A. Crozier, G. Tjensvoll, and M. Molinas, "All-electric wave energy converter with stand-alone 600vdc power system and ultracapacitor bank," in *2012 EVER International Conference and Exhibition on Ecological Vehicles and Renewable Energies*, march 2012.

[2] "The wave power climate at the wave hub site," Nov 2006, journal: Applied Wave Research Review of Wave Power Climate.

[3] I.Bjerke, E.Hjetland, G.Tjensvoll, and J.Sjolte, "Experiences from field testing with the bolt wave energy converter," in *Submitted to the European Wave and Tidal Energy Conference (EWTEC11)*, september 2011.

[4] J.Falnes and P.M.Lillebrekken, "Budal's latching-controlled-buoy type wave-power plant," in *5th European Wave Energy Conference*, 2003.

[5] J. Falnes and J. Hals, “Heaving buoys, point absorbers and arrays,” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 370, no. 1959, pp. 246–277, 2012. [Online]. Available: http://rsta.royalsocietypublishing.org/content/370/1959/246.abstract

[6] J. Falnes, *Ocean Waves and Oscillating Systems: Linear Interactions Including Wave-Energy Extraction*. Cambridge University Press, 2002.

[7] J. Sjolte, I. Bjerke, A. Crozier, G. Tjensvoll, and M. Molinas, “All-electric wave energy power take off system with improved power quality at the grid connection point,” in *Transmission and Distribution Conference and Exposition (T D), 2012 IEEE PES*, may 2012, pp. 1 –7.

[8] E. Tedeschi and M. Molinas, “Tunable control strategy for wave energy converters with limited power takeoff rating,” *IEEE Transactions on Industrial Electronics*, vol. 59, no. 10, pp. 3838–3846, 2012. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-84860439180\&partnerID=40\&md5=6c9b62f38538f73809c8838d19b8663a

[9] S. H. Salter, “World progress in wave energy 1988,” *International Journal of Ambient Energy*, vol. 10, no. 1, pp. 3–24, 1989. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/01430750.1989.9675119

[10] J. Sjolte, G. Tjensvoll, and M. Molinas, “All-electric wave energy converter connected in array with common dc-link for improved power quality,” in *Power Electronics for Distributed Generation Systems (PEDG), 2012 3rd IEEE International Symposium on*, june 2012, pp. 431 –436.

[11] ——, “Annual energy and power quality from an All-Electric wave energy converter array,” in *European Power Electronics and Motion Control and Applications Conference (EPE-PEMC’12)*, Novi Sad, Serbia, Sep 2012.

[12] ——, “All-electric wave energy converter array with energy storage and reactive power compensation for improved power quality,” in *Energy Conversion Congress and Exposition (ECCE), 2012 IEEE*, sept. 2012, pp. 954 –961.

[13] ——, “Power collection from wave energy farms,” *Applied Sciences*, vol. 3, no. 2, pp. 420–436, 2013. [Online]. Available: http://www.mdpi.com/2076-3417/3/2/420

[14] M.Molinas, O.Skjervheim, P.Andreasen, T.Undeland, J.Hals, T.Moan, and B.Sorby, “Power electroncis as grid interface for actively controlled wave energy converters,” International Conf. on Clean Energy Power (ICCEP07), Tech. Rep., 2007.

[15] O.Skjervheim, B.Sorby, and M.Molinas, “All electric power take off for a direct coupled point absorber,” Proceedings of the 2nd International Converence on Ocean Energy (ICOE2008), Tech. Rep., 2008.

[16] J.Sjolte, I.Bjerke, E.Hjetland, and G.Tjensvoll, “All-electric wave energy power take off generator optimized by high overspeed,” in *Submitted to the European Wave and Tidal Energy Conference (EWTEC11)*, september 2011.

[17] “Joint north sea wave observation project (jonswap)@ONLINE,” http://www.wikiwaves.org/Ocean-Wave_Spectra.